The Libyan Great Man-Made River Project Phase I
Paper 3. Conveyance system hydraulics and control

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■ **The Great Man-made River Project (GMRP), one of the world's largest civil engineering projects, will convey 6·18 million m^3 of water per day (MCMD) (71·5 m^3/s) from groundwater resources in the Sahara Desert to the coastal population of Libya. The water will be used for agricultural, municipal and industrial purposes. The first of the three phases is the Sarir/Sirt and Tazerbo/Benghazi (SSTB) system. It consists of the following: the Sarir and Tazerbo wellfields, each producing 1·0 MCMD; the necessary collection sysems from the wells; two 4000 mm diameter conveyance pipelines of prestressed concrete cylindrical pipe (PCCP) totalling over 1500 km; storage reservoirs; major ancillary works and an integrated communications and control system.**

This Paper considers the hydraulics design of the twin gravity flow conveyance pipelines from Sarir to Ajdabiya Reservoir operating under upstream control, with wellfields delivering the required flows to pipelines which at low flows run partially full. It also addresses the gravitational flow in pipelines from Ajdabiya to Sirt and Benghazi terminal reservoirs, into which the discharge is determined by the operation of end control valves, and the users *en route* are controlled by their own turnout valves, with closure times chosen to limit transient pressures. Ajdabiya Reservoir provides buffer storage and a hydraulic break between the wellfield and the end users. Computer modelling of fast and slow transients in full and/or partially full pipelines has been carried out.

Introduction

The scope of the Great Man-Made River Project (GMRP) is depicted in Fig. 1. Phase I, the Sarir/Sirt and Tazerbo/Benghazi (SSTB) system conveys water from the pumped wells, through wellfield collector pipework, along a 4000 mm diameter prestressed concrete cylindrical pipe (PCCP) main conveyance system to turnouts and terminal reservoirs from which secondary conveyance lines, covered by the Water Utilization Phase, will carry the water to the end user. Data illustrating the magnitude of Phase I are presented in Table 1.

2. The function of the system is to supply pre-agreed quantities of water at steady state flow conditions to meet the demands of the agricultural projects and of the relatively minor municpal and industrial users. Fluctuations in demand are also accommodated.

3. When the Libyan People's Congress reviewed methods of augmenting water supplies to coastal development, water desalination plants were considered but rejected because of the cheaper unit cost of GMRP water compared with desalting.

4. This Paper concentrates on the gravity flow capability of Phase I. The future phases and expansion of Phase I (albeit mentioned briefly herein) will be dealt with later.

Conveyance system design and base data

5. The Phase I system is shown schematically in Fig. 2 and consists of two wellfields, five hydraulically distinct conveyance pipelines, and various reservoirs and header tanks for storage and hydraulic control. Particular pipeline details are given in Table 1.

6. The final selection of the conveyance system is the result of many previous optimization studies which were made to determine the most technically feasible and cost-effective solution. The selection of a piping system over a canal system was based on practicality and cost. In the initial stages of the project a concrete-lined trapezoidal-shaped channel was evaluated. The evaluation covered both open and covered canals. Two typical study cases using pipes and canals are shown in Fig. 3.

Canal against pipeline system

7. A review of the topography of the Sarir–Ajdabiya area indicates that a canal system is not feasible. There are several areas along the route where the canal would encounter uphill slopes with no alternative routes, necessitating pumping stations to convey the water. This

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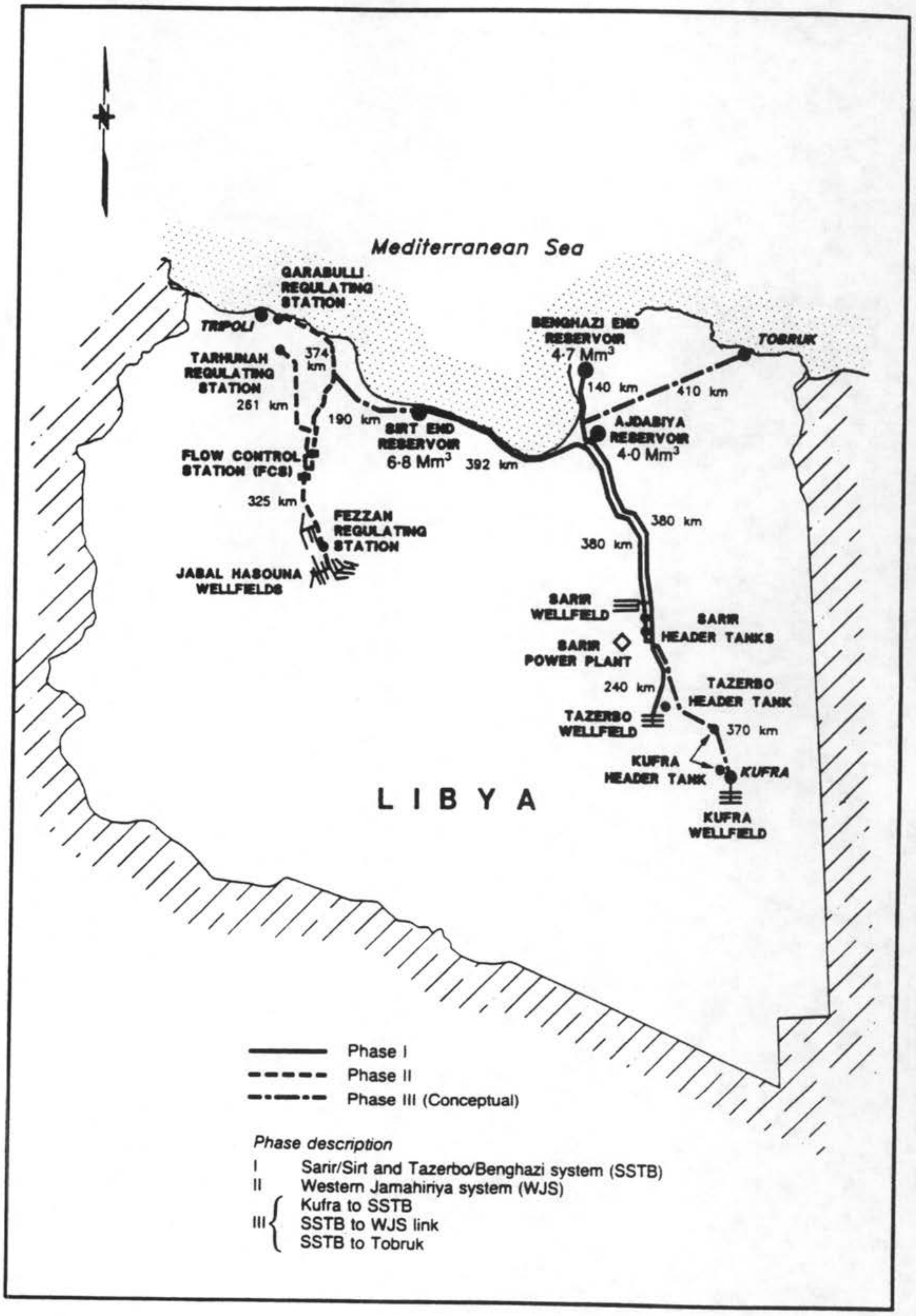


Fig. 1. The Great Man-Made River Project

means that no portion of the design flow could be delivered by gravity. Any unplanned pumping plant shut-down would completely stop water delivery. Conversely, on the downhill slopes, supercritical velocities would be encountered. This would require the construction of drop structures to dissipate the excess energy. In other areas, to preserve the uniform slope, the canal might be partially or entirely in a fill section which would not be desirable.

8. Another major disadvantage of the canal system is its vulnerability in high water-table areas. If the groundwater table is above the canal bottom, outside hydrostatic pressure could rupture the lining when the canal is empty or the water surface drawn down. A

Table 1. Data sheet for SSTB pipelines

Pipe	Diameter: mm	Length: km	Rating: bar	Flow		Future pumping stations	
				Initial: MCMD	Future: MCMD	No.	Power: MW
Sarir–Ajdabiya	4000	380	6–12	1·0	1·84	1	10
Ajdabiya–Sirt	4000	392	6–14	0·82	2·3	3	10
Tazerbo–Sarir	4000	240	6–18	1·0	2·68	—	—
Sarir–Ajdabiya (Tazerbo Part)	4000	380	6–12	1·0	1·84	1	10
Ajdabiya–Benghazi	4000	140	6–14	1·18	2·5	1	20

Sarir wellfield

Pipe diameter: mm	Length: km	Rating: bar	Flow: MCMD	Wells: number	Duty: l/s
1600	70·2	8	1·0	126	108
2000	89·1	8			
2800	6·6	8			

Tazerbo wellfield

Pipe diameter: mm	Length: km	Rating: bar	Flow: MCMD	Wells: number	Duty: l/s
1600	120·0	8	1·0	108	120
2000	10·0	8			
2800	10·0	8			

further consideration in the rejection of the open canal system was the contamination potential. The canal system is subject to contamination from wind-blown sand and dust which makes the maintenance costly. Furthermore, it is more difficult to maintain the security of a canal water conveyance system than that of a piped system, leaving it easily vulnerable to sabotage and to acts of nature, i.e. flooding or movement of sand deposits. Covered canals, on the other hand, also proved too costly. For a loading of 488 kg/m^2, the cover would be designed to withstand a 250 mm or 300 mm layer of blowing sand. Any deeper layer of blowing sand could result in the failure of the cover and in the subsequent blockage of the canal. If the cover were designed to withstand greater loading, the cost would be significantly increased. If the cover were designed to be suitable for vehicular support, the cost would become prohibitive.

9. Therefore, on the basis of a comparative evaluation of the technical as well as the economic aspects of the canal and pipeline systems, the pipeline system was considered the better system to use.

Pipeline size

10. The selection of the optimum diameter of the pipeline depends on the choice of single or multiple lines to provide the design flow and the choice of an all-gravity or a pumped-flow system. The pipeline size and the selection of material are also interrelated.

11. The possibility of using a combination of multiple, smaller diameter pipelines with a series of pumping stations was compared with a single, larger diameter gravity flow pipeline. The use of multiple smaller diameter lines was considered because of the restriction on the maximum available size for steel pipe. It was determined, however, that the use of the multiple pipeline concept as shown in Fig. 3 would be less economical and inferior with regard to the overall operation and maintenance. The use of multiple lines would also increase the amount of time required for construction of the project which would be detrimental to the overall schedule. The larger diameter pipe system was therefore adopted.

12. A major factor contributing to the decision to use a gravity flow system is the requirement that the conveyance system should be as

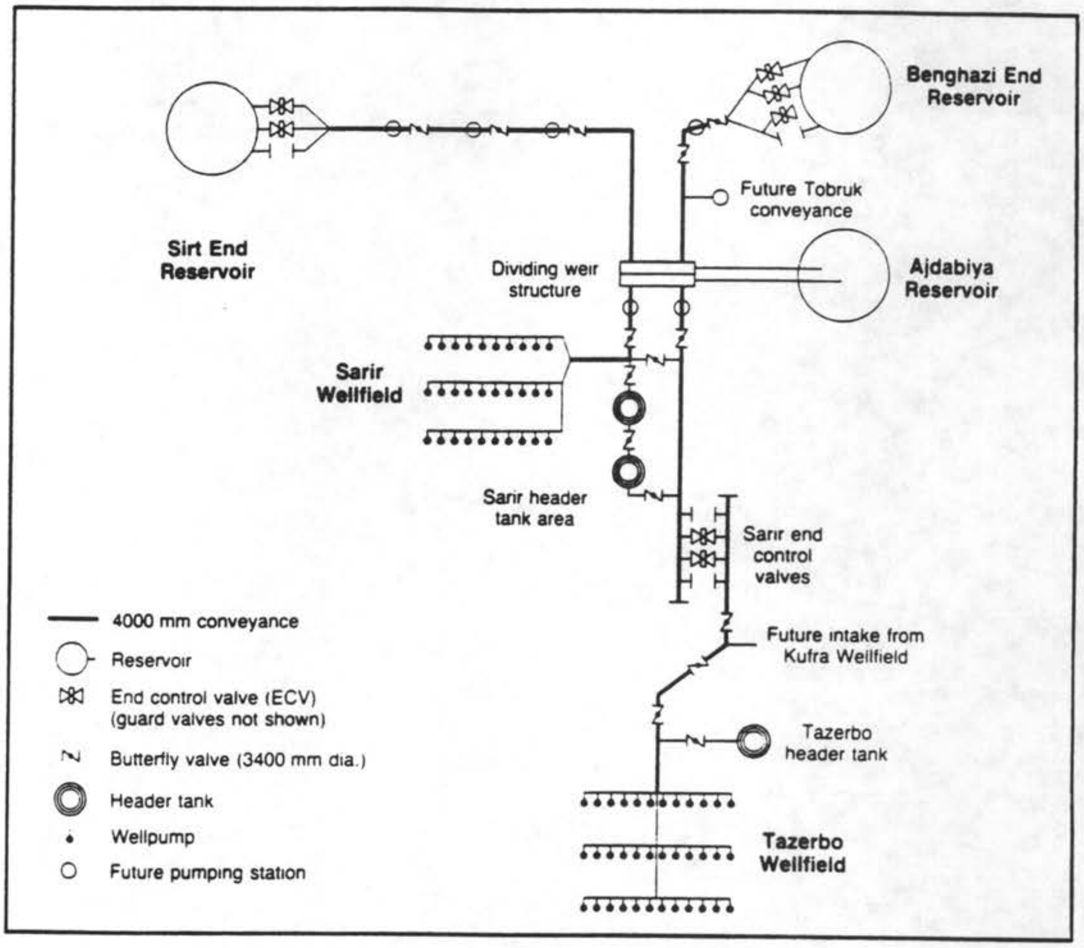


Fig. 2. Schematic
Phase I

simple as possible to operate and to maintain. The design also indicates that, while the initial investment cost for an all-gravity system and a low lift pumped system would be similar, the operating costs for the pumped system would be considerably greater.

13. It was therefore decided that the pipe should be sized to handle the initial system design flow rate of 2·0 MCMD by gravity, with the provision for a future flow to use intermediate pumping stations.

14. After it had been determined that the initial flow was to be achieved by an all-gravity system, it was established by hydraulic analysis that 4000 mm inside diameter pipe is required to convey this quantity of water. The only section of the system that is overdesigned for the gravity flow condition is from Tazerbo to Sarir, where the 4000 mm diameter pipe is capable of conveying more than 1·0 MCMD by gravity. It was determined, however, that this segment should also be 4000 mm because of the possibility of accommodating future flow from Tazerbo or Kufra.

Pipe material

15. Various pipe materials including steel, plastic and concrete have been evaluated for their suitability for the project.

16. The possible use of extruded plastic pipe (polyvinyl chloride, polyethylene and polypropylene) was ruled out because it is not available in sizes or pressure ratings that would be suitable for the main conveyance pipeline. The use of fibreglass reinforced plastic was also considered because it can be manufactured in diameters that would be suitable for the system. It was determined, however, that excessive wall thicknesses would be required for the design pressure ratings which would make the pipe as heavy as the required steel pipe. Fibreglass reinforced plastic has not been used in such lengths for a cross-country pipeline and none of the manufacturers contacted at that time could guarantee the satisfactory jointing of the pipe. A fibreglass pipeline system was also found to be more expensive than either a steel or concrete system. For these reasons, the use of fibreglass reinforced plastic was also ruled out.

17. Both steel and concrete pipelines were considered technically suitable for the project, although 4000 mm diameter steel pipe is not commercially available in large quantities. Concrete pipe could also be manufactured in local pipe plants specifically constructed for that purpose from locally available material, using a minimum of imported products.

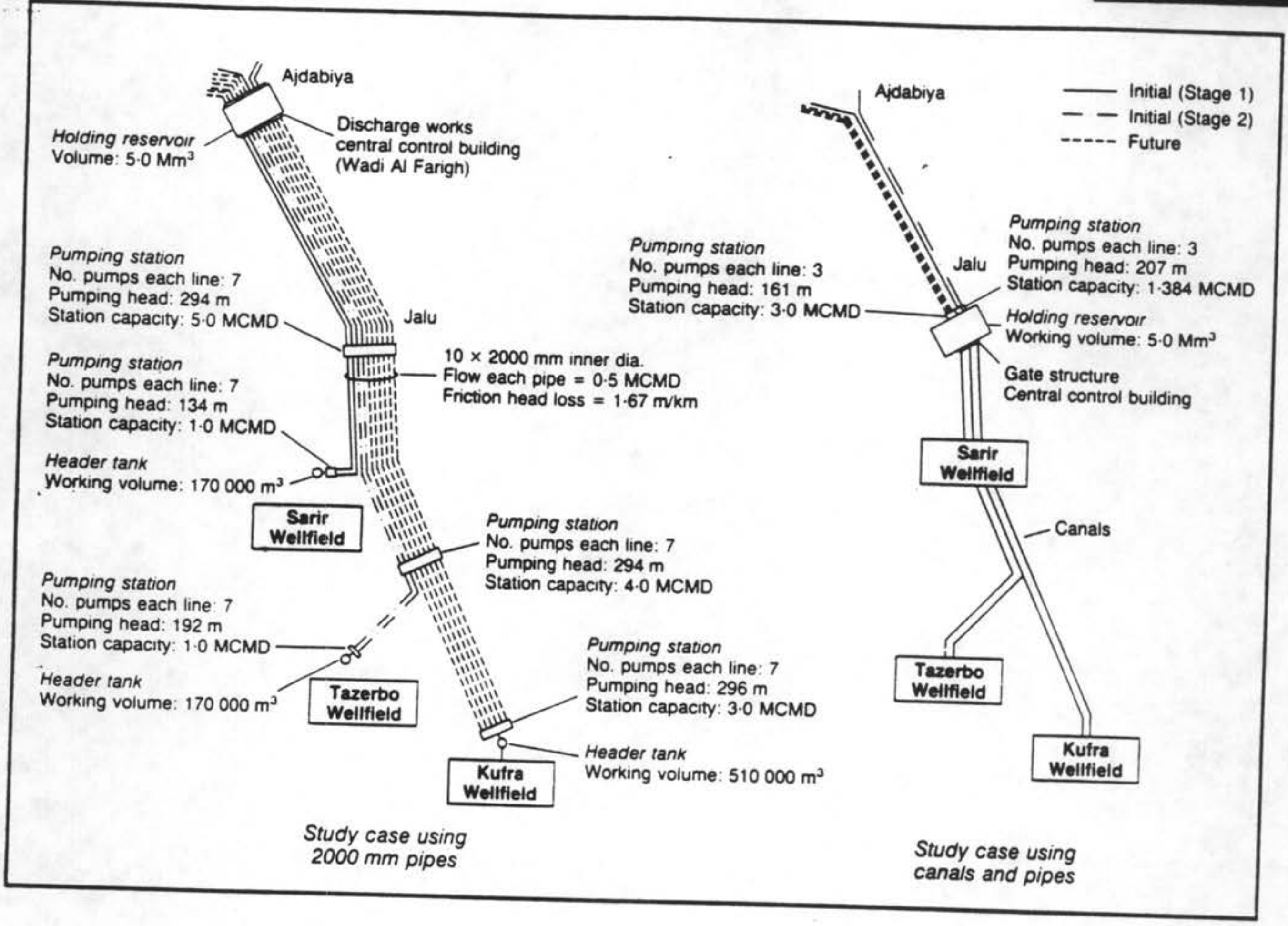


Fig. 3. Two typical optimization study cases

18. Prestressed concrete cylindrical pipe consists of a steel cylinder which is embedded in a concrete core, wrapped with high tensile steel wire and coated with a cement mortar. Steel bell and spigot joint rings are welded to the ends of the steel cylinder and embedded in the concrete core to provide jointing with the adjacent pipe sections. The steel cylinder prevents leaking of the pipe through cracks in the concrete; it contributes little to the strength of the pipe. The concrete core is cast on the inside and outside of the steel cylinder to a specified thickness. The prestressing wire is then continuously and circumferentially wrapped at a predetermined tension and spacing around the outside surface of the concrete core. This induces a compressive stress in the concrete core that enables it to resist the tensile forces caused by internal and external loads. The thickness of the core together with the prestressing tension and spacing of the wire are determined to provide the required pressure rating for the pipe section. The cement mortar coating is added to protect the prestressing wire.

Installation mode

19. An investigation of installation modes, buried or above ground, was conducted to determine the most feasible and economic method, recognizing that the excavation and backfilling of a trench would represent a significant portion of the cost of pipe installation if a buried mode were selected for this project. It was determined in this study that an above-ground installation on a continuous concrete footing for the large diameter concrete pipe would be more expensive than a buried pipe, even where excavation of rock was necessary. The other disadvantages of an above-ground installation include the exposure to a larger temperature range and the resultant thermal expansion, the greater susceptibility of an exposed pipe to vandalism, sabotage and accidents, and the barrier that such a pipeline would create for road and railroad crossings and future developments. It was therefore determined that a buried mode of installation was more desirable.

Hydraulic parameters

20. Fundamental to a hydraulics design is the formula for friction loss and the value to be used for pipe roughness (*ks*).

21. Initially, Wood's[1] explicit equations were adopted in the conceptual design for evaluating friction factor in the Darcy–

Weisbach equation. With the progress of design, these were replaced by Colebrook–White's[2] implicit equation to determine the friction factor iteratively for greater accuracy.

22. For pipe roughness, a desk study was instigated through the British Hydromechanics Research Association[3] for PCCP. This study led to the adoption of the following values of *ks*

0·27 mm:	maximum value used for rough pipe
0·15 mm:	expected value used for optimization studies
0·10 mm:	value used for transient analyses.

23. The value of $ks = 0{\cdot}27$ mm (0·00075 ft) was derived from US sources. In the context of pipeline sensitivity, even the viscosity has its effect on the hydraulic grade line (HGL), particularly at the end of a 392 km pipeline, in spite of the fact that it is 4000 mm in diameter. The viscosity of water depends on the water temperature. Water is pumped out of the ground at an average temperature of 30°C and is recorded as maintaining approximately that temperature in the buried pipeline until it is exposed to the atmosphere at Ajdabiya Reservoir, in which the temperature can range between an estimated 15°C and 35°C, depending on season and retention time.

24. It is worth noting here that there are two different schools of thought on the change of pipe roughness with time: firstly, that *ks* starts at 0·15 mm and increases to 0·27 mm (and beyond) as any flow erosion or aggressive attack on the surface occurs, and as any sediment, bacterial slimes and other biological growths build up; secondly, that *ks* is anywhere between 0·15 mm and 0·27 mm, depending on workmanship (albeit closer to 0·15 mm) and that it keeps the value throughout its life on the basis that any surface deposit or roughening has negligible effect in a 4000 mm pipe. This second school also postulates that any bacterial slime on the surface may even be smoother than the pipe's concrete finish.

25. Taking into account all of the above leads to the adoption of the following, using the 'worst' combination of factors for the particular case under consideration and the Colebrook–White equation for the Darcy–Weisbach friction factor.

(*a*) Steady-state friction loss calculations: use higher roughness $ks = 0{\cdot}27$ mm at a temperature of 20°C and kinematic viscosity $= 1{\cdot}14\ \text{mm}^2/\text{s}$.

(*b*) Transient calculations: use lower roughness $ks = 0{\cdot}1$ mm at a temperature of 35°C and a kinematic viscosity of $0{\cdot}897\ \text{mm}^2/\text{s}$.

26. Generally, for straight long pipelines the friction losses far exceed the minor losses, which are usually discounted. In the case of the GMRP, owing to very long pipeline lengths, the minor losses are not of great significance in absolute terms. However, the order of magnitude is established by an evaluation of minor losses over a 380 km long stretch, with the cumulative effect of manholes (4000 mm × 4000 mm × 600 mm tees) every 615 m, pipe reducers, bends and valves. This resulted in the following[4]

$$\text{minor losses} = 0{\cdot}049\ \frac{V^2}{2g}\ \text{m/km of pipeline}$$

For example, a flow of 1·0 MCMD in a 4000 mm pipe, with an average velocity = 0·921 m/s, produces a head loss = 0·128 (friction) + 0·002 (minor) = 0·130 m/km; the minor loss contribution is about 1·6% and is therefore considered as small.

27. The coastal pipelines supply the water partly to end reservoirs but mainly to intermediate user-dedicated branches or 'turnouts'. For strategic reasons, the system was designed to be able to convey all the water intended for each pipeline to its respective end reservoir as the detailed allocation of the water to intermediate users had not been finalized at that time. This permitted flexibility in both the detailed decisions and the timing of any decision on water allocation.

28. The adoption of PCCP designed to AWWA C301[5] introduces a pipe with standard pressure rating increments of 2 bar. Within the AWWA code, a transient overpressure is allowed of up to 40% above the nominal or sustained pressure bar rating (i.e. a nominal 10 bar pipe is permitted to have a surge-related overpressure of up to 14 bar). However, as can be seen from Table 1, the pipe lengths can be up to 392 km, with correspondingly long pressure [illegible] durations. This gives rise to the question: '[illegible]n is a surge not a surge but a sustained pressure?'. In some locations, the overpressure could be sustained for up to 20 minutes. The AWWA code refers only to 'short duration'. This, of course, is unqualified as it is relative to the system in question. For a pipeline system approaching 400 km, with a 50 year design life, even one hour or one day, is of relatively short duration. On account of the level of 'uncertainty' on this subject, it was decided to adopt two limits for the hydraulics design, a 20% overpressure for transients/surges generated under normal circumstances or those that could happen after, say, one level of maloperation; while in the case of extreme events, following, say, two levels of maloperation or a burst pipe, the transients then generated by control devices were allowed to rise to up to 40% overpressure.

29. Finally, a state-of-the-art transient analysis computing package known as GMRPFLO, developed by W. S. Atkins Engineering Sciences especially for this project,[6] is discussed in the next section.

Description and computing capability of GMRPFLO

30. In general, pipeline and piping systems are designed to maintain and operate under full pipe conditions. However, most systems will exhibit partially full to full behaviour under transient conditions or during system start-up (filling) and shut-down (emptying).

31. The GMRPFLO program can analyse a dual regime system—i.e. full and partially full reaches within the same system model—unlike single mode programs where two or three separate analyses are required, with simplifying assumptions being made to transfer between the modes and program restarts.

32. Three separate routines are employed in the program suite

(*a*) data pre-processor (DPP)
(*b*) computational program (CP)
(*c*) results post-processor (RPP).

The DPP allows the creation of a 'configution' file as a stand alone item, with all its components defined in essence: e.g. reservoirs, tanks, air vessels, pumps, valves, control switches, pipe parameters, etc. After the 'configuration' file has been established, a 'run control' file which defines the particular actions to be run, is attached. This contains the variable control data, e.g. simulation time, tolerances, valve closure time, reservoir and tank levels, number of pumps in operation, etc. In this way, the configuration file remains unchanged while as many run control files as necessary can be added.

33. The configuration and run control files together define the total system with control parameters, allowing the CP to perform the theoretical calculations and to analyse the regimes as they may occur, such as

(*a*) zero flow (including defining surface levels of water retained in pipeline troughs or behind closed valves)
(*b*) steady flow
(*c*) transient full pipe flow
(*d*) unsteady subcritical and supercritical open channel flow and moving boundaries
(*e*) full pipe/open channel moving boundaries
(*f*) air pressures above open channel flow.

34. The results are viewed by way of the RPP which allows both graphical and print formats. This includes overall system or specific boundary results, such as

(*a*) system profiles with pressure envelopes
(*b*) pressure/time histories, as a snapshot in time or as a moving video effect
(*c*) flow/time histories
(*d*) tank level variations
(*e*) air pressure traces
(*f*) air flow through air valves.

Examples of the program output will be used in subsequent sections.

35. Discussions follow on each segment of the system, beginning with the one that calls for the particular use of this 'state-of-the-art' software.

Sarir pipeline

36. The Sarir pipeline conveys water from Sarir wellfield (126 pumped wells over an area of 20 km × 50 km, with a design output of 1·0 MCMD) to Ajdabiya Reservoir. From Figs 1 and 2, it is seen that this pipeline runs parallel to part of the Tazerbo pipeline, which has a similar duty but also has inline pressure reducing/flow control valves just upstream of Sarir. Essentially, the two pipelines are operated independently but can be linked hydraulically through the Sarir header tanks. The Sarir pipeline is upstream controlled, with flow regulated by the number of wellpumps in operation. This is more economical than downstream control which would require more expensive higher pressure rated pipe. A consequence of upstream control is a 'partially full' mode of operation for parts of the pipeline. In a 4000 mm diameter pipe, part-full flow resembles a river, from which the name 'Great Man-Made River Project' was derived. However, unlike a river (continuous open channel flow), other parts of the Sarir pipeline flow full and under pressure. Using the software described earlier, the characteristics of the system under various operating conditions are being studied so that appropriate operating guidelines can be developed.

37. The pressure rating for the upstream controlled Sarir pipeline is set by the maximum operating hydraulic grade line (HGL). The initial design flow is 1·0 MCMD, but with the expected development of a future wellfield at Kufra and connection of a Kufra link with 1·68 MCMD design flow (to the Tazerbo pipeline some distance upstream of Sarir), the future carrying capacity requirement of the Sarir and Tazerbo pipelines, downstream of Sarir header tanks, each becomes 1·84 MCMD. This requires booster pumping near the downstream end as the gravity head is sufficient for only about 1·1 MCMD continuous flow in each pipeline. After technical and economic comparison studies, an inline pumping station (as opposed to a break pressure pumping station with fixed speed pumps, forebay tanks and inlet control valves) was adopted, with a HGL as shown in Fig. 4. The future increase in operating HGL just downstream of the pumping station has been taken into account in the selection of pipe pressure ratings for that locality. This demonstrates the need to consider the full scope of the project (potential or otherwise) whenever possible, so as not to impose unnecessary limitations on the future economic development of the system.

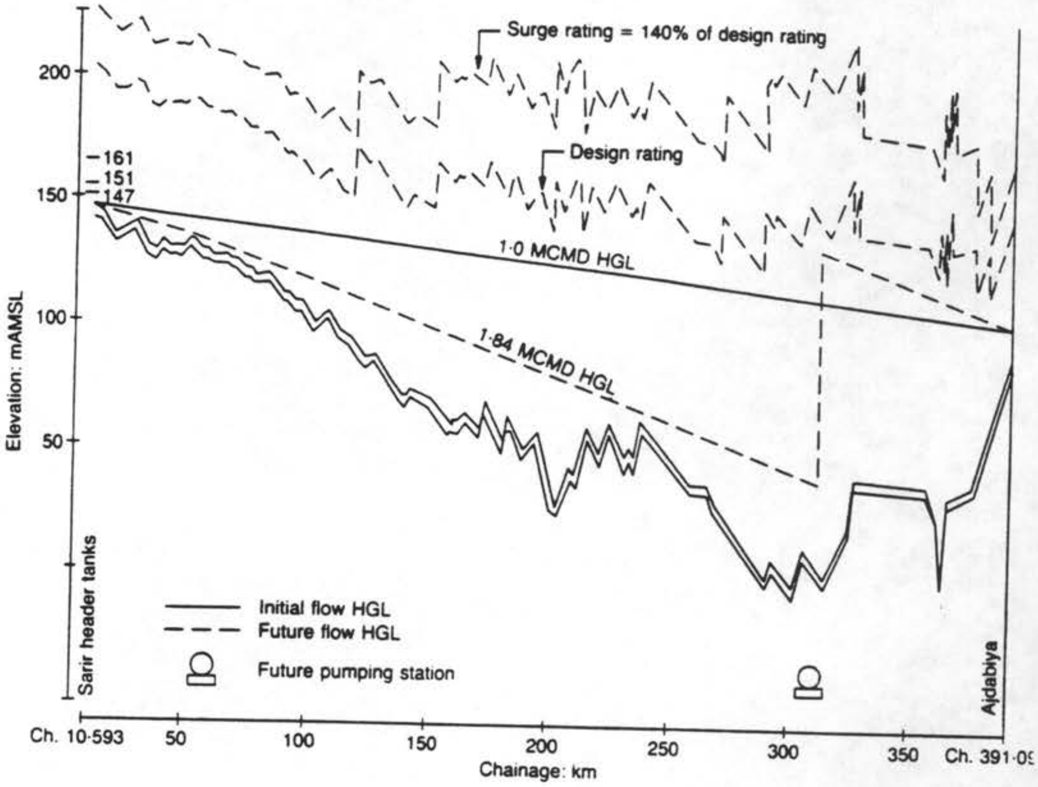


Fig. 4. Sarir pipeline HGLs

38. In the hydraulics design of the partially full pipeline, careful attention was also paid to the effects of hydraulic jumps, air entrainment, air binding and air pocket movement in the choice of pipe slopes and air valve installations.

39. The criteria for the filling and emptying rates of the pipeline are

(*a*) the rate at which air can be expelled/drawn in safely through the air valves (this is an economic balance between the time taken to fill/empty and the number of valves to be provided

(*b*) maximum velocity at upstream inlet point and all other intermediate steep slopes to eliminate or reduce risks of erosion of the internal pipe wall

Based on the pipes running full of water, the velocities in the range 0·05–0·15 m/s were adopted. For the 4000 mm main conveyance lines at 1 MCMD, this equated to 5–15% of design flow rate.

40. Hydraulic jumps will occur as a result of changes in pipe slope as the water depth adjusts from one level to the next. In most of the pipelines, designed to be kept full and pressurized (using flow control valves), these jumps will occur only during filling. However, the upstream end of the Sarir line and of the Sarir–Ajdabiya section of the Tazerbo line are different because partially full flow is anticipated to occur under various flow conditions (Figs 5 and 6).

41. Hydraulic jumps, by their very nature, exert hydrodynamic forces on the pipe and entrain air from the upstream air space where the line has not yet been filled. This can then 'pushed' by the jump into downstream sectio dependent on the flow and on the pipe slope a the downstream end of the jump. For flatter downslopes or higher flows, the downward drag force on the air bubbles will overcome th upward buoyancy force, with the result that th air is pushed downstream. For steeper slopes lower flows, the bubbles will move upstream and back to the original air space.

42. This entrained air may then accumulate in the downstream sections, and would both form air pockets along the pipe soffit and cause air 'binding' before it reached the high points, where it would be vented from the air valves. The effect of this trapped pocket of air is to reduce the flow area, thereby leading to an increased head loss. This can accumulate to a significant amount and the air pocket can become quite long. Therefore, it cannot be regarded as just a local 'bottleneck'; the carrying capacity of the line can be seriously affected.

43. Between the limits for air entrainment is a 'slug flow' zone where an air pocket can be moved upstream: this is known as 'blowback'. As it moves up a rising grade, it can accelerate and attain a high velocity. Its arrival at the high point, followed by the water that closes the gap, can generate a significant transient water column recombination forces.

44. All the above factors have been considered in the design of the system and its appurtenances. The pipe slopes have been set appropriately to reduce the occurrence of blowback and the onerous types of hydraulic jump.

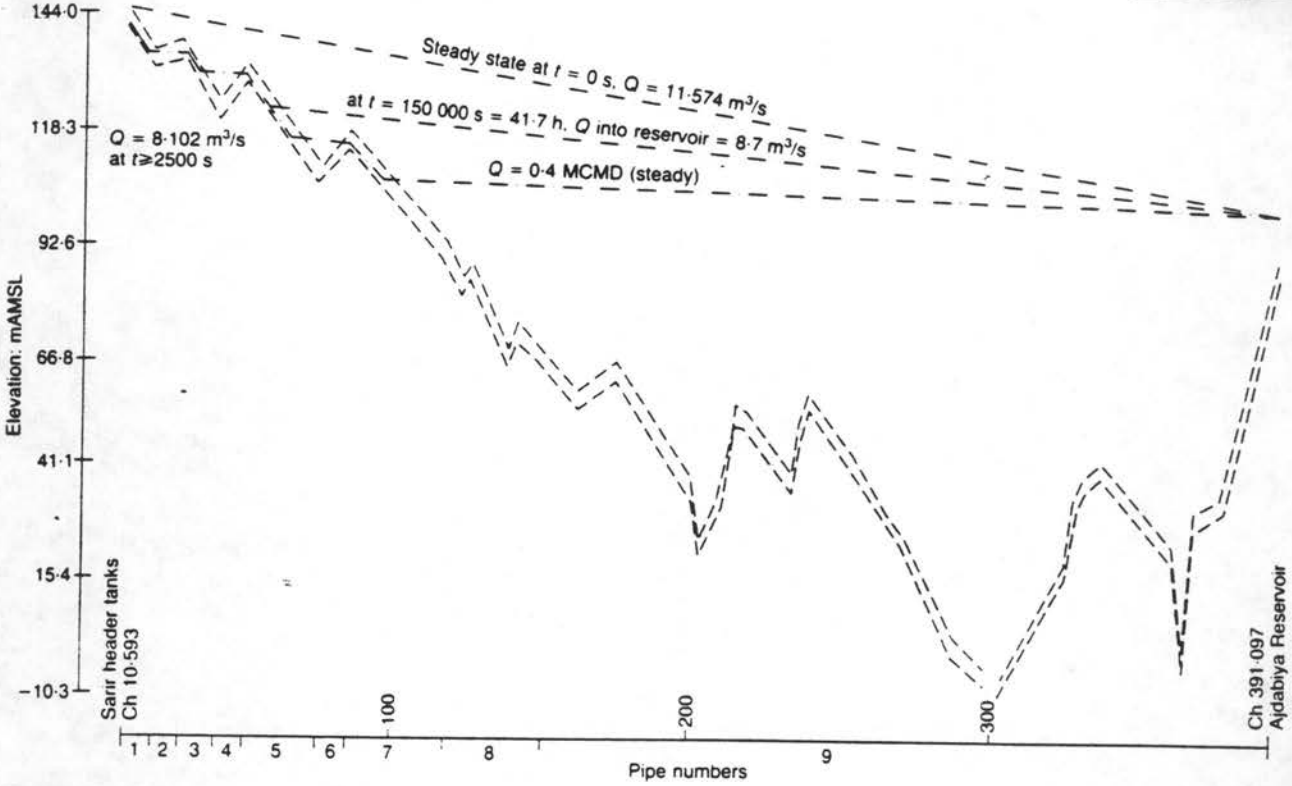
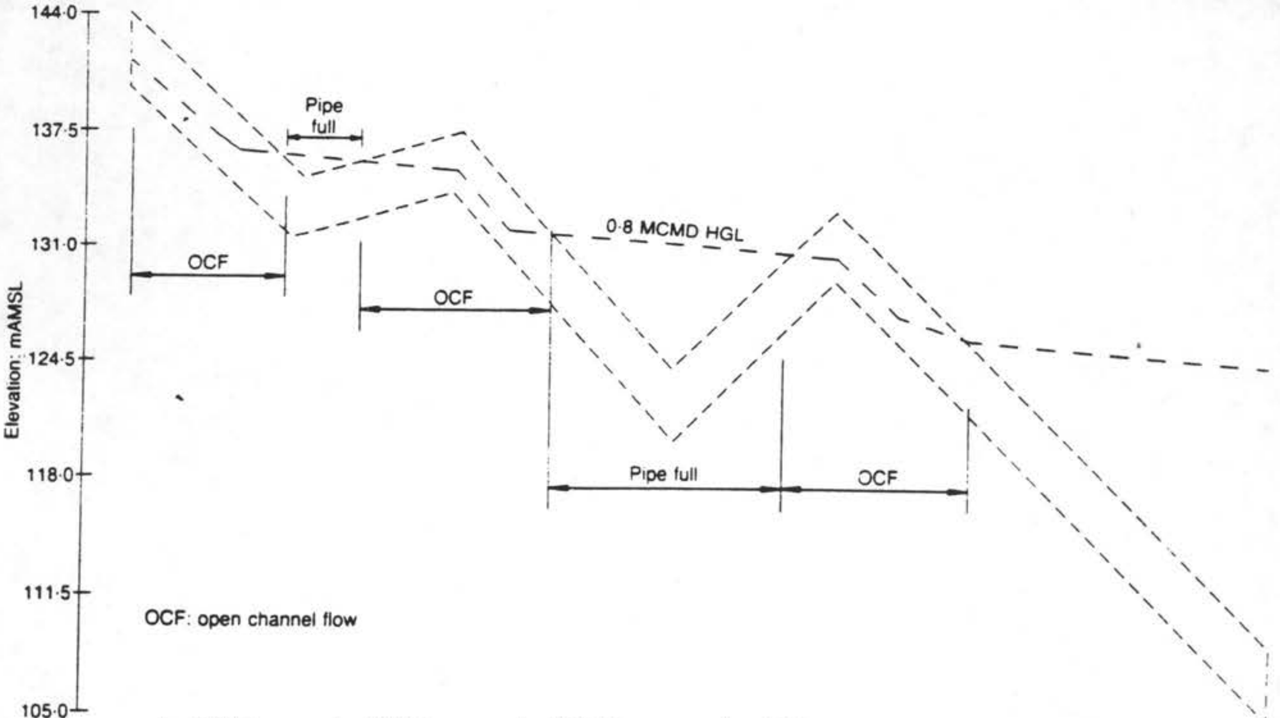


Fig. 5. Sarir pipeline part-full HGLs

Fig. 6. Sarir pipeline. exploded view of part-full reach



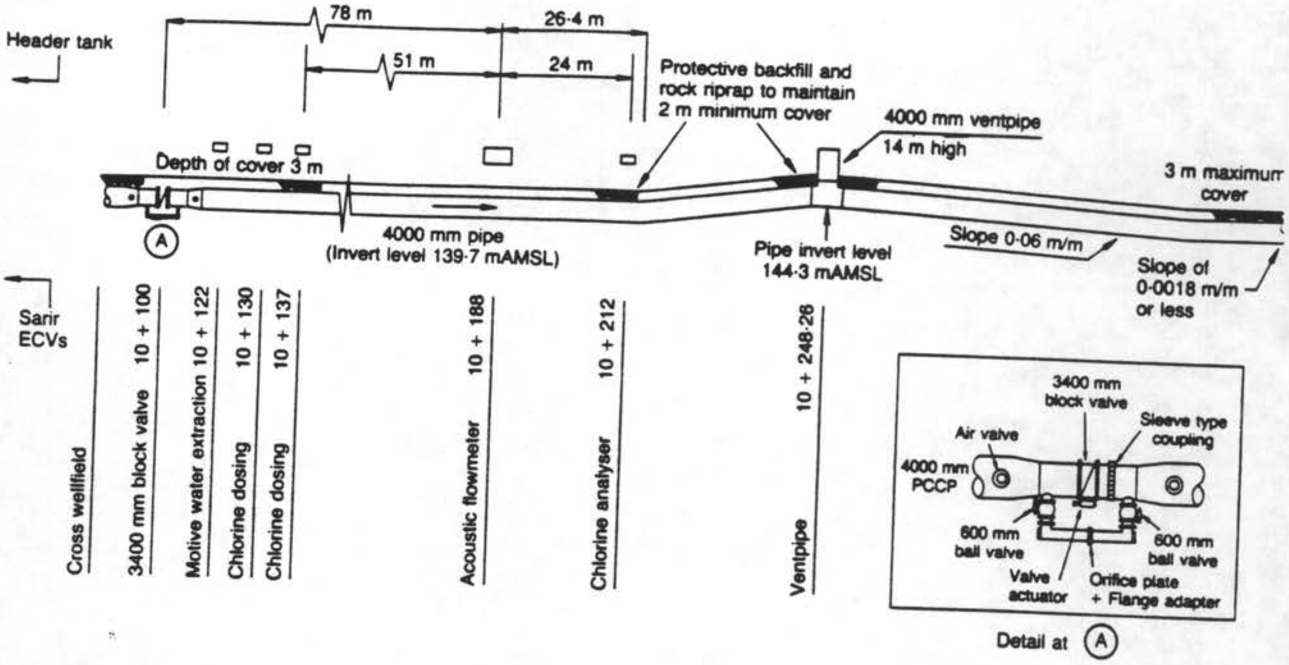


Fig. 7. Sarir header tank area, location of ventpipe

Air valves are located strategically, not only at high points but at a maximum spacing of 615 m. In the part-full region, the number of air valves at any location has been doubled to provide standby capacity in case any one air valve fails.

45. To allow for slow and steady evacuation of the air, pipeline filling is controlled by restricting the number of wellpumps in operation. This is to keep the velocity below 0·15 m/s (equivalent to 15% of the 1·0 MCMD design flow).

46. If the pipeline is shut down after filling and the block valves are closed to maintain full pipe upstream, then refilling is controlled by feeding water through a bypass on the block valve. The bypass arrangement is shown in the inset in Fig. 7. This will also allow the pressure across the valve to be equalized or to be reduced significantly before the valve is opened, thus reducing the wear and tear on the block valve (butterfly type valve is used). An orifice plate is used for flow control through the bypass. A 'full port' ball valve is located on either end to isolate the bypass for repair or maintenance. The bypass piping and isolating ball valves are sized to pass 15% of the design flow at a maximum velocity of 6 m/s, based on the nominal diameter of the bypass. The reduced flow rate is to prevent damage to the air/vacuum valves caused by rapid closure. The orifice plate opening is sized to restrict bypass flow to 6 m/s at maximum differential pressure head.

47. It takes about 25 days to fill the empty pipeline through block valve bypasses. The effects of air valves shutting and the interaction of the transients during filling and system start-up have been examined, and at the most critical location, which is at the upstream end, an air valve has been replaced by a ventpipe to eliminate the most onerous transient pressures and to satisfy the major air inflow and outflow requirements on draining and filling. The location of this ventpipe also coincides with the most energetic hydraulic jump. A 'hump' in both the Sarir and Tazerbo pipelines was created at this location by altering the pipe invert levels as shown in Fig. 7. This provides a degree of back pressure on the end control valves at the downstream end of the Tazerbo pipeline, to assist in the alleviation of cavitation conditions on those valves. The raising of the invert elevation of the pipe at this ventpipe is as a result of an economic balance between the hump and lowering the elevation of the valves themselves. In addition to the back pressure conditions, it also provides a flooded pipe section for locating the acoustic flowmeter, chlorination injection/ extraction facilities and rubber-seated butterfly valves as depicted in Fig. 7.

48. As an example of a potential operational problem, the system response time between Sarir Wellfield and Ajdabiya Reservoir is in the order of 48 hours (see Fig. 8). This time factor alone identifies one of the key hydraulics roles of the intermediate reservoir at Ajdabiya. Its main hydraulics aspects are as follows.

(*a*) It provides a pressure and hydraulic break between the upstream Sarir and Tazerbo pipelines and the downstream Sirt and Benghazi pipelines. This helps to limit the maximum possible pressures in the pipelines.

(*b*) It provides buffer storage during transitions from one end user demand level to another. Fluctuations should be dealt with by the diurnal storage of end users. Added

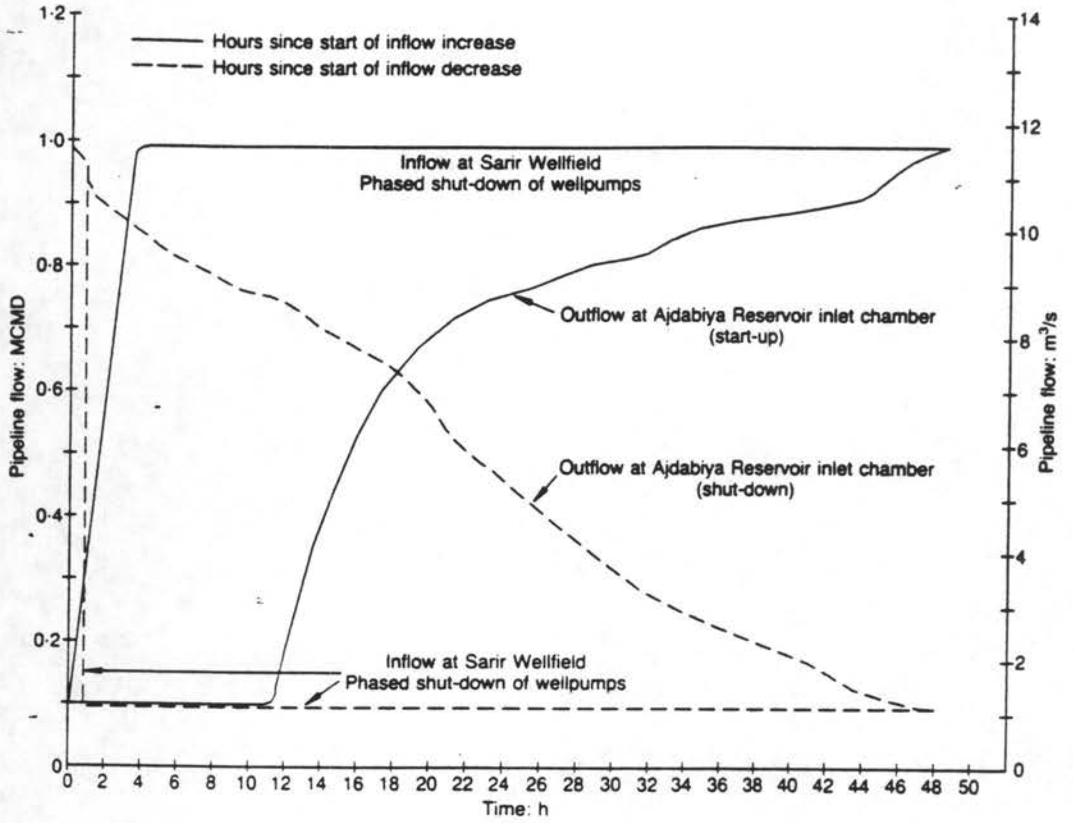


Fig. 8. Sarir pipeline response times

to the storage potential of the part-full Sarir line, this storage allows time for the wellfield outputs to be adjusted to match demand changes. Ajdabiya Reservoir volume also caters for the draindown of the two pipelines between Sarir and Ajdabiya (involving about 2·0 million m^3), as there is no valve to stop these pipelines from draining following the shutting down of the wellfield.

(*c*) It enables mixing of the different wellfield waters (Sarir, Tazerbo and the future Kufra) to provide the same water quality to the variety of end users.

Operations and controls

49. A communications and control system is provided to facilitate integrated control from wellfield production wells to end control valve (ECV) operation. Local control rooms at Tazerbo, Sarir, Ajdabiya and Sirt are linked by a telecommunications system to a master control centre at Ajdabiya (duplicated at Benghazi Headquarters). This Permanent Communication and Control System (PCCS) network is shown in Fig. 9. The system has also been designed to remain operational even without this network. This is achieved by the monitoring of the change in water level at the local buffer storages. Each site has a target level to be maintained in its tank or reservoir and takes local action as appropriate, e.g. start/stop a wellpump or adjust control valving.

50. The fundamental philosophies used to develop the operating and control procedures are simply to

(*a*) minimize operator intervention
(*b*) ensure continuity of supply
(*c*) minimize operating costs.

51. The aspects that these philosophies lead on to include the following

(*a*) local control systems to do as much of the 'control' as is practical
(*b*) provision of back-up facilities for key components, e.g. PCCS, wellpumps, control valves, etc.
(*c*) preventive maintenance.

52. The operational control of the SSTB entails the following procedure.

(*a*) Ajdabiya Control Centre receives forecast demand from the end users (turnouts). The Ajdabiya Reservoir is maintained at a target level within a specified set of operational requirements/constraints—such as the midpoint level. This is maintained to balance inflows and outflows with minor fluctuations accommodated within its storage capacity. Additional storage is available in the utilization reservoirs for the individual agricultural and municipal water supply projects.
(*b*) Ajdabiya Control Centre informs Sarir Control Room of the total demand. Sarir splits the demand between the wellfields (Sarir and Tazerbo) on the basis of well

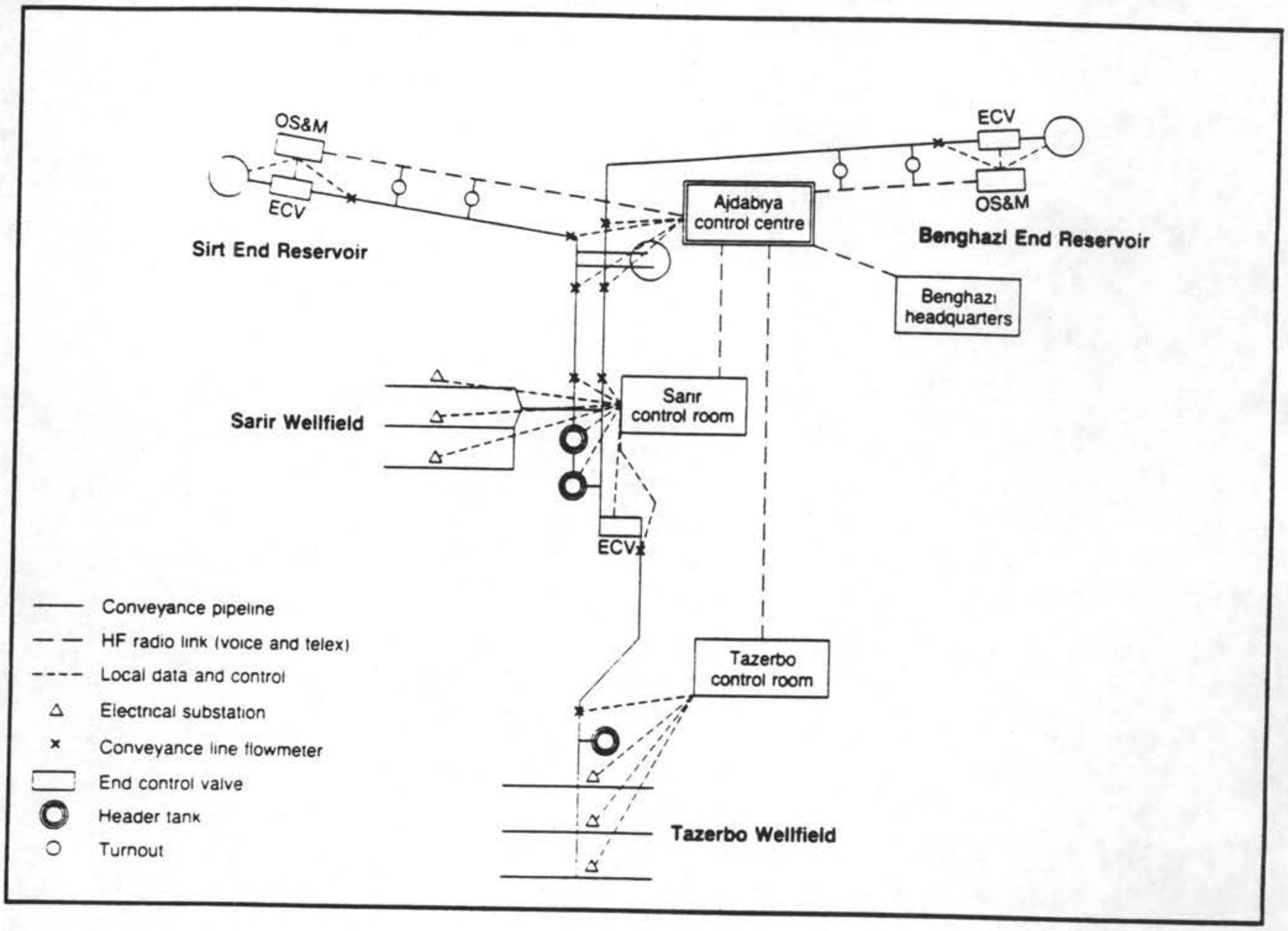


Fig. 9. Permanent Communication and Control System (PCCS)

availability, water quality, operational factors, maintenance schedule, and data on well operating costs. The Sarir ECVs are set and Tazerbo would be informed of its required production. Each wellfield control room operates its own plant with advice-instruction from Ajdabiya.

(*c*) As experience is gained, the operating rules can be changed to cope with deviations from steady flow conditions and can then be incorporated into the PCCS computer software.

53. To illustrate the system's ability to operate subsequent to a loss of communication, a description follows of the Tazerbo line which is end controlled at the Sarir ECVs (Figs 10 and 11). The operating sequence of this portion of the system is based on the detection of a change in water level in the header tank at Tazerbo. Therefore, the Sarir control room can adjust the Sarir ECVs to obtain the required flow, while, independently, the Tazerbo control room can physically see (as well as electronically monitor) the change in header tank level, thereby to instigate action in the wellfield to restore the header level to its target. It is this target level that is the important factor and that, in this particular case, has been chosen as 278 m AMSL, midway between the 273–283 m AMSL range (TWL = 283 m AMSL). This gives the maximum fluctuation of 5 m water level either side of the target level before overflow or entering into the 4 m 'dead band' at the bottom of the tank; this band is from 273 m to 269 m AMSL. With a tank diameter of 125·2 m, the 5 m fluctuation gives a volume of 61 500 m^3, which equates to a time within which the Tazerbo Control Room must take effective action and is dependent on the rate of change in demand. This period of time also makes allowance for the switching on or off of wellpumps in orderly sequence and for the well output change to be reflected in flow past the header tank: e.g. in the case of a change of 0·5 MCMD (say, from a flow of 0·4–0·9 MCMD or vice versa) the time would be of the order of three hours. The wellpumps would then be switched on at gradual intervals, avoiding unnecessary surge loadings on the electrical or hydraulics system. A timespan of this magnitude (i.e. hours) allows for the mobilization of a field crew for manual wellpump start-up, should the wellfield control system be inoperative.

54. As the intention is to operate the system initially on a manual basis (i.e. operator controlled and not automatic), with the PCCS intervening only when corrective action has not been taken by the operator, then the 5 m fluctuation will actually be reduced to allow for,

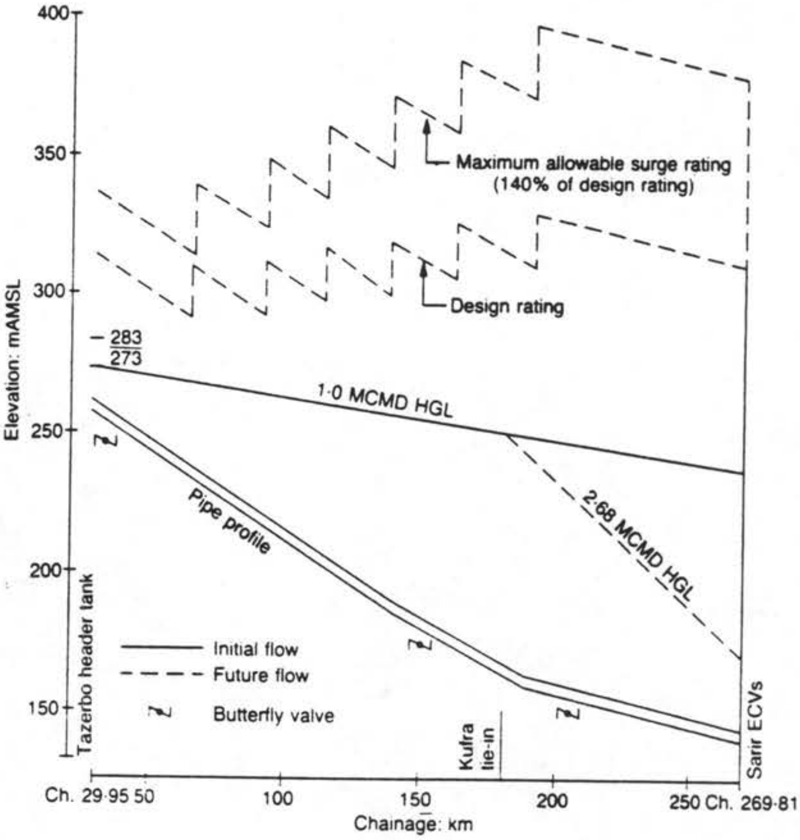


Fig. 10. Tazerbo pipeline HGLs

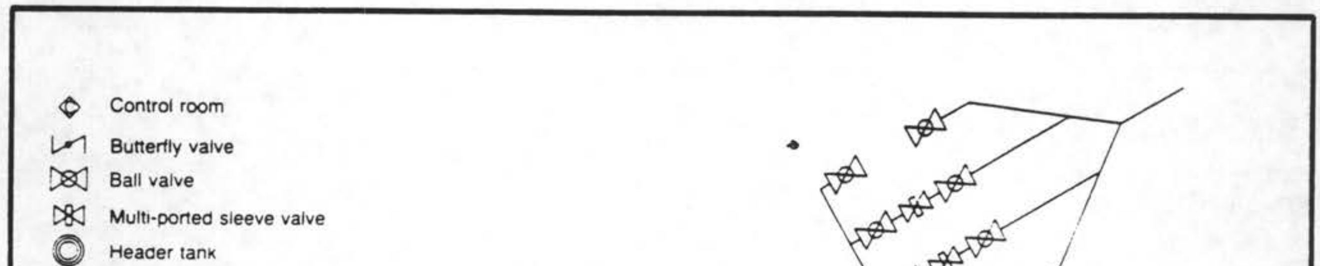


Fig. 11. Tazerbo subsystem schematic

say, a 0·5–1·0 m level change to install the PCCS pre-alarms and the automatic 'trips'.

55. The purpose of the 4 m dead band referred to earlier is to allow extra time in order to avoid the occurrence of the draindown situation. While tank overflow is undoubtedly safe (as drainage facilities have been provided), although obviously a waste of water, the question of uncontrolled draindown moves into an undesirable zone. Unlike the Sarir pipeline which has been designed to run in a partially full mode by limiting the pipe slopes in key regions and incorporating back-up air valves, this has not been the case on the Tazerbo line which, conversely, has been designed only as a full pipe system. To prevent the draindown situation from arising, the 4 m dead band provides a further margin of safety over the 5 m allowable fluctuation.

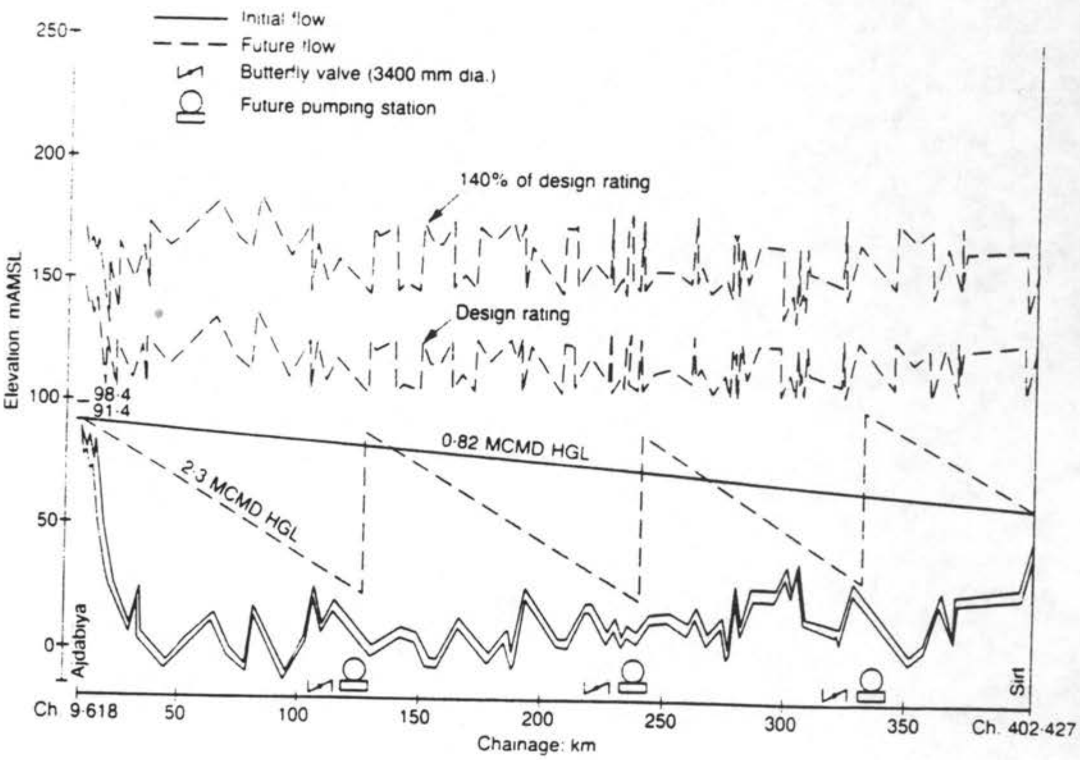
56. The above notwithstanding it had been anticipated that, in the future, when the operators have gained experience and knowledge of the system hydraulics and characteristics, the target level of 278 m AMSL could be lowered to 273 m AMSL to reduce the pumping head on the wellfield. This also reflected the thinking that after years of operation the demand should then be stable with little fluctuation. With the development of the engineering and the availability of final vendor data of the system components, it has been seen that the wellpumps are capable of overproducing and require throttling. Owing to the particular characteristics of the adopted wellpumps, the energy saved by lowering the header tank water level target from 278 m to 273 m AMSL is of the order of 5%; the issue, therefore, is no longer straightforward as it now becomes a balance between this cost and operational flexibility.

Sirt pipeline

57. The hydraulics aspects of the Sirt pipeline differ from the Sarir–Ajdabiya pipeline in that Sirt is a full pipe system with downstream valved control at Sirt End Reservoir. Fig. 12 shows the steady state HGLs for initial gravity design flow of 0·82 MCMD and a future pumped flow of up to 2·3 MCMD by use of three inline pumping stations. Intermediate inline valving is provided to allow isolation of sections for maintenance/repair while turnouts upstream remain in operation. These inline valves are 3400 mm diameter butterfly valves while the flow control valves at Sirt End Reservoir are 1600 mm diameter submerged discharge sleeve valves protected by 2200 mm butterfly valves. With the abundance of valving, all of which could be used (although some are intended only for emergencies) to stop the flow, the transient analysis has a major role to play in the design of the system.

58. In Fig. 13, the maximum pressure transient envelopes for four different valve operating conditions are shown. The characteristics of the inline butterfly valve are such that the main surge pressure is generated by final valve closure, i.e. during its movement from, say, 80 to 90° (0–10% open) of angular rotation. However, valve manufacturers are not as yet in a position to issue definitive characteristics in this zone and tend to provide curves of velocity head coefficient k against degrees of rotation.

Fig. 12. Sirt pipeline HGLs



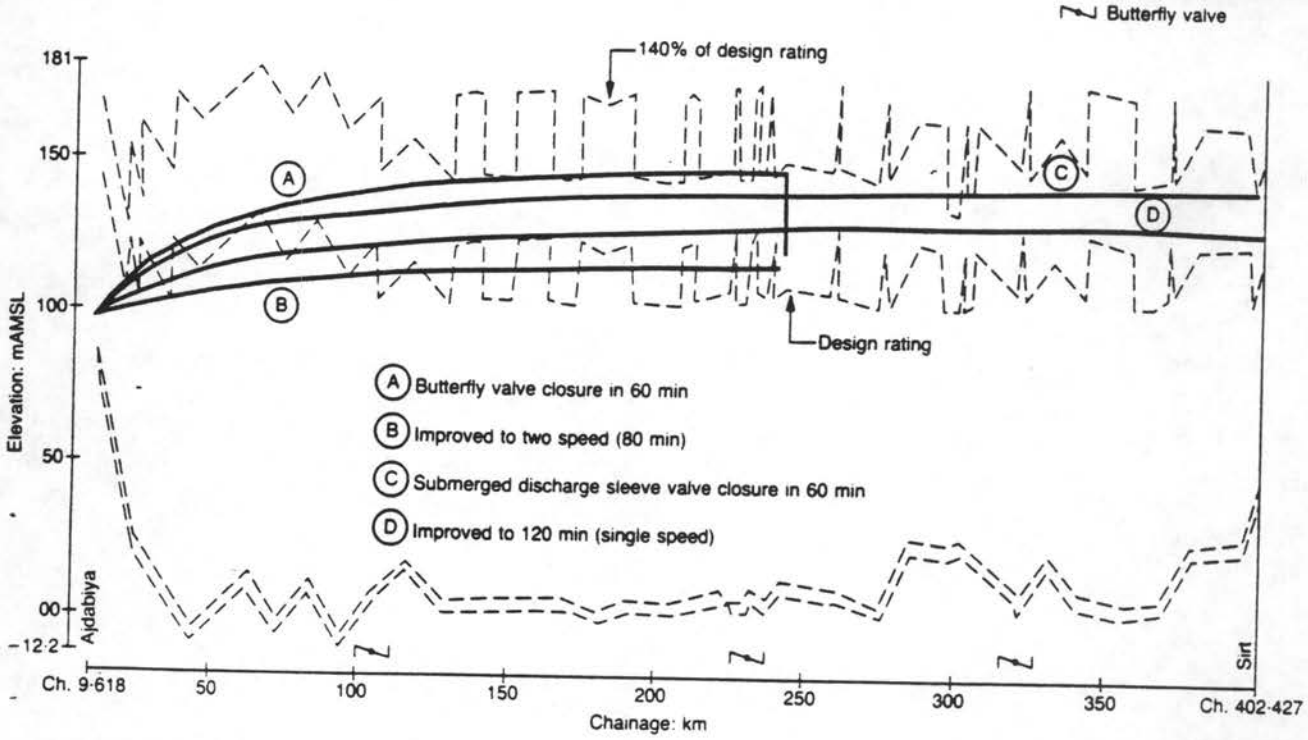


Fig. 13. Sirt pipeline, valve closure transients (design flow)

up to about 80° only. To model the valve closure in a computer program, estimates need to be made of *k* values between 80° and 90° (Fig. 14). Software programs generally calculate the transients by detecting a change in the characteristic slope, with interpolation between defined data points. Accordingly, definition of the points at 1° intervals from 80° would produce a different and less severe result than if points at just 5° intervals were used. Therefore, although the computer enables the examination of complicated and intricate systems, the more important need is to ensure that the system is being modelled correctly.

59. From the Sirt pipeline analyses, the valving has been specified to have long closure times of 60–90 min to reduce the transient effects on closure. Two-speed closure was also adopted in places (e.g. 0°–70° in 25 min, and 70°–90° in 55 min) where single speed movement would require too long a time, i.e. up to about 3 hours, and permit too great a quantity of water past the valve during the closure period than is considered acceptable (e.g. in the case of excessive water loss owing to overflow, pipe burst or other reason, with consequent damage and economic loss).

60. For the future pumped conditions, pressure transients caused by power failure have to be considered. Fig. 15 illustrates simultaneous failure at all three future pumping stations. The system is protected by air vessels strategically located along the pipeline, and a non-return

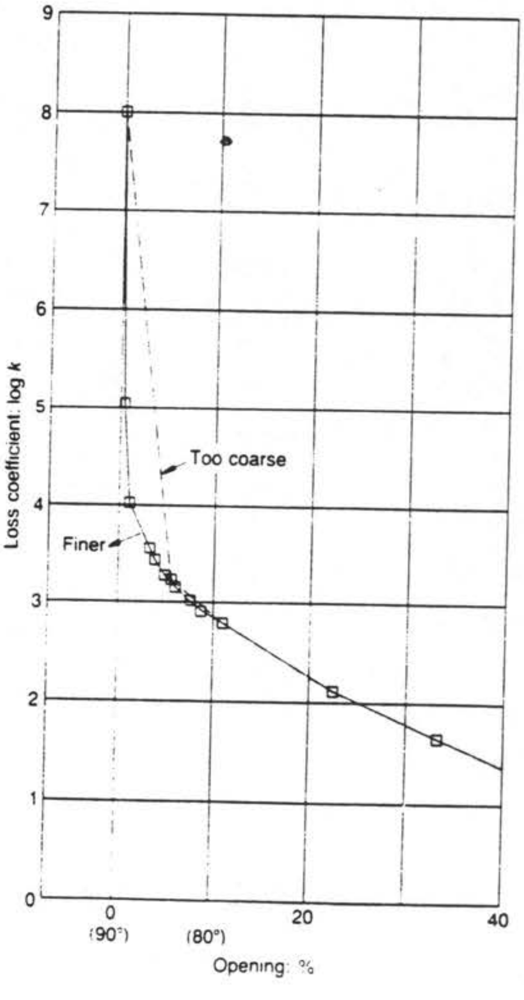


Fig. 14. Butterfly valve characteristics

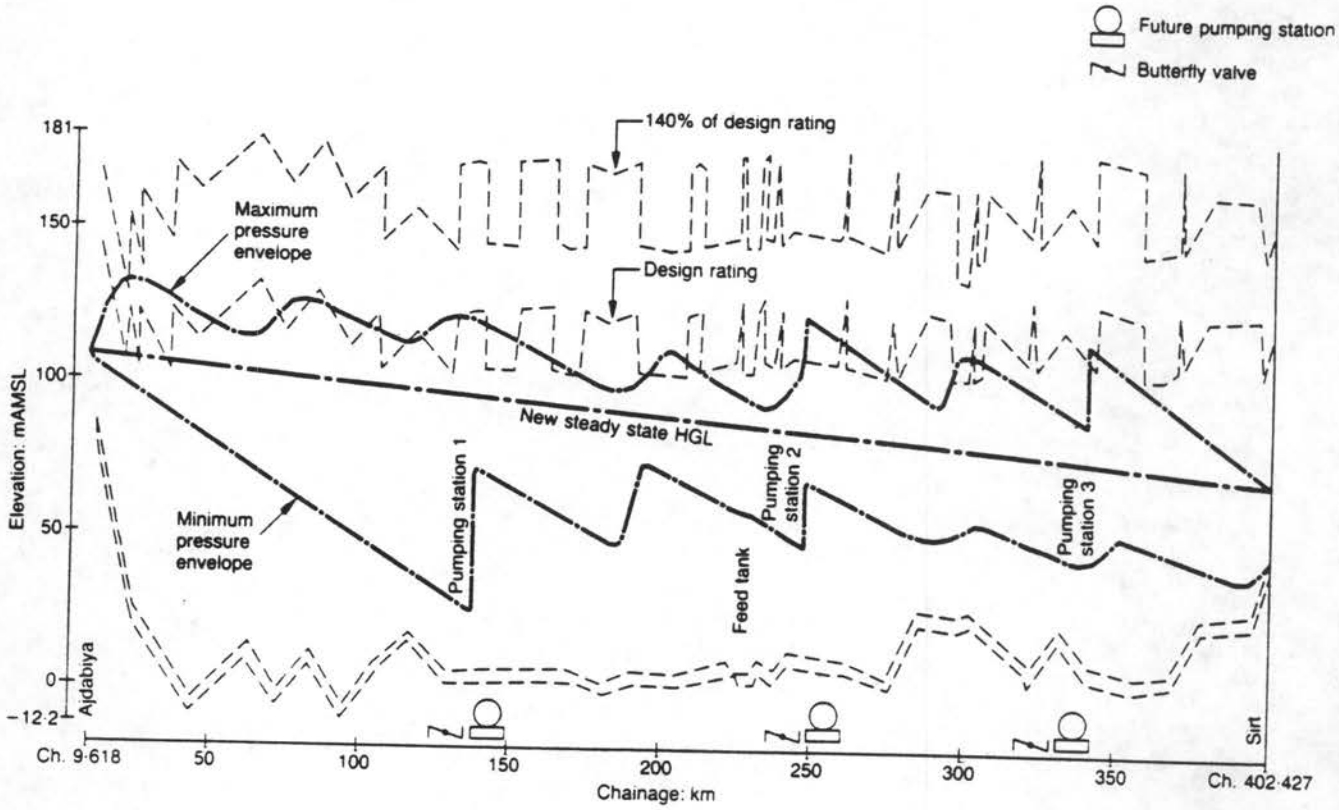


Fig. 15. Sirt pipeline, pumping station transients

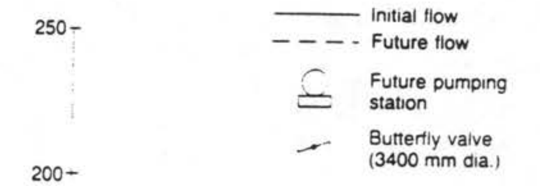


Fig. 16. Benghazi pipeline HGLs

valved bypass around each station allows gravity flow to continue. In fact, the transient analyses revealed that simultaneous power failure to all three pumping stations was not the worst case. Instead, the most onerous transient (high pressure on suction side and low pressure on discharge side of the station) was generated by the tripping of just two adjacent stations. The analysis of this future case was considered now in order to determine what provision, if any, needed to be made in the initial system to allow the future upgrading (e.g. 4000 mm × 4000 mm × 4000 mm tee pieces in certain locations to allow connections of the stations themselves and any surge protection devices.

Benghazi pipeline

61. The hydraulics aspects of the Benghazi pipeline are similar to those of the Sirt pipeline in that it is also a full pipe system with downstream valved control at Benghazi End Reservoir (BER). Fig. 16 shows the steady state HGLs for initial gravity design flow of 1·18 MCMD and a future pumped flow of up to 2·5 MCMD by use of an inline pumping station. Inline valves are 3400 mm diameter butterfly valves, while the flow control valves at BER are

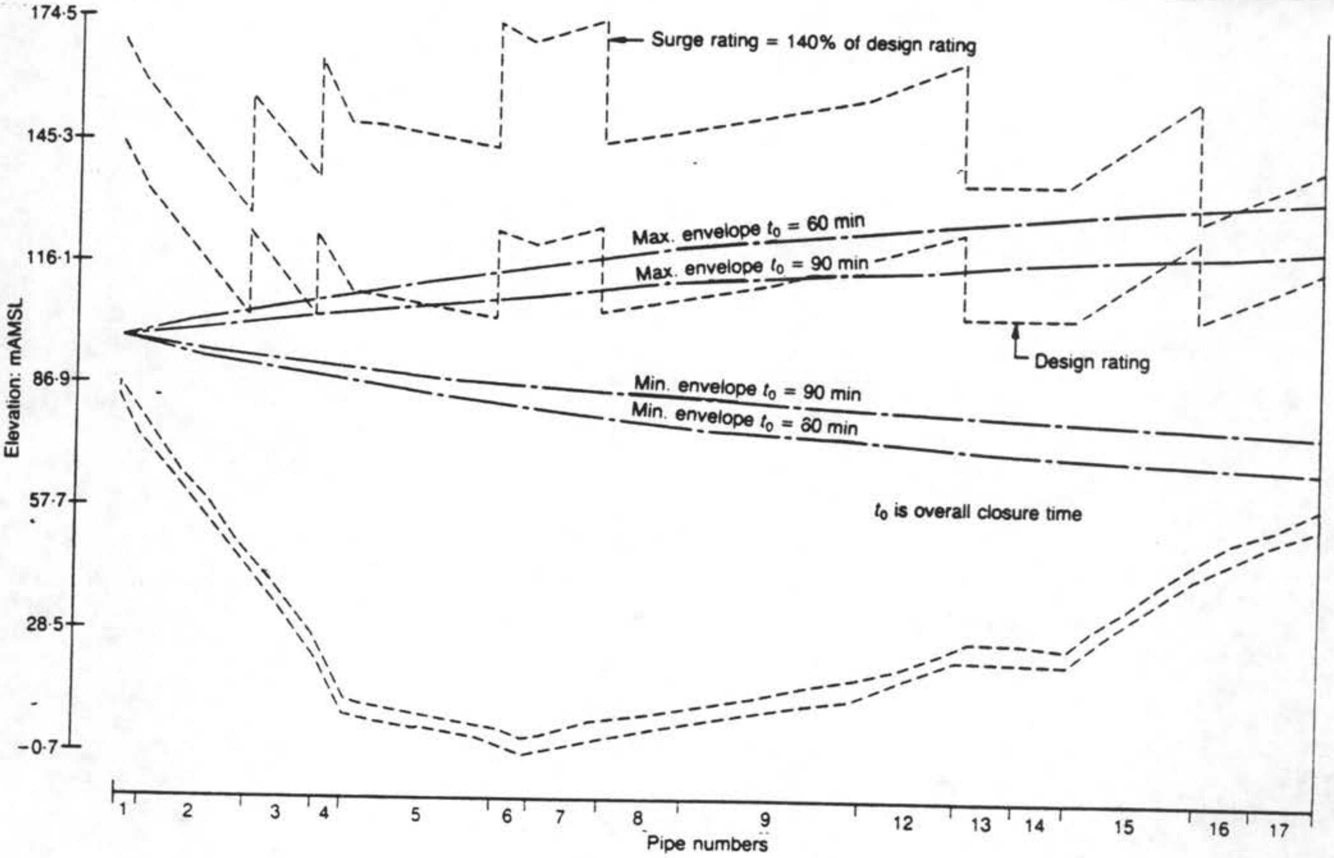


Fig. 17. Benghazi pipeline, valve closure transients (design flow)

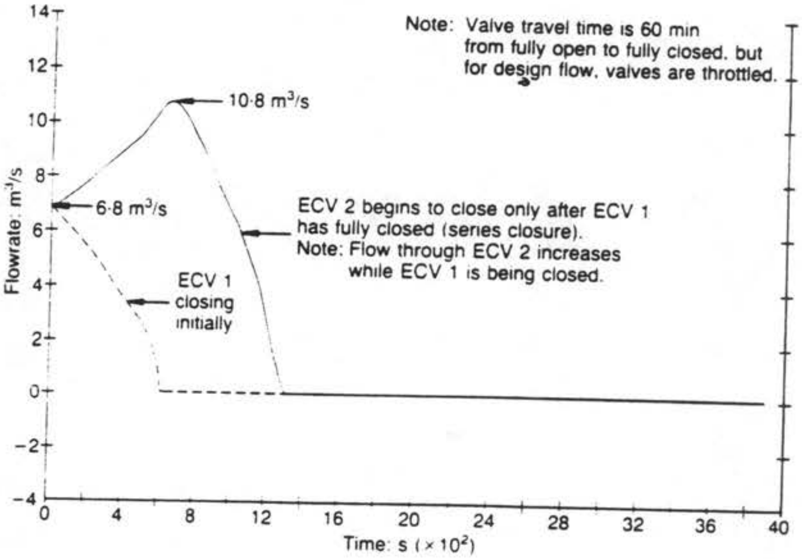


Fig. 18. Benghazi pipeline, series closure of ECVs (design flow)

1800 mm submerged discharge sleeve valves protected by 2000 mm butterfly valves. As in the case of the Sirt line, for stopping the flow, the transient analysis has an important role in the design of the system.

62. Figure 17 shows pressure envelopes during the closing of two end control valves in series for 60 min and 90 min overall closures. From the maximum pressure envelope, the 60 min overall closure is considered as unsafe. Fig. 18 illustrates how the flow through the valves varies during a closure of the valves in series.

Conclusion

63. The system is nearing completion and is expected to be in operation shortly, supplying a variety of users. The computer model of the hydraulics system will be used to assist the

development of the optimization of the operating procedures for the full range of normal conditions and for the planning of emergency procedures for any abnormal conditions which might possibly occur. The monitoring of actual pipeline flows and pressures will allow a comparison of the prototype behaviour with that predicted from the model, and will permit refining and updating of the model as required during the lifetime of the sytem. The knowledge and experience gained of the Phase I system will not only help the optimal development of that system but will also benefit the planning and detailed design of secondary systems and of Phases II and III of the Project.

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