Choice of Pipeline Material: PVC or DI Using a Life Cycle Cost Analysis

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ABSTRACT
As the world’s pipeline infrastructure continues to age and the demand for product delivery continues to grow, every utility has been required to make decisions about the condition and adequacy of their existing pipeline systems. When utilities find that the existing systems do not have adequate capacity or have become too costly or risky to operate to meet future needs, many times replacement is the only solution. As systems are being replaced, everyone is looking to reduce up-front capital, operational, and maintenance cost through detailed design. However, there are unconsidered environmental costs associated with these financial savings. This paper uses a Life Cycle Cost (LCC) approach to address the pros and cons of using Polyvinyl Chloride (PVC) or Ductile Iron (DI) pipeline material in design. The study considers the project life cycle and how each life cycle phase is impacted by standardized design approaches. For each pipeline material, the following life cycle phases have been evaluated: material production and pipeline fabrication, material transport, life cycle usage, and end of life. Each phase has been evaluated for both economic and environmental impacts.

The results of this particular case study are directly impacted by the applicable design standards for the each pipeline materials. In this design example, the PVC pipeline internal diameter was significantly less than the DI pipeline internal diameter. This design consideration made the DI pipeline material hydraulically more efficient, which over the life cycle, made the DI pipeline the most fiscally and ecologically attractive alternative. This study demonstrates that specific design standards and specific system design characteristics (flow rate, pressure requirements) influence the LCC and total CO₂ emissions. The conclusion of this study demonstrates that a complete pipeline design should be considered in the LCC approach before a decision is made on what material is used in design.

INTRODUCTION / RATIONALE
As pipeline engineering design tools become more sophisticated and the pipeline design process becomes more automated, the general trend in design has turned toward cost reduction. As part of this trend, pipeline designs are being bid with optional/alternate pipeline materials. By allowing multiple pipeline materials to bid, a lower initial capital cost is achieved by allowing the purchaser to capture the benefits of market pricing. However, the capital cost may not truly identify savings and/or

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additional cost of the project. The design and bid should include life cycle cost of the material. The material selected may potentially introduce unique operational life cycle cost and environmental impacts that may outweigh the initial saving of capital. Currently in design, it is typical to select a pipeline material early in the design process allowing specific material dependent design considerations to be integrated more easily (e.g. thickness, pressure constraints, hydraulic efficiency). Because of this early selection, the environmental impacts and operational efficiency of alternate materials may not be properly considered.

For this study, a Life Cycle Cost (LCC) analysis and consideration of CO₂ emissions has been made for design of a 24-inch potable water transmission pipeline located in southern Oregon, U.S. The pipeline was designed, bid and constructed in the year 1999. For this study, this pipeline project will be used to establish the boundary of the analysis and to relate specific design choices (diameter, thickness, and pressure criteria) to the LCC.

In 1999, the decision was made to use Ductile Iron (DI) pipeline with cement mortar lining. This study will evaluate that decision and compare it to an alternate material, Polyvinyl Chloride (PVC). Both DI and PVC are widely used in the water and wastewater conveyance industry and standard design approaches are used in the United States (U.S.). The design guidelines used in this study are outlined by the American Water Works Association (AWWA). The AWWA A21.51 standard design for DI pipeline was used in the original 1999 design of the pipeline. A similar AWWA standard C905 for PVC pipeline is used in this study for comparison of an alternate design. There have been many papers discussing the life cycle cost of both DI and PVC material; however, this previous work has been very broad and has not specifically addressed cost in relation to a specific design criteria.

OBJECTIVE
Compare Polyvinyl Chloride (PVC) or Ductile Iron (DI) based on fiscal and ecological parameters and recommend the most favorable pipeline material for the pipeline project. The fiscal and ecological parameters shall be developed from a standardized pipeline design approach and hydraulic analysis. The study will result in a recommendation of a pipeline material to be used for 10 miles (16 km) of 24-inch (600 mm) diameter potable water pipeline. The fiscal and ecological parameters are based on:

**Fiscal:** Capital cost of pipeline material and operational cost through a 50-year useful life.

\[
\text{Capital} => \text{USD/ft of pipeline and,} \\
\text{Operation} => \text{USD/kWh}
\]

**Ecological:** CO₂ emissions from pipeline manufacturing process, transport of material from plant to job site and operation of system through 50 years of operation.

\[
\text{Fabrication & Operation} => \text{Pounds of CO₂ / kWh and,} \\
\text{Transport} => \text{Pounds of CO₂ / mile}
\]
LITERATURE REVIEW
Many Life Cycle Analyses (LCAs) coupled with LCCs have been developed to compare PVC and DI pipeline materials. The LCAs generally focus on the emissions or environmental impacts associated with the manufacturing process of each material. Whereas, the LCCs generally evaluate the cost associated with manufacturing the pipeline material. There is a key reference, “Life Cycle Assessment of PVC and of principal competing materials” commissioned by the European Commission (July 2004) that provides a very comprehensive and objective evaluation of PVC and DI materials for multiple uses including water, wastewater and drainage pipeline. This study concludes that the PVC pipeline fabrication process consumes less energy than the DI pipeline, but when extraction of the raw materials (i.e. crude oil, rock salt) is included, the consumptive energy for PVC is higher. This study also concluded that the installation of the pipeline is an important component of the LCA and installation will favor PVC over DI because the PVC material is lighter and will not require the same equipment or energy consumption to install the pipeline. However, in a paper developed by the Ductile Iron Pipeline Research Association (DIPRA) entitled “Ductile Iron Pipe vs PVC”, DIPRA claims that a PVC pipeline greater than 12-inch diameter weighs 400 lbs, is too heavy for manual handling, and therefore will require similar equipment to the installation of a DI pipeline.

An LCA conducted by EMPA (Swiss Federal Laboratories for Materials Testing and Research) entitled “Life Cycle Assessment of Pipeline systems (1998)” found that inclusion of the operational phase is important when comparing pipeline materials. This study also found that energy usage in pressure pipeline systems was less for DI than for systems using PVC material, but for sewer and drainage systems, the operational energy usage of PVC was less than DI. These findings are supported in this study. In general, the literature reviewed for this study found that the differences in the overall cost and environmental impacts of PVC compared to DI pipelines were negligible. However, it should be noted that each material (PVC and DI) has only been studied for its environmental impacts on a national and global scale. There has been very few local and design specific LCAs and/or LCCs for comparison. It is apparent, that local level LCCs that include design specific details, regional impacts to transport and energy usage and emissions may provide the necessary detail to formulate a qualified recommendation. This study will use these parameters to recommend a pipeline material for the pipeline system.

ANALYSIS METHOD
As shown in Figure 1, four life cycle phases for each material were considered in this study. These phases included Material Production and Pipeline Fabrication, Material Transport, Life Cycle Usage, and End of Life. In each life cycle phase the energy used and the CO₂ emissions developed were quantified. Because this study emphasizes the regional and local influences to the LCC, the regional energy data was required to differentiate the impact of the various fuel types used in different regions in the U.S. on the CO₂ emissions. The regional energy data was obtained from a paper developed jointly by the U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA) entitled “Carbon Dioxide Emissions from the Generation of
Electric Power in the United States” (July, 2002). This paper provides data for years 1998 and 1999 disaggregated by census region and by fuel type. Map 1 shows how the data was regionally disaggregated. The East South Central, the West South Central and Pacific Contiguous divisions are particularly important to this study. The pipeline project site is located in the Contiguous Pacific Division while the PVC pipeline fabrication plant assumed in this study is located in the West South Central Division and the DI plant is located in the East South Central Division.

Figure 1-Project Flow Diagram PVC and DI
Figure 2 shows the percentage of fuels by type for each region and Figure 3 shows the CO₂ emissions for each fuel type per region. This data was coupled with energy usage data developed in the Material Production and Pipeline Fabrication and Life Cycle Usage phases to quantify the CO₂ emissions for each phase. Each analysis method will be discussed for each phase separately.

Material Production and Pipeline Fabrication:
One manufacturing plant for each material was chosen for this study. Each plant has provided similar product to the area on various projects and therefore should be considered a likely source of the pipeline product for this pipeline project. The PVC plant is a J-M Manufacturing (JMM) plant in Wharton, Texas and the DI plant is an American Cast Iron Pipe Company (ACIPCO) plant in Birmingham, Alabama. Each plant is equipped to process the material and produce the pipeline. Several
unsuccessful attempts were made to collect energy usage and emission data from each manufacturing plant. In addition, unsuccessful attempts to collect data from the local permitting/regulating agencies (Texas Department of Environmental Quality, Alabama Department of Environmental Management) were made for both energy and emissions data. Because both attempts were unsuccessful, a previous study was used in-lieu of actual data. The study that was used was performed in Australia by M.D. Ambrose, et al. and published in a paper entitled “Piping Systems Embodied Energy Analysis” (October 2002). In this paper, both DI and PVC pipeline materials were considered. Ambrose’s paper provided a cradle to gate evaluation of each material and summarized the findings in an embodied energy (MJ/Kg) for each material. In the paper, embodied energy was defined as:

“the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e. direct energy plus indirect energy.” (Treloar, 1994)

The embodied energy was then coupled with the DOE and EPA regional energy usage and CO₂ emissions based on location of the ACIPCO (East South Central Region) and JMM (West South Central Region) plants. *Table 1* represents the embodied energy of both the PVC and DI pipeline.
In this study, the PVC-M embodied energy data was used because it represents more closely the AWWA C905 standard. It should be noted however; in Ambrose’s study, the pipe manufacturing process for PVC-M was found to require 3% more energy and a 10% reduction in output than standard PVC. This resulted in a slightly more embodied energy than standard PVC. For the DI material, the DI cement mortar lined embodied energy was used because in the U.S. cement mortar lining is the design standard for potable water conveyance systems and is represented in the AWWA A21.51 standard.

**Material Transport:**
The transport was based on the mileage from each manufacturing plant to the job site. Google Maps was used to estimate the transport distance. The transport distance from the ACIPCO plant in Birmingham Alabama to the project jobsite in southern Oregon was approximately 2,650 miles and the transport distance from the JMM plant in Wharton, Texas to the job site was approximately 2,200 miles. It was assumed that one combination truck could carry 960 linear feet of 24-inch diameter pipeline and therefore, fifty-five (55) trucks were required to transport the total 52,800 linear feet of pipeline material from the plants to the job site.

The CO₂ emissions rate of combination trucks was obtained from the GREET model developed by the Argonne National Laboratory. The CO₂ emissions rate in GREET is 27.824 pounds of CO₂ per gallon of diesel fuel used. This loading rate was then combined with a year 1999 estimation of combination truck fuel consumption to obtain total pounds of CO₂ emitted from transport. The fuel consumption rate for combination trucks is maintained by the U.S. DOE in the “Transportation Energy Data Book: Edition 25”. From this data, in year 1999 each combination truck was assumed to consume 0.182 gallons of diesel fuel per mile.

**Life Cycle Usage:**
The Life Cycle is assumed to be 50 years. The durability and reliability of the pipeline materials were not considered in this study. However, it should be noted that DI pipeline is marketed with a life cycle of 100 years and literature shows that PVC is generally assessed with a 50-year life cycle. Potable water pipelines (any material) over 50 years of age are generally taken out of service or replaced due to increases in demand rather than durability and reliability issues. Again, for this study the life cycle is assumed to be 50 years. The energy usage over the life cycle is based on the

<table>
<thead>
<tr>
<th>Pipe Type</th>
<th>Embodied Energy (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ductile Iron</td>
<td>36.2</td>
</tr>
<tr>
<td>DI cement mortar lined</td>
<td>40.2</td>
</tr>
<tr>
<td>PVC-U</td>
<td>74.9</td>
</tr>
<tr>
<td>PVC-M</td>
<td>76.6</td>
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<tr>
<td>PVC-O</td>
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<tr>
<td>PE60B</td>
<td>75.2</td>
</tr>
<tr>
<td>PE100</td>
<td>75.2</td>
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</tbody>
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Table 1-Embodied Energy by Material Type
average design flow rate of 10 Million Gallons per Day (mgd) and an operating pressure head condition that is dependent on the material roughness and pipeline diameter.

The hydraulic efficiency for both material types is well documented. From the AWWA Manual M-23 entitled “PVC Pipe - Design and Installation” the recommended hazen-williams roughness coefficient (C) for PVC pipeline is 150 and from the AWWA Manual M-41 entitled “Ductile-Iron Pipe and Fittings” the recommended C for DI pipeline is 130. The C coefficient is an empirical coefficient that allows an estimate of energy loss in a flowing pipeline due to shear stresses at the pipeline walls. By using the C coefficient and a known flow rate, the required pumping head required for each pipeline material can be determined. The higher the C coefficient the more hydraulically efficient the pipeline is. Therefore, the PVC pipeline material is smoother and more hydraulically efficient than the cement mortar lined DI pipeline. From this fact, it appears intuitive that the operational efficiency of the PVC will result in lower energy usage and subsequent lower emissions over life cycle than the DI pipeline material. However, in this study a complete design approach is used as outlined by the AWWA A21.51 for DI and AWWA C905 for PVC design standards. In these standards, multiple pressure constraints are used to ensure the integrity and safety of the design approach. In the DI design standard the required pipeline thickness is 0.37-inches whereas, for the same design condition the PVC thickness requirement is 1.43-inches. This additional thickness not only accounts for an increase in mass of PVC material required per linear foot over DI, but also the reduction is the effective flow area. Both pipelines are manufactured with industry standard common outside diameters (OD) of 25.8 inches. This standard OD dimension is important because pipelines must connect seamlessly to other equipment such as valves, flanges, and pump headers that have standardized on a common OD. Therefore, for increases in the pipeline thickness, the inside diameter (ID) must decrease. Therefore, for the 24-inch nominal diameter pipeline design, the DI pipeline will have an ID of 25.03 inches and the PVC pipeline will have an ID of 21.76 inches. Using the 10 mgd design flow rate, the recommended C coefficients and the required design thickness and resultant ID, a system head curve was developed for the pipeline system. The system head curve represents the pumped pressure head required to convey the design flow rate. Figure 4 represents the system head curve for both PVC and DI materials. From Figure 4, it can be seen that the DI pipeline is hydraulically more efficient because the required pumped pressure head is less for the same design flow rate. This is due to the available ID for DI and is irrespective of the smoothness of the material. The design for each pipeline is shown in Table 3.

End of Life Cycle:
The end of life cycle for both PVC and DI pipelines are not well documented in the literature. In fact, many agencies abandon the pipeline in place because of the expense of excavation to recover the material. The design area in southern Oregon currently does not have a policy or history of recycling or reusing pipeline material at the end of life. In this study, the influence of recycling was not considered due to the
lack of pertinent data. However, note that in the analysis of the cradle to gate embodied energy, the DI was assumed to use 100% scrap material during its production and the PVC was assumed to use 100% virgin material. This assumption and a sensitivity of its impact to the materials embodied energy should be more closely evaluated to better define the end of impacts to both cost and CO$_2$ emissions.

**ANALYSIS, RESULTS AND DISCUSSION**

Both the fiscal and ecological components were evaluated. The fiscal cost included the capital cost of product fabrication, transport and installation as well as operating cost. The product fabrication, transport and installation cost were developed from a unit cost ($USD/diameter/ft) that originated from a constructed cost database maintained by MWH Americas, Inc. MWH Americas, Inc. is a global engineering consulting firm specializing in water and wastewater infrastructure design. The constructed cost database showed a unit cost of 24-inch PVC pipeline to be $80 per linear foot and the DI pipeline to be $110 per linear foot. Both costs are based on 1999 $USD. Using these unit costs, the initial capital costs for pipeline fabrication, transport and installation of 10-miles of pipeline were $4,224,000 for the PVC pipeline and $5,808,000 for the DI pipeline. Considering only the capital cost, the PVC pipeline is the economic choice of material.

The design of the 10-miles of pipeline required 5,031,840 pounds of DI material or 3,305,808 pounds of PVC material. The unit weight of 1 foot of pipeline is provided in the AWWA standards for each material. Using this mass and the associated
embodied energy data and regional energy emissions data, 37.5 million pounds of CO₂ emissions is produced in fabrication of the DI pipeline and 48.8 million pounds of CO₂ emissions for the PVC pipeline. Considering the ecological impacts by CO₂ emissions for the fabrication of the material the DI pipeline is the more favorable material.

The cost of transport is assumed to be embedded in the initial capital cost. However, the CO₂ emissions were based on the number of combination trucks, the fuel efficiency of the trucks, the distance of transport from each plant and the rate of emission per gallon of diesel used. For the PVC pipeline transport, CO₂ emission was 0.62 million pounds of CO₂ and for the DI pipeline transport the CO₂ emission was 0.75 million pounds of CO₂. Therefore, for the transport CO₂ emission, which is directly impacted by transport distance, the PVC pipeline is favored simply because the plant is closer to the pipeline job site.

The operational cost and CO₂ emitted during operation were directly related to the hydraulic efficiency of the pipeline system. As shown in the Analysis Method section, the DI material was more hydraulically efficient because of the larger ID even though the PVC pipeline provided a smoother pipe wall surface and higher C coefficient. This unexpected result was due to the thickness requirements of the PVC pipeline and its significant reduction in the ID of the PVC pipeline relative to the DI pipeline. The DI pipeline was shown to be able to convey the design flow rate of 10 mgd with 72 feet less pressure head than the PVC pipeline. This equates to approximately 150 HP or 114 kW of power savings and approximately 995,630 kWh of energy savings over a year of continuous use. This significant savings in energy resulted in less operating cost and CO₂ emissions for the DI material. The cost of energy during operation was assumed to be $0.08 per kWh. For the 50-year life cycle, the cost of operating the DI pipeline system is $24,189,988 and the cost of operating the PVC pipeline system is $28,172,515. The total operational emission for the 50-year life cycle of the DI pipeline produces 131.5 million pounds of CO₂ where the operation of the PVC pipeline produces 153.2 million pounds of CO₂.

Summary list of cost in 1999 $USD:

- Capital Cost - Includes Raw Resources, Manufacturing, Transport, and Installation
  - PVC:  $4.22 Million
  - DI:  $5.81 Million
- Operational Cost - Pumping cost for 50 years
  - PVC:  $28.19 Million
  - DI:  $24.17 Million
- Maintenance and End of Life Cost were assumed equivalent and not included for comparison
Summary list of Pounds of CO₂ Emissions:

- **Pipeline Manufacturing**
  - PVC: 48.8 Million lbs
  - DI: 37.5 Million lbs
- **Transport**
  - PVC: 0.62 Million lbs
  - DI: 0.75 Million lbs
- **Year 50 Operation at Design Capacity**
  - PVC: 153.2 Million lbs
  - DI: 131.5 Million lbs

**SENSITIVITY ANALYSIS**

The analysis shows an ecological favor and operating cost favor for DI pipeline as designed for the pipeline system. This is mainly due to the hydraulic efficiency of DI.
pipeline as a result of the larger available flow area (larger ID) at the design pressure. A break-even sensitivity analysis was performed on the ID by enlarging the PVC pipeline diameter to reduce operational cost and emissions to the level of the DI pipeline. This break-even analysis showed that a PVC pipeline with an ID of 26.1-inches would be required. This would reduce the overall CO₂ emissions to the DI level of 170 million pounds of CO₂ for the 50 life cycle. At this diameter the PVC pipeline fabrication CO₂ emissions increased by 9.0% but the operational CO₂ emissions and operating cost dropped by 24.2%. The capital cost went up 19.1% for the larger diameter PVC. For this pipeline, a larger diameter PVC pipeline that is designed to break even with the DI pipeline operating emissions and cost would be less expensive than the DI pipeline. However, it should be noted that the thickness required would be approximately 2.2-inches, which cannot be currently manufactured and is outside the AWWA C905 design parameters. So, this alternate pipeline, although fiscally and ecologically equal is not a viable alternative.

A second sensitivity analysis was performed on the pressure requirement and as a result the thickness requirements of the pipelines. The operating CO₂ emissions and cost break even point was again used to evaluate the designs. The results of this analysis show that even with the thinnest walled PVC pipeline (thickness = 0.506 inches) and the subsequent lowest pressure rating of 50 psi, the operating cost of the PVC system will still be higher than the DI pipeline and therefore a break even point for emissions and operating cost could not be found.

CONCLUSIONS
Pipeline manufactures are interested in supplying pipeline for applications that are best suited for their pipeline’s characteristics. It is in their best interest that their installed pipeline product provides a long service life with a high performance and minimum maintenance history. The goal of this paper was not to show favor or exclude one pipeline material, but to assess each material’s life cycle phases and how cost and CO₂ emissions of each phase are influenced by the applicable design criteria. Four life cycle phases were considered: Material Production and Pipeline Fabrication, Material Transport, Life cycle Usage, and End of Life. The End of Life phase requires further research and development. The study uses embodied energy and operational efficiency to make both the fiscal and ecological comparisons to draw the following recommendation:

For this pipeline project, a ductile iron pipeline material should be considered the better fiscal and ecological choice.

This conclusion is directly related to the increase in operational cost and CO₂ emissions impacted by ID reduction in the PVC pipeline.

This study has also found that specific design standards and specific system design characteristics (flow rate, pressure requirements) significantly influence the LCC and CO₂ emissions. Therefore, even though this study found in favor of the DI pipeline material for this specific pipeline project, the real conclusion is that each project
should be assessed independently using a LCC approach before a pipeline material is selected. A reduction in initial capital may cost more in the end.

REFERENCES