INVITED PAPER

Fluid Transients in Pipelines and Networks – use of Microcomputers for Design and Analysis in Developing Countries

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ABSTRACT

The analysis of fault conditions and fluid transients in pipelines tends to be surrounded by too much mystery, with this part of the design process often being left to 'the experts'. Whilst it is still necessary to understand the basic concepts to appreciate the possible consequences of rapidly changing flow situations, much can be done by competent network designers to assess the nature and scale of the risks to which their systems are exposed before calling in the specialist. This paper identifies some types of pipe system most at risk and outlines *strategies* for surge suppression and control. Examples are provided of computer analyses, relevant to Developing Countries, that can be undertaken on microcomputers with the aid of 'user friendly' software.

INTRODUCTION

The design and development of pipeline systems and networks usually proceeds in stages. An early stage is the feasibility study to evaluate the need and overall economic viability of the project. Following this will be the outline *engineering design*, for which certain of the principal features will be dictated by the locations of, for example, the need for supply, the available sources and possibly geographical/geotechnical factors. The remaining features would often be resolved primarily on purely economic criteria.

Ideally the next stage, before the design is frozen and construction begins, should be the fault analysis and fluid transient study. Unfortunately, in practice, this is not always the case. However, it is at this stage that the design engineer should be posing the questions:-

"What happens if........?"
"Can the system withstand........?"
"Are the anchor blocks adequate for shock loads....?"

To attempt answers to questions like these a sound understanding of fluid transient behaviour is essential. An appreciation is required of the fact that, following a pump trip/valve closure/system malfunction, pressures and flows do not change simultaneously throughout the system but as a result of pressure waves travelling to and fro. The initial pressure wave starts from the source of the disturbance, is propagated through the system at approximately the speed of sound in the fluid and is transmitted and reflected at each boundary condition and component within the system.

Computer-aided analyses are required for most pipeline systems - but the emphasis is on analysis, rather than design, hence the engineer needs to be able to identify possible hazards, assess the relative dangers and perhaps even propose technical solutions before any computer study is undertaken.

THE NATURE OF THE PROBLEM

Under transient flow conditions it is usually, though not always, the fluctuations in pressure that give rise to most concern. When superimposed on to the initial steady pressures occurring throughout the system they may well exceed the permissible maximum and/or minimum values. This leads to risks of mechanical damage to the pipeline and components, contamination of the fluid in the pipeline by ingress of harmful substances, and contamination of the surrounding environment through leakage out of the pipeline.

In some cases the consequences of fluid transients can be quite spectacular, such as the rupture of large pipelines. In others, the results are more insidious due, for example, to bacteriological contamination of drinking water.

The changing flow conditions may occur either through normal operational requirements or through situations quite outside the operator's control. Examples of the former are scheduled pump starts, stops, and changeovers, valve operations for controlling flow, etc. Some degree of control may be possible here but not always to a degree that eliminates unacceptable fluctuations in pressure.

It is the unscheduled, i.e. fault, events that often given rise to the more extreme fluctuations in pressure and dominate the assessment of fluid transient conditions.

Some types of system are at greater risk than others - especially the relatively simple pipelines. Networks, by virtue of the frequent intersections of pipelines, are inherently safer in general since the full Joukowski pressure changes will usually not be realised.

The most common hazard situation is the uncontrolled pump trip, possibly due to a power failure. In this case, the rapidly falling pressure may go sub-atmospheric and drop to vapour pressure allowing a large vapour cavity to form. The very rapid, and usually large, pressure rise following the collapse of this cavity (assuming the pipeline itself has not collapsed) is a serious problem.

Associated with pump trips is the phenomenon of check valve slam. Systems most at risk[1] are multi-pump systems when one of two or more running pumps is tripped. Also at risk are single pump systems where surge protection is an air vessel downstream of the pump, since the air vessel provides a high stored energy source similar to that of other pumps continuing to run in parallel.

Perhaps the most serious pump start problem is associated with submerged deep-well pumps for which the check valves are mounted at ground level. Upon start-up the pump may rapidly reach full speed against a negligible resistance as water rushes up the riser discharging air through a release valve at the top. Unless adequate resistance is provided the rapidly flowing water suddenly meets the closed check valve, suffers an instant deceleration and experiences a large pressure rise.

Pipeline supports are a matter of compromise. They need to allow freedom of movement to cater for the thermal effects of expansion and contraction, but adequate restraint to limit movement due to the passage of transient pressure waves which give rise to unbalanced forces on bends and junctions. These occur with both 'resonance' and 'single event' transients. Resonance effects are due to the cyclic behaviour of system components - positive displacement pumps, hunting of automatic control valves or between badly matched centrifugal pumps running in parallel. Failure of the system under these conditions may not be immediate, but cumulative fatiguing will result in a reduced period of trouble free operation.

PRACTICAL SOLUTIONS

Large and rapid changes in pressure are associated with large and rapid changes in the kinetic energy of the liquid in the pipeline. If the rate at which the kinetic energy changes occur can be regulated, so too can the pressure changes.

In a few situations this can be achieved directly such as by extending the effective operating time of a valve, or the inertia *(hence run-up/run-down time)* of pumps where these are the causes of the fluid transients.

An exception to the rule of slowing down component behaviour is the problem of check valve slam which is best alleviated by ensuring the selection of a valve with adequate response to changing conditions in the system. For a rapid response the ideal valve will have moving components that are light, do not have far to travel, and whose *closing motion is assisted by a spring or springs.* Manufacturers should be pressed to provide Dynamic Performance Characteristics.

For the majority of pipeline systems, however, it is *necessary to incorporate additional components with* a view to moderating the speed with which changes to flow rates would otherwise occur. Such components operate on the principle that a fluid is drawn into, or expelled from, pipelines in order to *regulate and control* the rate of change of flow and to give time for pressure waves to be reflected from other components in the system, which is normally beneficial.

Examples of the techniques used include air vessels, surge tanks, feed tanks, *relief* valves, air inlet-outlet valves, by-pass lines, etc. Some brief comments on these devices and techniques follow; greater detail being available in various texts[2-4].

Air vessels are the most common device used in the water *industry, particularly to guard* against the adverse effects of a complete pump shut-down. For this application they would be located, see Fig. 1, downstream of the pumps and their check valves which, as indicated above, must be selected with due regard to their dynamic performance characteristics. The air vessels may be single or multiple units.

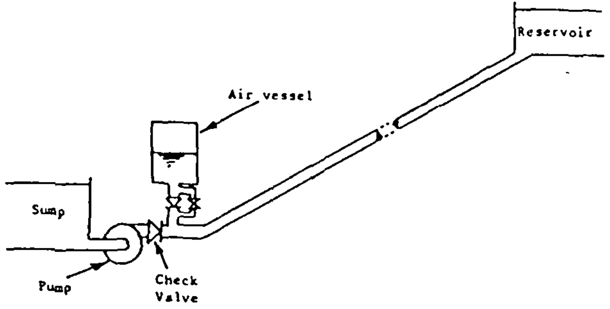

Fig.1. Air vessel downstream of a pump to control conditions after shutdown.

The latter would be chosen if a large capacity is required or where the staged development of a scheme is proposed. One or two would be installed initially with others being added later as the demand on the system warrants.

In very low head applications, where the hydraulic grade line is close to the pipeline profile, an open topped air vessel, i.e. surge shaft, may be used. Their main applications are in the field of hydro-electric systems but they can be useful in, for example, gravity feeds between reservoirs and treatment works.

For pipelines having undulating profiles, especially with elevated sections, air vessels alone would often be expensive and inadequate to avoid sub-atmospheric and vapour pressures occurring. Since air valves would be required to release air *during filling, and re-admitting it during* draining for maintenance, suitably designed valves may be used in some circumstances to suppress fluctuations in pressure under transient flow conditions. By admitting air freely when the local pressure falls to atmospheric the risk of pipeline collapse can be eliminated and by restricting its release an air cushion limits the magnitude of subsequent pressure peaks. Some care will, however, be required when restarting the system to allow the trapped air to escape in a controlled manner.

As an alternative to admitting air to a system when the pressure falls a feed tank (sometimes referred to as a one-way surge tank) may be used. These only provide protection against sub-atmospheric pressures and not against high pressures other than indirectly by avoiding those associated with vapour cavity collapse.

Although pump trips represent the major need for system protection, start-up operations also require care, especially if a downstream valve is completely closed. Deep-well pumps, too, can present problems. Controlled start-up with carefully sized air release valves at the top of the riser should be considered first. Air vessels also are a possible aid, but a cheaper alternative that should also be considered is illustrated in Fig. 2. This shows the application of a pressure regulating valve which should be open when the pump is run up to speed then closed gradually. As the discharge pressure builds up to the static head on the system the check valve opens and flow commences in the rising main.

In long pipelines booster pumps may be required, especially when high flow rates are envisaged. In the event of a loss of motive power to the pumps the pressure will rise on the upstream side, whilst falling on the downstream side. A simple by-pass line, fitted with a check valve, *around the pump can divert the high pressure upstream* to relieve the low pressure downstream.

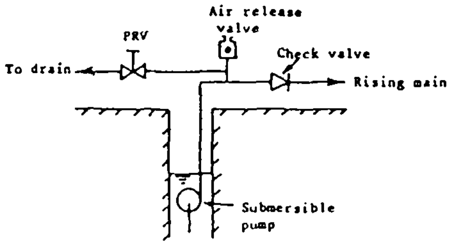

Fig.2. Schematic layout showing the use of a pressure regulating valve (PRV) for surge protection of a deep-well pump installation during pump starts.

Closing valves, like power failures to booster pumps, give rise to high pressure on the upstream side and low pressure downstream. Air vessels could be used, in principle, on both sides of the valve but on the upstream side pressure relief valves are often worthy of serious consideration. Such devices provide no protection against low pressures, however.

Relief valves can be of the conventional spring-loaded type, be controlled by a hydraulically operated pilot valve, or be one of the various patented designs. The essential features are a rapid opening (i.e. in much less than a pipeline period), followed ultimately by a slow closure. It is also essential that they should be of an adequate size and number to pass the required flow, allowing for valve isolation for maintenance purposes. By using two or more valves set to open at slightly different pressures the risk of relief valve hunting is avoided.

Note that the choice of relief valve cannot be made in isolation. The valves themselves should be close to the line being protected and hence the discharge line from the relief valves to waste, or to temporary storage facilities, must be considered since this will give rise to a back pressure resisting flow.

Since no two pipe networks or systems are the same the potential hazards from rapidly changing flow conditions will require practical solutions that will also be different. The advantages and disadvantages of the various possible solutions must be carefully assessed. In principle, any method of surge protection is valid provided it is practical, economic and gives adequate protection.

For simple pipe networks, some assessment of the risks and of the technical solutions can be achieved through the use of "Approximate methods". These may also be used to provide initial estimates for computer analyses since virtually all computer programs available analyse predetermined systems rather than design a protection system for a suggested fault or hazard.

DESIGN CHARTS AS AN INITIAL DESIGN AID

Although the well-known graphical method of Schnyder and Bergeron,[5] may be applied to many simple systems it has been superceded by various computer codes ranging from short ones for single pipe rising mains to much more complex models for multiple pipe networks. (Wood 1982; ESDU 1984; Martin 1987)[6-8].

Insofar as Approximate methods have a contribution to make, two types of situation arise. One is for water supply schemes having a phased development over some 30-40 years and in which, in the early phases, the flow velocities are in the order of a few centimetres/second. The other is to provide initial estimates of, for example, air vessel capacities, prior to a computer analysis of a complete system.

The former situation occurs in developing countries in those schemes where the pipelines installed initially are sized for the ultimate flows whilst the pump station is extended gradually, over, perhaps, 30 years, as the demand increases. The pressure fluctuations following a pump trip from a low flow velocity, v_0, of, for example, 10 cm/s, would be little over ±10 m. Superimposing this change on the hydraulic grade line enables the engineer with a sound understanding of the principles governing transient flow to decide if his system is at risk - but with such low initial flow rates many systems would not, in fact, require much in the way of protection from surge effects.

Pump trips and valve closures from higher flow rates will give higher pressure fluctuations for which simple superposition as above is less appropriate, but will often indicate if sub-atmospheric and column separation/cavitation conditions are probable. Computer studies are then essential but the pipe system to be modelled will require a prescribed device, e.g. an air vessel, surge tank, valve closure arrangement, etc. This initial prescription of preventative measures can only be decided on the basis of experience, rule of thumb, or a suitable "Approximate method", usually making use of design charts. The most common examples of these refer to the sizing of air vessels [2,9,10] and surge tanks[5,11,12] and to pressure changes following valve closure[2.4.13]. For the special problem of the start-up of deep-well pumps, should air vessels be under consideration, design charts have been devised [2,14] to aid their initial sizing.

Whether the principal hazard is excessive pressures in low lying sections of the system or cavitation problems in the more elevated parts, or a combination of the two, will depend not only on the cause of the transient flow conditions but also on the pipeline profile and complexity of the system. It has already been noted that simple pipelines are often more at risk than networks.

Once the experienced engineer has exercised his judgement, identifying the more serious risks and the strategies most suitable to contain them - including the estimation of, for example, air vessel or relief valve capacities - a computer simulation is usually essential.

APPLICATIONS OF MICROCOMPUTERS

The computer modelling of fluid transient phenomena has been a fruitful area of research for some 25 years and even now, especially for complex multiphase flows, there is still scope for further work. However, for purely liquid flows many satisfactory codes have been developed. These have mainly been on mainframe computers, but are now being made available on microcomputers.

This is particularly useful in Developing Countries in which more engineers have access to micros than mainframes, and also to the travelling scientists and consultants who are able more easily to transport and use software with which they are familiar.

Two characteristic features of microcomputers that have helped their adoption by engineers are their ease of use and the availability of graphics displays. In the former case, the interactive nature of many of the programs means that a knowledge of computer programming *per se* is not required - the programs are menu driven and the user simply responds to prompts on the screen. The graphical capabilities enable both pipe systems and the results of hydraulic analyses of them to be displayed and the salient features readily assimilated.

The following examples serve to illustrate some of these points.

Case (a) Water Supply Pipeline

This first example is typical of many schemes encountered in Developing Countries where water has to be pumped several kilometres either from a source to a treatment works or from a treatment works to a storage tank which then becomes the source for local use.

The pipeline in this case (in Africa) is buried for much of its length of nearly 20 km (see Fig.3). It is 82 mm in diameter, follows an undulating path, and is made of plastic. Three target flowrates were to be considered and transient analyses were required for two situations - loss of power to the pump at the upstream end, and rapid closure of a control valve at the downstream end.

Neither the pump performance characteristics nor the valve head loss characteristic were known. Another area of uncertainty was the wave propagation speed through the water in the plastic pipeline.

For an un-buried pipeline the wave speed would be of the order of 500 m/s. When buried the backfill material would provide some additional restraint for positive pressure waves, but the extent of this support depends on the nature and quality of the backfill as well as the previous history of fluid transient events. Hence, for the purposes of this investigation it was assumed that for downsurges, e.g. following a pump trip, the wave propagation speed would be 500 m/s. For upsurges following closure of the control valve 1000 m/s was used to err on the conservative side and assume some backfill support.

The Periodic Time (i.e. round-trip travel time) for the pipeline was therefore at least 40 seconds even for the higher wave speed. Both the pump run-down time and control valve closure were likely to occur in much less than this, therefore the lack of exact data on their operating characteristics was not so important and 'typical' ones were used.

Tables I and II show sample results for a pump run-down and valve closure using a program based on the Method of Characteristics numerical solutions of the equations for unsteady liquid flow. The first half of each Table contains data entered in response to questions appearing on the screen. The remainder is the result of the analyses.

Figs. 3 and 4 are longitudinal sections of the piplines with max-min head profiles shown on them - in the absence of surge suppression. The pump run-down is within the acceptable limits but the valve closure presents problems.

Case (b) Small Hydro-Electric Scheme

This example arose as a preliminary feasibility analysis in connection with preparing tenders for a design and construction project. The primary object of the study was to obtain an estimate of the pressure fluctuations in the penstock, upstream of the turbine main inlet valve assuming a rapid load reduction and complete closure of the guide vanes in 14 seconds.

```
Input file:  A:PT205
Output file: A:PT205OUT
Title of this simulation: Pump trip for phase 2 - c = 500 m/s

Date of this simulation: 6th July 1987

INPUT DATA
----------

CODE FOR ONE-LINE SYSTEM TYPE:
(2) Pump trip in unprotected pump discharge line

***SYSTEM DATA***

Pipe length = 19500 m
Pipe diameter = .082 m
Fanning friction factor of pipe walls (typically 0.001-0.025) = .0058
Wave speed in liquid = 500 m/s
Tank head above datum = 897 m
Steady-state flow rate = .00222 m^3/s
Number of pipe sections = 10

***PIPE PROFILE DATA***

Elevation above datum (m) for each of the 11 nodes
Node numbers : Upstream end =1 ; Downstream end = 11
Elevation =  864 m
Elevation =  858.5 m
Elevation =  859 m
Elevation =  864.5 m
Elevation =  861 m
Elevation =  869 m
Elevation =  868 m
Elevation =  856 m
Elevation =  873 m
Elevation =  880 m
Elevation =  882 m


***DATA FOR PUMP TRIP CASE***

Pump inlet head = 5 m
Rated head = 82.8 m
Rated flow = .00222 m^3/s
Rated speed = 1760 rev/min
Rated power = 2.17 kW
Rated efficiency (0-1) = .83
Inertia of rotating parts = 20 kg m^2

Pump Head,Torque,Flow and Speed modelled by non-dimensional
equations based on rated conditions
B1 =-.083 B2 =-.017 B3 = 1.1

B4 = .15 B5 = .32 B6 = .53


Period over which flow conditions are monitored (s) =  400
```

TABLE I. *System data, initial steady conditions and results from a transient analysis of a rising main pipeline subject to a loss of power to the supply pump.*

```
INITIAL CONDITIONS
------------------

Node        Flow          Head          Head
no.       velocity    above datum    (pressure)
           (m/s)          (m)           (m)
 1          0.42        946.69        82.69
 2          0.42        941.72        83.22
 3          0.42        936.75        77.75
 4          0.42        931.78        67.28
 5          0.42        926.81        65.81
 6          0.42        921.85        52.85
 7          0.42        916.88        48.88
 8          0.42        911.91        55.91
 9          0.42        906.94        33.94
10          0.42        901.97        21.97
11          0.42        897.00        15.00

RESULTS
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DATA OUTPUT EVERY 5 TIME STEP(S) FOR NODES 1 , 7 and 9


  Time   :      Heads above datum        :       Flow Velocities        :
   (s)   :             (m)               :           (m/s)              :
         : Node 1 : Node 7 : Node 9 : Node 1 : Node 7 : Node 9 :

    0.00 : 946.69 : 916.88 : 906.94 :   0.42 :   0.42 :   0.42 :
  19.500: 915.75 : 917.01 : 905.75 :   0.00 :   0.42 :   0.42 :
  39.000: 907.20 : 905.26 : 901.45 :   0.00 :   0.24 :   0.32 :
  58.500: 896.69 : 897.34 : 897.10 :   0.00 :   0.16 :   0.19 :
  78.000: 890.81 : 894.49 : 895.65 :   0.00 :   0.09 :   0.11 :
  97.500: 890.21 : 892.19 : 894.57 :   0.00 :  -0.03 :  -0.02 :

            ↓                                    ↓

 312.000: 898.98 : 897.75 : 897.39 :   0.00 :  -0.03 :  -0.04 :
 331.500: 899.41 : 898.77 : 897.94 :   0.00 :   0.00 :   0.00 :
 351.000: 899.05 : 898.14 : 897.51 :   0.00 :   0.02 :   0.03 :
 370.500: 897.01 : 897.09 : 897.02 :   0.00 :   0.04 :   0.04 :
 390.000: 895.38 : 896.39 : 896.69 :   0.00 :   0.03 :   0.03 :

TABULATION OF MAXIMUM AND MINIMUM HEADS AT EACH NODE

------------------------------------------------------------------
:  Node    : Max.head    : Max.head   : Min.head    : Min.head   :
: number   :above datum: (pressure) :above datum: (pressure)  :
:          :    (m)      :    (m)     :    (m)      :    (m)     :
------------------------------------------------------------------
:    1     :   946.69    :   82.69    :   890.15    :   26.15    :
:    2     :   941.72    :   83.22    :   890.18    :   31.68    :
:    3     :   936.76    :   77.76    :   890.44    :   31.44    :
:    4     :   931.82    :   67.32    :   890.50    :   26.00    :
:    5     :   926.83    :   65.83    :   890.81    :   29.81    :
:    6     :   921.89    :   52.89    :   891.38    :   22.38    :
:    7     :   917.09    :   49.09    :   892.19    :   24.19    :
:    8     :   911.94    :   55.94    :   893.20    :   37.20    :
:    9     :   906.95    :   33.95    :   894.39    :   21.39    :
:   10     :   902.03    :   22.03    :   895.66    :   15.66    :
:   11     :   897.00    :   15.00    :   897.00    :   15.00    :
------------------------------------------------------------------
```

TABLE I. (Continued)

```
Input file:  A:VC210
Output file: A:VC210OUT
Title of this simulation: Valve closure for Phase 2 - c=1000 m/s

Date of this simulation: 6th July 1987

INPUT DATA
----------

CODE FOR ONE-LINE SYSTEM TYPE:
(1) A constant pressure source feeding to valve

***SYSTEM DATA***

Pipe length = 19500 m
Pipe diameter = .092 m
Fanning friction factor of pipe walls (typically 0.001-0.025) = .0058
Wave speed in liquid = 1000 m/s
Tank head above datum = 946.69 m
Steady-state flow rate = .00222 m^3/s
Number of pipe sections = 10

***PIPE PROFILE DATA***

Elevation above datum (m) for each of the 11 nodes
Node numbers : Upstream end =1 ; Downstream end = 11
Elevation =  864 m
Elevation =  858.5 m
Elevation =  859 m
Elevation =  864.5 m
Elevation =  861 m
Elevation =  869 m
Elevation =  868 m
Elevation =  856 m
Elevation =  873 m
Elevation =  880 m
Elevation =  882 m


***DATA FOR VALVE CLOSURE CASE***

VALVE CLOSURE OPTION:
(3) Globe valve
Valve closure time = .5 s
Valve closure is linear

Head drop across valve (at steady-state) =  2.5 m

Period over which flow conditions are monitored (s) =  200
```

TABLE II.As Table I but for a rapid closure of the downstream control valve.

```
INITIAL CONDITIONS
------------------

Node        Flow           Head          Head
no.       velocity     above datum    (pressure)
           (m/s)           (m)           (m)
  1        0.42          946.69        82.69
  2        0.42          941.72        83.22
  3        0.42          936.75        77.75
  4        0.42          931.78        67.28
  5        0.42          926.81        65.81
  6        0.42          921.84        52.84
  7        0.42          916.88        48.88
  8        0.42          911.91        55.91
  9        0.42          906.94        33.94
 10        0.42          901.97        21.97
 11        0.42          897.00        15.00

RESULTS
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DATA OUTPUT EVERY 10 TIME STEP(S) FOR NODES 1 , 7 and 9


  Time   :       Heads above datum       :         Flow Velocities       :
  (s)    :             (m)               :             (m/s)             :
         : Node 1 : Node 7 : Node 9 : Node 1 : Node 7 : Node_9 :

   0.00 : 946.69 : 916.88 : 906.94 :    0.42 :    0.42 :    0.42 :
 19.500: 946.69 : 959.38 : 959.19 :    0.42 :    0.09 ;    0.05 :
 39.000: 946.69 : 959.29 : 963.33 :   -0.12 :   -0.13 :   -0.13 :
 58.500: 946.69 : 938.90 : 938.94 :   -0.24 :   -0.06 :   -0.03 :
 78.000: 946.69 : 938.40 : 935.85 :    0.08 :    0.08 :    0.08 :
 97.500: 946.69 : 952.40 : 952.44 :    0.17 :    0.04 :    0.02 :
117.000: 946.69 : 952.92 : 954.35 :   -0.06 :   -0.05 :   -0.05 :
136.500: 946.69 : 942.15 : 942.08 :   -0.13 :   -0.03 :   -0.02 :
156.000: 946.69 : 941.69 : 940.26 :    0.05 :    0.04 :    0.04 :
175.500: 946.69 : 950.47 : 955.56 :    0.10 :    0.03 :    0.01 :
195.000: 946.69 : 950.87 : 952.04 :   -0.04 :   -0.04 :   -0.03 :

TABULATION OF MAXIMUM AND MINIMUM HEADS AT EACH NODE

----------------------------------------------------------------------
:   Node    : Max.head    : Max.head   : Min.head    : Min.head   :
:  number   :above datum:(pressure)  :above datum:(pressure)  :
:           :     (m)     :    (m)     :     (m)     :    (m)     :
----------------------------------------------------------------------
:     1     :   946.69    :    82.69   :   946.69    :    82.69   :
:     2     :   963.64    :   105.14   :   937.02    :    78.52   :
:     3     :   965.15    :   106.15   :   935.87    :    76.87   :
:     4     :   966.74    :   102.24   :   931.66    :    67.16   :
:     5     :   968.50    :   107.50   :   926.70    :    65.70   :
:     6     :   970.40    :   101.40   :   921.66    :    52.66   :
:     7     :   972.45    :   104.45   :   916.87    :    48.87   :
:     8     :   974.48    :   118.48   :   911.91    :    55.91   :
:     9     :   976.52    :   103.52   :   906.66    :    33.66   :
:    10     :   978.60    :    98.60   :   901.97    :    21.97   :
:    11     :   980.56    :    98.56   :   897.00    :    15.00   :
----------------------------------------------------------------------
```

TABLE II. (Continued)

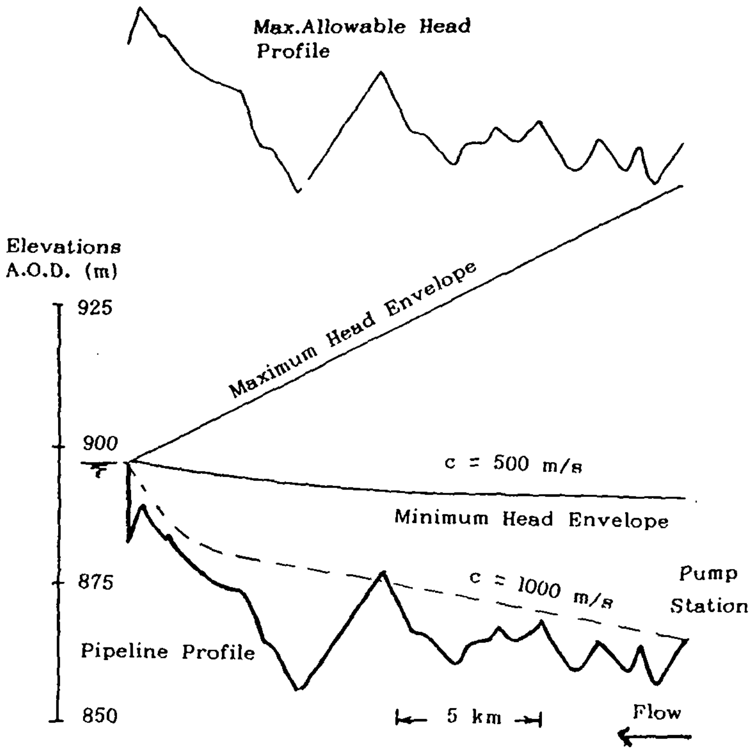

Fig.3. Single rising main system showing the pipeline profile, maximum permitted head profile and the max-min profile following a simulated pump trip

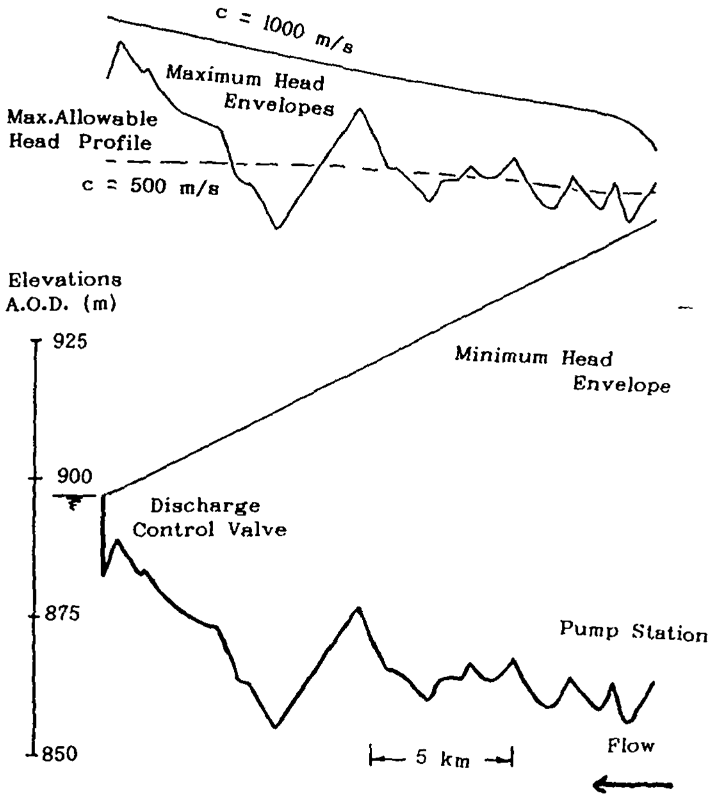

Fig.4. As Fig.3 but for a simulated valve closure at the downstream end.

The overall length of the pipeline, from supply reservoir to tailrace, was 1840 metres, of which the first 1230 metres was 1.2 m in diameter and the remainder 1 m in diameter. Near the upstream end were located a runaway valve and a vacuum breaking valve - each having small 'minor losses' associated with them.

The inlet guide vanes and turbine were modelled as a single component having a quadratic relationship between head drop across it versus flowrate, and which was time dependent.

Two programs were used to analyse a load reduction and guide vane closure, and similar results were obtained. Table III shows the output when using the same program as in the previous example. As this program will only analyse a "Single Line Situation" some idealisation was necessary - mainly an assumption of a pipeline having a uniform diameter of 1.1 m.

Using a more sophisticated program[6] not only can the two different line diameters be used but the minor losses associated with the runaway valve, connection to the vacuum breaking valve and the change in cross-sectional area were also included. The individual pipe lengths between these components ranged from 20 m to 1200 m.

Table IV provides an example of the system data and results but the most powerful demonstration of the use of micros are Figs.5 and 6 showing plots of time varying heads and flows.

This latter program is based on the wave-plan technique for transient flow analysis[16]. There is good agreement between the two sets of results, but exact agreement cannot be expected as the first set involve greater idealisations. Note that the start of the transient event is delayed for 3 seconds to ensure stable initial conditions to be confirmed.

Case (c) Network Analysis

As indicated previously, the analysis of transient flows in looped networks has normally been undertaken on mainframe computers due to requirements of computing capacity and data storage. These restrictions have now largely disappeared and Fig. 7 is an example of a relatively simple network used to demonstrate what can be achieved on popular microcomputers.

Greater details of this scheme have previously been reported[17].

This network is supplied by a pump drawing from a reservoir at the left hand side of the diagram and two elevated reservoirs at the right hand side. A transient

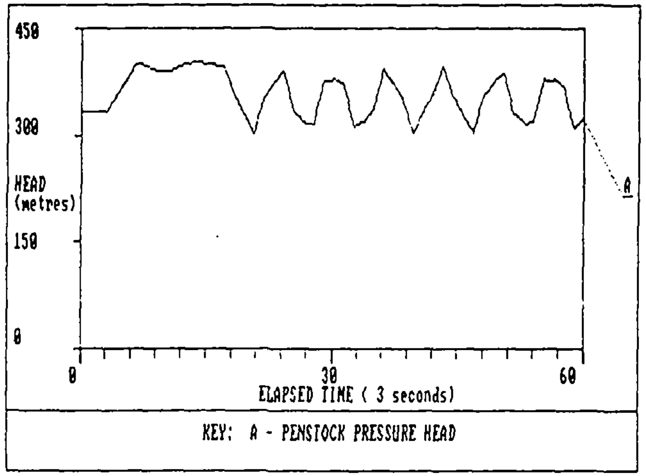

Fig.5. Pressure head versus time upstream of a hydro-electric turbine during and following a load reduction.

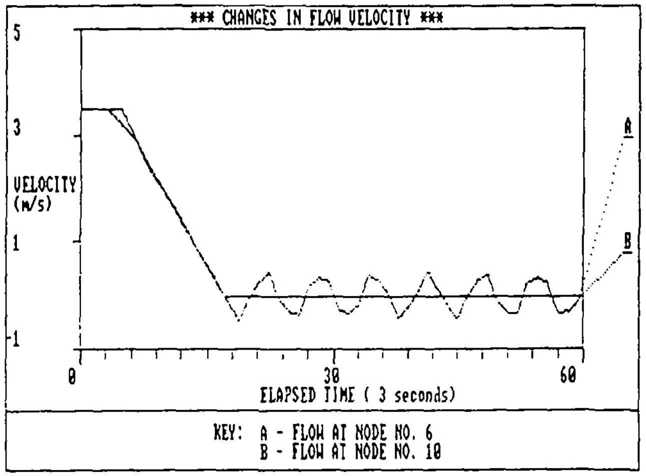

Fig.6. As Fig.5 but changing flow conditions at the turbine (Node 10) and at a point about 600 m upstream (Node 6).

```
Title of this simulation: LOAD REDUCTION

Date of this simulation: 12th October 1987

INPUT DATA
----------

CODE FOR ONE-LINE SYSTEM TYPE:
(1) A constant pressure source feeding to valve

***SYSTEM DATA***

Pipe length = 1840 m
Pipe diameter = 1.1 m
Fanning friction factor of pipe walls (typically 0.001-0.025) = .006
Wave speed in liquid = 1022 m/s
Tank head above datum = 430 m
Steady-state flow rate = 3.49 m^3/s
Number of pipe sections = 6

***PIPE PROFILE DATA***

Elevation above datum (m) for each of the 7 nodes
Node numbers : Upstream end =1 ; Downstream end = 7
Elevation =  430 m
Elevation =  373.3333 m
Elevation =  316.6667 m
Elevation =  260 m
Elevation =  203.3333 m
Elevation =  146.6667 m
Elevation =  90 m


***DATA FOR VALVE CLOSURE CASE***

VALVE CLOSURE OPTION:
(4) Butterfly valve
Valve closure time = 14 s
Valve closure is linear

Head drop across valve (at steady-state) =  321 m

Period over which flow conditions are monitored (s) =  60

Velocity and Head are being monitored
Velocity and head are being printed for 3 nodes (of nodes 1 to 7 )

Results output after every  5  time steps.
INITIAL CONDITIONS
------------------

Node        Flow          Head           Head
no.       velocity    above datum    (pressure)
            (m/s)         (m)            (m)
 1          3.67        430.00          0.00
 2          3.67        425.40         52.07
 3          3.67        420.80        104.13
 4          3.67        416.20        156.20
 5          3.67        411.60        208.27
 6          3.67        407.00        260.34
 7          3.67        402.40        312.40
```

TABLE III. Data for a simulation of a load reduction on a hydro-electric turbine, using a 'single-line' computer model.

```
RESULTS
-------

DATA OUTPUT EVERY 5 TIME STEP(S) FOR NODES 1 , 4 and 7


 Time   :       Heads above datum        :       Flow Velocities        :
  (s)   :              (m)               :           (m/s)              :
        : Node 1 : Node 4 : Node 7 : Node 1 : Node 4 : Node 7 :

   0.00 : 430.00 : 416.20 : 402.40 :    3.67 :    3.67 :    3.67 :
  1.500: 430.00 : 432.21 : 445.09 :    3.68 :    3.51 :    3.25 :
  3.001: 430.00 : 469.50 : 495.46 :    3.06 :    3.02 :    2.79 :
  4.501: 430.00 : 480.35 : 517.28 :    2.21 :    2.18 :    2.21 :
  6.001: 430.00 : 466.54 : 505.05 :    1.43 :    1.47 :    1.59 :
  7.502: 430.00 : 454.39 : 479.25 :    0.92 :    0.96 :    1.04 :
  9.002: 430.00 : 448.36 : 469.52 :    0.64 :    0.60 :    0.62 :
 10.502: 430.00 : 448.83 : 457.47 :    0.30 :    0.30 :    0.31 :
 12.003: 430.00 : 446.17 : 456.79 :    0.01 :    0.02 :    0.10 :
 13.503: 430.00 : 431.41 : 436.60 :   -0.15 :   -0.12 :    0.01 :
 15.003: 430.00 : 419.83 : 416.16 :   -0.09 :   -0.05 :    0.00 :
 16.504: 430.00 : 422.16 : 418.08 :    0.12 :    0.07 :    0.00 :

            ↓                                     ↓

 45.010: 430.00 : 424.01 : 421.43 :    0.08 :    0.03 :    0.00 :
 46.510: 430.00 : 431.76 : 434.20 :    0.09 :    0.06 :    0.00 :
 48.010: 430.00 : 437.64 : 439.33 :   -0.01 :   -0.01 :    0.00 :
 49.511: 430.00 : 429.83 : 432.48 :   -0.08 :   -0.08 :    0.00 :
 51.011: 430.00 : 423.53 : 422.22 :   -0.04 :   -0.02 :    0.00 :
 52.511: 430.00 : 426.03 : 423.67 :    0.08 :    0.05 :    0.00 :
 54.012: 430.00 : 433.10 : 437.54 :    0.07 :    0.05 :    0.00 :
 55.512: 430.00 : 435.71 : 437.98 :    0.04 :   -0.01 :    0.00 :
 57.012: 430.00 : 429.05 : 429.31 :   -0.08 :   -0.06 :    0.00 :
 58.513: 430.00 : 422.88 : 422.45 :   -0.02 :    0.00 :    0.00 :

TABULATION OF MAXIMUM AND MINIMUM HEADS AT EACH NODE

-----------------------------------------------------------------
:  Node    : Max.head   : Max.head   : Min.head   : Min.head   :
: number   :above datum :(pressure)  :above datum :(pressure)  :
:          :    (m)     :    (m)     :    (m)     :    (m)     :
-----------------------------------------------------------------
:    1     :   430.00   :     0.00   :   430.00   :     0.00   :
:    2     :   448.18   :    74.85   :   424.04   :    50.71   :
:    3     :   464.99   :   148.32   :   419.75   :   103.09   :
:    4     :   480.35   :   220.35   :   415.59   :   155.59   :
:    5     :   494.10   :   290.77   :   411.20   :   207.86   :
:    6     :   506.35   :   359.69   :   406.80   :   260.13   :
:    7     :   517.91   :   427.91   :   402.40   :   312.40   :
-----------------------------------------------------------------
```

TABLE III. (Continued)

```
TOTAL SIMULATION TIME = 60   TIME INCREMENT = .01

**** SUMMARY OF PIPE SYSTEM DATA ****

      NUMBERS OF SPECIFIC ITEMS
LINE SEGMENTS = 5       COMPONENTS = 3
JUNCTIONS = 2           BYPASS LINES = 0
SIDE ORIFICES = 1       RELIEF VALVES = 0
CHECK VALVES = 0        VARIABLE INPUTS= 1

               LINE SEGMENT DATA

POSITION     TRAVEL        C/GA       INITIAL      SEGMENT
OF ENDS    INCREMENTS                FLOWRATE    RESISTANCE
  1     2      2          92.10         3.49         0.01
  3     4      1          92.10         3.49         0.91
  6     7    117          92.10         3.49         0.45
  8     9     59         132.65         3.49         0.89
 10    11      1         132.65         3.49         0.00

               COMPONENT CHARACTERISTICS

POSITION NUMBERS = 2  3
A= 0  B= 0  C=-.0084
INITIAL FLOWRATE = 3.49      INITIAL HEADS = 4 - 3.8

POSITION NUMBERS = 7  8
A= 0  B= 0  C=-.0001
INITIAL FLOWRATE = 3.49      INITIAL HEADS = 164.5 - 164.4

POSITION NUMBERS = 9  10
A= 0  B= 0  C=-26.12
INITIAL FLOWRATE = 3.49      INITIAL HEADS = 331.5 - 13.3



      JUNCTION INFORMATION

 JUNCTION      NUMBER       INITIAL
 LOCATION      OF LEGS      HEAD
     1            0           4.0
    11            0          10.0

         SIDE ORIFICE CHARACTERISTICS

SDU LINE POSITION NUMBERS = 4  6  -  DISCHARGE POSITION =  5
   ARV EFFECTIVE ORIFICE AREAS = .09 (IN) -  5 (OUT)
AIR RELIEF VALVE AT POSITION  4



        VARIABLE INPUT DATA

A VARIABLE AREA VALVE IS AT POSITION NO. 9
REFERENCE VALUE = 26.12
TRANSIENT CHARACTERISTICS
 TIME         RATIO
 0               1
 3               1
 17              0



             **** SUMMARY OF INITIAL CONDITIONS ****


CONNECT. NODES      FLOW            HEAD              HEAD     ELEVATION
   #1     #2       1 to 2      #1          #2          LOSS     DIFFERENCE
   1       2        3.49       4.0         4.0          0.1        -0.1
   3       4        3.49       3.9         5.0          0.1        -1.2
   6       7        3.49       5.0       164.5          5.5      -165.0
   8       9        3.49     164.5       331.5         10.8      -177.8
  10      11        3.49      13.4        10.0          0.0         3.3
```

TABLE IV. As Table III but using a more sophisticated computer model.

```
****** FLOWRATE AND PRESSURE RESULTS ******
 TIME      H- 2       H- 3       H- 6      Q- 6     H- 9        H- 10       Q- 10
  0.100     4.0        3.9        5.0      3.490    331.5        13.4       3.490
  0.200     4.0        3.9        5.0      3.490    331.5        13.4       3.490
  0.300     4.0        3.9        5.0      3.490    331.5        13.4       3.490
  0.400     4.0        3.9        5.0      3.490    331.5        13.4       3.490
  0.500     4.0        3.9        5.0      3.490    331.5        13.4       3.490
  0.600     4.0        3.9        5.0      3.490    331.5        13.4       3.490

                       ↓                                          ↓

  3.000     4.0        3.9        5.0      3.490    331.5        13.4       3.490
  3.100     4.0        3.9        5.0      3.490    333.3        13.2       3.476
  3.200     4.0        3.9        5.0      3.490    335.3        13.2       3.462
  3.300     4.0        3.9        5.0      3.490    337.2        13.2       3.447
  3.400     4.0        3.9        5.0      3.490    339.2        13.2       3.432
  3.500     4.0        3.9        5.0      3.490    341.2        13.2       3.417
  3.600     4.0        3.9        5.0      3.490    343.2        13.2       3.402
  3.700     4.0        3.9        5.0      3.490    345.2        13.2       3.387
  3.800     4.0        3.9        5.0      3.490    347.3        13.2       3.372
  3.900     4.0        3.9        5.0      3.490    349.4        13.2       3.357
  4.000     4.0        3.9        5.0      3.490    351.5        13.2       3.342
  4.100     4.0        3.9        5.0      3.490    353.6        13.2       3.327
  4.200     4.0        3.9        5.0      3.490    355.7        13.1       3.311
  4.300     4.0        3.9        5.0      3.490    357.4        13.1       3.294
  4.400     4.0        3.9        5.0      3.490    359.2        13.1       3.276
  4.500     4.0        3.9        5.0      3.490    360.9        13.1       3.258

                       ↓                                          ↓

 14.500     4.6        4.6        6.0      0.667    401.3        13.0       0.688
 14.600     4.6        4.6        6.0      0.638    401.0        13.0       0.661
 14.700     4.6        4.6        6.0      0.610    400.7        13.0       0.633
 14.800     4.6        4.6        6.0      0.582    400.4        13.0       0.605
 14.900     4.6        4.6        6.0      0.554    400.0        13.0       0.577
 15.000     4.6        4.6        6.0      0.526    399.8        13.0       0.550
 15.100     4.6        4.6        6.0      0.498    399.7        13.0       0.522
 15.200     4.6        4.6        6.0      0.469    399.6        13.0       0.495
 15.300     4.6        4.6        6.0      0.441    399.4        13.0       0.467
 15.400     4.6        4.6        6.0      0.413    399.3        13.0       0.439
 15.500     4.6        4.6        6.0      0.385    399.1        13.0       0.412
 15.600     4.6        4.6        6.0      0.359    398.9        13.0       0.384
 15.700     4.6        4.6        6.0      0.333    398.7        13.0       0.357
 15.800     4.6        4.6        6.0      0.307    398.5        13.0       0.329

                       ↓                                          ↓

 59.196     3.8        3.8        4.8     -0.140    314.9        13.0       0.000
 59.296     3.6        3.6        4.5     -0.120    316.0        13.7       0.000
 59.396     3.2        3.2        4.1     -0.085    317.2        13.0       0.000
 59.496     3.3        3.3        4.1     -0.042    318.3        13.7       0.000
 59.596     3.3        3.3        4.1     -0.001    319.5        13.0       0.000
 59.696     3.3        3.3        4.1      0.040    320.6        13.7       0.000
 59.796     3.3        3.3        4.1      0.083    321.7        13.0       0.000
 59.896     3.3        3.3        4.1      0.127    322.6        13.7       0.000
 59.996     3.3        3.3        4.1      0.170    321.1        13.0       0.000

SUMMARY OF MAXIMUM AND MINIMUM HEADS
COMPONENT NO.    MAXIMUM     MINIMUM
       1            4.0         4.0
       2            5.0         3.1
       3            5.0         3.1
       4            6.7         3.9
       7          204.4       137.3
       8          204.4       137.3
       9          402.6       300.6
      10           13.7        13.0
      11           10.0        10.0

*** END OF THIS SIMULATION ***
```

TABLE IV. (Continued)

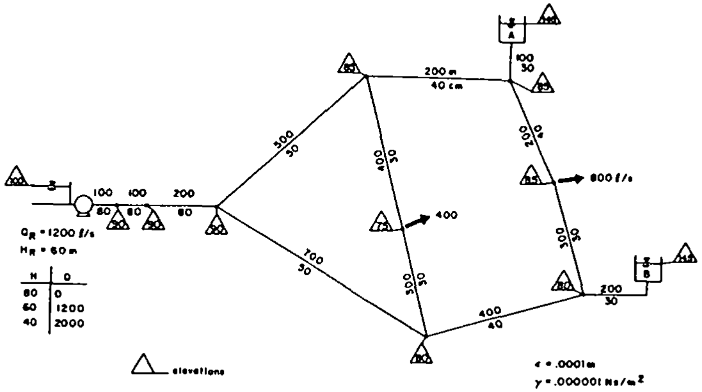

Fig.7. Small network showing dimensions, elevations, and external demands.

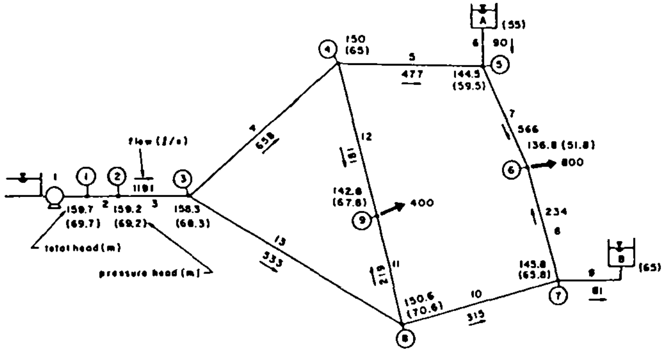

Fig.8. As Fig.7 with initial steady pressures and flows.

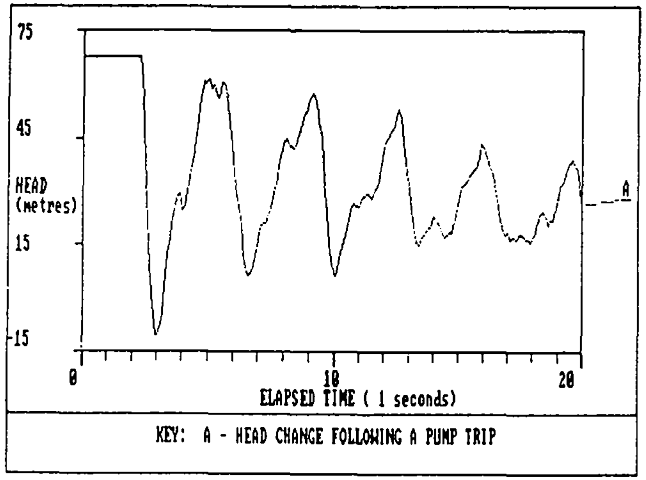

Fig.9. Pressure-time history at Node 9 in Fig.8 following a pump trip.

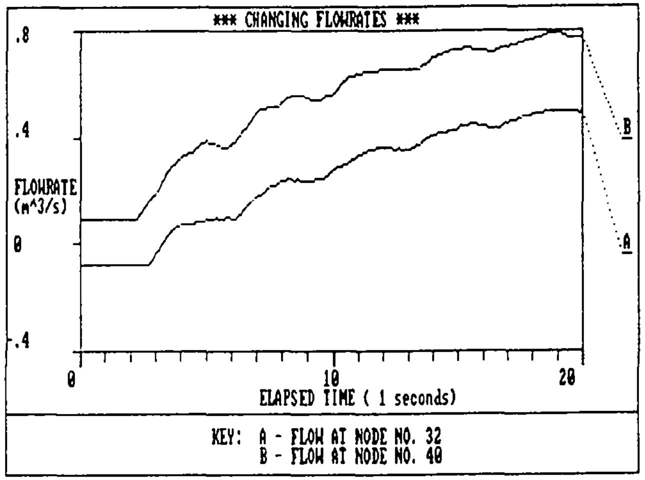

Fig.10. Changing flows from-to reservoirs A and B in the network of Figs.7 and 8.

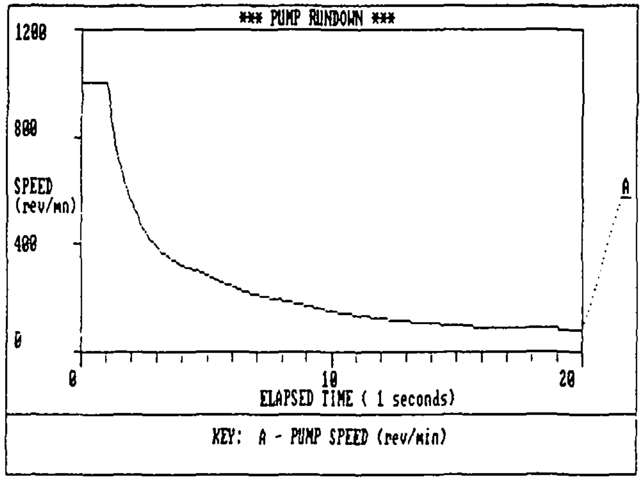

Fig.11. Speed change for the pump following loss of power at one second into the analysis.

analysis following loss of power to the pump driving motor is investigated.

Initial steady conditions are shown on Fig. 8. The outcome of a transient analysis using the SURGE-2 program[6] is illustrated in Figs. 9-11 and Table V. In this example a one second delay was used to confirm initial steady conditions being maintained by the transient flow equations.

Many aspects of the results can be displayed graphically - the user has the option to select those of particular interest. The fluctuating pressure heads, of which Fig.9 is but one example, enable the maximum and minimum values at particular locations to be readily observed. Fig. 10 illustrates the extent to which the reservoirs A and B take over the supply to the system once the pump has tripped out. Initially water was flowing through node 32 into reservoir B (see Figs.8,10), but flow reversal occurs some 3-4 seconds into the analysis with new steady state conditions ultimately being realised after about 25 seconds.

CONCLUDING REMARKS

Many more sets of graphic and tabular data could have been included, however it should now be apparent that microcomputers provide a powerful tool capable of being used to assist in the investigation of transient flows in pipelines and networks. It is still necessary for the user to have an understanding of the basic concepts of fluid transients and of practical methods and strategies for their alleviation. Without this background there is the risk of CAD being an abbreviation for Computer Aided Disaster.

REFERENCES

1. Thorley, A.R.D. (1983) "Dynamic response of check valves". Procs. 4th Intl. Conf. on Pressure Surges, Bath, England, pp.231-242, BHRA.
2. Thorley, A.R.D. and Enever, K.J. (1979) "Control and suppression of pressure surges in pipelines and tunnels", Design Guide Report 84, Construction Industry Research and Information Association, London,(Revised 1985).
3. Wylie, E.B. and Streeter, V.L.(1983) "Fluid Transients". F.E.B. Press, Ann Arbor, Michigan.
4. Chaudhry, M.H. (1987) "Applied Hydraulic Transients" Van Nostrand Reinhold.
5. Parmakian, J. (1963) "Water Hammer Analysis" Dover Publications, New York.
6. Wood, D.J. (1982) "Computer analysis of transient flow in pipe networks including surge control devices" *Users Manual for SURGE-2, a Computer Code for microcomputers.* Univ.of Kentucky.

7. ESDU (1984) "Fluid transients in pipes and tunnels" Vol.10a and 10b in the Fluid Mechanics - Internal Flow series - Data Items 84013 (1984), 84038 (1984), 85009 (1985), and 85044 (1985), Engineering Sciences Data Unit, London.
8. Martin, C.S. (1987) "Water hammer program AWHAM for IBM Personal Computers" Dept.of Civil Eng., Georgia Institute of Technology, Atlanta, Sept.1987.
9. Evans, W.E. and Crawford, C.C. (1954) "Design charts for air chambers on pump lines" Trans. Am. Soc. of Civil Engrs. Vol.119, Paper No.2710, pp.1025-1045.
10. Graze, H.R. and Forrest, J.A. (1974) "New design charts for air chambers". Procs. 5th Australian Conf. on Hydraulics and Fluid Mechanics, Univ. of Canterbury, N.Zealand.
11. Pickford, J.A. (1965) "Surge tank design by logarithmic curves" Water Power, Vol.17, Part 10, pp.397-400.
12. Fok, A.T.K. (1980) "Design charts for surge tanks on pump discharge lines", Procs. 3rd Intl. Conf. on Pressure Surges, Organised by BHRA, Paper J3, pp.445-472, Canterbury.
13. Wood, D.J. and Jones, S.E. (1973) "Waterhammer charts for various types of valves". Procs. Am. Soc. of Civil Engrs. J.Hyd.Div. HY1, Vol.99, pp.167-178.
14. Tucker, D.M. and Young, G.A.J. (1960) "Estimation of air vessel sizes" Report SP670, presented to 7th Conf. on Hydromechanics, BHRA, Cranfield, Beds.
15. Thorley, A.R.D. and Lastowiecki, P. (1985) "Air vessel design for rising mains" Procs. Intl.Conf. on the Hydraulics of Pumping Stations. pp.89-98, Manchester, England, Organised by BHRA Cranfield, Beds.
16. Wood, D.J., Dorsch, R.G. and Ligtner, C. (1966) "Wave-plan analysis of unsteady flow in closed conduits", Procs.ASCE, HY2, Jo.of Hydraulics Div. pp.83-110, Vol.131, Paper No.4716.
17. Thorley, A.R.D. and Wood, D.J. (1987) "Fault analysis and transient suppression in pipelines and networks:" Procs. Int.Conf.on Computer Applications for Water Supply and Distribution. Water Control Unit, Leicester Polytechnic, Sept.1987.

```
        VARIABLE INPUT DATA

PUMP START UP OR SHUT DOWN OCCURS AT POSITION NO. 1
TRANSIENT CHARACTERISTICS
 TIME         RATIO
 0              1
 1              1
 PUMP TRIP SPECIFIED



           **** SUMMARY OF INITIAL CONDITIONS ****


CONNECT. NODES      FLOW          HEAD                HEAD    ELEVATION
   #1     #2       1 to 2     #1          #2          LOSS    DIFFERENCE
    2      3        1.19      70.3        69.7         0.5       0.1
    4      5        1.19      69.7        69.2         0.5       0.0
    7     20        1.19      69.2        68.3         0.9      -0.0
   21     22        0.66      68.3        65.0         8.2      -4.9
   23     24        0.48      65.0        59.5         5.5      -0.0
   40     25        0.09      55.0        59.5         0.5      -5.0
   26     27        0.57      59.5        51.8         7.7      -0.0
   29     28        0.23      65.8        51.9         9.0       5.0
   34     31        0.32      70.6        65.8         4.9      -0.1
   35     36        0.22      70.6        67.8         7.9      -5.1
   38     37        0.18      65.0        67.8         7.3     -10.1
  .19     33        0.53      68.3        70.6         7.7     -10.0
   30     32        0.08      65.8        65.0         0.8       0.0


****** FLOWRATE AND PRESSURE RESULTS ******
TIME      H- 2      Q- 2      H- 20     H- 27     H- 36      Q- 32     Q- 40
 0.200    70.3      1.191     68.3      51.8      67.8      -0.081     0.090
 0.400    70.3      1.191     68.3      51.8      67.8      -0.081     0.090
 0.600    70.3      1.191     68.3      51.8      67.8      -0.081     0.090
 0.800    70.3      1.191     68.3      51.8      67.8      -0.081     0.090
 1.000    70.3      1.191     68.3      51.8      67.8      -0.081     0.090
 1.200    52.0      1.101     68.3      51.8      67.8      -0.081     0.090
 1.400    39.5      1.040     68.3      51.8      67.8      -0.081     0.090
 1.600    30.9      0.998     47.9      51.8      67.8      -0.081     0.090
 1.800    24.8      0.969     34.1      51.8      67.9      -0.081     0.090
 2.000    19.8      0.967     24.4      51.8      67.8      -0.081     0.090
 2.200    16.0      0.964     17.3      51.8      67.8      -0.081     0.090
 2.400    13.1      0.961     14.0      41.7      57.1      -0.081     0.116
 2.600    10.7      0.959     11.4      32.1      21.8      -0.081     0.145
 2.800     8.8      0.956      9.2      21.4      -2.1      -0.067     0.170
 3.000     7.3      0.953      7.9      19.2     -10.1      -0.033     0.195



 3.200     6.0      0.951      9.1      13.0      -3.9      -0.010     0.227
 3.400     5.2      0.947      7.6      15.4      12.7       0.024     0.261
 3.600     5.3      0.923      4.4      20.7      22.8       0.046     0.288
 3.800     4.8      0.925      0.5      37.2      29.0       0.061     0.306
 4.000     3.9      0.944     -1.1      48.0      24.9       0.074     0.323
 4.200     3.0      0.970      6.4      41.6      29.9       0.079     0.335
 4.400     3.0      0.963     15.3      38.8      39.5       0.077     0.345
 4.600     4.3      0.896     25.2      40.5      50.4       0.081     0.359
 4.800     5.7      0.830     31.3      36.5      60.8       0.085     0.378
 5.000     7.0      0.759     29.3      36.4      61.9       0.090     0.385
 5.200     8.0      0.699     27.8      46.6      59.6       0.092     0.380
 5.400     8.5      0.662     25.6      55.9      56.4       0.100     0.371
 5.600     9.1      0.621     21.8      58.0      60.4       0.093     0.365
 5.800     9.6      0.582     19.8      48.5      51.5       0.098     0.365
 6.000     9.5      0.565     14.6      32.4      35.0       0.094     0.375
 6.200     9.5      0.550      9.1      26.0      25.9       0.106     0.395
```

TABLE V. (Continued)

```
UNIVERSITY OF KENTUCKY - SURGE PROGRAM -  VERSION (7/24/87)

INPUT DATA FILE NAME =les1
OUTPUT DATA FILE NAME =les1out

TOTAL SIMULATION TIME = 20  TIME INCREMENT = .1

**** SUMMARY OF PIPE SYSTEM DATA ****

    NUMBERS OF SPECIFIC ITEMS
LINE SEGMENTS = 13       COMPONENTS = 1
JUNCTIONS = 11           BYPASS LINES = 0
SIDE ORIFICES = 0       RELIEF VALVES = 0
CHECK VALVES = 1        VARIABLE INPUTS= 1

           LINE SEGMENT DATA

POSITION    TRAVEL       C/GA      INITIAL    SEGMENT
OF ENDS   INCREMENTS               FLOWRATE  RESISTANCE
  2   3       1         203.00       1.19        0.34
  4   5       1         203.00       1.19        0.34
  7  20       2         203.00       1.19        0.67
 21  22       5         520.00       0.66       19.05
 23  24       2         809.00       0.48       24.22
 40  25       1        1436.00       0.09       56.79
 26  27       2        1436.00       0.57       24.13
 29  28       3        1436.00       0.27      163.50
 34  31       4         809.00       0.32       49.18
 35  36       3        1436.00       0.22      163.70
 30  37       4        1436.00       0.18      221.60
 19  33       7         520.00       0.53       26.93
 30  32       2        1436.00       0.08      113.80

  PUMP CHARACTERISTICS PROVIDED FOR THE PUMP LOCATED AT POSITIONS  1  -
     PUMP CHARACTERISTICS FILE NAME = 9991
      REFERENCE FLOW =  1.2            REFERENCE HEAD =  60
      REFERENCE SPEED =  1000          INITIAL SPEED =  1000
      REFERENCE TORQUE =  8222.9      EFFICIENCY =  .82
      MOMENT OF INERTIA OF ROTATING PARTS =  1000
      SPECIFIC SPEED FOR THIS PUMP =  50.8


            COMPONENT CHARACTERISTICS

POSITION NUMBERS = 1  2
A=-22.78136  B= 175.7834  C=-89.03171
INITIAL FLOWRATE = 1.19     INITIAL HEADS = 10 - 70.2
    JUNCTION INFORMATION

JUNCTION      NUMBER      INITIAL
LOCATION      OF LEGS      HEAD
    3            2         69.7
    5            2         69.2
   19            3         68.3
   22            3         65.0
   24            3         59.5
**** CONTINUITY AT ABOVE JUN. DOES NOT CHECK-NET FLOW (OUT)=  1.000047E-0
   27            2         51.8
**** CONTINUITY AT ABOVE JUN. DOES NOT CHECK-NET FLOW (OUT)=  .8
   29            3         65.8
   33            3         70.6
**** CONTINUITY AT ABOVE JUN. DOES NOT CHECK-NET FLOW (OUT)= -1.000002E-0
   36            2         67.8
**** CONTINUITY AT ABOVE JUN. DOES NOT CHECK-NET FLOW (OUT)=  .4
   32            0         65.0
   40            0         55.0


THERE IS A CHECK VALVE AT POSITION 1
    TIME DELAY FOR VALVE =  4    -  CV RESISTANCE =  .001
```

TABLE V. Sample of the tabular output from a surge analysis of a network

```
  6.400    9.0    0.561    7.5    20.1    11.4    0.123    0.420
  6.600    8.4    0.576    8.1    16.5     6.3    0.145    0.443
  6.800    8.3    0.574    7.9    18.0     9.5    0.165    0.472
  7.000    8.4    0.554    8.0    26.0    16.4    0.178    0.493
  7.200    8.2    0.562    9.6    36.7    21.0    0.191    0.506
  7.400    7.9    0.573    5.0    27.4    23.9    0.207    0.511
  7.600    8.1    0.555    8.9    29.2    30.1    0.216    0.512
  7.800    7.7    0.579   14.9    29.0    38.7    0.228    0.517
  8.000    8.1    0.549   19.2    29.6    44.1    0.237    0.531
 12.600   10.8    0.150   16.8    35.0    57.1    0.357    0.655
 12.800   10.8    0.141   18.0    31.7    44.3    0.352    0.656
 13.000   10.8    0.123   18.2    30.2    30.6    0.355    0.657
 13.200   10.9    0.100   17.3    23.2    18.4    0.361    0.658
 13.400   10.9    0.077   16.0    18.1    15.1    0.373    0.660
 13.600   10.8    0.076   13.8    15.9    17.7    0.386    0.671
 13.800   10.8    0.071    9.3    12.8    19.7    0.399    0.686
 14.000   10.8    0.070    6.8    15.5    23.0    0.403    0.698
 14.200   10.7    0.091    3.6    24.0    20.8    0.415    0.708
 14.400   10.7    0.114    4.5    22.7    17.5    0.417    0.715
 14.600   10.5    0.140    8.4    19.3    18.3    0.422    0.722
 14.800   10.5    0.130   13.7    20.0    21.4    0.425    0.726
 15.000   10.6    0.112   20.5    19.5    27.8    0.434    0.729


 18.400   10.6   -0.003   13.2    11.9    24.4    0.490    0.782
 18.600   10.6   -0.018   15.9    13.0    20.8    0.493    0.788
 18.800   10.6   -0.046   16.8    16.8    21.8    0.496    0.791
 19.000   10.6   -0.056   17.3    19.3    28.0    0.498    0.789
 19.200   10.7   -0.064   16.0    24.9    32.5    0.495    0.783
 19.400   10.7   -0.082   16.4    26.8    36.7    0.497    0.777
 19.600   10.8   -0.099   15.0    20.1    38.4    0.494    0.772
 19.800   10.9   -0.112   17.6    19.6    36.3    0.492    0.770
 20.000   10.8   -0.107   12.8    18.7    26.1    0.491    0.775

SUMMARY OF MAXIMUM AND MINIMUM HEADS
COMPONENT NO.    MAXIMUM    MINIMUM
      1            10.0       10.0
      2            70.3        2.6
      3            69.7       -0.4
      5            69.2       -1.5
     19            68.3       -1.7
     22            65.0        9.6
     24            59.5       18.9
     27            58.3       11.3
     29            65.8       22.7
     32            65.0       65.0
     33            70.6       -4.9
     36            67.8      -10.1
     40            55.0       55.0

*** END OF THIS SIMULATION ***


A PLOT FILE (lesplot) HAS BEEN CREATED WITH THE FOLLOWING DATA:

ITEM NO.   SPECIFIC RESULT
 1       HEAD AT POS. #  27
 2       HEAD AT POS. #  36
 3       FLOW AT POS. #  32
 4       FLOW AT POS. #  40
 5       PUMP SPEED AT POS. #  1
```

TABLE V. (Continued)

Computer Methods and Water Resources

1st International Conference, Morocco 1988

Vol. 2 Computational Hydraulics

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D. Ouazar
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Computational Mechanics Publications
Southampton Boston

Springer-Verlag Berlin Heidelberg New York
London Paris Tokyo

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British Library Cataloguing in Publication Data

Computer methods and water resources: first international conference, Morocco, 1988. 1. Natural resources: Water. Management. Applications of computer systems. I. Ouazar, D. (Driss) II. Brebbia, C.A. (Carlos Alberto) III. Barthet, H. (Henri).
333.91 '0028 '54

ISBN 1-85312-000-6 V.1
ISBN 1-85312-001-4 V.2
ISBN 1-85312-002-2 V.3
ISBN 1-85312-003-0 V.4
ISBN 1-85312-004-9 V.5
ISBN 1-85312-005-7 V.6

ISBN 1-85312-001-4 Computational Mechanics Publications Southampton
ISBN 0-931215-90-0 Computational Mechanics Publications Boston
ISBN 3-540-18854-1 Springer-Verlag Berlin Heidelberg New York London Paris Tokyo
ISBN 0-387-18854-1 Springer-Verlag New York Heidelberg Berlin London Paris Tokyo
ISBN 3-540-18859-2 6-volume set
ISBN 0-387-18859-2

Library of Congress Catalog Card Number 87-73387

Printed in Great Britain by Unwin Brothers Ltd., Old Woking, Surrey