AUTOMATIC CONTROL OF CAMDEN - KRIEL RAW WATER PIPELINE

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A Dissertation Submitted to the Faculty of Engineering
University of the Witwatersrand, Johannesburg in partial
fulfilment of the requirements for the Degree of Master of Science

Johannesburg 1978

DEDICATION

I, Fred Catlow, hereby declare that this dissertation is my own and has not been submitted to any other university for a degree.

....
SIGNED

ABSTRACT

The objective of this study is to examine the performance of the proposed automatic control system for the Camden - Kriel section of the Usutu River Government Water Scheme, in the Eastern Transvaal of South Africa, by extended period time simulation of the hydraulic system and the logics of the control on a computer model.

The scheme comprises reservoirs located at Rietspruit, Davel and Kriel Power Station, two fixed speed electrically driven pumps at Camden and motor operated flow control regulating valves at Davel and Kriel. All of these are at remote, unattended stations and connected by a single pipeline 104 km in length.

The purpose of the control system is to regulate the flow of water in the pipeline in order to satisfy the total demand by controlling the position of the regulating valves and by automatically starting and stopping the pumps. The control is non-linear and is of the on-off or bang-bang type. The study sets out to optimize the control system and to recommend reservoir level and valve position control parameters which avoid unnecessary change of state of valves and pumps without restricting the pipeline flow necessary to meet the demand.

The model of the hydraulic system was compiled from well known hydraulic equations and design data supplemented and modified by actual test information, as and when this became available. The control strategy was derived from a rational approach to the problems involved, based on reasoned argument and experience. Although the process computer will not be operational for some time to come and therefore confirmation of the results is not possible at present, it can be confidently expected that the predictions made will be borne out in practice.

In all, more than forty five computer runs were carried out over simulated time periods varying from three and a half days to eleven and a half days for a variety of operating conditions. The results showed that satisfactory performance can be achieved by introducing additional reservoir level set-points. The system was optimized for minimum energy consumption by restricting operation of the second pump to full flow conditions only. Values of control parameters were obtained which satisfy all the major requirements of the control system.

ACKNOWLEDGMENTS

I wish to express my thanks to the Electricity Supply Commission and the Department of Water Affairs for permission to carry out this study, to my collegues at Escom for their invaluable help and assistance and to the staff of the University of the Witwatersrand for their encouragement and guidance.

In particular I wish to thank D.G. Hazelton of Escom for his assistance with the hydraulics, and Professor J.O. Flower and M.B. Dewe of the University.

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LIST OF PRINCIPAL SYMBOLS AND DIMENSIONS

A - Cross sectional area ....m^2
A_S - Reservoir surface area ....m^2
D - Diameter of pipe .... .m
g - Gravitational acceleration ....m/sec^2
H - Head ....m
h_f - Friction headloss ....m
K - Constant ....dimensionless
L - Length of pipeline ....m
Q - Flow of water ....m^3/sec
T,t - Time ....sec
V - Valve opening ....%
v - Mean velocity of water ....m/sec
WL - Water Level (Set Point) ....m
λ - Pipeline friction factor ....dimensionless
ζ - Valve friction factor ....dimensionless

SUBSCRIPTS

1 - Camden Rietspruit Pipeline
2 - Rietspruit - Davel Pipeline
3 - Davel - Kriel Pipeline
C - Camden
D - Davel
K - Kriel
R - Rietspruit
P - Pipeline
T - Throat (of valve)

Numerical subscripts are also used to distinguish between items where there is more then one - e.g. pumps and valves at Camden, different set points etc.

1. INTRODUCTION

The Usutu River Government Water Scheme in the Eastern Transvaal of South Africa is a major project of the Department of Water Affairs. The scheme is approximately 170 kilometres in length and will be capable of delivering approximately 2,9 cumecs from dams in the East to the power stations on the Highveld. The principal consumers are Camden (1 600 MW) and Kriel (3 000 MW) Power Stations. The scheme will also supply some water to Matla Power Station as well as townships and other minor consumers along the pipeline route.

The main scheme which comprises two parts:-

1. Jericho to Camden Pipeline
2. Camden to Kriel Pipeline

will be automatically controlled from a computer station via a fixed link UHF radio network.

The main function of the Camden - Kriel Pipeline control system will be to maintain the level of water at Kriel Power Station storage reservoir within predetermined limits and hence regulate the flow of water through different parts of the pipeline by controlling valves and fixed speed pumps located at remote unattended stations. Apart from physical limitations, the system will be constrained by certain interlocks in order to ensure the safe operation of the water scheme.

In order to examine the performance of the proposed automatic control system over extended periods of time it was decided to simulate the scheme under various operating conditions on a computer model. The study also sets out to optimize the control system and to recommend reservoir level and flow control valve position control settings which will satisfy the major requirements of the system.

1.1 Description of the Scheme

Fig. 1.1 is a schematic representation of the Camden - Kriel part of the Usutu Scheme. This comprises three sections:-

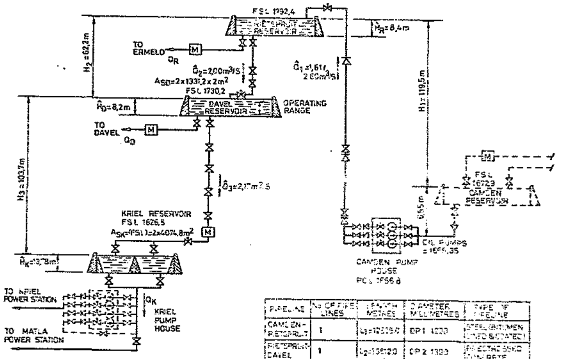
(a) A Rising Main 12,8 km in length which extends from a pump station located at Camden Power Station to Rietspruit Reservoir.

Three fixed speed pumps driven by 2 875 kW, squirrel cage induction motors are housed in the pump station. Of these there are two service pumps and a standby. The pumps operate in parallel, drawing water from Camden Reservoir and delivering it via a common 1,2 metre diameter pipeline to Rietspruit, an elevation of almost 120 metres.

A motor operated discharge valve is associated with each pump, which is closed when its pump is stopped or fully open when the pump is running. Intermediate positions are not permissible. Only two basic values of flow are therefore possible, corresponding to one or two pump operation.

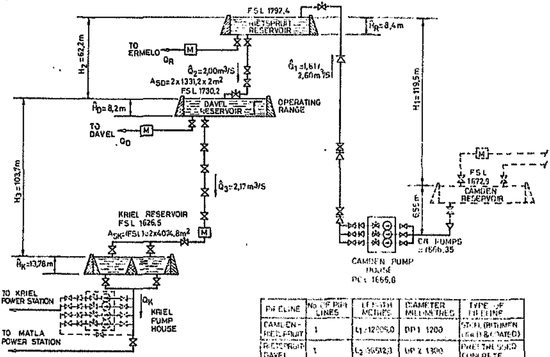
Water is delivered to Rietspruit via a stand pipe, located in the reservoir, the height of which is above the full supply level so that with the exception of variations in the suction head to the pumps, the static head between Rietspruit and the pumps will be a fixed value. As a result of this, if fluctuations in pump performance are to be disregarded, the two values of flow will be fixed.

(b) A Gravity Main 36,7 km in length from Rietspruit to Davel Reservoir.



PIPELINE	No OF PIPE LINES	LENGTH METRES	DIAMETER MILLIMETRES	TYPE OF PIPELINE
CAMDEN-RIETSPRUIT	1	L_1=12103,0	DP1 1200	STEEL (BITUMEN LINED & COATED)
RIETSPRUIT-DAVEL	1	L_2=13512,0	DP2 1300	PRESTRESSED CONCRETE
DAVEL-KRIEL	1	L_3=54392,0	DP3 1300	PRESTRESSED CONCRETE

Fig. 1.1 - Usutu River Government Water Scheme : Schematic of Camden - Kriel Section



PIPELINE	No OF PIPE LINES	LENGTH METRES	DIAMETER MILLIMETRES	TYPE OF PIPELINE
CAMDEN - RIETSPRUIT	1	$L_1 = 12005{,}0$	DP1 1200	STEEL (BITUMEN LINED & COATED)
RIETSPRUIT - DAVEL	1	$L_2 = 36512{,}3$	DP 2 1300	PRESTRESSED CONCRETE
DAVEL - KRIEL	1	$L_3 = 54392{,}0$	DP 3 1300	PRESTRESSED CONCRETE

Fig. 1.1 - Usutu River Government Water Scheme : Schematic of Camden - Kriel Section

The flow in this section of the (1,3 m diameter) pipeline is controlled by a motor operated regulating valve at Davel which in addition to full closed and full open has three intermediate adjustable positions.

The static head will vary between 53,8 m and 62,2 m depending on the water level at Rietspruit. It will, however, be unaffected by the level at Davel since water is discharged into Davel via a stand pipe equal in height to the maximum level.

The flow between Rietspruit and Davel will, therefore, depend on the degree of opening of the valve at Davel and variations in the static head.

(c) A Gravity Main 54,6 km in length from Davel to Kriel Reservoir.

The flow in this section of the (1,3 m diameter) pipeline is controlled by a motor operated regulating valve at Kriel which in addition to full closed and full open has three intermediate adjustable positions.

A stand pipe exists inside the Kriel Reservoir but as this will normally be below the water level, the static head for this section of the pipeline will be affected by the water level at Kriel as well as the water level at Davel (95,5 m to 117,48 m).

The flow between Davel and Kriel will therefore be a function of the degree of opening of the Kriel valve and variations in the static head.

Since the water level in each of the three reservoirs, Rietspruit, Davel and Kriel is a function of the inflow and outflow into each, the three sections of the scheme will interact with each other and the values of flow and reservoir level in the different sections will be interdependent.

The outflow from Kriel Reservoir will be dependent on the power generated by the station and the quantity of water consumed by Matla Power Station.

The outflow from Rietspruit and Davel respectively, will also be affected by the minor off-takes to Ermelo and Davel townships.

1.2 Description of Control System

1.2.1 Basic Principles

The problem of controlling the water level in a reservoir between set values is a simple problem when this involves only one or two variables. Referring to Fig. 1.2, q_o represents the outflow of water from the reservoir which varies with the demand at the point of consumption. The level in the reservoir is allowed to vary between L and L + ΔL, so that when the level reaches the low level represented by L, the valve V_i, controlling the inflow q_i is opened. Assuming that the inflow is greater than the maximum value of q_o, the reservoir fills and when the level reaches L + ΔL, the valve is closed.

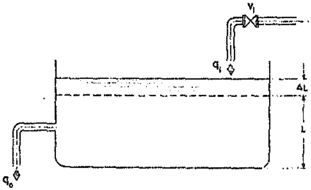


Fig. 1.2 - Simple Level Control

A refinement would be to provide a proportional controller so as to regulate the valve opening and hence the flow q_i in accordance with the outflow, thereby minimizing the fluctuation in level ΔL.

In the case of a reservoir supplying water to a power station the average outflow of water over a 24 hour period will be approximately proportional to the electrical load on the generators. The bulk of the water will be consumed in the power station cooling system and the remainder will be accounted for by boiler feed water make-up, potable water, water consumed by the mine which supplies the coal to the station and in some cases for ash transportation.

For the scheme question, Kriel Power Station Reservoir also supplies a certain amount of water to Matla Power Station.

1.2.2 Kriel Valve Control

For this scheme, it was decided, in order to avoid undue movement of the flow control valve at Kriel, to restrict the valve to four different openings, three of which are adjustable. These correspond to five set values of Kriel Reservoir water level. Above the first set point (full supply level), the valve will always be directed to fully closed, below that set point, the valve will either be closed or open one step depending on whether the water level is falling or rising (Fig. 1.3). and so on, until below the fifth set point the valve will always be directed fully open.

1.2.3 Davel Valve Control

The regulating valve at Davel is also restricted to four openings corresponding to five level set points in Davel Reservoir. In addition, the control system must protect against the dangerous condition of Davel Reservoir being emptied completely in the event of the outflow exceeding the inflow for prolonged periods of time. Should such a situation arise the Kriel valve must be throttled, regardless of the level of water at Kriel, to such an extent that the falling water level at Davel is halted. The constraint cannot be removed until the Davel level is no longer dangerously low.

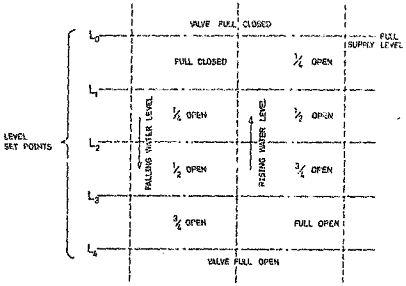


Fig. 1.3 - Regulating Valve Position Control

1.2.4 Camden Pump Control

The control of the pumps at Camden is based on a combination of absolute water level and rate of change of water level at Rietspruit Reservoir. The purpose of the rate of change control is an attempt to anticipate the demand for water at Kriel.

Should the rate of rise or fall not exceed the rate of change *set points (indicating light demand), absolute level set* points at the extremes of the operating range will initiate pump operation.

As with Davel Reservoir, protection is required to override the Davel level control and throttle off the Davel valve if the Rietspruit level becomes dangerously low (e.g. due to failure of a pump).

Since the reservoirs at Rietspruit and Davel are very much smaller than the reservoir at Kriel, they will be required to operate as balancing reservoirs and the water level allowed to fluctuate over the maximum safe operating range.

1.2.5 Set Points

In order to control the scheme effectively the following parameters must be optimized :-

Kriel Reservoir	-	*4 levels (assuming full supply* level fixed)
Kriel Regulating Valve	-	3 intermediate positions
Davel Reservoir	-	4 levels (excluding full supply level)
Davel Regulating Valve	-	3 intermediate positions
Rietspruit Reservoir	-	2 Rate of Change and 2 absolute levels

In addition to the above since each of the reservoirs consists of two halves, either one of which can be out of service for maintenance purposes, the control system must still operate effectively for half reservoir operation.

1.3 Functions of the Control System

The main functions of the control system are to:-

(i) supply sufficient volume of water at Kriel to meet the continuous needs of the Power Station.

(ii) optimize throughput in order that the maximum quantity of water over and above the needs of Kriel may be transported to Matla Power Station.

(iii) maintain a minimum storage volume of water in Kriel Power Station Reservoir sufficient for three days operation at normal electrical load factor.

(iv) supply the requirements of minor users such as municipalities and other consumers along the pipeline route.

(v) minimize pump starts/stops in order to avoid unnecessary strain on mechanical and electrical components due to mechanical shock or overheating.

(vi) economize on valve movement to avoid unnecessary wear.

(vii) protect against maloperation.

(viii) ensure satisfactory operation with one half of any particular reservoir out of service.

2. PROJECT RESEARCH AND LITERATURE SURVEY

2.1 Background

The project originated from a desire to provide effective control for the Usutu River Scheme using simple techniques which had been previously employed on other Escom systems. The background to the control system is as follows

(i) In the design of the Camden - Kriel pipeline certain advantages were to be gained by locating intermediate reservoirs at Rietspruit and Davel. †

As a result of the decision to provide full supervisory control the hydraulic engineers were able to specify extremely small reservoirs at Rietspruit and Davel thereby resulting in large savings in civil costs. Davel, the smaller of the two is less than one thirtieth of the size of Kriel and with full outflow and zero inflow can be drained in approximately 2,3 hours or in half this time for half reservoir operation.

Rietspruit is approximately 1,5 times the capacity of Davel, but still very much smaller than Kriel.

These reservoirs were believed to be adequate because they are intended primarily for operation as balancing reservoirs. A small amount of storage being required to provide the needs of minor consumers.

Full supervisory control with adequate protection can operate within smaller error margins, than is the case with manual control, because of its ability to operate quickly and to regulate the system automatically

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† Note: Davel was included as a break-pressure device thus avoiding the need to provide pipes at the Kriel end of the pipeline capable of withstanding the full static head from Rietspruit.

in order to avoid dangerous operating conditions. Apart from the reduction in civil engineering costs, additional benefits likely to accrue from incorporating supervisory control are improved performance and reduced maintenance costs.

(ii) Although the major purpose of the water scheme is to supply water to Kriel, minor consumers along the route have to be allowed for in the overall control scheme.

(iii) A control system based on maintaining constant level at Kriel would have required expensive variable speed pumps at Camden and proportional control for the flow control valve. As the power station demand is likely to remain substantially constant for prolonged periods of time the cost of providing variable speed pumps could not be justified and a proportional control scheme was deemed to be unnecessary. A much cheaper and simpler system of stepped control was therefore chosen, based on level control, as described in (1.2), but since this would involve a large number of adjustable parameters it was desirable to carry out a study in order to obtain the optimum settings for these parameters for a wide range of operating conditions.

(iv) Since it was decided to provide only two large fixed speed pumps at Camden, which are capable of supplying the maximum demand, it was desirable that the pumps should not be operated for very light demand unless the reservoir at Rietspruit reached a low level. This ensures that once a pump is started it will run for the maximum period of time before being stopped.

In order that a study could be carried out a certain amount of research had to be undertaken.

2.2 Defining the Water Scheme

In defining the water shceme the following information was obtained :-

(a) All relevant design data such as :-

- (i) Size and shape of reservoirs, their elevation above sea level, details of inlets, outlets and overspill weirs.
- (ii) Size, shape and length of pipelines, pipeline leakage and friction.
- (iii) Characteristics of pumps as obtained from performance tests.
- (iv) Manufacturers' data on pump discharge valves, size, type and operating time.
- (v) Manufacturers' data on flow control valves, size, type and operating time.

Much of the above data is given on Fig. 1.1

(b) Data obtained from the following Escom test reports :-

- (i) Report No. ME-R/47 "Usutu River Water Scheme, Camden Pumping Station : Contract No. W5071, No. 1 Electric Motor Driven Pump Set, Performance Tests".
- (ii) Report No. ME-R/53 "Usutu River Water Scheme, (i) Rietspruit - Davel Pipeline, (ii) Davel - Kriel Pipeline, Performance Tests".

(iii) "Usutu River Water Scheme, Davel - Kriel pipeline, Performance Tests on 'Krohne' Magnetic Flow Meter".

Details from these reports are given in Appendix C.

(c) Derivation of variables using information from :-

(i) "Fluid Mechanics for Civil Engineers" by N.B. Webber (publisher E. & F.N. Spon Ltd. 1965)

Chapters 1 - Properties of Fluids
4 - Basic Concepts of Fluid Motion
5 - Analysis of Pipe Flow
6 - Pipelines and Pipe Systems

(ii) "Fluid Mechanics" by V.L. Streeter (publisher Mcgraw Hill, Kogakusha 5th Ed. 1971)

Chapter 10 - Closed Conduit Flow.

This book gives some examples of programming in FORTRAN IV although these were not found to be relevant and were not used.

Refer to Appendix A.

2.3 Computer Programme

Three languages were available for programming, namely :-

(a) CSMP - "System/360 Continuous System Modeling Program" on the IBM Computer at the University of the Witwatersrand.

(b) FORTRAN - on either the IBM Computer at the University of the Witwatersrand or the CDC CYBER (172 & 174) Computer at Escom.

(c) CSSL - "Continuous System Simulation Language" on the Escom CDC Computer.

As it was more convenient to work at Escom it was decided to use the CDC computer. It was also decided to use a high level language and CSSL was chosen since :-

(i) It involved less programming effort. CSSL statements are compiled into FORTRAN automatically.

(ii) Unnecessary errors could be avoided by using tested Macro routines.

Whilst it is relatively easy for an untrained operator to write programmes in CSSL it suffers from a certain amount of inflexibility. In one instance a particular iteration problem could not be solved using CSSL statements and it was necessary to revert to FORTRAN. Nevertheless, CSSL will accept subroutines written in FORTRAN which therefore adds greatly to its flexibility.

The compilation time for this particular programme was not unusually long and was of the order of 6,5 seconds. One difficulty experienced was that of waiting for drivers to load CSSL from tape, especially during peak periods.

The plotting of results left much to be desired since these were not plotted as smooth curves and are limited to the first thousand data points. The latter meant that in order to obtain plots depicting several hours of simulated time, "continue" statements had to be introduced resulting in a number of discontinuous graphs, moreover, the range of the ordinate was adjusted by the computer to the range of the plotted variable over that time segment. One compensation is that the range of the abscissa could be specified so that if desired a particular section could be magnified in time, for instance during valve opening or pump start up.

2.4 Survey of Literature

Digital computers have been used to analyze and produce mathematical models of water supply systems for more than a decade. A large volume of literature has been written on the subject, in technical journals and in texbooks. So much so that time does not permit a complete survey of them all. It is intended therefore, to deal only with the salient points in a few of the papers and then to outline certain common areas between them and this particular study, making comparisons and observing trends that have taken place.

2.4.1 Water as a Compressible Fluid

Numerous papers have been written on this subject and although certain of them[1] deal with steady state conditions, by far the majority describe the simulation of transient effects in pipelines and in particular, water hammer[2].

2.4.2 Water as an Incompressible Fluid - Steady State Simulation of Water Distribution Networks.

In the design and analysis of water distribution systems it is traditional to calculate the flows and headloss in various parts of the system by solving certain basic equations (derived from the principles of continuity of flow and pressure) using the (iterative) Hardy Cross or similar manual methods. Digital computer models, however, can perform many more iterations and hence produce a more accurate solution in far less time[3]. Furthermore, a computer model is much more flexible and can be extended or modified to provide alternate solutions which will assist the hydraulics engineer to make basic design decisions or to formulate operating strategy. The latter will aid the choice of control system[4].

The most popular programmes appear to involve the Hardy Cross method for computing the head losses and flows and the Hazen - Williams formula for describing the headloss vs flow relationship[5]. Other methods include the finite element method[6], the linear theory method and the Newton - Raphson method[7]. The finite element method is designed to use either the Hazen - Williams or the Darcy - Weisbach formula for the flow-head loss relationship.

2.4.3 Dynamic Simulation of Water Distribution Networks

It would appear that many of the more recent studies have been based on the work of Gilman, Goodman and De Moyer[8] in the field of extended period simulation.

De Moyer[9] states, "Because interest is increasing in the automatic control of water-distribution systems, it is becoming more desirable to have a method for making rapid and accurate simulations of major system variables as a function of time". De Moyer proposes a macroscopic solution which deals only with major heads and flows associated with pumps and tanks in a distribution network rather than calculate all pressures and flows. He claims that the drawbacks associated with a complete network analysis for the purpose of control are that the solution time is excessive, certain inaccuracies result from the fact that consumptions must of necessity be concentrated into take-offs at the "nodes" of the simulated network and that pipe flow coefficients must be periodically measured or assumed. The macroscopic model determines empirical relations between variables derived from a statistical analysis of actual operating data. A model validation procedure is carried out in which tank flow is integrated to obtain tank depth at half hourly (simulated time) intervals and the error between simulated and measured values calculated. Optimization for least cost control can be carried out using dynamic programming techniques.

Kao and Bree[10] have produced a model for extended period simulation of water systems over a period of 24 hr - 48 hr under changing demand patterns. Unlike De Moyer's macroscopic model, this model can simulate a water distribution network of up to 1 500 nodes. The paper describes the application of efficient sparsity oriented programming techniques to provide a static solution and an integration scheme to link numerous static solutions to represent simulation of a system over an extended period of time.

2.4.4 Total Water Supply Control

A further development has been described in a paper by Hasegawa, Shimauchi and others[11] for the water supply system of Yokohama. The system includes :

(a) A model for predicting daily inflow of raw water into the system depending on daily and seasonal rainfall.

(b) A model for predicting the demand from the system.

(c) A model for operating the water supply system in accordance with the predicted water demand and the water available.

2.4.5 Major Water Transportation Systems

Unlike distribution networks for municipal water supply schemes there appear to be very few papers on water transportation systems. The probable reason for this is twofold :

(a) The steady state maximum flow conditions of such systems can be designed with a reasonable degree of accuracy, directly, without resorting to tedious iteration routines.

Because there are fewer unknowns, design errors are less likely to occur (e.g. oversizing pipes, etc.)

(b) The demand is normally reasonably steady since transportation is from a large dam or lake to a large reservoir.

As a result of the above, it would seem reasonable that the need for computer simulation is not as great as with distribution networks.

However, because of the advantages of automatic control systems in obtaining improved performance at less cost, computer analysis of such systems is likely to be more common in the future. Furthermore, computer models can be used to determine more efficient operating conditions by optimizing for such values as :

(i) Maximizing performance - hence reducing the desire to oversize pumps and other equipment thereby making most efficient use of the plant.

(ii) Minimizing operating costs - by operating the plant in such a way as to maintain the supply with least expenditure of energy - Alternatively, replenishing reservoirs at off peak periods when electricity tarriffs are low (not applicable in South Africa).

(iii) Maximizing plant life - reducing "wear and tear" on equipment in order to postpone replacement of plant and reduce maintenance.

In addition to the above, large water transportation pipelines are often the major "artery" to cities and industrial centres. Continuity of supply is therefore of great importance so that constraints may be imposed on the optimum solution because of the need for adequate protection of the water scheme and a high degree of reliability for the control system.

A paper on the National Water Carrier of Israel by Shamir and Damelin[12], describes an optimum policy for operating that scheme. Pumping operations are restricted to certain hours each day by the electricity supply authority and additional constraints are imposed by safety considerations. The simulation of the scheme is achieved by collecting statistical data of actual flows and levels in the system. The system comprises pipes, canals, reservoirs and pumping stations.

2.4.6 Comments and Comparisons

In this study water has been regarded as an incompressible fluid. As mentioned, studies which consider water as a compressible fluid are outside the scope of this project. Studies of water hammer[2] were included in the design of the Usutu water scheme in order to ensure that the pipeline could withstand the maximum pressure likely to be encountered in practice. Such transient effects however are not relevant to this particular project because they would not be observable on the time scale considered here.

Papers on water distribution networks are only relevant to this study where the mathematics is also applicable to single pipeline installations. The most widely used equation to describe the flow vs headloss relationship for distribution networks is the Hazen - Williams formula.

$$Q = 0{,}849 C_H \, A R^{0{,}63} \, S^{0{,}54} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.1)$$

in which C_H is the Hazen - Williams roughness coefficient, S is the slope of the energy line h_f/L, R is the hydraulic radius. C_H can be obtained for a pipe of a particular material from tables.

According to Jeppson[7] the most fundamentally sound method for computing the friction headlosses is by means of the Darcy - Weisbach formula

$$h_f = \frac{\lambda \ L v^2}{2g \ D} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

in which λ, is a dimensionless friction factor and is constant if turbulent flow is assumed, D is the pipe diameter, L is the length of the pipe, v is the average velocity of flow and g is the acceleration of gravity. For Usutu a value of λ, (which also included minor losses) was calculated from actual performance tests.

The Newton - Raphson iteration technique is considered to be superior to the Hardy - Cross method for computer applications. Jeppson[7] states ".... if quadratic convergence occurs, fewer iterations are needed to obtain a solution with a given precision". For the Usutu model the Newton - Raphson method was only used to obtain the relationship between pump flow and discharge valve opening (or closing) under varying pumping head during pump starting and stopping operations.

The papers which describe time simulated models mostly use statistical methods. Changes in flow due to pump operation are simulated by discrete changes. The Usutu model on the other hand evaluates a continuous relationship between time dependent variables and pump and valve operations are simulated as closely as possible so that the flow changes gradually, thereby giving a truer resemblence to the actual system.

3. THEORETICAL DESCRIPTION OF MODEL

3.1 Purpose of Model

The purpose of this particular work is to produce a computer model which :-

(i) Simulates the Camden - Kriel part of the Usutu River Water Scheme by using known physical data and the laws of fluid mechanics to derive mathematically, variable quantities such as the flows in different pipeline sections and the levels at various reservoirs for different operating conditions at any particular instant in time.

(ii) Simulates the automatic control system by means of a series of logical statements, so that from a knowledge of the simulated flows and levels decisions can be made such as whether to start or stop pumps, open or close flow control valves (and by how much).

(iii) Operates over a desired period of simulated time such as an hour, a day, a week, etc., so that the performance of the control system can be assessed.

Whilst it is difficult to predict the demand for water over a short period of time (such as one hour), the average demand over a longer period (such as one day) can be predicted with a fair degree of accuracy and therefore valuable operating data can be obtained.

(iv) Enables adjustable parameters to be set at their optimum values in order to minimize the number of pump starts/stops whilst maintaining the water level at Kriel Reservoir within predetermined limits.

The model could be used to optimize other operating conditions or to predict the operating costs of the system although that is not included in the scope of this project.

3.2 Assumptions Made

In order to simplify the mathematics the following assumptions have been made :-

(1) Water is an incompressible fluid. This assumes that the water column in the pipeline behaves as a rigid rod so that any change brought about at one end of the pipeline is immediately felt at the other to the same extent. In actual fact water is elastic (as is the pipeline) and any sudden changes in pressure at one end of the pipeline will not immediately be felt at the other due to the time constants of the system. It can be shown, however, that if the acceleration and deceleration of the water column is at a uniform rate which is less than a certain critical value the surge pressure is very small and may be neglected (Ref. 13 pages 132 - 134).

In designing the scheme, the hydraulic engineers specified the following:-

(a) Valve minimum operating times so that the rate of change of velocity of water is less than the critical value.

(b) Although pump motors are direct-on-line started, they are started against closed discharge valves. The valve is then opened gradually when the pump is operating at full pressure (head).

(c) When a pump is stopped, its discharge valve is first closed before the motor is stopped.

(The above features have been incorporated in the computer model).

Certain conditions can occur, such as electric power failure which can give rise to surging. Extensive studies were conducted by the hydraulic engineers in the design of the system to ensure that the installation would be sufficiently protected to withstand such pressure surges.

(2) Any transients which do occur may be neglected. This is justified since such effects will affect the results by a negligible amount over the time periods considered.

(3) Climatic variations have been neglected - i.e. the change in volume of a reservoir due to evaporation or due to rainfall is negligible in comparison with the change in volume due to operating flow values.

(4) Control valves move linearly from their initial position to final position and return via the same path. This is justified since the valves are of a high quality and the hysteresis in the links is minimal.

(5) Pipeline leakage is negligible in comparison to the normal flow through the pipeline. This has been borne out by tests conducted on the pipeline.

(6) Since transport delays have been assumed to be zero it follows that inertial effects may be neglected.

(7) Turbulent flow has been assumed throughout. Hence the friction factor, λ, for a particular pipeline is constant. (λ will actually vary (See Table 4.1) but this variation is small and can be neglected).

3.3 Calculation of Variables

An examination of Fig. 1.1 will show that the principal variables involved in the analysis are :-

Q_1 - the flow in the Camden - Rietspruit pipeline

H_R - the water level of Rietspruit Reservoir

Q_2 - the flow in the Rietspruit - Davel pipeline

H_D - the water level at Davel

Q_3 - the flow in the Davel - Kriel pipeline

H_K - the water level at Kriel

The flow Q_K from Kriel Reservoir, which represents the demand, is obviously fundamental but cannot be controlled by the system. Similarly the flows Q_R and Q_D, from Rietspruit to Ermelo township and Davel to Davel township respectively, which are of minor significance cannot be controlled.

As stated previously the controlled variables are interdependent.

3.3.1 Revervoir level

The change ΔH_R in water level H_R over a period of time Δt at Rietspruit is a function of the inflow, Q_1, and the outflow, Q_2 and Q_R, from Rietspruit.

$$\text{Hence,}\quad \Delta H_R = f\,(Q_1, Q_2, Q_R)\ \Delta t \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.1)$$

Neglecting minor effects (see Assumptions Made) the change in water level, ΔH_R, at Rietspruit over a period of time from t_o to t_1 (Appendix A) is :-

$$\Delta H_R = \int_{t_o}^{t_1} \frac{Q_1 - (Q_2 + Q_R)}{A_{SR}}\,.dt \ \ldots\ldots\ldots\ldots\ldots (3.2)$$

where A_{SR} is the surface area of water in Rietspruit Reservoir.

Similar expressions can be obtained for the change in water level at Davel and Kriel :-

$$\Delta H_D = \int_{t_o}^{t_1} \frac{Q_2 - (Q_3 + Q_D)}{A_{SD}} .dt \ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

and

$$\Delta H_K = \int_{t_o}^{t_1} \frac{Q_3 - Q_K}{A_{SK}} .dt \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

where A_{SD} and A_{SK} represent the surface area of water in Davel Reservoir and Kriel Reservoir respectively.

Since Kriel Reservoir is not cylindrical in shape, A_{SK} is not a constant value and varies with the depth of water in the reservoir. An expression for A_{SK} is derived in Appendix B.

The above expression for equation (3.2) is written in CSSL language as :-

HRDOT = $(Q_1 - Q_2 - Q_R)$/ASR

HR = INTEG (HRDOT, HRO)

where HRO is the initial value of HR at time $T = t_o$.

Similar expressions have been derived for the level H_D at Davel and H_K at Kriel.

3.3.2 Single pump flow

As stated in 1.1(a) above the inflow, Q_1, to Rietspruit can be either of two values, the flow produced by one Camden pump operating Q_{C2}, or two pumps $(Q_{C1} + Q_{C2})$.

The flow is dependent on the pumping head, the friction of the Camden - Rietspruit pipeline and the static head between Rietspruit and Camden Reservoirs (See Fig. 1.1).

A characteristic of head versus flow for the Camden pumps was obtained from pump performance tests and is given in Appendix C.

This characteristic was included in the computer programme as a table, P1TAB.

From the laws of fluid mechanics (Appendix A) an expression can be obtained for the pipeline friction head.

$$h_{f1} = \frac{\lambda_1 L_1 \; v_{P1}^2}{2g \;\; D_{P1}} + \frac{\zeta \, v_T^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

λ_1- the pipeline friction factor was calculated from actual pump performance tests and the valve friction factor, ζ, was obtained from manufacturer's curves (Appendix B). The valve friction factor is a function of the degree of opening of the valve. The valve characteristic was fed into the computer as a table, V1TAB.

Because of the stand pipe inlet to Rietspruit Reservoir, the static head between Rietspruit and Camden is dependent only upon variations in water level at Camden Reservoir. As computation of the water level at Camden is beyond the scope of this study and since it is likely to be small, a fixed value for static head was used. This was obtained from site performance tests (Report ME - R/47 - Appendix C).

When a pump is started, full pumping head is developed against a closed discharge valve. The discharge valve is then opened slowly at a steady rate. As the valve opens the valve friction factor steadily decreases from an infinite value with the valve fully closed. Water begins to flow and increases as the valve friction is reduced.

Whilst the flow increases, the pumping head is reduced until an equilibrium is reached, known as the pump duty point. At this point the difference between the pumping head and the static head is just sufficient to sustain the flow and is equal to the friction head.

If the pumping head is denoted by H_{C1} and the static head by H_1

$$H_{C1} - H_1 = h_{f1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

and substituting for the expression above, (3.5), for h_{f1}

$$H_{C1} - H_1 = \frac{\lambda_1 L_1 v_{P1}^2}{2g D_{P1}} + \frac{\zeta v_T^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

Substituting for the pipeline velocity v_{P1} and the valve throat velocity v_T this can be written as:-

$$H_{C1} - H_1 = \frac{16}{2g\pi^2 D_{P1}^4} \left(\frac{\lambda_1 L_1}{D_{P1}} + \zeta \frac{D_{P1}^4}{D_T^4} \right) Q_1^2 \quad \ldots\ldots\ldots (3.6)$$

$$= \{ K_{1.1} + K_{1.2}\zeta \} Q_1^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

$$\text{or} \qquad Q_1 = \sqrt{\frac{H_{C1} - H_1}{K_{1.1} + K_{1.2}\zeta}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

$$\text{where } K_{1.1} = \frac{16\lambda_1 L_1}{2g\pi^2 D_{P1}^5} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

and $$K_{1,2} = \frac{16}{2g\pi^2 D_T^4} \quad \text{.............................(3.10)}$$

Thus, since the static head, H_1 is constant, the flow Q_1 is a function of the pumping head and the valve opening. Note that H_{C1} in turn is a function of Q_1.

The problem was solved on the computer by iterating for Q_1 using the Newton - Raphson method, from an initial value for Q_1 of zero (Appendix D).

3.3.3 Dual Pump Flow

To simulate the flow from two pumps, two more tables P2TAB and V2TAB, were added to the computer programme, the characteristics of the second pump and its discharge valve.

When a second pump is started and its flow Q_{C2}, gradually increases, the pipeline friction head will increase. As a result of this, the balance between the head generated by the first pump and its flow will be disturbed, causing the head of that pump to increase and its contribution to the total flow to decrease slightly.

This trend will continue until the discharge valve of the second pump is fully open and the first pump will be operating at a new duty point.

Again the Newton - Raphson iteration method was use. CSSL was found to be inadequate for this calculation and the problem was solved by programming in FORTRAN (using nested DO loops).

As a fixed value was used for the static head and therefore the flow was not dependent on other variables in the system, except the arbitrary set points of Rietspruit level HR and HRDOT used in the control system, the results of this part of the study were used in tabulated form in the main programme in order to economize on computer time. Thus VC1TAB and

VC2TAB were compiled to plot valve opening versus flow. VC1TAB represents valve 1 plus valve 2 position in order to effect the changes in pump 1 flow, Q_{C1}, when pump 2 is operating.

3.3.4 Flow in a gravity pipeline

For a gravity pipeline, flow takes place by virtue of the potential energy of the water in the reservoir at the higher elevation (and hence its static head). The flow is controlled by the pipeline friction which is regulated by the degree of opening of the control valve. The static head is not constant and varies with the level of water in the higher reservoir.

The friction head is the same as the expression (3.4.4) used previously for a rising main. Thus for the Rietspruit - Davel pipeline

$$h_{f2} = \frac{\lambda_2 L_2 v_{P2}^2}{2g\, D_{P2}} + \frac{\zeta_D\, v_{TD}^2}{2g} \quad \ldots\ldots (3.11)$$

and is equal to the static head

$$H_2 + H_R = h_{f2} \quad \ldots\ldots (3.12)$$

As previously, an expression can be obtained for Q_2:-

$$Q_2 = \sqrt{\frac{H_2 + H_R}{K_{2.1} + K_{2.2}\,\zeta_D}} \quad \ldots\ldots (3.13)$$

where

$$K_{2.1} = \frac{16\lambda_2\, L_2}{2g\pi^2\, D_{P2}^5} \quad \ldots\ldots (3.14)$$

and

$$K_{2.2} = \frac{16}{2g\pi^2 D_T^4} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.15)$$

This has been written into CSSL as :-

```
NUM2     =    ZETADR   * (H2 + HR)
DEN2     =    (K21  * ZETADR) + K22
Q2       =    SQRT (NUM2/DEN2)
```

ZETADR is the reciprocal of the friction factor,   , for the Davel valve. The reciprocal was used since the computer cannot accept an infinite value of *zeta*.

ZETADR is obtained from the characteristic for the Davel valve and is written in the programme as :-

```
ZETADR    =    VDTAB (VD)
```

where VD is the percentage opening of the valve.

A similar expression to the above was used to obtain flow in the Davel - Kriel pipeline.

3.3.5 Valve Opening

Valve movement was simulated by a positive or negative ramp which can be halted at the desired position.

Initially, various CSSL functions were tried unsuccessfully to obtain the desired results. Eventually the best results were obtained by using a *straight integrator* with a +1.0, 0.0, -1.0 direction multiplier to obtain valve opening movement, halt and valve closing movement respectively.

To test if the valve had reached *its desired* position, conditional statements were used to set the value of the multiplier. As the computer could not calculate exactly the desired position a tolerance band was set. Thus if *UBD* is the desired opening for the Davel valve and ± 0,005% the tolerance:-

```
UBDM      =    UBD  -0.005
UBDP      =    UBD  +0.005
IF ((VDACTL.GE.UBDM) and (VDACTL.LE.UBDP)) DIRD = 0.0
IF (VDACTL.LT.UBDM) DIRD  =  1.0
IF (VDACTL.GT.UBDP) DIRD  = -1.0
VDDOT = DIRD * VDV
VD  =  INTEG (VDOT, VDO)
```

Where VDACTL represents actual valve position
VDV " valve velocity
VDO " valve initial position

Logic operators are defined as

.LT.	less than
.LE.	less than or equal to
.GT.	greater than
.GE.	greater than or equal to

Therefore if the desired valve opening is, for example, 25%, UBD is set to 25% and the valve will then open or close until it reaches the 25% position.

3.4 Control System

As explained in 1.2 above, the control scheme measures the water level in a particular reservoir and compares the value obtained with the appropriate set points. If a set point has been exceeded (positively or negatively) it will then take appropriate action.

The control system is represented in the computer programme by a number of conditional statements. These test the computed water level and then allocate a number to it which corresponds to a level band between two set points. This number is also equivalent (in the case of the gravity pipelines) to a particular desired valve opening. It is decremented by one for a falling water level.

The control statements for the Camden pumps, Daval and Kriel valves are given in Appendix E.

3.5 The Complete Simulation

The programme comprises the following structure statements :-

INITIAL - Defines a block of statements that are to be executed only at the beginning of a simulation run - these supply the complete data; parameters, constants and initial conditions required by the dynamic block.

DYNAMIC - Introduces statement specifying terminating condition.

DERIVATIVE - Defines those statements which describe the dynamic system for each of the three pipeline sections.

TERMINAL - Not used.

4. VERIFICATION OF MODEL

4.1 Preface

In describing the model, expressions were derived for:

- the variation in reservoir water level over a period of time evaluated from the change in volume of the particular reservoir (obtained from inflow and outflow).

- the flow in a section of the pipeline from the static head, pipeline friction and valve opening (or pumps operating).

The hydraulic model is built up from these expressions. For convenience the model is divided into three parts corresponding to:-

(a) Camden - Rietspruit pipeline

(b) Rietspruit - Davel pipeline

(c) Davel - Kriel pipeline

The control system model is designed to take the following action.

(a.i) Compare the simulated level and rate of change of level at Rietspruit against chosen set points and evaluate how many pumps should be operating at Camden.

(a.ii) Compare the actual number of pumps operating at Camden with the desired number and, if these are not the same, start or stop pumps to achieve the desired result and hence regulate the flow in the Camden - Rietspruit pipeline.

(b.i) Compare the simulated level at Davel against chosen set points and evaluate the desired position of the Davel regulating valve.

(b.ii) Compare the actual and desired position of the Davel valve and command the valve to open or close to the desired position and hence regulate the flow in the Rietspruit - Davel pipeline.

(c.i) Compare the simulated level at Kriel against chosen set points and evaluate the desired position of the Kriel regulating valve.

(c.ii) Compare the actual and desired position of the Kriel valve and command the valve to open or close to the desired position and hence regulate the flow in the Davel - Kriel pipeline.

The control system will therefore act to replenish the water removed from a particular reservoir by regulating the valves and pumps under its command. If the outflow is high it is required to increase the inflow, or if the outflow is low to curtail the inflow. The manner in which this is carried out will be discussed in the following chapter on control strategies.

In practice, action will be initiated by the demand at Kriel and Matla power stations, the outflow from Kriel Reservoir will be compensated by opening the inlet valve to Kriel and this in turn will cause the resulting inflow to Kriel to draw down the level at Davel. To counteract this, the Davel valve will be opened and water will flow into Davel from Rietspruit which will in turn cause the water level at Rietspruit to be reduced and eventually one or two pumps at Camden to be started.

In order to verify the model, it will only be necessary to show that the simulated flow rates from the model are the same as those of the actual installation for different valve and pump configurations. This follows because the simulated flow (for a particular valve opening or number of pumps running) is calculated from the characteristics of the scheme - that is, all the values contained in equations (3.8) and (3.13) must be correct.

Trial simulation runs were conducted to check the validity of the mathematics used in the model. The results were then compared with actual values obtained from site performance tests.

4.2 Adjustable Parameters

Initially values were used for the adjustable set points which could be regarded only as "intelligent guesses".

The intermediate values for the valves at Davel and Kriel were given arbitrary values of 25%, 50% and 75% opening.

The reservoir level settings were those which it was intended to use for the purpose of commissioning and testing the auto control software for the actual control system. As a result these values tended to be conservative.

Before attempting to undertake any optimization of these settings it was necessary to check that the computer model was a true simulation of the actual system.

4.3 Trial Simulation Run

In the first successful run, the Kriel reservoir level was set low (1[illegible],6 m) in order to call for a fully open valve at Kriel and hence actuate the entire system. At the start both Davel and Kriel valves were fully closed, Rietspruit and Davel reservoirs were set to full level and the number of pumps running was set to zero. The run was carried out over a simulated time of 30 000 seconds - i.e. approximately 8 hours 20 minutes.

In the simulation the following sequence of events occurred:-

1st 10 000 Seconds (2 hours 47 minutes)

(i) With a low water level at Kriel, the Kriel flow control (regulating) valve was called upon to open fully.

(ii) With a fully open valve at Kriel, the flow between Davel and Kriel increased to its maximum value.

(iii) Since the Davel valve was closed and the output from Davel was the maximum, the water level at Davel dropped rapidly. As the water level fell below the various set points, the Davel valve was opened progressively in steps until it was fully open.

(iv) Maximum flow was established between Rietspruit and Davel.

(v) The Rietspruit reservoir level dropped rapidly and two pumps were started at Camden on reaching the low set point (Rate of change control not set).

At this stage (10 000 seconds) there was maximum flow in all three pipelines, the Kriel reservoir was filling up, the level at Davel was still dropping slowly and the level at Rietspruit was rising.

2nd 10 000 Seconds (5 hours 33 minutes)

(vi) The rising level at Kriel caused the valve to close to 75% then 50% and 25% progressively as the water level rose above the set points.

(vii) As the flow from Davel to Kriel decreased, the water level at Davel started to rise and the Davel valve closed progressively to 75%, 50% and 25% open.

(viii) As a result of throttling the Davel valve, the Rietspruit - Davel flow decreased and caused the water level at Rietspruit to rise at an even faster rate. This caused first one and then two Camden pumps to be stopped.

(ix) With no inflow to Rietspruit and the Davel valve still 25% open the water level at Rietspruit started falling.

At the end of 20 000 seconds the flow in the Rietspruit - Davel - Kriel pipelines had fallen to approximately "quarter of the full value" and the flow from Camden to Rietspruit was zero. Kriel reservoir was still filling slowly as was Davel, and Rietspruit level was dropping slowly.

3rd 10 000 Seconds (8 hours 20 minutes)

(x) Davel water level reached full supply and closed the Davel valve completely.

(xi) With no flow from Rietspruit [illegible] Davel, the Rietspruit water level stopped falling and held at a steady value.

(xii) As the Kriel valve was still 25% open the Davel water level started to fall.

(xiii) Kriel reservoir attained full level, the Kriel valve was fully closed and the Davel level held steady.

After 8 hours 20 minutes, Kriel reservoir was full, Rietspruit and Davel were below full level (but not low enough to initiate action) and the system had attained equilibrium.

The values of flow obtained from the computer are given in table 4.1. below.

Table 4.1

Comparison of Pipeline Flow obtained from Computer Simulation and Site Performance Tests

Pipeline	Pump/ Valve	Simulated Flow m^3/s	Test Values m^3/s	
			Measured	Corrected
Camden - Rietspruit	1 Pump	1,61	1,63	1,61
Camden - Rietspruit	2 Pumps	2,60	-	
Rietspruit - Davel	100%	2,00	1,98	2,00
Rietspruit - Davel	75%	1,69	-	
Rietspruit - Davel	50%	1,25	-	
Rietspruit - Davel	25%	0,69	-	
Davel - Kriel	100%	2,17	2,16	2,17
Davel - Kriel	75%	1,61	1,62	
Davel - Kriel	50%	1,09	1,07	
Davel - Kriel	25%	0,56	0,54	

As can be seen the maximum flow values are identical to those obtained from volumetric tests (corrected). This is hardly surprising since the value of friction factor for each pipeline section, which was used in the compu [illegible] rogramme was *calculated from test results. The actual* [illegible]*s measured on* test were corrected for differences in head. The large correction for the Camden pumps was due to the fact that at the time of the tests, the Camden Reservoir was not in service and the pump suction was from Camden Power Station Reservoir. This accounted for a difference in static head of about 3,3 metres. The correction in the Rietspruit - Davel flow was necessary because the spare valve was installed at Davel at the time of the tests and this valve had a slightly higher value of friction factor than the correct valve. The discrepancy in the Davel - Kriel flow is accounted for because of different values for reservoir water level.

The values of flow with the Kriel valve partially open show reasonable agreement with the simulated values from the computer. Corrected figures were not evaluated since the readings for these partial valve positions from performance tests were not considered to be sufficiently accurate. A small percentage error in valve position at small openings will have a significant effect on the valve friction factor and this predominates at low values of flow. The error, however, remains small, indicating that there is no transition from turbulent to laminar flow. The decision to assume turbulent flow throughout is therefore justified. In addition the decision to use a constant value of friction factor, λ , on the assumption of turbulent flow can also be considered justified, thereby providing some verification of the Darcy-Weisbach formula.

In general, therefore, from the trial run described above, the model behaved in a manner which could be expected of the actual installation and gave results which, where these could be checked, closely agreed with the real values obtained. The mathematical expressions derived in Chapter 3, have been proved to be correct.

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In general, therefore, from the trial run described above, the model behaved in a manner which could be expected of the actual installation and gave results which, where these could be checked, closely agreed with the real values obtained. The mathematical expressions derived in Chapter 3, have been proved to be correct.

5. CONTROL STATEGIES

5.1 Methods of Control

There are three basic methods which can be employed to control a water system :-

(1) Continuous Flow Control

(2) On/Off Flow Control

(3) A combination of (1) and (2)

5.1.1 Continuous Flow Control (Constant Reservoir Level)

This type of control involves regulating reservoir inflow so that it approximates to the outflow. Whilst this has the advantage of maintaining the reservoir level substantially constant and hence minimizes reservoir size it involves expensive equipment such as variable speed pumps (since to vary the flow by throttling the pump discharge valves is wasteful of energy) and flow meters at the inlet and outlet of each reservoir (Fig 5.1). In addition a proportional controller is required to continuously regulate the inflow as the outflow varies.

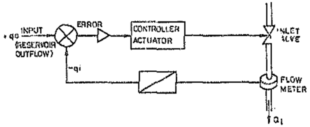


Fig. 5.1 - Continuous Flow Control - based on Flow Measurement

A cheaper alternative is to monitor reservoir level rather than flow (Fig. 5.2). Whilst less accurate than the above method it nevertheless requires a proportional controller and variable speed pumps.

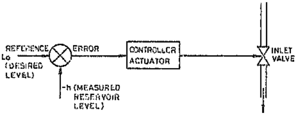


Fig. 5.2 · Continuous Flow Control - based Reservoir Water Level Measurement

Apart from the need to provide variable speed pumps a further disadvantage of this type of control is that is is likely to incur almost continuous valve movement. A factor which would contribute to greater wear of the moving parts of the valve. As there is no requirement to keep the reservoir levels constant for Usutu this method has not been pursued.

5.1.2 On/Off Flow Control (Fig. 5.3)

In this case wide fluctuations in reservoir level are permitted to take place within the physical limitations of the size of the reservoir. A low set level set point is used to initiate the inlet valve full open and a high level set point is used to initiate valve closed. The average inlet flow over a prolonged period equals the average outflow over the same period. Any imbalance in the actual values of inflow and outflow is taken up by the reservoir.

Whilst this system is a cheaper form of control, and involves less valve movement than (5.1.1) it results in inefficient use of expensive reservoirs, which would, for effective control, probably need to be larger than would otherwise be the case. If not correctly set, it could lead to unnecessary switching of pumps.

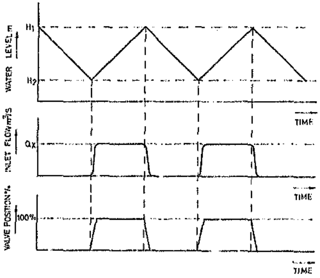


Fig. 5.3 - On/Off Flow Control

5.1.3 Combination Control

A compromise which makes better use of reservoirs and does not involve either the expense of *continuous flow adjustment* or unnecessarily large and expensive reservoirs and excessive pump operation is to employ a combination of the two methods of control. Such a method is described in 1.2 as applied to the Usutu Scheme. The problem now becomes one of setting the system parameters to give the required performance.

5.2 *Definition of Objectives*

Whilst the primary objective is to provide an adequate supply of water at Kriel to meet the demand the following considerations must be borne in mind :-

(a) Kriel Reservoir

(i) The purpose of Kriel Reservoir is to provide a sufficient store of water to maintain the power station operating for three days at a normal load factor (85%) when there is no inflow of raw water into the reservoir. That is, it acts as an insurance against failure of the water supply. Three days is considered ample time to overcome the worst problems that can occur.

The water level in the reservoir should therefore be maintained reasonably constant at its full value.

(ii) The power station at Kriel is at a slightly higher elevation than the reservoir. When the water in the reservoir is at a high level (above 1,5 m below full level) water will flow by gravity into the station. However, if the reservoir water level is low, water has to be pumped up to the station.

Keeping the reservoir reasonably full will thus conserve energy (and cost) by avoiding unnecessary pumping.

(iii) A pipeline connects Kriel Reservoir to Matla Power Station Reservoir so that any water in excess of Kriel's requirements can be pumped to Matla. To safeguard Kriel Power Station, however, these pumps can only be operated if the water level in the Kriel Reservoir is above a certain level (suggested level 1 625 m - i.e. 1,5 metres below Kriel full level).

(b) Camden Pumps

The squirrel cage motors which drive the Camden pump sets have been specified for not more than six direct-on-line starts in any 24 hour period. However in order to ensure longer life, greater reliability and reduced maintenance, the number of starts must be kept to a minimum and unnecessary starts avoided.

(c) Rietspruit and Davel Reservoirs

There is no requirement to keep the reservoirs at Rietspruit and Davel full or even at constant level. To do so would in any case, mean limiting the flow of water to Kriel. This is because both Rietspruit and Davel hold only a fraction of the water contained in Kriel reservoir and therefore could not sustain the flow to Kriel by themselves. Even a relatively small change (approximately 250 mm) in the level at Kriel Reservoir (at full supply level) represents a volume of water which is comparable to the entire capacity of Davel Reservoir. Hence, whilst the main purpose of Rietspruit and Davel reservoirs is to provide minor supplies to townships, and relieve the pipeline pressure, an important function is to balance the through flow.

The water level at each should therefore be allowed to vary over the widest possible range consistent with safe operation.

Operating limits are dictated by :-

(i) The reservoirs should not overflow since although this is not particularly dangerous, it is wasteful of water and energy.

(ii) The reservoirs should not be emptied. This would lead to air being drawn into the outlet pipes and could cause extensive damage, even rupture of the pipeline. To protect against this, the water level must at all times be maintained above the level of the outlet pipe.

(d) Control Valves

Although the control valves will adjust to different positions, excessive movement should be avoided in order to minimize wear of the moving parts.

A constraint is that the Kriel valve should not operate for prolonged periods in the region of 90 - 95% opening but should be opened fully for values approaching full flow.

(e) Maintenance

Whilst normal operation of the system is with both halves of the reservoirs at Rietspruit, Davel and Kriel in operation, from time to time it will be necessary to remove from service half of any of the reservoirs for repairs and routine maintenance. Whilst this may occur when one of the turbo-alternators is being serviced, the water scheme must still be capable of transporting the maximum quantity of water without affecting the safety of operation.

5.3 Summary of Objectives

(1) The normal operating range of water level at Kriel Reservoir should be as small as practicable.

(2) Once a pump is started it should be run for the maximum possible period of time and once stopped should remain in that condition for as long as possible.

(3) The normal operating range of water level at Rietspruit and Davel should be as large as practicable.

(4) An attempt should be made to economize on movement of flow control valves.

(5) The system must be constrained by safety interlocks at Rietspruit and Davel which if necessary will override all other controls.

(6) The system should be tested for half reservoir operation.

5.4 Control Strategy

In deciding on a control strategy to achieve the objectives stated in (5.3) above it was decided that a solution could be found through reasoned argument and computer simulation. Whilst there are well known techniques for optimizing control systems and it would have been an interesting exercise to employ one of them to solve this particular problem, the additional time involved was considered to be a major obstacle especially since results are required urgently to set up the actual system.

Consideration will first be given to boundary conditions (i.e. operating range of water level) and then to intermediate settings within those boundaries.

5.4.1 Kriel Reservoir - Range of Level Set Points

In accordance with (5.3) above the operating range of level which is monitored for control purposes shall comprise not greater than, 10%, say, of the total volume of Kriel Reservoir and be preferably in the region of 5%.

The upper operating limit shall be defined as the Full Supply Level (FSL) corresponding to inlet (regulating) valve fully closed ($V_K = 0\%$) and the lower operating limit shall be defined as the Low Supply Level (LSL) corresponding to inlet valve fully open ($V_K = 100\%$).

From figure 5.4, which depicts the relationship between percentage volume and level (metres depth), Full Supply Level is shown as 13,78 metres. 5% and 10% Volume changes represent an operating range of 0,44 metres and 0,9 metres respectively below FSL. Thus if equal steps are employed (since level vs volume is approximately linear over a small range) for the four values of inlet valve opening this would mean level settings at approximately 100 mm intervals for a

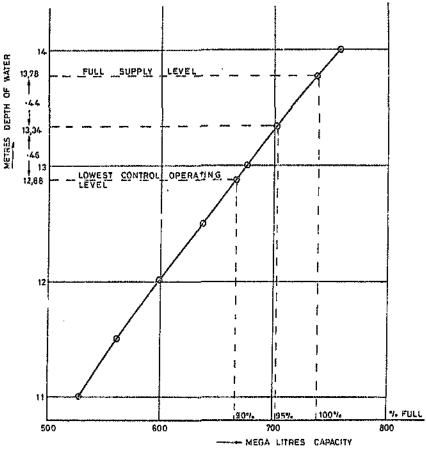


Fig. 5.4 - Kriel Reservoir - Depth versus Volume

5% range and 200 mm steps *for a 10% range.* The minimum size step that is practicable is considered to be 50 mm. Any settings smaller that this are likely to cause maloperation due to wave action in the stilling chamber

5.4.2 Camden Pump Operation

(a) *Single Pump Operation* – *the shortest* period of time that one pump will be required to operate is in filling Rietspruit Reservoir from an initially low level when there is no outflow from Rietspruit (Fig. 5.5). The operating range of level at Rietspruit must therefore be as large as possible so that when the demand at Kriel is less than one pump flow, the *maximum time is taken to* draw down the level to the low operating setpoint at which the pump is started and the maximum possible time is required to replenish the reservoir (Fig. 5.6).

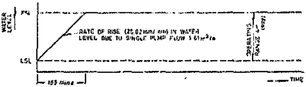


Fig. 5.5 – Filling Rietspruit Reservoir for Zero Outflow

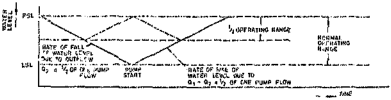


Fig. 5.6 – Effect of Rietspruit Reservoir Operating Range on Pump Duty Cycles

Under normal operating conditions there will always be a demand at Kriel and pump operation and standstill time will be greater than the minimum. The longest operating *time will be when the flow in the* Rietspruit –Davel and Davel – Kriel pipelines is equivalent to that of one pump (Fig. 5.7 vii) and the longest standstill time

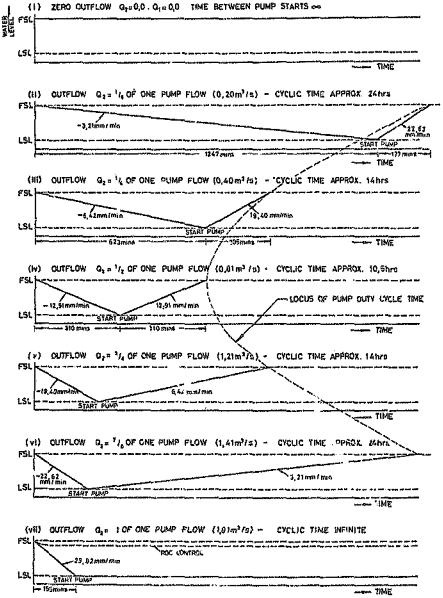


Fig. 5.7 - Rietspruit Reservoir - Single Pump Operation Effect of Varying Outflow on Pump Duty Cycle (Combined Reservoir Operation - Surface Area 2 x 1879,3 m^2)

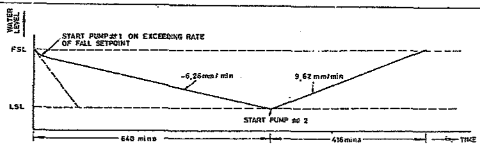
will be when the flow is zero and Rietspruit Reservoir is full (Fig. 5.7 i). Figure 5.7 (iv) illustrates that the minimum pump cyclic time (pump running and stopped time) occurs when the pipeline flow out of Rietspruit is equivalent to half of one pump flow.

(b) Dual Pump Operation - From Table 4.1 the maximum possible flow into Kriel Reservoir is 2,17 cumecs. Whilst this exceeds the flow from one Camden pump (1,61 cumecs) it is considerably less than the 2,60 cumecs, for dual pump operation. With two pumps operating there will always be a net gain of water at Rietspruit regardless of the demand. The second pump should therefore only operate when Rietspruit Reservoir level is low and the flow out of Kriel Reservoir exceeds that which can be supplied by a single pump. It should only be stopped when either Rietspruit is full or when the Rietspruit - Davel flow drops below 1,61 cumecs (single pump flow).

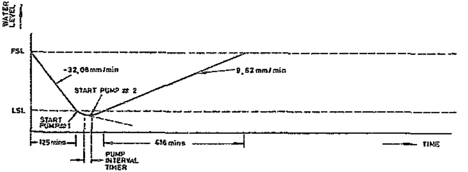
It would appear that the running time of the second pump could be prolonged by extending the operating range of water level at Kriel. This would serve little purpose, however, since the limiting factor is the flow in the Rietspruit - Davel pipeline which has a maximum value of only 2,00 cumecs, that is, providing the volume of water between the lowest and second lowest setpoint at Kriel is not less than the volume of water within the operating range at Davel.

5.4.3 Rietspruit Reservoir - Range of Operating Level

(a) The operating range at Rietspruit should be as large as possible not only so that Rietspruit can perform as an efficient balancing reservoir but as stated above in order to minimize pump starts and stops. The operating limits shall be defined as the Full Supply Level (FSL) and the Low Supply Level (LSL) corresponding to both Camden pumps stopped ($P = 0$, $V_{C1} = 0\%$, $V_{C2} = 0\%$) and at least one pump operating ($P = 1$, $V_{C1} = 100\%$), respectively. Setpoints based on rate of fall and rate of rise of



(i) WITH RATE OF CHANGE CONTROL (MAXIMUM OUTFLOW FROM RIETSPRUIT $Q_2 = 2,00\ m^3/s$)
CYCLIC TIME APPROX. 17,5 hrs



(ii) WITHOUT RATE OF CHANGE CONTROL (MAXIMUM OUTFLOW FROM RIETSPRUIT $Q_2 = 2,00\ m^3/s$)
CYCLIC TIME APPROX 9hrs

Fig. 5.8 - Rietspruit Reservoir - Dual Pump Operation
Effect of Rate of Change Parameter on Pump
Duty Cycle

water level within the operating range will, if exceeded, initiate pump start up or shut down in order to respond more quickly to large changes in demand. Once a pump has started this will have the effect of slowing down the rate of change and holding the level within the operating range. Figure 5.8 (i) and (ii) illustrates this.

(b) Safety Limits

(i) High limit

The overspill level at Rietspruit is 8,4 metres from the bottom of the reservoir (Appendix B.1). The high level setpoint *(WLRH) which will sound an alarm and stop both* Camden pumps should be set just below this level at approximately 8,2 metres. The full supply level should be set below this again by a sufficient margin to allow one pump to be stopped before the water level rises to 8,2 metres. If 5 mins. is allowed to stop a pump, this represents a depth of approximately 125 mm for a rate of rise of 25,7 mm/min. (or 250 mm at a rate of 51,3 mm/min. for half reservoir operation).

(ii) Low limit

In order to prevent the reservoir from draining in the event of failure to start the pumps, the outflow from the reservoir must be reduced if necessary to zero. Setpoints will be required to initiate progressive closure of the *Davel regulating* valve as the water level falls below the operating range.

A low level alarm (WLRL) acts as backup protection and will initiate an emergency routine of stopping the pumps and closing all valves. With an outflow of 2,0 cumecs, and no inflow, under the worst conditions, Rietspruit water level will fall at 64,16 mm/min. (half reservoir operation) and allowing 16 minutes for the Davel valve to close plus 2 mins. reaction time this represents a depth of approximately 1 000 mm. As this is an emergency level there should be at least 1,0 metre of water left in the reservoir when the flow has reduced to zero, hence the low alarm level should be set at approximately 2,0 metres.

From the computer the rate of fall with Davel valve 25% open is 1,1 mm/min. and again allowing the valve time to close from this position this represents a depth of 110 mm - i.e. the next setpoint should be set at least 150 mm above the alarm level (250 mm including safety margin). Each level setpoint can be calculated in this manner and the low supply level established. (Actual test set-points are shown in Table 6.6).

5.4.4 *Davel Reservoir - Range of Operating Level*

(a) The operating range at Davel should be as large as possible so that Davel can perform as an efficient balancing reservoir.

With maximum outflow from Davel (2,17 m^3/s) and maximum inflow (2,00 m^3/s) to Davel, the Davel level will always fall, there appears therefore to be a strong case for control on rate of change of level as at Rietspruit. This would allow the Davel valve to open to its maximum position whilst the reservoir is still relatively full and hence allow the maximum time of operation with full inflow and full outflow before the low operating limit is reached. In this case the low operating limit must be regarded as the level at which the Kriel valve must be throttled back.

The actual controls, however, have been based on absolute level setpoints at Davel. The level at which the Davel valve is commanded fully open must therefore be as high in the reservoir as possible, although sufficient margin must be allowed between it and the full level to enable steady operation at intermediate valve positions.

At Davel then, the operating limits shall be defined as Full Supply Level (FSL) and Low Supply Level (LSL) corresponding to the Davel valve fully closed ($V_D = 0\%$) and the Davel valve fully open and Kriel valve throttled one position ($V_D = 100\%$, $V_K = 75\%$) see Fig. 5.9.

Fig. 5.9 illustrates the changes in Davel water level with continuous maximum demand at Kriel. The sketch is greatly exaggerated since the difference between full outflow and full inflow is only 0,17 m^3/s - i.e. it would take approximately 780 minutes to complete (I) and approximately 340 minutes to complete (II)

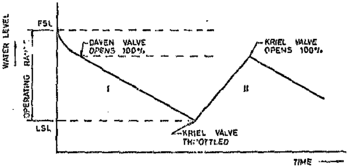


Fig. 5.9 - Davel Reservoir - Changes in Level with Maximum Continuous Demand at Kriel

(if the Kriel valve is throttled to the 75% position) - a total time of approximately eighteen and a half hours. This assumes an operating range of 4 metres as at Rietspruit. However, the top metre is allowed for intermediate positions of the Davel valve and the remaining three metres for the Davel valve fully open and the Kriel valve fully open. Under these conditions there is a net loss of water from Davel and the level drifts slowly down until at the limit of the range the Kriel valve is throttled back one step.

Although rate of change of level control would have the advantage of a slightly deeper operating range under maximum flow conditions, absolute level control tends to keep Davel reasonably full for light demand.

(b) The safety limit settings are based on similar arguments to those for Rietspruit (Test values are given in Table 6.5).

5.4.5 Flow Settings - Valve Position Parameters

As the flow in the Camden - Rietspruit pipeline can only have two values - viz. one or two pump operation, optimum pump cyclic times can only be achieved by manipulation of the Rietspruit Reservoir level setpoints and by controlling the values of outflow from Rietspruit. Figure 5.7 illustrates the effect of flow in the Rietspruit - Davel pipeline on the single pump operation duty cycle time.

At first, it would appear that the best operating conditions can be achieved by allowing only one intermediate valve position at Davel and Kriel - that corresponding to single pump flow, and eliminating the other two settings. (Nevertheless, there is perhaps a case for an intermediate setting between that of single pump operation and valve full open. This would have the effect of reducing the rate of fall at Rietspruit when the demand is greater than that of single pump flow and thereby extend the cyclic time for dual pump operation).

The above argument, however, ignores the values of outflow from Kriel Reservoir and assumes that the reservoir is an enormous "buffer" with no relationship between the outflow from Kriel and the inflow from the Usutu Water Scheme. Kriel Reservoir may be large but it is not of infinite size, moreover in order to keep Kriel approximately full, the level setpoints must, of necessity, be set close together.

Thus, although figure 5.7 (vii) predicts an infinite pump cyclic time when the Davel and Kriel valves are set to an opening which permits the equivalent of one pump flow, if this value is much greater than the outflow from Kriel Reservoir, the reservoir will fill relatively quickly and close the regulating valve at Kriel. The whole purpose of providing three intermediate adjustable openings for the two regulating valves was an attempt to crudely approximate the inflow to the outflow from Kriel Reservoir.

No. of M/cs on load at Kriel P.S.	No. of M/cs on load at Matla P.S.	Demand from Kriel Reservoir m^3/s
1	0	0,27
2	0	0,55
3	0	0,82
4	0	1,09
5	0	1,35
6	0	1,62
6	1	1,95
6	2	2,28
6	3	2,61

Table 5.1

Approximate Relationship between Power Station Electrical Output and Water Consumption

The argument also assumes that it is physically possible to set the valve positions exactly and that the flow will remain constant under varying head conditions. Neither of which is true.

Table 5.1 gives predicted values of demand at Kriel and Matla Power Stations. From this it will be seen that the demand is approximately 0,27 cumecs, for each of the six turbo-alternators at Kriel and 0,33 cumecs, for those at Matla. The rate of fall (in the top part of the reservoir) in water level is in the region of 0,2 mm/min. per Kriel machine on load. This means that if the level setpoints are 100 mm apart it will take 500 mins. (8,3 hrs.) to fall from one setpoint to another with one machine operating, 250 mins. for two machines and so on. If on reaching the setpoint, the regulating valve opens to a position such that the inflow is approximately equal to the outflow, the level will steady both at Kriel and Davel and the pump cyclic time will become a function of that particular flow.

An obvious valve setting to be avoided is that which is equivalent to half pump flow. Values which are less than one quarter or greater than three quarters of pump flow may in fact give good results whilst keeping Kriel and Davel reservoirs full. It must be acknowledged, however, that a demand of less than 1,0 cumec will not normally be encountered except during commissioning of the power station.

One definite advantage of retaining all the intermediate valve positions is in being able to throttle the valves gradually when the level at Rietspruit and Davel reservoirs becomes dangerously low. This is preferable to a sudden cut-off in flow and provides some back-up protection.

5.4.6 Computer Tests

Based on the foregoing, there are two possibilities of controlling the system :-

(i) Attempt to equate the flow in the three pipeline sections to that of pump flow.

(ii) Approximate the pipeline flow to that of the demand.

In either case the operating range of Kriel Reservoir must be relatively small and those of Rietspruit and Davel as large as possible consistent with safe operation.

The minor demands at Rietspruit and Davel have been ignored in this discussion since these are only 0,08 m^3/s from Rietspruit to Ermelo Municipality (by 1995) and 0,05 m^3/s from Davel Reservoir (by 1995).

6. APPLICATION OF CONTROL TO MODEL AND RESULTS

6.1 Summary of Tests Performed

Once the basic model has been proved (Chapter 4) to be a true replica of the actual water scheme, the next step is to manipulate the model in order to obtain the best control possible in terms of the stated objectives.

The discussion in Chapter 5 on control strategies provides a logical basis for the initial choice of control parameters. A series of tests can then be conducted to check whether those parameters do in fact fulfill all the control requirements and if not what modifications are necessary to achieve the desired results.

The tests chosen for this study were as follows :-

- Tests 1 & 2 — To set the correct values for the Rietspruit Reservoir rate of change of level control set points and to ascertain if these assist in providing better control by comparing the system performance with and without these parameters set.
- Tests 3 & 4 — Compare the merits of matching the pipeline flow throughout to :-

  (i) pump flow

  (ii) outflow from Kriel Reservoir for power station demand up to 1,61 m^3/sec.
- Test 5 — Compare the effect of varying the interval between water level set points at Kriel Reservoir.

- Tests 6 & 7 Repeat of tests 3 and 4 for demands in excess of 1,61 m^3/sec.

6.2 Rietspruit Reservoir Rate of Change Control

The first parameters to be set were the rate of change control at Rietspruit ROF and ROR.

ROF is the rate of fall of ter level setpoint and was set at -0,00045 m/s (27 mm/min) - i.e. just in excess of the rate of fall of level for the equivalent of single pump flow out of the reservoir with no inflow. If it was set less than this value, a pump could be started (under certain conditions) and then stopped quickly afterwards as the level at Rietspruit reached the full value. The purpose of this setpoint is to extend the time that the level is falling, thereby delaying the starting of the second pump and hence extending the pump duty cycle time.

ROR is the rate of rise of water level setpoint and was set at 0,00028 m/s (16,80 mm/min) - i.e. just in excess of the rate of rise of level produced by the difference between single and dual pump flow, the level will continue to rise *with only one pump operating but at a slower rate.*

These settings were tested by repeating the run referred to in Chapter 4.

In this test, the system was given a step input, by setting the initial level of Kriel low, and checking the response.

The full water level of Kriel, Davel and Rietspruit reservoirs was set conservatively at 13,20, 6,75, 6,50 metres respectively and the low operating limit at 13,00, 4,25 and 4,50 metres corresponding to operating ranges of 200 mm (Kriel), 2,50 m (Davel) and 2,00 m (Rietspruit). Initially, Davel and Rietspruit were set at full level, the Davel and Kriel regulating valves were set to fully closed and both pumps off. The demand at Kriel was set to zero and the water level at Kriel was set to an initial value of 12,80 m - i.e. a step input of 400 mm.

Two tests were conducted, one without the rate of change parameters and one with the parameters set. In the first test it took 23 700 seconds (6hrs. 35 minutes) for the system to reach a state of equilibrium and in the second test (6hrs. 33 mins.). Results were printed every minute, the calculation being carried out by means of variable step integration routine (Runge-Kutta/Moulton) with calculation interval of not less than 15 seconds. †

Initially the Kriel valve went to full open, drawing water from Davel. As the Davel level dropped, the Davel valve was opened progressively as each set point was exceeded, to 25%, 50%, 75% and finally full open. The pump(s) were started at Camden to replenish Rietspruit and as the reservoirs filled up, the valves at Davel and Kriel closed in steps. Finally the system came to rest with Kriel Reservoir full, both Kriel and Davel valves fully closed and both Camden pumps stopped.

The pump cyclic times are given below :-

Table 6.1

Test I - Without Rate of Change Control at Rietspruit.

T Seconds	H_R Metres	Pump 1	Pump 2	Pump 1 Run Time Secs	Pump 2 Run Time Secs
0,	6,50	Stopped	Stopped		
5940	4,50	Start		11220	
6540	4,42		Start		10320
16860	6,50		Stop		
17160	6,56	Stop			

Note : Pump 1 will always start first and stop last.

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† The Computer may be required to perform more than one calculation every 15 seconds dependent on whether the tolerance requirements are satisfied.

In this test the pump interval timer was set to 10 mins. between pump starts and 5 mins. between pump stops. Pump 1 ran for 3 hrs. 7 mins. and pump 2, 2 hrs. 52 mins.

Table 6.2

Test 2 - With *Rate of Change Control at* Rietspruit

ROF = -0,00045 m/s; ROR = 0,00028 m/s.

T Seconds	H_R Metres	Pump 1	Pump 2	Pump 1 Run Time	Pump 2 Run Time
0,	6,50	Stopped	Stopped		0,
3300	5,80	Start		20160	
23460	6,50	Stop			

In this test, pump 1 started on rate of change control with Rietspruit Reservoir still relatively full at 5,80 m and ran for 5 hrs. 36 mins.

A comparision of the two tests will show the value of the rate of change control:

Table 6.3

Comparison of Tests 1 and 2 - Showing Effect of Rate of Change Control at Rietspruit.

	Pump 1 Run Time	Pump 2 Run Time	Initial Kriel Level H_K	Final Kriel Level H_K	Minimum Davel Level H_D	Final Davel Level H_D	Minimum Riet-spruit H_R	Final Riet-spruit H_R
TEST 1	3hr 7min	2hr 52 min	12,80m	13,20m	4,90	6,56	4,42	5,46
TEST 2	5hr 36min	0,	12,80m	13,20m	4,92	6,59	4,80	6,56

Both tests achieved the same result - i.e. filled Kriel to *its full setting of* 13,20 m. With the rate of change control in operation, pump starts/stops were minimized since not only was pump 2 not started but the running time of pump 1 was extended. In addition both Davel and Rietspruit had a higher final level even though the total pumping time was less (this is attributed to the greater efficiency of single pump operation since the headloss is reduced). As the minimum values of level at Davel and Rietspruit were also higher for test 2 the change of level was reduced. The minimum value reached for Rietspruit was 4,80 metres – only 300 mm above the set point for switching pump 2, so that a larger step input at Kriel would undoubtedly have caused pump 2 to start. Nevertheless, the rate of change control does appear to be advantageous and could help to eliminate unnecessary starts under actual operating conditions (it must also be noted that in the above test, the operating range at Rietspruit was only [illegible] metres).

The reason the Rietspruit level ended at a lower value in the first test was because on attaining full level at Rietspruit both pumps were stopped but since the Davel valve was still partially open water continued to flow out of Rietspruit until Davel attained its full level. A similar argument applies to the final level at Davel since the Kriel valve was still partially open when the Davel valve was closed.

6.3 Setting of Regulating Valves

(a) From the discussion on control strategies in 5.4.6, clearly, one setting for each of the regulating valves is that which permits a flow equivalent to that of one pump – i.e. 1,61 m^3/s.

Table 4.1 shows that the flow from Davel to Kriel is 1,61 m^3/s with Kriel valve 75% open. It also shows that the flow for a 75% open valve at Davel is 1,69 m^3/s.

An initial run was tried with the 25% and 50% valve positions set to zero and the demand at Kriel, Q_K equal to 1,61 m^3/s. The valves at Kriel and Davel were set to 75% and 70% respectively. By a process of successive approximation the flow was matched with the Kriel regulating valve at 74,79% and the Davel regulating valve at 70,68%. The flows were matched within 0,0001 m^3/s with Rietspruit level, H_R, at 4,48 m, Davel level, H_D, at 5,35 m, and Kriel at 13,04 m.

Subsequently, the operating ranges were modified and the variation in flow with level was observed as follows :-

Rietspruit - Davel Flow, Q_2 : From 1,65 m^3/s to 1,59 m^3/s (range of level at Rietspruit 4,5 m).

Davel - Kriel Flow, Q_3 : Approximately 1,61 m^3/s to 1,62 m^3/s (range of level at Davel for this valve position 250 mm falling water level; 750 mm rising water level - i.e. a total of 1,0 m and variation at Kriel 400 mm).

(b) From 5.4.6 it was decided to conduct two series of tests :-

(i) Match the flow in each section of the pipeline to that of pump flow only.

(ii) Approximate the pipeline flow to that of the demand.

In the latter case it was necessary to set the nominal 25% and 50% valve positions.

These were set as follows :-

Corresponding to a demand from Kriel Reservoir of 1,09 m^3/s for 4 machines on load at the power station :

Davel valve	42,63%
Kriel valve	49,77%

Corresponding to a demand from Kriel Reservoir of 0,81 m^3/s for 3 machines on load at the power station :

Davel valve	29,42%
Kriel valve	35,92%

It is interesting to compare the computed flow versus valve position curves given in Appendix F for although the flow for a fully open Kriel Valve (2,17 m^3/s) is higher than that for a fully open Davel valve (2,00 m^3/s) the values of flow for intermediate valve positions is higher in every case for the Davel valve. This is due to the difference in frictional characteristics of the two valves.

The above settings are, of course, theoretical since in practice the valve set points can only be set to an accuracy of between 1% - 2% of the full range.

6.4 Reservoir Operating Range

(a) Kriel Reservoir

(i) The critical level at which water no longer gravitates into the power station from Kriel Reservoir is 1,5 metres below full level (12,28 m). Since it is intended to control the level at Kriel to within 90% or 95% of full volume this will not be restrictive, as the levels for 90% and 95% volume are approximately 1,0 metre and 0,5 metre below full level (13,78), respectively.

(ii) Intermediate levels - initially the operating range was set at 0,5 metres with intermediate levels set as given in table 6.4 :-

Table 6.4

Kriel Reservoir Set-Points

Set Point	Level H_K Metres	% Valve Opening V_K	Pipeline Flow Q_3 m^3/s
WLK0	13,78	0,0	0,0
WLK1	13,58	35,92	0,61
WLK2	13,48	49,77	1,09
WLK3	13,38	74,79	1,61
WLK4	13,33	100,0	2,17

WLK0 - Full Supply Level; WLK4 - Low Supply Level; WLK3 and WLK4 were set close together so that Camden pump 1 would start on rate of change control for a heavy demand at Kriel.

WLK4 was set just above 13,28 m in order that the level be held within the 0,5 m operating range.

(b) Davel Reservoir

(i) It was decided to set the high water alarm at 8,00 metres (200 mm below the overspill level) and the full supply level at 7,50 metres. This permitted an operating range of *4,5 metres down to 3,00 metres* at which level it was considered necessary to throttle the Kriel valve back one position.

(ii) Intermediate levels were set in accordance with table 6.5.

Table 6.5

Davel Reservoir Set-Points

Set Point	Level H_D Metres	% Valve Opening V_D	% Valve Opening V_K	Inflow Q_2 m^3/s
WLD0	7,50	0,0		0,0
WLD1	7,25	29,42		0,81
WLD2	7,00	42,63		1,09
WLD3	6,75	70,86		1,61
WLD4	6,50	100,0		2,00
WLD5	3,00	100,0	74,79	
WLD6	2,75	100,0	49,77	
WLD7	2,50	100,0	25,92	
WLD8	2,25	100,0	0,0	
WLDL	2,00	Low Level Alarm - Closes all valves; stops pumps		

Operating Range WLD0 - WLD5

(c) Rietspruit Reservoir

(i) It was decided to set the high level alarm at 8,00 metres (400 mm below the overspill) and the full supply level at 7,50 metres. This permitted an operating range of 4,50 metres down to a level of 3,0 metres. Below this level are the set points which caused the Davel regulating valve to be restricted.

(ii) Intermediate levels were set in accordance with table 6.6.

Table 6.6

Rietspruit Reservoir Set-Points

Set Point	Level H_R Metres	Camden Pumps	% Valve Opening V_D	Inflow Q_1 m^3/s
WLRH	8,00	High level alarm Stop both pumps		0,0
WLRO	7,30	(i) Stop one pump (ii) Stop 2nd pump if HRDOT > 0,0		0,0 or 1,61
ROR		If HRDOT > 0,00028 stop pump 2 only		
ROF		If HRDOT < - 0,00045 start pump 1 only		1,61
WLR1	3,00	(i) Start one pump (ii) Start 2nd pump if V_K commanded full open by Kriel Reservoir controls		1,61 2,60
WLR2	2,80		∤ 70,68	
WLR3	2,60		∤ 42,63	
WLR4	2,40		∤ 29,42	
WLR5	2,20		∤ 0,0	
WLRL	2,00	Low level alarm Close all valves stop all pumps		

(Operating Range WLRO - WLR1)

6.5 Tests and Results

In carrying out the two series of tests runs were carried out as follows :-

Test 3 :

Flow in each section of pipeline matched to single pump flow for demand at Kriel less than or equal to 1,61 m^3/s.

Table 6.7

Test 3 - Valve Positions and Level Set Points

Davel Valve Set Points	% Valve Opening V_D	Level Set Point Metres	Kriel Valve Set Points	% Valve Opening V_K	Level Set Point
VD CLSD	0,0	WLD0 = 7,50	VK CLSD	0,0	WLK0 = 13,78
VD1	0,0	WLD1 = 7,50	VK1	0,0	WLK1 = 13,78
VD2	0,0	WLD2 = 7,50	VK2	0,0	WLK2 = 13,76
VD3	70,68	WLD3 = 6,75	VK3	74,79	WLK3 = 13,38
VD OPEN	100,00	WLD4 = 6,50	VK OPEN	100,00	WLK4 = 13,33

Test 4 :

Flow in each section of pipeline approximately matched to demand at Kriel.

All intermediate valve positions, as detailed above in 6.3 and 6.4, operational.

For each of the tests, computer runs were carried out with different values of demand, Q_K corresponding to 1, 2, 3, 4, 5 and 6 machines on load at Kriel Power Station. The results were plotted and are given in figures 6.1 and 6.2. (Note: two additional points were plotted at $Q_K = 0{,}12\ m^3/s$ and $Q_K = 1{,}49\ m^3/s$ for completeness).

(a) Test 3

Figure 6.1 shows that with the set point for valve position, VK3, set at a depth of 400 mm, the most frequent starting of pump 1 will occur with a demand from Kriel of 0,81 m^3/s (one half of pump flow). This will result in the pump starting at intervals of 23,5 hrs. At this flow the ratio of time that the pump is running

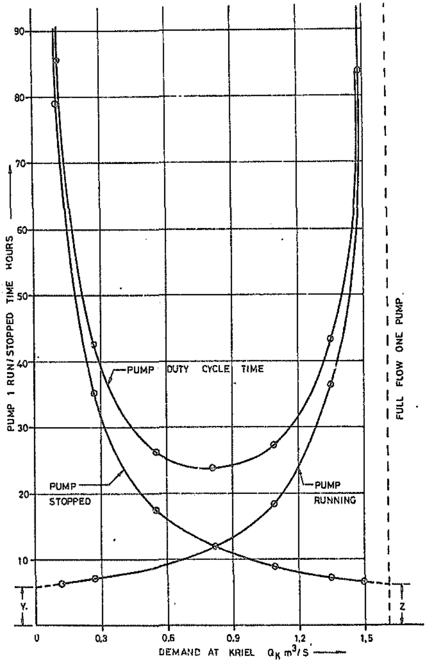

Fig. 6.1 - Test 3 - Variation of Pump Duty Cycle Time with Demand at Kriel (One Intermediate Valve Setting) - Single Pump Operation

to stopped is 1:1. At other values of flow from Kriel Reservoir the mean time between pump starts is greater, rising to very high values for flows approaching zero or 1,61 m^3/s (pump flow). For instance at a continuous outflow of 0,12 m^3/s the pump would only be called upon to start once every 85 hrs. - i.e. approximately twice per week.

Curves of pump running time and pump stopped have also been plotted. These curves do not pass through the ordinate at zero hours for flows of zero and pump flow as might be expected. This is because once a pump has started, it must run until Rietspruit Reservoir is completely full before it can be stopped and likewise, if a pump is stopped, the water level at Kriel must draw down to the point at which the Kriel valve is opened (and hence Rietspruit ultimately drawn down to a low level) before the pump will be started again. From figure 6.1, this time is 5,80 hrs. which corresponds to the time taken to fill Kriel Reservoir up to full supply level from a depth of 400 mm, with an inflow of 1,61 m^3/s and no outflow. It also corresponds to the time taken to draw the level down by 400 mm with an outflow of 1,61 m^3/s and no inflow.

It is interesting to note that in this test (with the flows matched) the cyclic time for Kriel valve open/close; Davel valve open/close and pump on/off were the same. The Davel valve had additional cycling between 70,68% and 100%. This was due to the following :-

(i) The two level set points were set close together.

(ii) Once the set point WLD3 is exceeded, the level continues to fall during the time the valve is opening, so that by the time it has stopped moving the level has almost reached the next level (WLD4).

(iii) There was a slight mis-match of the flow resulting in a slow fall of level at Davel.

This additional cycling of the Davel valve is not a serious problem and can be corrected on site by setting a larger margin between these two levels. The frequency depends on the levels in other parts of the system.

Table 6.8

Test 3 - Summary of the Computer Runs for Different Values of Demand at Kriel. Only One Intermediate Valve Setting at Davel and Kriel : Range at Kriel Reservoir 400 mm.

Demand at Kriel m^3/s	Kriel Valve Cyclic Time Hrs	Davel Valve Cyclic Time-Hrs	Pump 1 Run Time Hours	Pump 1 Stopped Time-Hrs	Pump 1 Cyclic Time-Hrs
0,12	85,75	85,75	6,25	79,50	85,75
0,27	42,50	42,50	7,25	35,25	42,50
0,55	26,25	26,25	8,92	17,38	23,30
0,81	23,50	23,50	11,25	12,38	23,63
1,09	27,00	27,00	18,38	8,63	27,01
1,35	43,00	43,00	36,00	7,00	43,00
1,49	83,00	83,00	77,00	6,25	83,25

Note 1: As the Davel valve opening was slightly inaccurate, there was additional cycling of the Davel valve between 70,68% and 100% once per cycle.

Note 2: Results output from the computer at 15 min. intervals.

(b) Test 4

Figure 6.2 depicts similar curves for Test 4 - approximating the valve settings at Kriel and Davel to the demand from Kriel Reservoir.

It will be observed that most frequent pump operations again occur at an equivalent flow of half pump flow but with a maximum safe operating range at Rietspruit of 4,5 metres the periodic time is only 11,5 hrs - i.e. approxmately half of that which can be achieved with a 400 mm change of level at Kriel. This is to be expected since the volume of a 400 mm span of water at Kriel Reservoir is greater than the entire volume of Rietspruit.

Unlike Test 3 which displayed a constant frequency of valve movement and pump operation for a particular demand, Test 4 resulted in general in fewer valve cycles (especially where the valve setting was exactly matched to the demand) and more pump operations. The pump cyclic time also varied, depending on the various reservoir levels at the commencement of a cycle, whereas in Test 3 the levels always start at the same values.

The curves of pump running and stopped time cross the "y" axis at approximately 4 hours illustrating that the pump operating time is no longer dependent entirely on the operating depth at Kriel but is more dependent on the depth at Rietspruit.

Table 6.9

Test 4 - Summary of Computer Runs for
Different Values of Demand at Kriel.
Three intermediate Valve Settings at
Davel and Kriel.
Range at Kriel Reservoir 400 mm.
Range at Rietspruit Reservoir 4,5 m.

Demand at Kriel m^3/s	Kriel Valve Cyclic Time Hrs	Davel Valve Cyclic Time-Hrs	Pump 1 Run Time Hours	Pump 1 Stopped Time-Hrs	Pump 1 Cyclic Time-Hrs
0,27	26,38	26,38	4,33	22,00	22,33
0,55	26,50	26,50	4,50	9,00	13,50
0,81	infinite	☆	5,88	5,79	11,67
1,09	infinite	infinite	8,90	4,35	13,25
1,35	17,75	18,00☆	18,00	4,13	22,13
1,61	infinite	☆			infinite

Note 1: Infinite valve cyclic times correspond to matched flows at Kriel valve openings (i.e. Kriel inlet matched to outlet Q_K)

Note 2: ☆ indicates additional cycling of Davel valve due to pipeline flows not being exactly matched.

Note 3: Results output from computer at 15 min. intervals.

(c) Test 5

As better results were obtained from Test 3 than Test 4 a further series of tests were conducted with the valves matched to the pump flow to determine the effect, on the pump and valve cyclic time, of varying operating depth at Kriel.

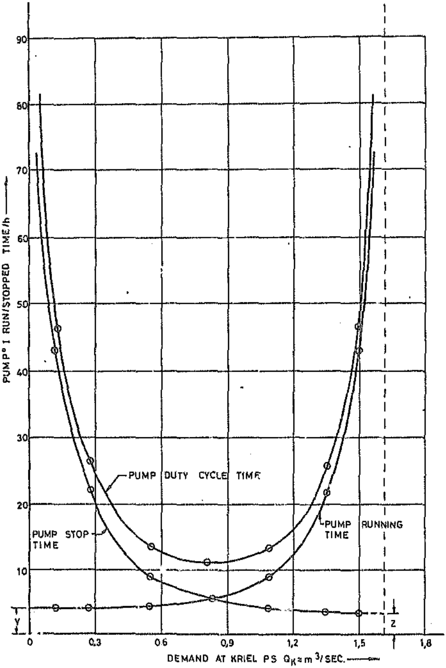

Fig. 6.2 - Test 4 - Variation of Pump Duty Cycle Time with Demand at Kriel (Three Intermediate Valve Settings) - Single Pump Operation

The results are plotted on figure 6.3.

As might be expected, there is a almost linear relationship between depth and cyclic time (especially at the minimum value). Thus increasing the depth from 400 mm to 800 mm results in the minimum cyclic time being increased from 23,5 hrs. to 46,5 hrs. - a factor of 1:2. On the other hand reducing the range to 200 mm results in a cyclic time of 12,2 hours. (The effect of the shape of Kriel Reservoir does not appear to be significant over such a small range of depth).

The curve for a depth of 100 mm is interesting since the pump cyclic time suddenly jumps from approximately 6 hrs. at 0,81 m^3/s to 12 hrs. for values of flow less than or greater than this.

The reason for this is that at 0,81 m^3/s the pump cyclic time is the same as that for the Kriel valve although lagging behind by approximately 15 minutes. At flows below 0,7 m^3/s and above 0,95 m^3/s, the Kriel valve frequency of operation is twice that of the pump. This is attributable to the fact that the volume of a 100 mm operating range at Kriel is approximately half of that of Rietspruit and the control shifts from control on Kriel level to control on Rietspruit level.

(d) Tests 6 and 7

With the same valve and level settings as for Tests 3 and 4 the Kriel demand was increased beyond that of one pump flow. Apart from a difference in time, the results were the same and are plotted on figure 6.4.

The reason the results of the two tests are the same is that the pipeline flows are no longer matched to the pumps since the flow for a fully open valve at Kriel is 2,17 m^3/s., for a fully open Davel valve 2,00 m^3/s and for two pumps 2,60 m^3/s. Whereas, for Test 3 for a

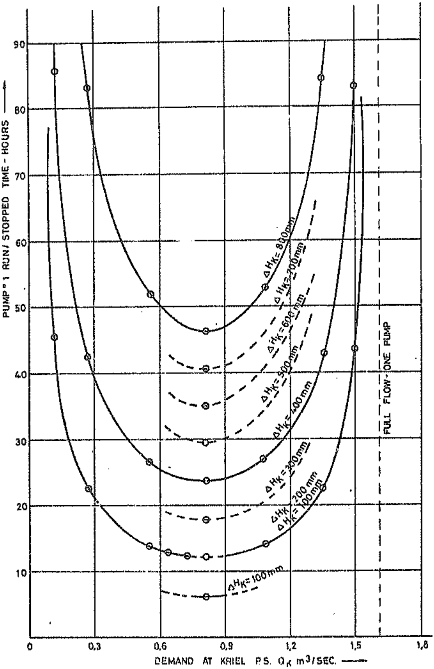

Fig. 6.3 - Test 5 - Effect of Varying Operating Range
at Kriel on Pump Duty Cycle Time

range of depth at Kriel greater than 300 mm, the control is independent of level settings at Davel and Rietspruit and dependent only on Kriel (providing the pipeline flows are correctly matched), for Tests 6 and 7, the converse is true.

For demands in excess of 2,00 m^3/s., the Davel valve will remain fully open and the pump cyclic time depends only on the operating range at Rietspruit. There is a cut-off point at this value and from the curve this is at a cyclic time of 20,0 hrs for a range of 4,5 metres at Rietspruit. For demands in excess of 2,00 m^3/s the Kriel level will fall steadily until the flow to Matla is inhibited at 12,28 m.

It will be observed that the points no longer lie on the curve. This is because the cyclic time varies slightly with the various reservoir levels and these do not rise and fall in synchronism due to the non-uniform pipeline flows.

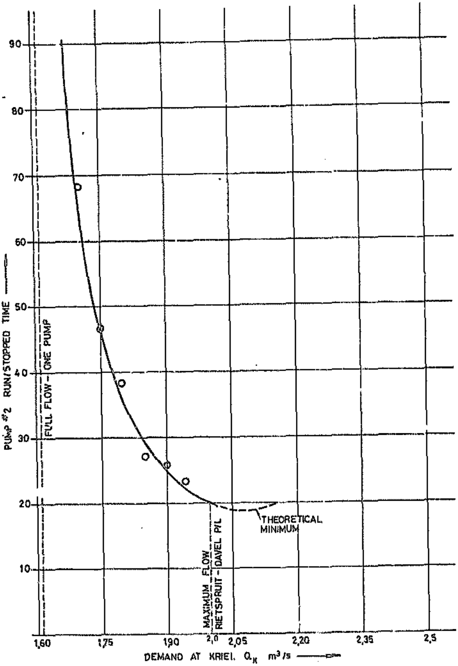

Fig. 6.4 – Tests 6 & 7 – Variation of Pump Duty Cycle Time with Demand at Kriel – Dual Pump Operation

7. CONCLUSION AND FUTURE WORK

7.1 Conclusions

7.1.1 Achievement of Objectives

As the purpose of the study was to evaluate the automatic control system for part of the Usutu River Scheme within the context of certain stated objectives (refer to 1.3), a comparison of results with objectives is given below.

The results have shown that these objectives can be achieved effectively by a control system which is both simple and economical. Sufficient information has been obtained from the study to enable the control system parameters to be set on site to optimum values. A better understanding has been gained of the significance of these parameters and their effect on the control system.

The following conclusions and recommendations can be made from the study:-

1. Values for valve position and reservoir level control parameters which satisfy all the requirements of the system.

2. An interlock was found to be necessary which restricts operation of the second pump to full flow conditions only, thereby optimizing the system for minimum energy consumption.

3. Additional low level set-points are required at Rietspruit and Davel Reservoirs which ensure safe operation of the system in the event of either of these reservoirs reaching a dangerously low level (for any reason but possibly due to failure of a pump or valve to respond to a control command.

7.1.2 Analysis of Results and Comparison with Objectives

(a) The water requirements of Kriel Power Station can be satisfied by one operating pump at Camden. As each pump operates at a fixed speed, the total demand at Kriel can be met by one pump operating continuously with unimpeded flow of water through the pipeline. Partial demand can be met by one pump operating in and on/off mode, the level setting(s) at Kriel determining the on/off time or mark/space relationship.

(b) The maximum pipeline throughput is determined by the Rietspruit - Davel pipeline and the regulating valve at Davel since this imposes a restriction on the total flow. The control must not impede the flow below this value. The maximum amount of water available for transportation to Matla Power Station can therefore be achieved by operating a second Camden pump in an on/off mode. The on/off time of the second pump is determined primarily by the level set points at Rietspruit. †

(c) The minimum water storage requirement at Kriel can be met by selecting a narrow operating range of level control at Kriel Reservoir.

(d) The amount of water consumed by minor users will upset the balance of flow through the system by a small amount. Whilst water drawn from the system at Rietspruit will not affect the maximum throughput, draw-offs downstream of Rietspruit will have a slight effect on the water available at Kriel.

(e) Pump starts/stops can be minimized without affecting the total flow as follows:-

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† This is because the scheme no longer operates as a single continuous pipeline. The flow in the different sections wil not be the same and the maximum flow will be in the Camden - Rietspruit section.

(i) Single Pump Operation (up to 1,61 m^3/sec)

The regulating valves at Davel and Kriel must have only one intermediate position each set to the output of a single pump so that the flow is matched throughout each section of the entire pipeline. The frequency of pump starts/stops is then determined by the level set points at Kriel Reservoir. The minumum cyclic time can be varied from less than 10 hours to more than 50 hours.

(ii) Dual Pump Operation (1,61 m^3/sec to 2,00^{+}m^3/sec)

With two pumps operating at Camden and both regulating valves (at Davel and Kriel) fully open the flow in each pipeline section will be different. The frequency of starts/stops for the second pump is then determined by the level set points at Rietspruit Reservoir. The minimum cyclic time for the second pump cannot be greater then 20 hours (for a safe operating range of 4,5 metres at Rietspruit) and will be reduced as the operating range at Rietspruit is reduced.

(f) Minimum regulating valve movement occurs for matched flow at different values of demand. Less valve cycling therefore takes place if the additional intermediate regulating valve postion settings are retained, unfortunately this results in additional starting and stopping of pumps.

The valve cyclic times with a single intermediate position of the regulating valves are not excessive (See Table 6.8).

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† Total flow value

(g) In order to protect Rietspruit and Davel Reservoirs from draining in the event of failure of pumps and/or valves it was found necessary to introduce additional low level set points at Davel and Rietspruit, to throttle the outflow from those Reservoirs, which exert overriding Control when the water level becomes dangerously low.

(h) Under matched flow conditions, the overall flow could be maintained with one half of any reservoir out of commission.

7.1.3 Recommended Control System Settings

7.1.3.1 *Valve Positions*

The regulating valves at Davel and Kriel should be set to operate between fully closed ($V_D = 0\%$, $V_K = 0\%$), an intermediate position corresponding to the output of one pump (1,61 m^3/sec), and fully open ($V_D = 100\%$, $V_K = 100\%$).

The intermediate valve positions are:-

Davel valve V_D = 70,68%

Kriel valve V_K = 74,79%

As it will not be possible to set the valves to this degree *of accuracy in practice, it may* be necessary to utilize one of the redundant valve settings so as to provide an upper and a lower boundary with the desired valve position as the mean value. Whilst this will result in greater valve movement, it will not result in increased pump starts and stops.

The extent of this additional valve cycling can be controlled by the difference in value of the corresponding Kriel and Davel level set points.

The ideal difference between the upper and lower valve position settings at Davel should correspond to a flow which is equivalent to the minor draw-offs along the Rietspruit - Davel pipeline (including the draw-off to the township from Davel Reservoir).

7.1.3.2 Kriel Reservoir Level Set Points.

These will command the Kriel regulating valve to the desired positon and for flows up to and including 1,61 m^3/sec., the difference in depth between the full supply level set point and the next lower set point will determine the frequency of pump starts. The lowest set point corresponding to valve full open should be set in reasonable proximity to the intermediate setting since:-

- providing the difference between the two settings is greater than a critical value (corresponding to a volume of water equal to that contained within the operating range at Rietspruit Reservoir) it will not affect the duty cycle of the second pump. If the difference is less than the critical value it will cause more frequent pump starts.

- providing the difference is not less than the critical value, the closer the levels are set to each other, the better the response of the rate of change control at Rietspruit Reservoir.

The recommended settings are:-

Level Set Point	Depth of Water	% Valve Opening, V_K	
		Falling Level	Rising Level
	Above Full Supply Level	0%	0%
WLK0	----13,78m----		
	Range =800mm	0%	74,79%
WLK1) WLK2) WLK3)	----12,98m----		
	Range =200mm	74,79%	100%
WLK4	----12,78m----		
	Below lowest Set Point	100%	100%

Should an additional intermediate setpoint be required this should be set as follows:-

WLK1 at 12,78m
WLK2 at 12,96m

and valve positions

VK1 = 70,0%
VK2 = 75,0%

7.1.3.3 Davel Reservoir Level Set Points.

These will command the Davel regulating valve to the desired position. The significant factor in selecting these values is that the Davel valve should not impede the through flow of water to Kriel (that is for flows less than the limiting value of 2,00 cumecs as already discussed).

The recommended settings are those given in Table 6.5 and Table 6.7.

Should an additional intermediate set-point be required this should be set as follows:-

WLD1 = WLD2 at 7,00m
WLD3 at 6,75m

and valve positions

VD1 = VD2 = 67,0%
VD3 = 72,0%

7.1.3.4 Rietspruit Reservoir Level Set Points.

These will command the pumps at Camden to start or stop as required. Whilst the frequency of operation of the first pump is determined by the level setting at Kriel, the frequency of operation of the second pump (for reasons discussed) is dependent on the level settings at Rietspruit. These are given in Table 6.6.

7.1.4 Justification for Computer Study.

Although the basic philosophy of the control system could have been determined by reasoned argument it would have been difficult to assess the overall control and set optimum values for the control parameters without the aid of the computer. This is largely due to the iterative nature of the problem since the flows and reservoir levels are all interactive. Moreover the computer model will serve as a valuable tool in any future work which is carried out not only on the Usutu River Scheme but also on any similar future projects.

7.2 Future Work

7.2.1 Updating the System

Once the process computer is operational it will be desirable to check the results obtained from the actual system and compare with those obtained from the study. Any discrepencies can be used to improve and update the computer model.

In addition the following are also possible areas for future work:-

(i) The power station water demand will not remain constant for long periods as simulated but will be stoichastic in nature. The computer programme could therefore be modified to include this feature. This, however, can only be achieved once it is possible to monitor the power station consumption.

(ii) Should the actual system be modified at some future date (for instance to increase the flow through Davel Reservoir), the computer model can be updated to account for this.

7.2.2 Fault Conditions

The computer model could be used to simulate fault conditions on the system and check the response. Some of the possibilities are:-

(i) Failure of a pump to start or stop.

(ii) Failure of a valve to operate correctly.

(iii) Burst or leaking pipe.

(iv) Reservoir water level too high or two low.

(v) An obstruction in the pipe.

There are, of course, many other possibilities, including loss of electrical supply or loss of a flow or level transducer, limited only by the imagination. Such studies, in which the computer model would prove to be an invaluable tool, could greatly assist in the operation of the system and in future design.

APPENDIX A

FLUID MECHANICS

A.1 Headloss/Flow - Darcy Weisbach Formula

Newton's laws of motion are applicable to fluid flowing in a pipeline. In order for flow to take place a force must be applied which is sufficient to overcome resistance to motion. This resistance can be expressed as an opposing force which is a combination of pressure and friction. For a rising main the opposing pressure is due to gravitational forces acting on the column of water in the pipeline. For a gravity main the force of gravity is itself the driving force.

Friction always opposes the motion and results in an energy loss which is caused by the motion of the fluid against the sides of the pipe and against itself and is therefore a function of the pipe roughness and the viscosity of the fluid. Darcy - Weisbach deduced a formula for pipe friction loss expressed as :-

$$h_f = \frac{\lambda L \; v_p^2}{2g \; D_p} \quad \text{..............................(A.1)}$$

where h_f is the friction headloss

λ is a dimensionless coefficient called friction factor

L is the length of the pipeline

v_p is the velocity of the fluid

D_p is the pipe diameter

g is the acceleration due to gravity

Since the flow $Q = A_P \cdot v_P$ where A_P is the cross sectional area of the pipe

$$h_f = \frac{L}{A_P^2} \cdot \frac{\lambda}{2g\ D_P} Q^2 \text{........................(A.2)}$$

or Substituting for $A_P^2 = \left(\frac{\pi\ D_P^2}{4}\right)^2$

$$\frac{16\ \lambda L}{2g\pi^2\ D_P^5} Q^2 \text{..................................(A.3)}$$

The above formula assumes a pipeline of uniform cross-section. If a constriction is introduced into the pipeline such as valve, this will introduce additional losses.

Thus for a pipeline with a flow control valve the equation now becomes :-

$$h_f = \frac{\lambda L\ \ v_P^2}{2g\ D_P} + \frac{\zeta\ v_T^2}{2g} \text{ ....(A.4)}$$

where ζ is the friction factor for the valve and is a function of the valve opening see (Appendix B).

v_T is the velocity of the fluid through the throat of the valve.

Since the flow can be assumed to be the same in the valve as in the pipeline

$$Q = A_P \cdot v_P = A_T \cdot v_T \text{ ....(A.5)}$$

where A_T is the cross-sectional area of the valve throat.

Hence

$$\frac{v_T}{v_P} = \frac{A_P}{A_T} = \frac{\pi D_P^2}{4} \cdot \frac{4}{\pi D_T^2} = \frac{D_P^2}{D_T^2} \quad \text{..........(A.6)}$$

i.e.

$$v_T = v_P \cdot \frac{D_P^2}{D_T^2} \quad \text{..........................(A.7)}$$

and

$$v_T^2 = v_P^2 \cdot \frac{D_P^4}{D_T^4} \quad \text{..........................(A.8)}$$

Substituting in equation (A.4)

$$h_f = \frac{\lambda L \; v_P^2}{2g \; D_P} + \frac{\zeta \; v_P^2 \; D_P^4}{2g \; D_T^4} \quad \text{................(A.9)}$$

Writing

$$Q = A_P \; v_P = \frac{\pi D_P^2}{4} \cdot v_P \quad \text{......................(A.10)}$$

$$v_P = \frac{4}{\pi D_P^2} \cdot Q \quad \text{...........................(A.11)}$$

and

$$v_p^2 = \frac{16}{\pi^2 \; D_p^4} . Q^2 \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(A.12)}$$

Substituting equation (A.12) for v_p^2 into equation (A.9) and simplifying:-

$$h_f = \frac{16}{2g\pi^2} \left\{ \frac{\lambda L}{D_p^5} + \frac{\zeta}{D_T^4} \right\} Q^2 \; \ldots\ldots\ldots \text{(A.13)}$$

For a given pipeline D_p, D_T and L are known, λ can be calculated and ζ can be obtained from the valve characteristic.

A.2 Flow and Varying Head

Figure A.1 depicts two reservoirs connected by a pipeline of uniform cross section.

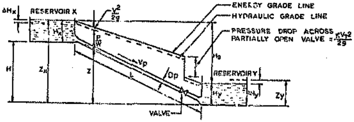


Figure A.1 - Flow and Varying Head

According to Bernoulli's principle, the total energy at any point in a pipeline is the sum of the elevation, pressure and velocity heads.

$$E = z + \frac{p}{w} + \frac{v^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (A.14)$$

where z is the elevation head (potential energy)
$\frac{p}{w}$ is the pressure head (w = unit weight of fluid)

$\frac{v^2}{2g}$ is the velocity head (kinetic energy)

The equation is graphically represented by the energy grade line in fig. A.1.

At Reservoir X and Reservoir Y, equation (A.14) can be written as:

$$E_x = z_x + \frac{p_x}{w} + \frac{v_x^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (A.15)$$

and

$$E_y = z_y + \frac{p_y}{w} + \frac{v_y^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots (A.16)$$

But as the velocity of the water at Reservoir X is zero and as the kinetic energy of the water on entry to Reservoir Y can be assumed to be dissipated since motion ceases and therefore the velocity at Reservoir Y may also be regarded as zero, the $\frac{v^2}{2g}$ terms can be ignored.

As the pressure head at the surface of each reservoir is zero, the $\frac{p}{w}$ term in equations (A.15) and (A.16) may also be ignored.

Subtracting (A.16) from (A.15)

$E_x - E_y = z_x - z_y$ ....(A.17)

$E_x - E_y$, the loss of energy is due to friction and can be expressed as the friction headloss h_f.

$z_x - z_y$, the difference in elevation is the static head, H_S.

Hence

$h_f = H_S$ ....(A.18)

The static head H_S will not be constant but will vary as the water level in Reservoir X and Reservoir Y varies.

Suppose the inflow to Reservoir X is Q_A and the outflow Q_B then during an interval of time Δt the quantity of water added to Reservoir X is

$Q_A \cdot \Delta t$ ....(A.19)

and the quantity of water removed in the same interval of time is

$Q_B \cdot \Delta t$ ....(A.20)

The net gain or loss in volume of Reservoir X is

$\Delta H_X \cdot A_{SX}$ ....(A.21)

Where ΔH_X is the change in level during interval Δt and A_{SX} is the surface area of X.

Equating (A.19), (A.20) and (A.21)

$\Delta H_X \cdot A_{SX} = Q_A \cdot \Delta t - Q_B \cdot \Delta t$ ....(A.22)

$$= (Q_A - Q_B) \,.\, \Delta t \quad \text{.............................} (A.23)$$

The change in level is

$$\Delta H_X = \frac{(Q_A - Q_B)}{A_{SX}} . \Delta t \quad \text{........................} (A.24)$$

in the limit $\Delta t \rightarrow 0$

$$dH_X = \frac{(Q_A - Q_B)}{A_{SX}} . dt \quad \text{........................} (A.25)$$

Thus the depth can be obtained by integrating the net flow.

$$\int_{H_o}^{H_1} H_X = \int_{t_o}^{t_1} \frac{(Q_A - Q_B)}{A_{SX}} . dt \quad \text{.....................} (A.26)$$

$$\{H_X\}_{H_o}^{H_1} = \frac{(Q_A - Q_B)}{A_{SX}} . (t_1 - t_o) + \text{Constant.....} (A.27)$$

If initially $t_o = 0$ and $H_X = H_{XO}$

Constant $= H_{XO} =$ the initial value of the water level

At instant of time t_1 the level will be H_{X1} and the change in level $H_{X1} - H_{XO}$.

Similarly the change in level for Reservoir Y can be obtained by integration.

The static head H_S can now be obtained for any instant of time and is

$$H_S = H + H_X(t) - H_Y(t) \quad \text{.....................} (A.28)$$

From (A.18)

$$h_f = H_S \ldots\ldots\ldots\ldots\ldots\ldots \text{(A.29)}$$

And substituting for h_f from (A.13)

$$H_S = \frac{16}{2g\pi^2}\left(\frac{\lambda L}{D_P^{5}} + \frac{\zeta}{D_T^{4}}\right)Q_A^{2} \ldots\ldots\ldots\ldots \text{(A.30)}$$

Rewriting and substituting for H_S from (A.28)

$$H + H_X(t) - H_Y(t) = (K_1 + K_2\zeta)\, Q_A^{2} \ldots \text{(A.31)}$$

where K_1 and K_2 are constants

$$Q_A = \sqrt{\frac{H + H_X(t) - H_Y(t)}{K_1 + K_2\,\zeta}} \ldots\ldots\ldots\ldots \text{(A.32)}$$

A.3 Rising Main

The expression (A.13) relating flow and headloss can be used for a rising main although in this case the headloss h_f is the difference between the pumping head and the static head.

$$h_f = H_p - H_S \ldots\ldots\ldots\ldots\ldots\ldots \text{(A.33)}$$

where H_p is the pumping head.

The pumping head is a function of the flow and is obtained from the pump characteristic.

APPENDIX B

PHYSICAL DATA

(Note: a considerable amount of physical data is given on figure 1.1)

B.1 Rietspruit Reservoir

Rietspruit Reservoir comprises two cylindrical halves each as illustrated :-

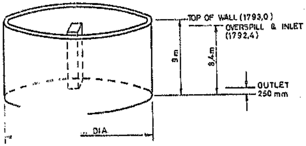


Figure B.1 - Rietspruit Reservoir - Dimensions

Surface area of each half reservoir

$$= \frac{\pi}{4} \times (48,8)^2 = 1\ 870,38\ m^2$$

Total surface area

$$A_{SR} = \underline{2 \times 1\ 870,38\ m^2}$$

Total capacity of combined reservoir

$= 2 \times 1\,870{,}38 \times 8{,}4 \text{ m}^3$
$= 31\,422{,}38 \text{ m}^3$
$=$ <u>31,42 megalitres</u>

B.2 Davel Reservoir

Davel Reservoir comprises two cylindrical halves each as illustrated :-

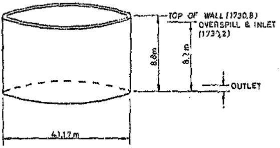


Figure B.2 - Davel Reservoir - Dimensions

Surface area of each half reservoir

$$= \frac{\pi}{4} \times (41{,}17)^2 = 1\,331{,}23 \text{ m}^2$$

Total surface area

$A_{SD} = \underline{2 \times 1\,331{,}23 \text{ m}^2}$

Total capacity of combined reservoir

$= 2 \times 1\,331{,}23 \times 8{,}2 \text{ m}^3$
$= 21\,832{,}10 \text{ m}^2$
$=$ <u>21,83 megalitres</u>

B.3 Kriel Reservoir

The shape of Kriel Reservoir is basically that of a truncated cone with a dividing embankment through the middle.

Figure B.3 - Kriel Reservoir - Shape

In order to obtain an equation for the surface area at varying depths, the solution is performed in two parts :-

(i) An equation is obtained for the area of the undivided reservoir.

(ii) An equation is derived for the area of the dividing portion.

(iii) The actual area is obtained by subtracting (ii) from (i)

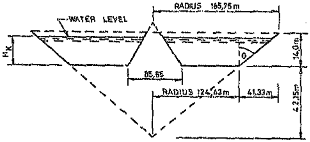


Figure B.4 - Kriel Reservoir - Cross Section

H_K = depth of water in reservoir

(i) Area of Undivided Reservoir A_1

Area of undivided reservoir at depth H_K,

$$= \pi R^2$$

$$= \pi(124,425 + H_K \tan\theta)^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\text{(B.1)}$$

$$\text{Now } \tan\theta = \frac{41,33}{14,00} = 2,95 \quad \ldots\ldots\ldots\ldots\ldots\text{(B.2)}$$

Hence substituting (B.2) in (B.1)

$$A_1 = \pi(124,43 + H_K.2,95)^2 \quad \ldots\ldots\ldots\ldots\ldots\text{(B.3)}$$

(ii) Area of Central Portion, A_2

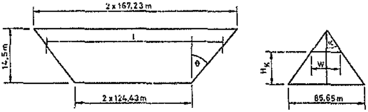


Figure B.5 - Kriel Reservoir - Area of Central Portion

Area of earth embankment, A_2, at depth H_K of water

$$= \text{length} \times \text{width} = l \times w$$

$$= \{2 \times (124,43 + H_K \tan\theta\ )\} \quad \times \quad \{2 \times (14,5 - H_K) \tan\alpha\} \quad \ldots\text{(B.4)}$$

where $\tan\theta$ = 2,95 from equation (B.2 above)

$$\text{and } \tan\alpha = \frac{85,65}{2 \times 14,5} = 2,95 \quad \ldots\ldots\ldots\ldots\ldots\text{(B.5)}$$

Substituting for $\tan\theta$ and $\tan\alpha$ in (B.4)

A_2 = 2 x (124,43 + 2,95 H_K) x 2 (14,5-H_K) 2,95 ..(B.6)

(iii) Surface area, A_{SK}, of Water in Kriel Reservoir at Varying Depth H_K

A_{SK} = A_1 - A_2 ....(B.7)

B.4 Pipelines

The diameter, and lengths of all three pipelines are given on figure 1.1

The values of friction factor, λ , were obtained from information given in the reports of performance tests (see Appendix C) using the Darcy - Weisbach formula. The values of friction factor thus obtained include minor losses.

Example : Camden - Rietpruit Pipeline
From Report ME R/47 (April 1976)
Static head Camden - Rietspruit, H_1 = 116,21 m
Pumping head (one pump), H_p = 140,02 m
Friction headloss, h_f = 140,02 - 116,21 m
= 23,81 m
Length of pipeline, L_1 = 12 805 m
Diameter of pipeline, D_p = 1,2 m. (D_P^5 = 2,4883 m^5)
Diameter of valve throat, D_T = 0,6 m (D_T^4 = 0,1296 m^4)
Full flow from pump, Q_1 = 1,634 m^3/sec. (Q_1^2 = 2,6700 $(m^3/s)^2$
For fully open pump discharge valve ζ = 1,2

From Appendix A: Darcy - Weisbach forumla,

$$h_f = \frac{16}{2g\,\pi^2} \left\{ \frac{\lambda_1\, L_1}{D_p^5} + \frac{\zeta}{D_T^4} \right\} Q_1^2$$

Re-arranging

$$\lambda_1 = \frac{D_P^{\;5}}{L_1} \left\{ \frac{h_f}{K.Q_1^{\;2}} - \frac{\zeta}{D_T^{\;4}} \right\}$$

where $K = \frac{16}{2g\,\pi^2} = 0{,}0826$

Substituting the above values

$$= \frac{2{,}4883}{12\ 805} \left\{ \frac{23{,}81}{0{,}0826 \times 2{,}67} - \frac{1{,}2}{0{,}1296} \right\}$$

$$= \underline{0{,}0192}$$

In a similar manner the values of λ_2 and λ_3 were obtained for the Rietspruit - Davel and Davel- Kriel pipelines respectively. These were found to be $\lambda_2 = 0{,}01728$ and $\lambda_3 = 0{,}01700$.

B.5 Pumps/Valves

(i) The data for the Camden pumps is given in Appendix C.1.

(ii) The Camden pump discharge valves characteristic is given in Fig. B.6 and table B.1. Each valve is assumed to have an identical characteristic. The valves are motor operated and each is driven by a constant speed squirrel cage induction motor giving a total travel time from fully closed to fully open (and vice versa) of 3,0 minutes.

(iii) The Davel flow control valve characteristic is given in Fig. B.7 (curve 95.5) table B.2. The third column in table B.2 is reciprocal of valve friction factor and is the information used in the computer table VDTAB.

The valve travels at uniform velocity and the total travel time fully closed to fully open (and vice versa) is 16,00 minutes.

(iv) The Kriel flow control valve characteristic is also given in Fig. B.7 (curve 97,5) and table B.3. The reciprocal of valve friction factor is used in the computer table VKTAB.

The travel time is the same as the Davel valve.

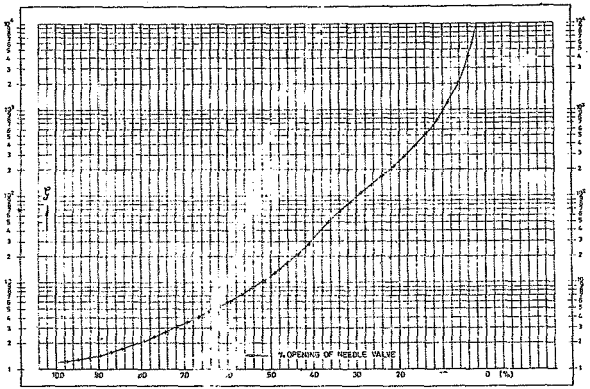


Fig. B.6 Camden Pump Discharge Valve Characteristic Curve
Friction Factor, ζ versus Valve Opening V %

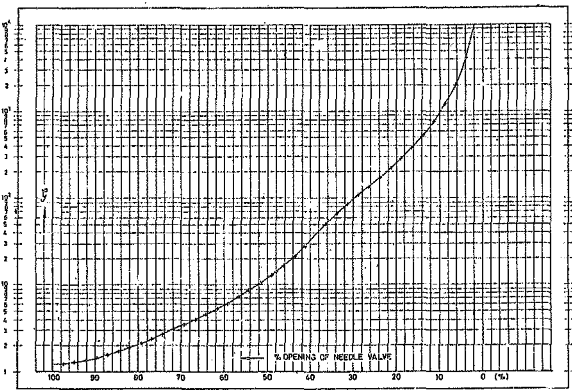


Fig. B.6 Camden Pump Discharge Valve Characteristic Curve
Friction Factor, ζ versus Valve Opening V %

Table B.1 - Camden Pump Discharge
Valve Characteristic

Valve Opening %	Valve Friction Factor ζ	Reciprocal of Friction Factor ZETC1R (or ZETC2R)
0,0	Infinity	0,0
2,5	$0,200 \times 10^5$	0,00005
5,0	$0,420 \times 10^4$	0,00024
7,5	$0,202 \times 10^4$	0,00050
10,0	$0,121 \times 10^4$	0,00083
12,5	$0,780 \times 10^3$	0,00128
15,0	$0,540 \times 10^3$	0,00185
17,5	$0,380 \times 10^3$	0,00263
20,0	$0,287 \times 10^3$	0,00348
22,5	$0,228 \times 10^3$	0,00439
25,0	$0,175 \times 10^3$	0,00571
27,5	$0,132 \times 10^3$	0,00758
30,0	$0,110 \times 10^3$	0,00909
32,5	$0,850 \times 10^2$	0,01176
35,0	$0,670 \times 10^2$	0,01493
37,5	$0,520 \times 10^2$	0,01923
40,0	$0,395 \times 10^2$	0,02532
42,5	$0,286 \times 10^2$	0,03497
45,0	$0,218 \times 10^2$	0,04587
47,5	$0,170 \times 10^2$	0,05882
50,0	$0,131 \times 10^2$	0,07634
52,5	$0,108 \times 10^2$	0,09259
55,0	$0,890 \times 10$	0,11236
57,5	$0,740 \times 10$	0,13514
60,0	$0,625 \times 10$	0,16000
62,5	$0,540 \times 10$	0,18519
65,0	$0,460 \times 10$	0,21739
67,5	$0,400 \times 10$	0,25000
70,0	$0,352 \times 10$	0,28409
72,5	$0,307 \times 10$	0,32573
75,0	$0,270 \times 10$	0,37037
77,5	$0,233 \times 10$	0,42918
80,0	$0,208 \times 10$	0,48077
82,5	$0,190 \times 10$	0,52632
85,0	$0,172 \times 10$	0,58140
87,5	$0,158 \times 10$	0,63291
90,0	$0,148 \times 10$	0,67568
92,5	$0,138 \times 10$	0,72464
95,0	$0,131 \times 10$	0,76336
97,5	$0,123 \times 10$	0,81301
100,0	$0,120 \times 10$	0,83333

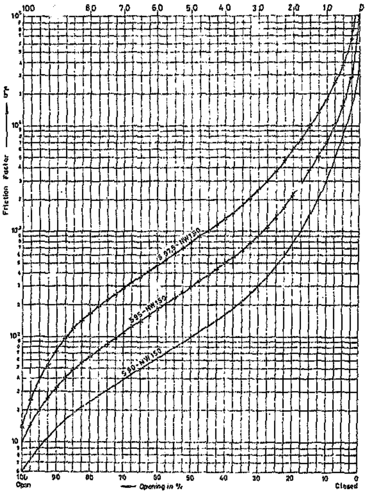


Fig B.7 - Flow Control (Regulating) Ring Needle Valve
Characteristic Curve
Friction Factor, ζ versus Valve Opening V %
Kriel Valve S 97.5 - NW 150
Daval Valve S 95.0 - NW 150

Table B.2 - Davel Flow Control Valve Characteristic (S 95)

Valve Opening %	Valve Friction Factor ζ	Reciprocal of Friction Factor ZETADR
0,0	Infinity	0,0
2,5	$0{,}285 \times 10^{5}$	$3{,}51 \times 10^{-5}$
5,0	$0{,}160 \times 10^{5}$	$6{,}25 \times 10^{-5}$
7,5	$0{,}101 \times 10^{5}$	$9{,}90 \times 10^{-5}$
10,0	$0{,}710 \times 10^{4}$	$1{,}41 \times 10^{-4}$
12,5	$0{,}510 \times 10^{4}$	$1{,}96 \times 10^{-4}$
15,0	$0{,}380 \times 10^{4}$	$2{,}63 \times 10^{-4}$
17,5	$0{,}280 \times 10^{4}$	$3{,}57 \times 10^{-4}$
20,0	$0{,}220 \times 10^{4}$	$4{,}55 \times 10^{-4}$
22,5	$0{,}170 \times 10^{4}$	$5{,}88 \times 10^{-4}$
25,0	$0{,}135 \times 10^{4}$	$7{,}41 \times 10^{-4}$
27,5	$0{,}109 \times 10^{4}$	$9{,}17 \times 10^{-4}$
30,0	$0{,}900 \times 10^{3}$	$1{,}11 \times 10^{-3}$
32,5	$0{,}760 \times 10^{3}$	$1{,}32 \times 10^{-3}$
35,0	$0{,}650 \times 10^{3}$	$1{,}54 \times 10^{-3}$
37,5	$0{,}570 \times 10^{3}$	$1{,}75 \times 10^{-3}$
40,0	$0{,}495 \times 10^{3}$	$2{,}02 \times 10^{-3}$
42,5	$0{,}430 \times 10^{3}$	$2{,}33 \times 10^{-3}$
45,0	$0{,}380 \times 10^{3}$	$2{,}63 \times 10^{-3}$
47,5	$0{,}340 \times 10^{3}$	$2{,}94 \times 10^{-3}$
50,0	$0{,}290 \times 10^{3}$	$3{,}45 \times 10^{-3}$
52,5	$0{,}265 \times 10^{3}$	$3{,}77 \times 10^{-3}$
55,0	$0{,}230 \times 10^{3}$	$4{,}35 \times 10^{-3}$
57,5	$0{,}200 \times 10^{3}$	$5{,}00 \times 10^{-3}$
60,0	$0{,}180 \times 10^{3}$	$5{,}56 \times 10^{-3}$
62,5	$0{,}157 \times 10^{3}$	$6{,}37 \times 10^{-3}$
65,0	$0{,}139 \times 10^{3}$	$7{,}19 \times 10^{-3}$
67,5	$0{,}121 \times 10^{3}$	$8{,}26 \times 10^{-3}$
70,0	$0{,}108 \times 10^{3}$	$9{,}26 \times 10^{-3}$
72,5	$0{,}950 \times 10^{2}$	$1{,}05 \times 10^{-3}$
75,0	$0{,}840 \times 10^{2}$	$1{,}19 \times 10^{-3}$
77,5	$0{,}740 \times 10^{2}$	$1{,}35 \times 10^{-3}$
80,0	$0{,}640 \times 10^{2}$	$1{,}56 \times 10^{-3}$
82,5	$0{,}560 \times 10^{2}$	$1{,}79 \times 10^{-3}$
85,0	$0{,}480 \times 10^{2}$	$2{,}08 \times 10^{-3}$
87,5	$0{,}405 \times 10^{2}$	$2{,}47 \times 10^{-3}$
90,0	$0{,}325 \times 10^{2}$	$3{,}00 \times 10^{-3}$
92,5	$0{,}265 \times 10^{2}$	$3{,}77 \times 10^{-3}$
95,0	$0{,}195 \times 10^{2}$	$5{,}13 \times 10^{-3}$
97,5	$0{,}145 \times 10^{2}$	$6{,}90 \times 10^{-3}$
100,0	$0{,}100 \times 10^{2}$	$1{,}00 \times 10^{-2}$

Note: Valve opening vs ZETADR is programmed as VDTAB

Table B.3 – Kriel Flow Control Valve
Characteristic (S 97.5)

Valve Opening %	Valve Friction Factor ζ	Reciprocal of Friction Factor ZETAKR
0,0	Infinity	0,0
2,5	$0,650 \times 10^{5}$	$1,54 \times 10^{-5}$
5,0	$0,365 \times 10^{5}$	$2,74 \times 10^{-5}$
7,5	$0,253 \times 10^{5}$	$3,95 \times 10^{-5}$
10,0	$0,180 \times 10^{5}$	$5,56 \times 10^{-5}$
12,5	$0,140 \times 10^{5}$	$7,14 \times 10^{-5}$
15,0	$0,100 \times 10^{5}$	$1,00 \times 10^{-4}$
17,5	$0,770 \times 10^{4}$	$1,30 \times 10^{-4}$
20,0	$0,590 \times 10^{4}$	$1,69 \times 10^{-4}$
22,5	$0,475 \times 10^{4}$	$2,10 \times 10^{-4}$
25,0	$0,370 \times 10^{4}$	$2,70 \times 10^{-4}$
27,5	$0,300 \times 10^{4}$	$3,33 \times 10^{-4}$
30,0	$0,245 \times 10^{4}$	$4,08 \times 10^{-4}$
32,5	$0,205 \times 10^{4}$	$4,88 \times 10^{-4}$
35,0	$0,175 \times 10^{4}$	$5,71 \times 10^{-4}$
37,5	$0,150 \times 10^{4}$	$6,67 \times 10^{-4}$
40,0	$0,130 \times 10^{4}$	$7,69 \times 10^{-4}$
42,5	$0,115 \times 10^{4}$	$8,70 \times 10^{-4}$
45,0	$0,101 \times 10^{4}$	$9,90 \times 10^{-4}$
47,5	$0,890 \times 10^{3}$	$1,12 \times 10^{-3}$
50,0	$0,780 \times 10^{3}$	$1,28 \times 10^{-3}$
52,5	$0,690 \times 10^{3}$	$1,45 \times 10^{-3}$
55,0	$0,610 \times 10^{3}$	$1,64 \times 10^{-3}$
57,5	$0,540 \times 10^{3}$	$1,85 \times 10^{-3}$
60,0	$0,470 \times 10^{3}$	$2,13 \times 10^{-3}$
62,5	$0,415 \times 10^{3}$	$2,41 \times 10^{-3}$
65,0	$0,365 \times 10^{3}$	$2,74 \times 10^{-3}$
67,5	$0,320 \times 10^{3}$	$3,13 \times 10^{-3}$
70,0	$0,285 \times 10^{3}$	$3,51 \times 10^{-3}$
72,5	$0,253 \times 10^{3}$	$3,95 \times 10^{-3}$
75,0	$0,222 \times 10^{3}$	$4,50 \times 10^{-3}$
77,5	$0,193 \times 10^{3}$	$5,18 \times 10^{-3}$
80,0	$0,165 \times 10^{3}$	$6,06 \times 10^{-3}$
82,5	$0,143 \times 10^{3}$	$6,99 \times 10^{-3}$
85,0	$0,119 \times 10^{3}$	$8,40 \times 10^{-3}$
87,5	$0,950 \times 10^{2}$	$1,05 \times 10^{-2}$
90,0	$0,725 \times 10^{2}$	$1,38 \times 10^{-2}$
92,5	$0,550 \times 10^{2}$	$1,82 \times 10^{-2}$
95,0	$0,380 \times 10^{2}$	$2,63 \times 10^{-2}$
97,5	$0,250 \times 10^{2}$	$4,00 \times 10^{-2}$
100,0	$0,136 \times 10^{2}$	$7,35 \times 10^{-2}$

Note: Valve opening vs ZETAKR is programmed as VKIAS

APPENDIX C

PERFORMANCE TESTS

C.1 Camden Pump Set (Report ME-R/47)

Tests were carried out on pump set no. 1, only, pumps 2 and 3 were assumed to be identical.

In this test the pumping head was measured for various settings of the pipeline isolating valve. The flow was determined for each of the different valve positions by using one half of the Rietspruit reservoir as a volumetric tank. Changes in volume were obtained by measurements taken, over a period of time, from three U-tubes connected by syphon at Rietspruit reservoir.

The test connections are shown in figure C.1 and the test results on figure C.2. Table C.1 gives the actual values of pump head versus flow as used in the computer programme P1TAB.

The table P2TAB used for the second pump is identical to P1TAB.

The maximum flow obtained from the test results for single pump operation is 1,634 cumecs.

C.2 Rietspruit - Davel Pipeline and Davel - Kriel Pipeline (Report ME-R/53)

Tests were carried out on the gravity pipelines from Rietspruit to Davel and Davel to Kriel. In order to determine the pipeline characteristics, bourdon-tube test pressure gauges and mercury U-tubes were used. The reservoirs at Rietspruit and Davel were used as volumetric tanks to determine pipeline flows. Volume changes were accurately determined by means of float gauges.

The test connections are shown in figures C.3 and C.4.

The report states that the maximum flow for the Rietspruit - Davel pipeline be taken as 1,983 cumecs and that for the Davel - Kriel pipeline as 2,156 cumecs.

C.3 Magnetic Flowmeter on Inlet to Kriel Reservoir (Addendum to Report ME-R/53)

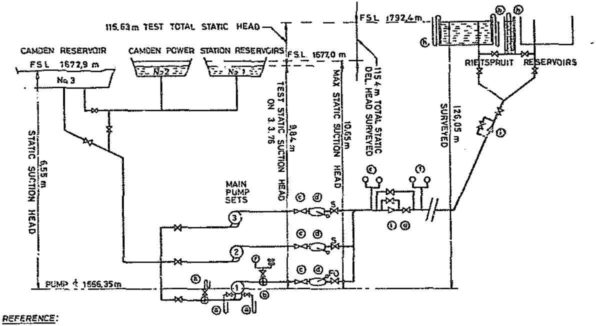
This test was carried out in a similar manner to those under C.2 above. The Davel reservoirs were used as volumetric tanks and volume changes in both reservoirs were accurately determined by the level change in the stilling chamber using a float gauge. Reservoir volume changes were read at constant intervals of time over a set period to determine the flows with the flow control valve set at openings of 25%, 50%, 75% and full open.

The results of the tests are given in table C.2.

Table C.2 – Performance Tests on "Krohne" Magnetic Flow Meter

Schedule of Test Results

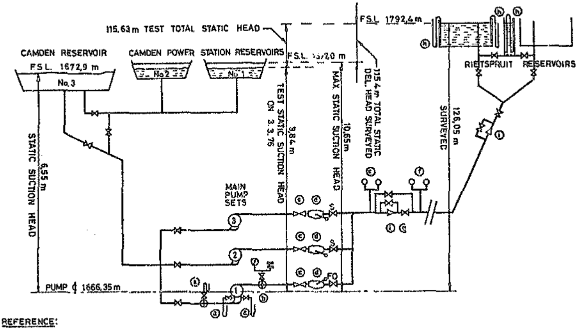
Test No.	Needle opening at Kriel	Needle valve position indicator opening at Kriel P.S.	Measured flow rate leaving Davel reservoirs	Measurement by "Krohne" magnetic flow meter situated at Kriel Power Station, 56 km from Davel				
				Chart indicator flow rate	Integrator flow rate	Output signal	Meter error	
							Chart	Integrator
Units		%	m^3/s	m^3/s	m^3/s	mA	%	%
1	F.O.	100	2,165	2,175	2,192	18,194	+0,46	+1,25
2	THROTTLED	Nominal 75	1,430	1,430	1,435	13,514	nil	+0,30
3	THROTTLED	Nominal 50	1,074	1,071	1,080	8,034	-0,28	+0,56
4	THROTTLED	Nominal 25	0,540	0,535	0,537	3,979	-1,0	-0,56
5	SHUT	0	0	0	0	0	0	0



REFERENCE:

a. SUCTION HEAD MERC ··3E
b. DISCHARGE HEAD TE' \OWEIGHT PRESSURE GAUGES
c VENTURI TUBE
d NEEDLE VALVE
e 1st AIR VALVE
f. 2nd AIR VALVE
g DISCHARGE VALVE USED FOR THROTTLING
h. SYPHON MANOMETERS
i REFLUX VALVES
S. ⋈ VALVES SHUT
F.O. ⋈ VALVES FULL OPEN

Fig. C.1 - Camden - Rietspruit Pipeline : Diagrammatic Arrangement of Pumps, Reservoirs and Pipelines



REFERENCE:

a. SUCTION HEAD MERCURY U-TUBE
b. DISCHARGE HEAD TEST & DEADWEIGHT PRESSURE GAUGES.
c. VENTURI TUBE.
d. NEEDLE VALVE
e. 1st AIR VALVE
f. 2nd AIR VALVE
g. DISCHARGE VALVE USED FOR THROTTLING
h. SYPHON MANOMETERS
i REFLUX VALVES
S ⋈ VALVES SHUT
F.O. ⋈ VALVES FULL OPEN

Fig. C.1 - Camden - Rietspruit Pipeline : Diagrammatic Arrangement of Pumps, Reservoirs and Pipelines

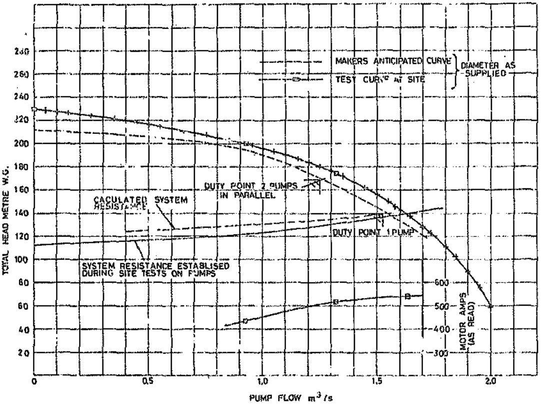


Fig. C.2 - Camden Pump Characteristic : Pumping Head vs Flow

Table C.1 - Cardiac Pump Head
Versus Flow Characteristic

Pump Flow M^3/sec	Pump Head m. Hg
0,00	230
0,05	229
0,10	228
0,15	227
0,20	226
0,25	224
0,30	223
0,35	222
0,40	220
0,45	218
0,50	217
0,55	216
0,60	214
0,65	212
0,70	210
0,75	208
0,80	205
0,85	203
0,90	200
0,95	198
1,00	196
1,05	193
1,10	190
1,15	187
1,20	184
1,25	180
1,30	176
1,35	172
1,40	167
1,45	162
1,50	156
1,55	150
1,60	144
1,65	137
1,70	130
1,75	122
1,80	113
1,85	102
1,90	92
1,95	76
2,00	59

Programmed as P1TAB, P2TAB

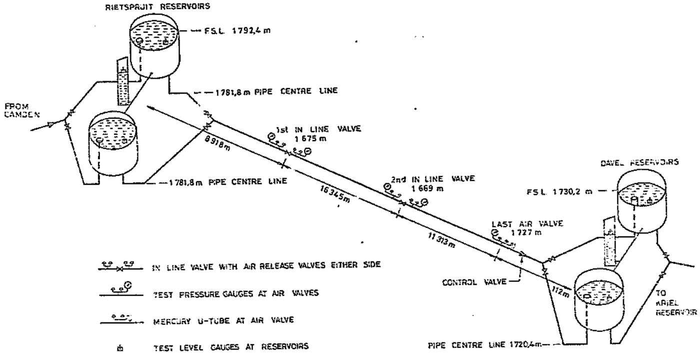


Fig. C.3 - Rietspruit - Davel Pipeline : Diagrammatic Arrangement of Reservoirs and Pipelines

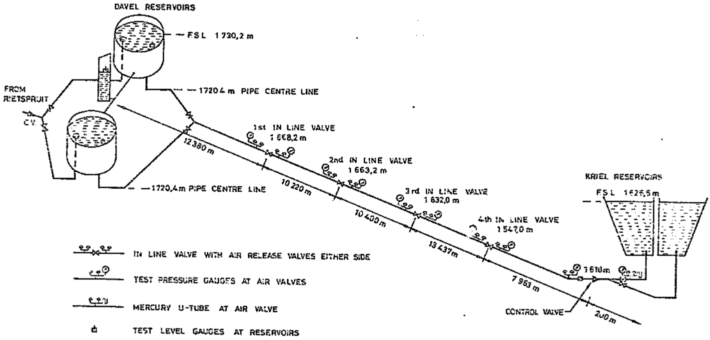


Fig. C.4 – Davel – Kriel Pipeline : Diagrammatic Arrangement of Reservoirs and Pipelines

APPENDIX D

PUMPING HEAD, FLOW AND PUMP DISCHARGE VALVE POSITION

Although a pump "Head vs Flow" characteristic had been obtained from tests performed on site (Fig. C.2) it was necessary to run a computer sub-routine to obtain the relationship between pump flow and discharge valve position. The flow is dependent on the pumping head, the static head and valve position. If the static head is assumed to be constant (for reasons stated earlier - see 3.3.2) then for a particular valve opening (i.e. value of friction) the flow is determined by the pumping head which itself is a function of the flow. It was necessary, therefore to obtain the flow by iteration.

D.1 Newton - Raphson Iteration

CSSL contains an implicit iterative operation for solution of equations of the form :-

$$Y = f\ (Y) \quad \ldots\ldots (D.1)$$

From an initial guess for Y, the iterative process calculates Y such that the relationship Y = f (Y) is satisfied. In addition to the initial value for Y, the number of [illegible], to be performed the tolerance and the increments in Y a[illegible]ed.

The iterative method used is the Newton - Raphson method.

$$Y_n + 1 = (F_n - C_n Y_n)/(1 - C_n) \quad \ldots\ldots (D.2)$$

$$C_n = \{f_n - (f_n - 1)\}/\{Y_n - (Y_n - 1)\} \ldots\ldots (D.3)$$

$$\text{where } f_n = f\ (Y_n) \quad \ldots\ldots (D.4)$$

D.2 Computer Programme

Whilst the CSSL function could be used to obtain single pump flow, it was not suitable for two pump operations. The problem was solved using nested DO loops in Fortran. The sub-routine is listed in this Appendix.

The reciprocal of valve friction factor was obtained from tables, i.e. ZETCIR = VC1TAB (V1); ZETC2R = VC2TAB (V2).

The values were incremented by Q1N, Q2N (chosen as 0,001) each calculation.

The function "f (y)" was denoted by QF1, QF2 (this is the Darcy-Weisbach formula used to obtain the flow for varying headloss).

D.3 Results

The results plotted by the computer are included as part of this appendix.

As the static head was assumed to be constant these results were then included in the main program in tabular form, discharge valve position versus flow - VC1TAB and VC2TAB - Table D.1.

Table D.1 – Camden Pump 1 Flow
& Camden Pump 2 Flow from Computer
Simulation (VC1TAB, VC2TAB)

Discharge Valve 1 % Open	Discharge Valve 2 % Open	Pump 1 Flow	Discharge Valve 1 % Open	Discharge Valve 2 % Open	Pump 1 Flow	Pump 2 Flow
0,0	0,0	0,00	100,0	0,0	1,61	0,0
2,5	0,0	0,09	100,0	2,5	1,60	0,08
5,0	[illegible]	0,20	100,0	5,0	1,58	0,18
7,5	0,0	0,28	100,0	7,5	1,57	0,24
10,0	0,0	0,36	100,0	10,0	1,55	0,31
12,5	0,0	0,44	100,0	12,5	1,54	0,38
15,0	0,0	0,52	100,0	15,0	1,53	0,44
17,5	0,0	0,61	100,0	17,5	1,51	0,51
20,0	0,0	0,68	100,0	20,0	1,50	0,57
22,5	0,0	0,75	100,0	22,5	1,49	0,62
25,0	0,0	0,83	100,0	25,0	1,48	0,68
27,5	0,0	0,92	100,0	27,5	1,46	0,75
30,0	0,0	0,98	100,0	30,0	1,45	0,79
32,5	0,0	1,07	100,0	32,5	1,43	0,86
35,0	0,0	1,14	100,0	35,0	1,42	0,91
37,5	0,0	1,22	100,0	37,5	1,40	0,97
40,0	0,0	1,30	100,0	40,0	1,39	1,03
42,5	0,0	1,37	100,0	42,5	1,37	1,09
45,0	0,0	1,42	100,0	45,0	1,36	1,13
47,5	0,0	1,46	100,0	47,5	1,35	1,16
50,0	0,0	1,49	100,0	50,0	1,33	1,20
52,5	0,0	1,51	100,0	52,5	1,33	1,21
55,0	0,0	1,53	100,0	55,0	1,32	1,23
47,5	0,0	1,54	100,0	57,5	1,32	1,24
60,0	0,0	1,56	100,0	60,0	1,32	1,25
62,5	0,0	1,56	100,0	62,5	1,31	1,26
65,0	0,0	1,57	100,0	65,0	1,31	1,27
67,5	0,0	1,58	100,0	67,5	1,31	1,27
70,0	0,0	1,58	100,0	70,0	1,31	1,27
72,5	0,0	1,59	100,0	72,5	1,31	1,28
75,0	0,0	1,59	100,0	75,0	1,31	1,28
77,5	0,0	1,60	100,0	77,5	1,30	1,29
80,0	0,0	1,60	100,0	80,0	1,30	1,29
82,5	0,0	1,60	100,0	82,5	1,30	1,29
85,0	0,0	1,60	100,0	85,0	1,30	1,29
87,5	0,0	1,60	100,0	87,5	1,30	1,29
90,0	0,0	1,60	100,0	90,0	1,30	1,30
92,5	0,0	1,61	100,0	92,5	1,30	1,30
95,0	0,0	1,61	100,0	95,0	1,30	1,30
97,5	0,0	1,61	100,0	97,5	1,30	1,30
100,0	0,0	1,61	100,0	100,0	1,30	1,30

LOOP FOR PUMP 1 FLOW

LOOP FOR PUMP 2 FLOW

```
  PROCEDURAL
   INTEGER I,J,M,N
     Q1=Q10
     DO C15 I=1,M
     Q2=Q20
     DO C11 J=1,N
     QF2=SQRT(ZETC2R*((P2TAB(Q2)-HC)-K2*(2.0*Q1*Q2+Q1**2.0))/DEN2)
     IF(ABS(Q2-QF2).LE.(ERR*ABS(Q2)))GO TO C12
     IF(J.NE.1)GO TO C10
     OLDQ2=Q2
     OLDQF2=QF2
     Q2=(1.0+Q2N)*Q20
     IF(Q2.EQ.0.0)Q2=Q2N
     GO TO C11
C10..Q2CH=(QF2-OLDQF2)/(Q2-OLDQ2)
     NEWQ2=(QF2-Q2CH*Q2)/(1.0-Q2CH)
     OLDQ2=Q2
     Q2=NEWQ2
     OLDQF2=QF2
C11..CONTINUE
     FL=0.
     GO TO C13
C12..FL=1.0
C13..CONTINUE
     QF1=SQRT(ZETC1R*((P1TAB(Q1)-HC)-K2*(2.0*Q1*Q2+Q2**2.0))/DEN1)
     IF(ABS(Q1-QF1).LE.(ERR*ABS(Q1)))GO TO C16
     IF(I.NE.1)GO TO C14
     OLDQ1=Q1
     OLDQF1=QF1
     Q1=(1.0+Q1N)*Q10
     IF(Q1.EQ.0.0)Q1=Q1N
     GO TO C15
C14..Q1CH=(QF1-OLDQF1)/(Q1-OLDQ1)
     NEWQ1=(QF1-Q1CH*Q1)/(1.0-Q1CH)
     OLDQ1=Q1
     Q1=NEWQ1
     OLDQF1=QF1
C15..CONTINUE
        FL=0.0


     GO TO C17
C16..FL=1.0
C17..CONTINUE
     HEAD1=P1TAB(Q1)
     HEAD2=P2TAB(Q2)
     END
```

Fig. D.1 - Subroutine for Pump Starting/Stopping
(Newton-Raphson Iteration)

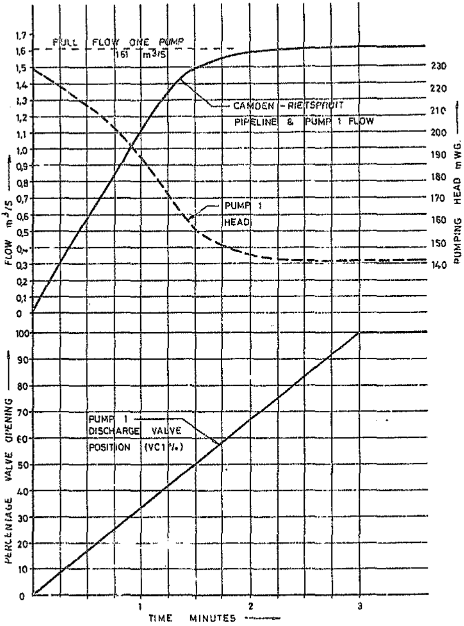


Fig. D.2 - Computer Simulation for Starting First Pump at Camden

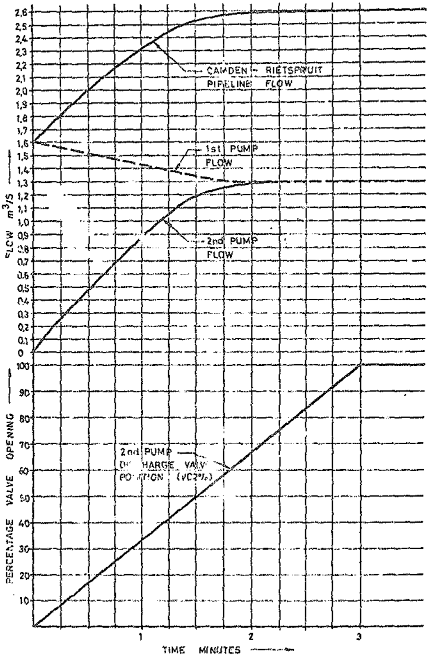


Fig. D.3 - Computer *Simulation* for Starting Second Pump at Camden

APPENDIX E

PROGRAMME LISTINGS

E.1 Explanatory Notes

As mentioned in paragraph 3.6 the programme was arranged in blocks as follows :-

```
PROGRAM  (NAME)
    -
    -
INITIAL
    -
    -
END
DYNAMIC
    -
    -
DERIVATIVE (NAME)
    -
    -
    -
END
END
TERMINAL
    -
    -
END
END
```

E.2 Initial Block

This defines a block of statements which are used only at the beginning of a simulation run and comprises the following headings :-

(i) Basic Inputs

These are inputs which are used to "start" the system from a state of equilibrium. They are values which are not influenced by the simulation such as the demand, Q_K, at Kriel and the demands, Q_R, Q_D, at Rietspruit and Davel. Fixed quantities have been used for these values for a particular simulation run.

(ii) Initialization of Controlled Variables

These include initial values of :-

Reservoir levels (HRO, HDO, HKO)
Valve positions (V1O, V2O, VDO, VKO)
Pumps operating (P)

These values can also be used to "start" the system. Equilibrium is with all reservoirs at full supply level (F.S.L.), all valves fully closed and both pumps stopped.

(iii) Control Parameters

These are adjustable control parameters which can be varied to give optimum performance and include :-

Reservoir level absolute and rate of change set points.
Flow control valve intermediate opening set points.
Number of reservoirs in service - i.e. full or half reservoir operation.

Timers for setting permissible time interval between pump starts (or stops) for dual pump operation.

(iv) Data and Constants

This comprises all fixed unalterable physical data such as :-

Tables

P1TAB, P2TAB for Camden pumps 1 and 2 Head (m.W.G.) vs Flow (m^2/s) characteristic.

VC1TAB, VC2TAB for Camden pump discharge valves 1 and 2, Valve opening (%) vs Pump flow (m^3/s) (derived by iteration - Appendix D)

VDTAB for Davel flow control valve, Valve opening (%) vs Reciprocal of friction factor, characteristic.

VKTAB for Kriel flow control valve, Valve opening (%) vs Reciprocal of friction factor, characteristic.

Data

Pipeline friction factor λ_1, λ_2, λ_3, (FRCTN1, FRCTN2, FRCTN3)

Reservoir surface areas (A_{SR}, A_{SD})

Pipeline diameter (DP1, DP2, DP3)

Pipeline constants (K11, K12, K21, K22, K31, K32)

Valve throat diameter (DT1, DT2, DT3)

Static head (H1, H2STAT, H3STAT)

Valve full open and full closed settings (V1 OPEN, V1 CLSD etc)

Valve travel time (V1T, V2T, VDT, VKT)

Valve velocity (V1V, V2V, VDV, VKV)

Flags, (FC1, FC2 etc)

For all three pipeline sections.

E.3 Dynamic (and Derivative) Blocks

This is arranged as follows.

(i) Camden Pump/Discharge Valve Configuration

A series of logic statements check the value of water level, H_R, for Rietspruit reservoir and decide how many pumps should be running. If there is any discrepancy pumps are started or stopped to give the correct conditions.

The pumping head and flow in the Camden - Rietspruit pipeline and the water level at Rietspruit, H_R is then derived.

(ii) Davel Valve Position, VD

A series of logic (or conditional) statements test the value of Davel water level against the set points and open or close Davel flow control valve to the correct position.

From the values of head and valve opening the flow in the Rietspruit - Davel pipeline is calculated and the water level, H_D at Davel obtained.

(iii) Kriel Valve Position, VK

In a similar manner to (ii) above for Davel, the Kriel valve position, Davel - Kriel pipeline flow and water level, H_K, at Kriel is determined.

The calculation for A_{SK}, the Kriel Reservoir surface area is included in this section since it varies with H_K.

E.4 Terminal Block

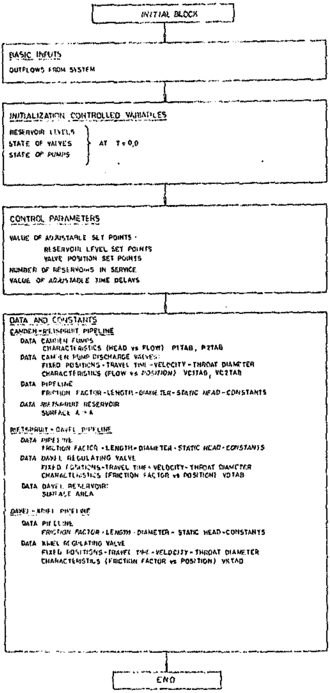
This block is not used in this simulation.

E.5 Run Time Control Statements

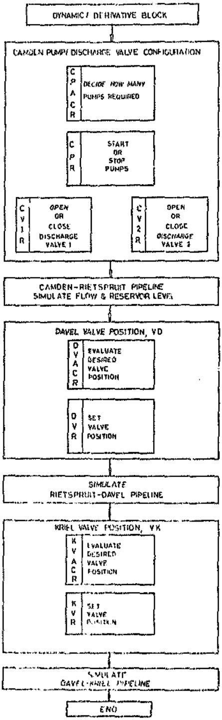
These are used to output results and plot them.

E.6 COMPUTER PROGRAMME LOGIC FLOW DIAGRAMS

PROGRAM USUTU ---

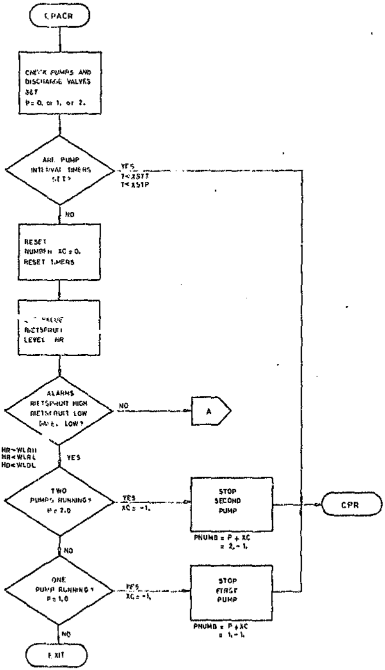


PROGRAM USUTU —

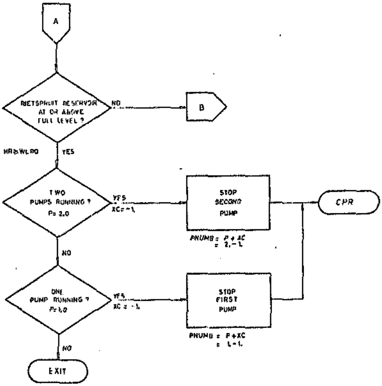


PROGRAM USUTU-CAMDEN PUMP AUTO CONTROL ROUTINE (1 of 4)

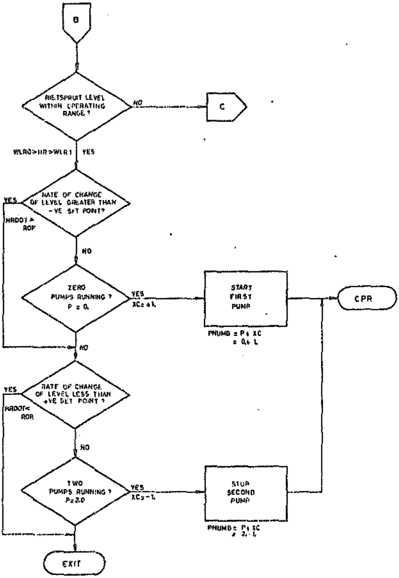
(EMERGENCY SHUT DOWN ROUTINE)



PROGRAM USUTU- CAMDEN PUMP AUTO CONTROL ROUTINE (2 of 4)
(NORMAL SHUT DOWN - ABSOLUTE LEVEL)

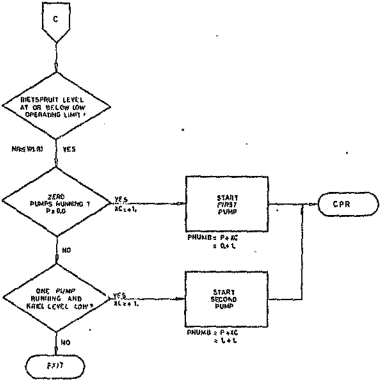


PROGRAM USUTU – CAMDEN PUMP AUTO CONTROL ROUTINE (3 of 4)
(RATE OF CHANGE OF RIETSPRUIT LEVEL SET POINTS)

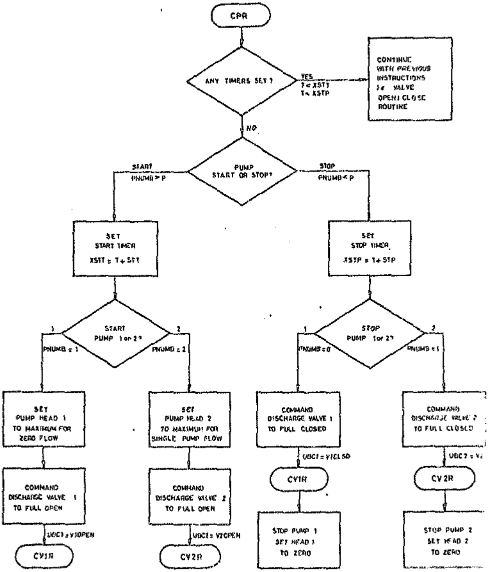


PROGRAM USUTU-CAMDEN PUMP AUTO CONTROL ROUTINE (4 of 4)

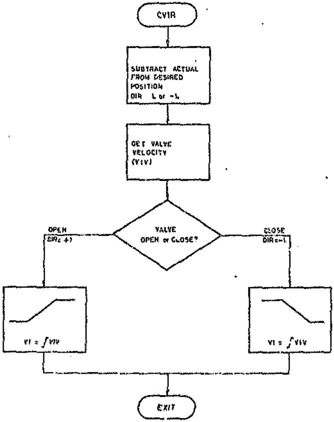
(NORMAL START UP – ABSOLUTE LEVEL)



PROGRAM USUTU-CAMDEN PUMP STOP/START ROUTINE (1 of 1)

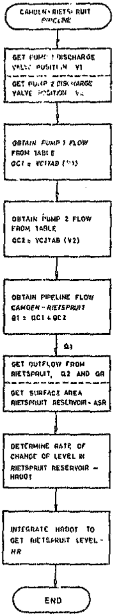


PROGRAM USUTU – CAMDEN PUMP DISCHARGE VALVE ROUTINE (1 of 1)

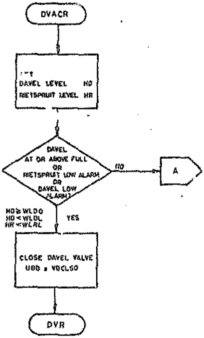


CV2R IS IDENTICAL TO CV1R

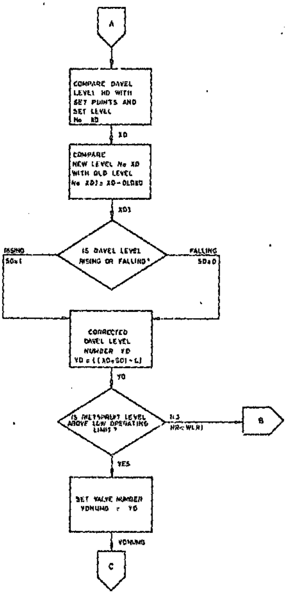
PROGRAM USUTU–CAMDEN-RIETSPRUIT PIPELINE SIMULATION (1 of 1)



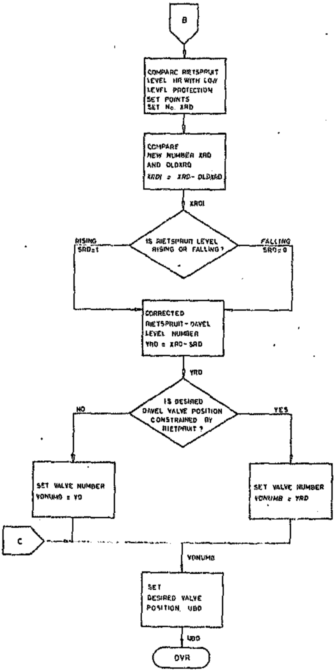
PROGRAM USUTU – DAVEL VALVE AUTO CONTROL ROUTINE (1 of 3)
(NORMAL AND EMERGENCY VALVE FULL CLOSE ROUTINE)



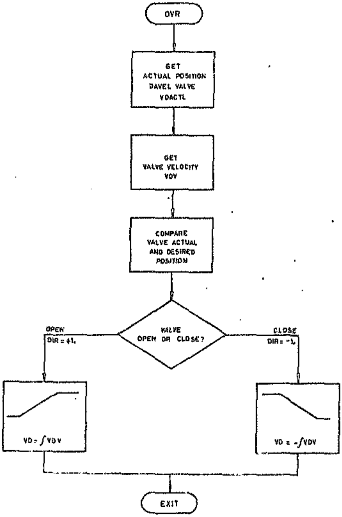
PROGRAM USUTU – DAVEL VALVE AUTO CONTROL ROUTINE (2 of 3)
(DECIDE DESIRED VALVE OPENING AS DETERMINED BY
DAVEL RESERVOIR LEVEL)



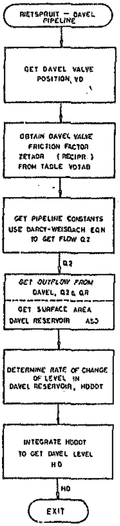
PROGRAM USUTU – DAVEL VALVE AUTO CONTROL ROUTINE (3 of 3)
(DETERMINE IF DAVEL VALVE POSITION SHOULD BE RESTRICTED BY LOW LEVEL AT RIETSPRUIT AND BY HOW MUCH)



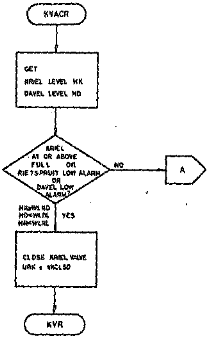
PROGRAM USUTU – DAVEL VALVE ROUTINE (1 of 1)



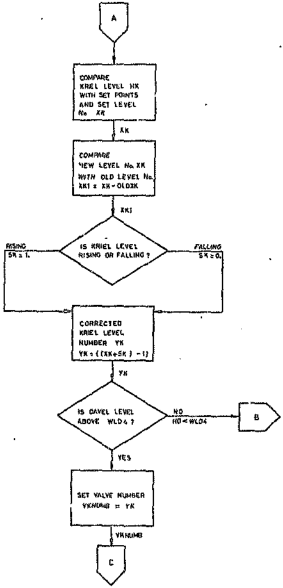
PROGRAM USUTU - RIETSPRUIT - DAVEL PIPELINE SIMULATION (1 of 1)



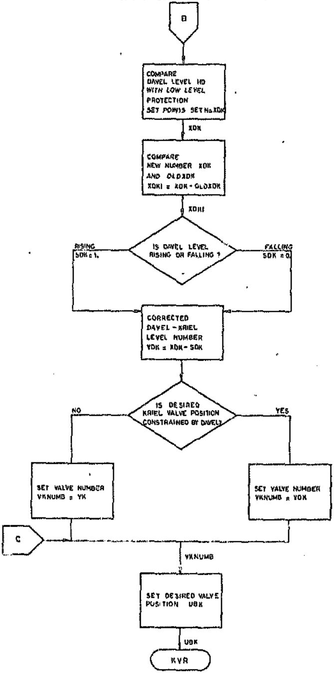
PROGRAM USUTU – KRIEL VALVE AUTO CONTROL ROUTINE (1 of 3)
(NORMAL AND EMERGENCY VALVE FULL CLOSED ROUTINE)



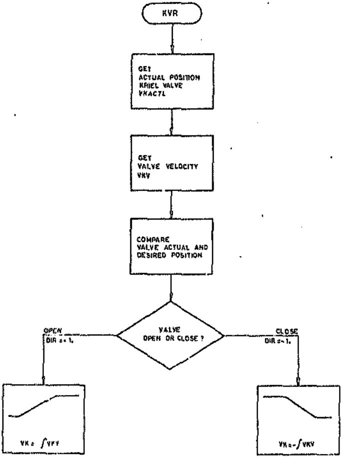
PROGRAM USUTU - KRIEL VALVE AUTO CONTROL ROUTINE (2 of 3)
(DECIDE DESIRED VALVE OPENING AS DETERMINED BY KRIEL RESERVOIR LEVEL)



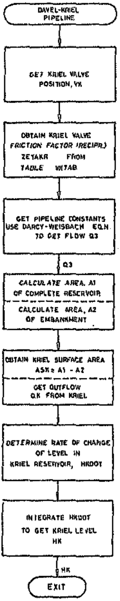
PROGRAM USUTU- KRIEL VALVE AUTO CONTROL ROUTINE (3 of 3)
(DETERMINE IF KRIEL VALVE POSITION SHOULD BE RESTRICTED BY LOW LEVEL AT DAVEL AND BY HOW MUCH)



PROGRAM USUTU- KRIEL VALVE ROUTINE (1 of 1)



PROGRAM USUTU – DAVEL - KRIEL PIPELINE SIMULATION (1 of 1)



E.7 PROGRAMME LISTINGS

```
      PROGRAM USUTU RIVER GOVERNMENT WATER SCHEME
COMMENT
COMMENT EXTENDED PERIOD TIME SIMULATION OF THE CAMDEN-KRIEL...
        PIPELINE IN ORDER TO EXAMINE AND OPTIMIZE THE PERFORMANCE...
        OF THE PROPOSED AUTOMATIC CONTROL SYSTEM
COMMENT
COMMENT REVISION 0,  JANUARY 1978
COMMENT
COMMENT  AUTHOR:  FRED CATLOW, SENIOR ENGINEER                   ...
        ELECTRICITY SUPPLY COMMISSION, JOHANNESBURG, SOUTH AFRICA
COMMENT
       INITIAL
       CONSTANT TF=100000.0
       CONSTANT HR=7.50
       CONSTANT HD=7.50
       CONSTANT HK=13.70
       CONSTANT V1=0.00
       CONSTANT V2=0.00
       CONSTANT PNUMB=0.0
       CONSTANT Q2=0.0
       CONSTANT Q3=0.0
COMMENT BASIC INPUTS(QK=KRIEL RESERVOIR OUTFLOW,QR=OFFTAKE TO...
        ERMELO TOWN,QD=OFFTAKE TO DAVEL TOWN
       CONSTANT QK=1.49000...
                QR=0.00000...
                QD=0.00000
COMMENT INITIALIZATION OF CONTROLLED VARIABLES ...
        VALVE POSITIONS
       CONSTANT V10=0.0...
                V20=0.0...
                VC0=0.0...
                VK0=0.0
COMMENT RESERVOIR LEVELS
       CONSTANT HR0=7.500...
                HD0=7.500...
                HK0=13.70
COMMENT PUMPS OPERATING
       CONSTANT P=0.0
COMMENT CONTROL PARAMETERS
COMMENT RIETSPRUIT RESERVOIR LEVEL SETTINGS  .  (M'S ABOVE FLOOR(=...
        1784.0)) WLRH/WLRL=HIGH/LOW LEVEL LI  .  WLR0=FSL(=1792.4);..
        WLR4=LSL;RATE OF CHANGE CONTROL OF CAMDEN PUMPS (M/MIN)ROR...
        =RISING,ROF=FALLING;WLR2-5 RESTRICT DAVEL VALVE OPENING
       CONSTANT WLRH=8.000...
                WLR0=7.500...
                ROF  0.00045...
                ROR=0.00045...
                WLR1=3.000...
                WLR2=2.800...
                WLR3=2.600...
                WLR4=2.400...
                WLR5=2.200...
                WLRL=2.000
COMMENT DAVEL VALVE POSITION SETTINGS (PER CENT OF RANGE)
       CONSTANT VD1=29.42...
                VD2=42.63...
                VD3=70.68
COMMENT DAVEL RESERVOIR LEVEL SETTINGS (METRES ABOVE FLOOR(=1722.0))...
        WLDL=LOW LEVEL LIMIT;WLD0=FSL(=1730.2);WLD4=LSL;WLD0-4...
        CONTROL DAVEL VALVE POSITION;WLD5-8 RESTRICT KRIEL VALVE
       CONSTANT WLD0=7.500...
                WLD1=7.250          ...
```

```
              WLO2=7.000      ...
              WLO3=6.750...
              WLO4=6.500...
              WLO5=3.000...
              WLO6=2.750...
              WLO7=2.500...
              WLO8=2.250...
              WLOL=2.000
COMMENT KRIEL VALVE POSITION [illegible] PER CENT OF RANGE)
       CONSTANT VK1=35.92...
              VK2=69.77...
              VK3=74.79
COMMENT KRIEL RESERVOIR LEVEL SETTINGS (METRES ABOVE FLOOR(=1612.72))...
        WLKO=FSL(=1626.[illegible])WLKO-4 CONTROL KRIEL VALVE POSITION
       CONSTANT WLKO=13.73...
              WLK1=13.5[illegible]...
              WLK2=[illegible]...
              WLK3=[illegible]
              WLK4=17.[illegible]
COMMENT ONE/TWO RESERVOIRS IN SERVICE
       CONSTANT FACTR=[illegible].00     ...
              FACTO=2.0     ...
              FACTI=2.0
COMMENT PUMPINTERVAL TIMERS-MUST EXCEED VALVE OPENING /CLOSING TIME
       CONSTANT STT=600.0 ...
              STF=300.0
COMMENT DATA AND CONSTANTS
COMMENT-DATA CAMDEN PUMP(SULZER HORIZONTAL CENTRIPUGAL 2-STAGE PUMP...
        NO.HPA3EDF DRIVEN BY 2875KW.3.3KV.592A.992R.P.M..S.C.I.M.
       TABLE P1TAB,1-41=0.0,0.05,0.10,0.15,0.20,0.25,0.30,0.35,0.40...
            0.45,0.50,0.55,0.60,0.65,0.70,0.75,0.80,0.85,0.90,0.95...
            1.00,1.05,1.10,1.15,1.20,1.25,1.30,1.35,1.40,1.45,1.50...
            1.55,1.60,1.65,1.70,1.75,1.80,1.85,1.90,1.95,2.00,...
           2.30E2,2.29E2,2.28E2,2.27E2,2.26E2,2.24E2,2.23E2,2.22E2...
           2.20E2,2.18E2,2.17E2,2.16E2,2.14E2,2.12E2,2.10E2,2.08E2...
           2.05E2,2.03E2,2.00E2,1.98E2,1.96E2,1.93E2,1.90E2,1.87E2...
           1.84E2,1.80E2,1.76E2,1.72E2,1.67E2,1.62E2,1.56E2,1.50E2...
           1.44E2,1.37E2,1.30E2,1.22E2,1.13E2,1.02E2,0.92E2,0.76E2...
           0.59E2
       TABLE P2TAB,1-41=0.0,0.05,0.10,0.15,0.20,0.25,0.30,0.35,0.40...
            0.45,[illegible],0.60,0.65,0.70,0.75,0.80,0.85,0.90,0.95...
            1.00,[illegible]1.10,[illegible],1.20,1.25,1.30,1.35,1.40,1.45,1.50...
            1.55,[illegible],1.75,1.80,1.85,1.90,1.95,2.00,...
           2.3[illegible],2.27E2,2.26E2,2.24E2,2.23E2,2.22E2...
           2.20E2,[illegible]2.14E2,2.12E2,2.10E2,2.08E2...
           2[illegible].98E2,1.96E2,1.93E2,1.90E2,1.87E2...
           [illegible].72E2,1.67E2,1.62E2,1.56E2,1.50E2...
           1.44E2,[illegible].13E2,1.0[illegible]E2,0.92E2,0.76E2...
           [illegible]
COMMENT-DATA [illegible] DISCHARGE VALVE(ERHARD RING NEEDLE VALVE...
        [illegible] TRAVEL TIME 3.0 MINUTES.V10/V20_INITIAL PERCENT OPEN....
        [illegible] CLSD-V1OPEN/V2OPEN-VALVE POSITIONS.FC1/FC2-FL.35....
        [illegible]-VALVE VELOCITY(TABLE FLOW VS V1+V2 CALCULATED-CONST HC
       CONSTANT V1CLSD=0.0...
              V1OPEN=100.0...
              V1CSSD=0.1...
              V1OPPN=99.9
       CONSTANT V2CLSD=0.0...
              V2OPEN=100.0...
              V2CSSD=0.1...
              V2OPPN=99.9
       CONSTANT V1T=3.00...
              V2T=3.00...
              FC1=1.0...
```

```
        FC2=1.0
   V1V=V1OPEN/(V1T*60.0)
   V2V=V2OPEN/(V2T*60.0)
   TABLE VC1TAB,1,82,-2.5,0.,2.5,5.0,7.5,10.0,12.5,15.0,17.5,20.,...
         22.5,25.0,27.5,30.0,32.5,35.0,37.5,40.0,42.5,45.0,47.5,...
         50.0,52.5,55.0,57.5,60.0,62.5,65.0,67.5,70.0,72.5,75.0,...
         77.5,80.0,82.5,85.0,87.5,90.0,92.5,95.0,97.5,100.0,...
         102.5,105.0,107.5,110.0,112.5,115.0,117.5,120.0,122.5,...
         125.0,127.5,130.0,132.5,135.0,137.5,140.0,142.5,145.0,...
         147.5,150.0,152.5,155.0,157.5,160.0,162.5,165.0,167.5,...
         170.0,172.5,175.0,177.5,180.0,182.5,185.0,187.5,190.0,...
         192.5,195.0,197.5,200.0,...
                             0.,0.0,0.092,0.20,0.28,0.36,0.44,...
         0.52,0.61,0.68,0.75,0.83,0.92,0.98,1.07,1.14,1.22,1.30,...
         1.37,1.42,1.46,1.49,1.51,1.53,1.54,1.56,1.56,1.57,1.58,...
         1.58,1.59,1.59,1.60,1.60,1.60,1.60,1.60,1.60,1.61,1.61,...
         1.61,1.61,1.60,1.58,1.57,1.55,1.54,1.53,1.51,1.50,1.49,...
         1.48,1.46,1.45,1.43,1.42,1.40,1.39,1.37,1.35,1.35,1.33,...
         1.33,1.32,1.32,1.32,1.31,1.31,1.31,1.31,1.31,1.31,1.30,...
         1.30,1.30,1.30,1.30,1.30,1.30,1.30,1.30,1.30
   TABLE VC2TAB,1,42,-2.5,0.,2.5,5.0,7.5,10.0,12.5,15.0,17.5,20.,...
         22.5,25.0,27.5,30.0,32.5,35.0,37.5,40.0,42.5,45.0,47.5,...
         50.0,52.5,55.0,57.5,60.0,62.5,65.0,67.5,70.0,72.5,75.0,...
         77.5,80.0,82.5,85.0,87.5,90.0,92.5,95.0,97.5,100.0,...
         0.,0.,0.08,0.18,0.24,0.31,0.38,0.44,0.51,0.57,0.62,...
         0.68,0.75,0.79,0.86,0.91,0.97,1.03,1.09,1.13,1.16,1.20,...
         1.21,1.23,1.24,1.25,1.26,1.27,1.27,1.27,1.28,1.28,1.29,...
         1.29,1.29,1.29,1.29,1.30,1.30,1.30,1.30,1.30
MENT DATA CAMDEN-RIETSPRUIT PIPELINE-FROM TEST REPORT ME R/47...
     PIPELINE FRICTN FACTOR-LANDA (H1STAT=1792.4-1672.9)=H1)...
     DT-VALVE THROAT DIA,DP=P/L DIA,L=LENGTH
   CONSTANT FRCTN1=0.01918    ...
            DIST1=12805.00    ...
            DT1=0.60...
            DP1=1.20...
            G=9.81 ...
            PI=3.1416 ...
            H1=119.5
            CONST=16.0/(2.0*G*PI**2.0)
            K11=CONST/(DT1**4.0)
            K12=(CONST*FRCTN1*DIST1)/(DP1**5.0)
MENT DATA RIETSPRUIT RESERVOIR--HR-HEAD,HRO-INIT.VALUE(HRMAX=8.4M...
   ASR-RSVR SURF.AREA(=1870.3*2)...
   CAPACITY COMBINED RSVRS=31.40ML
            ASR=1870.3*FACTR
MENT DATA RIETSPRUIT-DAVEL PIPELINE-FROM TEST REPORT ME R/83  ...
     PIPELINE FRICTN FACTOR-LANDA (H2STAT=1784.0-1730.2)...
     DT-VALVE THROAT DIA,DP=P/L DIA,L=LENGTH( D(T2)
   CONSTANT FRCTN2=0.01728...
            DIST2=36480.00    ...
            DT2=1.00...
            DP2=1.30...
            H2STAT=53.80
            K21=CONST/(DT2**4.0)
            K22=(CONST*FRCTN2*DIST2)/(DP2**5.0)
MENT-DATA DAVEL VALVE(BOPP REUTER RING NEEDLE VALV- 595.0-NW150...
   TRAVEL TIME 16.0 MINUTES,VDO-INITIAL PERCENT OPEN,VDCLSD-...
   VDOPEN-VALVE POSITIONS,FD1=FLAG,VDV=VALVE VELOCITY
   CONSTANT VDCLSD=0.0...
            VDOPEN=100.0...
            VDT=16.0...
            FD1=1.0...
            XD=0.0...
            XRD=5.0  ...
```

```
      DYNAMIC
      TERMT(T.GE.TF)
OMMENT
      DERIVATIVE SECTN1
      CINTERVAL CI= 15.0
      XERROR VO=1.E-3
      OUTPUT Q0,QC1,V1,HC1,QC2,V2,HC2,Q1,P,HR,Q2,VD,HD,Q3,VK,HK,...
                OK,HRDOT,HDDOT,HKDOT
      RANGE HR,HD,HK,Q1,Q2,Q3
COMMENT
COMMENT ---------CAMDEN PUMP/DISCHARGE VALVE CONFIGURATION-----------...
 ****************************************************************...
      PIETSPRUIT RESERVOIR LEVEL AND ROC OF LEVEL CHECKED AGAINST...
      NUMBER OF PUMPS RUNNING TO OBTAIN XC(FOR XC=1.0,START PUMP;
COMMENT FOR XC=-1.0,STOP PUMP) PNUMB DETERMINES HOW MANY PUMPS ...
      SHOULD BE RUNNING AND IF DIFFERENT FROM P,OPENS/CLOSES VALVES...
      TO GIVE CORRECT VALUE ALSO FOR PNUMB=0.0,PUMPS 1 AND 2 HEAD...
      ZERO,FOR PNUMB=1.0,PUMP 2 HEAD ZERO(STT-START TIMER,STP-STOP
         PROCEDURAL(HC1,HC2,P,V2= )
         IF((PNUMB.EQ.0.0).AND.(V1.LT.V1CSSD).AND.(V2.LT.V2CSSD))P=0.0
         IF((PNUMB.EQ.1.0).AND.(V1.GT.V1OPPN).AND.(V2.LT.V2CSSD))P=1.0
         IF((PNUMB.EQ.2.0).AND.(V1.GT.V1OPPN).AND.(V2.GT.V2OPPN))P=2.0
         IF((T.LT.XSTT).OR.(T.LT.XSTP))GO TO C7
         XC=0.0
         XSTT=XSTP=0.0
         IF((HR.GE.WLAM).OR.(HR.LE.WLRL).OR.(HD.LE.WLDL))GO TO C9
         IF                    (HR.GE.WLR0) GO TO C1
         IF((HR.LT.WLR0).AND.(HR.GT.WLR1))GO TO C2
         IF (HR.LE.WLR1)                      O TO C4
     C1..IF((P.EQ.1.0.AND.HRDOT.GE.0.0).OR.(P.EQ.2.0)) XC=-1 0
         GO TO C6
     C2..IF(HRDOT.GT.ROF) GO TO C3
         IF((P.EQ.0.0).OR.(P.EQ.1.0.AND.VKNUMB.EQ.4.0))XC=1.0
         GO TO C6
     C3..IF(HRDOT.LT.ROR) GO TO C6
         IF(P.EQ.2.0)                                   XC=-1.0
     C4..IF((P.EQ.0.0).OR.(P.EQ.1.0.AND.VK.EQ.4.0))     XC=1.0
         GO TO C6
         GO TO C6
     C5..IF(P.GT.0.0)                                   XC=-1.0
     C6..PNUMB=P+XC
         IF(PNUMB.GT.P)XSTT=T+STT
         IF(PNUMB.LT.P)XSTP=T+STP
         IF(PNUMB.EQ.0.0)UBC1=V1CLSD
         IF(PNUMB.GE.1.0)UBC1=V1OPEN
         IF(PNUMB.LE.1.0)UBC2=V2CLSD
         IF(PNUMB.EQ.2.0)UBC2=V2OPEN
     C7..IF((PNUMB.EQ.0.0).AND.(P.EQ.0.0))HC1=0.0
         IF((PNUMB.GE.1.0).OR.(P.GE.1.0))HC1=HEAD1
         IF((PNUMB.LT.2.0).AND.(P.LT.2.0))HC2=0.0
         IF((PNUMB.EQ.2.0).OR.(P.EQ.2.0))HC2=HEAD2
COMMENT
COMMENT-PUMP 1 DISCHARGE VALVE ROUTINE
         IF(FC1.EQ.1.0)V1ACTL=V10
         IF(FC1.EQ.0.0)V1ACTL=V1
         FC1=0.0
         URC1P=URC1+0.005
         URC1M=URC1-0.005
         IF((V1.LE.00.005).AND.(DIR1.LT.0.0))V1=0.0
         IF((V1.GE.99.995).AND.(DIR1.GT.0.0))V1=100.0
         IF((V1ACTL.GE.URC1M).AND.(V1ACTL.LE.URC1P))DIR1=0.0
         IF(V1ACTL.LT.URC1M)DIR1=1.0
         IF(V1ACTL.GT.URC1P)DIR1=-1.0
         V1DOT=DIR1*V1V
```

```
                 SD=0.0    ...
                 SRD=0.0
                 VDV=VDOPEN/(VDT*60.0)
          TABLE VDTAB,1,43,-2.5,0.,2.5,5.0,7.5,10.0,12.5,15.0,17.5,20.,...
               22.5,25.0,27.5,30.0,32.5,35.0,37.5,40.0,42.5,45.0,47.5,...
               50.0,52.5,55.0,57.5,60.0,62.5,65.0,67.5,70.0,72.5,75.0,...
               77.5,80.0,82.5,85.0,87.5,90.0,92.5,95.0,97.5,100.,102.5,...
               0.,0.,3.71E-05,6.25E-05,9.90E-05,1.41E-04,1.96E-04,...
               2.63E-04,3.57E-04,4.55E-04,5.88E-04,7.41E-04,9.17E-04,...
               1.11E-03,1.32E-03,1.54E-03,1.75E-03,2.02E-03,2.33E-03,...
               2.63E-03,2.94E-03,3.45E-03,3.77E-03,4.35E-03,5.00E-03,...
               5.56E-03,6.37E-03,7.19E-03,8.26E-03,9.26E-03,1.05E-02,...
               1.19E-02,1.35E-02,1.56E-02,1.79E-02,2.08E-02,2.47E-02,...
               3.00E-02,3.77E-02,5.13E-02,6.90E-02,1.00E-01,1.E-1
     COMMENT DATA DAVEL RESERVOIR--HD-HEAD,HD0-INIT. VALUE(HDMAX=8.2...
          ASD-RSVR SURF.AREA(=)331.2*21...
          CAPACITY COMBINED RSVRS=22.40ML
                 ASD=331.2*FACTD
     COMMENT DATA DAVEL-KRIEL  PIPELINE-FROM TEST REPORT ME R/53  ...
            PIPELINE FRICTN FACTOR-LAMDA (H2STAT=1722.50-1612.72)...
            DT-VALVE THROAT DIA,DP-P/L DIA,L-LENGTH( DIST3)
          CONSTANT FRCTN3=0.01700...
                 DIST3=54600.0    ...
                 DP3=1.30...
                 DT3=1.00...
                 H3STAT=109.28
                 K31=CONST/(DT3**4.0)
                 K32=(CONST*FRCTN3*DIST3)/(DP3**5.0)
     COMMENT-DATA KRIEL VALVE(800P REUTER RING NEEDLE VALVE 597.5-NW150...
            TRAVEL TIME 16.0 MINUTES-VK0-INITIAL PERCENT OPEN,VKCLSD-...
            VKOPEN-VALVE POSITIONS,FK1-FLAG,VKV-VALVE VELOCITY
          CONSTANT VKCLSD=0.0...
                 VKOPEN=100.0...
                 VKT=16.0  ...
                 FK1=1.0   ...
                 EK=0.0    ...
                 XDK=5.0   ...
                 SK=0.0    ...
                 SDK=0.0
                 VKV=VKOPEN/(VKT*60.0)
          TABLE VKTAB,1,43,-2.5,0.,2.5,5.0,7.5,10.0,12.5,15.0,17.5,20.,...
               22.5,25.0,27.5,30.0,32.5,35.0,37.5,40.0,42.5,45.0,47.5,...
               50.0,52.5,55.0,57.5,60.0,62.5,65.0,67.5,70.0,72.5,75.0,...
               77.5,80.0,82.5,85.0,87.5,90.0,92.5,95.0,97.5,100.,102.5,...
               0.,0.,1.56E-05,2.74E-05,3.95E-05,5.55E-05,7.14E-05,...
               1.00E-04,1.33E-04,1.69E-04,2.10E-04,2.76E-04,3.33E-04,...
               4.08E-04,4.88E-04,5.71E-04,6.67E-04,7.69E-04,8.70E-04,...
               9.90E-04,1.12E-03,1.28E-03,1.45E-03,1.64E-03,1.85E-03,...
               2.13E-03,2.41E-03,2.74E-03,3.13E-03,3.51E-03,3.95E-03,...
               4.50E-03,5.18E-03,6.06E-03,6.99E-03,8.40E-03,1.05E-02,...
               1.38E-02,1.82E-02,2.63E-02,4.00E-02,7.35E-02,7.35E-02
     COMMENT DATA KRIEL RESERVOIR--HD-HEAD,HD0-INIT. VALUE(HDMAX=13.7M...
            ASK-RES SURF AREA VARIES WITH DEPTH CALC IN DYNAMIC BLOCK ...
            CAPACITY COMBINED RESERVOIRS=681.9ML
          END
```

```
       DYNAMIC
       TERMT(T.GE.TF)
COMMENT
       DERIVATIVE SECTN]
       CINTERVAL CI= 15.0
       XERROR VO=1.E-3
       OUTPUT 60,QC1,V1,HC1,QC2,V2,HC2,Q1,P,HR,Q2,VD,HD,Q3,VK,UK,...
                QK,HRDOT,HDDOT,HKDOT
       RANGE HR,HD,HK,Q1,Q2,Q3
COMMENT
COMMENT ---------CAMDEN PUMP/DISCHARGE VALVE CONFIGURATION----------...
*****************************************************************...
       PIETSPRUIT RESERVOIR LEVEL AND ROC OF LEVEL CHECKED AGAINST...
       NUMBER OF PUMPS RUNNING TO OBTAIN XC;FOR XC=1.0,START PUMP;
COMMENT FOR XC=-1.0,STOP PUMP; PNUMB DETERMINES HOW MANY PUMPS ...
       SHOULD BE RUNNING AND IF DIFFERENT FROM P,OPENS/CLOSES VALVES...
       TO GIVE CORRECT VALUE ALSO FOR PNUMB=0.0,PUMPS 1 AND 2 HEAD...
       ZERO,FOR PNUMB=1.0,PUMP 2 HEAD ZERO;STT=START TIMER,STP=STOP
          PROCEDURAL(HC1,HC2,V1,V2= )
          IF((PNUMB.EQ.0.0).AND.(V1.LT.V1CSSD).AND.(V2.LT.V2CSSD))P=0.0
          IF((PNUMB.EQ.1.0).AND.(V1.GT.V1OPPN).AND.(V2.LT.V2CSSD))P=1.0
          IF((PNUMB.EQ.2.0).AND.(V1.GT.V1OPPN).AND.(V2.GT.V2OPPN))P=2.0
          IF((T.LT.XSTT).OR.(T.LT.XSTP))GO TO C7
          XC=0.0
          XSTT=XSTP=0.0
          IF((HR.GE.WLRH).OR.(HR.LE.WLRL).OR.(HD.LE.WLDL))GO TO C5
          IF                      (HR.GE.WLR0) GO TO C1
          IF((HR.LT.WLR0).AND.(HR.GT.WLR1))GO TO C2
          IF (HR.LE.WLR1)                           O TO C4
      C1..IF((P.EQ.1.0.AND.HRDOT.GE.0.0).OR.(P.EQ.2.0)) XC=-1.0
          GO TO C6
      C2..IF(HRDOT.GT.ROF) GO TO C3
          IF((P.EQ.0.0).OR.(P.EQ.1.0.AND.VKNUMB.EQ.4.0))XC=1.0
          GO TO C6
      C3..IF(HRDOT.LT.ROR) GO TO C6
          IF(P.EQ.2.0)                                 XC=-1.0
      C4..IF((P.EQ.0.0).OR.(P.EQ.1.0.AND.YK.EQ.4.0))    XC=1.0
          GO TO C6
          GO TO C6
      C5..IF(P.GT.0.0)                                 XC=-1.0
      C6..PNUMB=P+XC
          IF(PNUMB.GT.P)XSTT=T+STT
          IF(PNUMB.LT.P)XSTP=T+STP
          IF(PNUMB.EQ.0.0)UBC1=V1CLSD
          IF(PNUMB.GE.1.0)UBC1=V1OPEN
          IF(PNUMB.LE.1.0)UBC2=V2CLSD
          IF(PNUMB.EQ.2.0)UBC2=V2OPEN
      C7..IF((PNUMB.EQ.0.0).AND.(P.EQ.0.0))HC1=0.0
          IF((PNUMB.GE.1.0).OR.(P.GE.1.0))HC1=HEAD1
          IF((PNUMB.LT.2.0).AND.(P.LT.2.0))HC2=0.0
          IF((PNUMB.EQ.2.0).OR.(P.EQ.2.0))HC2=HEAD2
COMMENT
COMMENT-PUMP 1 DISCHARGE VALVE ROUTINE
          IF(FC1.EQ.1.0)V1ACTL=V10
          IF(FC1.EQ.0.0)V1ACTL=V1
          FC1=0.0
          UBC1P=UBC1+0.005
          UBC1M=UBC1-0.005
          IF((V1.LE.00.005).AND.(DIR1.LT.0.0))V1=0.0
          IF((V1.GE.99.995).AND.(DIR1.GT.0.0))V1=100.0
          IF((V1ACTL.GE.UBC1M).AND.(V1ACTL.LE.UBC1P))DIR1=0.0
          IF(V1ACTL.LT.UBC1M)DIR1=1.0
          IF(V1ACTL.GT.UBC1P)DIR1=-1.0
          V1DOT=DIR1*V1V
```

```
      DYNAMIC
      TERMT(T.GE.TF)
COMMENT
      DERIVATIVE SECTN1
      CINTERVAL CI= 15.0
      XERROR VD=1.E-3
      OUTPUT 60,QC1,V1,HC1,QC2,V2,HC2,Q1,P,HR,Q2,VD,HD,Q3,VK,HK,...
                QK,HRDOT,HDDOT,HKDOT
      RANGE HR,HD,HK,Q1,Q2,Q3
COMMENT
COMMENT ----------CAMDEN PUMP/DISCHARGE VALVE CONFIGURATION-----------...
****************************************************************,..
      RIETSPRUIT RESERVOIR LEVEL AND ROC OF LEVEL CHECKED AGAINST...
      NUMBER OF PUMPS RUNNING TO OBTAIN XC(FOR XC=1.0,START PUMP;
COMMENT FOR XC=-1.0,STOP PUMP) PNUMB DETERMINES HOW MANY PUMPS ...
      SHOULD BE RUNNING AND IF DIFFERENT FROM P,OPENS/CLOSES VALVES...
      TO GIVE CORRECT VALUE ALSO FOR PNUMB=0.0,PUMPS 1 AND 2 HEAD...
      ZERO,FOR PNUMB=1.0,PUMP 2 HEAD ZERO(STT-START TIMER,STP-STOP
         PROCEDURAL(HC1,HC2,V1,V2= )
         IF((PNUMB.EQ.0.0).AND.(V1.LT.V1CSSD).AND.(V2.LT.V2CSSD))P=0.0
         IF((PNUMB.EQ.1.0).AND.(V1.GT.V1OPPN).AND.(V2.LT.V2CSSD))P=1.0
         IF((PNUMB.EQ.2.0).AND.(V1.GT.V1OPPN).AND.(V2.GT.V2OPPN))P=2.0
         IF((T.LT.XSTT).OR.(T.LT.XSTP))GO TO C7
         XC=0.0
         XSTT=XSTP=0.0
         IF((HR.GE.WLRH).OR.(HR.LE.WLRL).OR.(HD.LE.WLDL))GO TO C5
         IF                        (HR.GE.WLR0) GO TO C1
         IF((HR.LT.WLR0).AND.(HR.GT.WLR1))GO TO C2
         IF (HR.LE.WLR1)                        GO TO C4
      C1..IF((P.EQ.1.0.AND.HRDOT.GE.0.0).OR.(P.EQ.2.0)) XC=-1.0
         GO TO C6
      C2..IF(HRDOT.GT.ROF) GO TO C3
         IF((P.EQ.0.0).OR.(P.EQ.1.0.AND.VKNUMB.EQ.4.0))XC=1.0
         GO TO C6
      C3..IF(HRDOT.LT.ROR) GO TO C6
         IF(P.EQ.2.0)                                 XC=-1.0
      C4..IF((P.EQ.0.0).OR.(P.EQ.1.0.AND.''.EQ.4.0))    XC=1.0
         GO TO C6
         GO TO C6
      C5..IF(P.GT.0.0)                                XC=-1.0
      C6..PNUMB=P+XC
         IF(PNUMB.GT.P)XSTT=T+STT
         IF(PNUMB.LT.P)XSTP=T+STP
         IF(PNUMB.EQ.0.0)UBC1=V1CLSD
         IF(PNUMB.GE.1.0)UBC1=V1OPEN
         IF(PNUMB.LE.1.0)UBC2=V2CLSD
         IF(PNUMB.EQ.2.0)UBC2=V2OPEN
      C7..IF((PNUMB.EQ.0.0).AND.(P.EQ.0.0))HC1=0.0
         IF((PNUMB.GE.1.0).OR.(P.GE.1.0))HC1=HEAD1
         IF((PNUMB.LT.2.0).AND.(P.LT.2.0))HC2=0.0
         IF((PNUMB.EQ.2.0).OR.(P.EQ.2.0))HC2=HEAD2
COMMENT
COMMENT-PUMP 1 DISCHARGE VALVE ROUTINE
         IF(FC1.EQ.1.0)V1ACTL=V10
         IF(FC1.EQ.0.0)V1ACTL=V1
         FC1=0.0
         UBC1P=UBC1+0.005
         UBC1M=UBC1-0.005
         IF((V1.LE.00.005).AND.(DIR1.LT.0.0))V1=0.0
         IF((V1.GE.99.995).AND.(DIR1.GT.0.0))V1=100.0
         IF((V1ACTL.GE.UBC1M).AND.(V1ACTL.LE.UBC1P))DIR1=0.0
         IF(V1ACTL.LT.UBC1M)DIR1=1.0
         IF(V1ACTL.GT.UBC1P)DIR1=-1.0
         V1DOT=DIR1*V1V
```

```
          V1=INTEG(V1DOT,V10)
        IF(V1.LT.0.05)QC1=0.0
COMMENT
COMMENT-PUMP 2 DISCHARGE VALVE ROUTINE
          IF(FC2.EQ.1.0)V2ACTL=V20
          IF(FC2.EQ.0.0)V2ACTL=V2
          FC2=0.0
          UBC2P=UBC2+0.005
          UBC2M=UBC2-0.005
          IF((V2.LE.00.005).AND.(DIR2.LT.0.0))V2=0.0
          IF((V2.GE.99.995).AND.(DIR2.GT.0.0))V2=100.0
          IF((V2ACTL.GE.UBC2M).AND.(V2ACTL.LE.UBC2P))DIR2=0.0
          IF(V2ACTL.LT.UBC2M)DIR2=1.0
          IF(V2ACTL.GT.UBC2P)DIR2=-1.0
          V2DOT=DIR2*V2V
          V2=INTEG(V2DOT,V20)
        IF(V2.LT.0.05)QC2=0.0
       END
COMMENT
COMMENT SIMULATION OF CAMDEN-RIETSPRUIT PIPELINE
        V12=V1+V2
        QC1=VC1TAB(V12)
        QC2=VC2TAB(V2)
        Q1=QC1+QC2
        HEAD1=P1TAB(QC1)
        HEAD2=P2TAB(QC2)
        HRDOT=(Q1-Q2-QP)/ASR
        HR=INTEG(HRDOT,HR0)
```

```
COMMENT
COMMENT --------------DAVEL VALVE POSITION,VD---------------------------...
**********************************************************************...
      DAVEL-VD,DERIVED FROM LEVEL NUMBER,XD,AND SD...
      SD=0.0,FOR FALLING WATER LEVEL(SD=1.0,FOR RISING WATER LEVEL
COMMENT-----YRD,DETERMINES INFLUENCE, IF ANY,OF LOW WATER LEVEL AT...
      RIETSPRUIT ON VALVE POSITION,DERIVED FROM XRD AND SRD...
      (=0.0 FALL) VALVE POSITION NUMBER, VDNUMB, DETERMINES UBD....
      DESIRED VALVE POSITION WHICH SETS UPPER BOUNDARY OF VLV RAMP
         PROCEDURAL(VD=)
         OLDXD=XD
         IF((HD.GE.WLD0).OR.(HD.LE.WLD8).OR.(HR.LE.WLR5))GO TO D3
         IF((HD.LT.WLD0).AND.(HD.GT.WLD1))XD=1.0
         IF((HD.LT.WLD1).AND.(HD.GT.WLD2))XD=2.0
         IF((HD.LT.WLD2).AND.(HD.GT.WLD3))XD=3.0
         IF((HD.LT.WLD3).AND.(HD.GT.WLD4))XD=4.0
         IF (HD.LE.WLD4)                          XD=5.0
         XDI=(XD-OLDXD)
         IF(XDI.GT.0.0)                           SD=0.0
         IF(XDI.LT.0.0)                           SD=1.0
         YD=((XD+SD)-1.0)
         IF                    (HR.GE.WLR1)GO TO D1
         OLDXRD=XRD
         IF((HR.LT.WLR1).AND.(HR.GT.WLR2))XRD=4.0
         IF((HR.LT.WLR2).AND.(HR.GT.WLR3))XRD=3.0
         IF((HR.LT.WLR3).AND.(HR.GT.WLR4))XRD=2.0
         IF((HR.LT.WLR4).AND.(HR.GT.WLR5))XRD=1.0
         XRDI=(XRD-OLDXRD)
         IF(XRDI.LT.0.0)                          SRD=0.0
         IF(XRDI.GT.0.0)                          SRD=1.0
         YRD=XRD-SRD
         IF(YRD.GE.YD)                            VDNUMB=YD
         IF(YRD.LE.YD)                            VDNUMB=YRD
         GO TO D2
     D1..VDNUMB=YD
         XRD=5.0
     D2..CONTINUE
         IF(VDNUMB.EQ.0.0)UBD=VDCLSD
         IF(VDNUMB.EQ.1.0)UBD=VD1
         IF(VDNUMB.EQ.2.0)UBD=VD2
         IF(VDNUMB.EQ.3.0)UBD=VD3
         IF(VDNUMB.EQ.4.0)UBD=VDOPEN
         GO TO D4
     D3..UBD=VDCLSD
         XD=0.0
         SD=0.0
     D4..CONTINUE
         IF(FD1.EQ.1.0)VDACTL=VD0
         IF(FD1.EQ.0.0)VDACTL=VD
         FD1=0.0
         UBDM=UBD-0.005
         UBDP=UBD+0.005
         IF((VDACTL.GE.UBDM).AND.(VDACTL.LE.UBDP))DIRD=0.
         IF (VDACTL.LT.UBDM)DIRD=1.0
         IF (VDACTL.GT.UBDP)DIRD=-1.0
         VDDOT=DIRD*VDV
         VD=INTGRL(VDDOT,VD0)
       ZETADR=VDTAB(VD)
       IF(VD.LT.0.05)ZETADR=0.0
         END
```

```
COMMENT
COMMENT SIMULATION OF RIETSPRUIT -DAVEL PIPELINE
        NUM2=ZETADR*(53.6-HR)
        DEN2=13.875*ZETADR+0.0020
        Q2=SQRT(NUM2/DEN2)
        HDDOT=(Q2-Q3-QD)/ASD
        HD=INTEG(HDDOT,HD0)
```

```
COMMENT
COMMENT ---------------KRIEL VALVE POSITION,VK-----------------------------...
*************************************************************************...
      KRIEL=YK,DERIVED FROM LEVEL NUMBER,XK,AND SK...
      SK=0.0,FOR FALLING WATER LEVEL(SK=1.0,FOR RISING WATER LEVEL
COMMENT-----YDK,DETERMINES INFLUENCE, IF ANY,OF LOW WATER LEVEL AT...
      DAVEL ON VALVE POSITION,DERIVED FROM XDK AND SDK(=0.0 FALL)...
      VALVE POSITION NUMBER, VKNUMB, DETERMINES UBK, DESIRED VALVE...
      POSITION WHICH SETS UPPER BOUNDARY OF VALVE RAMP
         PROCEDURAL(VK=)
         OLDXK=XK
         IF((HK.GE.WLK0).OR.(HD.LE.WLD8).OR.(HR.LE.WLR5))GO TO K3
         IF((HK.LT.WLK0).AND.(HK.GT.WLK1))XK=1.0
         IF((HK.LE.WLK1).AND.(HK.GT.WLK2))XK=2.0
         IF((HK.LE.WLK2).AND.(HK.GT.WLK3))XK=3.0
         IF((HK.LE.WLK3).AND.(HK.GT.WLK4))XK=4.0
         IF (HK.LE.WLK4)                         XK=5.0
         XKI=(XK-OLDXK)
         IF(XKI.GT.0.0)                          SK=0.0
         IF(XKI.LT.0.0)                          SK=1.0
         YK=((XK+SK)-1.0)
         OLDXDK=XDK
         IF                  (HD.GE.WLD4) GO TO K1
         IF(HD.GE.WLD4)XDK=5.0
         IF((HD.LT.WLD4).AND.(HD.GT.WLD5))XDK=4.0
         IF((HD.LE.WLD5).AND.(HD.GT.WLD6))XDK=3.0
         IF((HD.LE.WLD6).AND.(HD.GT.WLD7))XDK=2.0
         IF((HD.LE.WLD7).AND.(HD.GT.WLD8))XDK=1.0
         XDKI=(XDK-OLDXDK)
         IF(XDKI.LT.0.0)                         SDK=0.0
         IF(XDKI.GT.0.0)                         SDK=1.0
         YDK=XDK-SDK
         IF(YDK.GE.YK)                           VKNUMB=YK
         IF(YDK.LT.YK)                           VKNUMB=YDK
         GO TO K2
   K1..VKNUMB=YK
         XDK=5.0
   K2..CONTINUE
         IF(VKNUMB.EQ.0.0)UBK=VKCLSD
         IF(VKNUMB.EQ.1.0)UBK=VK1
         IF(VKNUMB.EQ.2.0)UBK=VK2
         IF(VKNUMB.EQ.3.0)UBK=VK3
         IF(VKNUMB.EQ.4.0)UBK=VKOPEN
         GO TO K4
   K3..UBK=VKCLSD
         XK=0.0
         SK=0.5
   K4..CONTINUE
         IF(FK1.EQ.1.0)VKACTL=VK0
         IF(FK1.EQ.0.0)VKACTL=VK
         FK1=0.0
         UBKM=UBK-0.005
         UBKP=UBK+0.005
         IF((VKACTL.GE.UBKM).AND.(VKACTL.LE.UBKP))DIRK=0.0
         IF  (VKACTL.LT.UBKM)DIRK=1.0
         IF  (VKACTL.GT.UBKP)DIRK=-1.0
         VKDOT=DIRK*VKV
         VK=INTEG(VKDOT,VK0)
      ZETAKR=VKTAB(VK)
      IF(VK.LT.0.05)ZETAKR=0.0
         END
```

```
COMMENT
COMMENT SIMULATION OF DAVEL-KRIEL PIPELINE
        DEN3=20.649*ZETAKR+0.0026
        NUM3=ZETAKR*(109.20-HD-HK)
        Q3=SQRT(NUM3/DEN3)
                A1=3.142*(124.425+(HK*2.952))**2
                A2=(240.850+(HK*2.952))*((14.5-HK)*2.952)
                ASK=A1-A2
         HKDOT=(Q3-QK)/ASK
         HK=INTEG(HKDOT,HK0)
       END
       END
COMMENT
       TERMINAL
       END
       END
```

APPENDIX F

COMPUTER OUTPUT CURVES

The following outputs from the computer are given in this Appendix.

Figure F.1 Computer Simulation for opening Davel Regulating Valve.

Figure F.2 Computer Simulation for opening Kriel Regulating Valve.

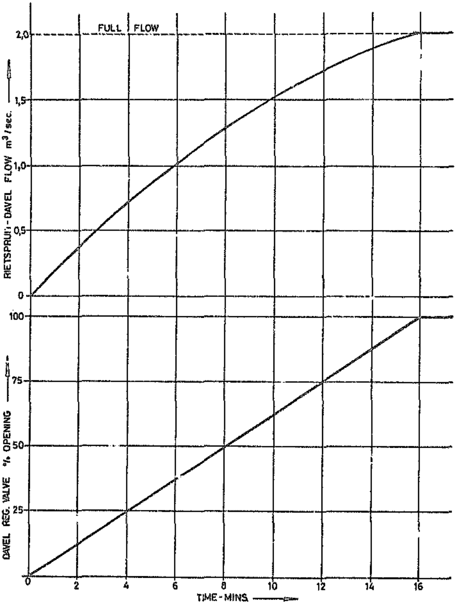


Fig. F.1 - Computer Simulation for opening Davel Regulating Valve

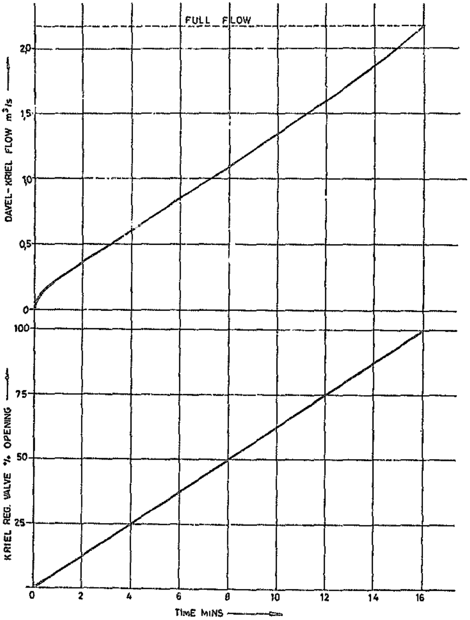


Fig. F.2 - Computer Simulation for opening Kriel Regulating Valve

APPENDIX G

LIST OF FORMULAE

Listed below are all the major equations given in this study with appropriate references:-

Equation (2.1) Hazen - Williams Formula

$$Q = 0{,}849\ C_H\ AR^{0{,}63}\ S^{0{,}5\text{[illegible]}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2.1)$$

(not used in this study)

Equations (2.2 and A.1) Darcy - Weisbach Formula

$$h_f = \frac{\lambda L\ v^2}{2g\ D} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2.2)$$

modified in equ. (A.4) to include for a flow control (regulating) valve

$$h_f = \frac{\lambda L\ v_P^{\ 2}}{2g\ \ D_P} + \frac{\zeta\ \text{[illegible]}^{\ 2}}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots(A.4)$$

equ. (A.8) expresses v_T in terms of v_P

$$v_T^{\ 2} = v_P^{\ 2} \cdot \frac{D_P^{\ 4}}{D_T^{\ 4}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(A.8)$$

equ. (A.9) is derived from (A.4) and (A.8)

$$h_f = \frac{\lambda L\ v_P^{\ 2}}{2g\ D_P} + \frac{\zeta v_P^{\ 2}\ \ D_P^{\ 4}}{2g\ \ D_P^{\ 4}} \quad \ldots\ldots\ldots\ldots\ldots\ldots(A.9)$$

equ. (A.13) gives Darcy-Weisbach formula as used in computer programme

$$h_f = \frac{16}{2g\pi^2}\left(\frac{\lambda L}{D_P^5} + \frac{\zeta}{D_T^4}\right)Q^2 \dots\dots\dots\dots \text{(A.13)}$$

Equation (A.14) Benoulli's Principle

$$E = z + \frac{p}{w} + \frac{v^2}{2g} \dots\dots\dots\dots \text{(A.14)}$$

Flow and Varying Head

Headloss, static head and pumping head:

gravity main,

$$h_f = H_S \dots\dots\dots\dots \text{(A.18)}$$

rising main,

$$h_f = H_P - H_S \dots\dots\dots\dots \text{(A.33)}$$

Equation (A.25) derivation of reservoir level

$$dH_x = \frac{(Q_A - Q_B)}{A_{SX}} \cdot dt \dots\dots\dots\dots \text{(A.25)}$$

Equation (A.32) derivation of pipeline flow from Darcy - Weisbach Formula

$$Q_A = \sqrt{\frac{H + H_x(t) - H_y(t)}{K_1 + K_2 \zeta}} \dots\dots\dots\dots \text{(A.32)}$$

Above equations as applied to Usutu River Scheme

Camden - Rietspruit Pipeline Headloss

$$h_{f1} = \frac{\lambda_1 L_1 v_{P1}^2}{2g \; D_{P1}} + \frac{\zeta v_T^2}{2g} \dots\dots\dots\dots \text{(3.5)}$$

Rietspruit - Davel Pipeline Headloss

$$h_{f2} = \frac{\lambda_2 L_2 v_{P2}^2}{2g \; D_{P2}} + \frac{\zeta_D \; v_{TD}^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

Davel - Kriel Pipeline Headloss

$$h_{f3} = \frac{\lambda_3 L_3 v_{P3}^2}{2g \; D_{P3}} + \frac{\zeta_K \; v_{TK}^2}{2g} \quad \ldots\ldots\ldots\ldots\ldots\ldots (G.1)$$

(not included in text)

Change in Level at Rietspruit Reservoir

$$\Delta H_R = \int_{t_o}^{t_1} \frac{Q_1 - (Q_2 + Q_R)}{A_{SR}} . \, dt \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.2)$$

Change in Level at Davel Reservoir

$$\Delta H_D = \int_{t_o}^{t_1} \frac{Q_2 - (Q_3 + Q_D)}{A_{SD}} . \, dt \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.3)$$

Change in Level at Kriel Reservoir

$$\Delta H_K = \int_{t_o}^{t_1} \frac{Q_3 - Q_K}{A_{SK}} \cdot dt \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.4)$$

Flow in Camden - Rietapruit Pipeline

$$Q_1 = \sqrt{\frac{H_{C1} - H_1}{K_{1.1} + K_1 \; \zeta}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

Flow in Bietspruit - Davel Pipeline

$$Q_2 = \sqrt{\frac{H_2 + H_R}{K_{2.1} + K_{2.2} \; \zeta_D}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

Flow in Davel - Kriel Pipeline

$$Q_3 = \sqrt{\frac{H_3 + H_D - H_K}{K_{3.1} + K_{3.2} \quad \zeta_K}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (G.2)$$

(not given in text)

Surface Area, A_{SK}, of Kriel Reservoir

$$A_{SK} = A_1 - A_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots (B.7)$$

$$A_1 = \pi(124,\ 425 + H_K \tan\theta\ )^2 \quad \ldots\ldots\ldots\ldots (B.1)$$

where $\tan\theta = 2{,}95$ ……………………………(B.2)

$$A_2 = \{2 \times (124{,}43 + H_K \tan\theta\ )\} \times \{2 \times (14{,}5 - H_K) \tan\alpha\} \quad \ldots (B.4)$$

where $\tan\alpha = 2{,}95$ ……………………………(B.5)

Newton - Raphson Iteration

$$Y = f(Y) \quad \ldots\ldots\ldots\ldots\ldots\ldots (D.1)$$

$$Y_n + 1 = (F_n - C_n Y_n) \ / \ (1 - C_n) \quad \ldots\ldots\ldots\ldots (D.2)$$

$$C_n = \{f_n - (f_n - 1)\} / \{Y_n - (Y_n - 1)\} \quad \ldots\ldots\ldots (D.3)$$

$$f_n = f(Y_n) \quad \ldots\ldots\ldots\ldots\ldots\ldots (D.4)$$

APPENDIX H

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Name of thesis Automatic Control Of Camden-kriel Raw Water Pipeline. 1978

PUBLISHER:
University of the Witwatersrand, Johannesburg