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A COMPRESSOR STATION MODEL FOR TRANSIENT GAS PIPELINE SIMULATION

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SUMMARY

SIROGAS is a computer programme for the simulation of steady state and transient behaviour of gas flowing in a complex network which may include a wide range of the hydraulic devices normally found in industrial flow networks. These include high pressure natural gas transmission networks. This paper describes a model of a 2 unit compressor station recently added to SIROGAS. The model includes all control modes and allows starting and stopping of either unit or the entire station. Comparison is made with measured data from an operating station, and a demonstration calculation is discussed in which several mode changes occur, including unit and station shutdown and startup.

1. INTRODUCTION

In recent years, computer modelling of pipeline networks in high cost plant has become an increasingly important tool for the optimisation of their design and operation. CSIRO is working with the Pipelines Authority of South Australia and The Pipeline Authority of the Australian Government to develop improved methods of natural gas pipeline networks. This has resulted in the SIROGAS computer programme (Turner, Bakker and Severs 1982; Turner and Rainbow 1983) for modelling the steady state and transient behaviour of natural gas in pipeline networks. Co-operation with The Pipeline Authority (an agency of the Australian Government) has resulted in a highly interactive, user friendly programme which enables a gas engineer to carry out rapidly analysis on all or part of the network of interest. The programme is used regularly by two large Australian gas transmission organisations for analyses required for operation, such as pipeline break studies, and planning. Selection of a licensee for world-wide marketing is in progress. Application to two-phase flow problems in the oil and gas industry is being investigated.

In Australia, gas pipeline networks transport natural gas over the long distances between sources and markets. In the early life of such networks compressor stations within the network may not be required, but to get the best return on the capital invested in the pipeline, compressor stations are eventually installed. Up to 5 per cent of gas transported in such pipelines may be burnt to drive the compressors which raise gas pressure and density, hence reducing gas speed and increasing the rate at which gas can be transported through the network.

The choice of compressors and their operating speed is a complex matter usually involving a computer model of the pipeline network. The first priority is to meet the needs of the market, the second to optimise the operation of the network. Limits on pipeline pressures and compressor operation must be observed, and gas must be supplied to customers according to contracts which often specify pressure limits. Currently available software packages use steady state models of the network and compressors. However, natural gas transmission networks are rarely operated in steady state; demands for gas vary in daily, weekly, and annual cycles. In this paper, a realistic transient model of a compressor station is given which is intended for use in such optimisation studies. Particular attention has been given to calculating the efficiency of the station and the fuel used to drive the compressors.

2. CENTRIFUGAL COMPRESSORS

Data describing the performance of a centrifugal compressor are usually given on performance charts (figure 1) which show two families of curves relating the volumetric flow to the isentropic head.

The first family of curves are lines of constant efficiency. Efficiency is the ratio of isentropic head to actual head. Thus it is a comparison of the actual compressor performance to that of a perfect compressor working between the same pressure limits. Efficiencies are generally about 70 to 80 per cent for gas pipeline compressors.

The second family of curves are the lines of constant speed. In general, only a limited range of flows can be achieved at a given speed. At the upper flow limit, choking occurs within the compressor limiting the flow, whereas at the lower flow limit a phenomenon called surge occurs. In this condition the gas velocities at the compressor blades are so far from the design point that a condition occurs which is closely related to stall in an aircraft. Large-scale oscillations may occur which, if unchecked, could damage the compressor. Surge is avoided by allowing some compressed gas from the compressor outlet to pass through a controlled valve back to the compressor inlet (figure 2). The opening of this valve is varied so that the flow through the compressor remains safely above the surge limit even when the net flow is below the limit.

3. A COMPRESSOR STATION

The model described in this paper is based on Compressor Station 7 of the Moomba to Adelaide natural gas pipeline, which is owned and operated by the Pipelines Authority of South Australia. The components important in the simulation are shown in figure 2. Two Solar Centaur 3C/3C compressors are connected in parallel. Each compressor consists of two stages which can be run in series or in parallel: currently, if only one compressor is running, its stages are in parallel: if two are running the stages are in series. Each unit has its own control system which controls the starting, stopping and speed of the unit. Overall station control is exercised by a programmable logic control unit which passes stopping and starting signals to the units, and changes unit speeds to meet the overall control requirements.

Compression of the gas has the undesired side effect of heating the gas. The gas may have to be cooled to prevent damage to the main transmission pipeline; cooling between compression stages is desirable because it improves the efficiency of the overall compression process. As always it is a matter of balancing capital and maintenance costs against operating costs. Recently a cooler was installed in Station 7 to prevent hot gas entering the main pipeline. Heat from the gas now passes to the air in a forced draught heat exchanger in which one or two fans operate depending on the number of compressors in service.

Filters at the station inlet prevent damage to the compressors. The pressure drop across these, the heater and other station piping is included in the model. Flow, pressure and temperature measurements important to the control of the station are made at three points: the station discharge after the cooler; and at the inlet to each compressor. Pressure and temperature are also measured in the discharge from each unit.

Valves play an important part in the operation of the station. The suction and discharge valves and the main line valve determine whether gas flows through the station or continues along the main pipeline, bypassing the station. The recirculation valves are controlled to prevent surge in the adjacent compressor. The bypass valves are only opened if the head across the unit becomes too small or when the unit is off-loaded. Non-return valves in the unit discharge lines prevent reverse flow through the units if the pressure in the suction header exceeds that in the discharge header. It prevents gas driving the compressor as would occur with a suction pressure above the discharge pressure.

4. SIROGAS

SIROGAS is an offshoot of the NAIAD computer programme developed originally by the Australian Atomic Energy Commission as part of its research into loss-of-coolant accidents in water-cooled nuclear power reactors (Turner and Trimble 1976). NAIAD is capable of calculating the transient and steady state behaviour of pipeline networks containing both single and two-phase fluid. The programmes are written so that the addition of new hydraulic components either for general use or for a specialised application is relatively simple once the model of the component has been formulated.

Both SIROGAS and NAIAD consider a network to be made up of two entities: flow paths and connections. The fluid flow in each flow path is modelled by an implicit finite difference representation of the one-dimensional equations for the conservation of mass, energy and momentum. Connections are present at both ends of each flow path and can represent a wide range of hydraulic components. In SIROGAS, these may be pipe junctions, demand or supply points, compressors, non-return valves, regulators, pipe breaks, tanks etc. The nonlinear finite difference equations and almost all connection equations are solved by a direct (no iteration) solution procedure. The finite difference scheme is unconditionally stable enabling highly efficient solution to be achieved by automatic time step control with large time steps when slow changes are occurring and small time steps during rapid changes.

The Pipeline Authority has developed an interactive, user-friendly preprocessor and monitor for SIROGAS. The preprocessor allows a pipeline engineer to quickly specify the required analysis; most of the data required for SIROGAS are taken from a databank containing a full description of all network components of possible interest. The monitor allows operators or engineers to specify boundary conditions, regulator valve settings, compressor modes and setpoints etc., either as functions of time or conditions in the network. Intermediate results may also be displayed during the SIROGAS calculation.

The evaluation of the thermodynamic properties of the gas is an important part of SIROGAS. The Starling generalized equation of state for light petroleum mixtures (Starling 1973) is used. This general equation contains several coefficients which are functions of the gas composition. These are evaluated at the start of a SIROGAS simulation to allow use of the generalized equation to calculate the gas temperature, density, entropy etc. from the pressure and enthalpy at every time step at every finite difference node. The equation of state, particularly the calculation of entropy, is also an important part of the compressor calculation.

5. THE COMPRESSOR STATION MODEL

In SIROGAS a compressor station is represented by two connections, one at the station inlet and the other at the station outlet. The model includes both compressors, a cooler, station piping, the recycle valves, the compressor bypass valves, the station mainline valve, and the station and unit controllers. The basis of the model is the set of nonlinear equations described below and given in the appendix.

5.1 Conservation of Mass and Energy in the Inlet Header

Gas flows into the inlet header from the main line and from the recirculation lines of both units. Gas flows from the inlet header to both units. Usually the gas burnt to drive the compressors is taken off before the gas from the main line reaches the inlet header. However, this is not the case in Station 7 where the fuel gas is taken from the station discharge line. SIROGAS allows both possibilities.

5.2 Conservation of Mass and Energy in the Outlet Header

The outlet header receives gas from each unit and supplies gas to the main pipeline and, in some cases, the fuel gas for both units.

5.3 Energy Conservation in the Cooler

It is assumed that the rate of heat transfer is proportional to the difference in temperature between the gas leaving the cooler and the air temperature. The proportionality coefficient is specified in the input data. In the case of Station 7, it depends on the number of fans forcing air through the cooler and was obtained from station operating data.

5.4 Flow Resistance in the Station

Small pressure losses occur in the filters at the station inlet, in the cooler, and in station pipework. Because flows are mostly in the fully turbulent regime and the losses are small anyway, all such losses are lumped together into one pressure drop at the station cooler and assumed to be proportional to the volumetric flow times the mass flow. The coefficient for Station 7 was obtained by analysis of station operating data.

5.5 Gas Compression Equations

The compressor efficiency is a function of the unit isentropic head and volumetric flow rate. This relationship is taken from the compressor manufacturer's performance chart. The isentropic head is related by the equation of state to the pressure rise across the unit and the pressure and temperature of the gas at the unit suction. If the unit is shut down the head is set to zero.

5.6 Fuel Flow

It is assumed that the fuel flow is proportional to the compressor power (actual head times mass flow). This simple assumption has only been tested over a small range of powers and may have to be modified later to include more details of the engine which supplies the burnt high pressure gas to the power turbine which drives the compressor.

5.7 Recycle

Surge is controlled by setting up a controller to monitor a linear relationship between the pressure drop across the unit and the output from a multiple hole Pitot tube flow measuring device in the unit inlet pipe. If the operating point of the unit is at flows above this line, the recirculation valve remains closed and the recirculation flow is zero. If the operating point moves to flows below the line, the controller opens the recirculation valve sufficiently to place the operating point on the line. Any recirculation flow greater than the corresponding compressor flow is corrected by setting the recirculation flow and compressor flow equal.

5.8 Control

The desired mode of operation and setpoint of each unit is specified in SIROGAS input data but may be changed at any time by monitor procedures. Currently seven modes are available: discharge flow; discharge pressure; suction pressure; station pressure difference; compressor speed; net unit flow (unit minus recycle minus fuel flow); and unit shutdown. During operation of Station 7 the compressor speed is controlled to maintain the specified variable at a specified value known as the set point. In the model, direct set point control is used. However, the actual operating mode may not always be possible because of limits to compressor operation. The following limits are included in the model: maximum power; maximum speed; and zero pressure difference (station closed). During a simulation change between requested modes of operation and limit modes of operation occur automatically in response to changes in the network and hence the unit operating point.

It is easily seen that the modes of operation of the two units are not independent. For example it is obvious that both units cannot control the discharge pressure. In fact, the first four modes are called station operating modes and only one unit may exercise this control; the other units' requested mode of operation must be speed, net flow control, or shutdown. Also, in some circumstances, the recycle flows are related and allowance is made in the model for this eventuality.

Thus in the model, each unit has ten modes of operation, most of which can occur with and without recycle. Not all of these modes are present in Station 7; the net flow, zero pressure difference, and unit shutdown are used in the model to allow a smooth shutdown and startup of units and station, and smooth operation of the main line valve as shown in the demonstration simulation described below.

6. COMPARISON WITH OPERATING DATA

To test the compressor station model against operating data, a simple network was constructed with SIROGAS, comprising a 200 metre long pipeline with a representation of Station 7 at the halfway point. The measured suction temperature and flow were used as the boundary conditions at the pipeline inlet, and the measured discharge pressure as the boundary condition at the pipeline outlet. Operating modes and setpoints in the simulation were identical to those in Station 7 during the measurement period. Unit A was in discharge pressure control mode with the setpoint at 7.2 megapascals, and unit B was in shutdown mode. Only one compressor (unit A) was operating during the period of the comparison.

Figure 3 shows the calculated and measured pressures. The agreement is excellent and within the accuracy of the pressure measurement. The calculated and measured temperatures are compared in figure 4. Because the suction temperature is the temperature of gas which has been underground for some time, it hardly varies. The inlet temperature is raised above the suction temperature by the addition of recycled gas. Over periods when there is no recycle, the inlet temperature often drops about two degrees below the suction temperature. Heat transfer to the air appears insufficient to account for this effect. The temperature change from unit inlet to outlet agrees very well with the measurements, but the two degree difference persists. The discharge temperature is the temperature of gas after leaving the cooler. This temperature is much affected by the air temperature which peaks at about 3 p.m. Again the temperature change agrees well but the two degree difference persists. Compressor powers are shown in figure 5. The scatter in the measured powers is to be expected, as the measured power is obtained by using the equation of state and measured pressures and temperatures to calculate the change in the enthalpy of the gas on passage through the compressor. Thus it is quite sensitive to small errors in the two temperature measurements. Both the actual and maximum allowed compressor power are shown in figure 5. It can be seen that in the calculation the compressor was operating at maximum power during the period when the two curves coincide. During the remaining period the compressor operated at maximum speed (figure 6) which was taken to be 16 166 rev/min. This is somewhat larger than the maximum speed limit of 15 730 rev/min set by the manufacturer. The measured recycle flow is the difference between the unit and station flow. Excellent agreement is shown between this and the calculated recycle flow (figure 7).

7. STATION SHUTDOWN AND STARTUP

This calculation is designed to demonstrate the capability of the model to change operating modes and to shut down and start up units and the station. A two unit compressor station is located halfway along a 360 kilometre pipeline between a constant pressure supply and a constant pressure demand. The analysis begins by calculation of a network steady state for given discharge flow, pressure and temperature, given unit B speed, and given suction pressure. Neither the requested unit B speed nor the requested suction pressure are achievable without exceeding the unit power limits, hence both units operate at maximum power at the start of the transient (figures 8 and 9). In the first few minutes of the transient, unit A is changed to discharge flow control and the discharge flow reduced so that both units leave their maximum power limits. Unit B is shut down over a period of six hours by first reducing the speed setpoint (figure 10), changing to net flow mode and reducing the net flow to zero (figure 11), then changing to unit closing mode and reducing the unit head to zero. At this point, unit B is running at about 5000 rev/min but because its head is zero and the net flow is zero, it makes no contribution to station mass or energy flow and uses no fuel. Unit B is shutdown. Over the next six hours, the station is shut down and the main line valve opened by changing to station pressure difference mode and reducing the station pressure difference to zero (figure 12). The station remains shut down for a short period, then the both units are started and the main line valve closed by reversing the above procedure. The locus of the unit operating points during the transient are shown in figure 1 on the compressor performance chart.

8. CONCLUSION

A two unit compressor station model has been incorporated in the SIROGAS pipeline simulation programme. The model simulates detailed behaviour of compressor stations including changes to setpoints and operating modes, and the startup and shutdown of units and stations. The improved SIROGAS programme shows excellent agreement with the data from Station 7. Comparison with other stations and other modes of operation are required to check the model fully. With this in mind, SIROGAS 1.1 has been passed to the Pipelines Authority of South Australia and to The Pipeline Authority for further testing.

9. ACKNOWLEDGEMENTS

The Station 7 operating data were supplied by the Pipelines Authority of South Australia. Discussions with personnel of The Pipeline Authority and the Pipelines Authority of South Australia, especially Mr. G.A. Clinch, were of considerable assistance in the work.

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12. APPENDIX

Symbols

k	constant
H	enthalpy
T	temperature
W	mass flow
ε	0/1 fuel gas from discharge/suction
η	efficiency
ρ	density

Subscripts

air	air
a	unit A
b	unit B
c	either unit
d	discharge
f	fuel gas
i	inlet header
o	outlet header
r	recycle

Mass conservation in inlet header

$$W_s + W_{ra} + W_{rb} = \varepsilon(W_{fa} + W_{fb}) + W_a + W_b$$

Energy conservation in inlet header

$$\left[W_s - \varepsilon(W_{fa} + W_{fb})\right]H_s + W_{ra}H_a + W_{rb}H_b = (W_a + W_b)H_i$$

Mass conservation in outlet header

$$W_d = W_a - W_{ra} + W_b - W_{rb} - (1-\varepsilon)(W_{fa} + W_{fb})$$

Energy conservation in outlet header

$$(W_a - W_{ra} + W_b - W_{rb})H_o = (W_a - W_{ra})H_a + (W_b - W_{rb})H_b$$

Heat transfer in cooler

$$W_s(H_o - H_d) = k_h(T_d - T_{air})$$

Flow resistance

$$P_o - P_d = k\, W_s^2/\rho_d$$

Compression

$$\eta_c = \eta_c\left[\frac{W_c}{\rho_i}, H_i + \eta_c(H_c - H_i)\right]$$

Fuel flow

$$W_{fc} = k_c W_c(H_c - H_i)$$

Recycle

$$W_{rc} = 0 \text{ or } P_o - P_s = k_{rc} W_c^2/\rho_i$$

Control

Specified quantity = setpoint

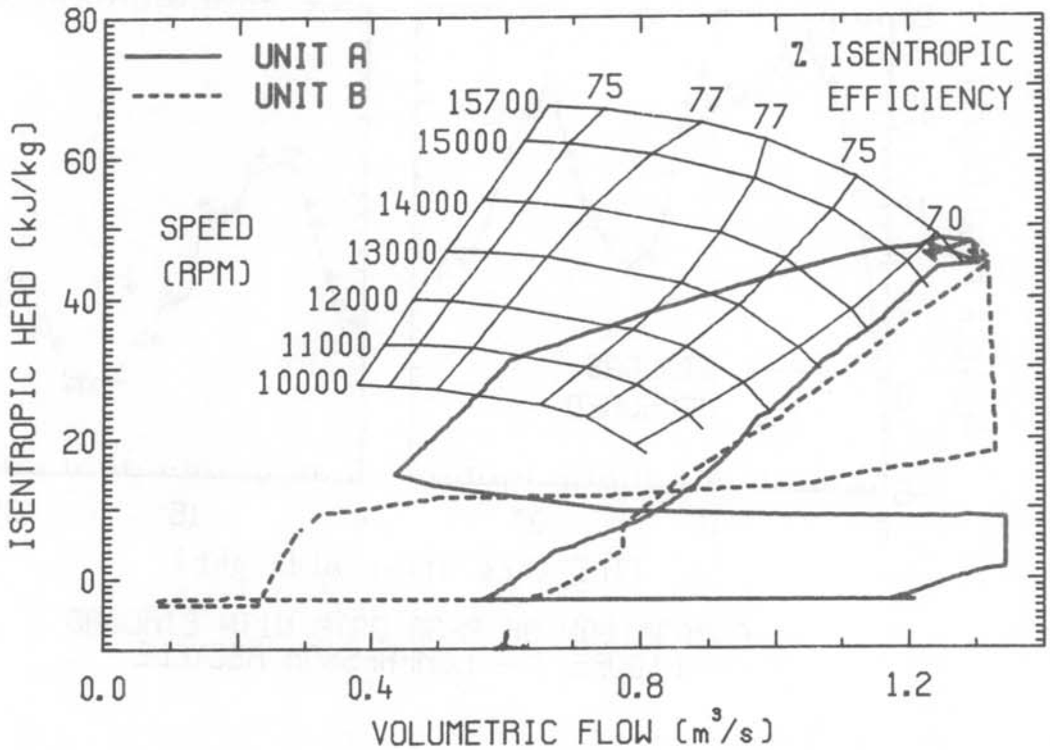


FIGURE 1 - LOCUS OF OPERATION AND PERFORMANCE OF SOLAR CENTAUR C3072 COMPRESSOR-(SERIES OPERATION)

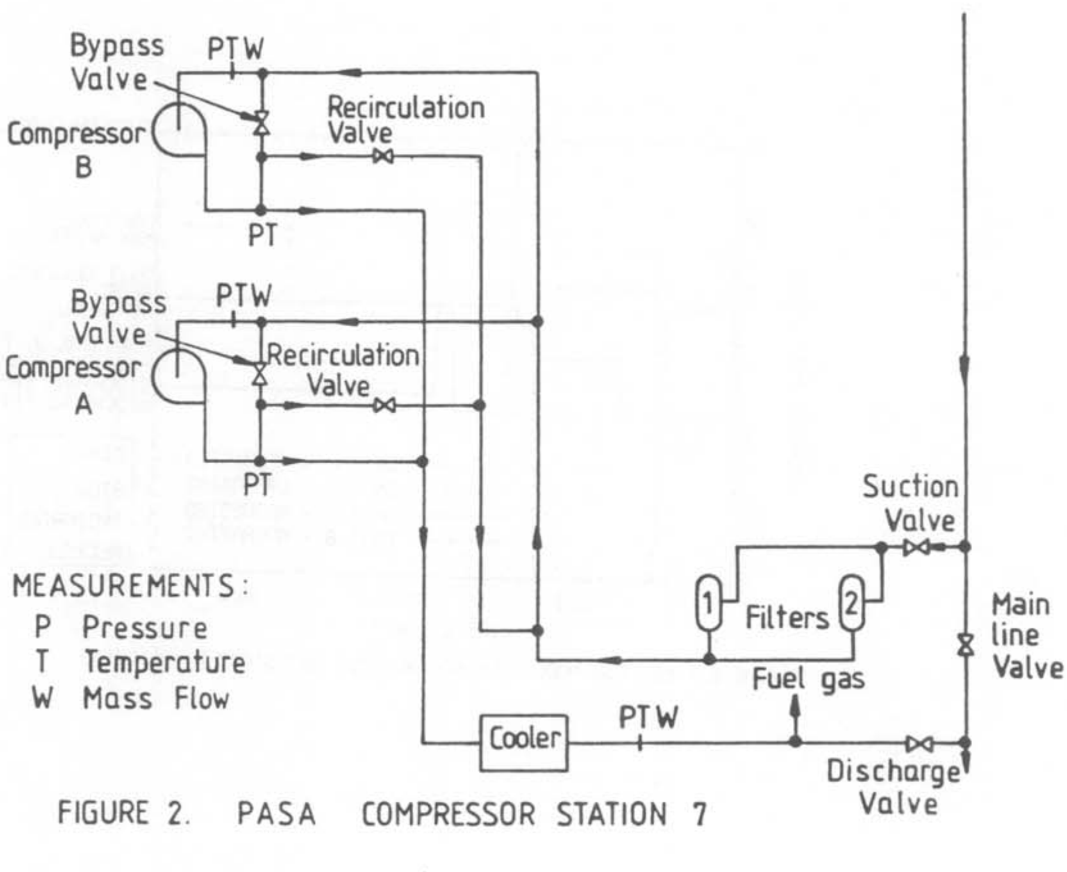
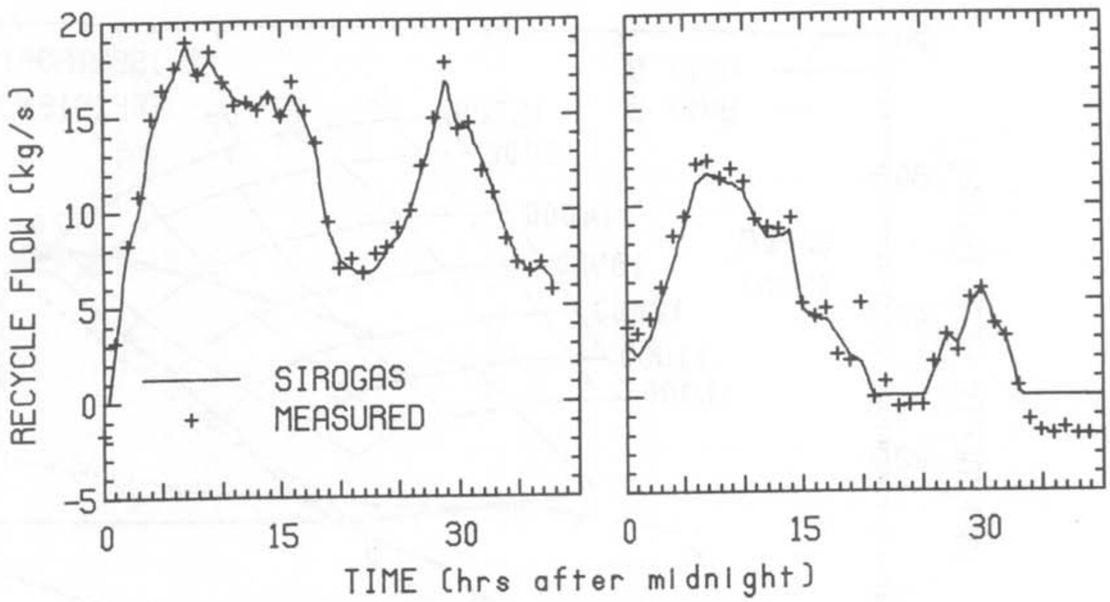


FIGURE 2. PASA COMPRESSOR STATION 7



COMPARISON OF PASA DATA WITH SIROGAS
FIGURE 7 - COMPRESSOR RECYCLE

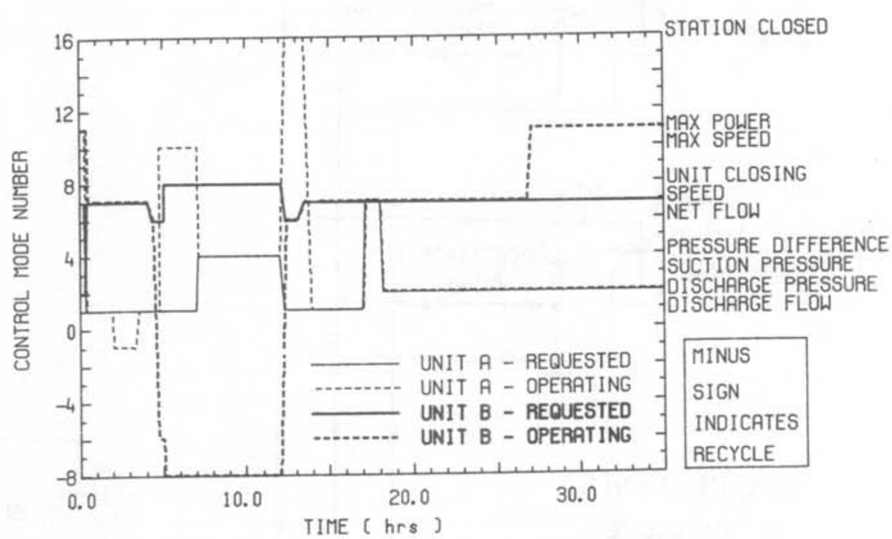


FIGURE 8 - CONTROL MODES DURING SHUTDOWN AND STARTUP TRANSIENT

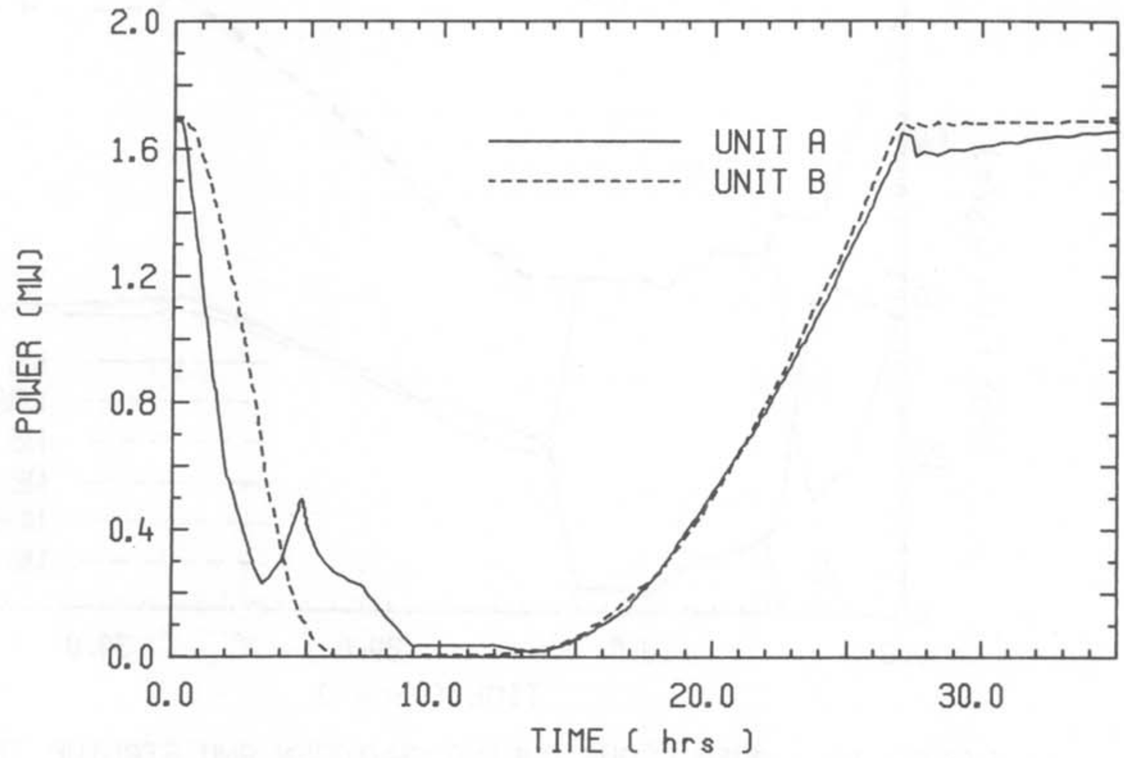


FIGURE 9 - UNIT POWERS DURING SHUTDOWN AND STARTUP TRANSIENT

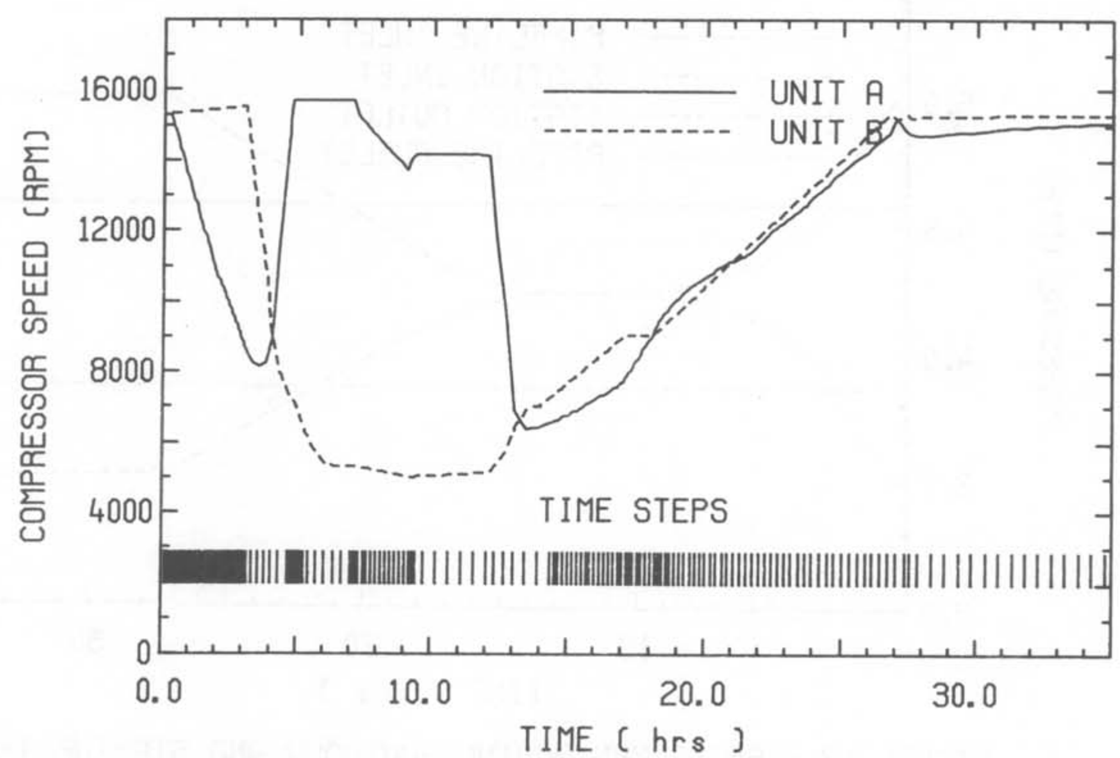


FIGURE 10 - UNIT SPEEDS DURING SHUTDOWN AND STARTUP TRANSIENT

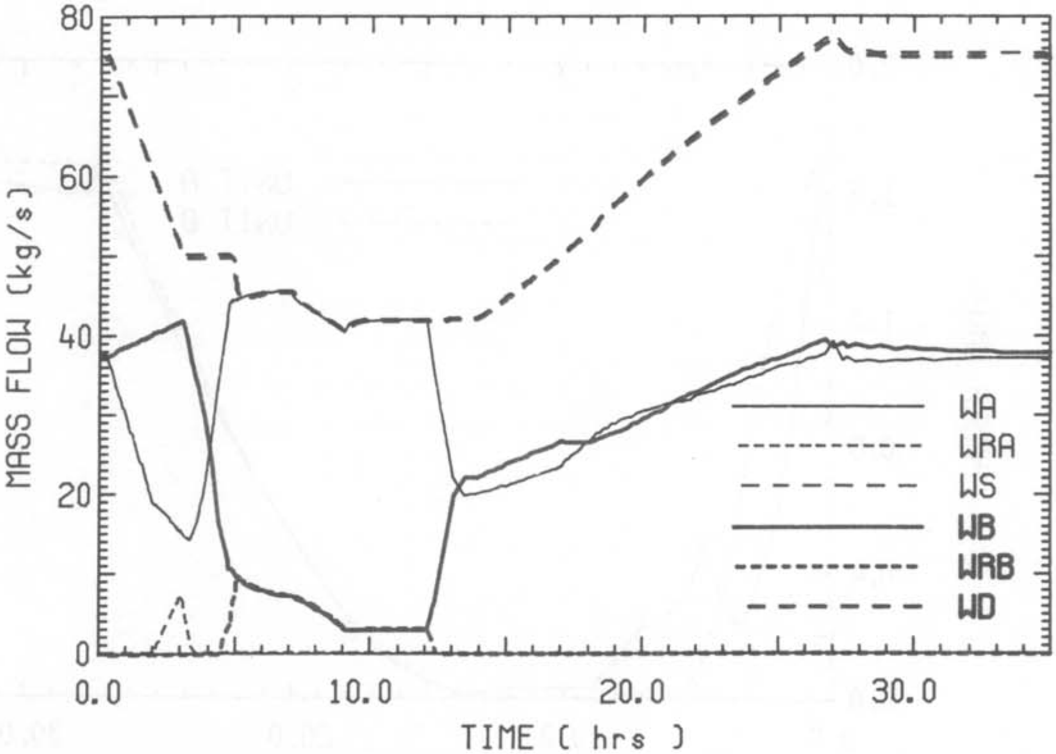


FIGURE 11 - MASS FLOWS DURING SHUTDOWN AND STARTUP TRANSIENT

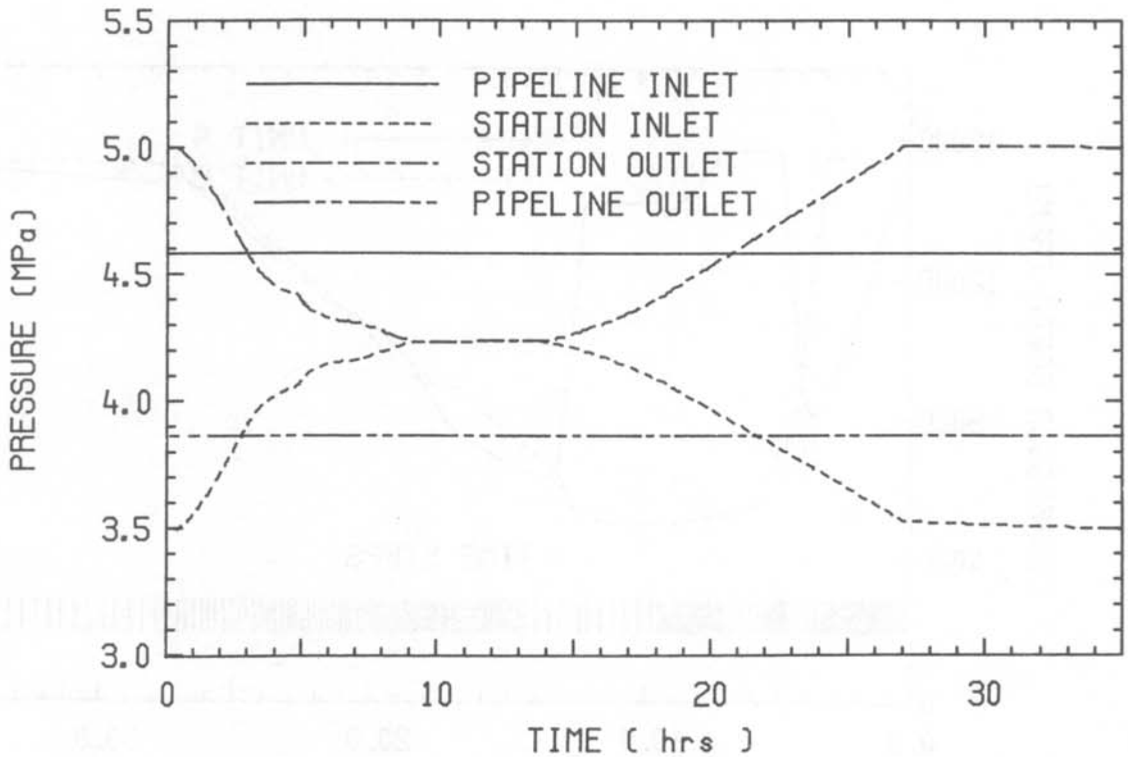


FIGURE 12 - PRESSURES DURING SHUTDOWN AND STARTUP TRANSIENT