Designing of a Natural Gas Pipeline

(Final Project Report)

Submitted for the partial fulfillment of

Bachelor of Technology (Gas Engineering)

(2004 - 2008)

SUBMITTED TO:

University of Petroleum & Energy Studies, Bidholi, Dehradun

Under the able guidance of:

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DESIGNING OF A NATURAL GAS PIPELINE

A thesis submitted in partial fulfillment of the requirements for the Degree of
Bachelor of Technology
(Gas Engineering)

By
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UNIVERSITY OF PETROLEUM & ENERGY STUDIES
(ISO 9001:2000 Certified)

CERTIFICATE

This is to certify that the work contained in this thesis titled "Designing of a Natural Gas Pipeline" has been carried out by Karthik P & Tilak S under my/our supervision and has not been submitted elsewhere for a degree.

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ABSTRACT

Natural gas can be transported from one place to another through various modes such as tankers, ships, etc. For a long distance transportation of natural gas over a long period of time, transportation through pipelines is the most economical option. Natural gas transportation through pipelines involve very low maintenance costs. But, huge investment costs are what burden pipeline transportation of natural gas. For this reason, pipeline transportation is only preferred for transporting fluid over long distances for a long period of time.

The major components of a pipeline are the pipes. These pipes come in various diameters and grades. The other important components used are valves, compressors, pressure and flow meters, etc.

Design of a pipeline involves various parameters that are to be found, such as, pipe internal diameter, friction factor, compression ratio, total volumetric flow rate, drop in pressure with respect to distance and the total costs incurred in constructing and maintaining the pipeline.

In this project, we have designed an optimized horizontal pipeline over a distance of 100 miles. We have considered an isothermal steady-state flow of natural gas through the pipeline with negligible kinetic change and a constant gas compressibility factor. Natural gas flows from station O at 15 MMSCMD and 90 bar through three different stations A, B and C. At station A, 3 MMSCMD of gas is withdrawn, 3 MMSCMD at station B and 9 MMSCMD at station C. With the help of hydraulic performance analysis and cost analysis we optimize the design using manual arithmetic calculations.

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First and foremost, we are thankful to ***University of Petroleum & Energy Studies*** *for giving us opportunity to carry out our major project on "****Designing of a Natural Gas Pipeline****".*

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INTRODUCTION:

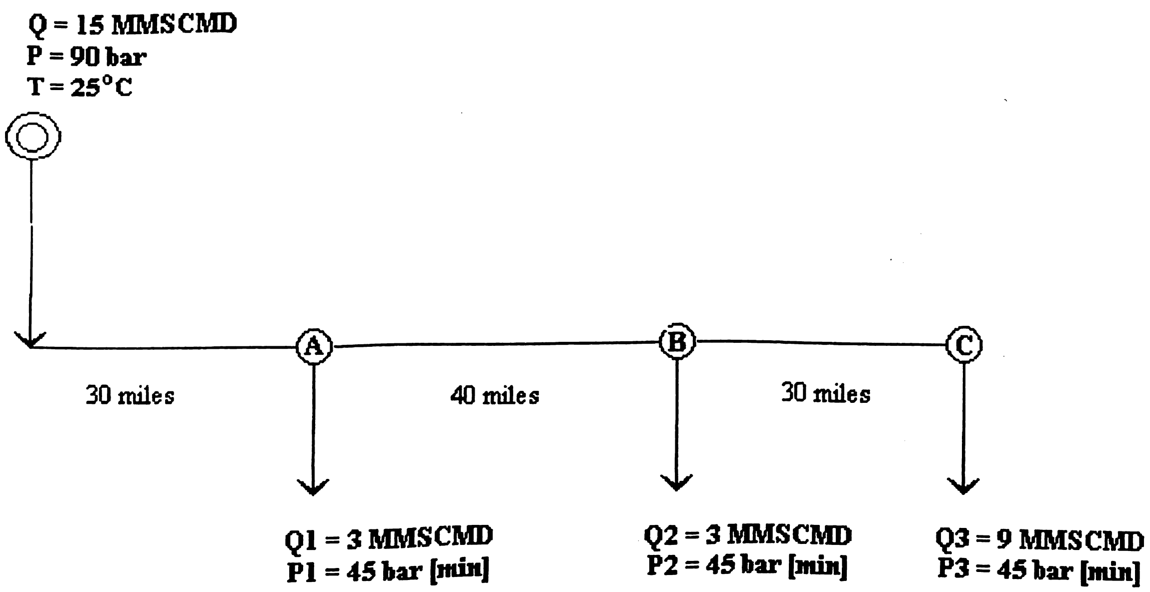
To obtain optimum design results for natural gas pipeline transmission system requires complex economic and engineering studies are necessary to decide on the pipeline diameter, material, compression power requirements and location of the pipeline route. The hydraulic study is one of the most important parts of the DFR.

Determining the diameter of the pipeline is the very important thing that would determine the least operating and investment cost. The objective of this project is to optimise the 100 mile pipeline diameter for the transportation of 15 MMSCMD Natural gas from Station O to C using manual arithmetic calculations.

The purpose is to compare various different configurations matching the requirements based on

- Hydraulic performances
- Investment cost
- Operating cost

The final design solution will be optimised based on all these criteria of evaluation.



(Figure 01 -- Basic system flow diagram)

CHAPTER 1 : DESIGN BASIS

Throughput	= 15 MMSCMD
Length Of pipeline	= 250 Km
Supply Pressure	= 95 bar
Supply Temperature	= 25^0C
Receiving Terminal Pressure	= 44 – 45 bar [Minimum]
Design Pressure	= 95 bar = MAOP

1.1 Mass fraction of natural gas

Methane	= 87.21 %
Ethane	= 6.8 %
Propane	= 2.98 %
i - Butane	= 0.41 %
n- Butane	= 0.82 %
i - Pentane	= 0.23 %
n - Pentane	= 0.22 %
Hexane	= 0.46 %
Carbon-di-oxide	= 0.74 %
Nitrogen	= 0.18 %

1.2 Diameter of Pipeline Considered

20 Inch

22 Inch

24 Inch

1.3 Grade of Line Pipe

X 60

X 70

1.4 Pipe Roughness

Internal Coated

Roughness of Line pipe = 5 Micron

1.5 Compressor Details

Compressor Type	= Centrifugal Compressor [1-4 Stages]
Maximum Working Pressure	= 105 bar
Maximum Design Inlet Flow	= 11300 m^3/hr
Design Speed [Range]	= 9000 – 13800 rpm
Compression Ratio	= 1.3

In this we analyze the hydraulic performances and cost analysis for six different cases taking into consideration the various combinations formed with the different diameters and grades.
The six cases formed are as shown below.

Case 1 – This involves a 20 inch outer diameter pipe of grade X60.

Case 2 – This involves a 20 inch outer diameter pipe of grade X70.

Case 3 – This involves a 22 inch outer diameter pipe of grade X60.

Case 4 – This involves a 22 inch outer diameter pipe of grade X70.

Case 5 – This involves a 24 inch outer diameter pipe of grade X60.

Case 6 – This involves a 24 inch outer diameter pipe of grade X70.

Gas	Formula	Molecular Weight	Vapor Pressure, psia at 100°F	Critical Constants: Pressure, psia	Critical Constants: Temp., °F	Critical Constants: Volume, ft³/lb	Ideal Gas, 14.696 psia, 60°F: Spgr (air = 1.00)	Ideal Gas, 14.696 psia, 60°F: ft³/lb-gas	Specific Heat, Btu/lb/°F 14.696 psia, 60°F Ideal Gas
Methane	CH_4	16.0430	5,000	666.0	-116.66	0.0988	0.5539	23.654	0.52676
Ethane	C_2H_6	30.0700	800	707.0	90.07	0.0783	1.0382	12.620	0.40789
Propane	C_3H_8	44.0970	188.65	617.0	205.93	0.0727	1.5226	8.6059	0.38847
Isobutane	C_4H_{10}	58.1230	72.581	527.9	274.4	0.0714	2.0068	6.5291	0.38669
n-butane	C_4H_{10}	58.1230	51.706	548.8	305.52	0.0703	2.0068	6.5291	0.39500
Iso-pentane	C_5H_{12}	72.1500	20.443	490.4	368.96	0.0684	2.4912	5.2596	0.38448
n-pentane	C_5H_{12}	72.1500	15.575	488.1	385.7	0.0695	2.4912	5.2596	0.38831
Neo-pentane	C_5H_{12}	72.1500	36.72	464.0	321.01	0.0673	2.4912	5.2596	0.39038
n-hexane	C_6H_{14}	86.1770	4.9596	436.9	453.8	0.0688	2.9755	4.4035	0.38631
2-methyl pentane	C_6H_{14}	86.1770	6.769	436.6	435.76	0.0682	2.9755	4.4035	0.38526
3-methyl pentane	C_6H_{14}	86.1770	6.103	452.5	448.2	0.0682	2.9755	4.4035	0.37902
Neo hexane	C_6H_{14}	86.1770	9.859	446.7	419.92	0.0667	2.9755	4.4035	0.38231
2,3-dimethylbutane	C_6H_{14}	86.1770	7.406	454.0	440.08	0.0665	2.9755	4.4035	0.37762
n-Heptane	C_7H_{16}	100.2040	1.621	396.8	512.8	0.0682	3.4598	3.7872	0.38449
2-Methylhexane	C_7H_{16}	100.2040	2.273	396.0	494.44	0.0673	3.4598	3.7872	0.38170
3-Methylhexane	C_7H_{16}	100.2040	2.13	407.6	503.62	0.0646	3.4598	3.7872	0.37882
3-Ethylpentane	C_7H_{16}	100.2040	2.012	419.2	513.16	0.0665	3.4598	3.7872	0.38646
2,2-Dimethylpentane	C_7H_{16}	100.2040	3.494	401.8	476.98	0.0665	3.4598	3.7872	0.38651
2,4-Dimethylpentane	C_7H_{16}	100.2040	3.294	397.4	475.72	0.0667	3.4598	3.7872	0.39627
3,3-Dimethylpentane	C_7H_{16}	100.2040	2.775	427.9	505.6	0.0662	3.4598	3.7872	0.38306
Triptane	C_7H_{16}	100.2040	3.376	427.9	496.24	0.0636	3.4598	3.7872	0.37724
n-octane	C_8H_{18}	114.2310	0.5371	360.7	564.15	0.0673	3.9441	3.322	0.38334
Di Isobutyl	C_8H_{18}	114.2310	1.1020	361.1	530.26	0.0676	3.9441	3.322	0.37571
Isooctane	C_8H_{18}	114.2310	1.7090	372.7	519.28	0.0657	3.9441	3.322	0.38222
n-Nonane	C_9H_{20}	128.2580	0.17155	330.7	610.72	0.0693	4.4284	2.9588	0.38248
n-Decane	$C_{10}H_{22}$	142.2850	0.06088	304.6	652.1	0.0702	4.9127	2.6671	0.38181
Cyclopentane	C_5H_{10}	70.1340	9.917	653.8	461.1	0.0594	2.4215	5.411	0.27122
Methylcyclopentane	C_6H_{12}	84.1610	4.491	548.8	499.28	0.0607	2.9059	4.509	0.30027
Cyclohexane	C_6H_{12}	84.1610	3.267	590.7	536.6	0.0586	2.9059	4.509	0.29012
Methylcyclohexane	C_7H_{14}	98.1880	1.609	503.4	570.2	0.0600	3.3902	3.8649	0.31902

(Table 01 – Gas properties (I))

Ethylene	C_2H_4	28.0540	1400	731.0	48.54	0.0746	0.9686	13.527	0.35789
Propylene	C_3H_6	42.0810	232.8	676.6	198.31	0.0717	1.4529	9.0179	0.35683
Butylene	C_4H_8	56.1080	62.55	586.4	296.18	0.0683	1.9373	6.7636	0.35535
Cis-2-butene	C_4H_8	56.1080	45.97	615.4	324.31	0.0667	1.9373	6.7636	0.33275
Trans-2-butene	C_4H_8	56.1080	49.88	574.9	311.8	0.0679	1.9373	6.7636	0.35574
Isobutene	C_4H_8	56.1080	64.95	580.2	292.49	0.0681	1.9373	6.7636	0.36636
1-Pentene	C_5H_{10}	70.1340	19.12	509.5	376.86	0.0674	2.4215	5.411	0.35944
1,2-Butadene	C_4H_6	54.0920	36.53	656.0	354	0.0700	1.8677	7.0156	0.34347
1,3-Butadene	C_4H_6	54.0920	59.46	620.3	306	0.0653	1.8677	7.0156	0.34223
Isoprene	C_5H_8	68.1190	16.68	582.0	403	0.0660	2.3520	5.571	0.35072
Acetylene	C_2H_2	26.0380		890.4	95.29	0.0693	0.8990	14.574	0.39754
Benzene	C_6H_6	78.1140	3.225	710.4	552.15	0.0531	2.6971	4.8581	0.24295
Toluene	C_7H_8	92.1410	1.033	595.5	605.5	0.0549	3.1814	4.1184	0.26005
Ethyl-benzene	C_8H_{10}	106.1670	0.3716	523	651.22	0.0564	3.6657	3.5744	0.27768
o-Xylene	C_8H_{10}	106.1670	0.2643	541.6	674.85	0.0557	3.6657	3.5744	0.28964
m-Xylene	C_8H_{10}	106.1670	0.3265	512.9	650.95	0.0567	3.6657	3.5744	0.27427
p-Xylene	C_8H_{10}	106.1670	0.3424	509.2	649.47	0.0572	3.6657	3.5744	0.27470
Styrene	C_8H_8	104.1520	0.2582	587.8	703	0.0534	3.5961	3.6435	0.26682
Isopropylbenzene	C_9H_{12}	120.1940	0.188	465.4	676.2	0.0569	4.1500	3.1573	0.30704
Methyl alcohol	CH_4O	32.0420	4.631	1174	463.01	0.0590	1.1063	11.843	0.32429
Ethyl alcohol	C_2H_6O	46.0690	2.313	891.7	465.31	0.0581	1.5906	8.2372	0.33074
Carbon monoxide	CO	28.0100		506.8	-220.51	0.0527	0.9671	13.548	0.24847
Carbon dioxide	CO_2	44.0100		1071	87.73	0.0342	1.5196	8.6229	0.19909
Hydrogen sulfide	H_2S	34.0820	394.59	1306	212.4	0.0461	1.1768	11.134	0.23838
Sulfur dioxide	SO_2	64.0650	85.46	1143	315.7	0.0305	2.2120	5.9235	0.14802
Ammonia	NH_3	17.0305	211.9	1647	270.2	0.0681	0.5880	22.283	0.49678
Air	N_2+O_2	28.9625		546.9	-221.29	0.0517	1.0000	13.103	0.2398
Hydrogen	H_2	2.0159		187.5	-400.3	0.5101	0.06960	188.25	3.4066
Oxygen	O_2	31.9988		731.4	-181.4	0.0367	1.1048	11.859	0.21897
Nitrogen	N_2	28.0134		493	-232.48	0.0510	0.9672	13.546	0.24833
Chlorine	Cl_2	70.9054	157.3	1157	290.69	0.0280	2.4482	5.3519	0.11375
Water	H_2O	18.0153	0.95	3200.1	705.1	0.04975	0.62202	21.065	0.44469
Helium	He	4.0026		32.99	-450.31	0.2300	0.1382	94.814	1.24040
Hydrogen Chloride	HCl	36.4606	906.71	1205	124.75	0.0356	1.2589	10.408	0.19086

(Table 02 – Gas properties (II))

CHAPTER 2: DETERMINATION OF PROPERTIES OF NATURAL GAS

2.1 Standing-Katz Method

The Standing-Katz method of calculating compressibility factor is based on the use of a graph that has been constructed for binary mixtures and saturated hydrocarbon vapor. This method is used generally for sweet natural gas mixtures containing various hydrocarbon components. When the natural gas mixture contains appreciable amounts of non-hydrocarbons such as nitrogen, hydrogen sulfide, and carbon dioxide, certain corrections must be applied for these components. These adjustments are applied to the critical temperatures and pressures.

Pseudo . reduced temperature, $Tr = T/Tc$

Pseudo . reduced pressure, $Pr = P/Pc$

Designing of a Natural Gas Pipeline

Compound	yi	mi	yi mi	Pci	Tci	yi Pci	yi Tci
C1	0.872	16.04	13.98688	673	344	586.856	299.968
C2	0.068	30.07	2.04476	709	550	48.212	37.4
C3	0.03	44.1	1.323	618	666	18.54	19.98
i-C4	0.004	58.12	0.23248	530	733	2.12	2.932
n-C4	0.008	58.12	0.46496	551	766	4.408	6.128
i-C5	0.002	72.15	0.1443	482	830	0.964	1.66
n-C5	0.002	72.15	0.1443	485	847	0.97	1.694
C6	0.005	86.18	0.4309	434	915	2.17	4.575
N2	0.002	28.02	0.05604	227	492	0.454	0.984
						664.694	**375.321**
CO2	0.007	44.01	0.30807	1073	548	7.511	3.836

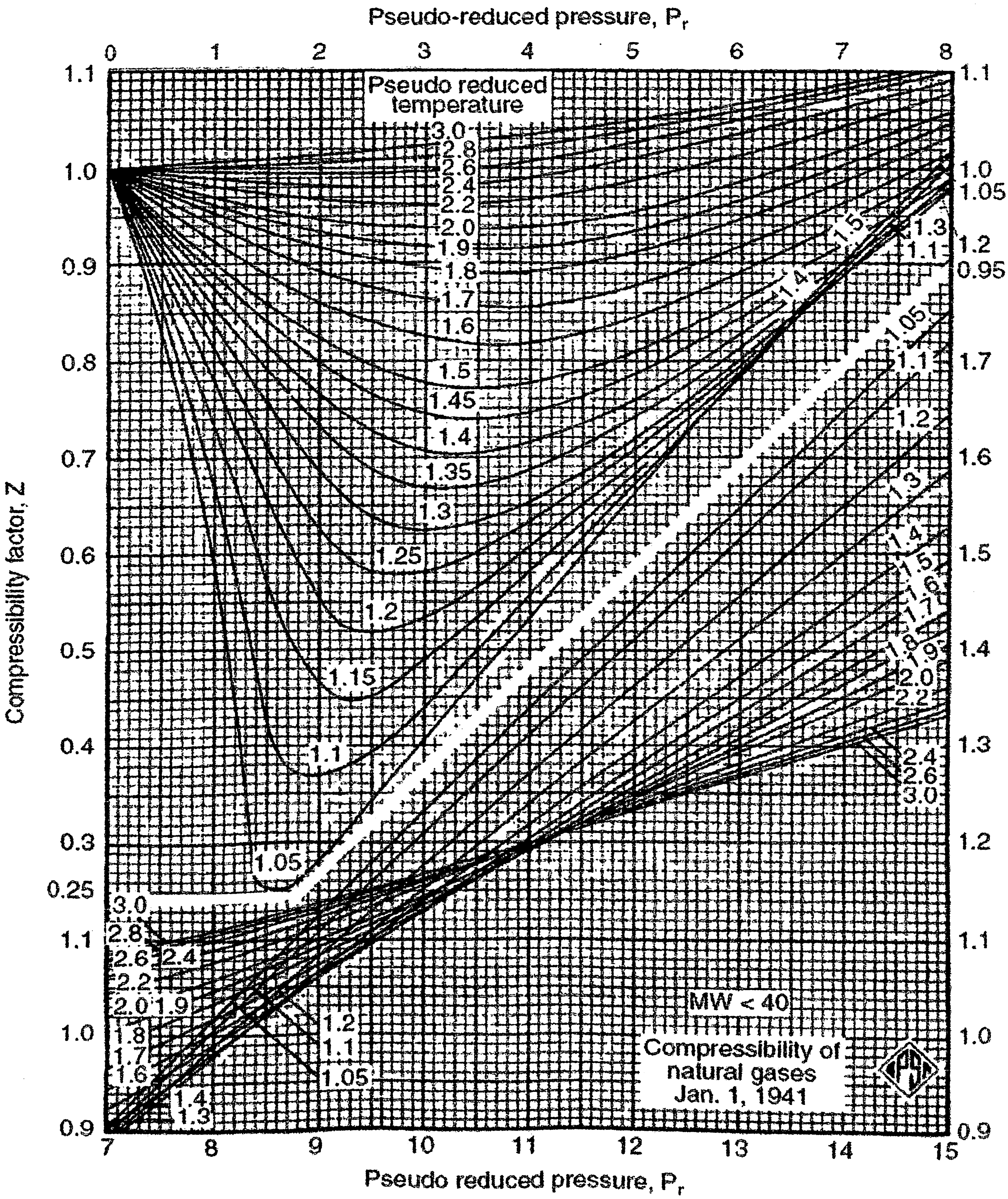
A = 0.007 $\quad$ ε = 1.336862

T'pc = 373.9841 °R $\quad$ Tr = 1.43589

P'pc = 662.3264 psi $\quad$ Pr = 0.022194

From Graph, Z = 0.996

2.2 Standing-Katz Chart



(Figure 02 – Standing Katz chart)

2.3 Compressibility Factor

The compressibility factor or gas deviation factor. It is a measure of how close a real gas is to an ideal gas. The compressibility factor is defined as the ratio of the gas volume at a given temperature and pressure to the volume the gas would occupy if it were an ideal gas at the same temperature and pressure. The compressibility factor is a dimensionless number close to 1.00 and is a function of the gas gravity, gas temperature, gas pressure, and the critical properties of the gas. From the Standing-Katz chart, compressibility factor,

Z = 0.996

2.4 Specific gravity

Specific gravity of a gas, sometimes called *gravity*, is a measure of how heavy the gas is compared to air at a particular temperature. It might also be called *relative density*, expressed as the ratio of the gas density to the density of air. Because specific gravity is a ratio, it is a dimensionless quantity.

First we calculate the density of the gas,

Density, $\rho = (p\,M)/(Z\,R\,T)$ (2.1)

Where,

p = Inlet pressure in psi.

M = molar mass in kg/mol.

Z = Compressibility factor.

R = Universal gas constant in psiaft^{3o}R^{-1}

T = Temperature in ^{o}R

From calculations, Density, $\rho = 4.351645$ kgmol/ft^3

Gas Specific Gravity = $\rho / \rho_{air} = 4.351645 / 28.97 =$ ***0.66***

2.5 Viscosity of natural gas

Gas viscosity is a measure of the resistance to flow exerted by the gas. Dynamic viscosity *(μg)* in centipoises (cp) is usually used in the natural engineering.

1 cp = 6.72 * 10-4 lbm/ft-sec

$$\nu_g = \frac{\mu_g}{\rho_g} \tag{2.2}$$

Kinematic viscosity (v_g) is related to the dynamic viscosity through density *(ρ_g.)*. Gas viscosity is very often estimated with charts or correlations developed based on the charts. The gas viscosity correlation of Carr, Kobayashi, and Burrows (1954) involves a two-step procedure: the gas viscosity at temperature and atmospheric pressure is estimated first from gas-specific gravity and inorganic compound content. The atmospheric value is then adjusted to pressure conditions by means of a correction factor on the basis of reduced temperature and pressure state of the gas. The following formulae show the correction factors for calculation of actual gas viscosity.

$$\mu_1 = \mu_{1HC} + \mu_{1N_2} + \mu_{1CO_2} \tag{2.3}$$

Where,

$$\mu_{1HC} = 8.188 * 10^{-3} - (6.5 * 10^{-3} * \log(\gamma_g)) + \{(1.709 * 10^{-5}) - (2.062 * 10^{-6} * \gamma_g)\}(T) \tag{2.4}$$

$$\mu_{1N_2} = \{(9.59 * 10^{-3}) + (8.48 * 10^{-3} \log(\gamma_g))\} * y_{N_2} \tag{2.5}$$

$$\mu_{1CO_2} = \{(6.24 * 10^{-3}) + \left(9.08 * 10^{-3} * \log\left(\gamma_g\right)\right)\}y_{CO_2} \tag{2.6}$$

2.6 Calculation of Viscosity using Carr et al correlation for Natural Gases

Input Data

Pressure	1305.34	psi
Temperature	77	^{o}F
Gas Specific Gravity	0.14	
Mole Fraction of N2	0.002	
Mole Fraction of CO2	0.007	
Mole Fraction of H2S	0	

Calculation

Pseudo Critical Pressure	662.33	psi
Pseudo Critical Temperature	373.98	^{o}R
Uncorrected Gas Viscosity at 14.7 psia	0.00932	cp
N2 Correction for Gas Viscosity at 14.7 psia	0.000016	cp
CO2 Correection for Gas Viscosity at 14.7 psia	0.000032	cp
Corrected Gas Viscosity at 14.7 psia	0.009368	cp
Gas Viscosity	0.009389	cp

CHAPTER 3: DETERMINATION OF PIPE SPECIFICATIONS:

3.1 Calculation of Pipe Thickness

Thickness of the pipe is calculated using the formula as per ASME B 31.8.

t = [P* D]/ [2*S*F*E*T] (3.1)

Where,

t = Thickness of line pipe in inch

P = Design Pressure of Pipeline in psi

D = Outer Diameter of Pipeline in inch

S = Yield strength of the pipe material psi

F = Basic Design Factor

3.1.1 Basic Design Factor [F]

Location class	Design Factor
Location Class 1, Division 1	0.80
Location Class 1, Division 2	0.72
Location Class 2	0.60
Location Class 3	0.50
Location Class 4	0.40

(Table 03 – Location and design factor)

ASME B31.8 has defined location classes as follows

Location Class 1 - A Location Class 1 is any 1 mile section that has 10 or fewer buildings intended for human occupancy. A Location Class 1 is intended to reflect areas such as wasteland, deserts, mountains, grazing land, farmland, and sparsely populated areas.

Division 1 :

A Class 1 location where the design factor of the pipe is greater than 0.72, but equal to or less than 0.80, and which has been hydrostatically tested to 1.25 times the maximum operating pressure.

Division 2 :

Class 1 location where the design factor of the pipe is equal to or less than 0.72 and which has been tested to 1.1 times the maximum operating pressure.

Location Class 2:

A Location Class 2 is any 1 mile section that has more than 10 but fewer than 46 buildings intended for human occupancy. A Location Class 2 is intended to reflect areas where the degree of population is intermediate between Location Class 1 and Location Class 3 such as fringe areas around cities and towns, industrial areas, ranch or country estates, etc.

Location Class 3:

A Location Class 3 is any 1 mile section that has 46 or more buildings intended for human occupancy except when a Location Class 4 prevails. A Location Class 3 is intended to reflect areas such as suburban housing developments, shopping centers, residential areas, industrial areas, and other populated areas not meeting Location Class 4 requirements.

Location Class 4:

Location Class 4 includes areas where multistory buildings are prevalent, and where traffic is heavy or dense and where there may be numerous other utilities underground. Multistory means 4 or more floors above ground including the first or ground floor.

3.1.2 Longitudinal joint factor, E

Longitudinal joint factor [E] for API 5L

Pipe class	**E Factor**
Seamless	1.0
Electric resistance welded	1.0
Electric flash welded	1.0
Furnace butt welded	0.6
Submerged arc welded	1.0

(Table 04 – Longitudinal joint factor)

3.1.3 Temperature Derarating factor, T

Temperature Derating Factor [T] for Steel Pipe

Temperature °F	T Factor
121 or less	1.000
149	0.967
177	0.033
204	0.900
232	0.867

(Table 05 – Temperature derating factor)

Considering the Location Class 2, Electric resistance welded pipe, and the temperature below 121 °F.

F = 0.60

E = 1.00

T = 1.00

3.2 Calculation of Pipe Diameter

The internal diameter is one of the most important variables to be used in flow calculations. The internal diameter is calculated using the formula,

Internal Diameter = Outer Diameter - 2 x (Pipe Thickness) (3.2)

Calculation For Internal Diameter			
Outer Diameter	SMYS	Thickness	Internal Diameter
inches	psi	inches	inches
20	60000	0.362594	19.27481111
20	70000	0.310795	19.37840952
22	60000	0.398854	21.20229222
22	70000	0.341875	21.31625048
24	60000	0.435113	23.12977333
24	70000	0.372954	23.25409143

(Table 06 – Calculation for internal diameter)

3.3 Reynold's Number

An important parameter in flow of fluids in a pipe is the non dimensional term *Reynolds number*. The Reynolds number is used to characterize the type of flow in a pipe, such as laminar, turbulent, or critical flow. It is also used to calculate the friction factor in pipe flow. We will first outline the calculation of the Reynolds number based upon the properties of the gas and pipe diameter and then discuss the range of Reynolds number for the various types of flow and how to calculate the friction factor. The Reynolds number is a function of the gas flow rate, pipe inside diameter, and the gas density and viscosity and is calculated from the following equation:

$$Re = Dv\rho/\mu \quad (3.3)$$

Or

$$Re = 0.5134*(P_b/T_b)*(\gamma Q/\mu D) \quad (3.4)$$

3.4 Calculation of Reynold's Number for the gas in all the given cases

INPUTS

Flow Rate	15 Mmscmd	=	529.313 Mscfd
Viscosity	0.009389 cp		
Gas Gravity	0.66		

Internal Diameter, inches	Reynold's Number
19.27481111	38607.97487
19.37840952	38401.57377
21.20229222	35098.15897
21.31625048	34910.52161
23.12977333	32173.31239
23.25409143	32001.31148

3.5 Friction Factor

Friction factor is defined as the ratio of the shear stress at the fluid solid surface interface and the kinetic energy of the fluid per unit volume, is used in computing the magnitude of the pressure drop due to the friction

Colebrooke-White Equation:

The Colebrook-White equation, sometimes referred to simply as the Colebrook equation, is a relationship between the friction factor and the Reynolds number, pipe roughness, and inside diameter of pipe. The following form of the Colebrook equation is used to calculate the friction factor in gas pipelines in turbulent flow.

$$\frac{1}{\sqrt{f}} = (-2)\ log_{10}[\frac{e}{3.7D} + \frac{2.51}{N_{Re}\sqrt{f}}] \qquad (3.5)$$

Where,

f = Friction Factor, dimensionless.

N_{Re} = Reynold's Number, dimensionless.

D = Internal diameter, inches.

e = pipe internal roughness, metres.

Since Re and f are dimensionless, as long as consistent units are used for both e and D, the Colebrook equation is the same regardless of the units employed. Therefore, In SI units, e and D expressed in mm.

For turbulent flow in smooth pipes, the first term within the square brackets is negligible compared to the second term, since pipe roughness e is very small.

Therefore, for smooth pipe flow, the friction factor equation reduces to,

$$\frac{1}{\sqrt{f}} = (-2)log_{10}(\frac{2.51}{N_{Re}\sqrt{f}}) \qquad (3.6)$$

To calculate the friction factor f, we must use a trial-and-error approach. It is an implicit equation in f, since f appears on both sides of the equation. We first assume a value of f (such as 0.01) and substitute it in the right-hand side of the equation. This will yield a second approximation for f, which can then be used to calculate a better value of f, and so on. Generally 3 to 4 iterations are sufficient to converge on a reasonably good value of the friction factor.

3.6 Calculation of Friction Factor for all the given cases

For pipe 20X60, Reynold's number = 38607.97

Friction Factor	Equaling
0.01	3.625994
0.02	0.396031
0.021	0.20443
0.022	0.025569
0.0221	0.008329
0.02211	0.006611

0.02212	0.004895
0.02213	0.003179
0.02214	0.001465
0.02215	-0.00025

For pipe 20X70, Reynold's number = 38401.57

Friction Factor	Equaling
0.01	3.630649
0.02	0.400687
0.021	0.209086
0.022	0.030225
0.0221	0.012985
0.02211	0.011267
0.02212	0.009551
0.02213	0.007835
0.02214	0.006121
0.02215	0.004407
0.02216	0.002695
0.02217	0.000984
0.02218	-0.00073

For pipe 22X60, Reynold's number = 35098.16

Friction Factor	Equaling
0.01	3.708779
0.02	0.478817

0.021	0.287215
0.022	0.108355
0.0221	0.091114
0.0222	0.073986
0.0223	0.056969
0.0224	0.040062
0.0225	0.023263
0.0226	0.006571
0.02261	0.004908
0.02262	0.003246
0.02263	0.001585
0.02264	-7.5E-05

For pipe 22X70, Reynold's number = 34910.52

Friction Factor	Equaling
0.01	3.713435
0.02	0.483473
0.021	0.291871
0.022	0.113011
0.0221	0.09577
0.0222	0.078642
0.0223	0.061625
0.0224	0.044718
0.0225	0.027919
0.0226	0.011227
0.02261	0.009564
0.02262	0.007902
0.02263	0.006241

0.02264	0.004581
0.02265	0.002922
0.02266	0.001264
0.02267	-0.00039

For pipe 24X60, Reynold's number = 32173.31

Friction Factor	Equaling
0.01	3.784356
0.02	0.554394
0.021	0.362792
0.022	0.183932
0.023	0.016433
0.0231	0.000261
0.02311	-0.00135

For pipe 24X70, Reynold's number = 32001.31

Friction Factor	Equaling
0.01	3.789012
0.02	0.55905
0.021	0.367448
0.022	0.188588
0.023	0.021089
0.0231	0.004917
0.02311	0.003305

0.02312	0.001695
0.02313	8.5E-05
0.02314	-0.00152

The friction factor for the various pipe combinations are shown below.

Pipes	Friction Factor
20x60	0.02214
20x70	0.02217
22x60	0.02263
22x70	0.02266
24x60	0.0231
24x70	0.02313

(Table 07 – Friction factor for various pipe combinations)

3.7 Transmission Factor

The transmission factor F is considered the opposite of the friction factor f. Where as the friction factor indicates how difficult it is to move a certain quantity of gas through a pipeline, the transmission factor is a direct measure of how much gas can be transported through the pipeline. As the friction factor increases, the transmission factor decreases and, therefore, the gas flow rate also decreases. Conversely, the higher the transmission factor, the lower the friction factor and, therefore, the higher the flow rate will be. The transmission factor F is related to the friction factor f as follows:

$$F = 2/\sqrt{f} \qquad (3.7)$$

3.8 Calculation of Transmission Factor

Pipes	Friction Factor	F
20x60	0.02214	13.4413
20x70	0.02217	13.4322
22x60	0.02263	13.29498
22x70	0.02266	13.28618
24x60	0.0231	13.15903
24x70	0.02313	13.1505

(Table 08 – Transmission factor for various pipe combinations)

3.9 Gas Flow Equation

One of the most widely used equations for long transmission lines is the Panhandle equation. The pipeline flow equation is thus given as follows:

$$q_{sc} = 109.364 * \left(\frac{T_{sc}}{P_{sc}}\right)^{1.020} \left(\frac{p_1^{\,2} - p_2^{\,2}}{Z_{av} T_{av} L}\right)^{0.51} \left(\frac{1}{\gamma_g}\right)^{0.49} \left(\frac{d^{2.53}}{\mu_g^{0.02}}\right) \tag{3.8}$$

Where,

q_{sc} = gas flow rate measured at standard conditions, Mscfd.

P_{sc} = pressure at standard conditions, psi

T_{sc} = temperature at standard conditions, ^{o}R

p_1 = upstream pressure, psi

p_2 = downstream pressure, psi

Z_{av} = average gas compressibility factor

T_{av} = flowing temperature, ^{o}R

L = Length of pipe, ft

γ_g = gas gravity (air = 1 basis)

d = diameter of the pipe, ft

μ_g = gas viscosity, cp

The Panhandle B equation is most applicable to large diameter pipelines, at high values of Reynold's number. Implications of this equation is made possible by the various assumptions we have considered for this analysis. They are as follows,

No mechanical work:

It is assumed that no work is done on the gas between the points at which the pressures are measured. This condition can be satisfied easily by putting pressure measurement stations such that no mechanical energy is added between these two points.

Steady-state flow:

Rarely, if ever, encountered in practice, this assumption is the major cause of discrepancies in pipeline calculations. Reasons for unsteady behavior include: pressure/flow pulsations or surges, liquids in the pipeline, variations in operating conditions, variations in withdrawal or supply rates, etc.

Isothermal flow:

This assumption is usually met because buried pipelines are used which are not affected much by atmospheric temperature variations. Heat of compression is also dissipated rapidly, usually within a few miles downstream of the compression station. For small temperature changes, the average temperature is generally satisfactory.

Negligible kinetic energy change:

This assumption is justified because the kinetic energy changes are negligible, compared to changes in pressure, for very long pipelines, such as commercial transmission lines.

Constant (average) gas compressibility factor:

This is a reasonable approximation, especially as Z is computed at the average pressure.

Horizontal pipeline:

In practice, flow is never truly horizontal. But, here we consider a horizontal pipeline in order to simplify calculations and reduce complications.

3.10 Pipeline efficiency

Pipeline efficiency is a correction for small amounts of liquid, general debris, weld resistance, valve installations, line bends, and other factors that reduce the gas flow rate to a point below the basic equation of state. The design value of .E. in a new clean gas line usually is estimated as **0.92.** Some companies arbitrarily use a graduated .E.:

E = 1.0, new straight pipe without bends, very seldom used in design

= **0.95,** excellent conditions (with frequent pigging)

= **0.92,** average to good conditions (normal design)

= **0.85,** adverse, unpigged, old dirty pipe

3.11 Steady flow in gas pipeline

The capacity (flow rate or throughput) of a pipe segment of length L, based on an upstream pressure of P_1 and a downstream pressure of P_2. It is assumed that there is no elevation difference between the upstream and downstream points; therefore, the pipe segment is horizontal.

A pipe segment of length L and diameter D, the gas flow rate Q (at standard conditions) depends on several factors. Q depends on gas properties represented by the gravity G and the compressibility factor Z. If the gas gravity is increased (heavier gas), the flow rate will decrease. Similarly, as the compressibility factor Z increases, the flow rate will decrease. Also, as the gas flowing temperature T_f increases, throughput will decrease. Thus, the hotter the gas, the lower the flow rate will be. Therefore, to increase the flow rate, it helps to keep the gas temperature low.

The impact of pipe length and inside diameter is also clear. As the pipe segment length increases for given pressure P_1 and P_2, the flow rate will decrease.

On the other hand, the larger the diameter, the larger the flow rate will be. The term P_{12} .P_{22} represents the driving force that causes the flow rate from the upstream end to the downstream end. As the downstream pressure P_2 is reduced, keeping the upstream pressure P_1 constant, the flow rate will increase. It is obvious that when there is no flow rate, P_1 is equal to P_2. It is due to friction between the gas and pipe walls that the pressure drop (P_1 . P_2) occurs from the upstream point 1 to downstream point 2. The friction factor f depends on the internal condition of the pipe as well as the type of flow (laminar or turbulent).

CHAPTER 4: HYDRAULIC PERFORMANCE:

Let us see the pressure difference in all the different cases based on the given conditions.

4.1 CASE 1 - 20 X60 PIPELINE:

First, let us take the case of the pipeline with 20 inch outer diameter and an yield strength of 60000. Our conditions have set a minimum pressure of 45bar. So, if we come across a situation where the pressure drops below this critical limit, we will make use of a compressor station to boost the gas pressure in the pipeline. We can make use of single and multiple stage compressors with a compression ratio of 1.3 to serve our purpose.

The calculations with respect to the length of the pipeline are as shown below.

To determine the location of the compressor stations

20 X 60 pipeline

Inputs

Flow rate	15 Mmscmd	= 529.31	Mmscfd
Starting pressure	90 bar	1305.34 psi	
Final pressure	45 bar	652.67 psi	
Gas Gravity	0.66		
Internal Diameter	19.2748111	inches	
Compressibility Factor	0.996		
Flowing Temperature	537	R	
Friction Factor	0.02214		
Viscosity	0.009389	cp	

SECTION 1

Distance, miles	Pressure, psi	Pressure, bar
1	1294.406627	89.24619
2	1283.380113	88.48594
3	1272.258038	87.7191
4	1261.037872	86.9455
5	1249.716974	86.16495
6	1238.292581	85.37726
7	1226.761801	84.58225
8	1215.121605	83.77968
9	1203.368819	82.96936
10	1191.500111	82.15104
11	1179.511982	81.32448
12	1167.400752	80.48945
13	1155.162549	79.64565
14	1142.793295	78.79282
15	1130.288687	77.93066
16	1117.644181	77.05885
17	1104.854975	76.17707
18	1091.915984	75.28495
19	1078.821818	74.38214
20	1065.566758	73.46824
21	1052.144722	72.54282
22	1038.549236	71.60545
23	1024.773397	70.65564
24	1010.809832	69.69288
25	996.6506487	68.71664
26	982.2873895	67.72633

27	967.710967	66.72132
28	952.911599	65.70094
29	937.8787318	64.66446
30	922.6009514	63.61109

At Outlet 1 - Exit Pressure = 63.61109 bar

SECTION 2

Inlet Pressure	63.6 bar	922.44 psi
Flow Rate	423.776	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	912.5842589	62.92047
2	902.4563943	62.22218
3	892.2135717	61.51596
4	881.8517855	60.80154
5	871.3667916	60.07862
6	860.7540877	59.3469
7	850.0088903	58.60605
8	839.1261094	57.85571
9	828.1003209	57.0955
10	816.9257344	56.32504
11	805.5961578	55.5439
12	794.1049575	54.75161
13	782.4450125	53.94768
14	770.608663	53.13159
15	758.5876518	52.30278
16	746.3730565	51.46061
17	733.9552122	50.60443

18	721.3236219	49.73351
19	708.4668528	48.84707
20	695.372415	47.94424
21	682.0266194	47.02408
22	668.41441	46.08555
23	654.5191651	45.12751
24	640.322459	44.14868

Compressor Station 1 outlet pressure = 76.26549 bar

Two stage compression

Distance, miles	Pressure, psi	Pressure, bar
1	1097.796236	75.69038
2	1089.391615	75.1109
3	1080.921646	74.52692
4	1072.384781	73.93832
5	1063.77941	73.34501
6	1055.103856	72.74685
7	1046.356374	72.14373
8	1037.535144	71.53553
9	1028.638269	70.92211
10	1019.663769	70.30334
11	1010.609577	69.67907
12	1001.47353	69.04917
13	992.2533672	68.41346
14	982.9467222	67.77179
15	973.5511146	67.12398
16	964.0639433	66.46987
17	954.482478	65.80925

At Outlet 2 - Exit Pressure = 65.80925 bar

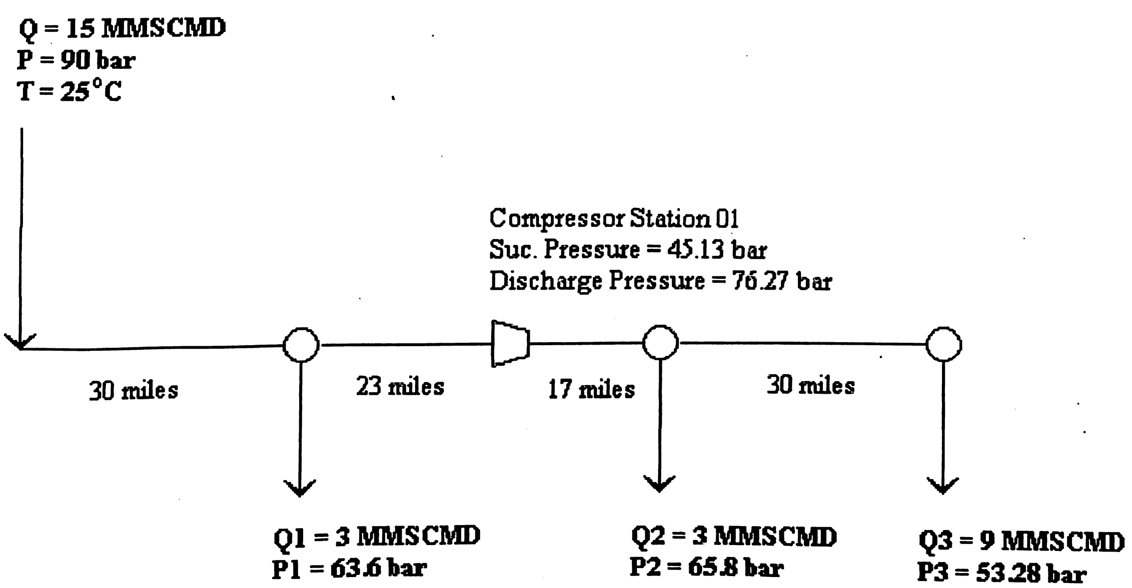
SECTION 3

Inlet Pressure	65.8 bar	954.5 psi
Flow Rate	317.832	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	948.9873987	65.43038
2	943.4602921	65.04929
3	937.9006146	64.66597
4	932.3077833	64.28036
5	926.681198	63.89242
6	921.0202402	63.50211
7	915.3242719	63.10938
8	909.5926356	62.7142
9	903.8246527	62.31651
10	898.0196227	61.91627
11	892.1768226	61.51342
12	886.2955054	61.10792
13	880.374899	60.69971
14	874.4142055	60.28873
15	868.4125994	59.87494
16	862.3692265	59.45826
17	856.2832025	59.03865
18	850.1536113	58.61603
19	843.9795038	58.19034
20	837.7598957	57.76151
21	831.4937659	57.32947
22	825.1800548	56.89416
23	818.8176615	56.45549

24	812.4054424	56.01338
25	805.9422081	55.56776
26	799.4267213	55.11853
27	792.8576939	54.66561
28	786.2337838	54.20891
29	779.553592	53.74833
30	772.815659	53.28376

At Outlet 3 - Exit Pressure = 53.28376 bar



(Figure 03 – Flow diagram for case 1)

From the calculations, we can clearly see that we have a need for a two-stage compression ratio at 53 miles from the starting point to keep up the pressure all the way upto the end. We also see that at the final outlet, after 100 miles we have gas at an existing pressure of 53.28 bar, which is well above our 45 bar mark and suffices our needs.

4.2 CASE 2 - 20X70 PIPELINE:

In the second case we consider the same diameter pipe of 20 inches but with an increased yield strength of 70000. Taking the same parameters under consideration we formulate the drop in pressure along the length of the pipeline for the same. This is as follows.

To determine the location of the compressor stations

20 X 70 pipeline

Inputs

Flow rate	15 Mmscmd	= 529.31	Mmscfd
Starting pressure	90 bar	1305.34 psi	
Final pressure	45 bar	652.67 psi	
Gas Gravity	0.66		
Internal Diameter	19.37840952	inches	
Compressibility Factor	0.996		
Flowing Temperature	537	R	
Friction Factor	0.02217		
Viscosity	0.009389	cp	

SECTION 1

Distance, miles	Pressure, psi	Pressure, bar
1	1294.6767	89.26481
2	1283.92485	88.5235
3	1273.08219	87.77592
4	1262.14639	87.02193
5	1251.11501	86.26134
6	1239.98549	85.49399

7	1228.75517	84.71968
8	1217.42126	83.93824
9	1205.98083	83.14945
10	1194.43083	82.3531
11	1182.76805	81.54898
12	1170.98912	80.73685
13	1159.09049	79.91647
14	1147.06844	79.08758
15	1134.91906	78.24991
16	1122.63819	77.40318
17	1110.22149	76.54707
18	1097.66435	75.68129
19	1084.96187	74.80548
20	1072.10891	73.9193
21	1059.09998	73.02237
22	1045.92926	72.11428
23	1032.59056	71.19461
24	1019.07729	70.2629
25	1005.3824	69.31867
26	991.498369	68.3614
27	977.41714	67.39054
28	963.130062	66.40548
29	948.627833	65.40558
30	933.900431	64.39017

At Outlet 1 - Exit Pressure = 64.39017 bar

SECTION 2

Inlet Pressure	64.4 bar	933.9 psi
Flow Rate	423.776	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	924.250556	63.72483
2	914.4993	63.0525
3	904.642941	62.37293
4	894.678004	61.68587
5	884.60082	60.99108
6	874.407508	60.28827
7	864.093959	59.57718
8	853.655815	58.85749
9	843.088447	58.1289
10	832.386935	57.39106
11	821.546036	56.6436
12	810.560158	55.88615
13	799.423323	55.1183
14	788.129133	54.33959
15	776.670722	53.54956
16	765.040711	52.7477
17	753.231153	51.93346
18	741.233465	51.10625
19	729.03836	50.26542
20	716.635758	49.41029
21	704.014694	48.5401
22	691.163201	47.65402
23	678.068175	46.75115
24	664.715225	45.8305

Compressor Station 1	outlet pressure =	77.454	bar
Two stage compression			

Distance, miles	Pressure, psi	Pressure, bar
1	1115.36598	76.90177
2	1107.29903	76.34558
3	1099.17288	75.7853
4	1090.98621	75.22085
5	1082.73764	74.65213
6	1074.42574	74.07904
7	1066.04904	73.50149
8	1057.60599	72.91936
9	1049.095	72.33255
10	1040.51439	71.74094
11	1031.86243	71.14441
12	1023.13731	70.54283
13	1014.33714	69.93608
14	1005.45995	69.32402
15	996.503683	68.70651
16	987.466187	68.08339

At Outlet 2 - Exit Pressure = 68.08339 barg

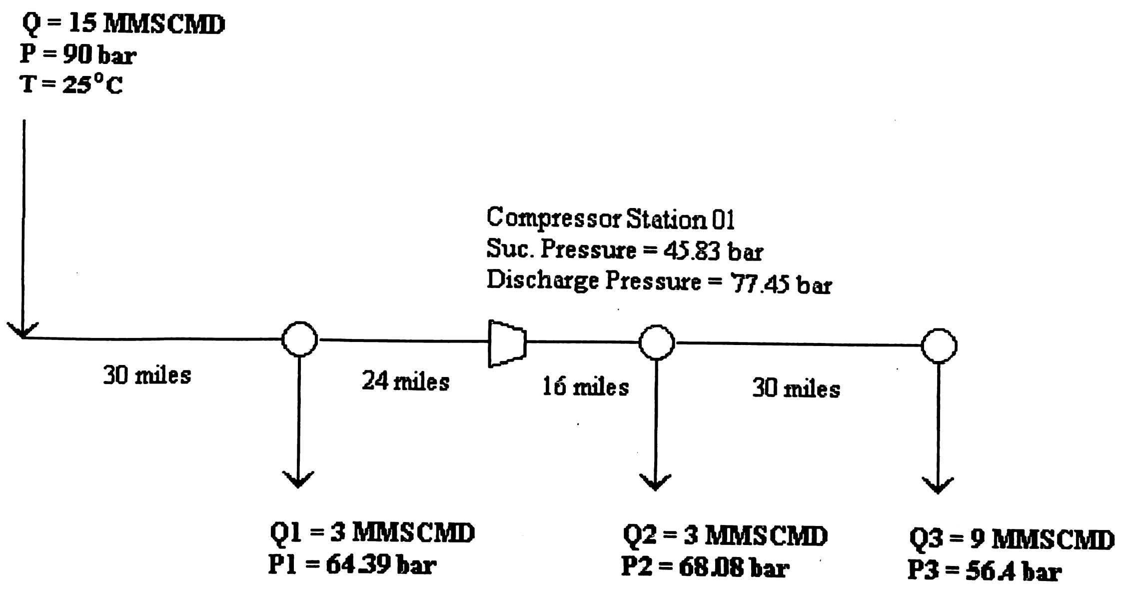
SECTION 3

Inlet Pressure	68.08 bar	987.5 psi
Flow Rate	317.832	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	982.286647	67.72628
2	977.079647	67.36727
3	971.844749	67.00633
4	966.5815	66.64345
5	961.289434	66.27857
6	955.968073	65.91168
7	950.616924	65.54273
8	945.235482	65.17169
9	939.823226	64.79853
10	934.379621	64.4232
11	928.904116	64.04568
12	923.396143	63.66592
13	917.855117	63.28388
14	912.280437	62.89952
15	906.671482	62.5128
16	901.027611	62.12366
17	895.348165	61.73208
18	889.632461	61.338
19	883.879797	60.94136
20	878.089447	60.54213
21	872.260659	60.14025
22	866.392657	59.73567
23	860.48464	59.32832
24	854.535778	58.91817

25	848.545212	58.50513
26	842.512051	58.08916
27	836.435375	57.67019
28	830.314228	57.24815
29	824.147618	56.82298
30	817.934518	56.3946

At Outlet 3 - Exit Pressure = 56.3946 bar



(Figure 04 – Flow diagram for case 2)

In this case we see that we have a need for a compressor at 54 miles. Though the better yield strength upheld the pressure, it was only for a one mile distance lead. With just one compressor in its line, the gas reaches the outlet line at a pressure of 56.39 bar.

4.3 CASE 3 - 22x60 PIPELINE:

In the third case, we consider a pipe with an outer diameter of 22 inches and of yield strength 60000. The same calculations are put out for this case also to study its effectivity.

To determine the location of the compressor stations

22 X 60 pipeline

Inputs

Flow rate	15 Mmscmd	= 529.31 Mmscfd
Starting pressure	90 bar	1305.34 psi
Final pressure	45 bar	652.67 psi
Gas Gravity	0.66	
Internal Diameter	21.2022922	inches
Compressibility Factor	0.996	
Flowing Temperature	537	R
Friction Factor	0.02263	
Viscosity	0.009389	cp

SECTION 1

Distance, miles	Pressure, psi	Pressure, bar
1	1298.38317	89.52036
2	1291.38887	89.03812
3	1284.35648	88.55326
4	1277.28537	88.06572

5	1270.1749	87.57547
6	1263.02439	87.08246
7	1255.83318	86.58665
8	1248.60054	86.08797
9	1241.32577	85.5864
10	1234.00811	85.08186
11	1226.6468	84.57432
12	1219.24104	84.06371
13	1211.79003	83.54998
14	1204.29291	83.03307
15	1196.74883	82.51292
16	1189.15689	81.98948
17	1181.51617	81.46267
18	1173.82572	80.93243
19	1166.08454	80.3987
20	1158.29164	79.86139
21	1150.44594	79.32045
22	1142.54637	78.7758
23	1134.59181	78.22735
24	1126.58107	77.67503
25	1118.51297	77.11875
26	1110.38625	76.55843
27	1102.1996	75.99398
28	1093.9517	75.42531
29	1085.64113	74.85232
30	1077.26646	74.2749

At Outlet 1 - Exit Pressure = 74.2749 bar

SECTION 2

Inlet Pressure	74.3 bar	1077.3 psi
Flow Rate	423.776	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	1071.81556	73.89908
2	1066.33679	73.52133
3	1060.82973	73.14163
4	1055.29393	72.75995
5	1049.72894	72.37626
6	1044.13429	71.99052
7	1038.5095	71.60271
8	1032.85408	71.21278
9	1027.16752	70.8207
10	1021.4493	70.42645
11	1015.69889	70.02997
12	1009.91574	69.63124
13	1004.09928	69.23021
14	998.248935	68.82684
15	992.364097	68.42109
16	986.444152	68.01293
17	980.488465	67.6023
18	974.496381	67.18916
19	968.467222	66.77346
20	962.400294	66.35516
21	956.294877	65.93421
22	950.150228	65.51055
23	943.965582	65.08413
24	937.740148	64.6549

25	931.473108	64.22281
26	925.163616	63.78778
27	918.810797	63.34977
28	912.413747	62.90871
29	905.971529	62.46454
30	899.483172	62.01718
31	892.94767	61.56657
32	886.36398	61.11264
33	879.731022	60.65532
34	873.047671	60.19452
35	866.312762	59.73016
36	859.525082	59.26217
37	852.683371	58.79045
38	845.786318	58.31491
39	838.832558	57.83547
40	831.820669	57.35201

At Outlet 2 - Exit Pressure = 57.35201 bar

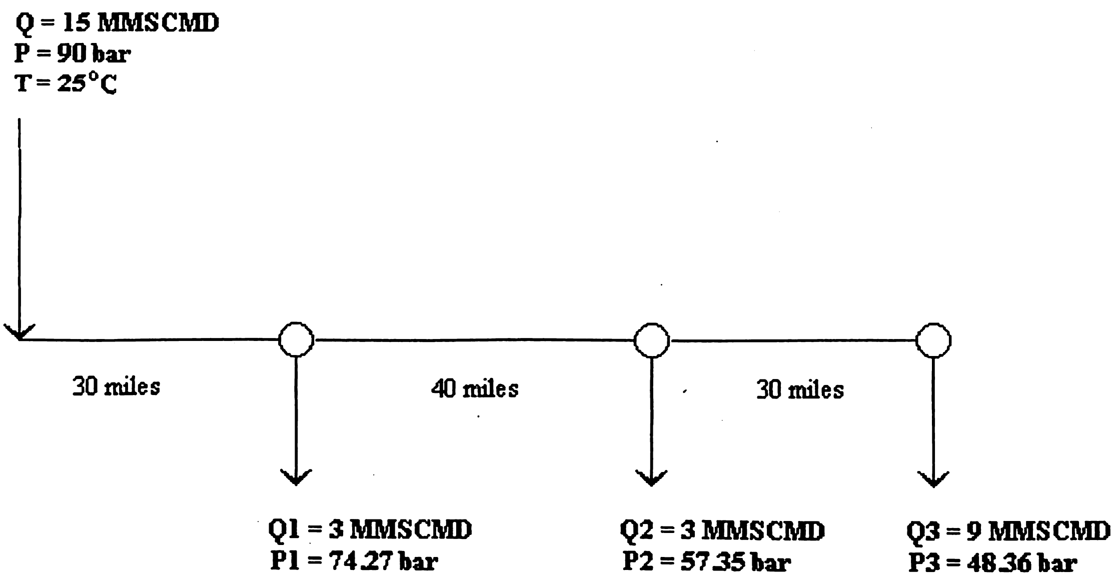
SECTION 3

Inlet Pressure	57.4 bar	831.8 psi
Flow Rate	317.832	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	827.804319	57.0751
2	823.768388	56.79683
3	819.712586	56.51719
4	815.636616	56.23616

5	811.540175	55.95372
6	807.422951	55.66985
7	803.284624	55.38452
8	799.124867	55.09772
9	794.943344	54.80941
10	790.739708	54.51958
11	786.513605	54.2282
12	782.264672	53.93525
13	777.992534	53.64069
14	773.696807	53.34451
15	769.377096	53.04668
16	765.032994	52.74717
17	760.664083	52.44594
18	756.269934	52.14297
19	751.850104	51.83824
20	747.404138	51.5317
21	742.931566	51.22333
22	738.431904	50.91309
23	733.904656	50.60094
24	729.349305	50.28686
25	724.765324	49.97081
26	720.152165	49.65274
27	715.509264	49.33263
28	710.836038	49.01042
29	706.131885	48.68608
30	701.396183	48.35956

At Outlet 3 - Exit Pressure = 48.35956 bar



(Figure 05 – Flow diagram for case 3)

We can clearly infer from the calculations that the gas travels the whole 100 miles without the need of any external compressor station to increase the pressure. The gas reaches the last and final outlet at a pressure of 48.36 bar.

4.4 CASE 4 - 22x70 PIPELINE:

In the fourth case we consider the same diameter pipe of 22 inches but with an increased yield strength of 70000. Taking the same parameters under consideration we formulate the drop in pressure along the length of the pipeline for the same. This is as folіows.

To determine the location of the compressor stations

22 X 70 pipeline

Inputs

Flow rate	15 Mmscmd	= 529.31	Mmscfd
Starting pressure	90 bar	1305.34 psi	
Final pressure	45 bar	652.67 psi	
Gas Gravity	0.66		
Internal Diameter	21.3162505	inches	
Compressibility Factor	0.996		
Flowing Temperature	537	R	
Friction Factor	0.02266		
Viscosity	0.009389	cp	

SECTION 1

Distance, miles	Pressure, psi	Pressure, bar
1	1298.5583	89.53244
2	1291.741	89.0624
3	1284.88752	88.58987
4	1277.9973	88.11481

5	1271.06972	87.63717
6	1264.10418	87.15691
7	1257.10005	86.67399
8	1250.05667	86.18837
9	1242.97338	85.69999
10	1235.84949	85.20882
11	1228.6843	84.7148
12	1221.47708	84.21788
13	1214.22708	83.71801
14	1206.93353	83.21513
15	1199.59564	82.7092
16	1192.21258	82.20016
17	1184.78352	81.68794
18	1177.30757	81.1725
19	1169.78386	80.65375
20	1162.21143	80.13165
21	1154.58935	79.60613
22	1146.91661	79.07711
23	1139.19219	78.54453
24	1131.41504	78.00832
25	1123.58406	77.46839
26	1115.69812	76.92467
27	1107.75603	76.37709
28	1099.7566	75.82555
29	1091.69855	75.26996
30	1083.58058	74.71025

At Outlet 1 - Exit Pressure = 74.71025 bar

SECTION 2

Inlet Pressure	74.7 bar	1083.6 psi
Flow Rate	423.776	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	1078.29799	74.34603
2	1072.9894	73.98001
3	1067.65441	73.61218
4	1062.29263	73.2425
5	1056.90365	72.87094
6	1051.48705	72.49748
7	1046.0424	72.12208
8	1040.56926	71.74472
9	1035.06719	71.36537
10	1029.53571	70.98399
11	1023.97435	70.60054
12	1018.38262	70.21501
13	1012.76001	69.82734
14	1007.10602	69.43751
15	1001.4201	69.04548
16	995.701719	68.65121
17	989.950303	68.25467
18	984.165277	67.8558
19	978.346045	67.45458
20	972.491991	67.05096
21	966.602485	66.64489
22	960.676872	66.23634
23	954.714483	65.82524
24	948.714622	65.41157

25	942.676574	64.99526
26	936.599601	64.57627
27	930.482941	64.15454
28	924.325805	63.73002
29	918.127379	63.30265
30	911.88682	62.87238
31	905.603259	62.43914
32	899.275794	62.00288
33	892.903491	61.56353
34	886.485382	61.12101
35	880.020468	60.67527
36	873.507707	60.22623
37	866.946021	59.77382
38	860.334292	59.31796
39	853.671356	58.85857
40	846.956004	58.39556

At Outlet 2 - Exit Pressure = 65.80925 bar

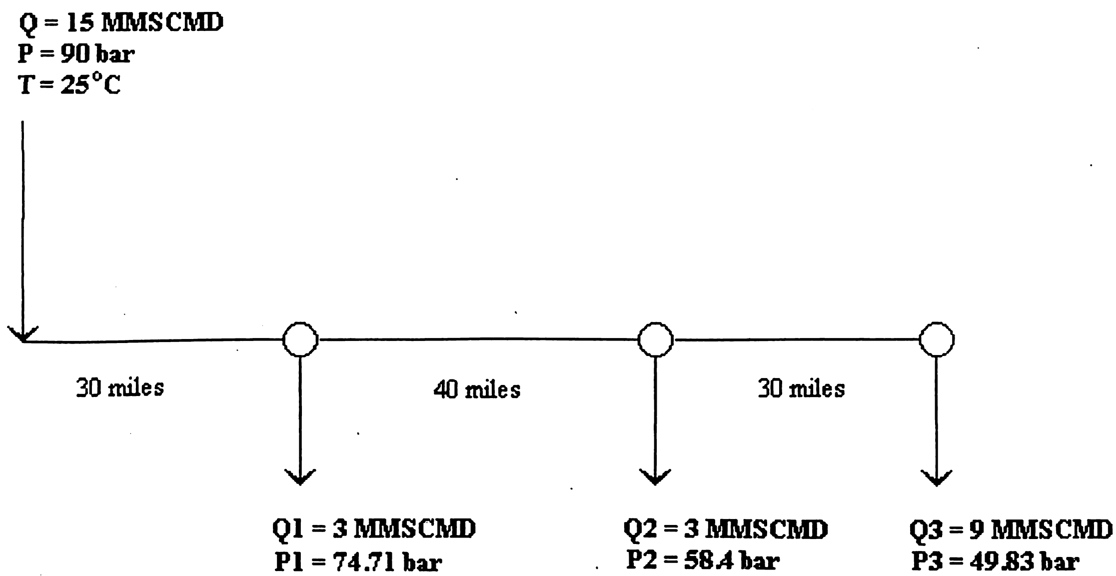
SECTION 3

Inlet Pressure	58.4 bar	846.95 psi
Flow Rate	317.832	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	843.111023	58.13046
2	839.248427	57.86414
3	835.367971	57.59659
4	831.469406	57.3278

5	827.552474	57.05773
6	823.616915	56.78638
7	819.66246	56.51373
8	815.688833	56.23976
9	811.695754	55.96445
10	807.682935	55.68778
11	803.650078	55.40972
12	799.596881	55.13026
13	795.523034	54.84938
14	791.428217	54.56705
15	787.312103	54.28326
16	783.174357	53.99797
17	779.014633	53.71117
18	774.832577	53.42282
19	770.627827	53.13292
20	766.400008	52.84142
21	762.148737	52.5483
22	757.873619	52.25354
23	753.574248	51.95711
24	749.250207	51.65898
25	744.901066	51.35912
26	740.526382	51.05749
27	736.125701	50.75408
28	731.698553	50.44884
29	727.244455	50.14174
30	722.762909	49.83275

At Outlet 3 - Exit Pressure = 49.83275 bar



(Figure 06 – Flow diagram for case 4)

We can clearly infer from the calculations that the gas travels the whole 100 miles without the need of any external compressor station to increase the pressure. The gas reaches the last and final outlet at a pressure of 49.83 bar.

4.5 CASE 5 - 24x60 PIPELINE:

In the fifth case, we consider a pipe with an outer diameter of 24 inches and of yield strength 60000. The same calculations are put out for this case also to study its effectivity.

To determine the location of the compressor stations

24 X 60 pipeline

Inputs

Flow rate	15 Mmscmd	= 529.31	Mmscfd
Starting pressure	90 bar	1305.34 psi	
Final pressure	45 bar	652.67 psi	
Gas Gravity	0.66		
Internal Diameter	23.12977333	inches	
Compressibility Factor	0.996		
Flowing Temperature	537	R	
Friction Factor	0.0231		
Viscosity	0.009389	cp	

SECTION 1

Distance, miles	Pressure, psi	Pressure, bar
1	1300.7315	89.68228
2	1296.1066	89.3634
3	1291.4652	89.04338
4	1286.807	88.72221
5	1282.1319	88.39988

6	1277.4396	88.07636
7	1272.7301	87.75165
8	1268.0031	87.42573
9	1263.2584	87.0986
10	1258.4958	86.77023
11	1253.7151	86.44061
12	1248.9162	86.10973
13	1244.0987	85.77758
14	1239.2624	85.44413
15	1234.4073	85.10938
16	1229.5329	84.77331
17	1224.6392	84.4359
18	1219.7258	84.09713
19	1214.7926	83.757
20	1209.8392	83.41547
21	1204.8655	83.07255
22	1199.8711	82.7282
23	1194.8559	82.38241
24	1189.8196	82.03517
25	1184.7618	81.68645
26	1179.6823	81.33623
27	1174.5809	80.9845
28	1169.4573	80.63124
29	1164.311	80.27642
30	1159.142	79.92002

At Outlet 1 - Exit Pressure = 79.92002 bar

SECTION 2

Inlet Pressure	79.9 bar	1159.1 psi
Flow Rate	423.776	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	1155.7868	79.68869
2	1152.4217	79.45668
3	1149.0469	79.22399
4	1145.6621	78.99062
5	1142.2672	78.75655
6	1138.8623	78.52179
7	1135.4471	78.28632
8	1132.0217	78.05014
9	1128.5858	77.81325
10	1125.1394	77.57563
11	1121.6825	77.33728
12	1118.2148	77.0982
13	1114.7364	76.85837
14	1111.2471	76.61779
15	1107.7468	76.37645
16	1104.2354	76.13435
17	1100.7128	75.89147
18	1097.1789	75.64782
19	1093.6336	75.40338
20	1090.0767	75.15814
21	1086.5082	74.9121
22	1082.928	74.66525
23	1079.3358	74.41758
24	1075.7317	74.16909

25	1072.1155	73.91976
26	1068.487	73.66958
27	1064.8461	73.41855
28	1061.1928	73.16666
29	1057.5268	72.91391
30	1053.8481	72.66027
31	1050.1565	72.40574
32	1046.4519	72.15032
33	1042.7341	71.89398
34	1039.003	71.63673
35	1035.2585	71.37856
36	1031.5004	71.11944
37	1027.7285	70.85938
38	1023.9427	70.59836
39	1020.1429	70.33637
40	1016.3289	70.07341

At Outlet 2 - Exit Pressure = 70.07341 bar

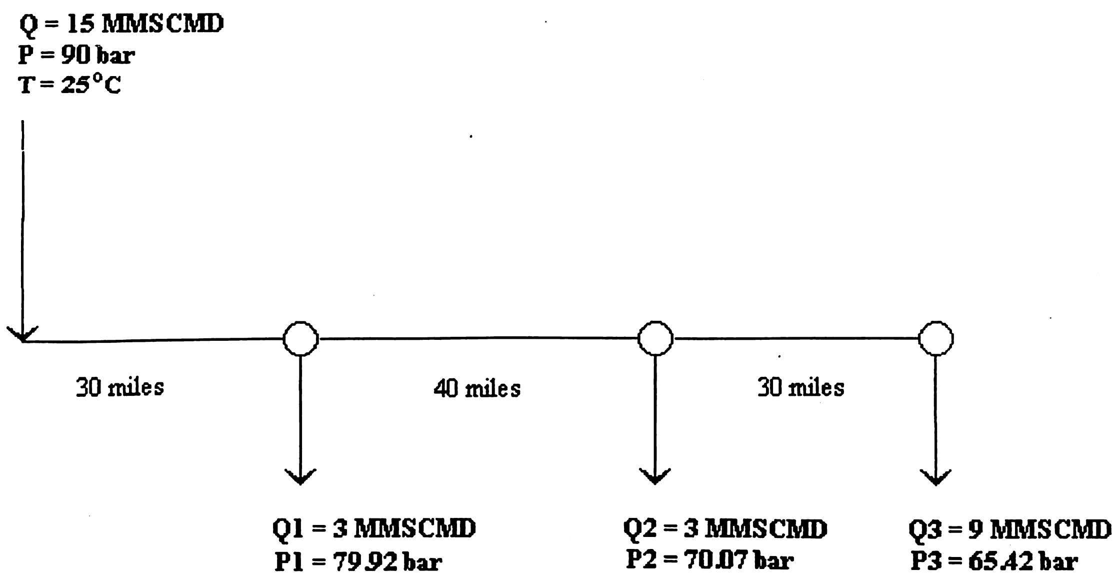
SECTION 3

Inlet Pressure	70 bar	1016.3 psi
Flow Rate	317.832	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	1014.1523	69.92334
2	1011.971	69.77294
3	1009.785	69.62222

4	1007.5942	69.47117
5	1005.3987	69.3198
6	1003.1983	69.16809
7	1000.9932	69.01605
8	998.78314	68.86367
9	996.5682	68.71096
10	994.34832	68.5579
11	992.12348	68.4045
12	989.89364	68.25076
13	987.65876	68.09667
14	985.41882	67.94223
15	983.17377	67.78744
16	980.92358	67.6323
17	978.66822	67.4768
18	976.40765	67.32093
19	974.14184	67.16471
20	971.87074	67.00813
21	969.59432	66.85117
22	967.31255	66.69385
23	965.02538	66.53615
24	962.73277	66.37809
25	960.4347	66.21964
26	958.13111	66.06081
27	955.82197	65.9016
28	953.50724	65.74201
29	951.18687	65.58202
30	948.86083	65.42165

At Outlet 3 - Exit Pressure = 65.42165 bar



(Figure 07 – Flow diagram for case 5)

We can clearly infer from the calculations that the gas travels the whole 100 miles without the need of any external booster or compression station to increase the pressure. The gas reaches the last and final outlet at a pressure of 65.42 bar.

4.6 CASE 6 - 24x70 PIPELINE:

In the fourth case we consider the same diameter pipe of 24 inches but with an increased yield strength of 70000. Taking the same parameters under consideration we formulate the drop in pressure along the length of the pipeline for the same. This is as follows.

To determine the location of the compressor stations

24 X 70 pipeline

Inputs

Flow rate	15 Mmscmd	= 529.31	Mmscfd
Starting pressure	90 bar	1305.34 psi	
Final pressure	45 bar	652.67 psi	
Gas Gravity	0.66		
Internal Diameter	23.25409	inches	
Compressibility Factor	0.996		
Flowing Temperature	537	R	
Friction Factor	0.02313		
Viscosity	0.009389	cp	

SECTION 1

Distance, miles	Pressure, psi	Pressure, bar
1	1300.846	89.6902
2	1296.337	89.37931
3	1291.813	89.06734
4	1287.272	88.75426
5	1282.715	88.44008
6	1278.142	88.12478

7	1273.552	87.80835
8	1268.946	87.49077
9	1264.324	87.17203
10	1259.684	86.85213
11	1255.027	86.53104
12	1250.352	86.20876
13	1245.661	85.88527
14	1240.951	85.56055
15	1236.223	85.2346
16	1231.478	84.90739
17	1226.714	84.57892
18	1221.931	84.24917
19	1217.13	83.91813
20	1212.309	83.58577
21	1207.469	83.25209
22	1202.61	82.91706
23	1197.731	82.58067
24	1192.833	82.24291
25	1187.914	81.90376
26	1182.974	81.56319
27	1178.014	81.2212
28	1173.033	80.87776
29	1168.03	80.53286
30	1163.006	80.18647

At Outlet 1 - Exit Pressure = 80.18647 bar

SECTION 2

Inlet Pressure	80.2 bar	1163 psi
Flow Rate	423.776	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	1159.745	79.96162
2	1156.476	79.73618
3	1153.196	79.51009
4	1149.908	79.28336
5	1146.61	79.05598
6	1143.303	78.82794
7	1139.986	78.59924
8	1136.659	78.36988
9	1133.323	78.13984
10	1129.976	77.90912
11	1126.62	77.67771
12	1123.254	77.44562
13	1119.877	77.21283
14	1116.491	76.97933
15	1113.094	76.74512
16	1109.687	76.5102
17	1106.269	76.27455
18	1102.84	76.03817
19	1099.401	75.80105
20	1095.952	75.5632
21	1092.491	75.32458
22	1089.019	75.08522
23	1085.536	74.84508

24	1082.042	74.60417
25	1078.537	74.36249
26	1075.02	74.12001
27	1071.492	73.87674
28	1067.952	73.63266
29	1064.4	73.38778
30	1060.836	73.14207
31	1057.26	72.89553
32	1053.673	72.64816
33	1050.072	72.39995
34	1046.46	72.15087
35	1042.835	71.90094
36	1039.197	71.65014
37	1035.547	71.39845
38	1031.884	71.14587
39	1028.207	70.89239
40	1024.518	70.63801

At Outlet 2 - Exit Pressure = 70.63801 bar

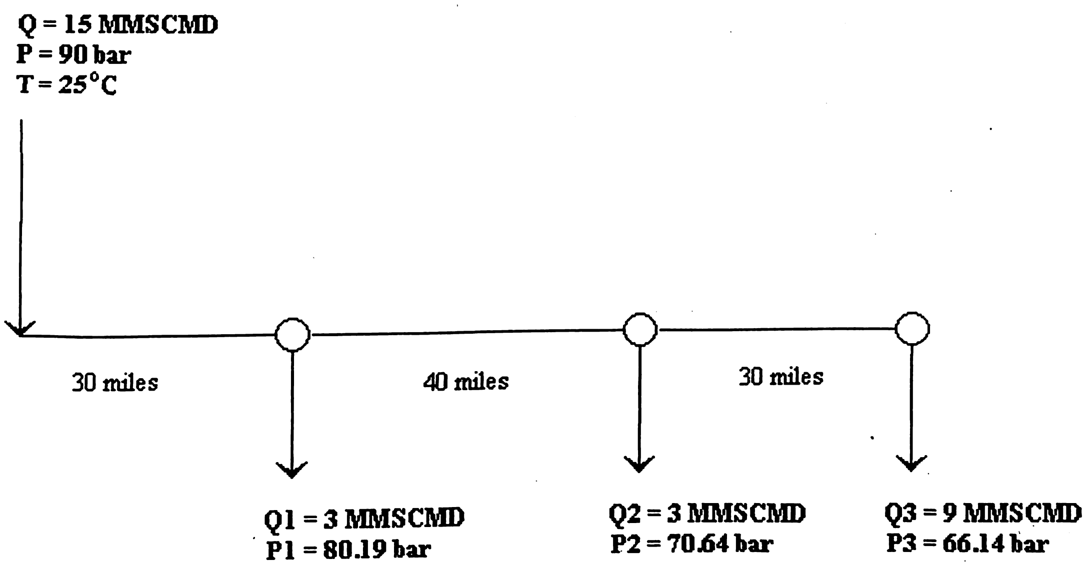
SECTION 3

Inlet Pressure	70.6 bar	1024.5 psi
Flow Rate	317.832	Mmscfd

Distance, miles	Pressure, psi	Pressure, bar
1	1022.413	70.49287
2	1020.303	70.34741
3	1018.189	70.20165

4	1016.07	70.05559
5	1013.948	69.90922
6	1011.82	69.76254
7	1009.688	69.61556
8	1007.552	69.46826
9	1005.411	69.32066
10	1003.266	69.17273
11	1001.116	69.02449
12	998.961	68.87593
13	996.8017	68.72705
14	994.6376	68.57785
15	992.4689	68.42832
16	990.2954	68.27846
17	988.1172	68.12828
18	985.9341	67.97776
19	983.7462	67.82691
20	981.5534	67.67572
21	979.3556	67.52419
22	977.153	67.37232
23	974.9454	67.22011
24	972.7327	67.06756
25	970.515	66.91465
26	968.2923	66.7614
27	966.0644	66.60779
28	963.8314	66.45383
29	961.5932	66.29951
30	959.3497	66.14483

At Outlet 3 - Exit Pressure = 66.14483 bar



(Figure 08 – Flow diagram for case 6)

We can clearly infer from the calculations that the gas travels the whole 100 miles without the need of any external booster or compression station to increase the pressure. The gas reaches the last and final outlet at a pressure of 66.14 bar.

The following figure shows a brief summary of the above calculations on the basis of the number of compressors used and the shift in the pressure of the gas in the pipeline.

Pipe dia	Grade	No. of Compressors	P1, bar	P2, bar	P3, bar	Throughput, MMSCMD
20	X 60	1	63.61	65.81	53.28	15
20	X 70	1	64.39	68.08	56.4	15
22	X 60	nil	74.28	53.35	48.36	15
22	X 70	nil	74.71	58.4	49.83	15
24	X 60	nil	79.92	70.07	65.42	15
24	X 70	nil	80.19	70.64	66.14	15

(Table 09 – Summary of Hydraulic Performance)

CHAPTER 5: ECONOMICAL ANALYSIS

External coating Cost	= 1500 Rs/m^2
Internal coating Cost	= 300 Rs/m^2
Steel cost	= 65 Rs/Kg
Construction Cost	= 40% in excess of Line pipe cost
Power cost	= HP*0.764*Operating Hours*Unit Cost/Motor Efficiency

Weight Of steel	= 16*Outer Diameter*Thickness
	= Tons/km
Internal coating area	= 3.14*Inside Diameter*Length
	= Area in m^2
External Coating Area	= 3.14*Outer Diameter*Length
	= Area in m^2

Infrastructure costs:

CASE 1

Weight of Steel, Kg	1734860.32
Internal Coating Area, Sq m	2968810.978
External Coating Area, Sq m	3080508.505
Steel Cost, Rs	112765900
Construction Cost, Rs	157872260
Internal Coating Cost, Rs	890643293.3
External Coating Cost, Rs	4620762757
Total Cost, Rs	5782044211

CASE 2

Weight of Steel, Kg	1487023.815
Internal Coating Area, Sq m	2984767.767
External Coating Area, Sq m	3080508.505
Steel Cost, Rs	96656560
Construction Cost, Rs	135319184
Internal Coating Cost, Rs	895430330.1
External Coating Cost, Rs	4620762757
Total Cost, Rs	5748168832

CASE 3

Weight of Steel, Kg	2099184.146
Internal Coating Area, Sq m	3265692.075
External Coating Area, Sq m	3388559.355
Steel Cost, Rs	136446960
Construction Cost, Rs	191025744
Internal Coating Cost, Rs	979707622.6
External Coating Cost, Rs	5082839033
Total Cost, Rs	6390019360

CASE 4

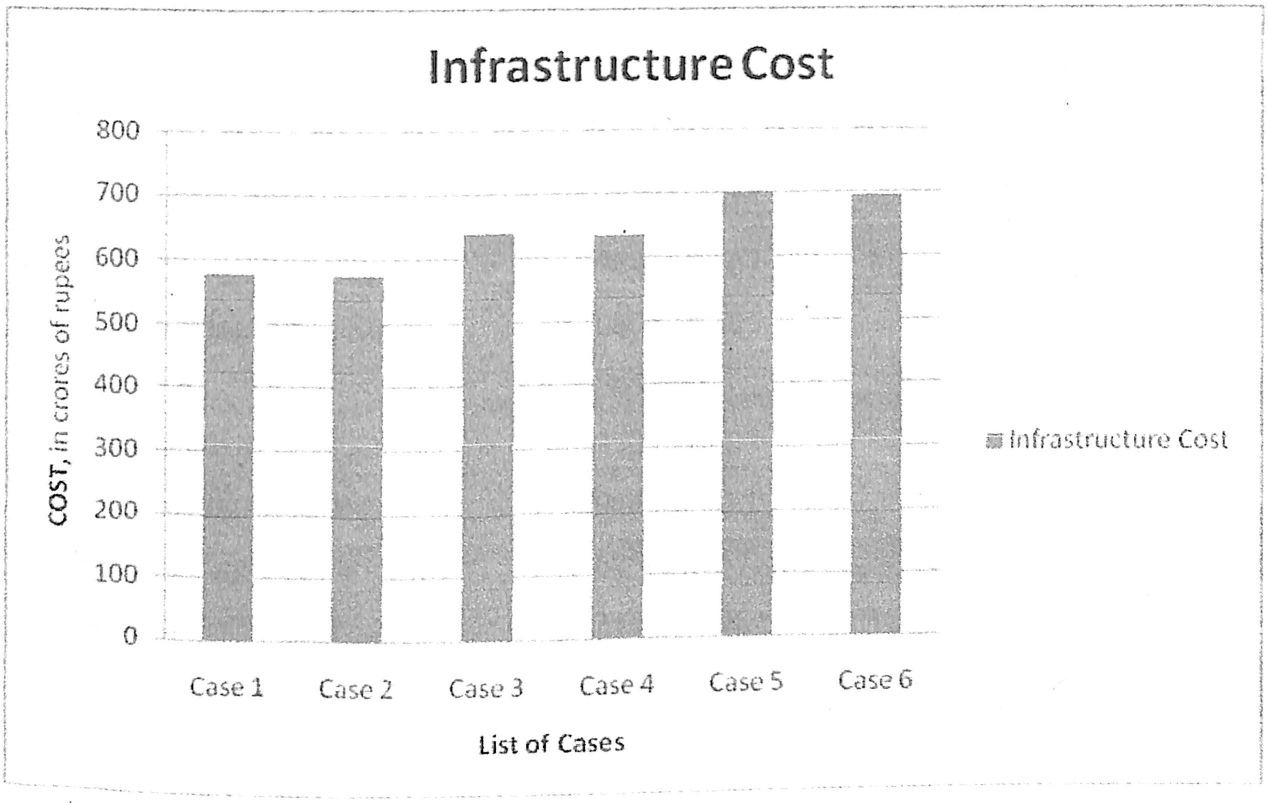
Weight of Steel, Kg	1799301.448
Internal Coating Area, Sq m	3283244.545
External Coating Area, Sq m	3388559.355
Steel Cost, Rs	116954591
Construction Cost, Rs	163736427.4
Internal Coating Cost, Rs	984973363.5
External Coating Cost, Rs	5082839033
Total Cost, Rs	6348503415

CASE 5

Weight of Steel, Kg	2498200.01
Internal Coating Area, Sq m	3562573.173
External Coating Area, Sq m	3696610.206
Steel Cost, Rs	162383000
Construction Cost, Rs	227336200
Internal Coating Cost, Rs	1068771952
External Coating Cost, Rs	5544915309
Total Cost, Rs	7003406461

CASE 6

Weight of Steel, Kg	2141314.294
Internal Coating Area, Sq m	3581721.321
External Coating Area, Sq m	3696610.206
Steel Cost, Rs	139185429.5
Construction Cost, Rs	194859602
Internal Coating Cost, Rs	1074516396
External Coating Cost, Rs	5544915309
Total Cost, Rs	6953476737



Operating costs: Considering the life period of the pipeline to be 30 years, we calculate the costs incurred with the pipeline over this period.

CASE 1

Weight of Steel, Kg	1734860.32
Internal Coating Area, Sq m	2968810.978
External Coating Area, Sq m	3080508.505
Steel Cost, Rs	112765900
Construction Cost, Rs	157872260
Internal Coating Cost, Rs	890643293.3
External Coating Cost, Rs	4620762757
Power cost, Rs	3105717300
Maintenance Cost, Rs	47361678
Total Cost, Rs	8935123189

CASE 2

Weight of Steel, Kg	1487023.815
Internal Coating Area, Sq m	2984767.767
External Coating Area, Sq m	3080508.505
Steel Cost, Rs	96656560
Construction Cost, Rs	135319184
Internal Coating Cost, Rs	895430330.1
External Coating Cost, Rs	4620762757
Power Cost, Rs	3235745898
Maintenance Cost, Rs	40595755.2
Total Cost, Rs	9024510485

CASE 3

Weight of Steel, Kg	2099184.146
Internal Coating Area, Sq m	3265692.075
External Coating Area, Sq m	3388559.355
Steel Cost, Rs	136446960
Construction Cost, Rs	191025744
Internal Coating Cost, Rs	979707622.6
External Coating Cost, Rs	5082839033
Maintenance Cost, Rs	57307723.2
Total Cost, Rs	6447327083

CASE 4

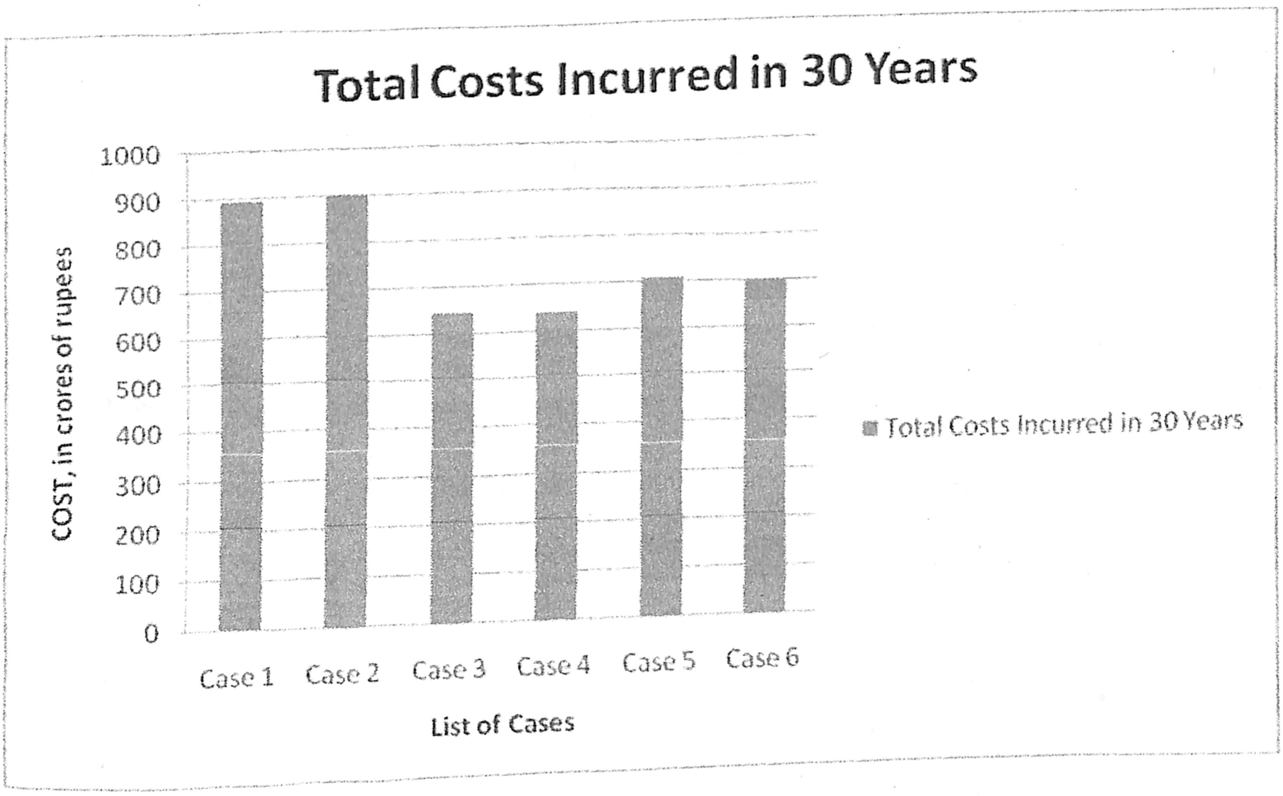
Weight of Steel, Kg	1799301.448
Internal Coating Area, Sq m	3283244.545
External Coating Area, Sq m	3388559.355
Steel Cost, Rs	116954591
Construction Cost, Rs	163736427.4
Internal Coating Cost, Rs	984973363.5
External Coating Cost, Rs	5082839033
Maintenance Cost, Rs	49120928.22
Total Cost, Rs	6397624343

CASE 5

Weight of Steel, Kg	2498200.01
Internal Coating Area, Sq m	3562573.173
External Coating Area, Sq m	3696610.206
Steel Cost, Rs	162383000
Construction Cost, Rs	227336200
Internal Coating Cost, Rs	1068771952
External Coating Cost, Rs	5544915309
Maintenance Cost, Rs	68200860
Total Cost, Rs	7071607321

CASE 6

Weight of Steel, Kg	2141314.294
Internal Coating Area, Sq m	3581721.321
External Coating Area, Sq m	3696610.206
Steel Cost, Rs	139185429.5
Construction Cost, Rs	194859602
Internal Coating Cost, Rs	1074516396
External Coating Cost, Rs	5544915309
Maintenance Cost, Rs	58457880.6
Total Cost, Rs	7011934617



The Hydraulic analysis was performed using the Panhandle B equation. The cost analysis was conducted taking into account the various steel cost, construction cost, investment and operating costs. The results show that, case 4, i.e. the 22 inch pipe with X 70 grade proved to be most economical according to the graph.

CONCLUSION:

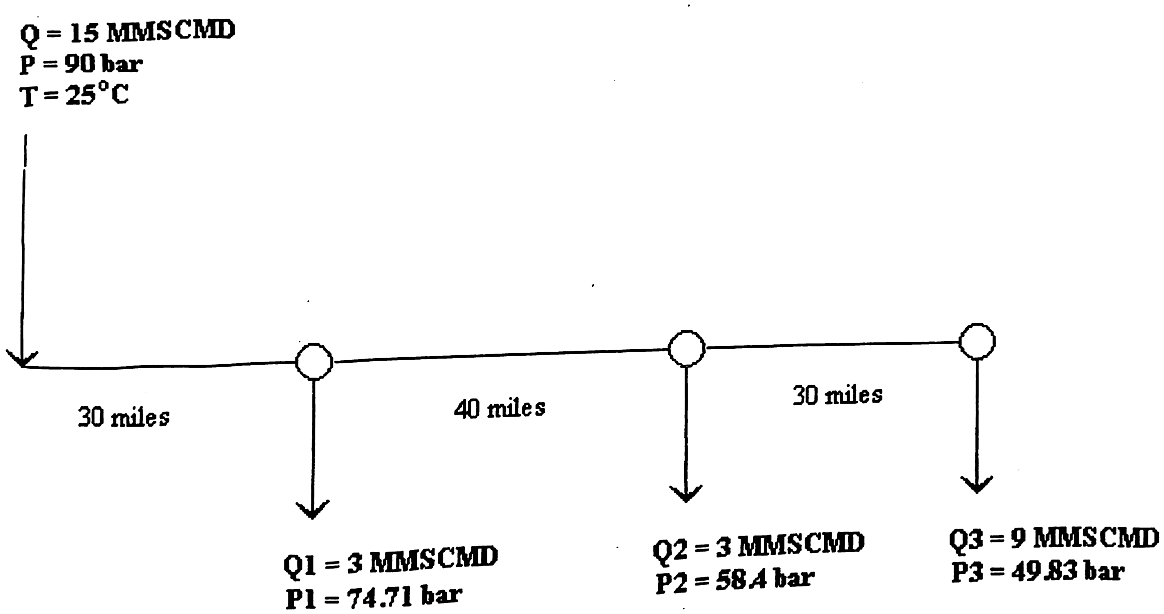
From the hydraulic performance analysis and the total cost analysis, we can conclude that the following design parameters give the optimized design of a natural gas pipeline for the given inputs.

CASE 4 - 20 X 70 PIPELINE_ INTERNAL COATED_ WITHOUT COMPRESSOR

Optimum Diameter : 22 Inch

Thickness : 0.342 Inch

Internal Coated
Pipe Roughness : 5 Micron



(Figure 10 – Optimized flow diagram)

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