# Optimal Design of a Gas Transmission Pipeline

© Copyright (2012) Harvey D. Hensley. This document is for your private use. Any commercial use is prohibited without written permission by the author. Use at your own risk. The author makes no guarantee of the accuracy of program results.

| | |
|---|---|
| ORIGIN = 1 | This worksheet was developed with ORIGIN = 1 for vector indexes. |

## Objectives

Design a gas pipeline to obtain the maximum netback price (i.e. lowest transportation cost) at the gas supply source.
Both onshore and offshore pipelines may be designed. The example is an onshore line.

The following variables are examined:
- number of booster stations
- number of spare compressors at compressor stations
- delivery pressure (at market pressure or below market pressure)
- pipe grade (X70 and X80)
- pipe diameter

Pipe wall thickness is determined by the maximum compressor discharge pressure required for each case.

netback = price of gas at source that allows recovery of the cost of transmission (including ROI) to the market price...this price sets the maximur value that the transportation company or division can pay for the gas supply.

## Input

All input may be changed for different projects, but the inputs highlighted in green may be varied to determine their effect on the optimum of a given project.

| | |
|---|---|
| n_booster := 1 | number of booster stations, excluding the inlet and recompression compressors<br>this variable affects the optimum diameter and netback |
| spares := 1 | number of spares at compressor stations<br>this variable changes the netback but not the optimum diameter |
| fuel_fraction := 0.025 | fraction of production that is needed for fuel for boosters and the recompression compressors<br>update this guess after a first pass through the program |

$\text{Cap\_scf} := 0.6 \cdot 10^{9} \cdot \frac{\text{ft}^{3}}{\text{day}}$ production capacity at the market in scfd

$L := 1500 \cdot \text{km}$ pipeline length

$SG := .595$ gas specific gravity

$Mw := SG \cdot 29 \cdot \frac{\text{lb}}{\text{lb} \cdot \text{mole}}$ gas molecular weight

$$\text{Cap\_wt} := \frac{\text{Cap\_scf} \cdot Mw}{379 \cdot \frac{\text{ft}^{3}}{\text{lb} \cdot \text{mole}}}$$

$\text{Cap\_wt} = 4.526 \times 10^{6} \cdot \frac{\text{tonne}}{\text{yr}}$ production capacity by weight

$Mw = 16 \frac{\text{lb}}{\text{lb} \cdot \text{mole}} \cdot (1 - \text{ethane}) + 30 \cdot \frac{\text{lb}}{\text{lb} \cdot \text{mole}} \cdot \text{ethane}$ solve for "ethane" using symbolic math

$\text{ethane} := \frac{Mw \cdot \text{mole}}{14} - \frac{8}{7}$ symbolic solution of above

$\text{ethane} = 0.09$ ethane fraction in methane-ethane mixture of given Mw

$p0 := 250 \cdot \frac{\text{lbf}}{\text{in}^{2}}$ supply pressure for gas prior to compression

© Copyright (2012) Harvey D. Hensley

$p2 := \begin{pmatrix} 600 \\ 250 \end{pmatrix} \cdot \frac{lbf}{in^2}$ pipeline outlet pressure

$pr := 600 \cdot \frac{lbf}{in^2}$ pressure to market pipeline

$\varepsilon := .00015 \cdot ft$ pipe roughness

$T0 := (120 + 460) \cdot R$ supply temperature

$T_{amb} := (90 + 460) \cdot R$ ambient temperature above ground

$T_{pipe} := (90 + 460) \cdot R$ pipeline temperature

$Rg := 10.7315 \cdot \frac{lbf}{in^2} \cdot \frac{ft^3}{lb \cdot mole \cdot R}$ gas law constant

critical constants and physical properties (methane)

$T_c := 190.6 \cdot K$

$V_c := 99 \cdot \frac{cm^3}{gm \cdot mole}$

$k := 1.28$ heat capacity ratio

$P_c := 45.4 \cdot atm$

$Z_c := .288$

$\mu := .00008 \cdot poise$

$LHV := 850 \cdot \frac{BTU}{ft^3}$ lower heating value of gas

© Copyright (2012) Harvey D. Hensley

compressor efficiencies

| | |
|---|---|
| $eff\_poly := .80$ | polytropic compression efficiency |
| $eff\_turbine := .22$ | turbine efficiency |

steel properties

| | |
|---|---|
| $\rho_{steel} := 490 \cdot \frac{lb}{ft^3}$ | density |
| $F := .80$ | B31.8 factor for pipe yield stress |
| $S := \begin{pmatrix} 70000 \\ 80000 \end{pmatrix} \cdot \frac{lbf}{in^2}$ | pipe yield stress |

## Cost Parameters

WARNING! All economic data are extremely out-of-date.

No unit exists for dollars, so financial variables assume US dollar is the unit of currency.

Offshore pipeline

| | |
|---|---|
| $matl\_offshore := \begin{pmatrix} .486 \\ .50 \end{pmatrix} \cdot \frac{1}{lb}$ | cost of pipe plus coatings, anodes |
| $day\_per\_inchmi := .03 \cdot \frac{day}{mi \cdot in}$ | slope for lay rate |
| $day\_per\_mi := .1 \cdot \frac{day}{mi}$ | intercept of lay rate |

© Copyright (2012) Harvey D. Hensley

| | |
|---|---|
| $\text{lay\_barge} := 13.6 \cdot 10^{6}$ | annual fixed cost for barge |
| $\text{barge\_rate} := \frac{230000}{\text{day}}$ | daily cost of lay barge |
| $\text{connects} := 1.01$ | factor for installation of connectors |
| $\text{survey\_daymi} := .075 \cdot \frac{\text{day}}{\text{mi}}$ | inverse of survey speed |
| $\text{survey\_rate\_off} := \frac{2000}{\text{day}}$ | survey cost per day |

Overland pipeline (onshore)

| | |
|---|---|
| $\text{matl\_onshore} := \begin{pmatrix} .386 \\ .40 \end{pmatrix} \cdot \frac{1}{\text{lb}}$ | cost of pipe and associated materials |
| $\text{install\_onshore} := \frac{25000}{\text{in} \cdot \text{mi}}$ | installation factor |
| $\text{opex\_pipeline} := .04$ | annual fraction of pipeline investment |

Compressors

| | |
|---|---|
| $\text{ref\_comp\_inv} := 12.5 \cdot 10^{6}$ | equipment cost of base system (single body, no intercooler, one aftercooler ($2 MM)<br>add $2 MM if discharge press >700 psi (add cooler)<br>add $3 MM if discharge press >1000 psi (add body and cooler) |
| $\text{comp\_instl} := 2.5$ | multiplier of equipment cost for installed cost |
| $\text{turbine\_capacity} := 25000 \cdot \text{hp}$ | power per turbine |
| $\text{comp\_maint} := 100000$ | annual maintenance for one gas turbine and compressor |

© Copyright (2012) Harvey D. Hensley

### Financial parameters

| | |
|---|---|
| $NROI := .17$ | net return on equity (17% gives 17% IRR for 25 yr) |
| $equity := 1$ | ratio of equity to total capital |
| $interest := .09$ | interest on debt |
| $tax := .45$ | Federal and state tax rate |
| $life := 25$ | project life |
| $dep := \frac{1}{life}$ | straight line depreciation |
| $market := \frac{4.00}{10^6 \cdot BTU}$ | market value of gas |

## Calculations

| | |
|---|---|
| $i := 1 .. 8$ | index for pipe OD |
| $p := 1 .. 2$ | index for outlet pressure |
| $s := 1 .. 2$ | index for pipe grade |

### Pipeline size and pressure drop

| | |
|---|---|
| $D_i := [24 + 2 \cdot (i - 1)] \cdot in$ | pipe OD |
| $t := .5 \cdot in$ | guess for thickness |
| $d_i := D_i - 2 \cdot t$ | ID |
| $G(w, d) := \frac{w}{\left[\frac{\pi \cdot (d)^2}{4}\right]}$ | mass flux |

© Copyright (2012) Harvey D. Hensley

$\text{dmax} := \text{rows}(D)$

$$\text{Re} := \frac{G\left(\text{Cap\_wt}, d_{\text{dmax}}\right) \cdot d_{\text{dmax}}}{\mu}$$

$\text{Re} = 2.429 \times 10^{7}$ Reynolds Number for largest diameter indicates that all cases are turbulent

$$f(d) := \left(\frac{1}{-4 \cdot \log\left(\frac{\varepsilon}{3.7 \cdot d}\right)}\right)^{2}$$

von Karman equation for Fanning friction factor in fully turbulent flow in rough pipes

Perry's Hbk, 6 ed, p 5-24

$T_r := \frac{T_{pipe}}{T_c}$ $\quad P_r := 2 \cdot \frac{p0}{P_c}$ reduced temperature and pressure

$T_r = 1.603$ $\quad P_r = 0.749$

$Z_{pipe} := .95$ compressibility from chart at nominal pipeline conditions
(Reid et al)

© Copyright (2012) Harvey D. Hensley

**Parametric Solve Block to obtain thickness and compressor discharge pressure functions**

Starting guess values (may need changing if some cases don't converge)

$ii := 4$ $t := .6\cdot in$ $pd := 2000\cdot psi$ compressor discharge pressure

$di := D_{ii} - 2\cdot t$ $\rho := \frac{pd\cdot Mw}{Rg\cdot T_{pipe}}$ $v := \frac{G(Cap\_wt, di)\cdot(1 + fuel\_fraction)}{\rho}$

Given

$$-\ln\left(\frac{p2_p}{pd}\right) + \frac{1}{2}\cdot\left[\left(\frac{p2_p}{pd}\right)^2 - 1\right]\cdot\frac{Rg\cdot T_{pipe}}{Mw\cdot(v)^2} + \frac{2\cdot f(di)\cdot L}{(n\_booster + 1)\cdot D_i} = 0$$

mechanical energy balance
Bird et al, 2 ed, p 464

$\rho = \frac{pd\cdot Mw}{Rg\cdot T_{pipe}}$ $v\cdot\rho = G(Cap\_wt, di)\cdot(1 + fuel\_fraction)$ $di = D_i - 2\cdot t$

$t = \max\left(\frac{pd\cdot D_i}{2\cdot F\cdot S_s}, \frac{D_i}{100}\right)$ first answer is bursting strength, second answer is a buckling constraint

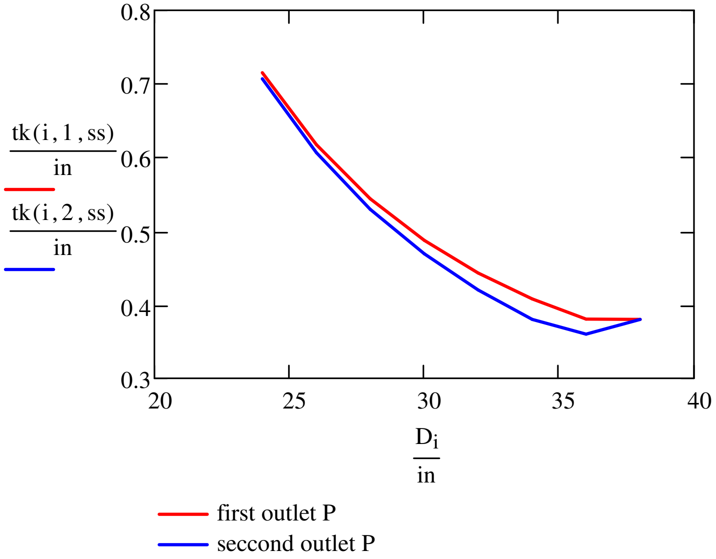
$(tk(i,p,s)\ \ d(i,p,s)\ \ p1(i,p,s)\ \ vd(i,p,s)\ \ rho1(i,p,s)) := Find(t, di, pd, v, \rho)$ Quasi-Newton method used for speed.

**End of Solve Block**

© Copyright (2012) Harvey D. Hensley

Wall Thickness

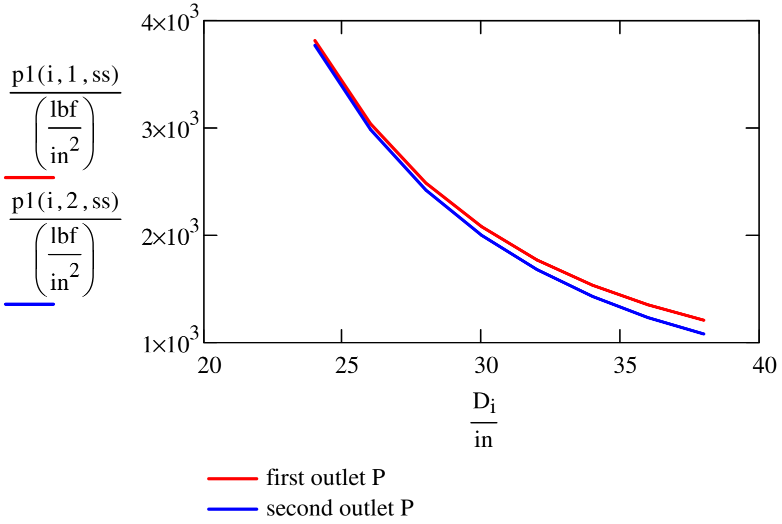
$ss := 2$



plot to check solve block results for reasonable values

Conclusion from graph on right: Does inlet pressure exceed maximum compressor discharge pressure of 4500 psi? If so, then increase the number of booster stations.

Inlet Pressure



© Copyright (2012) Harvey D. Hensley

## Pipe weight

$$wp(i,p,s) := \pi \cdot \frac{\left(D_i\right)^2 - d(i,p,s)^2}{4} \cdot \rho_{steel} \cdot L$$

## Compressor horsepower

$Tr_{in} := \frac{T0}{T_c}$ $Pr_{in} := \frac{p0}{P_c}$

$Tr_{in} = 1.691$ $Pr_{in} = 0.375$ $Z_{in} := .98$ Z values read from a chart

$Tr_{max} := \frac{(500+460)\cdot R}{T_c}$ $Pr_{max} := \frac{1200\cdot psi}{P_c}$

$Tr_{max} = 2.798$ $Pr_{max} = 1.799$ $Z_{max} := 1.0$

$Tr_{out} := \frac{(300+460)\cdot R}{T_c}$ $Pr_{out} := \frac{pr}{P_c}$

$Tr_{out} = 2.215$ $Pr_{out} = 0.899$ $Z_{out} := .97$

$Z_{fd} := \frac{Z_{in} + Z_{max}}{2}$ $Z_{rec} := \frac{Z_{out} + Z_{in}}{2}$

$Z_{fd} = 0.99$ $Z_{rec} = 0.975$

© Copyright (2012) Harvey D. Hensley

$$\gamma := \frac{k}{k-1}\cdot eff\_poly$$

$$HP(w,Z,T,p2,p1) := \frac{w\cdot Z\cdot Rg\cdot T\cdot \gamma}{Mw\cdot eff\_poly}\cdot\left[\left(\frac{p2}{p1}\right)^{\frac{1}{\gamma}} - 1\right]$$

compression horsepower function

## Economics

capex = interest+Net ROI+tax on equity return+depreciation

I = total investment

$$int(I) := I\cdot(1 - equity)\cdot interest$$

$$return(I) := I\cdot equity\cdot NROI$$

$$taxes(I,tax) := return(I)\cdot\frac{tax}{1 - tax}$$

$$depr(I,dep) := I\cdot dep$$

$$capex(I,btu) := \frac{depr(I,dep) + return(I) + taxes(I,tax) + int(I)}{btu}$$

Recompression

$$HP\_rec(p) := HP\left(Cap\_wt, Z_{rec}, T_{amb}, pr, p2_{p}\right)$$

$$HP\_rec(1) = 0\cdot hp$$

© Copyright (2012) Harvey D. Hensley

loss to fuel

$$\text{num\_mkt}(p) := \text{ceil}\left(\frac{\text{HP\_rec}(p)}{\text{turbine\_capacity}}\right)$$

add spare if requested in Input section

$$\text{num\_turbine\_market}(p) := \text{if}\,(\text{num\_mkt}(p) > 0, \text{num\_mkt}(p) + \text{spares}, 0)$$

$$\text{num\_turbine\_market}(2) = 3$$

$$\text{loss\_out}(p) := \frac{\text{HP\_rec}(p)}{\text{eff\_turbine}}\cdot\frac{1}{\text{Cap\_scf}\cdot\text{LHV}}$$

$$\text{btua} := \text{Cap\_scf}\cdot\text{yr}\cdot\text{LHV}$$

annual heating value of gas delivered to market

extra compressor investment for high levels of discharge pressure

$$\text{extra} := \text{if}\left(\text{pr} > 1000\cdot\text{psi}, 3\cdot 10^{6}, \text{if}\left(\text{pr} > 700\cdot\text{psi}, 2\cdot 10^{6}, 0\right)\right)$$

$$\text{extra} = 0$$

$$\text{addon}(p) := \text{if}\left(\text{pr} > \text{p2}_{p}, \text{extra}, 0\right)$$

$$\text{addon}(1) = 0 \qquad \text{addon}(2) = 0$$

recompression investment

$$\text{comprec}(p) := \text{num\_turbine\_market}(p)\cdot(\text{ref\_comp\_inv} + \text{addon}(p))\cdot\text{comp\_instl}$$

$$\text{netp\_1}(i,p,s) := \left(\begin{array}{l}\text{market} \ldots \\ + -\text{capex}(\text{comprec}(p), \text{btua}) \ldots \\ + -\text{if}\left(\text{p2}_{p} < \text{pr}, \dfrac{\text{comp\_maint}\cdot\text{num\_turbine\_market}(p)}{\text{btua}}, \dfrac{0}{\text{BTU}}\right)\end{array}\right)\cdot(1 - \text{loss\_out}(p))$$

netback due to compression
at market end

© Copyright (2012) Harvey D. Hensley

Pipeline

variables with "on" in name are on shore, with "off" in name are offshore, except for "addon" which is an extra charge for a higher pressure level compressor

$$\mathrm{btup}(p) := \frac{\mathrm{btua}}{1 - \mathrm{loss\_out}(p)}$$

annual heating value of gas prior to any recompression at the market pipeline

$$\mathrm{survey\_off} := \mathrm{survey\_daymi} \cdot \mathrm{survey\_rate\_off} \cdot L$$

$$\mathrm{install\_off}(i) := \mathrm{survey\_off} \ \ldots \\ + \left[ 13.6 \cdot 10^{6} + L \cdot \left( \mathrm{day\_per\_mi} + \mathrm{day\_per\_inchmi} \cdot D_{i} \right) \cdot \mathrm{barge\_rate} \right] \cdot \mathrm{connects}$$

total pipeline investment

$$\mathrm{pipeoff}(i,p,s) := \mathrm{wp}(i,p,s) \cdot \mathrm{matl\_offshore}_{s} + \mathrm{install\_off}(i)$$

$$\mathrm{pipeon}(i,p,s) := \mathrm{wp}(i,p,s) \cdot \mathrm{matl\_onshore}_{s} + L \cdot D_{i} \cdot \mathrm{install\_onshore}$$

$$\mathrm{netp\_off\_2}(i,p,s) := \mathrm{netp\_1}(i,p,s) \ \ldots \\ + -\mathrm{capex}(\mathrm{pipeoff}(i,p,s), \mathrm{btup}(p)) \ \ldots \\ + \frac{-\mathrm{opex\_pipeline} \cdot \mathrm{pipeoff}(i,p,s)}{\mathrm{btup}(p)}$$

off shore netback after recompression and pipeline

$$\mathrm{netp\_on\_2}(i,p,s) := \mathrm{netp\_1}(i,p,s) \ \ldots \\ + -\mathrm{capex}(\mathrm{pipeon}(i,p,s), \mathrm{btup}(p)) \ \ldots \\ + \frac{-\mathrm{opex\_pipeline} \cdot \mathrm{pipeon}(i,p,s)}{\mathrm{btup}(p)}$$

on shore netback after recompression and pipeline

© Copyright (2012) Harvey D. Hensley

Compression, boosters and feed

boosters

$$\mathrm{HP\_boost}(i,p,s) := \mathrm{HP}\left(\frac{\mathrm{Cap\_wt}}{1-\mathrm{loss\_out}(p)}, Z_{fd}, T_{amb}, \mathrm{p1}(i,p,s), \mathrm{p2}_p\right)$$

loss to fuel for boosters

$$\mathrm{loss\_bst}(i,p,s) := \frac{\mathrm{HP\_boost}(i,p,s)}{\mathrm{eff\_turbine}} \cdot \frac{1-\mathrm{loss\_out}(p)}{\mathrm{Cap\_scf} \cdot \mathrm{LHV}}$$

$$\mathrm{loss\_boost}(i,p,s) := \left[\frac{1}{(1-\mathrm{loss\_bst}(i,p,s))^{\mathrm{n\_booster}}}\right] - 1$$

$$\mathrm{num\_bst}(i,p,s) := \mathrm{ceil}\left(\frac{\mathrm{HP\_boost}(i,p,s)}{\mathrm{turbine\_capacity}}\right)$$

add spare booster

$$\mathrm{num\_turbine\_boost}(i,p,s) := \mathrm{if}\,(\mathrm{num\_bst}(i,p,s) > 0, \mathrm{num\_bst}(i,p,s) + \mathrm{spares}, 0) \cdot \mathrm{n\_booster}$$

The logic statement is too long for the addon_boost(i,p,s) function.  It is defined in the collapsed area below.

$$\mathrm{comp\_boost}(i,p,s) := \mathrm{num\_turbine\_boost}(i,p,s) \cdot (\mathrm{ref\_comp\_inv} + \mathrm{addon\_boost}(i,p,s)) \cdot \mathrm{comp\_instl}$$

feed compressors

$$\mathrm{HP\_fd}(i,p,s) := \mathrm{HP}\left[\frac{\mathrm{Cap\_wt}}{(1-\mathrm{loss\_out}(p)) \cdot (1-\mathrm{loss\_boost}(i,p,s))}, Z_{fd}, \mathrm{T0}, \mathrm{p1}(i,p,s), \mathrm{p0}\right]$$

© Copyright (2012) Harvey D. Hensley

$$\text{num\_fd}(i,p,s) := \text{ceil}\left(\frac{\text{HP\_fd}(i,p,s)}{\text{turbine\_capacity}}\right)$$

add spare feed compressor

$$\text{num\_turbine\_fd}(i,p,s) := \text{if}\,(\text{num\_fd}(i,p,s) > 0, \text{num\_fd}(i,p,s) + \text{spares}, 0)$$

$$\text{addon\_fd}(i,p,s) := \text{if}\left(\text{p1}(i,p,s) > 1000\cdot\text{psi}, 3\cdot 10^{6}, \text{if}\left(\text{p1}(i,p,s) > 700\cdot\text{psi}, 2\cdot 10^{6}, 0\right)\right)$$

$$\begin{aligned}\text{compin\_bst}(i,p,s) := {} & \text{comp\_boost}(i,p,s)\ \ldots \\ & + \text{num\_turbine\_fd}(i,p,s)\cdot(\text{ref\_comp\_inv} + \text{addon\_fd}(i,p,s))\cdot\text{comp\_instl}\end{aligned}$$

loss to fuel for feed compressors

$$\text{loss\_in}(i,p,s) := \frac{\text{HP\_fd}(i,p,s)}{\text{eff\_turbine}}\cdot\frac{(1-\text{loss\_out}(p))\cdot(1-\text{loss\_boost}(i,p,s))}{\text{Cap\_scf}\cdot\text{LHV}}$$

off shore netback at gas source

$$\text{netp\_off\_3}(i,p,s) := \left[\begin{aligned}&\text{netp\_off\_2}(i,p,s)\ \ldots \\ &+ -\text{capex}\,(\text{compin\_bst}(i,p,s), \text{btup}(p))\ \ldots \\ &+ \frac{-\left[\text{comp\_maint}\cdot\left(\begin{aligned}&\text{num\_turbine\_fd}(i,p,s)\ \ldots \\ &+ \text{num\_turbine\_boost}(i,p,s)\end{aligned}\right)\right]}{\text{btup}(p)}\end{aligned}\right]\cdot[(1-\text{loss\_boost}(i,p,s))\cdot(1-\text{loss\_in}(i,p,s))]$$

© Copyright (2012) Harvey D. Hensley

on shore netback at gas source

$$\mathrm{netp\_on\_3}(i,p,s) := \begin{bmatrix} \mathrm{netp\_on\_2}(i,p,s)\ \ldots \\ + -\mathrm{capex}(\mathrm{compin\_bst}(i,p,s),\mathrm{btup}(p))\ \ldots \\ + \dfrac{-\left[\mathrm{comp\_maint}\cdot\begin{pmatrix}\mathrm{num\_turbine\_fd}(i,p,s)\ \ldots \\ +\,\mathrm{num\_turbine\_boost}(i,p,s)\end{pmatrix}\right]}{\mathrm{btup}(p)} \end{bmatrix}\cdot(1-\mathrm{loss\_boost}(i,p,s))\cdot(1-\mathrm{loss\_in}(i,p,s))$$

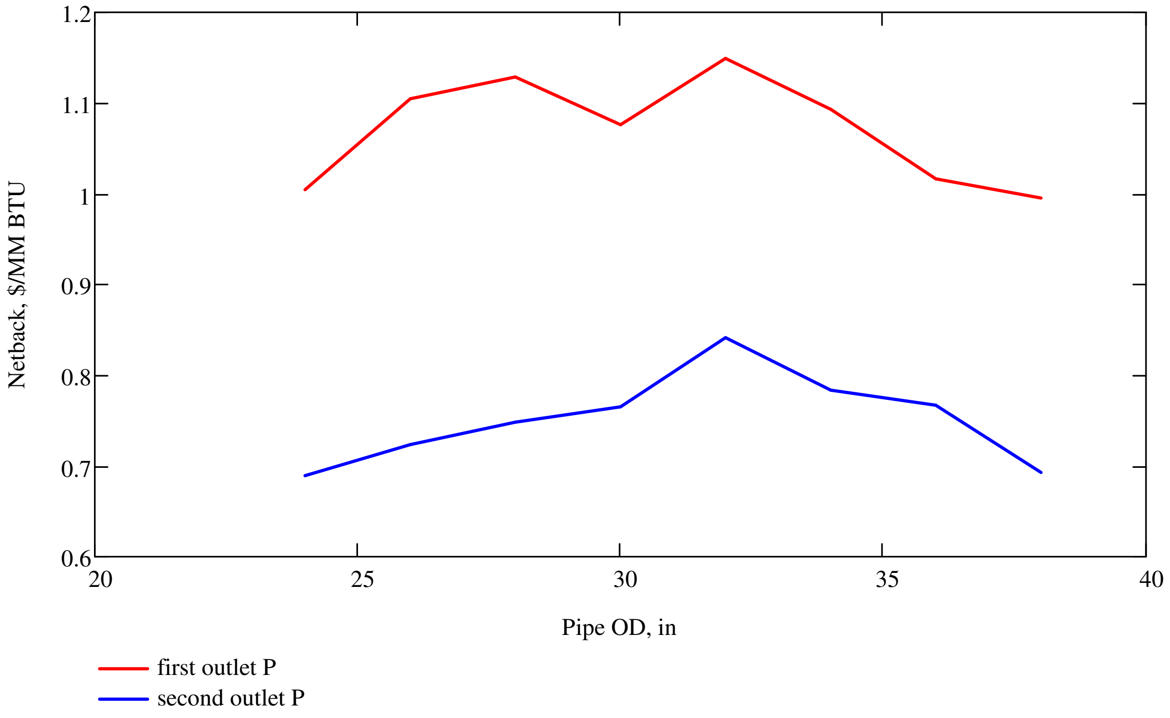
© Copyright (2012) Harvey D. Hensley

## Results

$ss := 2$ ss = 1 or 2 for grade index Change to see effect on graph below

Netback at Source for Outlet Pressures: $p2_1 = 600\cdot\frac{lbf}{in^2}$ , $p2_2 = 250\cdot\frac{lbf}{in^2}$

,

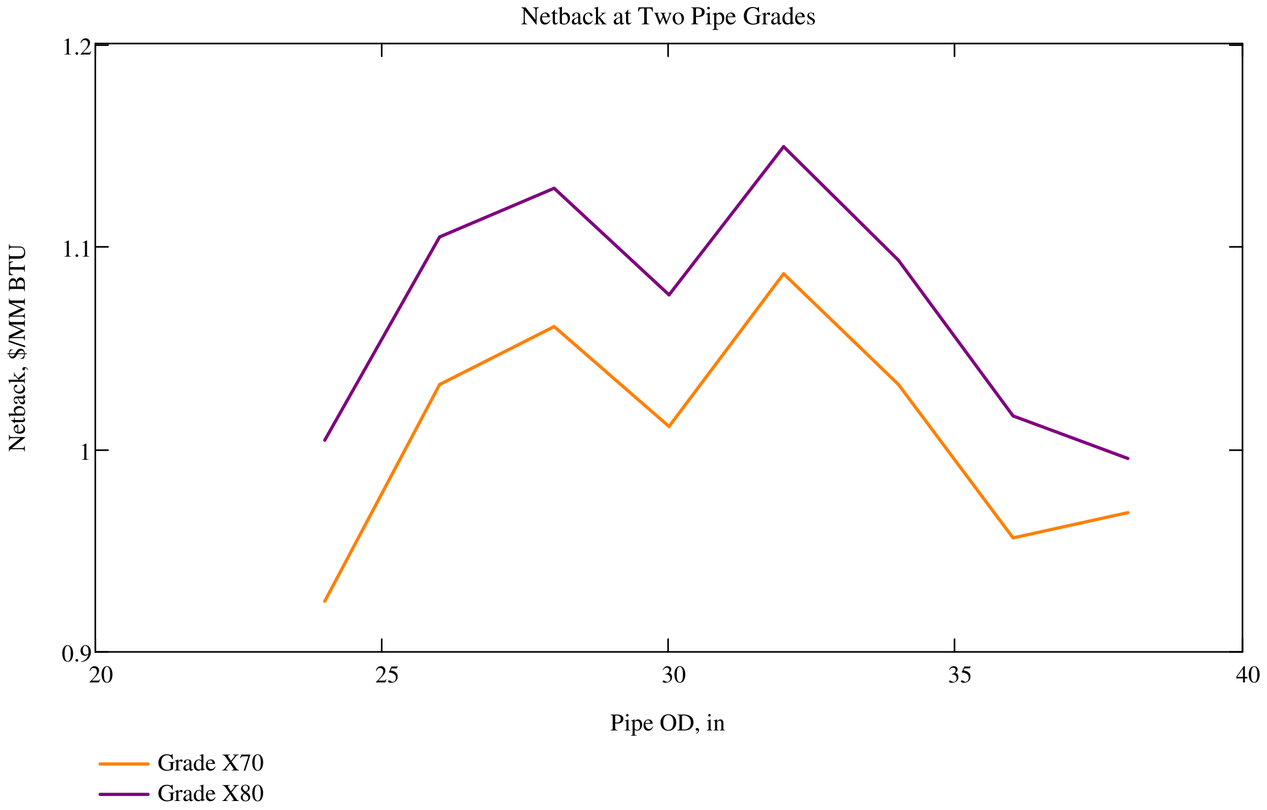


The above graph shows that it is better to deliver the gas at the market pressure without the need for recompression at the exit.

© Copyright (2012) Harvey D. Hensley

$pp := 1$

The following chart is for outlet pressure, $p2_{pp} = 600 \cdot \frac{lbf}{in^2}$



The graph above shows that the X80, stronger grade pipe is the more economical.

© Copyright (2012) Harvey D. Hensley

Check fuel fraction estimated at start of program and update fuel_fraction if needed

$$\text{fuel\_fract}(i,p,s) := \frac{1}{(1-\text{loss\_out}(p))\cdot(1-\text{loss\_boost}(i,p,s))} - 1$$

pick optimum indexes from above plots

| | |
|---|---|
| $ii := 5$ | diameter index |
| $pp := 1$ | pipeline discharge pressure index |
| $ss := 2$ | steel grade index |
| $\text{fuel\_fract}(ii,pp,ss) = 0.025$ | new value for fuel_fraction at start of program |
| $\text{fuel\_fraction} = 0.025$ | original value estimated at beginning of program |

© Copyright (2012) Harvey D. Hensley

## Conclusions

**for** $L = 1.5 \times 10^{3} \cdot \text{km}$ **and** $\text{Cap\_scf} = 6 \times 10^{8} \cdot \dfrac{\text{ft}^{3}}{\text{day}}$

- The strogner grade (X80) is the more cost effective grade.
- The pipeline should be designed to deliver at the required market pressure without recompression at the exit.
- A 32" pipe with 1 booster station is optimal.
- The optimal netback is $1.15 MM BTU with 1 spare at each compressor station.

### Summary for grade X80, each D and p2 case

$ss := 2$

$$\text{btu0}(i,p,ss) := \frac{\text{btua}}{(1-\text{loss\_out}(p))\cdot(1-\text{loss\_boost}(i,p,ss))\cdot(1-\text{loss\_in}(i,p,ss))}$$

total annual heating value at source

$\text{netback}_{i,p} := \text{netp\_on\_3}(i,p,ss)$

$\text{thick}_{i,p} := \text{tk}(i,p,ss)$

$\text{p\_out}_{i,p} := \text{p1}(i,p,ss)$

$$\text{netback} = \begin{pmatrix} 1.004 & 0.689 \\ 1.105 & 0.724 \\ 1.129 & 0.748 \\ 1.076 & 0.765 \\ 1.149 & 0.841 \\ 1.093 & 0.783 \\ 1.016 & 0.767 \\ 0.995 & 0.693 \end{pmatrix} \cdot \frac{1}{10^{6}\cdot \text{BTU}}$$

$$D = \begin{pmatrix} 24 \\ 26 \\ 28 \\ 30 \\ 32 \\ 34 \\ 36 \\ 38 \end{pmatrix} \cdot \text{in} \quad \text{thick} = \begin{pmatrix} 0.715 & 0.707 \\ 0.618 & 0.606 \\ 0.544 & 0.53 \\ 0.487 & 0.469 \\ 0.443 & 0.42 \\ 0.408 & 0.38 \\ 0.38 & 0.36 \\ 0.38 & 0.38 \end{pmatrix} \cdot \text{in}$$

$$\text{p\_out} = \begin{pmatrix} 3.815 \times 10^{3} & 3.77 \times 10^{3} \\ 3.04 \times 10^{3} & 2.986 \times 10^{3} \\ 2.487 \times 10^{3} & 2.421 \times 10^{3} \\ 2.079 \times 10^{3} & 2.001 \times 10^{3} \\ 1.772 \times 10^{3} & 1.681 \times 10^{3} \\ 1.535 \times 10^{3} & 1.431 \times 10^{3} \\ 1.352 \times 10^{3} & 1.234 \times 10^{3} \\ 1.21 \times 10^{3} & 1.08 \times 10^{3} \end{pmatrix} \cdot \text{psi}$$

© Copyright (2012) Harvey D. Hensley

$$\mathrm{pdesign}_{i,p} := \frac{\left(2\cdot F\cdot S_{ss}\right)\cdot \mathrm{tk}(i,p,ss)}{D_i}$$

$$\mathrm{total\_inv}_{i,p} := \mathrm{comprec}(p) + \mathrm{pipeon}(i,p,ss) + \mathrm{compin\_bst}(i,p,ss)$$

$$\mathrm{total\_interest}_{i,p} := \mathrm{int}\left(\mathrm{total\_inv}_{i,p}\right)$$

$$\mathrm{pdesign} = \begin{pmatrix} 3.815\times 10^{3} & 3.77\times 10^{3} \\ 3.04\times 10^{3} & 2.986\times 10^{3} \\ 2.487\times 10^{3} & 2.421\times 10^{3} \\ 2.079\times 10^{3} & 2.001\times 10^{3} \\ 1.772\times 10^{3} & 1.681\times 10^{3} \\ 1.535\times 10^{3} & 1.431\times 10^{3} \\ 1.352\times 10^{3} & 1.28\times 10^{3} \\ 1.28\times 10^{3} & 1.28\times 10^{3} \end{pmatrix}\cdot \mathrm{psi}$$

$$\mathrm{total\_inv} = \begin{pmatrix} 1.413\times 10^{9} & 1.581\times 10^{9} \\ 1.362\times 10^{9} & 1.566\times 10^{9} \\ 1.354\times 10^{9} & 1.556\times 10^{9} \\ 1.389\times 10^{9} & 1.549\times 10^{9} \\ 1.35\times 10^{9} & 1.506\times 10^{9} \\ 1.383\times 10^{9} & 1.542\times 10^{9} \\ 1.426\times 10^{9} & 1.551\times 10^{9} \\ 1.435\times 10^{9} & 1.59\times 10^{9} \end{pmatrix}$$

$$\mathrm{total\_interest} = \begin{pmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\begin{aligned} \mathrm{tot\_opex}_{i,p} := {} & \mathrm{comp\_maint}\cdot\left(\begin{aligned} & \mathrm{num\_turbine\_market}(p) + \mathrm{num\_turbine\_boost}(i,p,ss)\ \ldots \\ & + \mathrm{num\_turbine\_fd}(i,p,ss) \end{aligned}\right)\ \ldots \\ & + \mathrm{opex\_pipeline}\cdot \mathrm{pipeon}(i,p,ss) \end{aligned}$$

$$\mathrm{total\_return}_{i,p} := \mathrm{return}\left(\mathrm{total\_inv}_{i,p}\right)$$

$$\mathrm{tot\_opex} = \begin{pmatrix} 0.377 & 0.38 \\ 0.385 & 0.389 \\ 0.397 & 0.399 \\ 0.411 & 0.411 \\ 0.424 & 0.423 \\ 0.44 & 0.437 \\ 0.458 & 0.456 \\ 0.482 & 0.486 \end{pmatrix}\cdot 10^{8}$$

$$\mathrm{total\_return} = \begin{pmatrix} 2.403 & 2.687 \\ 2.315 & 2.662 \\ 2.302 & 2.645 \\ 2.362 & 2.634 \\ 2.295 & 2.56 \\ 2.351 & 2.622 \\ 2.425 & 2.637 \\ 2.44 & 2.703 \end{pmatrix}\cdot 10^{8}$$

© Copyright (2012) Harvey D. Hensley

$$\text{total\_taxes}_{i,p} := \text{taxes}\left(\text{total\_inv}_{i,p}, \text{tax}\right)$$

$$\text{total\_taxes} = \begin{pmatrix} 1.966 & 2.199 \\ 1.894 & 2.178 \\ 1.884 & 2.164 \\ 1.932 & 2.155 \\ 1.877 & 2.095 \\ 1.924 & 2.145 \\ 1.984 & 2.158 \\ 1.996 & 2.212 \end{pmatrix} \cdot 10^{8}$$

$$\text{total\_depr}_{i,p} := \text{depr}\left(\text{total\_inv}_{i,p}, \text{dep}\right)$$

$$\text{total\_depr} = \begin{pmatrix} 0.565 & 0.632 \\ 0.545 & 0.626 \\ 0.542 & 0.622 \\ 0.556 & 0.62 \\ 0.54 & 0.602 \\ 0.553 & 0.617 \\ 0.571 & 0.621 \\ 0.574 & 0.636 \end{pmatrix} \cdot 10^{8}$$

$$\text{tot\_capex}_{i,p} := \text{capex}\left(\text{total\_inv}_{i,p}, \text{btua}\right) \cdot \text{btua}$$

$$\text{tot\_capex} = \begin{pmatrix} 4.934 & 5.518 \\ 4.754 & 5.467 \\ 4.728 & 5.432 \\ 4.85 & 5.408 \\ 4.712 & 5.258 \\ 4.828 & 5.384 \\ 4.979 & 5.416 \\ 5.01 & 5.551 \end{pmatrix} \cdot 10^{8}$$

$$\text{total\_fuel}_{i,p} := \frac{\text{btu0}(i, p, \text{ss}) - \text{btua}}{\text{btua}}$$

$$\text{total\_fuel} = \begin{pmatrix} 0.144 & 0.209 \\ 0.123 & 0.183 \\ 0.107 & 0.162 \\ 0.093 & 0.144 \\ 0.082 & 0.129 \\ 0.072 & 0.117 \\ 0.064 & 0.106 \\ 0.057 & 0.096 \end{pmatrix}$$

fuel as a fraction of product

$$\text{booster\_turbines}_{i,p} := \text{num\_turbine\_boost}(i, p, \text{ss})$$

$$\text{booster\_turbines} = \begin{pmatrix} 5 & 7 \\ 4 & 7 \\ 4 & 6 \\ 4 & 6 \\ 3 & 5 \\ 3 & 5 \\ 3 & 4 \\ 3 & 4 \end{pmatrix}$$

$$\text{feed\_turbines}_{i,p} := \text{num\_turbine\_fd}(i, p, \text{ss})$$

$$\text{feed\_turbines} = \begin{pmatrix} 8 & 8 \\ 7 & 7 \\ 6 & 7 \\ 6 & 6 \\ 5 & 5 \\ 5 & 5 \\ 5 & 5 \\ 4 & 4 \end{pmatrix}$$

© Copyright (2012) Harvey D. Hensley

## References

*Perry's Chemical Engineers' Handbook*, 6th Ed, McGraw-Hill (1984)

Bird, R. B. et al, 2nd Ed, *Transport Phenomena*, John Wiley and Sons (2002)

Reid, R. C. et al, 3rd Ed, *The Properties of Gases and Liquids*, p 27-28, McGraw-Hill (1977)

© Copyright (2012) Harvey D. Hensley