HYDRAULIC ANALYSIS OF DUCTILE IRON PIPE

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Head Loss

Friction head loss or drop in pressure in a pipeline is an everyday concern for the water works engineer. Head loss calculations are based on equations developed by hydraulic engineers who conducted numerous flow tests on in-service water mains. Several formulas were developed by Darcy, Chezy, Cutter, Manning, Hazen-Williams, and others. Of these, the formula developed by Hazen-Williams has proven to be the most popular.

A convenient form of the Hazen-Williams equation is:

$$H_L = 1{,}000\left[\frac{V}{0.115C(d)^{0.63}}\right]^{1.852} \qquad (1)$$

where:
- H_L = Head loss (ft./1,000 ft.)
- V = Velocity of flow (fps)
- C = Flow coefficient (C factor)
- d = Actual inside diameter (in.)

C Factor

For a pipe to have satisfactory flow characteristics, it initially must provide a high Hazen-Williams flow coefficient "C factor" and must be able to maintain a high flow coefficient through years of service. Numerous flow tests of both new and old cement-mortar-lined Gray and Ductile Iron pipelines have been conducted to determine how well cement-mortar linings meet these requirements. The average value of "C" for new pipe was found to be 144, while for the older systems, the average value of "C" was found to be 140. Therefore, a C factor of 140 for Ductile Iron is a realistic, long-term value that has been demonstrated in actual operating systems.

Smooth Pipes

For laminar, fully developed flow in a pipe, friction depends only on the Reynolds number (a function of velocity, inside pipe diameter and the kinematic-viscosity of the fluid being transported). It is interesting to note that the roughness of the pipe wall is not considered. When laminar flow exists, the fluid seems to flow as several layers, one on another. Because of the viscosity of the fluid, a shear stress is created between the layers of the fluid. Energy is lost from the fluid by the action of overcoming the frictional force produced by the shear stress, not because of friction at the pipe wall.

To suggest that a "smoother" pipe is available would require stepping outside the bounds of modern hydrodynamics.

For turbulent flow of fluids in circular pipes, there is a layer of laminar flow called the laminar sublayer adjacent to the pipe wall. If this laminar sublayer is thicker than the roughness of the pipe wall, then flow is "hydraulically smooth" and the pipe has attained the ultimate in hydraulic efficiency. Laboratory tests have been conducted on cement-mortar-lined iron pipe at the extremes of the normally recommended operating flow velocities — namely 2 fps and 10 fps. The test results reported Hazen-Williams coefficients ranging from 150-157. When these laboratory tests were plotted on the Moody diagram, the plotted points generally conformed to the curve for "smooth pipes." This demonstrates that other pipe materials might be touted to have higher flow coefficients, but in reality none of those materials is "smoother" than Ductile Iron pipe. To suggest that a "smoother" pipe is available would require stepping outside the bounds of modern hydrodynamics.

Ductile Iron Pipe

Ductile Iron pipe designed in accordance with ANSI/AWWA C150/A21.50 and specified with the standard cement-mortar lining will typically have a larger inside diameter than other pipe materials while offering essentially the same smoothness of surface for water or wastewater. As a result, for a given flow and nominal size of pipe, cement-mortar-lined, minimum pressure class Ductile Iron pipe typically experiences less head loss than alternate material pipelines. In other words, less energy is consumed overcoming losses when pumping through Ductile Iron pipe than when pumping through any substitute pipe routinely specified. When this difference is taken into account, significant savings can result from the use of Ductile Iron pipe.

Engineering Economy: Pumping Costs and Equivalent Pipelines

One way to realize the savings available with Ductile Iron pipe is to consider pumping costs. These costs are proportional to the quantity of water pumped as well as the head loss. Therefore, an annual pumping cost can be determined for each pipe material with the difference being the annual savings realized from using Ductile Iron over substitute piping materials. More importantly, the present worth of projected annual savings adjusted for inflation can be calculated for a pipeline's design life. **The present worth of these annual savings is the amount that should be incorporated into comparisons of alternate bids on a pipeline.**

Another way to realize the savings available from Ductile Iron pipe's larger inside diameter is to consider equivalent head losses in the pipeline. For a substitute material pipeline to produce the lower head loss of a Ductile Iron pipeline, the substitute material pipeline can be designed using the nominal size pipe for only a portion of the pipeline. The remaining portion of the pipeline would be made up of the next largest size pipe. Conversely, a Ductile Iron pipeline can be designed to produce the same head loss as a substitute material pipeline. The Ductile Iron pipeline, however, will be made up of pipe of the chosen nominal size for only part of the length of the pipeline with the remainder being the next smallest size pipe. **Either of these equivalent pipeline approaches will result in equal annual pumping costs. However, the first method will result in an increased initial cost for the substitute pipeline material while the second method will reflect a savings in initial costs for the Ductile Iron pipeline.**

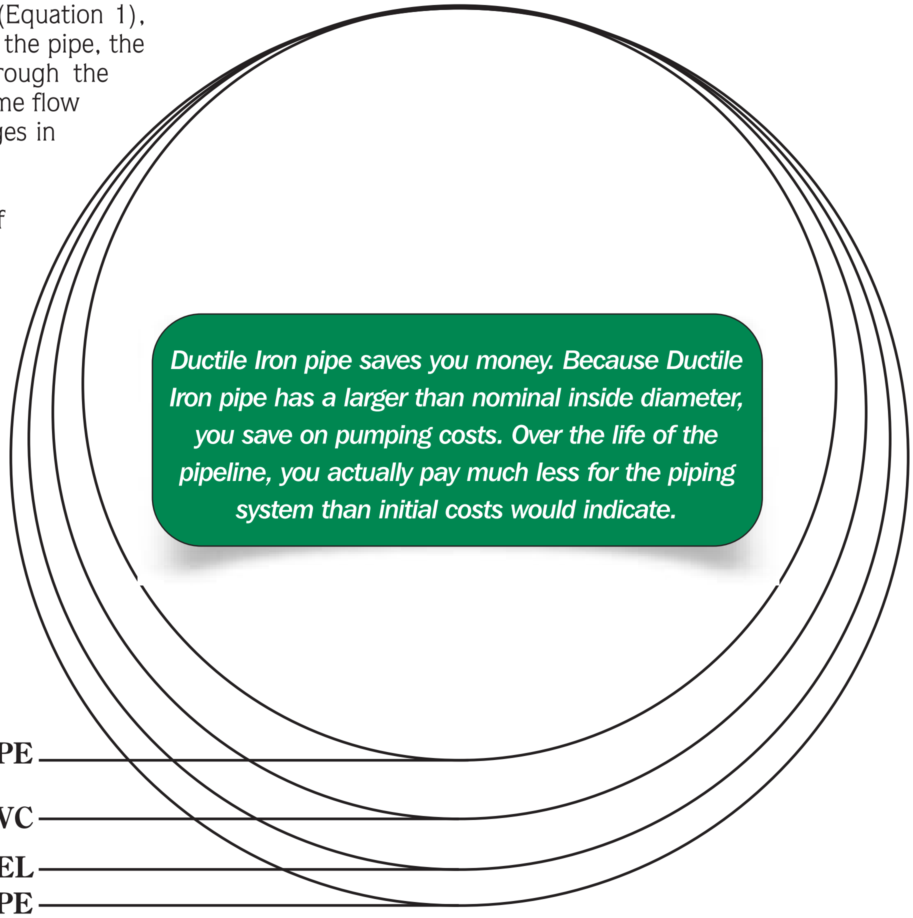
Such analyses allow the utility engineer to provide true **value engineering**, assuring that the needs of the utility are met while conserving energy or lowering bid costs through the use of Ductile Iron pipe. What follows is a detailed discussion of those analyses.

Inside Diameter Versus Flow Coefficient

Looking again at the Hazen-Williams formula (Equation 1), it is clear that the larger the inside diameter of the pipe, the smaller the head loss for water pumped through the pipeline. This assumes alternatives have the same flow coefficient. But which has more impact: changes in the inside diameter or the flow coefficient?

The best way to analyze the combined effect of changes in inside diameter and changes in flow coefficient is to use actual data from different pipe materials. First, we can tabulate actual inside diameters for the various pipe materials that might be part of the design of a project: Ductile Iron, pvc (both C900 and C905), steel, concrete cylinder pipe (pccp) and polyethylene pipe (hdpe).

Ductile Iron pipe saves you money. Because Ductile Iron pipe has a larger than nominal inside diameter, you save on pumping costs. Over the life of the pipeline, you actually pay much less for the piping system than initial costs would indicate.



Comparison Of Actual Inside Diameters Of 24" Pipe
Scale: 3/16" = 1"

Table One

Comparison of Actual Inside Diameters (in.) of Piping Materials for Water Transmission and Distribution Systems																
Nominal Size - in.	6	8	10	12	14	16	18	20	24	30	36	42	48	54	60	64
DIP [1]	6.28	8.43	10.46	12.52	14.55	16.61	18.69	20.75	24.95	31.07	37.29	43.43	49.63	56.29	60.28	64.30
PCCP [2]	–	–	–	–	–	16.00	18.00	20.00	24.00	30.00	36.00	42.00	48.00	54.00	60.00	–
STEEL [3]	6.00	8.00	10.00	12.00	14.00	16.00	18.00	20.00	24.00	30.00	36.00	42.00	48.00	54.00	60.00	–
PVC [4]	6.09	7.98	9.79	11.65	13.50	15.35	17.20	19.06	22.76	28.77	34.43	40.73	46.49	–	–	–
HDPE [5]	5.57	7.31	8.96	10.66	12.35	14.05	15.74	17.44	20.83	25.83	32.29	38.41	44.47	51.34	–	–

(1) From AWWA C150, Table 5, using the nominal wall thickness of the lowest available pressure class with Standard C104 cement-mortar lining. (2) From AWWA C301 - IDs are based on nominal sizes for pre-stressed concrete cylinder pipe. (3) From manufacturers' information - IDs are based on nominal sizes for routine manufacture of steel pipe. (4) Cast Iron equivalent outside diameters. Sizes 6"-12" from AWWA C900, and sizes 14"-48" from AWWA C905, using average ODs and minimum wall thickness plus 1/2 wall tolerance. DR 18 for sizes 6"-24", DR 21 for sizes 30"-36", and DR 25 for sizes 42"- 48". (5) From AWWA C906 using average Ductile Iron pipe equivalent outside diameters and average wall thickness. DR 11 for sizes 6"-30", DR 13.5 for 36", DR 15.5 for 42", DR 17 for 48", and DR 21 for 54".

Now, in Table Two, we can list the C factors as recommended* by the respective industries of the pipes being considered:

Finally, if we take an example of a 24-inch nominal diameter water transmission pipeline that is 10,000 feet long with water flowing at 4,000 gpm, we can see the relative effects of C factors and actual inside diameters. The results are shown in Table Three.

Table Two

Flow Coefficients (C Factors) of Piping Materials for Water Transmission and Distribution

Ductile Iron Pipe	140*
PCCP	140
Steel	140
PVC	150

* The C=140 value for Ductile Iron pipe has been demonstrated in actual operating systems.

Table Three

Head Loss Comparison for Piping Materials — 24-inch Nominal Diameter

Pipe Material	C Factor	Flow Rate (gpm)	Actual Inside Diameter(in.)	Velocity of Flow (fps)	Head Loss (ft.)
Ductile Iron	140	4,000	24.95	2.63	8.15
PCCP	140	4,000	24.00	2.84	9.85
Steel	140	4,000	24.00	2.84	9.85
PVC	150	4,000	22.76	3.15	11.22
HDPE	155	4,000	20.83	3.77	16.26

The results of our analysis show that the inside diameter has more effect on head loss than the relative smoothness of the pipe's inside surface. In our example, substitute piping materials head losses range from 20.9% to 99.5% greater than that of Ductile Iron pipe.

The bottom line is that the inside diameter of the pipe is the governing criterion in determining head losses in modern piping systems. The greater the inside diameter, for a given flow and nominal size, the lower the head loss.

Pumping Costs

The cost to pump through a given pipeline can be shown to be a function of head loss, pump efficiency, and power cost, as shown in the following equation:

$$PC = 1.65\, H_L Q \frac{a}{E} \qquad (2)$$

where:
- PC = Pumping cost ($/yr. based on 24-hr./day pump operation/1,000 ft.)
- H_L = Head loss (ft./1,000 ft.)
- Q = Flow (gpm)
- a = Unit cost of electricity ($/KWH)
- E = Total efficiency of pump system (%/100)

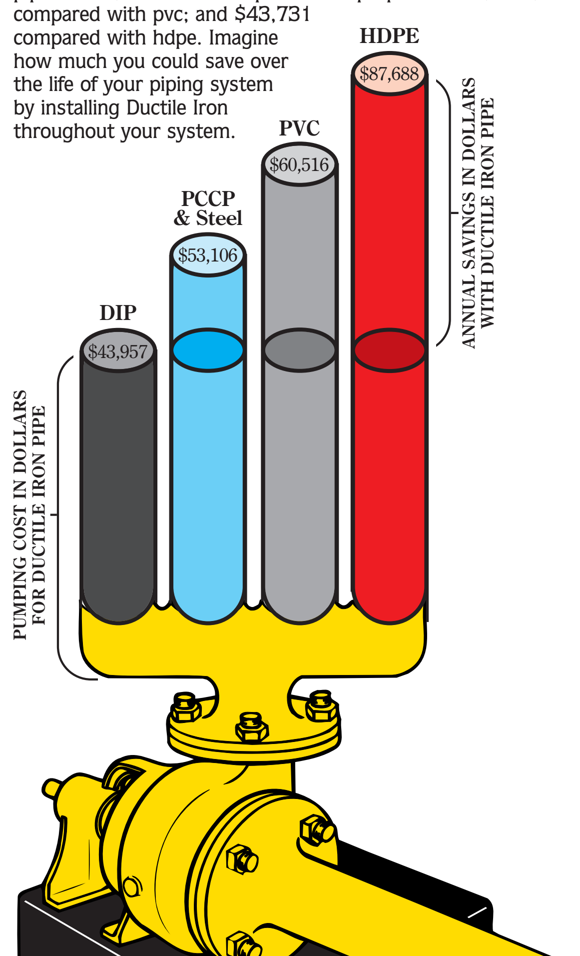
Velocity is related to flow by the equation:

$$V = \frac{Q}{2.448d^2} \qquad (3)$$

where:
- Q = Flow (gpm)
- V = Velocity (fps)
- d = Actual inside diameter (in.)

Pumping Cost In Dollars Per Year Per Pipeline

Based on pumping costs alone, Ductile Iron pipe saves you money every year. The amounts shown here are based on only one pipeline. In this example, annual savings with Ductile Iron pipe are $9,149 when compared with pccp and steel; $16,559 compared with pvc; and $43,731 compared with hdpe. Imagine how much you could save over the life of your piping system by installing Ductile Iron throughout your system.



Energy Savings

To calculate the present worth of the annual savings realized when pumping through Ductile Iron pipe, follow these simple steps:

> ***The present worth of the annual savings is the amount that should be used in comparing alternate bids on a pipeline.***

1. Convert flow to gallons per minute:
   - Q (gpm) = Q (mgd) x 694.4
   - Q (gpm) = Q (cfs) x 448.8
   - Q (gpm) = $2.448\ Vd^2$
2. Calculate the velocity (V) of flow for each pipe material using actual inside diameters and Equation 3. Actual inside diameters for each pipe material under consideration may be found in Table One.
3. Calculate head losses (H_L) for each pipe material under consideration using Equation 1.
4. Calculate the pumping cost (PC) per 1,000 feet for each material using Equation 2. Use known or estimated values for "a" and "E."
5. Multiply PC times the length of the pipeline divided by 1,000 feet.
6. Multiply the result of Step 5 by the fraction of each day the pump will operate.
7. Take the difference in pumping costs from Step 6 to obtain the annual savings (AS) realized with Ductile Iron pipe.
8. Calculate the present worth (PW) of the annual savings adjusted for inflation using the appropriate equation below:

when $r \neq g$:

$$PW = AS \left[\frac{(1+i)^n - 1}{i(1+i)^n} \right] \qquad (4)$$

$$i = \frac{r-g}{1+g} \qquad (5)$$

when $r = g$

$$PW = AS\,(n) \qquad (6)$$

where:

- PW = Present worth of annual savings in pumping costs ($)
- AS = Annual savings in pumping costs ($)
- n = Design life of the pipeline (years)
- i = Effective annual investment rate, accounting for inflation (%/100)
- r = Annual rate of return on the initial investment (%/100)
- g = Inflation (growth) rate of power costs (%/100)

Example Problem

Given:
- 24-inch diameter pipeline
- 30,000-foot pipeline length
- 6,000 gpm design flow
- $0.06/KWH unit power cost
- 70 percent pumping efficiency
- pump to operate 24 hours per day
- 50-year design life
- 8 percent desired rate of return on initial investment
- 4 percent annual inflation rate for power costs

Step No.	DIP	PCCP & Steel	PVC	HDPE
1. Q (gpm) =	6,000	6,000	6,000	6,000
2. V (fps) =	3.94	4.26	4.73	5.65
3. H_L (ft./1,000 ft.) =	1.73	2.09	2.38	3.45
4. PC ($/yr./1000 ft.) =	$1,465	$1,770	$2,017	$2,923
5. PC ($/yr./pipeline) =	$43,957	$53,106	$60,516	$87,688
6. same as 5				
7. AS (with DIP)		$9,149	$16,559	$43,731
8. PW		$201,837	$365,303	$964,724

Note: The above values were all first generated by computer and then rounded off; therefore, it may be necessary to use more precise numbers than those shown to obtain these values.

The Annual Savings (AS) results represent the additional dollars being spent annually to pump water or wastewater through substitute pipe materials. Bringing these dollars back to the present worth (PW) shows the amount of money that must be invested today to pay for those additional pumping costs over the lifetime of the pipeline. The present worth amount should be discounted against the initial capital cost of the Ductile Iron pipe before comparing bids with substitute materials.

In the example, the additional pumping costs to install pvc pipe are $16,559 annually. Over a 50-year life, this equates to a Present Worth value of $365,303 — the hidden cost for using pvc pipe. For a 30,000-foot pipeline, this means that you could justify discounting the cost to purchase a 24-inch Pressure Class 200 Ductile Iron pipeline by $12.18 per foot when compared to a pvc substitute. Similarly, Ductile Iron pipe could be discounted by $6.73 per foot when compared to a pccp or steel substitute, and by $32.16 per foot when compared to an hdpe substitute.

Equivalent Pipelines

The Energy Savings analysis defines the annual additional pumping costs associated with the selection of a substitute material over Ductile Iron pipe but assumes that both pipelines are the same nominal diameter. It is possible to lower head losses through a substitute material pipeline by up-sizing a portion of the total pipeline. Thus, a 24-inch Ductile Iron pipeline would be compared to a 24- and 30-inch substitute pipeline with sections that combine to have a total head loss equal to the 24-inch Ductile Iron pipeline. This would increase the cost of the substitute pipeline. Or, the Ductile Iron pipeline can be designed to have the same higher head loss of the substitute pipeline. In this way the Ductile Iron pipeline would consist of 20- and 24-inch sections whose combined head loss is raised to that of the 24-inch diameter substitute pipe material. This will result in lower capital costs for the Ductile Iron alternate.

To upsize a portion of the substitute materials pipeline:

$$S_{LS} = L\left[\frac{H_D - H_S}{H_{LS} - H_S}\right] \qquad (7)$$

To downsize a portion of the Ductile Iron alternative:

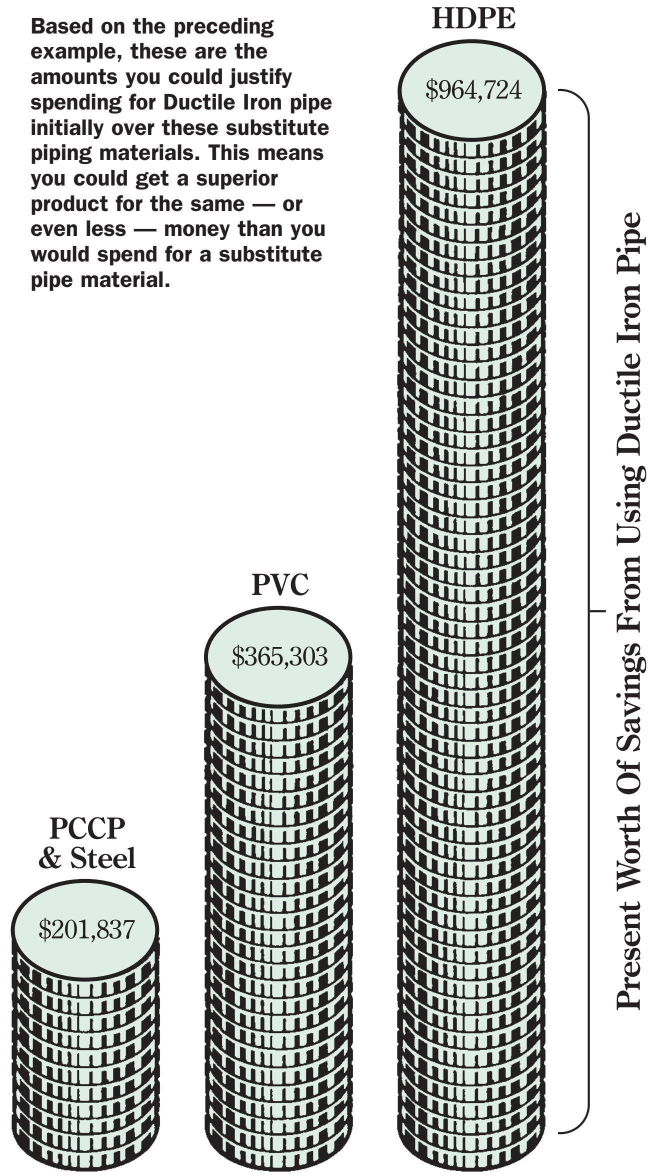
$$S_{SD} = L\left[\frac{H_S - H_D}{H_{SD} - H_D}\right] \qquad (8)$$

where:

- S_{LS} = Length of larger diameter substitute pipe required in feet
- L = Total length of pipeline in feet
- H_D = Head loss in feet per 1,000 feet of Ductile Iron pipe
- H_S = Head loss in feet per 1,000 feet of substitute pipe
- H_{LS} = Head loss in feet per 1,000 feet of next larger size substitute pipe
- S_{SD} = Length of smaller diameter Ductile Iron pipe required in feet
- H_{SD} = Head loss in feet per 1,000 feet of next smallest size Ductile Iron pipe.

Present Worth Of The Projected Annual Savings From Using 24-Inch, Pressure Class 200 Ductile Iron Pipe Over These Substitute Piping

Based on the preceding example, these are the amounts you could justify spending for Ductile Iron pipe initially over these substitute piping materials. This means you could get a superior product for the same — or even less — money than you would spend for a substitute pipe material.



By using equivalent pipeline theories, you can realize immediate savings with Ductile Iron pipe. Because of Ductile Iron's lower head loss, substitute pipelines with equivalent head loss would require larger diameters of pipe over portions of your pipeline or a portion of the Ductile Iron pipeline can be downsized to increase the head loss to that of the substitute material pipeline.

Example

Using Equation 7, to up-size a portion of the substitute material pipeline to meet the lower head loss of the Ductile Iron pipeline, we find that the following five pipelines are hydraulically equivalent:

- 30,000 feet of 24-inch Pressure Class 200 Ductile Iron pipe
- 22,201 feet of 24-inch pccp and 7,799 feet of **30-inch** pccp
- 13,991 feet of 24-inch steel and 16,009 feet of **26-inch** steel
- 17,366 feet of 24-inch DR 18 pvc and 12,634 feet of **30-inch** DR 18 pvc
- 6,959 feet of 24-inch DR 11 hdpe and 23,041 feet of **30-inch** DR 11 hdpe

Using Equation 8 to downsize a portion of the Ductile Iron pipeline to match the higher head loss of the substitute material pipelines, we find that the following sets of pipelines are equivalent:

Ductile Iron versus pccp or steel
30,000 feet of 24-inch pccp or steel
25,706 feet of 24-inch PC 200 Ductile Iron and 4,294 feet of **20-inch** PC 250 Ductile Iron

Ductile Iron versus pvc
30,000 feet of 24-inch DR 18 pvc
22,229 feet of 24-inch PC 200 Ductile Iron and 7,771 feet of **20-inch** PC 250 Ductile Iron

Ductile Iron versus hdpe
30,000 feet of 24-inch DR 11 hdpe
9,477 feet of 24-inch PC 200 Ductile Iron and 20,523 feet of **20-inch** PC 250 Ductile Iron

Value Engineering

From this we have three dollar amounts to compare: the Present Worth of the Annual Savings in pumping costs realized by selecting Ductile Iron pipe over a substitute material, applied as a discount to the Ductile Iron pipe; the added cost to up-size a portion of that substitute material pipeline in order to lower its head losses to that of Ductile Iron; and the lower costs associated with downsizing a portion of the Ductile Iron pipeline to increase its head loss to that of the substitute material. From an economic standpoint, these costs are directly comparable.

Conclusion

Including Ductile Iron pipe as an alternative in pipeline projects presents the engineer with opportunities to provide a superior product with value in engineering. The value realized when pumping through Ductile Iron pipe's larger inside diameters, whether applied toward annual savings in pumping costs or capital savings in equivalent pipeline analysis, is there for the utility's advantage.

NOTE: DIPRA has developed a computer program, Hydraulic Analysis of Ductile Iron Pipe. It is a Windows-based program that is easy to use. For your free copy of this valuable resource, contact your local DIPRA Regional Engineer, DIPRA headquarters in Birmingham, or download it from our Web site (http://www.dipra.org).

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Canada Pipe Company, Ltd.
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Clow Water Systems Company
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Griffin Pipe Products Co.
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Downers Grove, Illinois 60515-5707

McWane Cast Iron Pipe Company
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Pacific States Cast Iron Pipe Company
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