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## PIPELINE OPTIMIZATION BY COMPUTER SIMULATION

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### ABSTRACT

#### Introduction

The optimization of the design of a pipeline to transmit fluids involves a number of variables, which include pipe diameter, pressure, temperature, line length, space between pumping or compressor stations, required inlet and delivery pressures and delivery quantity.

Each of these parameters influences the overall construction and operating cost in some degree and the selection of one or more will determine the economics of the construction and operation of the system.

This is as true for the design of a system from a clean sheet of paper (grass roots) as it is for the development and upgrading of an existing system, the only real difference between these two examples is the extent to which some of the variables are already fixed.

Because of the number of variables involved, the task of establishing the optimum can be quite involved and in order to ensure a robust solution, many options may have to be investigated. Also, all of the "what if" scenarios need to be studied to ensure that no possibilities are overlooked and the future unknowns can be adequately covered.

The simulation program which has been developed and which will be described in this paper is intended to provide optimum solutions to the design of a pipeline system and to permit the rapid investigation of the effects of significant variables on the optimum design.

The program as described is applicable to all pipeline systems conveying fluids, typically gas and oil are considered. The formulae for flow can be readily changed to suit the fluid and the flow regime, be it laminar or turbulent.

For the purposes of this paper and the illustration of the process, the presentation has been somewhat simplified in order to present a complex subject in a reasonably concise form.

#### Origin of the Simulation

Pipeline designers and pipeline companies have over time developed their own methods for the optimum system design and continue to use these. This program is not intended to supplant some of these tried and true methods, it is intended to show how the process can be accelerated and how the optimum solution can be easily demonstrated, thereby cutting short the long and laborious process of investigating, by "long hand" all the possible options.

An example of an optimization exercise for a "grass roots" system undertaken some years ago required over a man year of work to arrive at the optimum answer which satisfied all the defined scenarios.

The program is intended to reduce the time and expense of this procedure by several orders of magnitude. The simulation is an extension of a simple program, which was developed to evaluate the selection of compressor driver for gas pipelines. It may be helpful to describe this program before discussing the more complex pipeline model.

#### Selection of Compressor Driver

A question that frequently arises for the system designer concerns the selection of a compressor driver. Should a gas turbine, an electric motor or a reciprocating engine drive the compressor, and what will be the owning and operating cost of each option?

The key variables in this study are the capital costs, the maintenance costs, the fuel or energy costs, the utilization and the overall efficiency of each option. Combining these in a simple model allows the designer to show the overall cost of each on an annual and a total life of project cost basis. In addition to this, the program permits a number of sensitivity studies to be carried out, demonstrating the effect of changes in cost of fuel and utilization, for example. This program has been successfully employed in a number of feasibility studies to demonstrate to clients the possible choices within the constraints of operating variables such as energy costs and utilization.

An example of the application of this program is a comparison between an existing electrically driven compressor on a pipeline and the possibility of its replacement by a gas turbine. The question of replacement of the driver arose because of a projected increase in utility rates.

The use of the program permitted a very rapid review of the consequences of changes in the power costs and a graphical presentation of the results.

Tables 1 and 2 set out the parameters of the cases and the comparison of the electric and turbine cases are shown on Figure 1.

It will be noted that if the electric power rates increase to \$.05/kwhr the turbine replacement can be paid for in 5 years. A sensitivity analysis can be readily carried out using the simulation to study all possible variations of the energy cost and capital cost parameters.

Tables 1 and 2 summarize the numerical output data of the calculation.

The efficiency of the driver and compressor are incorporated in the power calculations, pressure losses in fittings, scrubbers are taken into account in the overall station pressure rise estimates. These latter items are of course very site a project specific, in the first instance for generic calculation and comparison, generalized data is used. This, of course, does not affect the validity of the comparative results.

**Table 1**  
Life Cycle Estimate: Gas Turbine Installation

| N  | F | H     | P      | I    | M      | S     | FV        | PV        | CPV        |
|----|---|-------|--------|------|--------|-------|-----------|-----------|------------|
| 1  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 3,942,500 | 15,942,500 |
| 2  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 3,745,375 | 19,687,875 |
| 3  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 3,558,106 | 23,245,981 |
| 4  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 3,380,201 | 26,626,182 |
| 5  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 3,211,191 | 29,837,373 |
| 6  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 3,050,631 | 32,888,004 |
| 7  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,898,100 | 35,786,104 |
| 8  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,753,195 | 38,539,299 |
| 9  | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,615,535 | 41,154,834 |
| 10 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,484,520 | 43,642,600 |
| 11 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,360,520 | 46,000,111 |
| 12 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,242,494 | 48,242,600 |
| 13 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,130,370 | 50,372,970 |
| 14 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 2,023,851 | 52,396,828 |
| 15 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 1,922,659 | 54,319,480 |
| 16 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 1,826,526 | 56,146,011 |
| 17 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 1,735,199 | 57,881,211 |
| 18 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 1,648,439 | 59,529,651 |
| 19 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 1,566,017 | 61,095,661 |
| 20 | 2 | 7,000 | 25,000 | 0.05 | 50,000 | 8,000 | 4,150,000 | 1,487,717 | 62,583,381 |

Cumulative Cost: \$ 83,000,000.00  
Present Value Cost: \$ 50,583,385.02

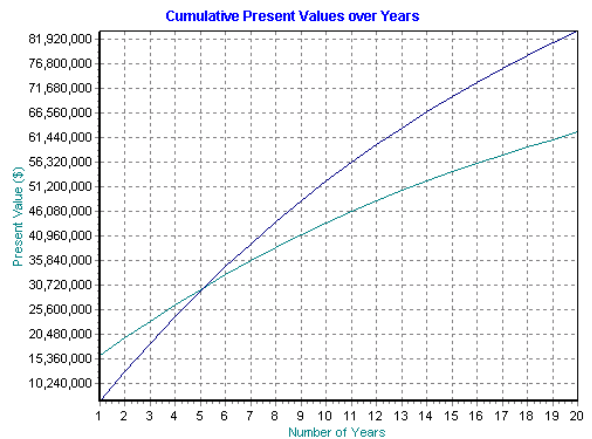
Figure 1 compares the total owning and operating costs of the existing electric driver and the replacement gas turbine. After 5 years the turbine solution is the least cost. An extension of the method used here can be applied to the more difficult case of pipeline optimization.

**Table 2**  
Life Cycle Estimate: Electrical Motor Installation

| N  | F     | H      | P    | I      | M | Y         | FV        | PV         | CPV |
|----|-------|--------|------|--------|---|-----------|-----------|------------|-----|
| 1  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 6,524,435 | 6,524,435  |     |
| 2  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 6,198,213 | 12,722,648 |     |
| 3  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 5,889,302 | 18,610,950 |     |
| 4  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 5,593,887 | 24,204,837 |     |
| 5  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 5,314,193 | 29,519,030 |     |
| 6  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 5,049,483 | 34,567,514 |     |
| 7  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 4,796,059 | 39,363,573 |     |
| 8  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 4,552,420 | 43,916,153 |     |
| 9  | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 4,318,175 | 48,234,328 |     |
| 10 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 4,092,932 | 52,327,200 |     |
| 11 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 3,876,300 | 56,204,899 |     |
| 12 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 3,667,987 | 59,877,426 |     |
| 13 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 3,467,602 | 63,354,878 |     |
| 14 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 3,274,854 | 66,657,232 |     |
| 15 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 3,089,452 | 69,794,584 |     |
| 16 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 2,911,006 | 72,776,836 |     |
| 17 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 2,739,226 | 75,614,062 |     |
| 18 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 2,573,822 | 78,317,274 |     |
| 19 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 2,414,504 | 80,896,478 |     |
| 20 | 7,000 | 18,000 | 0.05 | 20,000 | 1 | 6,867,826 | 2,261,081 | 83,351,559 |     |

Cumulative Cost: \$ 137,356,521.74  
Present Value Cost: \$ 83,710,335.23

**Figure 1**  
Cumulative Present Values over Years for the two alternates



**The Pipeline Program**

The foregoing compressor program has relatively few variable parameters; the pipeline case has considerably more and involves a greater degree of calculation. The principal variables for a pipeline and the dependent parameters can be listed as follows:

Maximum pressure, limits of pipe stress, affecting pipe thickness and pipe cost; Throughput, affecting pipe diameter, compressor (pump) horsepower and cost; Compressor station spacing, affecting compressor (pump) horsepower and cost; Delivery pressure limits; Line length.

The cost elements include not only material cost but also construction cost, operating cost and maintenance, fuel or energy cost and represent the life cycle cost of the project.

A general definition is the transport of a volume of gas "Q" from point "A" to point "B" over a distance of "X" km.

A typical case for a green fields pipeline project would specify the throughput and the length of the line from reception point to delivery and the limiting pressure at delivery. The evaluation would then examine the impact of pipe stress limit and maximum pressure, variations in pipe diameters, compressor station spacing and horsepower, from which a set of "J" curves can be produced.

The depiction of these relationships in a 2-dimensional form requires a number of different screens, each one of which can demonstrate an optimum point, assuming for example that least capital cost or the least owning and operating cost are the desired ends.

The simulation program provides outputs in the form of Tables, which provide data on all parameters influencing the design of the pipeline. Since the number of variables is large when a new pipeline design is being considered, several screens are incorporated in the output.

However the ultimate objective is a series of Jcurves which will, in combination, show the influence of changes in the key variables.

The optimum pipeline system may be presumed to be the system, which, within the prescribed limits, will provide the lowest or most economic cost of transportation for the quantity of fluid.

**The PipeTrack Program**

The development of the pipetrack program follows the pattern of the Compressor driver program, using established pipeline data and formulae and compressor data and formulae.

The first element comprises the hydraulic analysis which is based upon the use of one or other of the well known fluid flow formulae, in the examples used in the Paper, the modified Panhandle has been incorporated. This permits the relation between throughput and pipe size and compression power to be established. One of the key parameters and the basis for design will be the maximum operating pressure. Selection of maximum pressure for the system and the throughput required the effect of compressor station spacing and pipe diameter could be demonstrated.

With the hydraulic calculations set up in terms of maximum pressure, throughput and pipe size, the compressor power can be found as a function of station spacing, and following this process compressor capital and operating cost can be established, given assumptions on fuel or energy cost and escalation.

The calculation process includes all cost elements as well as the hydraulics, stress and thermodynamic performance elements.

Any combination of key parameters can be used to explore the effect of changes in the others to show the impact on overall cost.

**Summary.** The program evaluates the interactions of the following parameters: Hydraulics, flow, maximum pressure limits, pipe diameter, line length, compressor power, station spacing, material, maximum pressure, pipe stress, pipe diameter and thickness, station placement, pressure loss and horsepower, and fuel consumption.

**Cost**

The cost elements include all of the above physical parameters: Cost of material, pipe, cost of compressors, cost of fuel and energy, cost of construction, cost of operation, (fuel maintenance; utilization), total life cycle cost, etc.

The cost of each and every set of variations can be tabulated on a year by year basis and the total cost over the project life compared.

Costs are backed up with an extensive database of all the cost components and the performance of compression units based on latest published information.

The cost components can be varied to include changes as a result of new technology. For example, high-speed electric drive for compressors, new construction techniques, etc.

The program is not limited to the evaluation within the above defined problem limits but may be extended to examine the impact of a change in quantity to be delivered on the overall economics as would be the case of expansion of an existing system. It also could influence the initial design of a new system to study the possible effects of future, additional supplies being brought on stream.

**Table 3**  
Capital and Operating Cost Case 1

The screenshot shows the 'Pipeline System Optimization' software interface. At the top, it displays 'Timothy's Turbine Sample' and navigation buttons. Below that, there are radio buttons for 'Turbine Formula' (selected) and 'Electric Formula', along with 'Rebuild', 'Recalculate', and 'Compare!' buttons. The 'Turbine Variables' section includes input fields for Pipe Length From (30), to (30), increment by (30), FPC (2.5), Rate of Flow (1,100), Efficiency (.8500), Interest (0), Inlet Pressure (1,200), Years (20), and Operating Hours (8,000). At the bottom, there is a 'Summary Listing' table with columns for Length, Diam, HP, Pressure, Compressor\$, Pipeline\$, Total Capital\$, Operating\$, Total\$, and Error.

| Length | Diam | HP     | Pressure | Compressor\$ | Pipeline\$ | Total Capital\$ | Operating\$ | Total\$    | Error |
|--------|------|--------|----------|--------------|------------|-----------------|-------------|------------|-------|
| 30     | 30   | 12,985 | 964      | 17,529,219   | 22,500,000 | 40,029,219      | 41,600,742  | 81,629,961 |       |
| 30     | 32   | 8,762  | 1,034    | 14,019,656   | 24,000,000 | 38,019,656      | 28,089,312  | 66,108,968 |       |
| 30     | 36   | 4,527  | 1,111    | 8,148,164    | 27,000,000 | 35,148,164      | 14,535,625  | 49,683,789 |       |
| 30     | 40   | 2,590  | 1,148    | 4,661,497    | 30,000,000 | 34,661,497      | 8,337,106   | 42,998,603 |       |
| 30     | 42   | 2,011  | 1,159    | 3,620,086    | 31,500,000 | 35,120,086      | 6,485,709   | 41,605,796 |       |
| 30     | 48   | 1,018  | 1,179    | 1,831,980    | 36,000,000 | 37,831,980      | 3,306,853   | 41,138,834 |       |
| 30     | 56   | 469    | 1,190    | 843,918      | 42,000,000 | 42,843,918      | 1,550,298   | 44,394,216 |       |

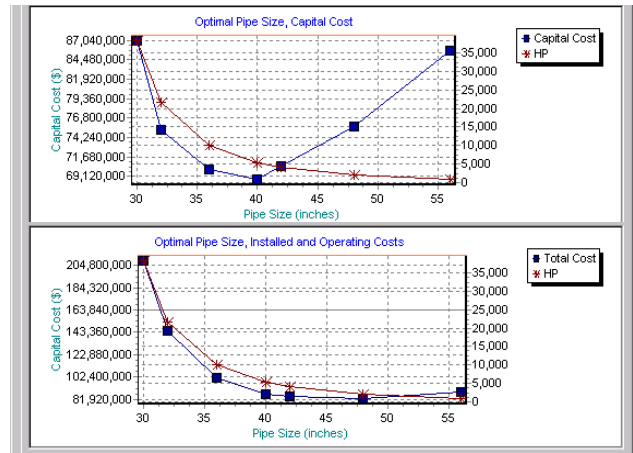
The results that are presented in the following section are generic examples, which do not specifically refer to any particular system and have been simplified to some degree by eliminating some elements such as coolers. These elements are incorporated in the program but like some other elements need to be tailored for each specific project.

The extensive output of data which can be made available from the simulation, resulting in many different screens, cannot be adequately shown in full within the confines of this paper, so the following illustrations are only sample outputs to illustrate some of the possibilities.

Table 3 and Table 4 compare the costs for a pipeline system to transmit 1,100 MMscfd using compressor station spacing of 30 and 60 miles. The results are presented on Figures 2 and 3.

**Table 4**  
Capital and Operating Cost Case 2

| Length | Diam | HP     | Pressure | Compressor\$ | Pipeline\$ | T/C | Capita\$   | Operating\$ | Total\$     | Er |
|--------|------|--------|----------|--------------|------------|-----|------------|-------------|-------------|----|
| 60     | 30   | 38,197 | 648      | 42,017,105   | 45,000,000 |     | 87,017,105 | 122,281,578 | 209,298,683 |    |
| 60     | 32   | 21,774 | 836      | 27,216,959   | 48,000,000 |     | 75,216,959 | 69,725,414  | 144,942,373 |    |
| 60     | 36   | 9,981  | 1,013    | 15,969,826   | 54,000,000 |     | 69,969,826 | 31,989,653  | 101,959,479 |    |
| 60     | 40   | 5,460  | 1,093    | 8,736,593    | 60,000,000 |     | 68,736,593 | 17,523,187  | 86,259,780  |    |
| 60     | 42   | 4,188  | 1,117    | 7,538,501    | 63,000,000 |     | 70,538,501 | 13,451,780  | 83,990,280  |    |
| 60     | 48   | 2,076  | 1,158    | 3,737,594    | 72,000,000 |     | 75,737,594 | 6,694,611   | 82,432,205  |    |
| 60     | 56   | 946    | 1,181    | 1,703,160    | 84,000,000 |     | 85,703,160 | 3,077,840   | 88,781,000  |    |



**Figure 3**  
Optimal Pipe Size Case 2

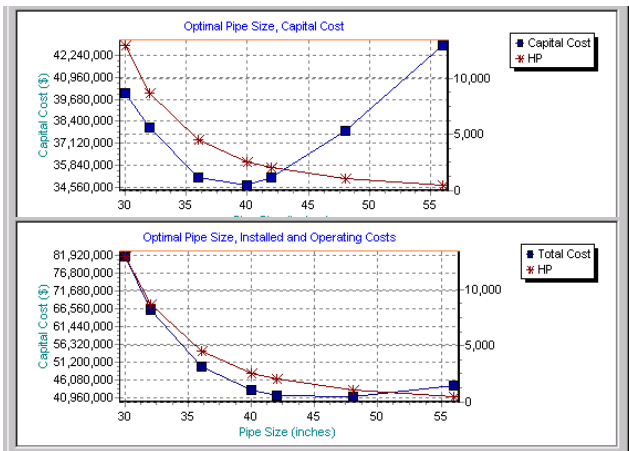
Table 5 and Table 6 show the effects of similar spacing for a throughput of 1,200 MMscfd. These results are presented on Figures 4 and 5.

All of these results are based on “generic” data for the purposes of demonstrating the capability of the simulation, and do not incorporate information from databases related to compressor units and pipeline construction costs.

The simulation program to suit a particular pipeline project has to be developed in cooperation with the company concerned with the project.

**Table 5**  
Capital and Optimum Cost Case 3

| Length | Diam | HP     | Pressure | Compressor\$ | Pipeline\$ | T/C | Capita\$   | Operating\$ | Total\$     | Er |
|--------|------|--------|----------|--------------|------------|-----|------------|-------------|-------------|----|
| 30     | 30   | 17,754 | 914      | 23,079,784   | 22,500,000 |     | 45,579,784 | 56,861,777  | 102,441,561 |    |
| 30     | 32   | 11,741 | 1,000    | 15,849,953   | 24,000,000 |     | 39,849,953 | 37,620,259  | 77,470,211  |    |
| 30     | 36   | 5,958  | 1,093    | 9,532,200    | 27,000,000 |     | 36,532,200 | 19,114,401  | 55,646,601  |    |
| 30     | 40   | 3,383  | 1,138    | 6,088,868    | 30,000,000 |     | 36,088,868 | 10,874,655  | 46,963,523  |    |
| 30     | 42   | 2,621  | 1,152    | 4,718,292    | 31,500,000 |     | 36,218,292 | 8,438,074   | 44,656,366  |    |
| 30     | 48   | 1,322  | 1,175    | 2,379,001    | 36,000,000 |     | 38,379,001 | 4,279,336   | 42,658,337  |    |
| 30     | 56   | 608    | 1,189    | 1,093,729    | 42,000,000 |     | 43,093,729 | 1,994,406   | 45,088,135  |    |



**Figure 2**  
Optimal Pipe Size Case 1

**Table 6**  
Capital and Optimum Cost Case 4

Pipeline System Optimization

Timothy's Turbine Sample

Turbine Formula Electric Formula

Rebuild Recalculate Compare

Turbine Variables

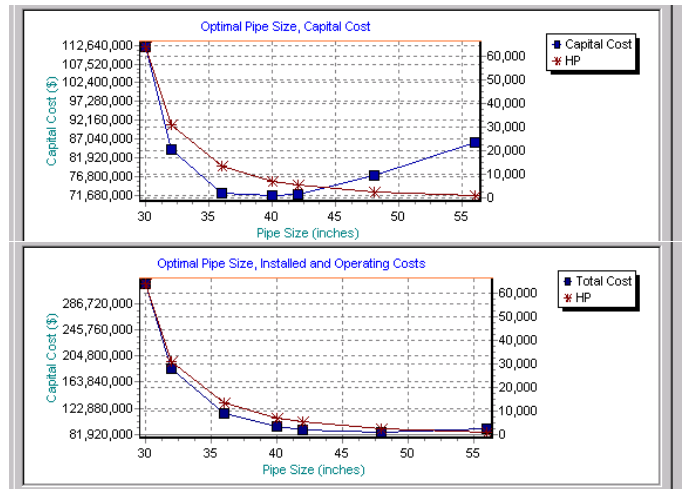
Pipe Length From 60 to 60 Increment by 60 FPC 2.5

Rate of Flow 1,200 Efficiency .8500 Interest 0

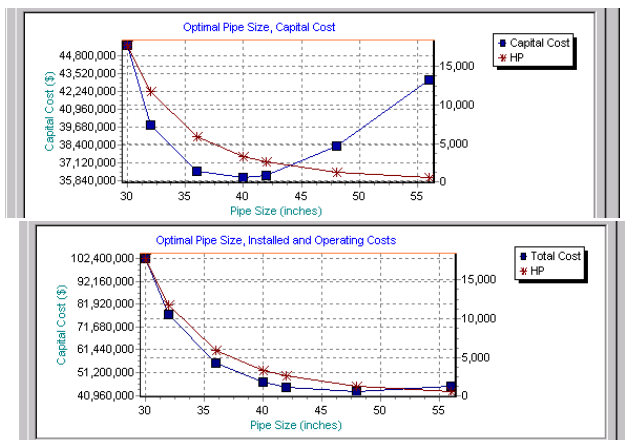
Inlet Pressure 1,200 Years 20 Operating Hours 8,000

Summary Listing Detailed Listing Capital Cost Summary Graph Total Cost Summary Graph

| Length | Diam | HP     | Pressure | Compressor | Pipeline\$ | T | Capital\$   | Operating\$ | Total\$     | Er |
|--------|------|--------|----------|------------|------------|---|-------------|-------------|-------------|----|
| 60     | 30   | 64,036 | 480      | 67,238,034 | 45,000,000 |   | 112,238,034 | 204,965,912 | 317,203,946 |    |
| 60     | 32   | 31,340 | 749      | 36,041,210 | 48,000,000 |   | 84,041,210  | 100,338,584 | 184,379,794 |    |
| 60     | 36   | 13,449 | 975      | 18,156,038 | 54,000,000 |   | 72,156,038  | 43,086,534  | 115,242,572 |    |
| 60     | 40   | 7,214  | 1,072    | 11,541,880 | 60,000,000 |   | 71,541,880  | 23,133,761  | 94,675,641  |    |
| 60     | 42   | 5,504  | 1,101    | 8,807,011  | 63,000,000 |   | 71,807,011  | 17,664,023  | 89,471,034  |    |
| 60     | 48   | 2,707  | 1,150    | 4,872,680  | 72,000,000 |   | 76,872,680  | 8,712,543   | 85,585,223  |    |
| 60     | 56   | 1,228  | 1,177    | 2,211,132  | 84,000,000 |   | 86,211,132  | 3,980,901   | 90,192,034  |    |



**Figure 5**  
Optimal Pipe Size Case 4



**Figure 4**  
Optimal Pipe Size Case 3

## Conclusions

The development of a pipeline optimization simulation has been described.

The work was initiated and based on an earlier program to evaluate alternative compressor drives in terms of overall owning and operating costs. The simulation program permits the rapid evaluation of a number of design parameters and their effect on overall cost of a system with the objective of defining a robust, least cost pipeline. The original compressor driver program, developed for the evaluation of alternative driver options, was successfully employed in a number of feasibility studies.

The simulation, which is based on established methods of hydraulic and performance calculation used in the industry; links together the selection of key parameters with cost data, to permit the rapid evaluation of a number of alternative configurations and to solve the pipeline design criteria.

The benefits of this method are that all possible options can be readily compared within a short period of computer time, and the target area that represents the most "robust" solution can be identified. At that point, a more detailed study can be undertaken, with confidence that all other alternatives can be discarded.

The application is not limited to new, "grass roots" systems, but can be equally applied to the expansion and re-evaluation of existing systems to meet changing circumstances.