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ADVANCED SOFTWARE FOR DEMAND AND ENERGY REDUCTION IN CALIFORNIA PIPELINES

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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ABSTRACT

Petroleum pipeline operations consume significant amounts of California's finite power and energy supply. Reducing consumption would benefit California because it allows for the reallocation of saved power and energy, which also avoids exceeding supply limits. The power and energy budget necessary for pipeline operations can be dramatically reduced by adding relatively small amounts of drag reducing agents to the shipped petroleum products. Presently, these reducing agents are not universally used due to high cost and restrictions concerning their use in petroleum products. Thus, the goal of this project was to increase the use of drag reducing agents across California's petroleum pipelines, which is only possible if two needs are met: 1. standardized, accurate, and easy-to-use methodology must be employed to assess whether agent use is justified hydraulically. For instance, drag reducing agents are not allowed in certain petroleum products, and the pipeline layout may limit the benefits of agent use. 2. Drag reducing agent use needs to be financially viable. The trade-offs between low pump costs and high drag reducing agent costs depend on a wide variety of factors, including the pipeline geometry, the fluids being transported, and utility company costs. These needs can be met with a properly designed and implemented web-based calculation tool, practical to both pipeline and utility company personnel for the evaluation of drag reducing agent use on a case-by-case basis. As a result, the researchers constructed a mathematical software application called DRAnalysis. DRAnalysis serves as a standardized, manageable tool for all parties. As for determining if the results from the newly developed software are accurate, assessments of DRAnalysis results with real data from a California pipeline have been successfully compared. By applying DRAnalysis, drag reducing agent use will increase and the power and energy required for transportation of California's petroleum liquids will certainly decrease.

Keywords: petroleum, pipeline, optimization, DRA, energy, power, efficiency, savings

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EXECUTIVE SUMMARY

Introduction

California consistently ranks among the most energy-efficient states within the United States. However, as California grows, higher energy consumption is inevitable. Strain on energy production infrastructure, like power plants, the electrical grid, and fuel sources, is unavoidable and will eventually lead to higher costs for all California energy users. The need for continued conservation and consumption reduction is clear now more than ever. Significant concerns with the on-going California drought, hydroelectric output, environmental impact, and California's robust economic recovery, (as evidenced by 500,000 in-state jobs being added in 2014) all emphasize the importance of finding possible ways to reduce energy. This project addressed the need for reducing energy consumption, specifically for petroleum pipelines.

Large-scale users of California energy include underground petroleum fluids pipelines. Pipelines deliver crude oil to refineries, gasoline and diesel fuel for gas stations, jet fuel to airports, and they support much of California's economy. As fluids move along these pipelines, friction causes pressure loss, and large pumps are needed at intervals to maintain pressures and flow rates.

Pipeline pumps are driven by motors that can use either electricity or fuels, such as diesel or kerosene. These pumps usually consume 5,000 kilowatts, the equivalent of 50,000 100 watt light bulbs. A medium sized pipeline, with twenty pumps running at any given time, can consume 100 megawatts of electric power, totaling over 800,000 megawatt-hours of electrical energy use per year. For a single pipeline, these levels exceed the generation capacity of several California power plants, representing a significant percentage of all but the largest plants. A typical California household uses approximately 6 megawatt-hours yearly (determined as of 2009, the last year this data was available). In comparison, a single pipeline can consume as much electricity as a medium sized city.

One option for reducing the energy required to power pipeline pumps is to mix drag reducing agents (DRA's) into the pipeline fluids. Invented in the late 1940's, DRA’s act as a lubricant and reduce friction. Since these agents will essentially alleviate resistance, less energy will be needed to operate pipelines when DRA is used.

The impact that DRA technology will have could potentially change pipeline industry, using DRA's on 20 California pipelines, each saving an estimated 10 percent in consumption, implies savings equivalent to the output from several small power plants. Important side benefits include less strain on existing plants, a lower overall carbon footprint, and, ultimately, less expensive utility costs.

Two barriers interfere with use of DRA for pipeline energy consumption reduction. First, complex hydraulic and economic trade-offs mean that DRA can't be used effectively everywhere. Each situation has to be analyzed; however, convenient tools to perform this analysis do not exist. The second challenge is that, once a case is analyzed, pipeline operations considerations and DRA costs mean that California's utilities and pipeline companies will have

to work together to find cases where electricity and fuel can be saved economically without disrupting pipeline schedules.

Project Purpose

A computer application with the ability to accurately model the hydraulic and economic effects of DRA is needed to overcome the first of the two barriers and help pipeline and utility engineers quantify the benefits and costs of DRA use. Development of this application will allow pipeline and utility engineers to collaborate and share data from specific DRA injection scenarios. This improves streamlined development of strategies for energy consumption savings, while minimizing and sharing the cost increases associated with adding DRA to pipelines. The researchers who conducted this project sought to develop such a tool.

Hydraulic modeling software packages currently available for pipeline studies calculate variables such as flow, pressure, fluid types, and time. These software packages have not been tailored to study the hydraulic effects of injecting DRA at various points along the pipeline and balancing DRA costs against the economics of complex utility bills. A pipeline engineer must be able to easily model a potential DRA injection site, examining hydraulics and economics as a function of flow rate and DRA concentration. In regard to costs, utility companies use complex billing formulae for large industrial users such as pipelines. Utility companies must be able to easily study various ways of billing pipeline companies that take into account the consumption savings of DRA. This would require hydraulics information that the utility company engineer may have little exposure to.

The software tool needs to deliver accurate results, with the ability to easily model different pipelines, fluids, types of DRA, and fluid specifications versus actual performance. A pipeline engineer can then estimate the level of consumption reduction resulting from DRA use. At promising DRA injection sites, pipeline and utility company engineers need to be able to share data and calculation results. A utility company engineer can then suggest billing strategies or adjustments designed to help the pipeline company offset DRA costs and encourage DRA use at that site.

Finally, considerations, such as which computer hardware and software technologies to use and how to provide simultaneous controlled access to the tool, have an important impact on data security and cannot be overlooked. The purpose of this project was to create a properly designed program satisfying the functionality described above to stimulate DRA use for consumption reduction of California's petroleum pipeline pumps.

Project Process

The project was conducted within two phases. The first phase contained three similar efforts that aided in the design of the software tool, which included: 1. the derivation of the equations to describe the combined hydraulics and economics of pipelines and DRA, 2. an examination of the pipeline scheduling process and the impact of the schedule on energy consumption, and 3. the design of the software and hardware environment for the tool.

Combined formulas for pipeline costs, hydraulics performance, and potential consumption savings were expressed in terms of pipeline, type of fluid, DRA parameters, and utility

company cost variables. These formulas were then applied to injection strategies to develop guidelines for effective DRA use. Since high-accuracy modeling of pipeline hydraulics is known to have certain challenges, the formulas were cast into a form allowing for easy 'tuning'. The researchers used actual pipeline data, to adjust theoretical results to match live data from any given pipeline.

After creation of the program theory and a complete design of its environment, the second phase of the project required writing and testing the software. To fulfil this phase, the researchers had to consider the optimal balance between DRA use, DRA cost, energy savings, and energy costs. To easily incorporate the different pricing structures , it was necessary to employ a symbolic pricing scheme using a shorthand method; this shorthand pricing scheme was midway between the complex contract language found in utility contracts and low-level computer code. Data protection for each user, combined with easily shared data using a case-by-case basis for utility companies and pipeline engineers, dictated a web-accessible database application with robust cyber security components. Finally, a clear format for the results of the analysis resulted in creation of both plots for immediate review and downloadable spreadsheet files for further analysis.

Project Results

The result of this project was a mathematical software application that analyzed the combined results of hydraulics and economics effects of DRA use. It highlighted the economic impact and consumption savings possible with DRA use. The official name for the software is DRAnalysis.

Mathematical expressions for longer-term survey results (averaged over a month long period) and more exact shorter-term simulation formulations were obtained for implementation of DRAnalysis. Surveys will determine promising DRA injection sites; higher precision simulations allow for final validation of sites prior to the efforts of field testing and full DRA implementation. Once DRA is injected at a site, the simulation mode can be used to verify the benefits and costs of the DRA.

DRAnalysis was designed to let users easily set up rapid surveys of sections of pipelines and more detailed simulations where product shipment schedules can be employed and simulation results can be compared against actual energy usage and costs.

Since the DRAnalysis is a database-driven web-based application, utility and pipeline company engineers can use DRAnalysis independently or can set up cases for simultaneous, collaborative analysis. Actual pipeline data was used to validate both the process and results from the analysis. After being introduced to pipeline and utility companies in the third quarter of 2015, DRAnalysis will be actively offered as a pathway towards consumption reduction in the state of California.

Due to the increased computational effort of simulations over surveys, it is envisioned that the survey mode will be offered to users without charge, while use of DRAnalysis for simulations will be based on a user subscription. The package may also be leased as a desktop application.

Benefits to California

Reducing energy consumption from pipeline pumps requires both an analysis tool and collaboration between California pipeline and utility companies. To satisfy the first requirement, researchers developed the DRAnalysis, which will be used to assist in the collaborative effort to reach the goal of significant energy and power reduction from the petroleum pipelines operating in California.

Realizing conservative estimates of from one to several gigawatt-hours per year in energy savings will help to reduce strain on California's generating capacity and delay expensive capacity expansion.

DRAnalysis will play a modest but important role in California's bright future by encourage consumption reduction through DRA use in pipelines.

CHAPTER 1:
Introduction – Power and Energy Requirements for Hydrocarbon Pipeline Operations

1.1 Liquid Petroleum Products Transportation

The state of California uses large amounts of petroleum products. Gasoline for cars, diesel for engines in trucks and trains, fuel oil for heating, and jet fuel for airplanes are just a few of the products and uses for which California must maintain adequate supplies and reserves. Cutting across all demographic boundaries, the infrastructure providing California with these resources must operate efficiently and punctually for the well-being of everyone in the state. This report summarizes efforts that will increase the efficiency of the petroleum supply and distribution network, benefiting all.

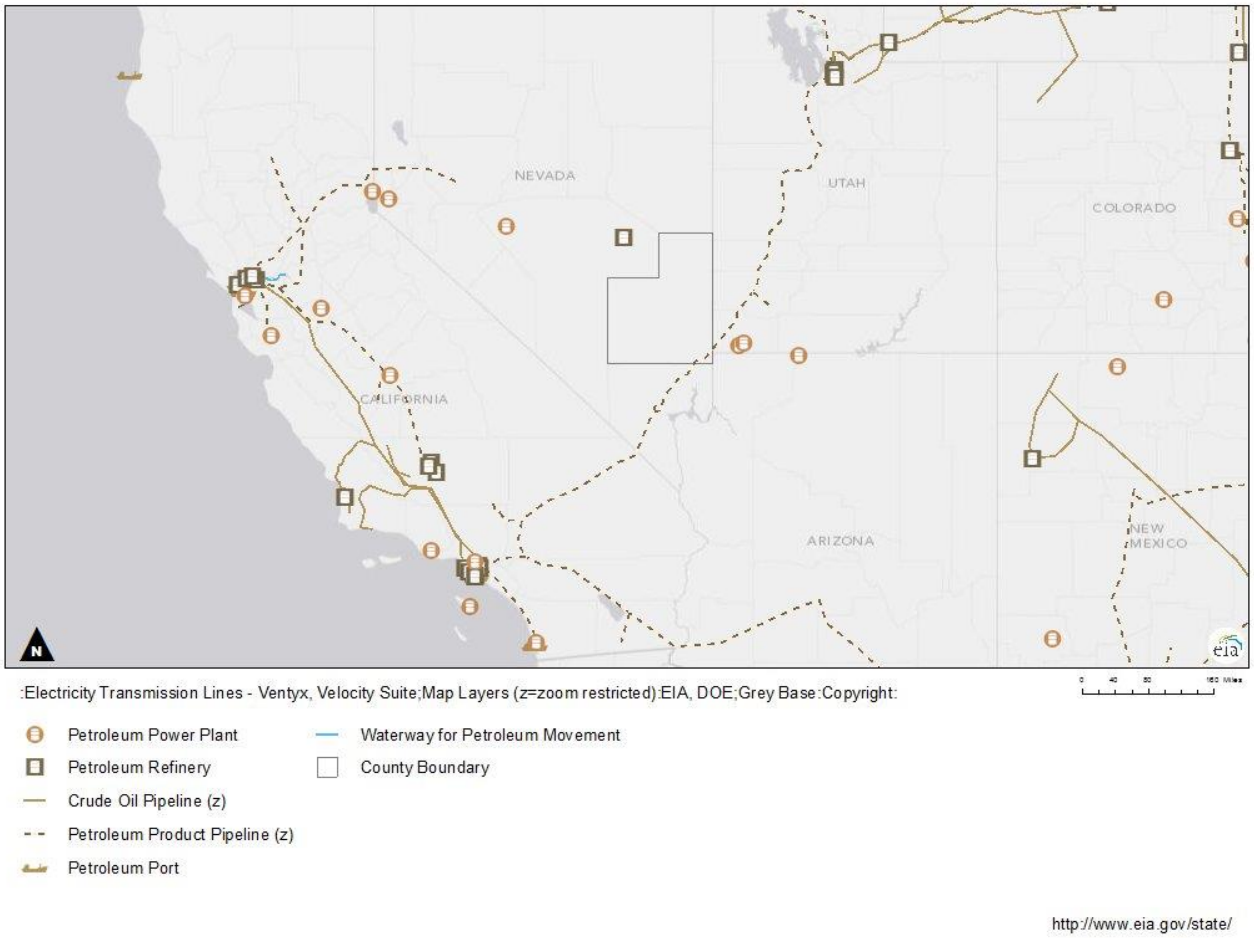
The supply-side of the liquid hydrocarbon life-cycle begins with the extraction of raw material, such as crude oil, from the ground. Typically found at some distance from any processing facilities, the material must then be brought to refineries, where it is transformed into the long list of refined products needed. Finally, the refined liquids must then be taken to distribution points and markets, for consumer access. Typical transport mechanisms for carrying these large liquid volumes across California include railways, ships, trucks, and pipelines. Pipelines are often the preferred transport mode due to their relatively low operating costs and excellent safety records. Despite pipelines having advantageous economics compared with other shipment methods, pipeline operations still require significant power and energy, resources which are at a premium in California's complex mix of utility markets and end users.

In all but the very simplest cases, a fact of pipeline operations is that consumption, over a given period of time, is never truly minimized; for instance, there are always customer-driven schedule adjustments that would increase short-term consumption over baseline levels. Given that complex schedule requirements limit feasible schedule generation, software-aided pipeline scheduling is becoming a key component of pipeline operations. Understanding how to schedule the addition of Drag Reducing Agents (DRA's) to products as they enter the pipeline is a first step towards a general scheduling solution. Due to the dramatic consumption savings possible with DRA, it serves as a worthy and measurable first goal, especially in areas where utility company capacity is of concern.

1.2 Pipeline Operations

There are many long-distance petroleum pipelines within the United Sates and several significant ones in California. Typically run 24 hours a day, they require motor-driven pumps, at stations spaced at intervals along each pipeline, to maintain the pressures and flows needed to meet injection and delivery schedules for the pipeline contents. California's major crude and refined petroleum pipelines are shown in Figure 1.

Figure 1: Major California Crude and Products Pipelines



Stations with several pumps, each with ratings of several thousand kilowatts (kW) per pump, are typical. The pumps are needed to overcome fixed elevation changes and variable molecular-scale viscous friction losses, which can be controlled, at least to some extent. To gain an appreciation for relative equipment sizes, a small motor and pump are shown in Figure 2.

Figure 2: Small 800 Horsepower (HP) / 600 kW Motor and Pump on a Skid

1.2.1 Viscous Losses

Viscous friction losses in pipelines can be understood as the non-recoverable transformation and dispersal of some of the kinetic energy of the hydrocarbon fluid as it is transported through the pipeline. Zero kinetic energy implies that the flow rate is zero and that viscous friction losses are absent (molecular-level kinetic energy is not factored into the macroscopic energy). For non-zero flows, there are several dispersal channels through which the transfer of energy can occur. In addition to deliveries where part of the flow is diverted from the main pipeline, heat, vibration, and elevation changes all serve as channels through which the kinetic energy of the fluid is transformed and redirected. Viscous losses occur as molecular forces resist shearing and slippage, both at the wall of the pipeline and in the fluid volumes. Ordinarily these losses are transformed into heat, which is distributed through normal mechanical and thermal transfer. Focusing on the viscous losses alone, even for a perfectly level pipeline segment, with no elevation change, in order to maintain product flow, energy must be added to the pipeline fluid at intervals. (Note that, if the pipeline starts at a higher elevation and goes downhill, it may be that energy needs to be dissipated at a given site, as gravitational potential energy is converted; this is found only in geographically isolated cases and energy addition and replacement is by far the more common requirement).

1.2.2 Pump Power and Energy Consumption

The fluid energy needed for pipeline operations is provided by pumps. The pumps found on pipelines are driven by motors which use either electricity or liquid fuels, such as diesel or jet fuel. Because of the sizes of the pumps, the energy and power needed to operate the motors, whether from electricity or liquids, is large (in the utility industry, while energy is referred to by name, power is often referred to as 'demand'). A typical residential power bill contains a simple energy charge, with no power component. For industrial-scale electrical usage, however, separate energy and power charges are billed, and monthly charges for pipeline pump stations often exceed $100,000.00. Significant responsibility is placed on utility companies to provide uninterrupted service at levels needed to satisfy all customers, including pipeline operators.

Consumption reduction through management of pipeline power and energy usage will ease utility service requirements, which is the overall goal addressed by this grant.

1.2.3 Consumption Management Classifications

As California grows, its power and energy usage will also grow, and pipeline throughput requirements will increase. In general, two ways California can control this growth are, first, through management of the demand for the products. Obvious cases are that smaller cars use less fuel and, with two people carpooling, consumption is roughly cut by half. This would allow product reallocation while minimizing impact to the end users. The second way is through supply-side conservation, with the lowering of power and energy consumption by both refineries and transportation mechanisms, including pipelines operations. Pipeline use management can be further separated into two categories, one regarding immediate power requirements (how to operate the pipeline at maximum efficiency given a specific fluid and flow scenario), and the other category involving how best to control a list of such scenarios so that the use from each adds up to minimal use (how to schedule the pipeline so that the pipeline doesn't have to run wastefully in order to satisfy poorly scheduled injections or deliveries).

1.2.4 Consumption Management Methods

For short-term operations, there is a particularly attractive means of reducing the power and energy consumption of pipelines. By adding small amounts of a Drag Reducing Agent (DRA) to the pipeline contents, viscous friction losses can be dramatically reduced. This immediately translates to decreases in required pump use, leading to consumption savings, and/or increased fluid throughput. For schedule-driven usage minimization, optimal schedule generation, while technically extremely difficult, can also have a dramatic effect on power and energy consumption.

Pipeline schedule creation is an active field of research and, due to the complexities of creating any feasible schedule, let alone a consumption-optimized one, the research has not yet generally impacted the pipeline industry. On the other hand, the technology behind DRA use in pipelines is mature, but is currently used for operating cost reductions or increasing pipeline throughput, not overall pipeline power and energy reduction.

Usage reduction, the goal of this grant, will be achieved with software capable of providing DRA strategy feasibility evaluation and operational guidance for DRA usage. The software has to examine all relevant factors, weighting each according to short-term criteria, such as safety and immediate costs, and longer-term requirements, such as making sure product schedules are met. The real-time linking of the operational guidance with pipeline schedule requirements ensures usage reduction over extended periods of time

1.2.5 Operational Constraints

Effectively controlling power and energy usage during pipeline operations presupposes meeting several constraints. First and foremost among these constraints is pipeline safety. Any controller action or pipeline configuration that would increase risks above carefully calculated limits cannot be part of any suggested procedure, regardless of perceived benefits. For instance, excessive pressure cycling of a section of pipeline should be avoided, even if the pressures are

within the steady-state limits (in much the same way as a paper clip will break if you repeatedly bend a section of it back and forth, pressure cycling adversely affects the pipe metal and decreases the lifetime of the pipe).

The next important concern involves injection and delivery schedules. Although one has to be careful when making broad statements about pipeline schedules, it is easy to illustrate the trade-off between, on the one hand, power and energy consumption, and schedule requirements on the other. Because of the nonlinear dependence of consumption on flow rate, minimal consumption for a given product sequence over a given period of time determines the flow rates. As every pipeline scheduler knows, such flow rates seldom, if ever, fulfill external injection and deliver schedule requirements. This implies, first, that minimal consumption cannot be the sole criterion determining schedule feasibility, and second, that the questions of schedule flexibility and tolerance must be addressed.

As an example, take as a starting point that higher flows obviously require higher consumption. Scheduling a product delivery ahead of time (i.e. at a higher flow rate than necessary), to allow extra time for unforeseen events either from along the pipeline or at the delivery location, implies a higher flow rate and higher consumption than strictly necessary. If a flow rate sequence $\{f_i(t)\}$ satisfies the delivery requirement with no time to spare, and alternate flow sequences $\{f_j(t)\}_k$ finish the delivery well before the deadline, each with relatively higher flow rates and higher consumptions, a strategy must be implemented on how to balance delivery schedule requirements against increased usage. Again, even specifying a single delivery time in a batched pipeline is enough to preclude a schedule with minimal consumption over any window containing the delivery event.

Another inexact but important measure for schedule feasibility involves pipeline controller workload. A given schedule determines the number and timing of actions required of the controller. If an excessive number of actions are required over too small a time period, the schedule places an undue influence over the controller's time management. Because of the complexities of modern pipeline control, a controller's concentration must be already divided among multiple tasks, and exacerbation of the situation is to be avoided. This implies that, without automatic control of variable speed pumps, schedules must limit to 'reasonable' levels discrete pump selection operations.

Clearly, minimizing consumption while satisfying input / output requirements and maintaining safety is a very complex task.

1.3 Goals Summary

Pipeline pump consumption reduction (i.e. energy and power reduction) is an important component of California's energy sector future. With the addition of DRA to products entering pipelines, significant consumption reduction can be realized. Because of the non-linear effects of DRA, and since DRA is relatively expensive, overuse of DRA can increase operating costs beyond benefits achieved from lower consumption requirements. Determination of optimal DRA usage is one of the two key goals of this project. The other is promotion of optimal DRA usage throughout the California pipeline industry. This will involve engaging pipeline and

utility companies, working with pipelines to promote 'best practices', and working with utilities to develop incentivized utility rate contracts.

An added opportunity may arise where the DRA manufacturers can offer either alternate DRA formulations that are, for example, 95% as effective, but are manufactured at 75% of the cost, or, through greatly increased DRA usage, volume / pricing structures that further incentivize DRA use.

In the first four sections of chapter 2 of this report, we develop the mathematical model for the effects of DRA, including hydraulic behavior, economics impact, and scheduling considerations. As will be seen, the complex nature of the model clearly suggests the necessity of software-assisted evaluation of DRA injection profiles before general industry adoption of DRA and the resulting consumptions savings can be expected. The last section of Chapter 2 describes in broad terms the design of the software tool and usage procedures needed for optimal implementation of DRA in consumption reduction strategies.

Methods for verification of the accuracy of the hydraulics model from Chapter 2 is shown in the first section of Chapter 3, which describes the field data needed and analysis techniques used on this data. Once the model is properly set up, or 'tuned', hydraulic, economic, and consumption calculations can be generated for a given pipeline situation and for any number of DRA injection profiles. The second section of Chapter 3 describes the tool developed to allow such analysis, which has been named DRAnalysis. Using DRAnalysis, both pipeline and utility companies can generate data needed to assess both pricing and use strategies for DRA. Selected usage strategies can then be passed to pipeline control rooms for implementation. The last section of Chapter 3 shows implementation of the overall strategy, using tuning data from a California pipeline as a real-world example.

Chapter 4 describes the strategies to be used in the immediate future for encouraging the pipeline and utility industries to adopt DRAnalysis and DRA as a significant feature in both day-to-day operations and longer-term consumption reduction plans in California.

By skipping from here to the last section of Chapter 3, the reader will be presented with a complete, non-technical description of this project and its potential benefits, based on the implementation of its recommendations. A complete reading from this point will additionally cover the mathematical background needed for an understanding of the simulation of pipeline operations, upon which the results are based.

CHAPTER 2:
Modeling Reduction of Pipeline Power and Energy Requirements

This chapter explains the calculations and characteristics needed in a software tool that utility and pipeline companies will use to routinely incorporate DRA in consumption reduction efforts in California pipelines. In this chapter, the advantages of and the need for software to accomplish this complex task will become obvious.

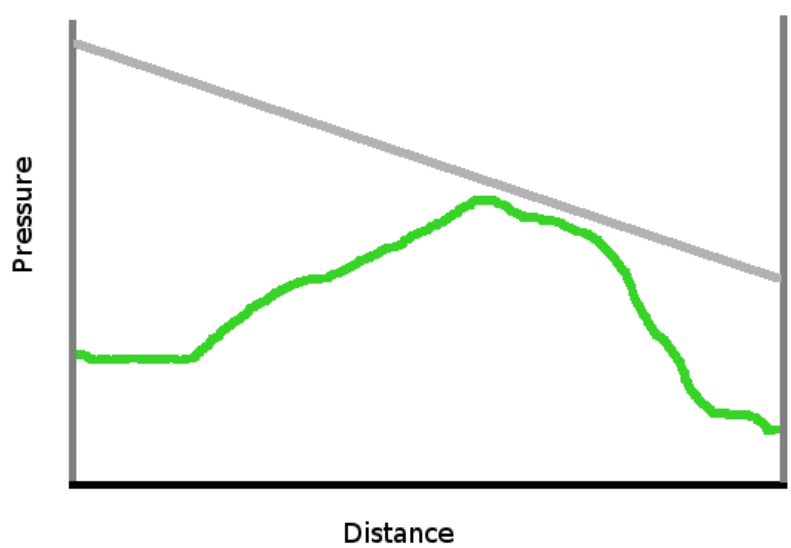
The first two sections of this chapter describe the instantaneous modeling of the hydraulics and economics of pipeline operations, respectively. The third section explains the generalization of the combined instantaneous models to periods of time relevant to pipeline operations (e.g. hours, days, or weeks). The fourth section presents the design requirements for a usable software tool that places the generalized model at the disposal of end users, namely pipeline and utility companies.

2.1 Pipeline Hydraulic Modeling

2.1.1 Pipeline Hydraulics Overview

To help in developing mathematical expressions for quantitative evaluation of DRA concentration profiles versus fuel and electricity usage levels, the relationship between power requirements and flow rates, for a given segment of pipe and its contents, can be visualized with the help of a plot of the fluid pressure and elevation profiles along the segment (see Figure 3 below).

Figure 3: Pressure (in head) and Pipeline Elevation (in green), versus Distance



For the purposes of modeling a pipeline, the 'state' of a segment of pipe can be characterized by a given diameter, elevation profile, fluid content (characterized by specific gravity and viscosity), and flow (exact specification, involving implicit quantities like temperature, will be skipped, for brevity). Any pipeline segment will require a minimum starting pressure to maintain downstream flow and pressures. As the distance from the start of the segment increases, the fluid pressure will decrease due to viscous friction losses. Graphically, the segment pressure profile, when expressed in terms of head (the grey line in Figure 3), can be plotted on the same vertical scale as the elevation profile (in green). The heads and elevations must be in the same units. For instance, if the head units are head-feet or head-meters, then the elevation profile must be in feet or meters, respectively.

Note that Figure 3 shows a straight-line pressure profile, which is characteristic of constant flow situations where the segment contains one homogenous fluid and transient pressure waves from, for instance, pump or valve changes, have dissipated, leaving the pressure steady at each point along the pipeline. Again, the steady decrease in the head represents the constant viscous friction losses, per unit length along the pipeline.

For such steady-state conditions, the viscous friction losses for a given fluid, which are a function of the segment state, determine the slope of the pressure profile. The pressure profile of a fluid that had no viscous friction losses would have zero slope (i.e. would be a horizontal line). Hence, for a pipeline that is shut down, with zero flow rate and zero viscous losses, all steady-state pressure profile plots on the pipeline would be horizontal.

For a pipeline with nonzero flow, to maintain a given segment starting pressure, each new slug (unit of mass) of fluid that arrives at the start of the segment must have or be provided with energy equivalent to the slug immediately preceding it (as an example, consider the strain on the two couplings of a single railway car, in the middle of a very long train, if it alone had its wheels locked). The necessary energy is a combination of potential and kinetic energy and this is the steady-state segment energy requirement. The flow rate determines the rate at which energy must be supplied and gives the segment power requirement (the 'demand').

If the supplied energy per slug is decreased, the pressure at the start of the segment decreases, and the gauge pressure profile will shift down, maintaining the same slope if the flow rate is maintained.

The minimum starting pressure can come from pumps located at the start of a given segment or at upstream stations. If the incoming (suction) pressure of this segment is as low as possible, then the maximum amount of energy needs to be added, at the start of the segment, to each slug of fluid, to maintain the desired pressures and flows. If DRA can be injected, maximum local energy and power savings are possible. If there are no pumps at the segment start, but DRA can be injected there, DRA-related energy and power savings may still be realized at upstream stations as pumps running at those locations are modified as the DRA reduces downstream viscous losses.

The gage pressure in Figure 3, at any point along the segment, is simply proportional to the graphical/algebraic difference between the pressure and elevation profile lines at that point. If

the pressure is low enough for the head curve to intersect the elevation profile, the vertical distance between the two profiles and, hence, the gauge pressure at that point, is 0 (for a fluid with a vanishingly small vapor pressure). This is operationally undesirable as the fluid will 'boil'. Such intersection points are termed control points, since they affect hydraulic behavior. Control points may occur anywhere along a pipeline segment and may move up or down the pipeline, sometimes quite rapidly. The analysis necessary for this project requires only steady-state modeling.

One final point is that, just as the pressure profile changes as pumps are turned on or off, it is also affected as different fluids enter and leave the pipeline segment. So, even with the same base fluid being shipped, as DRA enters and fills the segment, adequate analysis requires that transit times necessary for the DRA to fill the segment be taken into account. That is, DRA concentrations, viscous losses, profile slopes, and potential energy/power usage and savings, will be functions of position and time.

Next, expressions, suitable for incorporation in quantitative simulations, will be developed for instantaneous hydraulics and economics quantities of interest.

2.1.2 Pipeline Hydraulics Model

Starting with the minimum possible suction pressure at the start of the segment, without any DRA, the total power needed for a given flow rate is the sum of two components; the first is the power necessary to achieve any flow at all, and is the power necessary to overcome the segment elevation profile (graphically, this is equivalent to avoiding intersection of a horizontal head profile and the elevation profile). The second gives the power necessary to overcome the pressure drop due to viscous friction losses in the segment, determined by, among other things, the various hydraulic variables for the pipeline contents. Thus,

$$P_T = P_e + P_f \tag{2.1}$$

where

P_e is the power necessary to offset elevation-related pressure changes
P_f is the power necessary to offset viscous friction losses

Again, the first term on the right accounts for elevation effects, or that part of the head in Figure 3 that will allow a zero-flow (horizontal) gradient to clear the high point of the pipeline segment. (Extreme elevation changes, with associated changes in the gravitational constant and ambient pressure, are atypical and are not considered here.) The second term on the right accounts for the additional power required as the flow in the segment is increased and viscous friction losses become important.

The relationship between head, in feet, and hydraulic power required is:

$$P_T = \lambda \cdot (head_e + head_f) \cdot f \cdot SG \qquad (2.2)$$

where

$head_e$	is the head rise, in feet, needed to overcome elevation
$head_f$	is the head rise, in feet, needed to overcome viscous friction losses
f	is the flow, in gallons per minute
SG	is the specific gravity of the pipe contents

and

λ	is $\frac{1}{3956}$ for h.p. and $\frac{745.7}{3956}$ for W

For MKS units (which uses meters and cubic meters / second for the variable units), λ is 9802.368. Within the segment, as pipeline diameters or products change, the viscous friction losses are additive and are the sum of contributions from homogenous lengths (i.e. viscous friction losses occur at each point along the pipeline).

Integrating instantaneous values of P_T over time will yield the energy requirements for a given scenario. Properly incorporating a pipeline schedule, with both fluid and flow variations over time, equation 2.2 can be used to calculate energy and power budgets for shipment of a given list of products through the pipe segment.

Determination of consumption savings must entail comparison of shipment consumption budget calculations, both without DRA and with DRA using a variety of injection profiles, to yield the potential fuel / electricity savings. Implementation and comparison of the potential savings with both instantaneous and integrated historical utility data will provide verification of those savings.

It should be noted that, at any instant in time, the hydraulic power needed is less than the total power drawn to operate any pipeline segment, given the losses in conversion of the utility fuel or power provided to the power imparted directly to the fluid. The ratio of the two yields station and pump efficiencies, can be mined from historical data, and should be factored into the calculations.

Since the elevation term necessary for proper operations is not a function of DRA concentration, this term will be dropped from further analysis.

The standard expression for the additional head required for overcoming viscous friction losses is:

$$head_f = f_D \cdot \frac{L}{D} \cdot \frac{V^2}{2g} \tag{2.3}$$

where

$head_f$	is the viscous friction head loss
f_D	is the Darcy friction factor
L	is the length of the pipe segment
D	is the hydraulic diameter (for circular pipe, the inner diameter)
V	is the velocity of the fluid in the pipe

and

g	is the gravitational acceleration

If the high point of the segment is at the start of the segment, regardless of flow rate, then, since downstream viscous losses will not impact the power needed to overcome the initial gravitational barrier, the power needed will be constant and DRA use will be completely ineffective. However, taking the case at the other extreme, where the high point is at the end of the pipeline segment, L in formula (3) does not vary with flow, the power needed to offset viscous friction loss is:

$$P_f = \Lambda \cdot SG \cdot f_D \cdot L \cdot \left(\frac{f^3}{D^5}\right) \tag{2.4}$$

where, using MKS units,

$$\Lambda = 8.1021555 \cdot 10^2$$

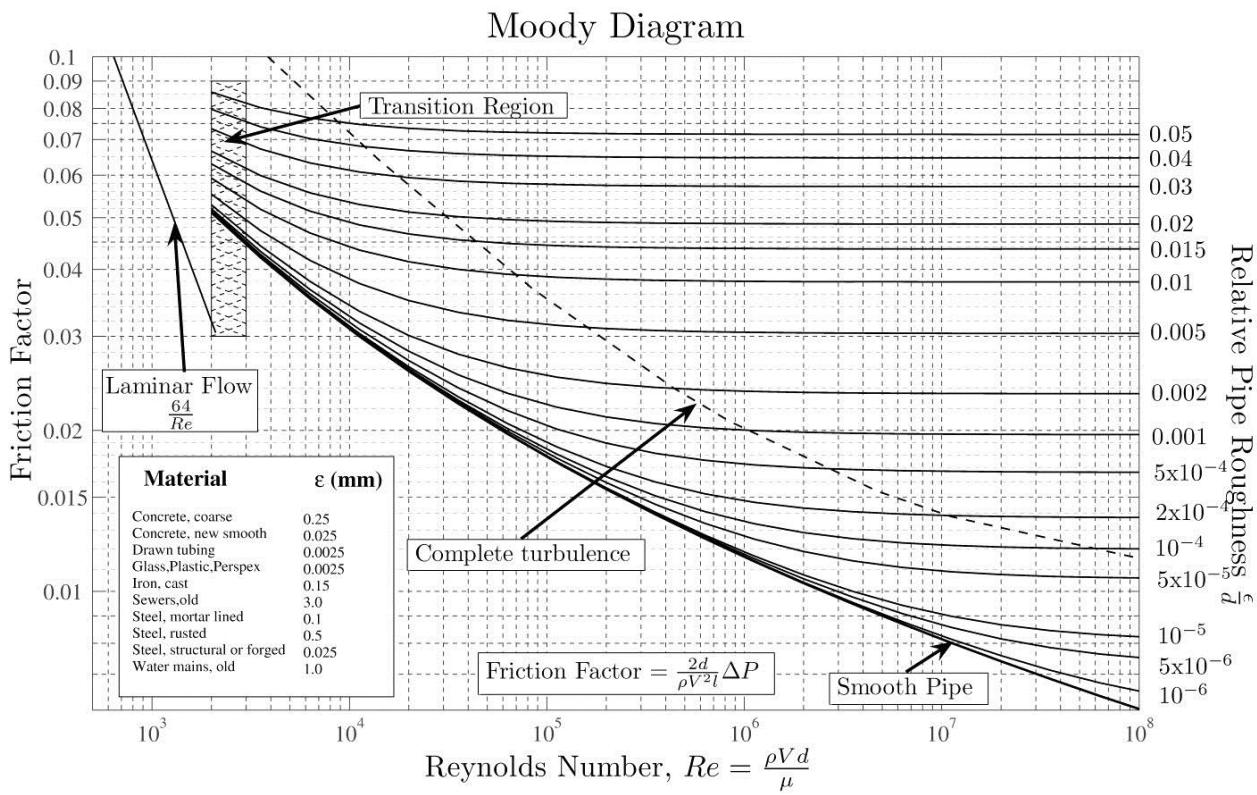
and DRA use can have a dramatic impact on the needed power.

This formula for power requirement applies to fully developed turbulent flow, where the velocity profile is constant throughout the cross-section of the pipe. Operating in this regime allows batching of pipeline products, where dissimilar products are sequentially injected into the pipeline, one after another. The constant velocity profile ensures minimal mixing of the products.

Explicitly expressing f_D in terms of the flow is not straightforward. This relationship is graphically expressed in the well-known Moody Diagram, where f_D is given as a function of

Reynolds number, defined below, at the bottom of Figure 4, for a variety of pipe roughness ratios.

Figure 4: Moody Diagram



With the introduction of DRA, the desired quantities are the required power, as a function of DRA concentration, the rate of change of power requirements with respect to changes in DRA concentration, and the corresponding cost changes.

An examination of equations 2.3 or 2.4 indicates that DRA affects can be viewed as a modification of f_D only.

2.1.3 Modeling Hydraulics Effects of DRA

As discussed at the end of the previous section, the effects of DRA on the power required to overcome viscous friction losses can be expressed through a modified friction factor:

$$P_f = \Lambda \cdot SG \cdot f'_D \cdot L \cdot \left(\frac{f^3}{D^5}\right) \tag{2.5}$$

where

$$f'_D = f_D \cdot (1 - \frac{C}{A+b \cdot C})$$

The mathematical form for the modification to f_D given above reflects standard DRA models. C is the DRA concentration, in parts per million (ppm), and A and b are constants that depend upon the DRA type, product type, and various state variables. In calculations, an implicit formula for f_D is normally used, such as the Colebrook-White equation. However, several adequate explicit approximations exist for f_D. One suitable choice is the Swamee-Jain formula:

$$f_D = \frac{.25}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{Re^{0.9}}\right)\right]^2} \tag{2.6}$$

where

ϵ is the surface roughness

and

$$Re = \frac{\rho \cdot V \cdot D}{\mu}$$

where

ρ is the fluid density
μ is the dynamic viscosity of the fluid

Substituting this into equation 2.5 gives the instantaneous power required, in closed form, with DRA effects:

$$P_f = \frac{\Lambda^* \cdot SG \cdot L}{D^5} \cdot \left(1 - \frac{C}{A + b \cdot C}\right) \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{\left(\frac{\rho \cdot D \cdot f}{\mu \cdot \sigma}\right)^{0.9}}\right)\right]^2} \tag{2.7}$$

where

Λ^* is $\frac{\Lambda}{4}$
σ is the cross-sectional area of the pipe

An important quantity for understanding the effectiveness of DRA on consumption reduction is the rate of change of pumping power required as the DRA concentration varies:

$$\frac{\partial P_f}{\partial C} = \frac{\Lambda^* \cdot SG \cdot L}{D^5} \cdot \frac{10^{-6}}{f} \cdot \frac{-A}{(A + b \cdot C)^2} \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{\left(\frac{\rho \cdot D \cdot f}{\mu \cdot \sigma}\right)^{0.9}}\right)\right]^2} \tag{2.8}$$

The decrease in power needed to run the pipeline segment decreases with increased DRA concentration, meaning that the greatest incremental power requirement reductions will be at low concentrations.

One note regarding the development of equation 2.8 is that the Swamee-Jain approximation formula, which contains the Reynolds number, assumes a particular functional dependence for f_D. DRA effects come from physical processes outside the scope of the original dependence. For this reason, it is to be expected that adjustments, based on field measurements, will be necessary for the best fit between the calculations and live pipeline data. As will be shown below, these adjustments are minor.

With the first major components necessary for DRA analysis in hand (equations 2.7 and 2.8), section 2.2 will discuss the various types of utility rate structures, examine viable DRA profiles (i.e. the effects of varying DRA concentration with time), and quantify the overall impact on consumption and operating costs, including costs for DRA, electricity, and fuel.

It will be seen that, while fuel costs for engines have a simple structure and change slowly, utility rates for large electrical motors can and usually do change over time, often quite drastically and with long-term effects.

2.2 Pipeline Economics Modeling

Equations 2.7 and 2.8 are analytical expression for the power required to offset viscous friction losses in a pipe segment, and the way that requirement changes with DRA concentration. The

next step is to quantify the economic impact of different DRA injection strategies. This section will address DRA costs and some of the detail related to utility company pricing contracts, for pipeline companies, for fuel and electricity. Following this, section 2.3 will examine the hydraulics and economics of differing DRA injection profiles.

Though most pipeline pumps are driven by electric motors, some are driven by hydrocarbon fuel. Commonly used fuels are kerosene, natural gas, and diesel oil. As is seen at gasoline stations, fuel costs, whether provided externally by a utility company, or internally from pipeline company product inventories, change slowly with time, and can be adequately represented using a constant cost per volume or energy equivalent.

Electrical contracts, however, need a more detailed treatment.

2.2.1 Electrical Contract Economics

Like the typical residential electrical bill, utility companies present pipeline companies with electrical bills on roughly a monthly basis. Unlike the typical residential electrical bill, consisting of energy usage multiplied by a simple dollars-per-usage charge, the large electrical loads required to drive pipeline pumps are typically provided by utility companies under industrial-scale rate contracts between the utilities and the pipeline operators (several are presented in the appendices). Rates can be classified into several general groups, based primarily on how they handle energy and power charges (power is often referred to as 'demand' in utility contracts and bills, as in 'demand for energy'). These contracts can become quite involved and, because of the way the actual energy and power usage may be adjusted, per the contract, the billing kW and billing kWh may not reflect the actual metered values of kW and kWh.

Billing of the energy used by a pump or pumps at a pipeline station is usually directly related to actual usage at the station for the billing period. The higher the use, the higher the kWh portion of the bill, although there may be different rates at which different segments of that use are billed. For instance, the first 100,000 kWh may be billed at a different rate than kWh usage above that limit.

Additional complexities are common in specification of how the power usage, or demand, is billed. The simplest form of billing demand is where the maximum instantaneous demand is used in the bill calculation. With residential water usage as an analogy, if all the taps in a home were turned on at once, briefly, then shut off, this level of demand, in, say, gallons per minute, would be the billing demand, regardless of lower demand during the rest of the billing period.

However, when a large electrical motor is turned on, power spikes occur. While these spikes can be reduced with appropriate motor design techniques, the spikes can be significantly higher than steady-state demand levels. Using instantaneous demand would therefore penalize the use of large motors on pipelines by setting billing demand charges at levels only seen for fleeting periods of time. Since the utility companies service the general public, they are required to meet these increased loads without sacrificing supply to the broader public, but do not have to supply these peak loads constantly. Working with the pipeline companies, the utilities have incorporated several ways of the measuring and getting equitably compensated for usage

spikes. Averaging of the demand over a time window longer than the extent of startup spike events is the approach adopted by the industry. Using contract language from one provider:

"Electric demand is a measure of the average rate at which your facility consumes electricity in a 15-minute interval."

This methodology strikes the desired balance of mitigation of the cost effects of short-lived pump demand spikes, and allowing for adequate compensation to the utility companies for generation and delivery of the electricity at the demand levels required by all customers.

Variations are often seen, include use of different times over which the average is performed; 15-minute intervals are typical, and 30-minute intervals are not uncommon. Contracts where averaging of the highest three or more such demand intervals are used for calculation of billing demand and provide an example of how utility / customer needs can be fine-tuned and expressed in the electrical contracts.

A number of typical electrical contract clauses will now be described. In the following discussions, any constant, recurring charges, such as utility equipment costs billed to the pipelines, will not be considered.

2.2.1.1 Fixed Energy and Demand Rates

The simplest rate structure is where the energy and demand rates are fixed throughout an entire billing period (typically approximately a month, and may be tied to either calendar dates or to meter reading schedules), and actual energy and demand are used in calculating billing kWh and billing kW.

$$Electrical\ Bill = \mathrm{a\,A} + \mathrm{bB}$$

A – billing kWh

B – billing kW

a - fixed energy charge ($/kWh)

b - fixed demand charge ($/kW)

This case is most like a typical residential bill, where the homeowner incurs a fixed charge for each kWh used, with no demand charge (i.e. b=0).

2.2.1.2 Time-of-Use Rates

From the case of actual energy and demand used with fixed energy and demand charges, layers of case-specific energy and demand categories are used across the industry to balance provider / customer needs. The time at which electricity is used is important to the providers and is reflected in time-varying electrical charge components. Both energy and demand costs can vary based on when consumption occurs. Higher costs are associated with heavy co-incident (usually residential) usage, an example being when 'everyone' turns their air conditioner thermostats down when they get home from work on weekday summer afternoons. The increased load on the electrical grid can strain and, sometimes, compromise the grid. The classic law of demand is not valid for pipelines, when some factors are deemed at least as important as

the cost of pump operations, so the utility companies often incorporate time-of-use structures in pipeline company rate contracts. These associate various utility-relevant time-of-day periods with different energy and demand pricing. Terms such as 'on-peak', 'off-peak', and 'mid-peak' are used.

For instance:

$$Electrical\ Bill = \sum_{i=0}^{2} (a_i A_i + b_i B_i)$$

A_i – billing kWh each distinct period

B_i – billing kW for each distinct period

a_i - fixed energy charge ($/kWh) for i^{th} period

b_i - fixed demand charge ($/kW) for i^{th} period

where

i = 0

on-peak – year-round, weekdays, 16:00-22:00

fixed energy charge #1 ($/kWh)

fixed demand charge #1 ($/kW)

i=1

mid-peak – year-round, weekends and holidays

fixed energy charge #2 ($/kWh)

fixed demand charge #2 ($/kW)

i=2

off-peak – year-round, all other times

fixed energy charge #3 ($/kWh)

fixed demand charge #3 ($/kW)

These types of rate structures are often extended to deal with seasonal variations in usage patterns (e.g. air conditioner use typically falls off during winter months). Accordingly, pricing or timing of peak periods may be different between winter and summer months, and cases exist where three or more different groups of months have different price levels.

Regarding the specification of times for switching between rates, pipelines often cross time zone boundaries, with a corresponding impact on consumption management. For instance, different groups of pump stations, covered by the same utility, may change their peak designation at the

same clock time but at different absolute times. An analogous situation occurs when groups of stations are serviced by different utility companies and, hence, different utility rate contracts.

2.2.1.3 Demand Ratchets

Since the ability to delivery peak demand requires adequate, expensive equipment, utility companies often choose to construct their rates with demand components that factor historic usage into billing demand calculations. This helps in ensuring sufficient revenues to recover the capital equipment costs needed to meet customer demand. As an example:

Current billing demand = the greater of

a) a fixed percentage of the maximum billing demand level from the past 11 months,

b) the current billing cycle demand levels

c) a minimum contracted kW level.

Note that, even if a station under this rate is not used during a billing cycle, either of the clauses a) or c) above will result in a non-zero billing demand.

Section 2.2.1.4 – Block Energy Rates

Another rate mechanism commonly used by the power providers is termed 'block' energy pricing. In this type of rate, blocks of energy are charged at different rates, typically decreasing in cost / kWh with increased usage. The size of the blocks may be either fixed or governed by the demand component of the customer's monthly usage. So, as an example of a fixed, declining block structure:

$$Energy\ Component\ of\ Electrical\ Bill\ = \sum_{i=0}^{2} (a_i\ A_i)$$

A_i – billing kWh level for each distinct energy block

a_i - fixed energy charge ($/kWh) for i^{th} block

where

a_0 = $0.05/ kWh, for energy consumed up to a maximum of 250,000 kWh

a_1 = $0.04/ kWh, for energy consumed for the next 150,000 kWh

a_2 = $0.03/ kWh, for energy consumed above 400,000 kWh

As an example of when block boundaries are tied to the monthly billing demand:

$$Energy\ Component\ of\ Electrical\ Bill\ = \sum_{i=0}^{2} (a_i\ A_i)$$

A_i – billing kWh level for each distinct energy block

a_i - fixed energy charge ($/kWh) for i^{th} block

where

a_0 = \$0.05/ kWh, for energy consumed up to a maximum of 50 kWh/kW

a_1 = \$0.04/ kWh, for energy consumed for the next 30 kWh/kW

a_2 = \$0.03/ kWh, for energy consumed above 80 kWh/kW

Here, the boundaries between the energy blocks are determined by multiplying each of the a_i factors by the appropriate demand level (this may be the maximum demand from the current month or a billing demand calculated, for instance, with the use of demand ratchets, as discussed above). Note that if the demand level used in the calculation is 5,000 kW, the blocks would be identical to those from the preceding example.

Note that a block energy pricing structure may be layered on top of, for instance, time-of-use rates, further complicating electrical bill calculation.

2.2.1.5 Daily and Hourly Designation / Curtailable Rates

Given an electrical rate, up to and including a 'fully-developed' electrical utility pricing structure, with all of the components and features described above, another layer of complexity is sometimes added, involving daily or hourly designations. In this type of rate, alternate energy and demand rates are applied to some or all time and energy blocks. The way the costs change is set by contract, and the changes are typically triggered by actual or expected electrical demand on the infrastructure of a specific utility company. Contract language in this case might designate that, over the course of a billing cycle, up to but no more than a certain number of 'A' days, 'B' days, 'C' days, etc. may be declared by the utility, with an advanced warning of, say, 24 hours of the start of said designation. Pipeline companies are given the option of following tighter usage constraints (typically demand limits). Advantageous rates for limiting demand have to be weighed against penalties for exceeding the limits. This day/hour designation mechanism gives a utility the ability to proactively manage broader usage spikes caused by, for instance, high air conditioning use and transmission line loss during heat waves.

Curtailable rates have the same object as the day/hour designation scheme, allows providers to notify pipeline companies of high collateral use, and gives the pipelines the opportunity to reduce electrical usage in exchange for relaxed rates or billing levels. For instance, a curtailable rate in active use (see appendix C) specifies who can use this rate and how this rate is structured:

> **Curtailable Rate**
>
> **Applicable:**
>
> To any customer, other than residential, for light and power purposes where the customer agrees during a period of requested curtailment to curtail as a minimum the greater of: (a) 25 kW or (b) 25% of their average monthly billing demand (based on the most recent twelve (12) months or, where not available, a projection for twelve (12) months).
>
> And gives the following price adjustments:
>
> **Curtailable Demand Credit:** \$ 3.74 per kW of Curtailable Demand
>
> with the following billing demand calculation instructions:

Determination of Billing Demand:

The billing demand shall be the maximum 30-minute kW demand established during the current billing period.

Determination of Curtailable Demand:

The Curtailable Demand shall be the difference, if any, between the current Billing Demand and the contract Non-Curtailable Demand determined in accordance with Special Provision No. 2 of this rate. In no event shall the Curtailable Demand be less than zero.

A natural extension of these two approaches leads to real-time pricing, where there is a close coupling between overall utility load and the bills presented for providing that load.

2.2.1.6 Real-Time Pricing / Energy Markets

With real-time pricing, the utility can achieve close tracking of electricity generation and delivery costs to revenues generated. In these types of rate structures, the price paid for the electricity varies, typically, on an hourly basis. Both power and energy bill components may be affected, but explicit power charges may be accounted for in consumption and transmission bill components, which are energy-based charges. With real-time pricing, hour-by-hour costs are determined and released to the customer within some fixed period of time before the prices take effect. The costs may be tied to overall demand or, in some cases, energy markets that the utility companies have to employ to maintain adequate demand margins. For instance, time-varying rates might be published every weekday, by 16:00, for use the next day, with rates for 72-hour periods or longer being published to account for weekends and holidays. This type of rate ensures utility company profits that closely adhere to preset margins. One disadvantage is that scheduling pipeline operations to avoid heavy pump use during periods of higher cost becomes difficult.

An example of language from an actual real-time pricing (RTP) rate is:

RTP BILLING

Customers participating in the RTP Program will be billed monthly based on the following calculation:

$$\text{RTP Bill} = BC + PC + \sum_{t=1}^{n} \{ (CCt + EDt) \times (ALt - CBLt) \}$$

$$RTP\ Bill\ Rate = BC + PC + \sum_{t=1}^{n} (CC_t + ED_t) (AL_t + CBL_t)$$

Where:

BC = Baseline Charge

PC = Program Charge

CC_t = Commodity Charge for hour t

ED_t = Energy Delivery Charge for hour t

AL_t = Customer Actual Load for hour t

CBL_t = Customer Baseline Load in hour t

n = total number of hours in the billing window

t = an hour in the billing period

subject to:

CUSTOMER BASELINE LOAD

The CBL is one complete year of Customer hourly load data that represents the electricity consumption pattern and level of the Customer's operation under the Standard Rate Schedule. The CBL is the basis for achieving bill neutrality for Customers billed under this Rate RTP, and must be mutually agreeable to by both the Customer and the Company as representing the Customer's usage pattern under the Standard Rate Schedule (non-RTP). Agreement on the CBL is a requirement for participation in the RTP Program.

2.2.1.7 Rider Costs

Finally, there are charge components in large industrial electrical contracts that are often not known, but can only be estimated, until the bill arrives. Varying coal or natural gas costs associated with electrical generation at a hydrocarbon-based power plant is a common example. The varying costs of the fuels, incurred by the plant operator, are typically passed on to the end user. One frequently used mechanism by which such additional charges are assessed, for large users, is a contract 'rider'. This is an addendum to the base rate contract describing how such fluctuating costs are assessed. Often in the form of an additional, simple energy-based charge, there may be several riders attached to a contract, each covering a specific cost the utility is recovering.

2.2.1.8 Rate Discussion Summary

The energy and demand-related cost components of monthly pipeline electricity bills must often be calculated using more than one line of algebra that depends on the usage patterns for the entire current month, usage from previous months, and rider costs that are, again, unknown to the pipeline user until the end of the month.

A close examination shows that, although abrupt changes in rates may occur at specific usage levels at a few points in time throughout a billing period, the incremental costs for running pumps at a station and drawing the needed load are, away from these usage-related cost jumps, described by simple relationships. Incremental costs are those that can directly be related to an increment in the monthly bill at a station over a small (i.e. incremental) period of time (e.g. 5 minutes). They are, for the great majority of the time, simply the added energy-related costs for the operational usage level, again for a small time span, over what the bill would be if that station were not used, from that point on until the end of the billing period.

As an example, if a station has just turned off one of three running pumps (so that the new demand is known to be less than the maximum for the month), the incremental cost for that station, for a brief period, is usually as simple as the product of the kWh used during that period and the sum of a known energy rate and an energy-based rider rate that can be estimated with reasonable accuracy. The key point is that extended periods of time can be divided into sections where calculation of the kW and kWh costs are very straightforward. Identification and prediction of when and where the usage thresholds are crossed becomes key in usage and bill management.

These incremental calculations can be extended across a complete pipeline or pipeline network, still at a specific time, to arrive at a total incremental system cost. Many such discrete, constant-hydraulics / constant-rate periods can be added together, using a pipeline schedule detailing the injections and deliveries of products in and out of the pipeline system. As scheduled flows change, the loads for pump configurations necessary to achieve the schedule can be calculated, and an estimated cost for operations over the course of the schedule results. The handling of stochastic quantities (including the degree of certainty of the pumping schedule and allowances for unscheduled events) will be addressed as necessary within the next several sections.

2.2.2 DRA-Related Economics

DRA costing is based on volume and does not fluctuate rapidly. There are several manufacturers of DRA; two industry leaders in North America are Baker Hughes and Phillips Specialty Products Incorporated (PSPI), each providing several varieties of DRA, engineered for use with specific classes of fluids:

- http://www.bakerhughes.com/products-and-services/downstream-chemicals/refining/flo-pipeline-drag-reducer-products-and-equipment
- http://www.liquidpower.com/EN/aboutcspi/Pages/index.aspx

While exact prices vary as a function of DRA type, manufacturer and end user, a cost per volume / volume discount model is adequate since it is safe to assume that the DRA costs will

not vary over the time spans of weeks and months being examined. Mention has been made of the fact that the DRA manufacturers are obviously key players in any efforts to use DRA in reducing pipeline power and energy consumption. As the use of DRA spreads across California pipelines, there will be the opportunity for volume-based price negotiations with the manufacturers, as well as the ability to ask for directed research towards formulating DRA with both improved cost/benefit ratios and an expanded target list of hydrocarbon products as research goals.

The price negotiations should also include input from California utility companies. For instance, using a mechanism similar to curtailable contracts, DRA incentivization by the utilities, for pipeline companies, can be implemented. A rider approach is a straightforward option, where use of DRA during periods of heavy coincident usage can be linked to pipeline consumption reduction targets and electrical bill savings. In addition to the cost of the DRA, the costs associated with installing equipment to inject the DRA into the pipeline fluids has to be taken into account, and is discussed below.

Given that there are multiple stakeholders in the pipeline consumption reduction goal, ensuring good communications among all will be a key to the success of the effort. This will be discussed further in chapter 4.

2.3 Extended Time Considerations

Expressions for the instantaneous power needed as a function of relevant pipeline variables and an outline of fuel, power, energy, and DRA costing have been developed in section 2.1 and 2.2. The next steps are to examine, for different DRA injection strategies, the incremental costs and the power and energy savings as compared to the baseline, no-DRA case. This will result in the incremental cost versus consumption savings relationships needed for optimal planning of DRA use.

2.3.1 DRA Injection Profiles - Introduction

From the standpoint of a pipeline segment, there are three distinct operational phases of DRA use. Described by the terms ‘loading’, ‘loaded’, and ‘unloading’, they reflect, in order, the loading phase, where DRA injection has started or has increased in rate, but the DRA concentration profile is not constant along the pipeline segment, the loaded phase, where, with an active DRA injection, the DRA concentration profile is uniform along the length of the segment, and the unloading phase, where the DRA injection rate has decreased or stopped and, again, the DRA concentration profile is not constant along the pipeline segment.

Several types of DRA injection strategies can be eliminated as sub-optimal from first principles. For instance, any injection strategy resulting in point-of-injection DRA profiles with longitudinal variation on scales shorter than scales of the process of longitudinal diffusion for a particular fluid and pipeline can be ignored. In other words, quickly cycling the DRA injection rate between two levels does not offer any possible hydraulic advantage and can be ignored, regardless of any operational considerations. Also, the rate of change of dependence of DRA performance on concentration (equation 2.8) shows that increasing the concentration achieves a decrease in the baseline power required, but with incrementally less effect as concentrations

increase. This implies that, all other variables being equal, the optimal DRA profile for a pipeline segment containing, for instance, a homogenous fluid should be uniform along that section. Situations where two or more different concentrations levels exist would require a larger and therefore more expensive net volume of DRA to achieve identical hydraulic results.

A second set of limiting factors on profile selection involve the fact that the DRA concentration levels are usually under the control of pipeline operators who manually set the concentration to some desired level, with the exact DRA flow rate being automatically controlled in the field as the local pipeline flow rate changes. As DRA loads a specific segment, the pump requirements for that section will gradually decrease and adjustments to the pumps, made by the controller, will be needed to realize the consumption savings.

Both the setting of DRA concentrations and the adjustment of pumps require additional pipeline controller attention over and above normal activities, and must be properly managed for each site and pipeline for best results. An advantageous situation exists for segments with upstream variable speed pumps controllable via downstream setpoints. In this case, the controllers need only monitor the reduction of pump speeds as DRA effects increase during the loading phase of the DRA cycle.

As discussed in section 2.2, and as shown in Appendices A-C, the electricity pricing structures that apply to pipeline stations can be fairly complex. Pipeline companies desiring to reduce their electrical bills while operating under such structures can spend significant time in data analysis, even without the added complexity of DRA use to reduce consumption. To this must be added the complications associated with pipeline schedules for batched pipelines, where flow rates change and different products pass through a pipeline segment available for DRA injections.

Optimal DRA guidance requires a software solution incorporating accurate price analysis as well as pipeline schedules and forecasts. To clearly develop a cost versus power savings relationship with all relevant variables, a simple, baseline case will serve as a guide for more complex situations. As the restrictions defining the simple case are removed, the effects can be examined at each step.

2.3.2 DRA Injection Profiles – Baseline Case

Recalling equation 2.7 from section 2.1:

$$P_f = \frac{\Lambda^* \cdot SG \cdot L}{D^5} \cdot \left(1 - \frac{C}{A + b \cdot C}\right) \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{\left(\frac{\rho \cdot D \cdot f}{\mu \cdot \sigma}\right)^{0.9}}\right)\right]^2} \tag{2.7}$$

where

Λ^* is $\frac{\Lambda}{4}$
σ is the cross-sectional area of the pipe

This equation can be applied directly to any homogenous segment of pipeline, meaning that both the properties of the fluid throughout the segment as well as the DRA concentrations are constant.

When there are two or more distinct types of fluids in a segment, as will be the case in any batched pipeline, homogeneous volumes of the larger inhomogeneous volume of fluid can and must be treated separately. The above equation can be applied in detail to any number of homogeneous volumes. For instance, with only the DRA concentration varying along the segment:

$$P_f = \frac{\Lambda^* \cdot SG}{D^5} \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{\left(\frac{\rho \cdot D \cdot f}{\mu \cdot \sigma}\right)^{0.9}}\right)\right]^2} \cdot \sum_{i=0}^{n}\left[L_i \cdot \left(1 - \frac{C_i}{A + b \cdot C_i}\right)\right] \tag{2.9}$$

Note that, in general, the L_i are not required to be equal.

Examining a very simple operational case, covering one complete DRA injection cycle, will highlight the DRA loading and unloading effects. It will be assumed that, over the cycle, the fluid, flow rates, and utility rates do not change, and the DRA injection profile, at the start of the segment, is a step function with a baseline concentration of 0 ppm (parts per million, the typical unit of measure for DRA concentrations in hydrocarbon liquids). The no-DRA consumption and cost scenario will be compared against the changes in cost and consumption when DRA is incorporated.

For clarity, this case will assume the following:

Table 1: Baseline Case Assumptions

Assumption #	Description
1	Constant diameter pipeline and roughness
2	One variable speed pump operating at the start of the segment, covering the range of pressures needed to meet the fixed flow rate
3	The pressure supplied by the pump exactly offsets the viscous friction losses
4	Homogenous fluid, with no temperature variations
5	Constant flow rate over entire DRA cycle
6	Fixed DRA cost, per volume used
7	Fixed energy cost, per kWh
8	No power (demand) cost
9	Initially, no DRA in pipeline segment

Given these conditions, everything to the left of the summation sign in equation 2.9 evaluates to a constant, which will be designated $\mathbb{K}$. The baseline (no DRA) power requirement is:

$$P_{max} = \mathbb{K} \cdot \sum_{i=0}^{n} \left[L_i \cdot \left(1 - \frac{C_i}{A + b \cdot C_i} \right) \right] = \mathbb{K} \cdot L_s \qquad (2.10)$$

where L_S is the length of the pipeline segment and, as seen, there is no time dependence. Over the course of the complete injection cycle, of time T, the baseline energy used is:

$$E_{max} = \mathbb{K} \cdot L_s \cdot T \qquad (2.11)$$

The time T, in seconds, includes all three hydraulically relevant periods of the DRA injection cycle, not just the time of active DRA injection. For the list of assumptions in Table 1 and for the goal of maximum power and energy reduction over a specific period of time, T would be the sum of times over which the utility company desires power reduction and the times for loading and unloading the DRA. E_{max} in equation 2.11 is in Watt·seconds. With the proper conversion factor, the baseline operating cost for this cycle is simply:

$$\$_{kWh_{max}} = \mathbb{K} \cdot L_s \cdot T \cdot \mathbb{R}_{kWh} \cdot 2.778 \cdot 10^{-7} \qquad (2.12)$$

where $\mathbb{R}_{kWh}$ is the fixed rate charged for electrical energy usage, in $/kWh.

Use of DRA will decrease this cost non-linearly, while simultaneously adding a term to the total cost directly related to both DRA use and time.

Evaluated power and energy consumption reductions, over the course of all three phases of a full DRA injection cycle, are, respectively:

$$P_{sav} = -\mathbb{K} \cdot \sum_{i=0}^{n} \left[L_i \cdot \left(\frac{C_i}{A + b \cdot C_i} \right) \right] = \begin{cases} \mathbb{K} \cdot \frac{f \cdot t}{\sigma} \cdot \left(\frac{C}{A+b \cdot C} \right), & 0 \leq t \leq \frac{\sigma \cdot L_s}{f} \\ \mathbb{K} \cdot L_s \cdot \left(\frac{C}{A+b \cdot C} \right), & \frac{\sigma \cdot L_s}{f} \leq t \leq T - \frac{\sigma \cdot L_s}{f} \\ \mathbb{K} \cdot \frac{f}{\sigma} \cdot (T-t) \cdot \left(\frac{C}{A+b \cdot C} \right), & T - \frac{\sigma \cdot L_s}{f} \leq t \leq T \\ \text{with } T \geq 2 \cdot \frac{\sigma \cdot L_s}{f} & \end{cases} \qquad (2.13)$$

and:

$$E_{sav} = -\mathbb{K} \cdot L_s \cdot \left(\frac{C}{A + b \cdot C} \right) \cdot \left(T - \frac{\sigma \cdot L_s}{f} \right) \qquad (2.14)$$

The difference in cost over the baseline (in this case, energy only) costs are:

$$\$_{\delta} = C \cdot \left(T - \frac{\sigma \cdot L_s}{f} \right) \cdot \left[\frac{\mathbb{R}_{DRA} \cdot f}{3.785 \cdot 10^3} - \frac{\mathbb{K} \cdot L_s \cdot \mathbb{R}_{kWh} \cdot 2.778 \cdot 10^{-7}}{A + b \cdot C} \right] \qquad (2.15)$$

Note that, for identical hydraulic situations, the change in cost (equation 2.15) can be either positive or negative, depending on the electricity and DRA rates. This is important because as

market driven DRA costs change, the consumption savings / operating cost trade-off points will also change.

With a simple energy-only electric billing structure, an obvious strategy for DRA incentivization by a utility company is to reduce the energy rate, which results in:

$$\$_\delta = C \cdot \left(T - \frac{\sigma \cdot L_s}{f} \right) \cdot \left[\frac{\mathbb{R}_{DRA} \cdot f}{3.785 \cdot 10^3} - \frac{\mathbb{K} \cdot L_s \cdot (\mathbb{R}_{kWh} - \mathbb{R}_{inc}) \cdot 2.778 \cdot 10^{-7}}{A + b \cdot C} \right] \quad (2.16)$$

The incentive can be tailored for each pipeline and situation to offset DRA costs incurred during consumption reduction efforts. This balance point serves as a useful boundary for evaluation of various values in the incentivization rate. From equation 2.16, the balance point can be expressed as follows:

$$\frac{\mathbb{R}_{kWh} - \mathbb{R}_{inc}}{\mathbb{R}_{DRA}} = 23.5466 \cdot \frac{f \cdot (A + b \cdot C)}{\mathbb{K} \cdot L_s} \quad (2.17)$$

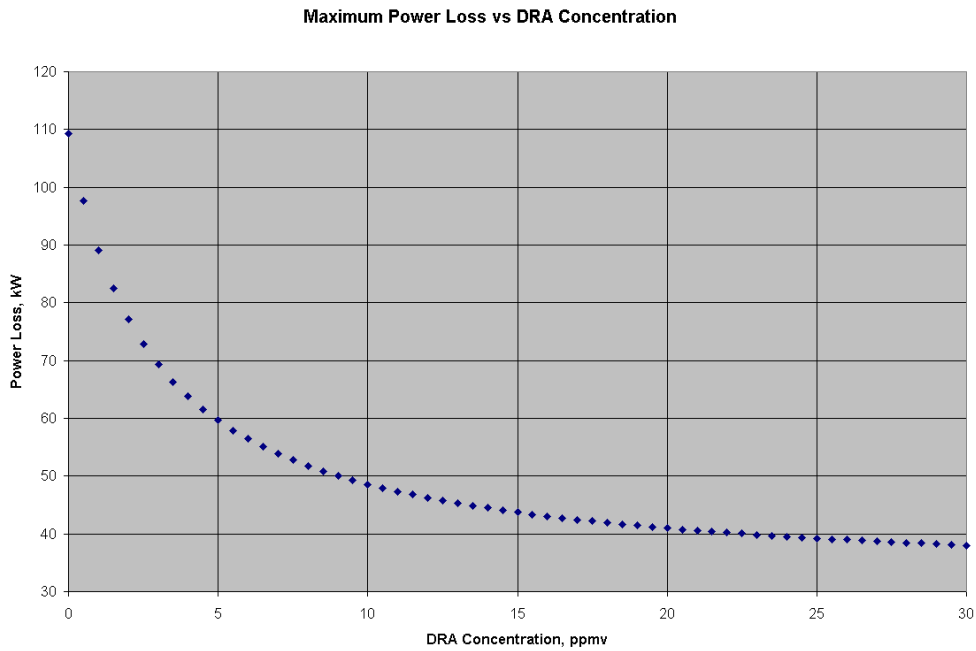
This form applies equally to fuel-powered motors, as long as the fuel costs are strict functions of energy usage alone. Using the following values in a numerical example:

Table 2: DRA Usage Example

Pipe Diameter	0.5 m
Pipe Length	20,000 m
Pipe Roughness (e)	0.0 m
Product Gravity	35 API
Product Viscosity	15 cP
Flow Rate	5000 bph
DRA Concentration	0-30 ppmv
DRA Performance Constant A	4.00
DRA Performance Constant b	1.45
Cost, Energy	$00.25/kWh
Cost, DRA	$25.00/gallon

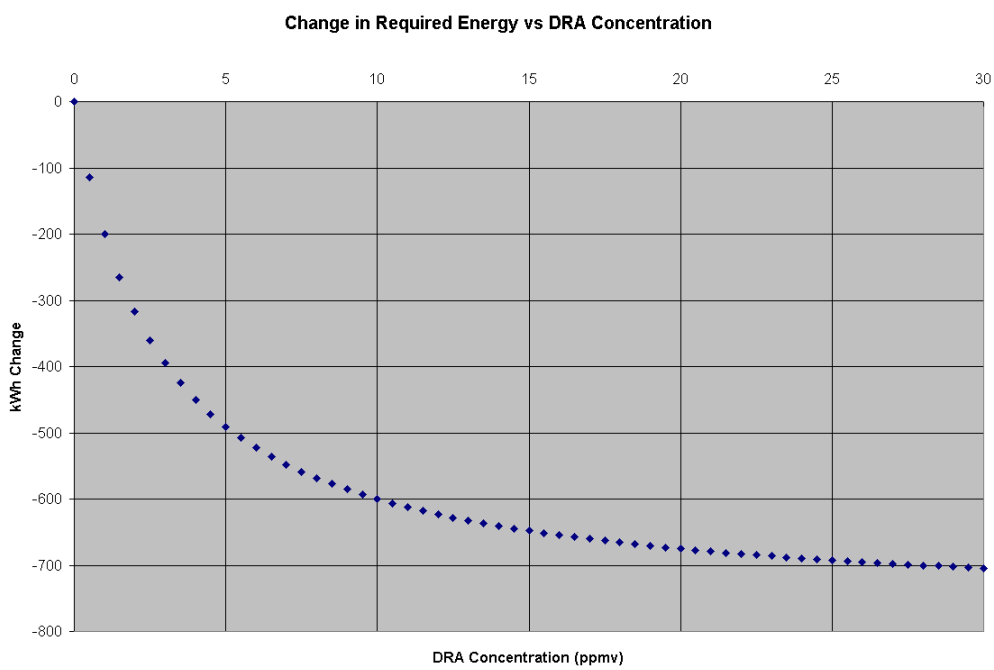
the maximum hydraulic power loss, as a function of DRA concentration, is:

Figure 5: Maximum Power Loss



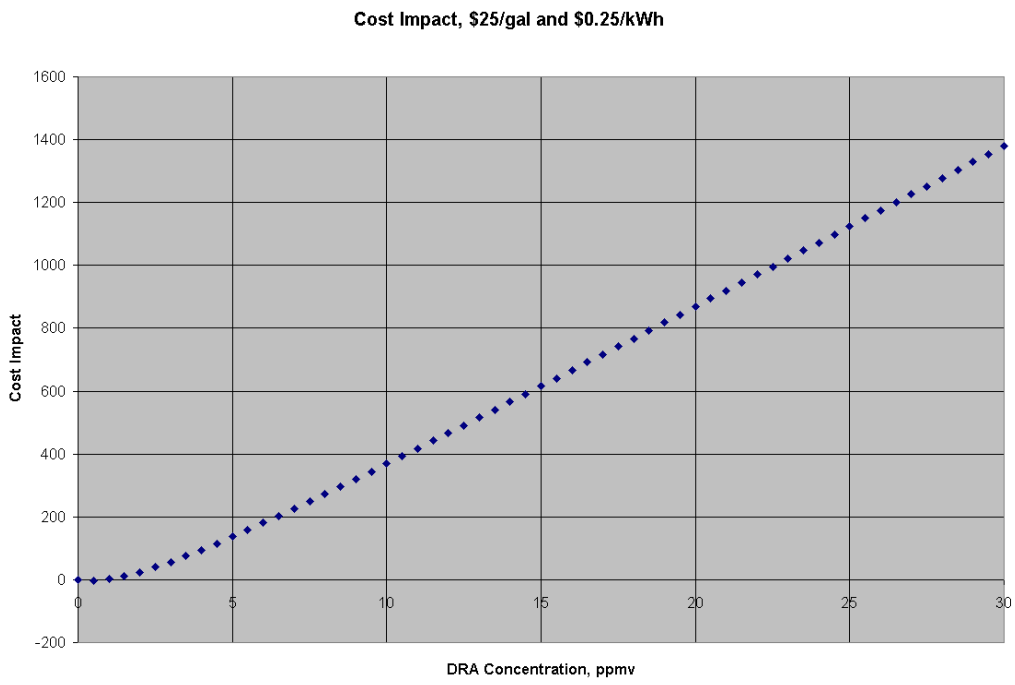
For $T = 3 \cdot T_{fill}$, where T_{fill} is the time to load and unload the pipeline segment, the change in required energy, as a function of the DRA concentration C, is:

Figure 6 :Change in Required Energy



The impact on operating costs for DRA use shows the increase in costs for greater DRA use:

Figure 7: Combined Cost Impact



Referring to figure 6, the energy required decreases with increasing DRA concentration. Both figures 5 and 6 clearly show the pronounced effects at low concentrations tapering off as concentrations are increased. The overall cost impact curve (figure 7) starts with a slightly negative slope before inflecting and approaching a limiting slope of approximately $45.00/ppmv.

A negative cost impact indicates that DRA costs are more than offset by consumption savings, and total operating costs are actually lowered with DRA use. All California pipelines should be surveyed for cases where this might occur. Incentivization for DRA use may still be necessary due to the capital expense of installation of DRA injection equipment, and will be discussed below.

To aid in the evaluation of a specific DRA injection scenario, the consumption savings can be conveniently expressed in several ways. From the standpoint of the electrical providers, the time dependence of the both the power saved and the incremental and cumulative energy savings are the relationships of primary interest. Figures 8-11 show graphical representations of consumption savings for a pipeline segment and DRA injection cycle following the base assumptions from table 1.

Figure 8: kW Savings Levels For a Simple DRA Injection Cycle

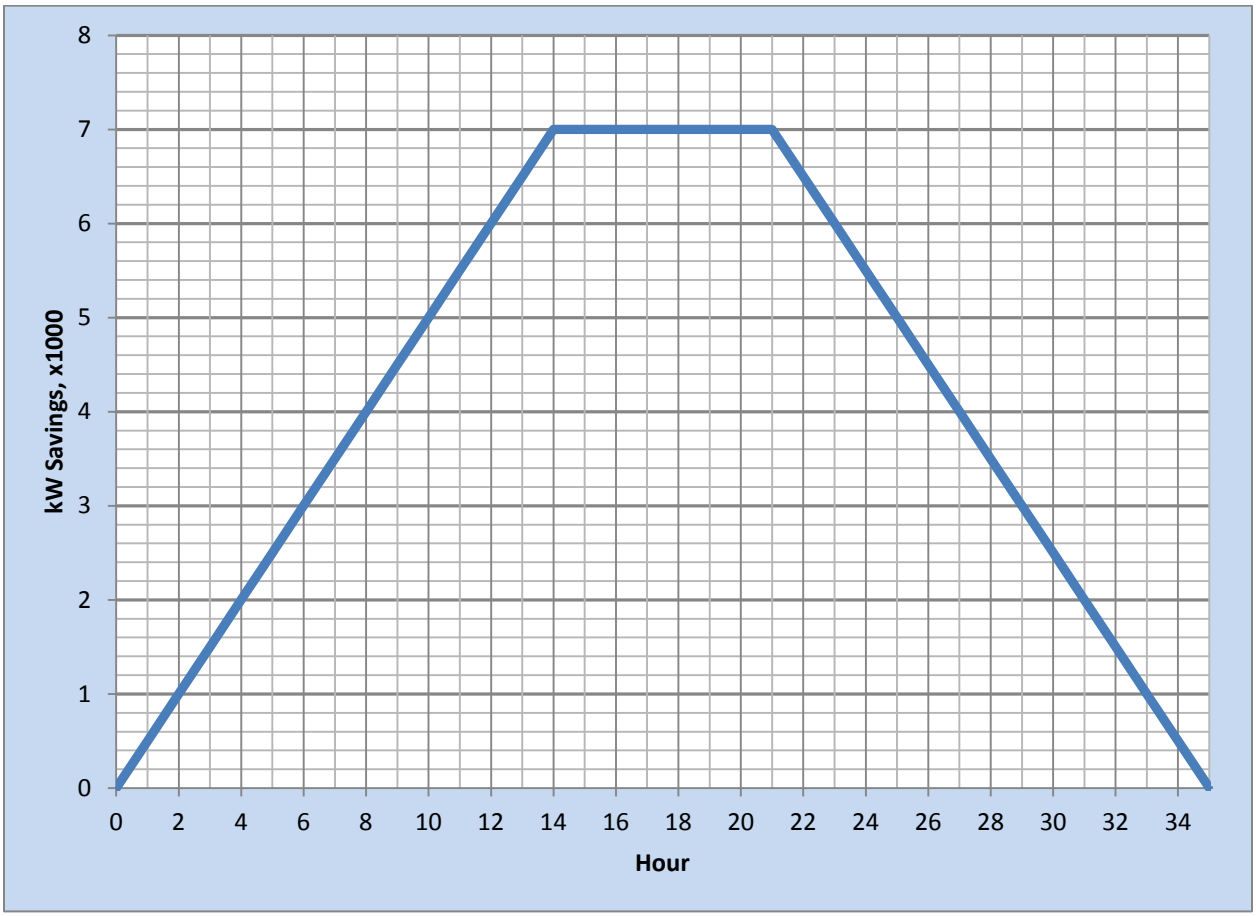


Figure 8 shows that, as DRA is injected into a pipe segment, at a constant concentration, the power savings increases linearly until the segment is uniformly filled. At this point, while the DRA injection continues, the maximum power savings is maintained. When the DRA injection ceases, at hour 21, and as the DRA-loaded fluid leaves the segment, the hydraulic effects seen during loading are mirrored. This type of graph, when compared with coincident use from other utility customers, can aid utility providers in analysis of DRA benefits and incentivization. Pipeline companies operating under electricity contracts with demand ratchets can use the same data to identify times at which ratchets might be set, allowing for some level of control over billing demand and costs.

The graph in figure 8 serves a dual purpose in that it also represents the energy savings, in kWh. By picking a point on the graph and reinterpreting the vertical axis as kWh (multiplying that kW savings level by 1 hour), the energy savings at that point is given.

Figure 9: Cumulative kWh Savings for a Simple DRA Injection Cycle

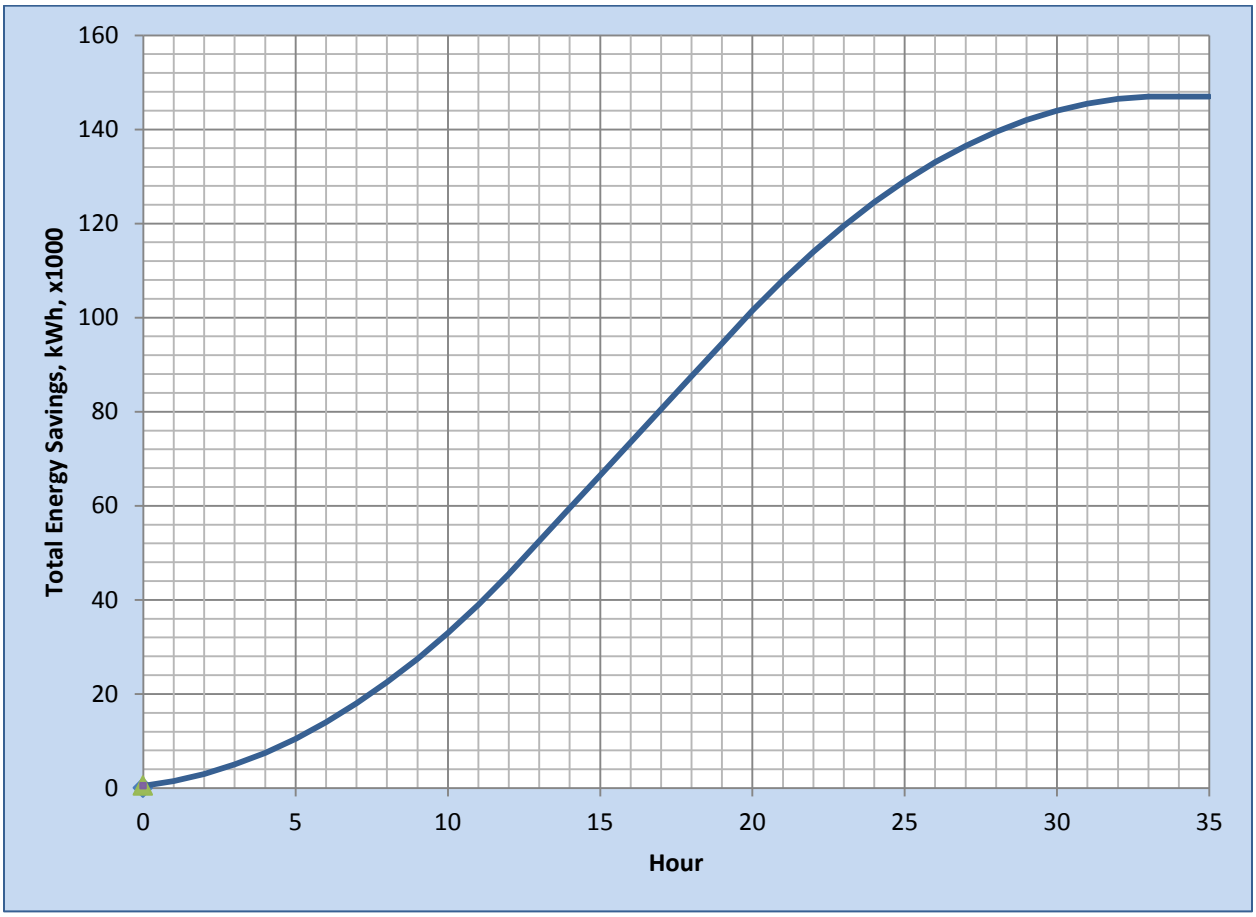


Figure 9 above shows the cumulative energy savings over the DRA injection cycle, calculated from integration of the power savings over time. For an optimized DRA injection profile, or for profile comparison, representations such as those in figures 8 and 9 clearly indicate consumption savings. Based on the availability of field data, DRA use and effect can be automatically documented, using the same representation, by sampling DRA injection, motor consumption, and hydraulic data from the field using the pipeline supervisory control and data acquisition (SCADA) system which is the communications system through which a pipeline is controlled and monitored from a central location. This would allow comparison of planned versus actual consumption savings, give pipeline companies an avenue for demonstrating to utility companies their use of DRA, and allow analysis of the effects of schedule changes or other deviations from the conditions assumed during the process of determining optimal DRA profiles.

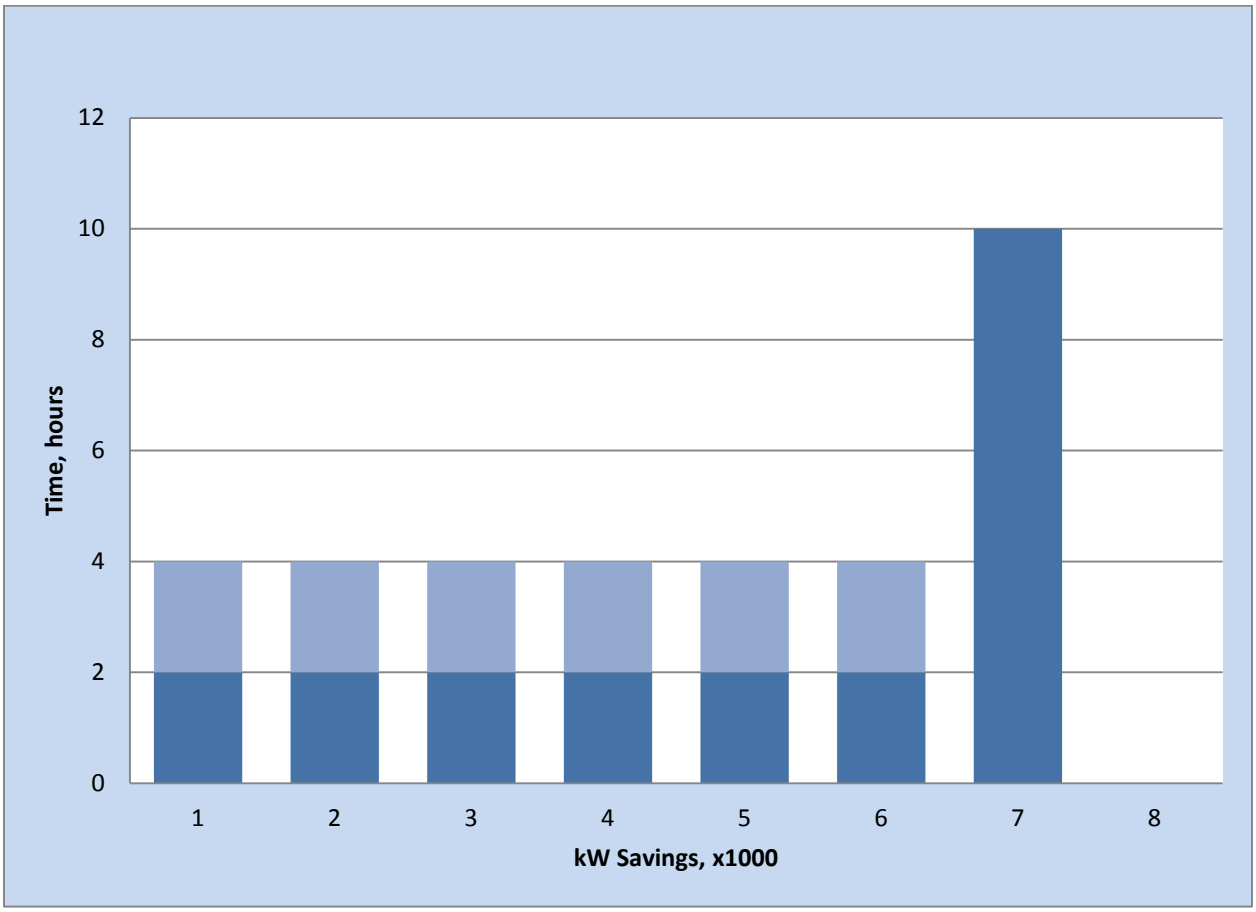
A standard recipe for comparison of modeled/optimized, hydraulic, and actual use is problematic. The wide variety of permutations of field instrumentation at pump stations forces a case-by-case treatment of the best way to estimate consumption levels. The ideal situation would be to have an accurate kWh meter for each pipeline pump, with the meter output being

fed through the SCADA system to the control center. This level of instrumentation seldom occurs. Often, there is one utility company-installed meter at a station and, if that station is manned, data from that meter can reflect not only motor usage, but other use at the station, such as lighting and HVAC. Furthermore, the utility company's meter data is not typically connected to the SCADA system. Monthly usage reported to the pipeline companies at billing time, as single kW and kWh levels, does not allow analysis of the time dependence of the usage, except on a monthly basis.

When there are no available electrical readings, and the pipeline engineer is limited to comparison of the usage reported in a bill and calculation and analysis of the instantaneous hydraulic power from SCADA data, station-wide efficiency estimates can be made. When a station has more than one pump and different pump configurations are used, comparison of data from the different configurations can allow consumption and efficiency estimates of a given pump even if that pump is not run by itself. Though this type of analysis can become involved and the results lack a direct cause and effect relationship, repeated analysis over time can, for instance, highlight equipment degradation and indicate the need for preventative maintenance.

Regardless of how electrical usage data is made available, comparison of power calculations from electrical and hydraulic data provides a check on meter accuracy, gives a way of gauging the efficiencies of motors over time, and is the means for verifying the consumption savings from DRA use. Comparison of power levels calculated from modeled/optimized DRA scenarios and live hydraulic data gives the additional ability to closely track the effects of the DRA strategy and monitor changes in projected savings from schedule changes. Finally, using electrical meter data or as efficiency estimates are honed, estimates of monthly bills can be made and used to guide pump usage.

Figure 10: kW Savings Histogram for a Simple DRA Injection Cycle



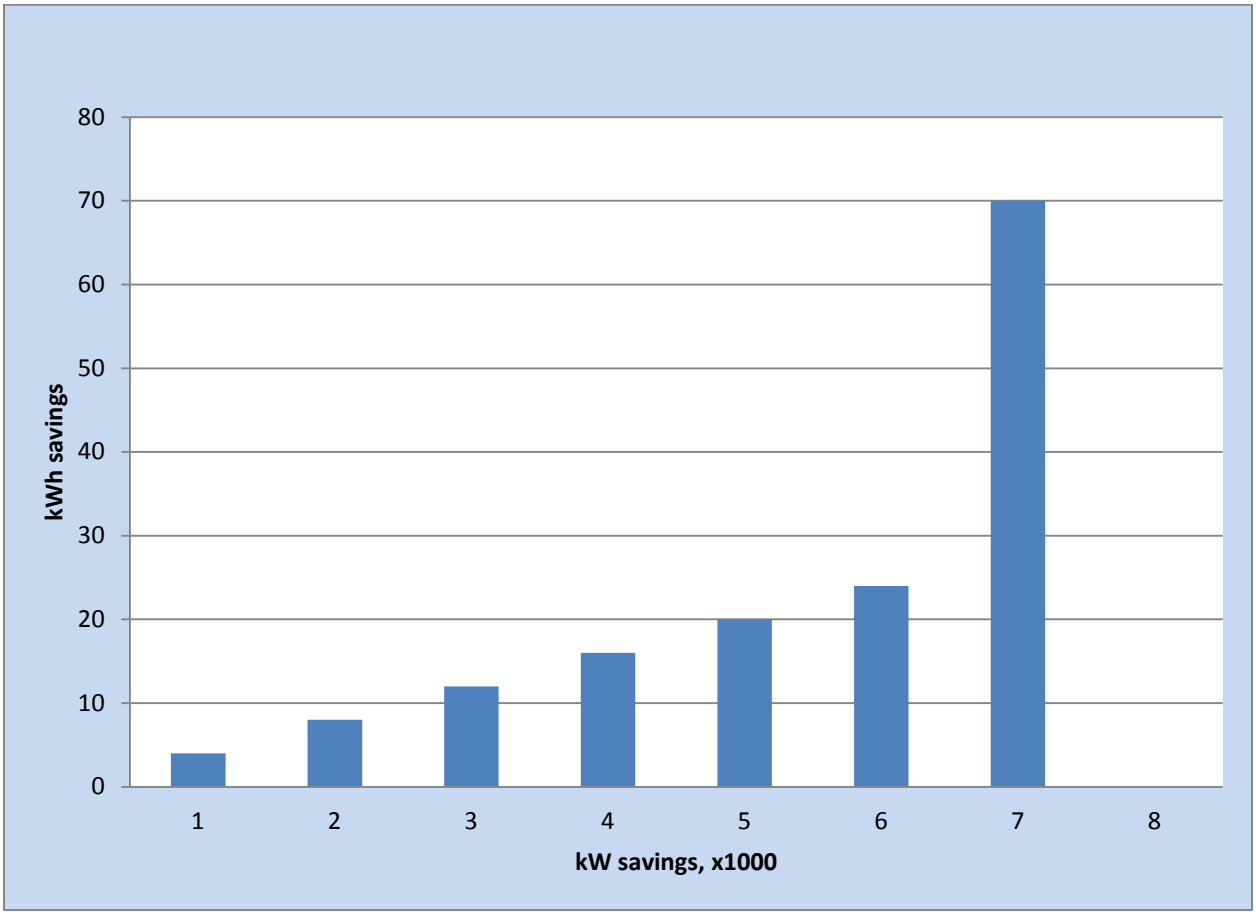
The power savings can also be represented as a histogram, where power savings levels are grouped in discrete, contiguous, and equal ranges, or brackets, and the cumulative time that the savings falls in a given range is represented by the height of the rectangle centered on that range (the data used in figures 8 and 9 is shown in histogram format in figure 10, above, where the 1,000 kW savings bracket range is from 0 to 1,000 kW, the 2,000 kW savings bracket range is from 1,000 to 2,000 kW, etc.).

Each of the bars for the first 6 histogram ranges differentiate between equal loading and unloading profiles by using two colors. Changes in the pipeline flow rate or the DRA concentration would change the times the kW savings falls within each of the brackets, and be reflected by changes in the heights of the bars. The 7,000 kW savings bracket represents the time when the pipeline segment is fully loaded with DRA and maximum consumption savings for the level of DRA injected is achieved, with no instances of savings in the 7,000 to 8,000 kW bracket.

The histogram representation gives one convenient and straightforward way of gauging the impact of the loading and unloading of a pipeline segment with DRA, against the time during which the pipeline is fully loaded. The example in figure 10 shows that loading and unloading

took 12 hours each, while the maximum kW savings was realized for 10 hours. The cumulative energy savings while in each bracket is simply the product of the kW savings bracket levels and the time, in hours, spent at those levels (see figure 11, below):

Figure 11: kWh Savings Histogram for a Simple DRA Injection Cycle



Slight differences in totals from figures 9 and 11 are the result of the discretization of the kW usage levels.

Data in the formats shown in figures 8-11, along with the exact timing of DRA injection cycles, give the utility companies the physical information they need to anticipate and verify DRA consumption reduction without pipeline companies releasing business-sensitive information.

2.3.3 DRA Injection Profiles – Assumption Relaxation

Relaxation of several assumptions made during the derivation of the case shown in figures 5-7 requires additional equation modification. As when dealing with different DRA concentrations, several affect the instantaneous consumption calculation and can be dealt with through further subdivision of the pipeline segment into volumes where all variables can be treated as constants. These assumptions were:

1. Pipeline diameter and roughness

4. Homogeneous segment contents

When electrical contracts stipulate different costs for different times and usage levels, the following assumptions must be relaxed for realistic estimates of both incremental costs and billing costs:

7. Fixed energy cost

8. No power costs

Recalling equation 2.9:

$$P_f = \frac{\Lambda^* \cdot SG}{D^5} \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{\left(\frac{\rho \cdot D \cdot f}{\mu \cdot \sigma}\right)^{0.9}}\right)\right]^2} \cdot \sum_{i=0}^{n}\left[L_i \cdot \left(1 - \frac{C_i}{A + b \cdot C_i}\right)\right] \quad (2.9)$$

This gives the instantaneous power necessary for the flow rate f. By placing leading terms inside the summation, variable pipeline diameter, pipeline surface roughness, and batched fluids with varying properties are dealt with, each separate L_i adhering to the full list of original hydraulic assumptions:

$$P_f = \sum_{i=0}^{n} \frac{\Lambda^* \cdot SG_i}{D_i^5} \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon_i}{3.7 \cdot D_i} + \frac{5.74}{\left(\frac{\rho_i \cdot D_i \cdot f}{\mu_i \cdot \sigma_i}\right)^{0.9}}\right)\right]^2} \cdot \left[L_i \cdot \left(1 - \frac{C_i}{A_i + b \cdot C_i}\right)\right] \quad (2.18)$$

All subscripted variables are local, so the changes to equations 2.13-2.16 are analogous. In addition to the beginning and end of the segment, the boundaries of the L_i are at any change in DRA concentration, base fluid property (specific gravity or viscosity), pipe diameter, or pipe roughness. As the fluid moves through the pipe segment, the L_i will change. Suitable choice of the time step over which the conditions are assumed constant will depend upon the particulars of fluid in and flow rate through the segment. As the consumption and cost of running the pipeline over many time steps is evaluated, simulation software can use this formula along with the associated cost equations necessary to evaluate the consumption savings and cost impact.

2.3.4 DRA Injection Profiles – Fixed-Speed Pumps

Contrary to assumption #4, the majority of operating pipelines have pumps that have a fixed operating speed, which means that the head generated from these pumps is also fixed, determined from 'pump curves' which give head as a function of flow rate and properties of the fluid at the pump. With a suction (inlet) pressure of h_o at a pump station at the start of a segment, and for a set of P pumps at that station, in series, there are a total of 2^P possible pressure levels at the discharge side of the pump station. Note that some pressure levels may be degenerate (the same final pressure may arise from different combinations of the available pumps). For a given DRA injection profile, the overall operational effect of fixed-speed pumps is to reduce the energy and power savings for a given DRA cycle, while leaving the DRA costs the same.

Given the set of available discharge head values:

$$\mathbb{H} = h_0 + \begin{cases} 0 \cdot h_{p_1} + 0 \cdot h_{p_2} + \cdots + 0 \cdot h_{p_P} \\ 1 \cdot h_{p_1} + 0 \cdot h_{p_2} + \cdots + 0 \cdot h_{p_P} \\ \quad \vdots \\ 1 \cdot h_{p_1} + 1 \cdot h_{p_2} + \cdots + 1 \cdot h_{p_P} \end{cases} \tag{2.19}$$

At the start of a potential DRA injection cycle, it will be assumed that the pipeline pumps are optimally configured for cost savings, precluding immediate switching of a pump configuration to one where there is a lower acceptable discharge pressure.

Assume there are one or more pump configurations that provide lower head than the no-DRA configuration, each of which supply the energy necessary to overcome both the elevation differential as well as the DRA-loaded friction losses (if no pumps need be selected at the DRA injection site, then the argument applies to the first upstream station with a running pump). They will be in the set described by equation 2.19 and candidate configurations can be calculated. Selecting one from these candidates, the power savings will be:

$$P_{sav} = -\mathbb{K} \cdot \sum_{i=0}^{n} \left[L_i \cdot \left(\frac{C_i}{A_i + b \cdot C_i} \right) \right] = \begin{cases} \mathbb{K} \cdot L_s \cdot \left(\frac{C}{A+b \cdot C} \right), & \frac{\sigma \cdot L_s}{f} \leq t \leq T - \frac{\sigma \cdot L_s}{f} \\ \quad \text{with } T \geq 2 \cdot \frac{\sigma \cdot L_s}{f} \end{cases} \tag{2.20}$$

The procedure is to select the lowest DRA concentration, C, that, when DRA loading is completed, will allow a switch in pump configuration to lower consumption levels. The power and energy savings associated with DRA loading and unloading is lost in the case of fixed-speed pumps. With more than one unique lower-power configuration possible, maximum

power savings is obviously achieved by setting the DRA concentration for the maximum savings configuration. Then, as the DRA loading progresses, switching pumps to progressively lower power configurations will minimize electrical usage. As mentioned above, care should be taken not to create a situation where the pipeline controller is overly burdened with monitoring and switching pumps.

The DRA concentration necessary to allow a single configuration switch is given by:

$$C = \frac{A \cdot \lambda \cdot \mathbb{H}_i \cdot f \cdot SG}{\mathbb{K} \cdot L_s - b \cdot \lambda \cdot \mathbb{H}_i \cdot f \cdot SG} =$$

$$\frac{A \cdot \mathbb{H}_i}{L_s \cdot \frac{\Lambda^\dagger}{D^5} \cdot \frac{f^2}{\left[log_{10}\left(\frac{\epsilon}{3.7 \cdot D} + \frac{5.74}{\left(\frac{\rho \cdot D \cdot f}{\mu \cdot \sigma}\right)^{0.9}}\right)\right]^2} - b \cdot \mathbb{H}_i}$$

$$\text{where} \quad \Lambda^\dagger = \frac{\Lambda^*}{\lambda} \quad (2.21)$$

The energy savings for a single switch, is:

$$E_{sav} = -\mathbb{K} \cdot L_s \cdot \left(\frac{C}{A + b \cdot C}\right) \cdot \left(T - \frac{2 \cdot \sigma \cdot L_s}{f}\right) \qquad (2.22)$$

Comparing these results with equation 2.14, the effect of the length of the segment is clear, in that, if:

$$T \leq \frac{2 \cdot \sigma \cdot L_s}{f} \tag{2.23}$$

there will be no energy savings, since the unit configuration switch cannot be made. Finally, the cost differential from the baseline, no-DRA cost, is:

$$\begin{aligned} \$_\delta = & \left(T - \frac{\sigma \cdot L_s}{f}\right) \cdot \frac{\mathbb{R}_{DRA} \cdot C \cdot f}{3.785 \cdot 10^3} \\ & - \left(T - \frac{2 \cdot \sigma \cdot L_s}{f}\right) \cdot \frac{C}{A + b \cdot C} \cdot \mathbb{K} \cdot L_s \cdot \mathbb{R}_{kWh} \cdot 2.778 \cdot 10^{-7} \end{aligned} \tag{2.24}$$

Following the development of equation 2.17, the point at which there is no added pipeline expense at the maximum flow rate, in terms of R_{inc}, is:

$$\mathbb{R}_{inc} = \mathbb{R}_{kWh} - 951.047 \cdot (A + b \cdot C) \cdot \left[\frac{T - \frac{\sigma \cdot L_s}{f}}{T - \frac{2 \cdot \sigma \cdot L_s}{f}}\right] \frac{\mathbb{R}_{DRA}}{\mathbb{K} \cdot L_s} \tag{2.25}$$

This result, combined with equations 2.21 and 2.22, provide the description of savings versus cost desired for fixed speed pumps.

2.3.5 DRA Injection Profiles – Variable Flow Rate

Next, scheduled flow rate changes during a window where consumption reduction is desired can be addressed in a couple of different ways. Minimization of consumption implies reduction of flow rates. The interplay of schedule requirements and consumption limits the available course of action, though. First, the schedule can be changed, picking a lower flow rate to extend throughout the critical utility company time period, with DRA applied to further reduce energy and power use. There will exist hard flow limits, determined by the pipeline schedule and customer needs, that cannot be violated. Second, without altering the schedule, the DRA profile can be tailored to achieve a balance between consumption reduction and DRA cost, differing from any constant flow case. The profile and balance will shift depending on cost of the DRA and the value of reduced consumption to the utility. With adequate analysis, an optimal combination of the two approaches will, in general, be possible and can be chosen for implementation.

The first option will, in general, not always be possible, but when it is, the analysis in sections 2.5.2 and 2.5.3 apply. When a flow rate change cannot be avoided, lower flow rates should be

extended for as long as possible, given the constraints of the schedule. Nonetheless, for flow changes within the full DRA injection cycle, the instantaneous power savings is now:

$$P_f = \sum_{i=0}^{n} \frac{\Lambda^* \cdot SG_i}{D_i^5} \frac{f(t)^3 \cdot \left[L_i \cdot \left(1 - \frac{C_i}{A_i + b \cdot C_i} \right) \right]}{\left[log_{10} \left(\frac{\epsilon_i}{3.7 \cdot D_i} + \frac{5.74}{\left(\frac{\rho_i \cdot D_i \cdot f(t)}{\mu_i \cdot \sigma_i} \right)^{0.9}} \right) \right]^2} \tag{2.26}$$

where the flow is now explicitly a function of time. The cubic relationship between the flow rate and power requirements implied by the numerator is affected by the flow dependence of the Reynolds number term in the denominator. However, as mentioned above, DRA use alters the microstructure of the flow. The functional dependence of the friction factor on the Reynolds number, as expressed in the Swamee-Jain formula (equation 2.6), may not represent actual behavior. From the standpoint of operational analysis, actual pipeline data should be used to correct any theoretical or empirical model.

Consider consumption reduction with two extremal flow rates scheduled during a DRA injection cycle. Utility company usage goals may be based on target usage levels. In this case, even when lower flow rates result in usage below a threshold recognized by the utility company as the maximum wished for at a location, the pipeline segment should be sufficiently loaded with DRA so that, at the time of the change to the higher flow rates, by pump reconfiguration or by variable speed pump adjustments, the power requirements are also below the desired levels. If the lowest flow rate is at the start of the critical period, the DRA loading phase can be planned to finish at the time of transition to the highest flow, with the added benefits of the lower power and energy usage during all lower flow periods. Similarly, if the highest flow is at the start of the critical period, DRA loading prior to the critical utility period will allow lower power levels at the start of the period, with DRA unloading beginning at the transition to lower flow rates. These simple cases are described by equation 2.13 and minor extensions of equations 2.14 and 2.15.

If the lowest period flow rate exceeds the usage threshold wished for by the utility company, the DRA concentration providing for satisfactory usage reduction at the highest flow rate will ensure usage below targets at the lower flow rates. The issue is simply one of timing the start and stop of the DRA injection cycle and what the concentration profile should be, keeping in mind the goal of simple DRA profiles with the fewest changes in concentration over any injection cycle.

The expression relating desired instantaneous power savings to the DRA concentration (equation 2.13) has to be modified to take into account the different flow rates. Judicious choice of the timing of the DRA injection cycle, for two flows such that $f_1 < f_2$, yields:

$$P_{sav} = \begin{cases} \mathbb{K}_1 \cdot \frac{f_1 \cdot t}{\sigma} \cdot \left(\frac{C}{A_i + b \cdot C}\right), & 0 \leq t \leq \frac{\sigma \cdot L_s}{f_1} \\ \mathbb{K}_2 \cdot L_s \cdot \left(\frac{C}{A_i + b \cdot C}\right), & \frac{\sigma \cdot L_s}{f_2} \leq t \leq T - \frac{\sigma \cdot L_s}{f_2} \\ \mathbb{K}_2 \cdot \frac{f_2}{\sigma} \cdot (T - t) \cdot \left(\frac{C}{A_i + b \cdot C}\right), & T - \frac{\sigma \cdot L_s}{f_2} \leq t \leq T \\ \quad \text{with } T \geq \left(\frac{\sigma \cdot L_s}{f_1}\right) + \left(\frac{\sigma \cdot L_s}{f_1}\right) & \end{cases} \tag{2.27}$$

and, for energy savings in a situation with a variable speed pump:

$$E_{sav} = -\sum_{i=1}^{2} \mathbb{K}_i \cdot L_s \left(\frac{C}{A_i + b \cdot C}\right) \cdot \frac{\sigma \cdot L_s}{f_i} - \mathbb{K}_j \cdot L_s \left(\frac{C}{A_i + b \cdot C}\right) \cdot \left(T - \frac{\sigma \cdot L_s}{f_1} - \frac{\sigma \cdot L_s}{f_2}\right)\Bigg|_{j=2} \tag{2.28}$$

where the subscript j is used to specify one of the two cases of either increasing or decreasing the flow rate. In words, when DRA is more expensive than electricity, the desired power and energy reductions at the higher flow rate should be possible at exactly the time of the change in flow rates. For stations with fixed speed pumps, this may or may not preclude any energy or power benefit during loading and unloading.

The cost difference over the baseline case is given by equation 2.24, modified by decoupling each of the loading, loaded, and unloading phases to allow for the changing flow rates.

2.3.6 DRA Injection Profiles – Batched Pipeline

The consumption and cost equations for batched pipelines, where different product types are placed into the pipeline, end-to-end, have already been developed. Recall equation 2.18, which provides the instantaneous pipeline segment power requirements:

$$P_f = \sum_{i=0}^{n} \frac{\Lambda^* \cdot SG_i}{D_i^5} \cdot \frac{f^3}{\left[log_{10}\left(\frac{\epsilon_i}{3.7 \cdot D_i} + \frac{5.74}{\left(\frac{\rho_i \cdot D_i \cdot f}{\mu_i \cdot \sigma_i}\right)^{0.9}}\right)\right]^2} \cdot \left[L_i \cdot \left(1 - \frac{C_i}{A_i + b \cdot C_i}\right)\right] \tag{2.18}$$

where, as before, for each subscript i, all physical quantities are constant. The quantities include pipeline diameter and roughness, changes in DRA concentrations, and any change in base fluid

property for the batches of product in the pipeline. The volumes of constant DRA concentration and the batch interfaces travel along the pipeline while the pipe diameter and roughness changes are fixed. Over the course of the DRA injection cycle, the L_i for a batched pipeline will evolve and must be re-evaluated. In light of section 2.4, flow changes may also have to be taken into account.

One specific case worth examining involves the setting of DRA concentrations so that two dissimilar products have equal friction losses, per unit length. Relaxing only the homogeneity assumption from Table 1, the DRA concentrations needed for equal viscous friction losses between two dissimilar fluids are:

$$\frac{\frac{A_2}{C_2}+b}{\frac{A_1}{C_1}+b} = \frac{\rho_2}{\rho_1}\left[\frac{log_{10}\left(\frac{\epsilon}{3.7\cdot D}+\frac{5.74}{\left(\frac{\rho_1\cdot D\cdot f(t)}{\mu_1\cdot\sigma}\right)^{0.9}}\right)}{log_{10}\left(\frac{\epsilon}{3.7\cdot D}+\frac{5.74}{\left(\frac{\rho_2\cdot D\cdot f(t)}{\mu_2\cdot\sigma}\right)^{0.9}}\right)}\right] \qquad (2.29)$$

In particular, the bracketed term on the right side will evaluate to unity if the ratios of the viscosities to densities are the same for the two products. If the two fluids consist of different molal fractions, but have the same density, viscosity, and velocity, the same DRA formulation will likely yield different hydraulic results, even though, in equation 2.29, the right hand side (RHS) and the A_i are constant. This case has a single, non-physical pole at:

$$\frac{A}{b} = C_1 \cdot \left(\frac{1}{RHS} - 1\right) \qquad (2.30)$$

A more exact formulation would require taking into account the compositions of the hydrocarbons being shipped. A macroscopic treatment, using separate A's and b's for each fluid component, might be sufficient, but would require field testing for validation.

2.3.7 DRA Injection Profiles – Effect of Energy and Demand Charge Structures

As discussed above, electrical contracts available to pipeline companies are often relatively complicated. The underlying reason for this is the complex economics related to the utility companies being obligated to supply electricity to both the public and businesses, and the heavy loads pipeline pumps draw from the power grid. Even with complicated contract pricing, employing time-of-day pricing, demand ratchets, block energy structures, or other mechanisms, it is safe to say that there isn't a single perfect utility contract. The economic and hydraulic effects of DRA add to the complexity and the process of negotiation and implementation of effective electrical riders and/or contracts for DRA use will have to include historical and projected analysis of, on the one hand, utility capacity and loads and, on the other hand, pipeline usage. While contract modifications might entail something similar to existing usage

curtailment mechanisms, billing usage adjustments coupled with rate reduction offer simple avenues of achieving DRA incentivization without adding too much complexity to the contracts.

The assumptions made in Table 1 regarding energy and power pricing are valid for usage and cost evaluations as a function of DRA concentration, and when contracted electricity pricing rates do not change over an injection cycle. As shown, both baseline and incremental cost calculations are straightforward. The periods of time of most interest to the utilities for power reduction will typically have already been indicated in any time-of-day pricing structure, so the DRA injection cycles will be roughly aligned with peak period pricing, although DRA loading and unloading may fall in adjacent pricing structures.

With DRA used to reduce power, peak-period demand at non-DRA levels should be automatically avoided and, depending on the details of the electrical contract, the billing demand may be effectively lowered. Usage reduction is also possible by avoiding high flow rates or heavy fluids shipment through certain pipeline segments during these periods. This necessarily puts additional constraints on a pipeline schedule and must be dealt with on a case-by-case basis at the time of schedule creation. Combining peak period DRA use with judicious scheduling, billing demand covered by electrical contracts with demand ratchets can, over the long term, be lowered. Close monitoring and cooperation between pipelines and utilities can avoid situations where, for instance, the contract language for billing demand stipulates highest use over a 15 minute window, and a pipeline station violates this by, say, having a spike in demand due to pump startup and a combination of scheduling requirements and product movement over a 16 minute window.

Similarly, in addition to lowering demand, DRA lowers energy usage which, when falling under a peak-period energy rate, will be directly related to lower energy costs. If and when block energy pricing is in effect, DRA use can have the additional affect of shifting the transition of the pricing levels. For example, when a boundary is set using a ratio of kWh to kW usage, not only does the rate at which the boundary is approached decrease, but, with an effect on billing demand, the boundary itself is shifted.

Real-time pricing, where the energy price can change on an hourly basis, offers the utility companies the greatest flexibility in matching consumer load (and market energy price, if purchased) with cost recovery. On the other hand, it limits flexibility in pipeline scheduling and concomitant usage reduction. By the time real-time prices are published (typically the afternoon or evening before they are in effect), the pipeline schedules have already been set. This hinders schedule optimization. In such cases, cooperation between utilities and pipeline companies is especially critical. It would be advantageous for the utilities to share with pipeline companies the planning data and decisions that go into making the daily slate of real-time prices.

2.3.8 DRA Injection Profiles – Discussion

There are two broad approaches for DRA use for consumption reduction. First, DRA can be injected at specific times to lower power requirements during periods of high concurrent load on electrical infrastructure. It has been shown that preloading a pipeline segment with DRA

may be necessary to achieve desired levels of time-critical power savings. Second, with continuous, low concentration injections of a few parts per million, a significant decrease in long-term energy use is possible, regardless of peak period designations.

The hydraulic effect of both approaches depends on the pump equipment at pipeline stations. The economic effects depend upon specific details of the utility rate contracts at each station. Optimal consumption reduction will involve both these factors, in addition to pipeline schedule considerations. Economic incentives designed to offset DRA costs and make the added operational concerns of DRA injections worthwhile for the pipeline companies will play a key role in implementation of DRA for state-wide consumption reduction.

The analysis above quantifies the effects of DRA in reducing the power required from a pump station. When used for peak period consumption reduction, DRA can play a major role in reducing demand during these periods. There is a secondary effect, as discussed in section 2.2.1, involving current spikes when starting large pipeline pumps. Although power averages are usually implemented to prevent skewed billing demands, the spikes may, in cases when a utility's infrastructure is near maximum capacity, be very much less desired than usual. Minimization or elimination of pump starts during a given window is not a usual pipeline operations consideration and, if such a need is established by a utility, implementation will require additional communications between the pipeline control room and scheduling arms of pipeline operations.

There may be instances where DRA use will reduce electrical bills enough to justify implementation (figure 7, in section 2.3.2). This was found to occur at low DRA concentrations where the automatic adjustment of variable speed pumps will play a major role in realizing consumption savings and offsetting the increased operational concerns associated with DRA implementation.

The two broad approaches are not mutually exclusive, and merge when continuous consumption reduction is desired by utilities. The utility companies will obviously play a key role in developing DRA injection strategies by helping in setting reduction levels and providing the incentives to pipeline companies needed for pipeline industry-wide DRA use. The incentives can range from simple rebates or adjustments to rates to more complex scenarios where, for instance, billing energy and demand calculations are changed. In cases with an economic benefit from DRA, the minimal implementation cost is limited to the capital expense of the DRA injection equipment and may involve replacement or installation of variable pressure pumps. Incentives for installing this equipment will aid in broad adoption.

The need for creating pipeline schedules that address consumption is clear. Beyond scheduling DRA injections, avoidance of flow rate changes involving the starting of any pumps and lowering flow rates during peak periods, the various means of influencing consumption through an optimized schedule, will be addressed in more detail in section 2.5.

2.4 Model Accuracy

The first three sections of this chapter provide the hydraulic theory for the effects of DRA. A brief discussion of errors and error compensation here will be expanded in chapter 3. The theory above depends upon physical quantities that are, at best, known only approximately.

Of the fluids in the pipelines, specific gravity and, to an even greater extent, viscosity can only be estimated. Despite mixing within storage tanks, some difference in specific gravity is to be expected between the fluid that first leaves a full tank and that which leaves last. In addition, the temperature profiles of pipelines are not known. A pipeline, which is typically buried under the surface of the ground or, at river crossings, submerged under the surface of the water, carries fluids of varying temperature through a variable environment that changes that temperature. The viscosity of hydrocarbon fluids varies with temperature. While the model can be used so that the lengths of segments are chosen so that the temperature of the fluid is guaranteed to be treatable as constant across each segment, and while fluid temperature readings are often taken at pumping stations, the value of that temperature away from any station can only be estimated. Compounding this issue is the fact that gravity and viscosity are seldom well known to begin with.

Beyond issues of the fluids being transported, lack of knowledge of the surface roughness of the inside of pipelines will also contribute to differences between field measurements and calculated pressure drops (refer to the right=hand side of the Moody diagram in figure 4). Over the course of time the surface roughness will change, and that change will be different for different sections of a pipeline. For instance, waxy buildup can coat the inside diameter of a pipeline carrying high molecular weight hydrocarbon fluids, changing the surface roughness and create a systematic error in the calculation of pressure drops (the error is usually cyclic due to periodic scraping of the inside walls of the pipe).

In addition to unknown inaccuracies in static or slowly changing fluid property and pipeline-related values, measurement errors in flow rates, pressures, and other dynamic variables, including temperature readings from stations, have non-negligible effects on the correlation between calculated and measured pressure drops.

Finally, the Swamee-Jain formula for the friction factor is an approximation of an empirical relationship, and corrections to hydraulic calculations based on real pipeline data are needed to ensure the accuracy of the hydraulic and economic predictions. Gathering as many cases as possible from different fluids, pipeline segments, and DRA types will help estimate the accuracy of model predictions and repeated measurements over time will help assess the variability in the effects of DRA.

2.5 Consumption Reduction and Optimization Considerations

The first four sections of this chapter provide the framework for modeling the hydraulic and economic behavior of a petroleum pipeline and, in particular, one in which DRA is used. Beyond the driving forces behind consumption reduction, several points need to be taken into

account in order to forge this framework into a useful tool set for combined use by utility and pipeline companies.

First, the hydraulic formulae above depend upon physical quantities that are, at best, known only approximately. The last section ended with a discussion of model accuracy. However, using real pipeline data, it has been found that a tuned hydraulic model can replicate real-world pipeline behavior to well within 5%. Because of the linear structure of many utility company contracts for pipelines, the uncertainty dependencies will often carry over, without modification, to the economics effects. Properly interpreted, this is within the limits needed to plan and execute engineering projects designed for consumption reduction.

Second, because of the complexity of the analysis required, application software is clearly indicated as the feasible path for broad adoption of DRA as a consumption reduction tool. The requirements for such a package include the ability for users with very different goals to extract different answers. A utility company would want to know how much energy and power can be saved and the volume of DRA necessary to achieve it. Armed with this data, creation of DRA-incentivized utility contracts becomes a matter of negotiation. A pipeline company, with such a contract in place, will want to know how to minimize costs while meeting pipeline schedules.

These guidelines have been considered in the implementation of the model presented above into a tool to best aid both pipeline companies and utility companies in pipeline operations consumption reduction.

2.5.1 Driving Forces

A large number of requirements and factors control petroleum pipeline operations. Desired sets of competing extrema are requested by each of the parties involved in the transport chain.

First, the operators want to meet throughput requirements and minimize both risk and the costs of running the pipeline. The relevant operational costs include power, energy, and maintenance components. It is generally an assumption that there is a zero-tolerance policy for pipeline breach events, meaning that associated costs are considered infinite. Revenues from transportation of petroleum products through pipelines come through a variety of often complex rate and tariff mechanisms. Maximizing the net revenues from shipments is an obvious pipeline company goal and includes costs and both direct revenues and intangible benefits, such as customer loyalty and continued business built from superior customer service (e.g. prioritizing shipment according to the customers' schedules as opposed to, for instance, electrical supply considerations).

The entities delivering the fuel or electricity required to operate a pipeline constitute another group of stake-holders in this process. While some pipelines may divert part of their hydrocarbon product shipments to fuel-driven pumps used to run the pipeline, the majority of pipelines rely on utility companies to supply the fuel or electricity that pumps require. Beyond the need for generation of revenue, the utility companies have finite resources and, when these resources are strained, effects can range from contract-based increases in energy and power costs charged to the pipeline operators, to an inability to fulfill real-time power requirements to its customers.

Glossing over the issue of custody transfer, the owners of the products in a typical common-carrier pipeline, the (possibly different) shippers and receivers, have their own set of economics variables they wish to optimize. They provide product of sufficient volume for shipment at the input(s) of the pipeline, and/or provide delivery facility capacity for receipt of volumes from the pipeline. The timing requirements of each shipper and receiver, driven in turn by their customers, heavily influence the overall pipeline schedules created by the pipeline operator, which typically involve multiple customers and competing receipt and delivery requirements from each batch of product.

The end user is the last direct segment of this complex supply chain, and may be the government, private enterprise, or the public. Nationally, petroleum pipeline products shipped are destined, in part, for direct consumption in gasoline, diesel, or natural gas vehicles, jets, and general appliances. Large percentages of shipped volumes are also devoted for use in manufacturing processes, both for energy and for chemical purposes. A sudden change in end user product demand can force major modifications to schedules throughout the pipeline planning and operations chain. This, in turn, affects consumption and when demand for product is high, works against consumption management efforts. The concept of variable tariffs geared for surcharges based on specialized scheduling considerations, while outside the scope of this project, should be examined. There may be circumstances in which it takes both DRA-incentivized utility contracts and increased revenues from pipeline customers to justify DRA use to pipeline operators.

Finally, in terms of the byproducts of usage of petroleum products, and despite the lack of short term impact, carbon imprints should be taken into account, given the fact that data indicates a man-made component to rising global temperature is likely.

In combination, all the stake-holders' requirements are, to some extent, met. The evidence is simply that pipelines operate, transport product, satisfy customer needs, and generate net revenues. Singling out power and energy usage and developing protocols for intermittent DRA injections for usage reduction must be subject to the full set of requirements. What is optimal for one party will not, in general, apply globally.

Against that backdrop, it has been shown above that implementation of DRA for usage reduction can proceed locally, without impacting pipeline schedules. DRA can be injected at the beginning of a pipeline segment, resulting in decreased consumption in that segment. Schedule optimization can be applied separately.

A complete analysis of a pipeline segment for power and energy savings requires that both local and global constraints be prioritized for each of the stake-holders presented above, and the impact of these constraints on overall pipeline operations, and in particular, potential savings, must be understood. Local analysis methodology, in light of the global constraints operating costs and consumption reduction, is discussed next.

2.5.2 Steps in Consumption Reduction / DRA Feasibility Analysis

Some power and energy is wasted on every California pipeline. Physical limitations ensure that 100% efficiency is unattainable. The lower the consumption at a pipeline station, the less

absolute effect a given percentage inefficiency will have. When a given threshold on consumption savings at a pipeline station is of worth to the utility provider there, that station and downstream segments can be considered candidates for further consideration. A comprehensive examination of consumption reduction should involve several steps in conjunction with DRA analysis. These involve analysis of the baseline hydraulics of the pipeline, including factors covering the entire pipeline, such as schedules and their variability.

Analysis of operations for overall power and energy savings should begin with the mining of existing data. Studying historical SCADA data can help identify degraded performance of the motors, pumps and valving of any pipeline station. Analysis comparing actual power transferred to the pipeline fluid against the power provided by either the fuel or electricity supplying the pumps should be a first step. Part of the provided power is transformed into heat, both in the operation of the pump motors and the pumps themselves. Further heat is generated within the pipeline product itself, as it passes through pumps. On a macroscopic scale, poor mechanical performance, such as valve leakage, results in waste. Accounting for all these effects yields a measure of station efficiency, which is simply the ratio of useful power (the hydraulic power) and the power provided to the station. The highest field values of this ratio are in the neighborhood of 80%, and, with proper data mining techniques, performance of motors, pumps and impellers, and valve operation can be tracked, monitored for degradation, and flagged for corrective maintenance. The net effect of station inefficiencies is simply to increase the power required for product shipment, regardless of DRA use; correction of the causes can result in worthwhile savings and can be conducted in parallel to DRA consumption reduction efforts.

Underlying DRA-related power and energy savings potential, and DRA use in both pipeline operations planning and control, is the direct relationship between power and energy use and volume throughput (flow rate). Therefore, an immediately available step for reduction of power and energy use is the reduction of the flow rate. Beyond the elementary considerations of throughput cost versus direct revenue, incentivized flow reduction and/or load shifting is in limited use through utility company / pipeline company cooperation and is practically implemented using curtailable rate structures offered by the utilities. Roughly, these rates set aside certain time periods where pipeline companies voluntarily lower power and energy requirements at one or more stations in exchange for incentives, which can be in the forms of lower power or energy rates, or billing usage adjustments. The time periods are designed to coincide with heavy coincident usage, as when 'everyone' goes home on summer afternoons and lowers their thermostats.

As discussed above, pipeline flow rates are governed by schedules balancing the timing of supplies of products at the pipeline injection locations against demand for those products at the delivery locations. A pipeline slowdown to flow rates achieving desired power and energy reductions for the utility company may violate pipeline customer deadlines. On the other hand, combining schedule alteration with preloading of DRA for effect during periods of high coincident usage offers the possibility of maintaining customer needs while reducing fuel or electricity loads, albeit at a possibly higher overall cost to the pipeline operators. A broad look

at schedule requirements and customer needs is a second major component in consumption reduction.

However, due to the role customer satisfaction plays in pipeline scheduling and the complexities of building a schedule in the first place, a usable DRA methodology should begin with the premise of adhering to the pipeline schedule and customer deadlines. This still allows, when possible, added power and energy savings through the periodic lowering of flow rates, as with the current curtailable rate procedures, and is simply a specific case in the DRA analysis.

After these preliminary steps, DRA analysis involves several important factors that place bounds on DRA use. Summarizing points discussed above, first is the added DRA cost, balanced against revenues, decreased power and energy costs, and DRA incentives.

Second, there are obvious limitations on concentration levels of the DRA, beyond the fact that the effects of DRA decrease as the concentration increases (i.e. increasing a DRA injection to twice a given concentration level will have less than twice the hydraulic effect).

Next, DRA effects have a range limited to sections of pipe between the DRA injection point and the point at which the DRA-laden product has either left the pipeline, or when the bonds of the long DRA molecules have been broken, or sheared. Shearing occurs when flow-related molecular forces exceed DRA chemical bond strength. For instance, DRA is completely sheared when passing through pipeline pumps.

Limitations on DRA concentration may also come from regulation; specifications on the maximum concentration of DRA allowed in a particular pipeline product may come from either the product customers or the government. For instance, jet fuel specifications do not allow any DRA to be injected since the DRA can accumulate on injection nozzles of jet engines, impeding their ability to operate. General batched pipeline operations procedures add no-DRA buffer zones on either end of jet fuel batches to guarantee against contamination. Another common instance of DRA concentration regulation is when, for product quality purposes, a maximum total DRA concentration is allowed in a fluid, including both sheared and unsheared DRA. This requirement forces concentration tracking and reporting during custody transfer, another issue that must be taken up by a pipeline company which is considering DRA injection.

Each of these points effectively reduces the possible consumption savings over maximum levels suggested by hydraulic considerations alone. Summarizing, a baseline DRA analysis methodology that will have the least impact on pipeline operations is one that assumes that pipeline flow rates and product ordering in the pipeline are fixed by the pipeline schedule, while taking into account the following:

1. the limited distance over which DRA is effective
2. the nonlinear behavior of DRA performance in viscous friction loss reduction
3. DRA concentration limits

The following data is needed to perform a full analysis:

1. Pipeline geometry, including inner diameters and elevations
2. Pipeline pump data (pump curves showing pressure versus flow relationships)
3. Fluid properties
4. Pipeline schedules (to include actual batch location information)
5. Pipeline economics data (station contracts, usage, and bills)
6. Historical SCADA data (flows, pressures, temperatures, specific gravities, etc.)

Given the detailed geometry and SCADA data available, selection of reasonable limits on the data resolution is needed. For instance, some pipeline companies maintain elevation profiles at increments in the neighborhood of 25 feet, so that a 500 mile pipeline could have over 100,000 elevation profile points. Much like the straight-line distance between two coastal cities can be much less than the length of coastline between them, undersampling elevation profiles can produce a systematic error in pipe lengths and result in underestimation of pressure drops in a segment. On the other hand, incorporating this many points into a model is cumbersome and there is a practical limit beyond which increased spatial sampling is of little worth. Recommended guidelines for resolution of the pipeline geometry depend on the terrain the pipeline was built on, but elevations at 1 mile increments will satisfy most cases.

Similarly, selection of the temporal resolution for the SCADA data should be guided by practical concerns. First, SCADA systems often use sampling techniques to reduce the telecommunications traffic and the amount of data collected. For instance, the 'polled / report-by-exception' method, used on a pressure level at a point on the pipeline, would yield distinct SCADA data points only when that pressure changes more than a set threshold, say 2 or 3 psi. This prevents sequences of data where the pressure readings oscillate between two values at the resolution of the pressure sensor. (Periodically, the point is polled, to eliminate the possibility of drift.). Second, as a rule of thumb, pipeline flows and pressures are usually relatively steady. Periods of rapid variation, where pumps, flow rates, and pressures are changing are the exception. This fact, combined with typical utility company billing demand measurements with 15 minute windows, indicates that 5 minute SCADA data sampling is reasonable.

Once the data listed above is obtained, formatted for the model, and the model tuned to the data, the following broad steps will result in an estimate of consumption savings potential and the cost to achieve it:

1. Calculate station efficiencies
2. Create histograms of pressure drops for each pipeline segment as a function of flow, fluid, etc. (this must be filtered to exclude fluids which cannot contain DRA and the buffer zones employed for quality control)
3. Compare pressure histograms with pump head and DRA performance data to define windows of opportunity

4. Perform economic analysis, to include consumption savings value, DRA costs, as-is contract costs, and DRA-incentivized contract scenarios.

Figures 5-7 showed the theoretical impact on hydraulics and consumption from varying DRA concentrations, all at a given flow rate. What is required, both in evaluation and implementation phases of DRA use, is hydraulic and consumption impact for varying DRA concentrations for realistic pipeline schedules.

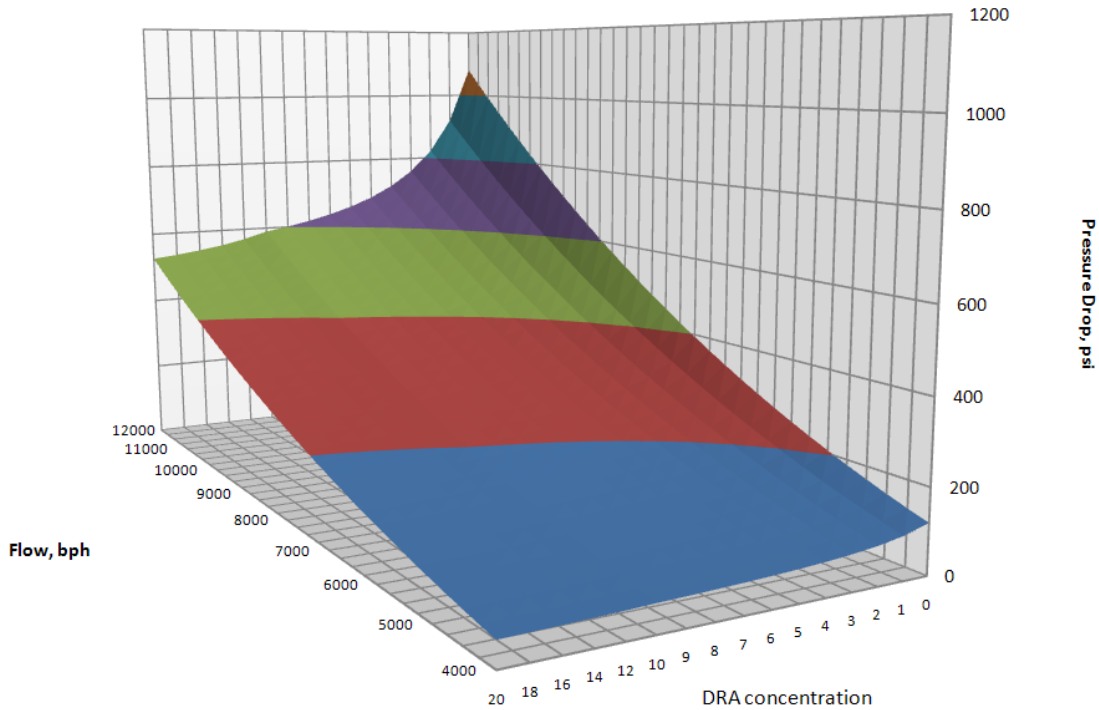
The time required for the brute-force method of running a pipeline simulation using a multi-month schedule can grow to prohibitive proportions. However, in much the same way as the passage of fluid batches and DRA loading / unloading was treated above, a reasonable estimate of potential savings for a pipeline segment can be arrived at by analyzing values of certain key variables:

Table 3: DRA Consumption Savings Estimation Input Variables

Item	Description
1	Relevant physical variables for pipeline segment
2	Volume fractions of product types in segment, along with specific gravities and viscosities
3	Percentage of time that segment is filled with single product type (alternatively, maximum batch size)
4	Distribution of flow rates during times segment is filled with each single product type (alternatively, flow rate histogram)

Given the prevalence of relational database technology layered into SCADA systems in the pipeline industry, building information for such a table will usually be straightforward. Using this information, calculation of a conservative estimate on consumption savings is achieved by a linear combination of flow rate / DRA concentration / product type terms. The figure below shows the hydraulic functional dependence of one such term:

Figure 12: Single Product Type Hydraulic Effect Surface



From this data, an overlay of pump pressure ranges for the segment and pumps in question can reveal the recoverable consumption. This step will highlight cases where, for instance, an existing fixed-speed pump must be run, regardless of DRA concentration, to maintain single-phase flow at the desired rates, and replacement with a variable pressure pump would allow for consumption reduction.

Also note that on pipeline segments where DRA is already in use, initial calculations can first back out the effects of DRA, providing a DRA-free baseline for comparison. The pressure drop data with DRA concentrations provide a series of calibration points closer to potential target levels and should be used during the model tuning process.

For a pipeline segment carrying only one type of fluid at one flow rate, simple cost versus consumption reduction calculations and visualizations remain. A strong argument can be made for using raw consumption values (kW and kWh) along with very simple cost structures based on these values. Examining overly complicated costing / contract structures at this early stage will cloud analysis. The real costs are derived, based on complex relationships other than consumption minimization. So, referring to simple case from the figure above, for a pipeline segment carrying a single fluid, a constant concentration DRA profile, properly integrated over the various flow rates scheduled for the segment, serves as the baseline for cost analysis.

When searching for a minimum of a separable function of multiple variables of the following form:

$$F(X,Y,Z,\ldots) = X(x,y,z,\ldots)\ Y(x,y,z,\ldots)\ Z(x,y,z,\ldots)$$

the minima remain defined by the component functions. This is currently the case with incremental cost minimums, where, for a given pipe segment and product, the DRA concentrations and flows can be related to real value to the utility company of consumption savings by using, for example:

$$\text{Savings Value} = \int_0^T \alpha(t)\ \mathrm{kW}_{\mathrm{savings}}\ dt$$

or

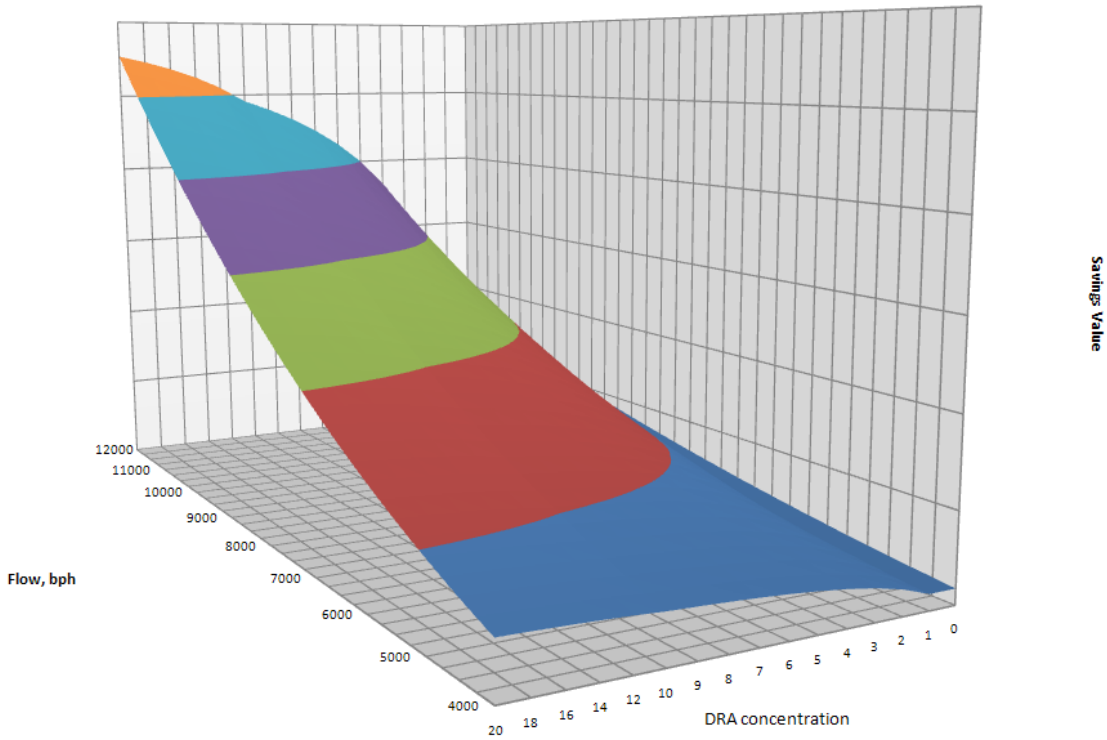
$$\text{Savings Value} = \int_0^T \alpha(t)\ \mathrm{kW}_{\mathrm{savings}}\ dt - \beta\ \mathrm{Max}_{15\mathrm{min}}[\mathrm{kW}_{\mathrm{savings}}]$$

which mimic simpler billing contract language, or, by making α explicitly a function of kW, higher weighting for higher use can readily be incorporated:

$$\text{Savings Value} = \int_0^T \alpha(t,\ \mathrm{kW}(t))\ \mathrm{kW}_{\mathrm{savings}}\ dt$$

Applying this approach, an example of a consumption savings value surface, still corresponding to the single fluid case from above, is shown in the figure below:

Figure 13: Single Product Type Consumption Savings Value Surface



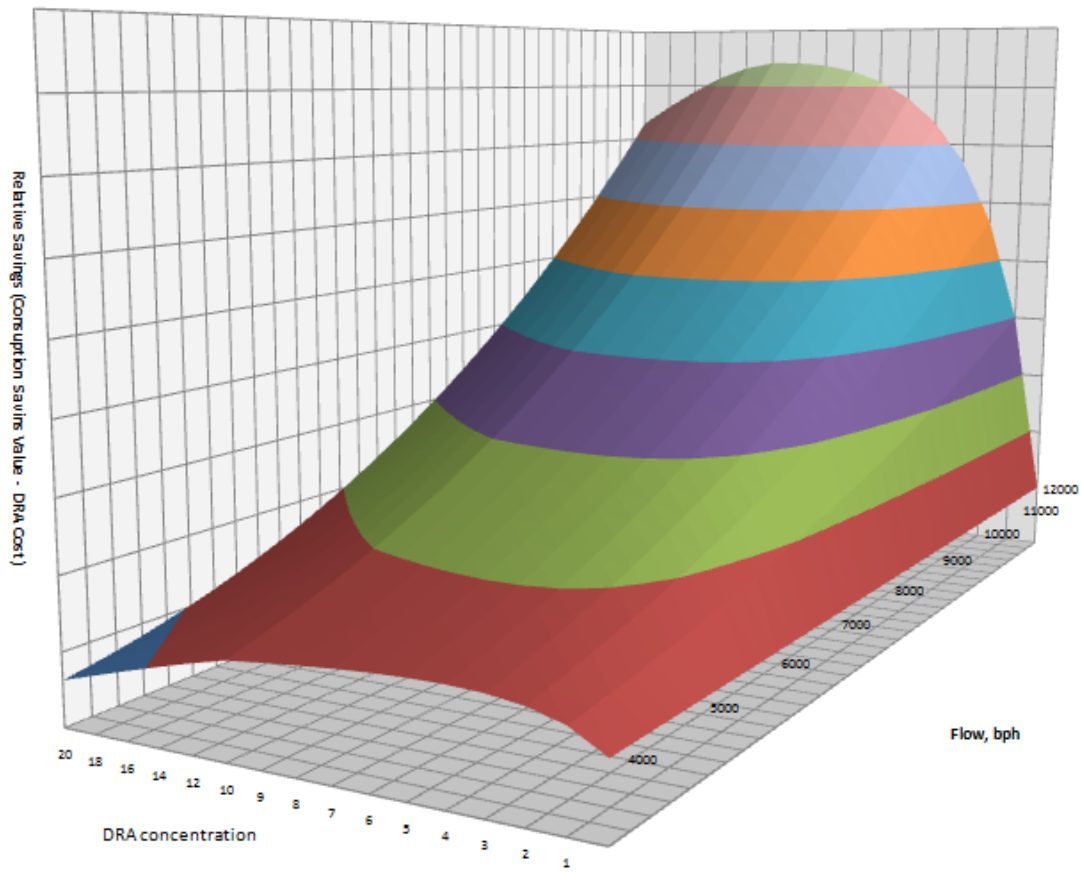
From this type of pipeline segment-specific data, utilities can gauge the effects of DRA-consumption reduction and prioritize the various locations along pipelines they service.

Finally, by including DRA costs:

$$\text{Adjusted Savings Value} = \int_0^T \alpha(t,\ kW(t))\ kW_{savings}\ dt \quad - \quad Cost_{DRA}$$

and the combined hydraulics and economics effects are shown:

Figure 14 : Single Product Type Total Economic Value Surface



The diminishing economic benefits of DRA at higher concentrations are clearly displayed when the linear DRA cost relationship is included in the value analysis. Again, the surface shows consumption savings values for segments with variable pumps. When only one or more fixed speed pumps are installed, only one or several discrete consumption savings values are possible.

Note that without including pump characteristics in this analysis, a rather conservative savings value estimate is calculated. Based on typical industry-wide pump characteristics data, the estimates will safely be 10% low. The rationale for excluding pump characteristics and efficiencies during initial savings evaluations is simply to arrive at engineering-level estimates quickly and with minimal effort.

For pipeline segments carrying two or more product types, appropriate time-weighting, relative to scheduled volume ratios of one or another fluid being in the segment under examination, will yield savings estimates for multiple fluids. In keeping with the goal of engineering-level savings estimates, a low but effective DRA concentration can be chosen for each fluid for the analysis. The issue of transitioning between fluids in the pipeline segment is trivial when looked at as a

simulation, but can also be dealt with adequately using monthly schedule data, including total volumes shipped for each product type and range of batch sizes, filtered flow histograms , etc. For the purposes of savings evaluations, and to minimize computation time, similar products can be grouped together to reduce the total number of such groups requiring analysis. This includes products for which DRA injections are not permitted (e.g. jet fuels).

2.5.3 Consumption Reduction / DRA Feasibility Analysis Summary

The steps for DRA-related consumption reduction feasibility analysis necessarily involve interaction between the energy suppliers and pipeline operators, each with related but distinct purposes behind their interest. The utility company wants to reduce load at critical times without adversely affecting revenue streams. The pipeline company wants to ensure normal pipeline operations so that customer needs are met without increasing cost. The means of determining when both sets of competing goals might be met and how to best incentivize the effort to strike a balance between consumption reduction and the value it provides on the one hand, and increased costs associated with DRA usage on the other, are described in detail above.

To summarize, a two-phased feasibility analysis begins with a high-level examination to arrive at rough consumption savings and cost estimates that will serve to highlight sites worthy of closer study. All linked to pipeline segments and station sites where utility companies wish decreased usage, an engineering estimate requiring geometry, product types, product throughputs, pump capabilities, and DRA performance as inputs can quickly yield consumption savings estimates.

It is during this initial examination that questions on a few fine points can start to be addressed. For instance, there might be instances where local analysis on a single segment of pipeline suggests worthwhile savings but, due to the particulars of the pipeline being evaluated, higher consumption might result in neighboring segments.

Similarly, if a particular segment holds the promise of savings limited by the fact that there are only fixed speed pumps installed there, variable pump acquisition costs can be factored in. An alternative to capital expenditure is identification of a spare or underutilized variable pump identified from inventory elsewhere. There may also be unused DRA injection equipment available for retasking to a given segment.

The goal of the first phase of the analysis is to identify DRA injection sites along California pipelines where significant consumption savings potentials warrant focus on these sites. During the second phase of the analysis, the consumption savings and cost estimates should be calculated with higher accuracy by running operations simulations, taking into account the range of schedules for the segments. The output from the simulations allows time-dependent analysis not possible using the averaging procedures employed in the first phase. It is during this stage that pipeline engineers can take the opportunity to examine operations and scheduling procedures to assess, for instance, the impact of flow reduction during peak usage periods.

Once the approximation and simulation analyses have been performed, the stage is set for detailed discussions between pipeline and utility company personnel on DRA-specific utility rate contract language tailored to incentivizing DRA use and consumption savings for each specific segment examined. Mention has been made of adapting existing curtailable contract language to the DRA situation. Other options include sharing DRA costs based on the shared benefits of DRA usage. The benefits to utilities of consumption reduction are evident. The possible benefits to be looked for from DRA use by a pipeline operator include the obvious decrease in electrical and/or fuel cost associated with reduced pump requirements. In addition, less wear and maintenance on pump equipment and reduced pressure cycling of pipe can be added as long term advantages.

The relationships between DRA use, pressure drop, consumption reduction, and physical wear on pipeline components are complex. Simply examining a range of DRA injection concentrations for each fluid type greatly complicates the analysis. An optimal formula or set of weighted factors derived for one pipeline segment will not necessarily carry over to other segments. The two stage approach outlined above should, however, serve to steer pipeline and utility engineers towards an optimal compromise between consumption reduction and DRA expense, and serve as a basis for DRA incentivized contracts.

The next chapter describes DRAnalysis, the web-based software package created to perform the DRA analysis tasks described above. Tuning the underlying model using pipeline SCADA data and use of the package is discussed for both the approximation and simulation analysis phases.

The last chapter describes the short and mid-term steps planned for introducing the capabilities of the DRAnalysis package to the utility and pipeline companies in California. Introduction of the package will coincide with the 2015 Pipeline Energy Group meeting, a yearly gathering of pipeline energy engineers, utility companies, and DRA and other vendors. Based on utility consumption reduction need and availability of suitable pipeline segments, prospective utilities and pipeline companies will be identified. From there, the first stage of the two-stage analysis will be performed, results shared, and if the second stage analysis is warranted and yields positive results, implementation of DRA will be undertaken.

CHAPTER 3:
Project Results – DRAnalysis Software Tool

One of the main results from this project is the mathematical exposition of the DRA consumption reduction relationships discussed in some detail in the previous chapter. This chapter will describe DRAnalysis, the software tool created to help bring that theory to bear on the problem of consumption reduction. First, the general features necessary for the tool to be accessible and useful to both pipeline and utility companies are discussed. Model tuning and a description of how secure use of actual pipeline data is incorporated is then followed by an outline of how DRAnalysis is used to accomplish the survey and simulation phases of the two-step analysis needed to quantify the consumption savings potential of any pipeline segment.

3.1 DRAnalysis - Basic Software Requirements

In order to assess the feasibility of using DRA for consumption reduction in California pipelines, both utility and pipeline companies need quantitative analysis based on data held, in part, by the other party. For instance, pipeline schedule data dictates the lowest consumption levels possible without violating pipeline customer delivery constraints, while utility company data on actual production costs set absolute bounds on power and energy costs. Without adequate analysis, pipeline companies see little incentive and higher costs in adopting a DRA injection strategy without aid from customized utility company pricing structures. Again, without adequate analysis, utility companies will not have realistic consumption level estimates, both with and without DRA, from which to assess the impact of added load from pipeline companies.

Given the need for pipeline companies to feed horsepower requirements and DRA hydraulic impact into any proper analysis and the need for utility companies to input actual and proposed cost structures into the same analysis, a web-based application linked to a secure database and calculation engine is indicated over a single-user desktop application. In such an environment, a given pipeline company engineer can create and study different hydraulic scenarios with differing levels of complexity and detail, while retaining the ability to share promising scenarios with utility companies. Similarly, utility companies would be able to use the same application, setting up scenarios with different consumption pricing structures and levels, and working together with pipeline company engineers to arrive at a mutually beneficial balance of energy, power and DRA costs on the one hand, and consumption reduction on the other.

From a software design standpoint, the key functional blocks are data input (and the associated database design), data analysis, and data reporting. While DRAnalysis is an application created to fulfill a specific set of requirements for a relatively small number of users, use of industry-standard software technologies makes creation of the data input and reporting blocks easier. It also helps their use conform to, in this case, web application standards for user interface look and feel. In terms of the data analysis, use of existing software libraries for performing pressure drop, DRA, and economics calculations make creation of the analysis software a much simpler exercise. Use of program development strategies employed in writing the libraries can be

directly carried over to creation of the analysis routines. This means that program maintenance, modification, and expansion become much easier, extending the useful life of the software.

In more application-specific detail, each of the prospective users of DRAnalysis will need the ability to input cost and/or hydraulic data and extract analyzed results that will help in determining consumption savings potential for a given pipeline segment. Once a pipeline engineer inputs the hydraulically important variables of the segment (pipeline geometry, product type, etc.), the DRA cost, and the structure of utility contracts in effect at the segment pumps, DRAnalysis has sufficient information to calculate the consumption and cost for varying levels of injected DRA and for varying flow rates. Sharing the costs and consumption savings numbers with the utility company serving that segment will let the utility, using the same tool and data, analyze their costs associated with providing energy to the pipeline, their savings derived from the lower consumption DRA can provide, and determine what portion of the savings to pass to the pipeline company in order to help the pipeline absorb the added operational costs of the DRA. The mutual use of a software package that properly handles both hydraulics and economics will remove a major barrier to the interaction between pipeline and utility companies necessary for broadly increasing the use of DRA.

For both phases of analysis, the output provided to engineers for viewing, download, and further analysis consists of a matrix of pressure drops, maximum consumption savings, costs, and relative savings as a function of the inputs, which include flow rate, DRA concentration, and product type (including hydraulic characteristics). In the case of the survey phase of analysis, a weighted average is used, based on relative volumes of each product type, to arrive at the summary costs and savings. In the case of the simulation phase, each matrix element becomes time dependent, so that as the simulation unfolds and different fluids passing through the pipeline segment with different velocities, each element is time dependent. With either the survey or simulation data in hand, the pump equipment servicing the segment can then be examined for its ability to deliver the savings. The analysis results apply directly to segments where variable pumps are installed. When fixed speed pumps service segments being investigated, modifications (e.g. impeller trimming) or exchange with units from other stations or storage may be indicated.

The advantages of a web-based application for sharing data between users have been discussed. This approach offers the important capability of simultaneous access to the tool by multiple users. By allowing multiple logins for a given username, DRAnalysis can also serve as a discussion and presentation tool. For instance, pipeline and utility company engineers can simultaneously log into DRAnalysis with the same username and view and discuss data and graphics from different locations.

Given not only the amount but the proprietary nature of data required, a major requirement of the DRAnalysis package is secure data retention using standard enterprise-level software architectures and components. Standard login protocols should provide the main mechanism for data security; data entered should utilize a robust database, persist across user sessions, and never be accessible to other users. Normal production-level backup procedures should be implemented to ensure against server-side malfunctions.

Given a sound architecture, the next consideration is the user interface used to populate the user-specific database entries. A pipeline engineer may have data expressed in a wide variety of units. For instance, the length of a pipeline segment may be expressed in yards, feet, or miles. Viscosity of a particular fluid type may be in centistokes or centipoise. The DRAnalysis user interface should allow for specification of each of the wide variety of units encountered in the data from California pipelines, relieving the engineer of the tedious task of conversion. The pipeline engineer may also want to mimic existing power contracts in the specification of energy and demand costs. This implies a requirement to easily enter what are at times complex relationships. This capability is also needed by the utility company engineer who, using pipeline data given by his/her pipeline counterpart, will want to investigate alternate pricing structures tailored for DRA injection sites.

The final requirement is a calculation engine that uses the input data to produce the output matrices described above. In addition to the use of existing software libraries to perform the pressure drop, DRA, and economics calculations, a web-based application requires multi-threaded processing. This means, simply, that once a user has finished entering data for a scenario, calculation of the results should proceed immediately and separate from other calculations from other users. The design of the DRAnalysis calculation engine incorporates a control module whose task is to monitor user requests for survey or simulation runs and start a separate dedicated calculation process for each request. The issue of calculation accuracy and tuning will be discussed in the next section.

3.2 Input Data Validation and Calculation Verification

The results of DRAnalysis calculations will be used to steer efforts in both pipeline and utility companies. Confidence in these results is obviously critical. Validation of the input data and verification of the calculations are both necessary to achieve the needed confidence.

3.2.1 Input Data Validation

The ultimate responsibility for the accuracy of both hydraulic and economic input data lies with the users. By allowing for the various units found among pipeline companies in describing, for instance, pipeline segments (e.g. miles versus yards for length or inches versus feet for diameter), some of the burden is relieved in that the user doesn't have the task of translating the data into an approved set of units.

Some basic consistency checking is performed by DRAnalysis. Much like inputting data into a spreadsheet, the input fields presented to the user are not checked as they are entered. However, in keeping with spreadsheet usage, once a calculation is requested (equivalent to entering a formula into a cell), errors in format or value become evident. DRAnalysis reports a variety of errors, including missing data values, range errors (e.g. tiny or negative pipe diameters), and unrecognized entries (a number with an invalid format or character).

The format for the input data and the details of which units are recognized are covered in the DRAnalysis User Manual, included in the appendices.

3.2.2 Calculation Verification

Existing software libraries for performing the hydraulics and economics analysis provide a required foundation for confident use of the results. The libraries used have been repeatedly validated using data from a number of pipelines. There are three prongs to DRAnalysis hydraulics calculation verification. The first, trivial step is to check hydraulics calculations against other hydraulics tools using a few simple test cases. Checking hydraulics calculations using data for specific pipeline segments and against SCADA data is the next recommended step for assessing the requirement for customized tuning, and is discussed below. Finally, the verification of effects of DRA should be addressed. This is important in that the effects of DRA vary somewhat and are influenced by pipeline-specific factors.

The first prong for pipeline engineers to verify pressure drop calculations involves comparing the results from simple test scenarios using, for example, a single diameter and fluid, with the results from either in-house hydraulic modeling software or online calculation tools.

The next step in verification involves incorporating actual pipeline data. Comparison should be made between the theoretical results from modeling a specific pipeline segment and pressure drop data from the pipeline SCADA system. Small variations are to be expected based on, for instance, pressure meter errors, unknown pipeline inner surface roughness, or differences between the viscosity used in the calculations and that of real fluids in the pipeline. If the discrepancies are relatively large, then pipeline tuning may be needed. As an example of the impact of such errors, for a single rate energy-based electrical utility contract (like that from a home, where the resident is charged based on kWh usage alone), a 5% error in calculated energy consumption would translate directly into a 5% error in electrical cost estimates.

The last step in calculation verification involves matching DRA calculations to performance, and can be carried out once DRA is in use on the segment being analyzed. If DRA is in use at another segment on the same pipeline, data from that segment can be used to estimate corrections, although DRA shearing can occur at specific sites along one pipeline segment without similar sites being present along the segment being analyzed. Without pressure, flow, and DRA concentration data from SCADA, DRAnalysis uses DRA vendor algorithms for predicting baseline DRA performance. With sufficient SCADA data, differences between calculated and actual DRA performance can be tallied and used to correct for the differences. These corrections are applied by the DRAnalysis calculation engine.

3.2.3 Pipeline Tuning

During the survey phase of analyzing a pipeline segment, close matches between calculated and live pressure drop values are not of critical importance given that the purpose of this phase is to remove from further examination segments where injecting DRA would neither yield sufficient consumption savings nor be financially feasible. It should be remembered that for certain products, especially crude oils and heavier hydrocarbon fluids, the accuracies of the temperature dependent viscosities used in the calculations will be limited by uncertainties in the temperature profile of the fluids along the pipeline segment being analyzed. This will have a noticeable effect on pressure drop accuracies, even if fluid temperatures at the start of the segment are known.

After passing consumption savings and cost thresholds from the survey-level segment examination, systematic corrections to the pressure drop and DRA performance calculations are appropriate for the simulation phase of segment analysis. It is during this phase that final determination of viability of a given segment for DRA injections occurs. Since DRAnalysis calculates pressure drops and DRA effects separately, use can be made of the viscosity or pipeline inner diameter to adjust calculated pressure drop values. Although this will affect the flow dependence of the pressure drop calculations, it provides a quick and easy way of tuning the pressure drops to match live data. Alternately, a matrix of multiplicative factors can be built from comparison between DRAnalysis calculations and SCADA data as a function of flow rates, using best estimates of properties for the fluids in the segment when the SCADA data was captured.

DRA manufacturers have a wealth of experience in modeling DRA performance across fluid types and flow rates, and for each type of DRA. DRA analysis uses these models, which typically describe performance in different fluids through the values of two or more constants. Always ensuring proper handling of proprietary data, and just as with the pressure drop tuning matrices, DRAnalysis can store customer-specific and product-specific sets of DRA model constants, arrived at after comparison between calculations and SCADA data.

Both the pressure drop and DRA tuning matrices are controlled solely by DRAnalysis system administrator and employed by the calculation engine. This is because of the proprietary nature of the SCADA and DRA model data.

3.3 DRAnalysis - Implementation

Implementation of DRAnalysis was planned and carried out using industry-standard design techniques and technologies. The three key software components are the user interface, the database, and the calculation engine. These will be described in turn, followed by a brief description of the hardware environment for this web-based application.

3.3.1 Front End / User Interface

Given the need for a browser-based web interface, Java was selected as the technology to use. Incorporating military-quality security modules ensures data protection and the feature rich GUI libraries provides standard graphical components familiar to web users. A major factor in choosing Java was the desire to offer the package as a desktop hydraulic and economics modeling application to interested pipeline and utility companies. The platform independence of Java eliminates deployment problems that might occur when installing DRAnalysis on hardware running unknown operating system.

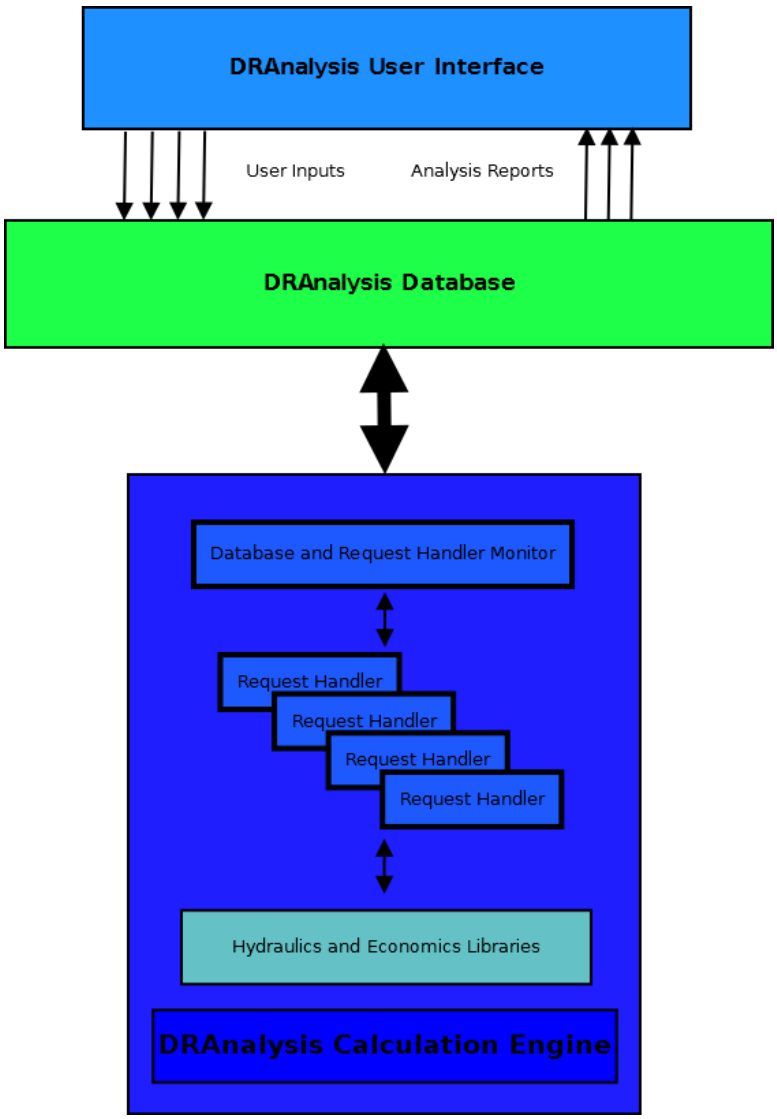
3.3.2 Database

Database selection for DRAnalysis amounted to a choice between a structured query language (SQL) server, mySQL, and Oracle. mySQL was chosen for a number of reasons, not the least of which was its superior performance in web applications (Google, Yahoo, and Facebook all use mySQL). In line with the choice of Java, mySQL is not limited to a specific operating system, easing deployment problems as DRAnalysis is offered as a desktop application. That it has no

hardwired database size limitations and that it has a small footprint were strong factors in favor of mySQL.

Two final considerations pointing to mySQL were its scalability and its replication methodology, the latter making it well-suited for multi-user web environments where active database backup is a critical systems administration requirement.

Figure 15: DRAnalysis Block Diagram



3.3.3 Calculation Engine

The heart of DRAnalysis is the calculation engine (see Figure 15 above). DRAnalysis uses a proven set of libraries for economics and hydraulics calculations. These libraries have been validated through use on a number of pipelines carrying a wide variety of products. The libraries are called exclusively from standalone request handler processes. When a user requests

analysis of a set of data, a database flag is set and the Database Monitor module recognizes the request, locks and checks the data, and begins the analysis by starting an instance of the DRAnalysis request handler.

Multiple request handlers can operate simultaneously, with central processing unit (CPU) allocation for each request handler being controlled by the operating system. The request handlers are the exclusive users of the hydraulics and economics libraries. When analysis is completed, the user can view or download the results from the DRAnalysis interface.

All DRAnalysis modules are designed and written to conform to a sandbox software model, so called since a user is free to 'play' in his own sandbox without affecting other users or being affected by them. This is one of Java's core principles, and a properly designed mySQL database inherits this security. Lastly, using separate request handler processes for each user analysis request, each process with its own memory space, isolates any proprietary data.

The user manual for DRAnalysis is included as an appendix. The next two sections give a brief description of how a user can request DRAnalysis to perform survey and simulation analyses. Recall that a survey is an estimate based on net product shipment volumes and averaged flow rates while simulations allow for more realistic pipeline schedules.

3.4 DRAnalysis – Survey Mode

There are four categories of data needed by DRAnalysis, divided into separate user interface input screens:

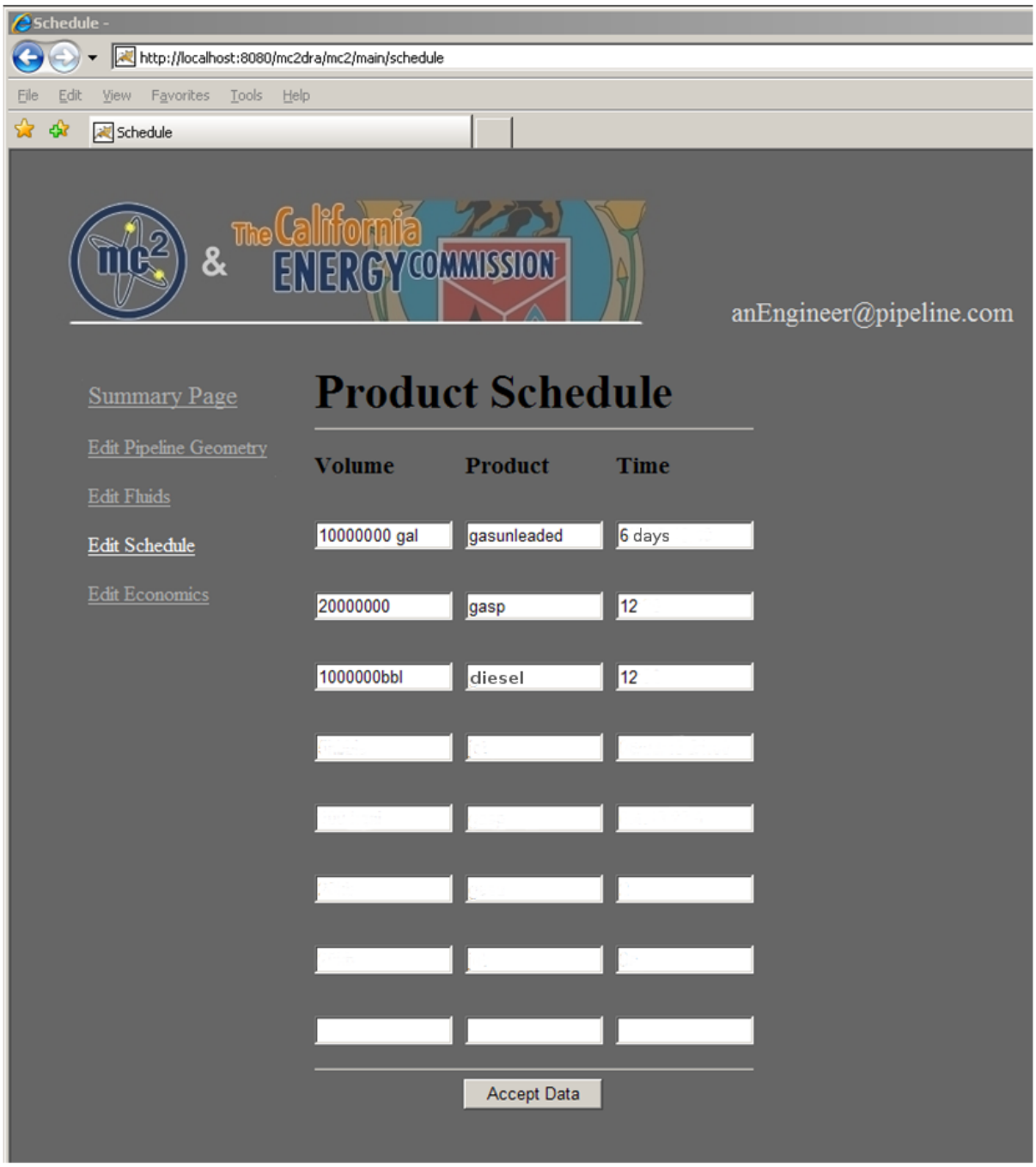
1. Pipeline geometry
2. Fluid properties
3. Pipeline schedule
4. Economics

The pipeline geometry data needed consists of a list of elevations, lengths, and inner diameters. The fluid properties input page allows the user to input product name, specific gravity, and viscosity. Input fields specifying the economics for DRA and pump operations are described in the economics section of the Data Entry chapter of the DRAnalysis user manual. Billing kW and kWh levels, kW and kWh rates, and times those rates are applicable are entered from this page. For the survey mode, peak period structures are not relevant. Aggregate hydraulics load calculations bypass exact load profiles necessary for realistic billing economics. By using simple economics for kW and kWh levels, comparison against DRA costs is simplified and utility companies can get a clear, though simplified picture of the economic incentives required by pipelines to incorporate DRA into their operations.

DRAnalysis interprets the schedule page data to determine whether survey or simulation results are to be generated. The three fields for each schedule entry are volume, product, and time. The key difference that signals which calculations to perform is the specification of a beginning linefill, or lack thereof. Without a beginning linefill, DRAnalysis carries out the set of

calculations needed for survey results (see the figure below). Shown are three batches with their volumes and the number of days allocated for shipment through the pipeline segment being analyzed. Specification of product volume with a time allocated for shipment specifies the mean flow rate for that product, allowing for lowering flow rates for heavier fluids. A set of graphs are generated (see, as examples, Figures 12-14 above). The input data, the graphs, and the analyzed data used to create them are available for download from the DRAnalysis server.

Figure 16: DRAnalysis Schedule Entry Screen - Survey Mode



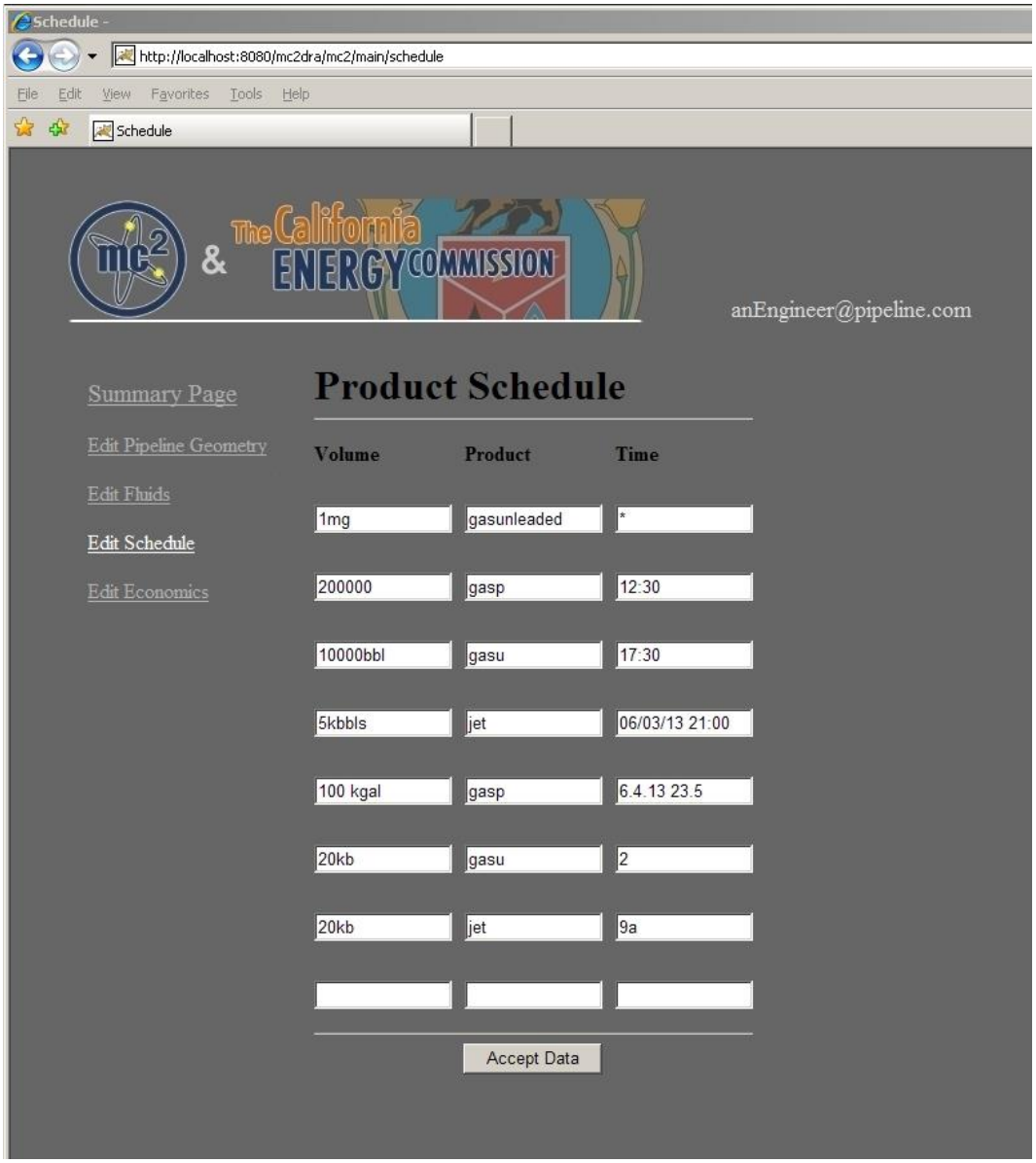
The results contain both an overall summary for the specific schedule created for the survey and separate sets of data and figures, one set for each of the products being shipped. This allows some comparison of results across different surveys.

DRAnalysis' survey mode is offered free of charge.

3.5 DRAnalysis – Simulation Mode

An example of a product schedule set up for a time-specific simulation analysis is shown in the figure below:

Figure 17: DRAnalysis Schedule Entry Screen - Simulation Mode



Note that the first entry, for 'gasunleaded', has a '*' entered in the 'Time' field. Use of this character in this way designates this entry as the initial segment contents and directs DRAnalysis to perform a simulation analysis once the request for analysis is made.

A full explanation of the entries shown may be obtained from the DRAnalysis user manual. Briefly, if the linefill consists of only one product, then the volume field is irrelevant in that DRAnalysis uses the volume calculated from the pipeline geometry data. If more than one product type is needed to specify the linefill, the numerical values of the volumes entered are internally interpreted as ratios applied to the calculated segment volume. The remaining volume entries show the flexibility DRAnalysis provides for using different units of measure.

The time entries shown demonstrate the built-in flexibility DRAnalysis provides for uniquely placing the schedule on a calendar and specifying flow rates. The fourth and fifth entries fix those schedule entries to specific dates and times. These and the remaining time entries are sufficient for specifying flow rates throughout the entire schedule, limited only to having a constant flow rate for a given entry. Special techniques, such as using the same product on two consecutive schedule entries to designate first one, then another flow rate for that product, are covered in a series of technical notes.

The output of a simulation analysis includes the hydraulic losses as a function of time and DRA concentration. The DRA concentration is considered constant across a given schedule entry and, despite this simplification, a large quantity of analysis data is generated.

Due to the computational load required by DRAnalysis' simulation mode, a license is required to perform this analysis, and is discussed in the next section.

3.6 DRAnalysis – Commercial Considerations

DRAnalysis survey analysis is offered to pipeline and utility company users free of charge. This mode is tailored to assist in identification of pipeline segments where use of DRA for consumption reduction is viable, both hydraulically and economically. A simple on-line registration process provides users with accounts and the ability to perform sequential surveys (for each user, the system finishes calculating the results of one request before starting the next request).

The ability to execute simulation requests and to have multiple simultaneous survey requests both require a fee-based subscription. Additionally, DRAnalysis is offered as a desktop or network application for companies wishing to make extensive use of the simulation features of the program.

Additional assistance with analysis and data mining of hydraulic and economic data is available from mc^2 Consulting upon request.

CHAPTER 4:
Project Benefits – DRAnalysis Use and DRA Implementation on California Pipelines

Large-scale electrical and fuel consumption will always be an issue for California for a variety of reasons. As usage nears the supply capacity, real costs rise quickly. Over the long term, growth projections show that the existing capacity will need to be increased, a costly undertaking that is borne by both industry and the general public. Optimization of use of electricity and fuel is essential both from the standpoint of the environment and usage footprints and the ever-increasing competitiveness of California's business environment, as recent events show.

To emphasize the point, 500,000 jobs were added in California last year, signaling a robust economic recovery, but at the same time signaling higher energy use now and in the future. Prudence dictates that consumption reduction programs be vetted and put into effect to help offset the expected higher use .

This report quantifies how DRA use dramatically reduces fluid pressure loss and offers the possibility of commensurate reductions in pump-related electrical and fuel consumption. The main reasons why this strategy is not in wide use in California pipelines revolve around operating cost increases not offset by the pipeline's electrical or fuel bill savings. Also, the technique is equipment intensive, requiring the installation of DRA injection equipment, and adds another variable to manage for a pipeline controller with an already busy workload.

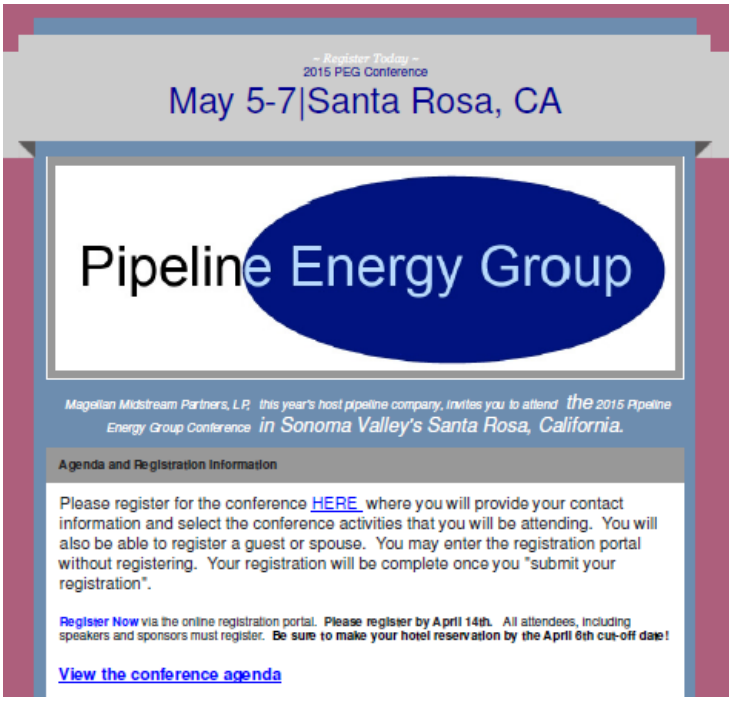
Aside from the need for resource conservation, when electrical grids become strained, fuel prices spike, or, as is the case now in California, hydroelectric generation is affected by drought, real costs to utility companies to supply the pipeline pumps increase and the economics of DRA need to be reexamined. The key to broad implementation of DRA lies in easing some of the economic burden, described above, that would be seen by pipeline companies. Especially when near capacity, utility companies are justified in presenting incentivized utility rate structures to their pipeline customers. Based on real savings for the utilities, derived from the reduced consumption, rates can be crafted that help pipelines justify the burden of DRA use, a necessary step for wide adoption of a DRA strategy for California.

Pipeline and utility companies are, in general, aware of DRA use in pipelines. Because of the factors discussed above, there is a certain inertia to be overcome before significant DRA use becomes a reality in California. The answers as to how to start a dialog with the utility companies, the pipeline companies, and, critically, between them, involve finding common ground where all parties benefit. It will obviously involve working individually with the companies. However, industry gatherings, where representatives from the various concerns meet, talk, and exchange ideas, provide a means of kick-starting the DRA discussions.

To this end, there is an informal pipeline industry group, the Pipeline Energy Group, or PEG, that focuses on pipeline consumption. PEG holds a yearly meeting where pipeline power

engineers, pipeline equipment vendors, DRA vendors, software vendors, and utility companies all join for three days to discuss pipelines and energy related issues. Though not California-specific, the attendees for the meeting this year are expected to be weighted towards west coast participation in that the site for the meeting is Santa Rosa, California (see Figure 18 below). Regardless, this meeting offers a timely opportunity to create a favorable environment for discussions leading to the use of DRAnalysis to survey pipeline segments and identify candidates for DRA injections. Beneficial effects of positive feedback from this initial effort, even if on non-California pipelines and from joint discussions between pipelines and utilities outside the state boundaries, can spur interest within California that will lead to increased awareness and participation in DRA-driven consumption reduction efforts in the near future.

Figure 18: 2015 Pipeline Energy Group Meeting Brochure



During the meeting, discussions will be held covering, in part:

1. How DRAnalysis survey results can be used by pipeline company engineers to identify pipeline segments where DRA could be effective.
2. How DRAnalysis simulation results can be used to obtain load profiles for specific pipeline schedules.
3. How DRAnalysis can be used for designing incentivized rate structures to encourage DRA adoption.

After the meeting, DRAnalysis use by interested engineers will be followed up by discussions focused on answering any questions they might have about the tool, interpretation of the results, and DRA implementation issues in general.

4.1 DRAnalysis - Strategy for Utility Companies

Since offsetting the added costs and operational issues pipelines have to address with DRA will encourage and speed the adoption of DRA for consumption reduction, identification of California utility companies that both provide service to pipeline pump stations and are near capacity, if only infrequently, will be key in minimizing the time to installation and operation of DRA injection equipment and realization of consumption savings. Identification of these utilities is expected to begin with initial communications and nondisclosure agreements between mc^2 Consulting and the utilities and, if required, the pipeline companies they serve. From there, utility company load data, and real and billed cost patterns can be studied, and possible rate structures acceptable to the utilities can be discussed.

An initial step in the exchange of data will be to have each applicable utility complete a questionnaire covering such issues as number of pipeline pump stations serviced, rough estimates of the time spent within a given percentage of maximum capacity, and load growth projections. These results will be compiled and a preliminary profile of pipeline-specific loading can be created.

The next step will involve examination of load profiles at specific pipeline sites, starting with simple statistical techniques aimed at identifying wide swings in usage. Where this occurs, discussions can be started with the pipeline to understand the basis for the variations and look for ways of alleviating them.

Concurrently, mc^2 Consulting will discuss with the utilities development of acceptable rate structures incentivizing DRA use at pricing levels that make it attractive for pipelines they service. Based on actual generation and delivery costs of the energy, these rates can then be presented for review by the pipeline companies.

The focus of utility discussions will initially be limited to California utilities. Based on interest from out-of-state pipeline companies, selected utilities servicing candidate pipeline segments will be asked to participate in the questionnaire and help develop DRA-related rates.

A map of the regions serviced by California's electrical utility providers is shown in the map below:

Figure 19: California Utility Regions

A complete list of California's electrical utilities, available from the California Energy Commission web site, will provide initial contact points for distributing the questionnaire described above. The results will be used to narrow the focus of efforts to those pipeline stations where the greatest utility company benefits might be realized. To see a list of the electrical utility organizations within California, please visit the following web address: http://energyalmanac.ca.gov/electricity/utilities.html

Again, utility companies and pipelines outside of California may serve as catalysts to peak interest among California's utilities and pipelines. Instead of contacting the very large number

of utilities across the country, pipelines will be contacted first and DRAnalysis surveys will be carried out on prospective pipeline segments; based on results, utilities serving those pipeline segments will be contacted.

4.2 DRAnalysis - Strategy for Pipeline Companies

At the conclusion of this year's PEG meeting in Santa Rosa, California, a list of pipeline companies will be asked to complete questionnaires for identifying pipe segments where DRA is in use and segments which should be considered for DRA use. This communication will also describe DRAnalysis and act as an invitation to its use. As with utility companies, it is expected that nondisclosure agreements will be required for the data and the in depth discussions anticipated with pipeline engineers. The questionnaires will serve as a mechanism for execution of the agreements and the questionnaire results will be used to focus on pipeline segments that show promise for DRA-related consumption reduction.

Following that, the next steps will be to follow up on the consumption savings estimates from DRAnalysis surveys by gather economics profiles of the promising segments, and have the pipeline company estimate the costs of DRA implementation. Simultaneously, utility companies servicing those segments will be contacted and discussions started towards offering the pipelines utility contracts designed for DRA use.

A partial list of California pipelines that will be contacted includes Plains All American Pipeline, ARCO, Chevron, Four Corners, Mobil, Shell, Texaco, Unocal, Calnev, Kinder-Morgan, Shell, and Conoco Phillips.

Non-California pipelines that will be contacted include:

- Colonial Pipeline
- Conoco Phillips Pipeline
- Plains All American Pipeline, L.P
- Magellan Midstream Partners, L.P
- Marathon Pipe Line
- Enbridge
- Kinder Morgan
- Buckeye Partners
- Explorer Pipeline Company
- Nustar
- NuStar Energy
- Shell, Shell ECS-Energy

- Enterprise Products
- Enterprise Pipeline (EPCO, Inc.)
- LOOP LLC
- Centurion Pipeline, L.P. (OXY)

4.3 DRAnalysis - Strategy for DRA Manufacturers

The use of DRA manufacturer-supplied pressure drop modification algorithms will provide DRAnalysis survey results with first-tier estimates of possible consumption savings. When possible, DRAnalysis simulations using SCADA data to tune the DRA algorithms will increase the accuracy of the hydraulics calculations. As permitted by the pipeline companies, pressure drop data can help the DRA manufacturers fine-tune the DRA algorithms. Adoption of improved algorithms throughout the industry can help not only the DRA manufacturers, but the pipeline users as well.

Given the potential long-term increase in demand for DRA brought on by general implementation on California pipelines, an opportunity exists for affecting the market price of DRA. In addition, discussions with DRA manufacturers may show that by changing DRA formulations or manufacturing processes, most of the DRA benefits can be obtained at a significant reduction in manufacturing cost.

Beginning with discussions with DRA vendors at the 2015 PEG meeting, a strategy of joint utility rate incentivization coupled with DRA volume-based cost discounts will be explored as immediately available options for California pipelines. Discussions with the DRA manufacturers regarding formulation or process changes should and will be pursued. Timeframes for the realization of benefits along these lines will be affected to a large extent by increased pipeline company interest in DRA, so communications between pipelines and the DRA vendors will be actively encouraged.

4.4 DRAnalysis - Conclusions

Given long-term electrical and fuel needs of California, the use of DRA offers both pipelines and utility companies significant consumption reduction. While lowering utility-related costs for pipelines adopting DRA injection strategies, the cost of DRA offsets the utility cost savings and, coupled with the added operational issues involved with DRA injections, utility company incentivization through the offering to pipelines of lowered utility rates at segments employing DRA injection is an important component in the important task of lowering California's utility consumption.

A suitable tool for use by both pipeline and utility company engineers for the hydraulics and economics analysis necessary for prudent DRA implementation overcomes a major obstacle to that implementation; DRAnalysis is that tool and, through active interaction with pipeline and utility users, it can assist in significant, long-term reductions in consumption by California pipelines.

GLOSSARY

Term	Definition
A	DRA constant
AL	Customer actual load
API	American Petroleum Institute
b	DRA constant
B	Baseline charge
bph	Barrels per hour
C	Concentration of DRA
CBL	Customer baseline load
CC	Commodity charge
cP	Viscosity index
CPU	Central processing unit
D	Inside diameter of pipe
DRA	Drag Reducing Agent
DRAnalysis	Software tool to aid pipeline operations consumption reduction
ϵ	Surface roughness
E_{max}	Baseline energy over time
E_{sav}	Energy savings over time
EDC	Energy delivery charge
fi(t)	Flowrate sequence as a function of time
$F_i(t)_k$	Alternate flow rate sequence as a function of time
f	Flow, gallons per minute
f_d	Darcy fluid flow factor
g	Gravitational constant
$head_e$	Pump head required to overcome elevation difference

$head_f$	Pump head required to overcome friction losses in pipeline
HP	Horsepower
K	Constant
kW	Kilowatts – electric power or billed demand
kWh	Kilowatt hour – electric energy
L	Equivalent length of pipe
Λ	Lambda (upper case); constant = 8.1021655×10^2
λ	Lambda lower case; constant = 1/3956 = hp; 745.7/3956 = kW
m	meter
MKS	Meter-kilogram system
n	Number of hours in billing window
μ	Dynamic viscosity of a fluid
p	Number of pumps
P_e	Power required to offset pressure change due to elevation differnce
P_f	Power required to offset friction losses in pipeline
P_{sav}	Power savings
P_t	Total power required
PC	Program charge
PEG	Pipeline Energy Group
ppm	Parts per million
ppmv	Parts per million by volume
PSPI	Phillips Specialty Products, Inc.
R_e	Reynolds number
R_{inc}	Point at which there is no added pipeline expense at maximum flow
R_{kWh}	Energy charge $/kWh

ϱ	Fluid density
RTP	Real time pricing
SCADA	Supervisory Control and Data Acquisition
SG	Specific gravity
σ	Cross sectional area of pipe
SQL	Structured query language
T	time
TOD	Time of Day
V	Velocity of fluid flow in pipe

APPENDIX A:
Typical Large-User Electrical Utility Contract

Duke Energy Carolinas, LLC

Electricity No. 4
North Carolina Eighth Revised Leaf No. 29
Superseding North Carolina Seventh Revised Leaf No. 29

SCHEDULE LGS (NC)
LARGE GENERAL SERVICE

AVAILABILITY (North Carolina Only)
Available to the individual customer with a kilowatt demand of more than 75 kW. If the customer's measured demand is 75 kW or less for twelve consecutive months, the customer will be served under Schedule SGS.

Service under this Schedule shall be used solely by the contracting Customer in a single enterprise, located entirely on a single, contiguous premises.

This Schedule is not available to the individual customer who qualifies for a residential or industrial schedule nor for auxiliary or breakdown service. Power delivered under this schedule shall not be used for resale or exchange or in parallel with other electric power or as a substitute for power contracted for or which may be contracted for, under any other schedule of the Company, except at the option of the Company, or for service in conjunction with Rider SCG or Rider NM, under special terms and conditions expressed in writing in the contract with the customer.

The obligations of the Company in regard to supplying power are dependent upon its securing and retaining all necessary rights-of-way, privileges, franchises and permits, for the delivery of such power. The Company shall not be liable to any customer or applicant for power in the event it is delayed in or is prevented from, furnishing the power by its failure to secure and retain such rights-of-way, rights, privileges, franchises and permits.

TYPE OF SERVICE
The Company will furnish 60 Hertz service through one meter, at one delivery point, at one of the following approximate voltages, where available:

Single-phase, 120/240 volts, 120/208 volts, 240/480 volts or other available single-phase voltages at the company's option; or
3-phase, 208Y/120 volts, 460Y/265 volts, 480Y/277 volts; or
3-phase, 3-wire, 240, 460, 480, 575, or 2300 volts: or
3-phase, 4160Y/2400, 12470Y/7200, or 24940Y/14400 volts; or
3-phase voltages other than those listed above may be available at the Company's option if the size of the Customer's contract warrants a substation solely to serve that Customer, and if the Customer furnishes suitable outdoor space on the premises to accommodate a ground-type transformer installation, or substation, or a transformer vault built in accordance with the Company's specifications.

The type of service supplied will depend upon the voltage available. Prospective customers should determine the available voltage by contacting the nearest office of the Company before purchasing equipment.

Motors of less than 5 H.P. may be single-phase. All motors of more than 5 H.P. must be equipped with starting compensators. The Company reserves the right, when in its opinion the installation would not be detrimental to the service of the Company, to permit other types of motors.

RATE:

I.	Basic Facilities Charge per month	$23.34
II.	Demand Charge	
	For the first 30 KW of Billing Demand per month, per kW	No Charge
	For all over 30 KW of Billing Demand per month, per kW	$3.6301
II.	Energy Charge	
	For the First 125 kWh per kW Billing Demand per Month:	
	For the first 3,000 kWh per month, per kWh	11.2282 ¢
	For the next 87,000 kWh per month, per kWh	6.9892 ¢
	For all over 90,000 kWh per month, per kWh	6.9315 ¢
	For the Next 275 kWh per kW Billing Demand per Month:	
	For the first 6,000 kWh per month, per kWh	6.5743 ¢
	For the next 134,000 kWh per month, per kWh	5.8277 ¢
	For all over 140,000 kWh per month, per kWh	5.7360 ¢
	For all Over 400 kWh per kW Billing Demand per Month:	
	For all kWh per month, per kWh	5.4983 ¢

North Carolina Eighth Revised Leaf No. 29
Effective for service on and after September 1, 2012
NCUC Docket No. E-7, Sub 986, Order dated August 20, 2012

Page **1** of **3**

SCHEDULE LGS (NC)
LARGE GENERAL SERVICE

RIDERS

The Renewable Energy Portfolio Standard (REPS) Rider charge as shown on Leaf No. 68 will be added to the monthly bill for each agreement for service under this schedule.

The following Riders are applicable to service supplied under this schedule. The currently approved cents/kWh rider increment or decrement must be added to the cents/kWh rates shown above to determine the monthly bill.

Leaf No. 60	Fuel Cost Adjustment Rider
Leaf No. 62	Energy Efficiency Rider
Leaf No. 63	BPM Net Revenues and Non-Firm Point to Point Transmission Revenues Adjustment Rider
Leaf No. 64	Existing DSM Program Costs Adjustment Rider
Leaf No. 65	DSM Deferral Balance Rider
Leaf No. 77	Coal Inventory Rider
Leaf No. 94	Coastal Demonstration Wind Turbine Project Rider
Leaf No. 97	Merger Fuel-Related Savings Rider
Leaf No. 98	Merger Capacity Mitigation Rider

DEFINITION OF "MONTH"

The term "month" as used in this Schedule means the period intervening between meter readings for the purposes of monthly billing. Readings are taken once a month at intervals of approximately thirty (30) days.

DETERMINATION OF BILLING DEMAND

The Billing Demand each month shall be the largest of the following:

1. The maximum integrated thirty-minute demand measured during the month for which the bill is rendered.
2. Fifty percent (50%) of the maximum integrated thirty-minute demand during the billing months of June-September within the previous 12 months including the month for which the bill is rendered.
3. Fifty percent (50%) of the Contract Demand
4. 30 kilowatts (kW)

The Company will install a permanent demand meter for all customers under this Schedule.

MINIMUM BILL

The minimum bill shall be the bill calculated on the Rate above including the Basic Facilities Charge, Demand Charge and Energy Charge, but the bill shall not be less than the amount determined as shown below according to the type of minimum selected by the Company:

Monthly

$1.92 per kW per month of Contract Demand

If the Customer's measured demand exceeds the Contract Demand, the Company may, at any time, establish the minimum based on the maximum integrated demand in the previous 12 months including the month for which the bill is rendered, instead of the Contract Demand.

Annual

$38.54 per kW per year of Contract Demand

The Company may choose this option when the Customer's service is seasonal or erratic, or it may offer the Customer a monthly minimum option.

Unless otherwise specified in the contract, the billing procedure for annual minimums will be as follows:

For each month of the contract year when energy is used, a monthly bill will be calculated on the Rate Above. For each month of the contract year when no energy is used, no monthly amount will be billed. The bill for the last month of the contract year will be determined as follows:

-- If the total of the charges for 12 months exceeds the annual minimum, the last bill of the contract year will include only the charges for that month.
-- If the total of the charges for 12 months is less than the annual minimum, the last bill of the contract year will include an amount necessary to satisfy the annual minimum.

SCHEDULE LGS (NC)
LARGE GENERAL SERVICE

POWER FACTOR CORRECTION

When the average monthly power factor of the Customer's power requirements is less than 85 percent, the Company may correct the integrated demand in kilowatts for that month by multiplying by 85 percent and dividing by the average power factor in percent for that month.

PAYMENT

Bills under the Schedule are due and payable on the date of the bill at the office of the Company. Bills are past due and delinquent on the fifteenth day after the date of the bill. If any bill is not so paid, the Company has the right to suspend service. In addition, all bills not paid by the twenty-fifth day after the date of the bill shall be subject to a one percent (1%) late payment charge on the unpaid amount. This late payment charge shall be rendered on the following month's bill and it shall become part of and be due and payable with the bill on which it is rendered.

CONTRACT PERIOD

Each customer shall enter into a contract to purchase electricity from the Company for a minimum original term of one (1) year, and thereafter from year to year upon the condition that either party can terminate the contract at the end of the original term, or at any time thereafter by giving at least sixty (60) days' previous notice of such termination in writing; but the Company may require a contract for a longer original term of years where the requirement is justified by the circumstances. If the Customer requests an amendment to or termination of the service agreement before the expiration of the initial term of the agreement, the Customer shall pay to the Company an early termination charge as set forth in the Company's Service Regulations.

APPENDIX B:
Curtailable Electrical Utility Contract

Progress Energy

SECTION NO. VI
TWENTY-SEVENTH REVISED SHEET NO. 6.230
CANCELS TWENTY-SIXTH REVISED SHEET NO. 6.230

RATE SCHEDULE CS-1
CURTAILABLE GENERAL SERVICE
(Closed to New Customers as of 04/16/96)

Availability:

Available throughout the entire territory served by the Company.

Applicable:

To any customer, other than residential, for light and power purposes where the customer agrees during a period of requested curtailment to curtail as a minimum the greater of: (a) 25 kW or (b) 25% of their average monthly billing demand (based on the most recent twelve (12) months or, where not available, a projection for twelve (12) months).

Character of Service:

Alternating current, 60 cycle, single-phase or three-phase, at the Company's standard voltage available.

Limitation of Service:

Standby or resale service not permitted hereunder. Curtailable service under this rate schedule is not subject to curtailment during any time period for economic reasons. Curtailable service under this rate schedule is subject to curtailment during any time period that electric power and energy delivered hereunder from the Company's available generating resources is required to a) maintain service to the Company's firm power customers and firm power sales commitments or b) supply emergency interchange service to another utility for its firm load obligations only. The Company will not make off-system purchases during such periods to maintain service to curtailable loads except under the conditions set forth in Special Provision No. 6 of this rate schedule.

Service under this rate is subject to the Company's currently effective and filed "General Rules and Regulations for Electric Service."

Rate Per Month:

Customer Charge:

Secondary Metering Voltage:	$ 75.96
Primary Metering Voltage:	$ 210.93
Transmission Metering Voltage:	$ 787.26
Demand Charge:	$ 7.37 per kW of Billing Demand
Plus the Cost Recovery Factors on a $/ kW basis in Rate Schedule BA-1, *Billing Adjustments*:	See Sheet No. 6.105 and 6.106
Curtailable Demand Credit:	$ 3.74 per kW of Curtailable Demand
Energy Charge:	
Non-Fuel Energy Charge:	1.346¢ per kWh
Plus the Cost Recovery Factors on a ¢/ kWh basis in Rate Schedule BA-1, *Billing Adjustments*, except for the Fuel Cost Recovery Factor:	See Sheet No. 6.105 and 6.106

Premium Distribution Service Charge:

Where Premium Distribution Service has been established after 12/15/98 in accordance with Subpart 2.05, General Rules and Regulations Governing Electric Service, the customer shall pay a monthly charge determined under Special Provision No. 8 of this rate schedule for the costs of all additional equipment, or the customer's allocated share thereof, installed to accomplish automatic delivery transfer including all line costs necessary to connect to an alternate distribution circuit.

In addition, the Demand Charge included in the Rate per Month section of this rate schedule shall be increased by $0.99 per kW for the cost of reserving capacity in the alternate distribution circuit.

(Continued on Page No. 2)

ISSUED BY: Lori J. Cross, Manager, Utility Regulatory Planning - Florida

EFFECTIVE: January 1, 2013

RATE SCHEDULE CS-1
CURTAILABLE GENERAL SERVICE
(Closed to New Customers as of 04/16/96)
(Continued from Page No. 1)

Determination of Billing Demand:

The billing demand shall be the maximum 30-minute kW demand established during the current billing period.

Determination of Curtailable Demand:

The Curtailable Demand shall be the difference, if any, between the current Billing Demand and the contract Non-Curtailable Demand determined in accordance with Special Provision No. 2 of this rate. In no event shall the Curtailable Demand be less than zero.

Delivery Voltage Credit:

When a customer takes service under this rate at a delivery voltage above standard distribution secondary voltage, the Demand Charge hereunder shall be subject to the following credit:

For Distribution Primary Delivery Voltage:	$0.36 per kW of Billing Demand
For Transmission Delivery Voltage:	$1.35 per kW of Billing Demand

Metering Voltage Adjustment:

Metering voltage will be at the option of the Company. When the Company meters at a voltage above distribution secondary, the appropriate following reduction factor shall apply to the Non-Fuel Energy Charge, Demand Charge, Curtailable Demand Credit and Delivery Voltage Credit hereunder:

Metering Voltage	Reduction Factor
Distribution Primary	1.0%
Transmission	2.0%

Power Factor:

For customers with measured demands of 1,000 kW or more for three (3) or more months out of the twelve (12) consecutive months ending with the current billing period, bills computed under the above rate per month charges will be increased 26¢ for each KVAR by which the reactive demand exceeds, numerically, .62 times the measured demand, and will be decreased 26¢ for each KVAR by which the reactive demand is less than, numerically, .62 times the measured kW demand.

Additional Charges:

Fuel Cost Recovery Factor:	See Sheet No. 6.105
Gross Receipts Tax Factor:	See Sheet No. 6.106
Right-of-Way Utilization:	See Sheet No. 6.106
Municipal Tax:	See Sheet No. 6.106
Sales Tax:	See Sheet No. 6.106

Minimum Monthly Bill:

The minimum monthly bill shall be the Customer Charge. Where special equipment to serve the customer is required, the Company may require a specified minimum charge.

Terms of Payment:

Bills rendered hereunder are payable within the time limit specified on bill at Company-designated locations.

Term of Service:

Service under this rate schedule shall be for a minimum initial term of two (2) years from the commencement of service and shall continue thereafter until terminated by either party by written notice sixty (60) days prior to termination.

(Continued on Page No. 3)

RATE SCHEDULE CS-1
CURTAILABLE GENERAL SERVICE
(Closed to New Customers as of 04/16/96)
(Continued from Page No. 2)

Special Provisions:

1. As used in this rate schedule, the term "period of requested curtailment" shall mean a period for which the Company has requested curtailment and for which energy purchased from sources outside the Company's system, pursuant to Special Provision No. 6, is not available. If such energy can be purchased, the terms of Special Provision No. 6 will apply and a period of requested curtailment would not be deemed to exist while such energy remains available.

2. Under the provisions of this rate, the Company will require a contract with the customer upon the Company's filed standard contract Form No. 2. An initial Non-Curtailable Demand shall be specified in the contract and shall be based on specifications for power requirements supplied to the Company. (Note: the initial contract Non-Curtailable Demand cannot be set any greater than 75% of the customer's average monthly billing demand in accordance with the Applicable Clause of this rate schedule). The contract Non-Curtailable Demand shall be reestablished under the following conditions:

   (a) If a change in the customer's power requirements occurs, the Company and the customer shall establish a new contract Non-Curtailable Demand.

   (b) If the customer establishes a demand higher than the contract Non-Curtailable demand during any period of requested curtailment in the billing period, such higher demand shall become the contract Non-Curtailable Demand effective with the next billing period. In addition. Special Provision No. 5 is applicable.

   (c) If the customer establishes a demand lower than the contract Non-Curtailable demand during all periods of requested curtailment in the billing period, such lower demand upon request by the customer shall become the contract Non-Curtailable Demand effective with the next billing period.

   (d) If the customer's contract Non-Curtailable Demand exceeds 75% of the customer's average monthly billing demand (based on the most recent twelve (12) months or, where not available, a projection of twelve (12) months), the contract Non-Curtailable Demand shall be set equal to 75% of the customer's average monthly billing demand effective with the current billing period. A re-establishment of the customer's contract Non-Curtailable Demand under this condition shall supersede any other establishment.

3. As an essential requirement for receiving the Curtailable Demand Credit provided under this rate schedule, a customer shall be strictly responsible for the curtailment of his power requirements to no more than his contract Non-Curtailable Demand upon each request of the Company. Such requests will normally be made during periods of capacity shortages on the Company's system; however, other operating contingencies may result in such requests at other times. The Company shall also have the right to request one additional curtailment each calendar year irrespective of capacity availability or operating conditions.

4. A customer will be deemed to have complied with their curtailment responsibility if the maximum 30-minute kW demand established during each period of requested curtailment does not exceed his contract Non-Curtailable Demand.

5. If the maximum 30-minute kW demand established during a requested curtailment in the billing period exceeds the customer's contract Non-Curtailable Demand, the customer will be billed the following additional charge for all billing periods from the most recent prior billing period of requested curtailment through the current billing period, not to exceed a total of twelve (12) billing periods:

   1.25 times the difference in Demand and Energy Charges which would result under Rate Schedule GSD-1 and those Demand and Energy Charges calculated under this rate schedule. This calculation shall be exclusive of any additional charges rendered under Special Provision No. 6 of this rate schedule.

Continued on Page 4

RATE SCHEDULE CS-1
CURTAILABLE GENERAL SERVICE
(Closed to New Customers as of 04/16/96)
(Continued from Page No. 3)

Special Provisions: (Continued)

6. To minimize the frequency and duration of curtailments requested under this rate schedule, the Company will attempt to purchase additional energy, if available, from sources outside the Company's system during periods for which curtailment would otherwise be requested. The Company will also attempt to notify any customer, desirous of such notice, in advance when such purchases are imminent or as soon as practical thereafter where advance notice is not feasible. Similar notification will be provided upon termination of such purchases. Any energy associated with curtailable loads used during these periods will be subject to the additional charges set forth in the second paragraph of this provision. Customers may avoid these higher charges by curtailing their usage during such periods to no more than their established Non-Curtailable Demand pursuant to the third paragraph of these provisions.

   In the event a customer elects not to curtail, the customer will be required to pay an additional charge, in lieu of the otherwise applicable energy charges (Non-Fuel Energy Charge, Capacity Cost Recovery Factor and Fuel Cost Recovery Factor), provided hereunder, based on the customer's proportionate share of the higher cost of such purchased energy, plus 3.0 mills per kWh, for all consumption above the customer's Non-Curtailable Demand during the period for which curtailment would have otherwise been requested. The cost of such purchased energy shall be based on the average cost of all purchased power and energy provided under this rate schedule and under similar provisions in Rate Schedules IS-1, IST-1, CST-1, IS-2, IST-2, CS-2, CST-2, CS-3, CST-3, SS-2 and SS-3 during the corresponding calendar month. If, for any reason during such period, the customer is notified that the energy purchased from outside sources is no longer available, the terms of this Special Provision will cease to apply and curtailments to no more than the customer's Non-Curtailable Demand will be required for the remainder of such period.

   In the event a customer elects to curtail irrespective of the availability of additional energy purchased by the Company and does not exceed his Non-Curtailable Demand during the period for which curtailment would have otherwise been requested, the customer will incur no responsibility for the payment of any additional cost of such energy.

7. If the customer increases his power requirements in any manner which requires the Company to install additional facilities for the specific use of the customer, a new Term of Service may be required at the Company's option.

8. The Company will furnish service under this rate at a single voltage. Any equipment to supply additional voltages or any additional facilities for the use of the customer shall be furnished and maintained by the customer. At its option, the Company may furnish, install and maintain such additional equipment upon request of the customer, in which event an additional monthly charge will be made at the rate of 1.67% times the installed cost of such additional equipment.

9. Customers taking service under this curtailable rate schedule who desire to transfer to a firm rate schedule will be required to give the Company written notice at least sixty (60) months prior to such transfer. Such notice shall be irrevocable unless the Company or the customer receives waiver of this Special Provision No. 9 from the Florida Public Service Commission.

10. Where all or a part of the facilities of a customer receiving service under this rate schedule are designated by the appropriate governmental agency for use as a public shelter during periods of emergency or natural disaster, the Company shall not curtail service to the customer during such periods; provided however, that the Company receives notice of the facilities' use as a public shelter sufficiently in advance to permit the deactivation of automatic devices.

APPENDIX C:
Real Time Pricing Utility Contract

Duke Energy Ohio
139 East Fourth Street
Cincinnati, Ohio 45202

RATE RTP

REAL TIME PRICING PROGRAM

APPLICABILITY

Applicable to Customers served under the Standard Offer Rate DS, Rate DP, or Rate TS. Service under the RTP Program will be offered through the Market Development Period starting on January 1, 2001. The incremental cost of any special metering required for service under this Program beyond that normally provided under the applicable Standard Tariff shall be borne by the Customer. Customers must enter into a service agreement with a minimum term of one year. Customers electing a Certified Supplier will not be eligible to participate in the Program.

For customers taking service under any or all of the provisions of this tariff schedule, this same schedule shall constitute the Company's Standard Service Offer.

PROGRAM DESCRIPTION

The RTP Program is voluntary and offers Customers the opportunity to manage their electric costs by either shifting load from higher cost to lower cost pricing periods and adding new load during lower cost pricing periods or to learn about market pricing. Binding Price Quotes will be sent to each Customer on a day-ahead basis. The program is intended to be bill neutral to each Customer with respect to their historical usage through the use of a Customer Baseline Load (CBL) and the Company's Standard Offer Rates.

CUSTOMER BASELINE LOAD

The CBL is one complete year of Customer hourly load data that represents the electricity consumption pattern and level of the Customer's operation under the Standard Rate Schedule. The CBL is the basis for achieving bill neutrality for Customers billed under this Rate RTP, and must be mutually agreeable to by both the Customer and the Company as representing the Customer's usage pattern under the Standard Rate Schedule (non-RTP). Agreement on the CBL is a requirement for participation in the RTP Program.

RTP BILLING

Customers participating in the RTP Program will be billed monthly based on the following calculation:

$$\text{RTP Bill} = BC + PC + \sum_{t=1}^{n} \{ (CC_t + ED_t) \times (AL_t - CBL_t) \}$$

Where:

BC	= Baseline Charge
PC	= Program Charge
CC_t	= Commodity Charge for hour t
ED_t	= Energy Delivery Charge for hour t
AL_t	= Customer Actual Load for hour t
CBL_t	= Customer Baseline Load in hour t
n	= total number of hours in the billing period
t	= an hour in the billing period

Issued pursuant to an Order dated March 29, 2006 in Case No. 06-407-GE-ATA before the Public Utilities Commission of Ohio.

Issued: March 31, 2006 Effective: April 3, 2006

Issued by Sandra P. Meyer, President

BASELINE CHARGE

The Baseline Charge is independent of Customer's current monthly usage, and is designed to achieve bill neutrality with the Customer's standard offer tariff if no change in electricity usage pattern occurs (less applicable program charges). The Baseline Charge is calculated at the end of the billing period and changes each billing period to maintain bill neutrality for a Customer's CBL.

The Baseline Charge will be calculated as follows:

BC = (Standard Bill @ CBL)

Where:

BC	=	Baseline Charge
Standard Bill @ CBL	=	Customer's bill for the specific month on the applicable Rate Schedule using the CBL to establish the applicable billing determinants

The CBL shall be adjusted to reflect applicable metering adjustments under the standard Rate Schedule.

PRICE QUOTES

The Company will send to Customer, by 3:00 p.m. each day, Price Quotes to be charged the next day. Such Price Quotes shall include the applicable Commodity Charge, the Energy Delivery Charge, and the Ancillary Services Charge.

The Company may send more than one-day-ahead Price Quotes for weekends and holidays identified in Company's tariffs. The Company may revise these prices by 3:00 p.m. the day before they become effective.

The Company is not responsible for failure of Customer to receive and act upon the Price Quotes. It is Customer's responsibility to inform Company of any failure to receive the Price Quotes by 5:00 p.m. the day before they become effective.

COMMODITY CHARGE

The Commodity Charge is a charge for generation. The applicable hourly Commodity Charge (Credit) shall be applied on an hour by hour basis to Customer's incremental (decremental) usage from the CBL.

Charge (Credit) For Each kW Per Hour From The CBL:

For kWh_t above the CBL_t, $CC_t = MVG_t \times LAF$
For kWh_t below the CBL_t, $CC_t = MVG_t \times 80\% \times LAF$

Where:

LAF	=	loss adjustment factor
	=	1.0530 for Rate TS
	=	1.0800 for Rate DP
	=	1.1100 for Rate DS
MVG_t	=	Market Value Of Generation As Determined By Company for hour t

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Issued: March 31, 2006 Effective: April 3, 2006

Issued by Sandra P. Meyer, President

COMMODITY CHARGE (Contd.)

The MVG_t will be based on the expected market price of capacity and energy for the next day. The expected market price will be based on forecasts of market conditions for the next day using publicly available market indices and/or bona fide third-party price quotes to establish the expected market price.

The kW Per Hour incremental or decremental usage from the CBL shall be adjusted to reflect applicable metering adjustments under the standard Rate Schedule.

ENERGY DELIVERY CHARGE

The hourly Energy Delivery Charge is a charge for using the distribution system to deliver energy to the Customer. The applicable hourly Energy Delivery Charge (Credit) shall be applied on an hour by hour basis to Customer's incremental (decremental) usage from the CBL.

Charge (Credit) For Each kW Per Hour From The CBL:

Rate DS .....$ 0.012088 per kW Per Hour
Rate DP ..... $ 0.006838 per kW Per Hour
Rate TS ..... $ 0.000327 per kW Per Hour

The kW Per Hour incremental or decremental usage from the CBL shall be adjusted to reflect applicable metering adjustments under the standard Rate Schedule.

PROGRAM CHARGE

Company will provide Internet based communication software to be used to provide Customer with the Price Quotes. Customer will be responsible for providing its own Internet access. A charge of $183 per billing period per Customer shall be added to Customer's bill to cover the additional billing, administrative, and cost of communicating the hourly Price Quotes associated with the RTP Program. Customer may purchase from either Company or any other third-party suppliers any other necessary equipment or software packages to facilitate participation in this program. While Customers are encouraged to use such equipment or software packages to maximize benefits under this Program, it is not a requirement for program participation. It is Customer's responsibility to ensure the compatibility of third-party equipment or software packages with any Company owned equipment or software packages.

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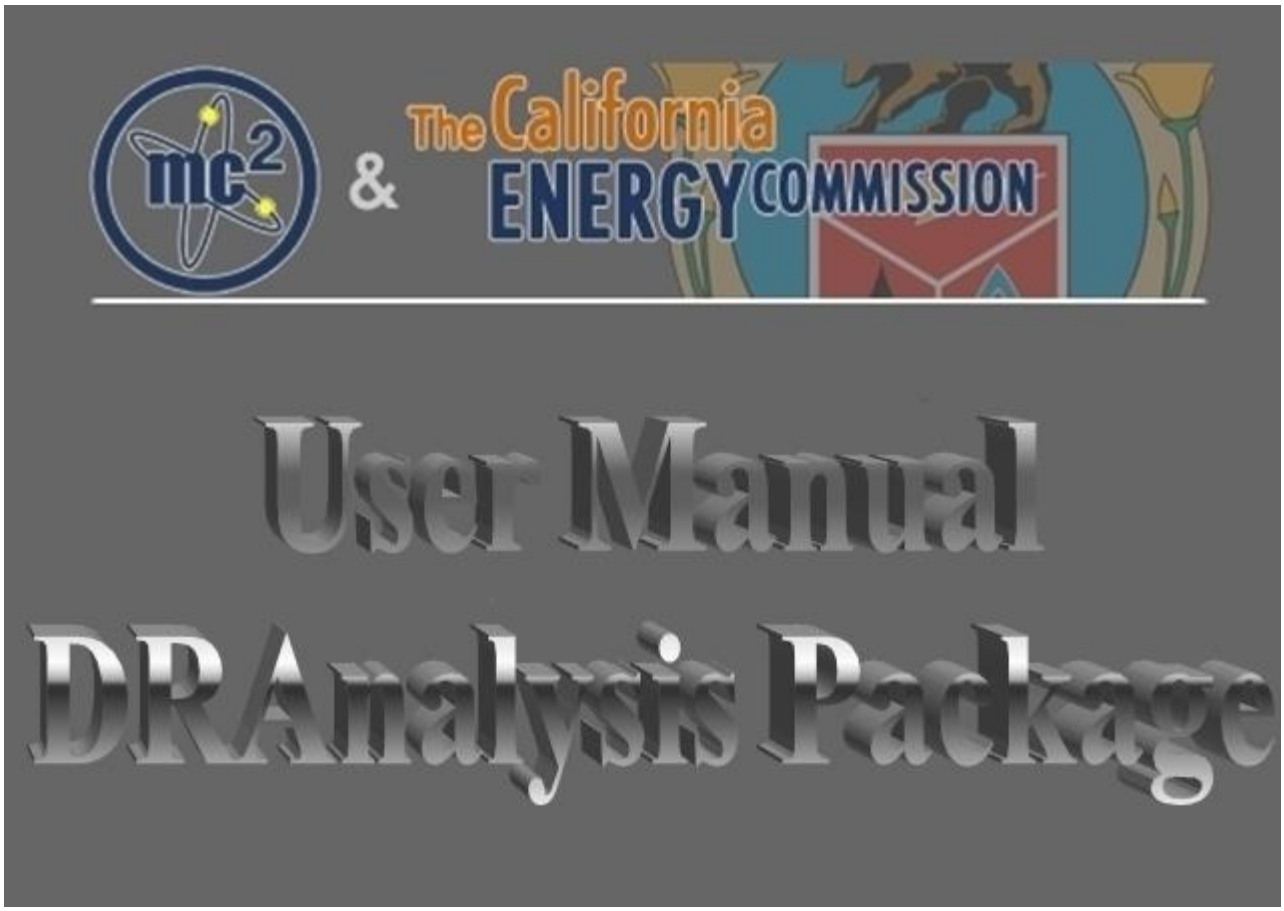
APPENDIX D: DRAnalysis User Manual



mc^2 Consulting, Inc.
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1. Introduction

This manual describes the operation of the Graphical User Interface (GUI) to the mc^2 DRAnalysis Package, which analyzes the cost / performance relationship between Drag Reducing Agent (DRA) use and the power required to operate long-distance hydrocarbon pipelines.

The introduction of small quantities of DRA into fluids being pumped through a pipeline alters large-scale turbulent structure in the fluid flow and can effect dramatic reductions in the viscous friction losses, losses that must otherwise be offset by pipeline pumps.

The interest in this problem comes through two factors. First, the lowering of electrical pump power requirements during periods of high concurrent electrical use reduces the stress on electrical grids and can minimize or eliminate brown-outs or black-outs. Second, when pump motors are diesel or natural gas engines, reduction of power requirements lowers carbon emissions.

In either of these two cases, reduced pump requirements implies reduced pump operating costs. This savings is, of course, cancelled, at least in part, by the cost of the DRA. Proper analysis of this interplay can help utility companies in development of DRA incentivization programs for pipeline companies and can assist pipeline companies in determining where, when, and how much DRA to use to assist in optimal pipeline operations.

The requirement, then, is for a tool that allows a pipeline or power company engineer to set up scenarios that realistically describe the power requirements for pipeline operations as a function of DRA usage and presents each of the cost components for such operations. DRAnalysis is that tool.

The need to provide usable results, while at the same time keeping data entry to a minimum, required an assessment of the trade-offs between the amount of data entered and incremental impacts on the results. For example, the inner surface roughness of a heavy oil pipeline changes with time through wax deposition. Typical maintenance procedures periodically remove this build-up, The DRAnalysis package assumes smooth pipeline, leaving variables such as surface roughness and temperature for more detailed analysis. The data naturally falls into the following groupings:

5. Pipeline geometry
6. Fluid properties
7. Pipeline schedule
8. Pipeline economics

Data from each of these groups is stored in corresponding database tables, populated from separate pages in the user interface. This manual describes the requirements for each of the tables, as well as general functionality of the user interface.

The next section (section 2) covers user registration and login procedures. Section 3 describes the data entry requirements for each of the four groupings listed above. Section 4 explains the data submission procedure, where data is routed to the analysis servers for processing. Also covered is the retrieval of previously submitted data sets.

2. Registration and Login

This section briefly describes the DRAnalysis package user registration procedure.

2.1 Accessing DRAnalysis

Due to the complexities of the algorithms used, the DRAnalysis package resides on mc2 host servers. Users access the package through web browsers, using the following URL:

http://mc2na.com/cec/DRAnalysis.html

The user is presented with the following login page:

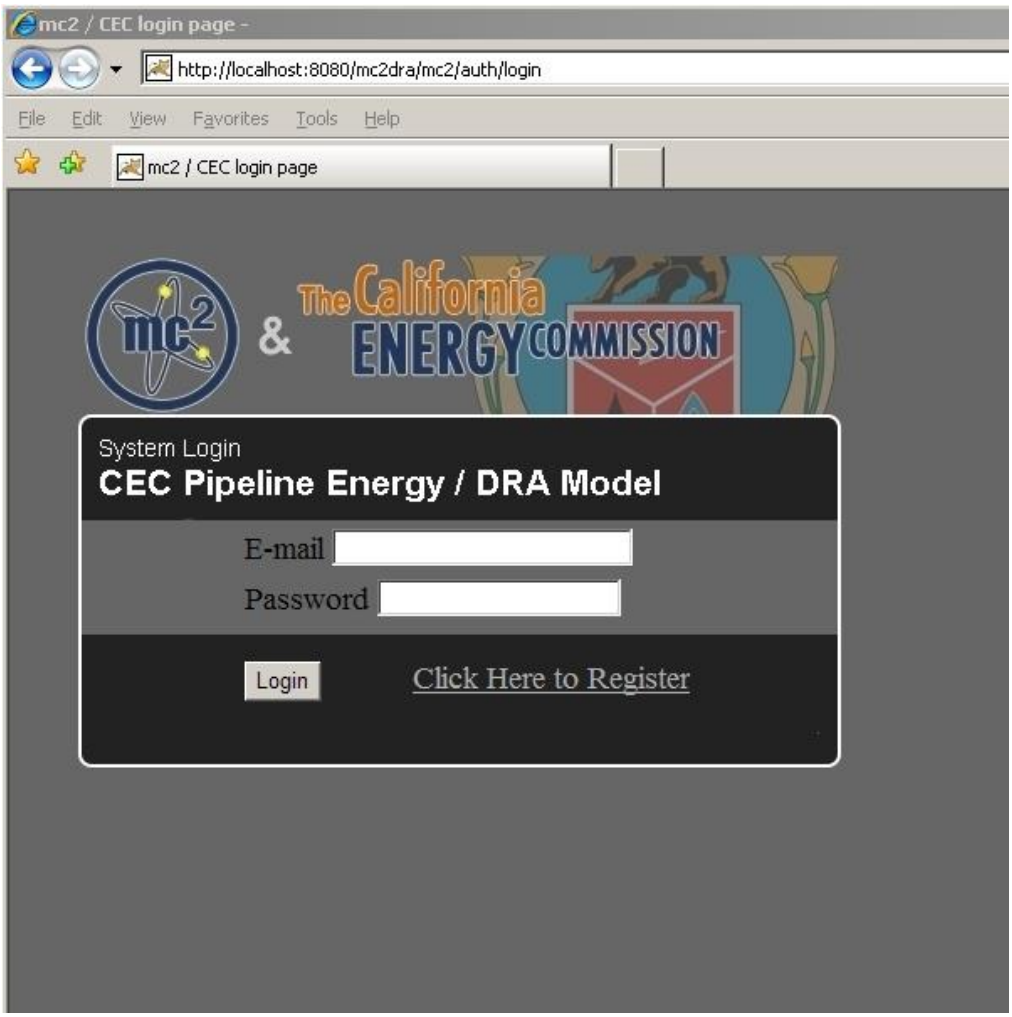

Figure 1.

From this page, the first-time user can register and return users can log into the package.

2.2 Registration

A first-time user must register before using the package. The login information is kept secure and confidential. Once successfully registered, the user is granted full access to all package features.

The required fields are shown below in figure 2.

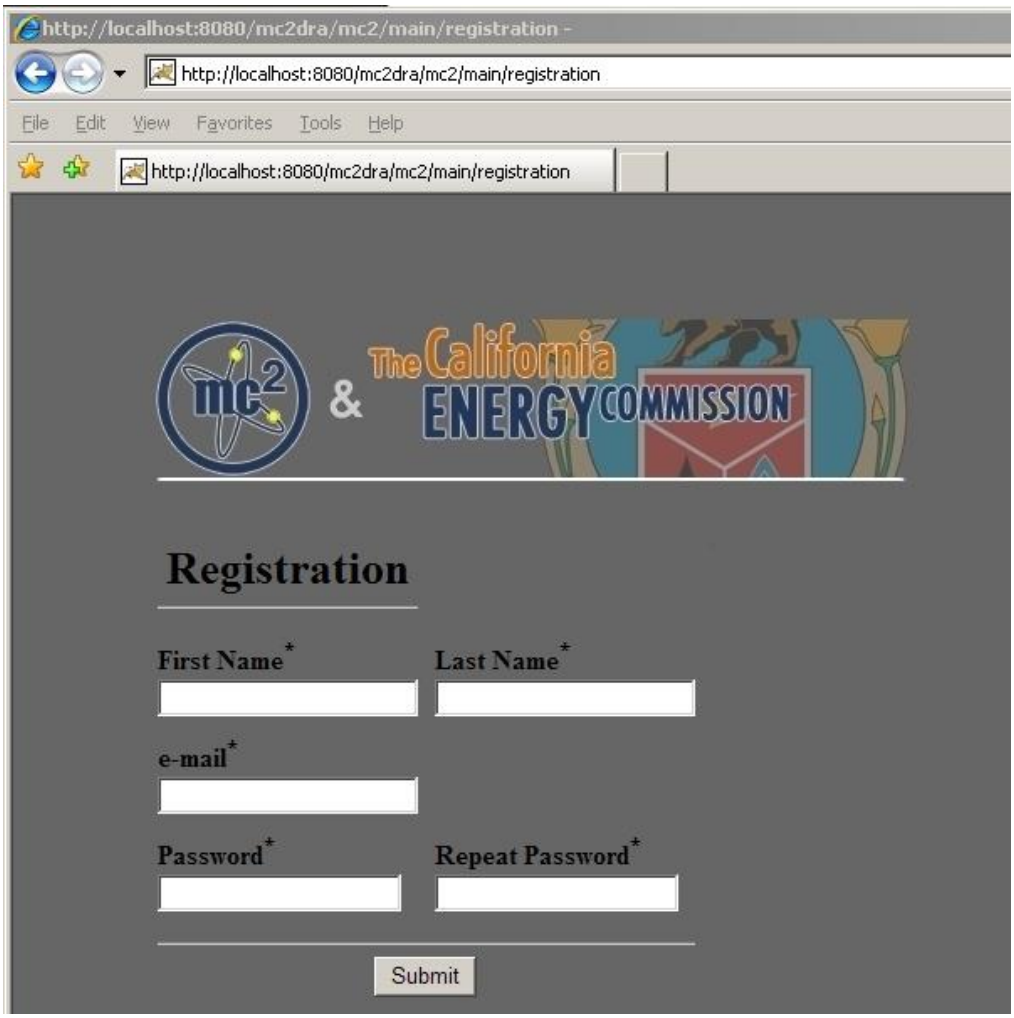

Figure 2.

All fields are required and only passwords greater than three alpha-numeric characters are valid.

Since the duplication of user first and last names is a possibility, the e-mail field is required and used to formulate the database table names for each user.

For instance:

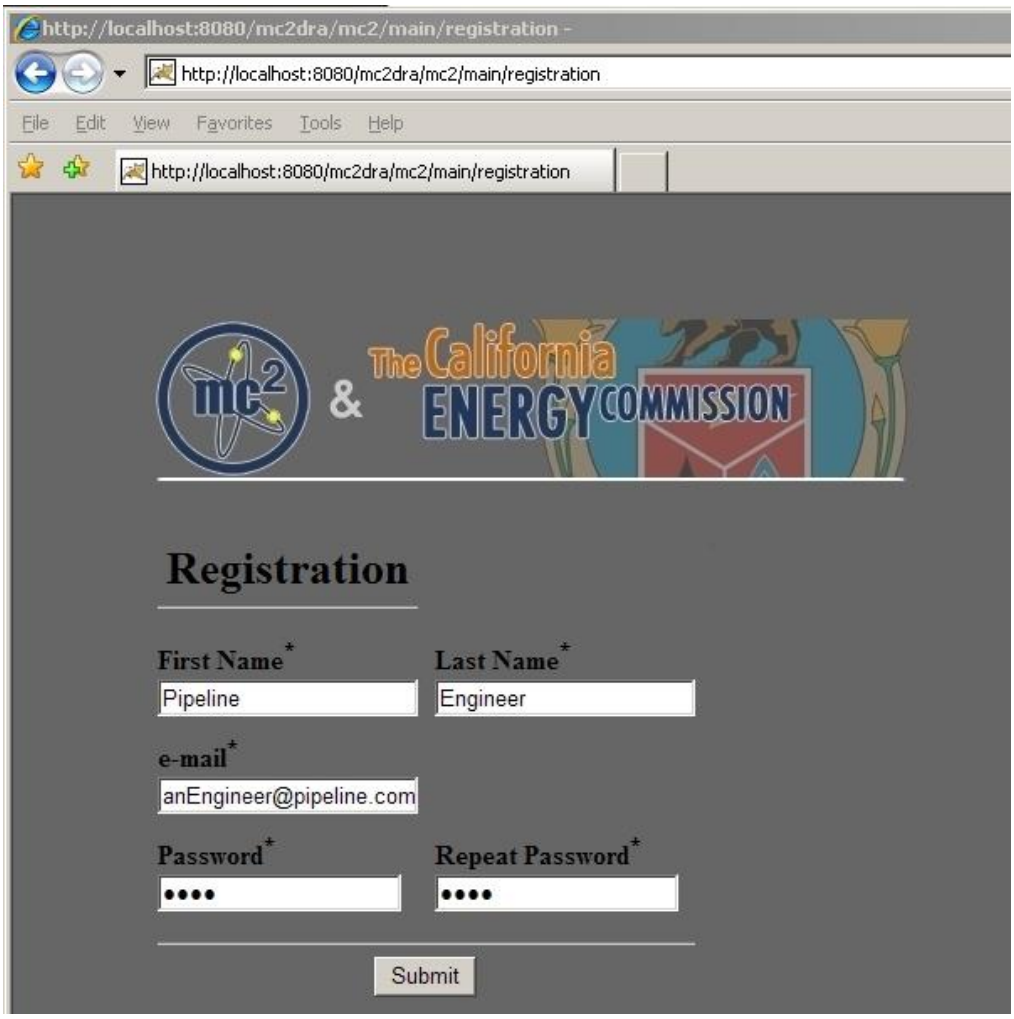

Figure 3.

Upon submission, several checks are performed against the user inputs and, if necessary, warnings issued notifying the user of the source of the error and of the need to correct them before continuing. Upon successful registration, the user's server environment is set up, a confirmation e-mail is sent, and the following page is presented:

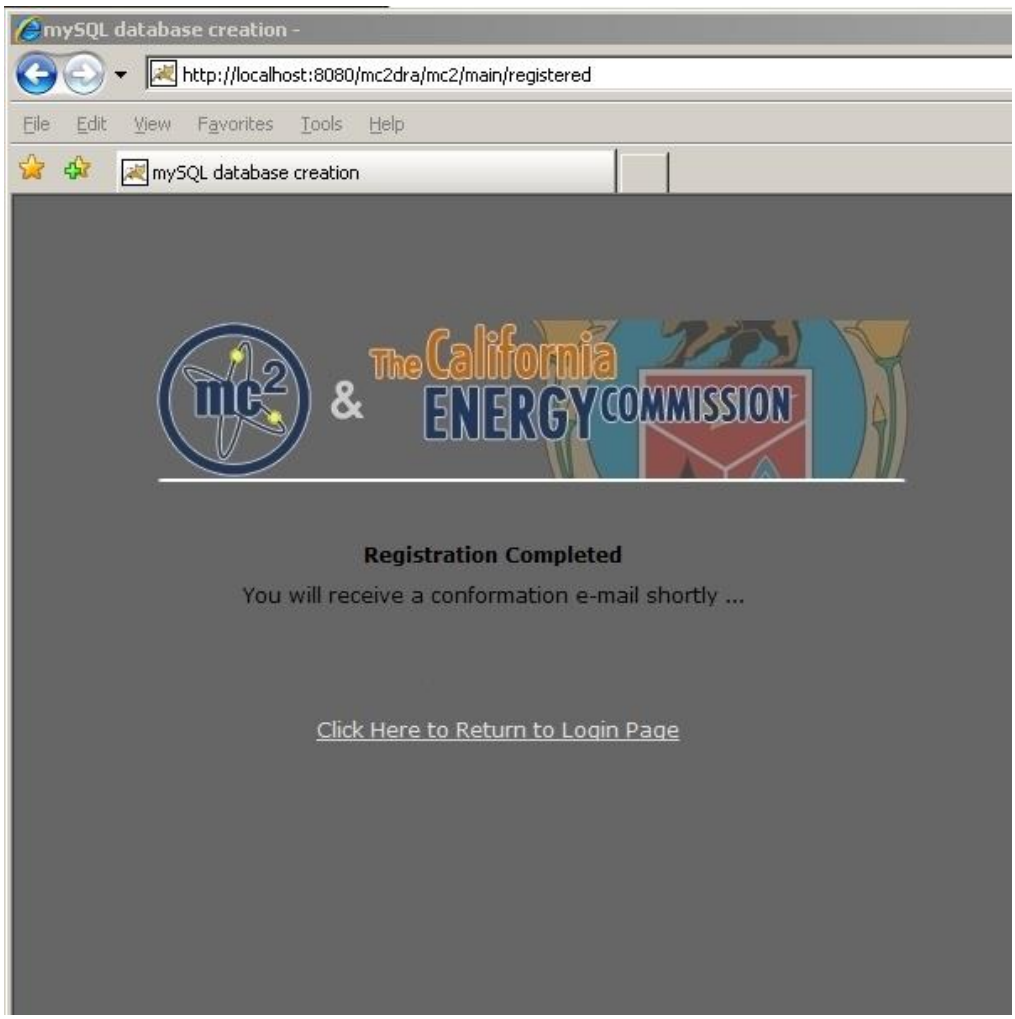

Figure 4.

Clicking on the '...Return to Login ...' link returns the user to the login page, where the e-mail and password used for registration can be used to access the package.

2.3 Summary Page

Using the login information from figure 3, the following page is presented to the user:

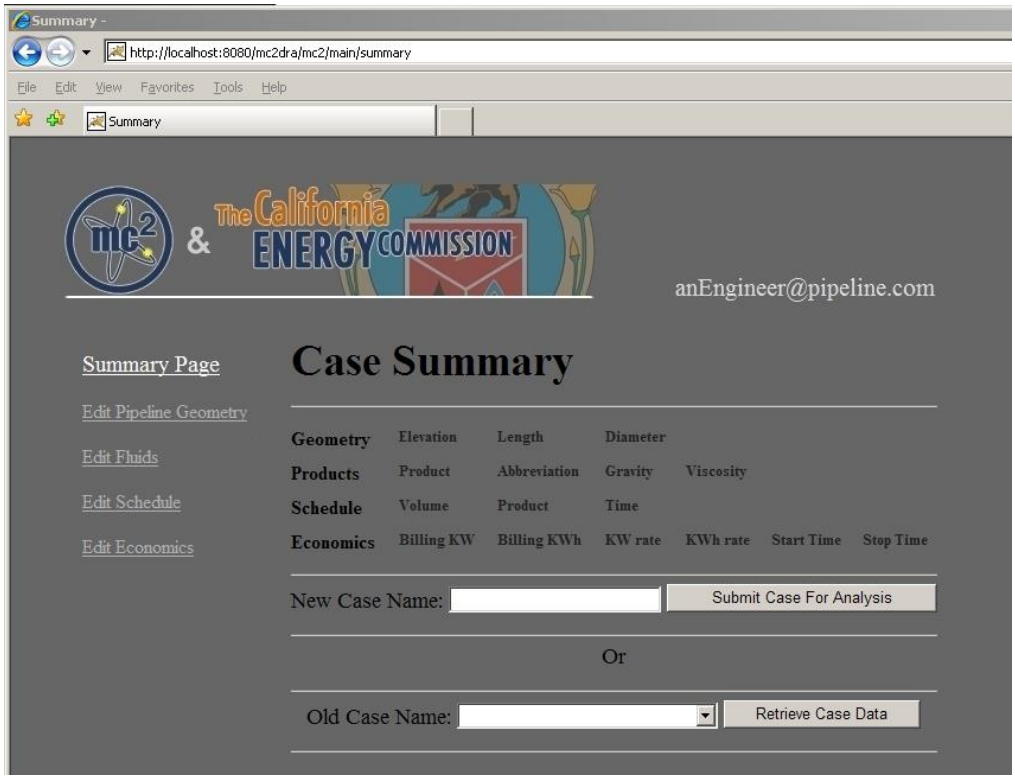

Figure 5.

This overview page gives the current user, whose login e-mail is shown in the upper right of the screen, a summary of all current data from the user's database. This data persists across user sessions. From here, the user may perform the following actions:

1. Edit data, altering the database contents of one or more of the following tables:
    a. Pipeline geometry
    b. Fluid properties
    c. Pipeline schedule
    d. Economics (utility rate structures)
2. Submit the database contents to the DRAnalysis server for evaluation
3. Recall previously submitted cases for data editing and resubmission

Editing data is accomplished by selecting one of the four 'Edit' links on the left of the page. The data entry pages so presented will be discussed in the next section. The current, active case data is shown under the 'Case Summary' heading, sectioned according to the data entry pages. A first-time user will have no data entered, so, as shown, no data appears below the column headings of each of the summary categories. Below the case summary, there are two text field / button pairs that allow the user to either submit the active case for analysis or recall previously submitted data for editing and resubmission. Until submission of an initial case, no histories exist for recall. Previous cases can be selected from a list in the drop-down menu to the right of "Old Case Name:". Guidelines for case names are covered in section 4.

3. Data Entry

Operation of a petroleum pipeline, unless gravity-fed, requires pumps to offset the elevation effects and viscous friction losses and to achieve desired flow rates. Operation of these pumps costs money, as does the introduction of DRA for reduction of pump-related costs. The data entry screens described in this section allow a user to specify scenarios in sufficient detail to estimate the effects of DRA use on operating cost and power requirements. Covered, in turn, are:

a. Pipeline geometry
b. Fluid properties
c. Pipeline schedule
d. Economics (utility rate structures)

3.1 Pipeline Geometry

The necessary geometry data for description of a pipeline segment consists of the following set, taken, at a minimum, at the segment start and end, and including any hydraulically critical points in between:

a. elevation
b. length from longitudinal datum
c. inner diameter

To clarify, only a small number of geometry points will be necessary for proper analysis in the vast majority of cases analyzed. The elevations of the beginning and end of the pipeline segment are obviously needed. The critical points in between consist of points at which flow separation could occur. These points are at elevation maxima and can be determined by either calculation or straightforward visual inspection of an elevation profile.

By selecting the 'Edit Pipeline Geometry' link, shown in figure 5, the following page is presented:

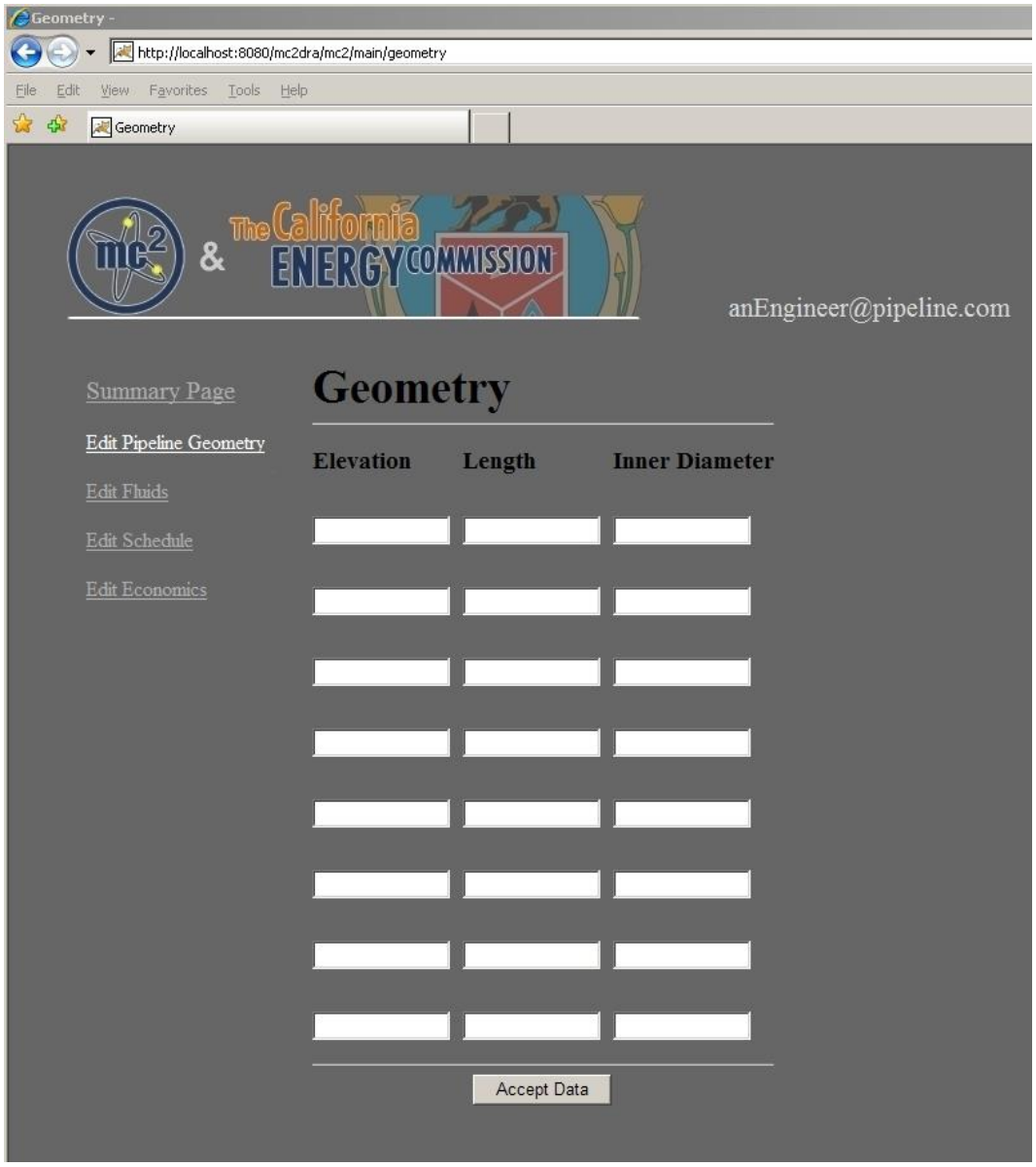

Figure 6.

This array of text boxes can, for example, be filled in as shown below:

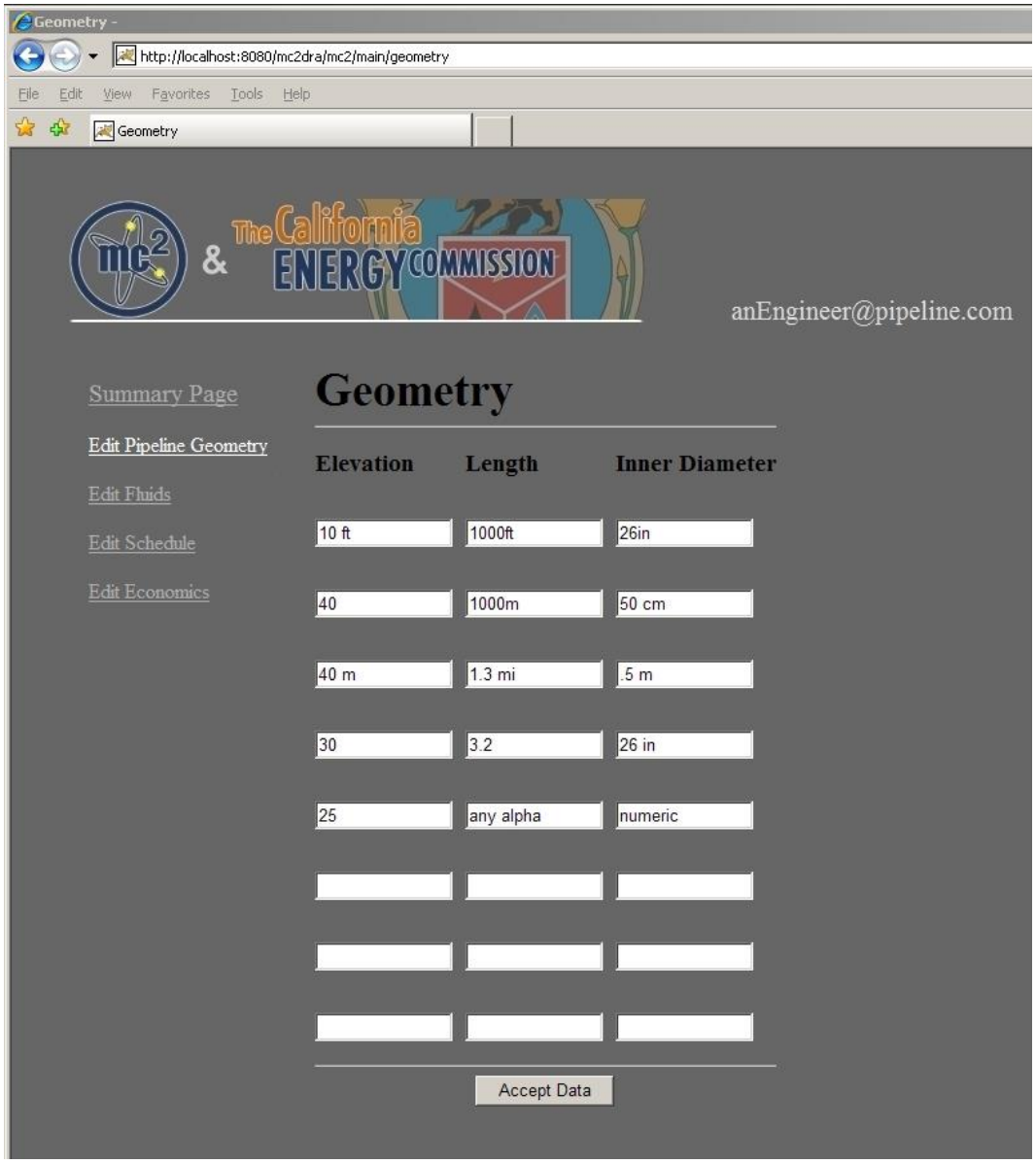

Figure 7.

Clicking on the 'Accept Data' button will return the user to the Case Summary page and this set of entries will result in the following display:

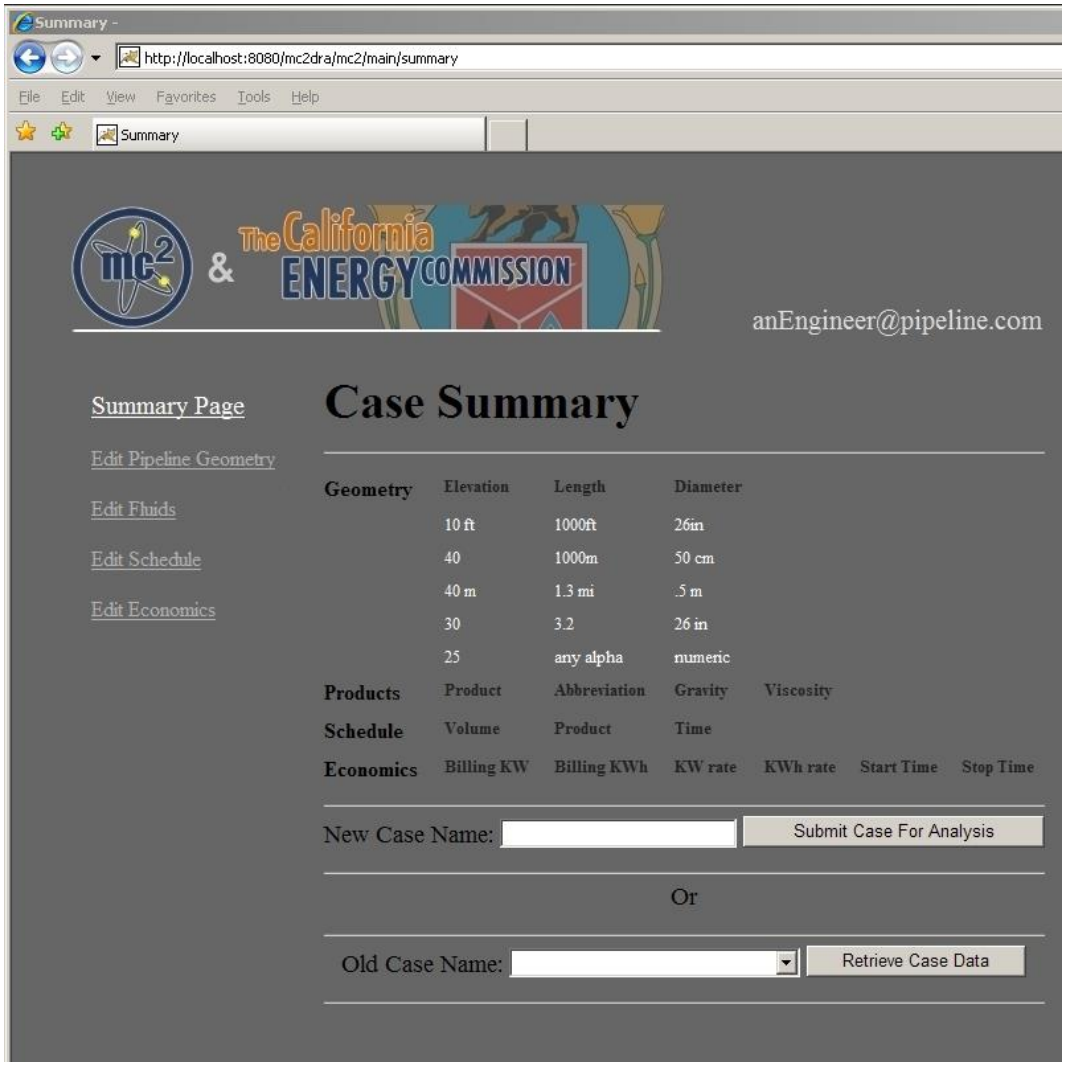

Figure 8.

Comparing figures 7 and 8 reveals the rules for data entry, applicable to this and all other data entry pages, and can be summed up as follows:

a. All columns in any row must contain something in order for that row to be accepted. This can be immediately checked from the Case Summary page, after clicking on the 'Accept Data' buttons. For visibility, '*' is the preferred character, used for either an irrelevant column or any case where a 'ditto' would be used to indicate use of data from the same column of the preceding row. **Single and double quotes, solitary periods, white spaces, or tabs are either not recognized or not encouraged**.

b. No white spaces are permitted when specifying numeric values (e.g. "- 3.5" is invalid and must be entered as "-3.5").
c. For data where units of measure (UOM) are applicable, the UOM must be specified. Columns containing such quantities must contain a UOM in at least the first row. UOM specified in earlier rows of a particular column are either inherited by or overridden in later rows. The overriding UOM is applied to subsequent rows. White spaces are allowed but not required between numeric quantities and the UOM.

All geometry data are linear distance measures, and table 1 shows the recognized UOM designations for any of the Geometry inputs:

Designation	UOM
i[nches]	inches
f[eet]	feet
mi[les]	miles
c[m]	centimeters
c[entimeters]	centimeters
m[eters]	meters
k[m]	kilometers
k[ilometers]	kilometers

Table 1.

Here, and in all following UOM tables, characters enclosed in '[...]' are accepted but not necessary, and there is no differentiation between minuscule and majuscule representation.

After clicking the 'Accept Data' button on any of the entry pages, the user should immediately review the data presented on the Case Summary page for accuracy.

3.2 Fluid Properties

The necessary fluid properties data for accurate calculation of pressure drops and viscous friction losses consists of the following set, to include any fluid present in the case under consideration:

a. product name (type)
b. product batchcode or abbreviation
c. product gravity
d. product viscosity

By selecting the 'Edit Fluids' link, shown in the figures, the following page is presented, shown here after sample data entry:

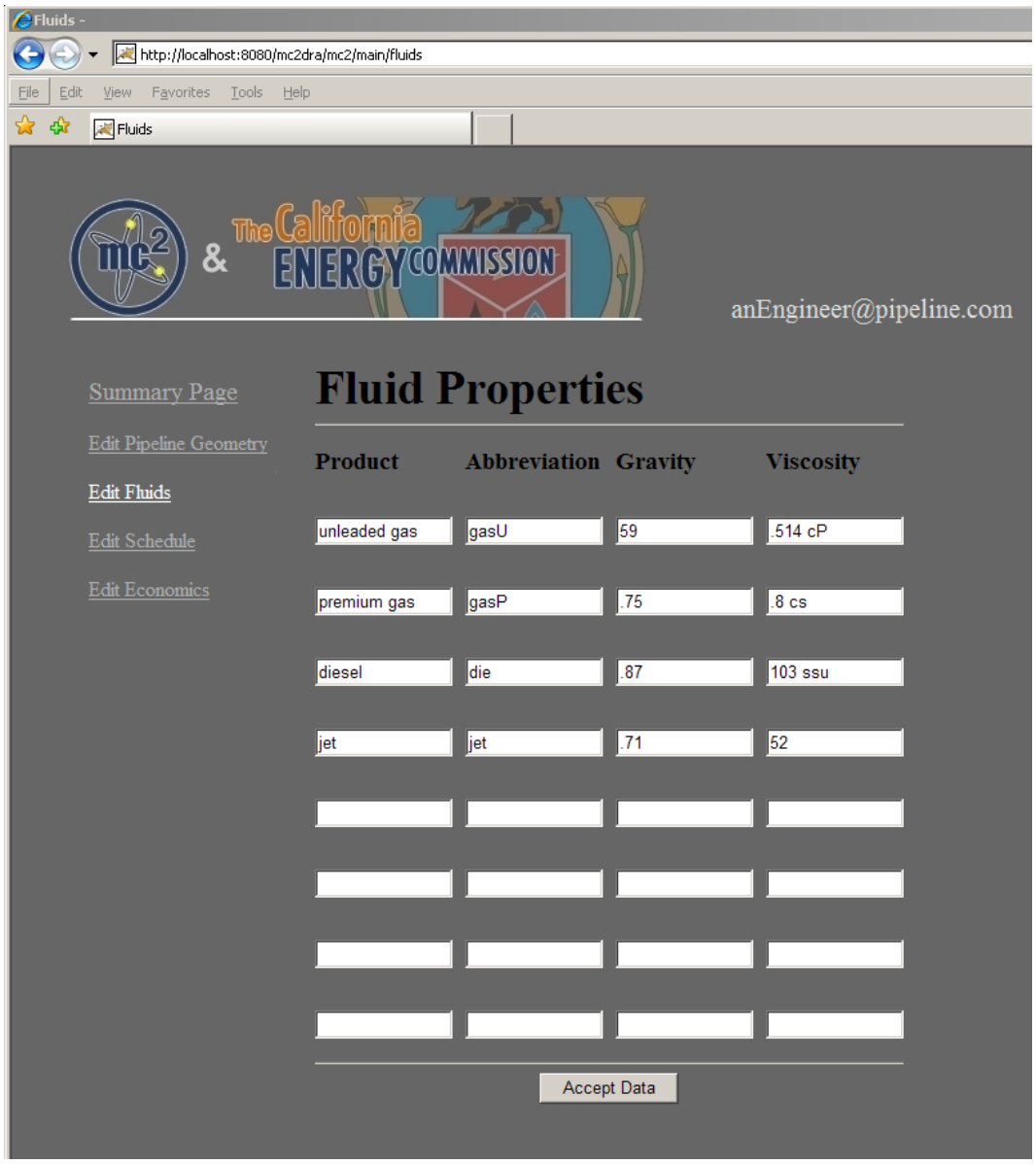

Figure 9.

Clicking on the 'Accept Data' button will return the user to the Case Summary page and the above set of entries will result in the following display:

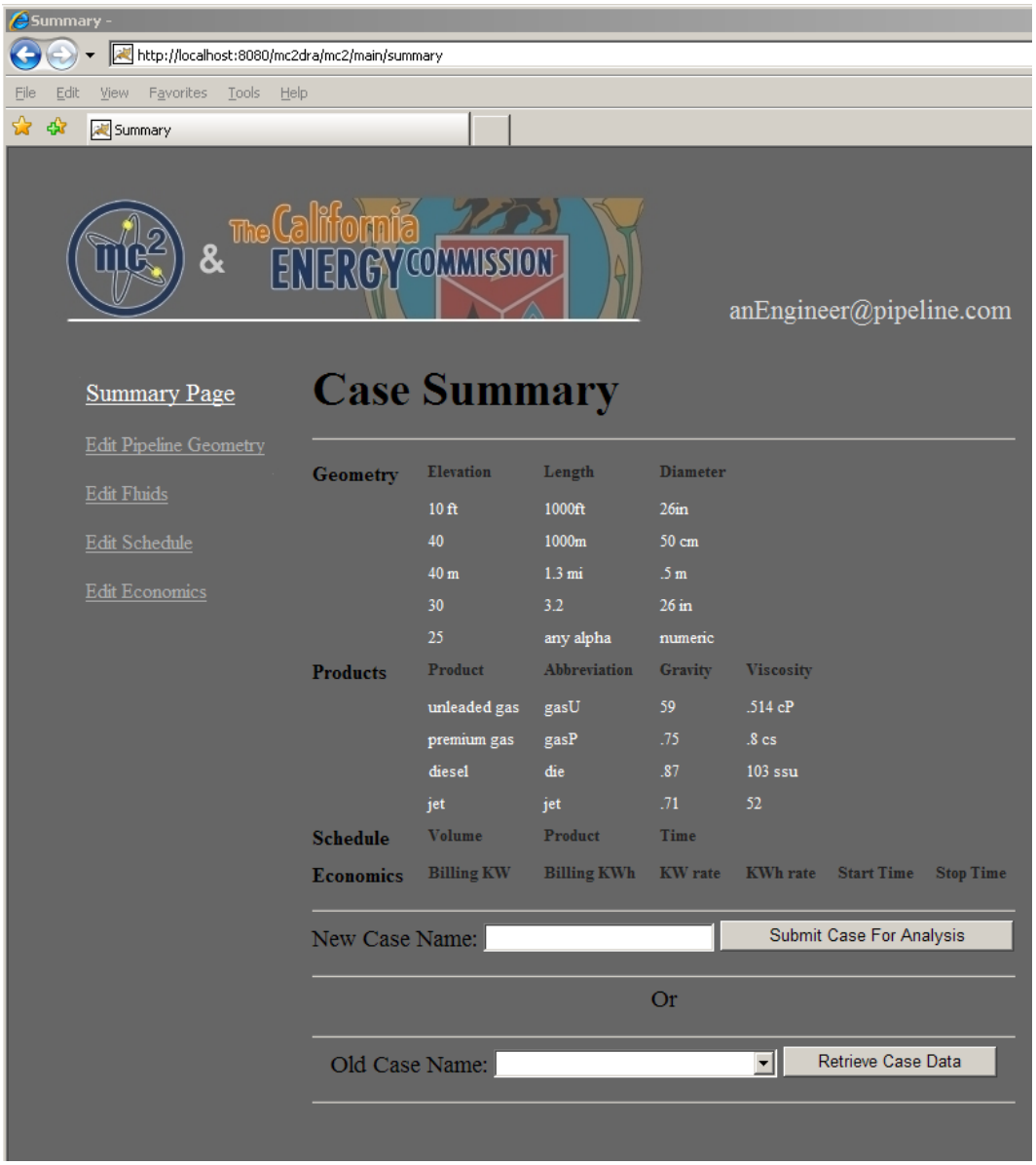

Figure 10.

The product types are used during schedule specification and must satisfy only the criterion that the schedule uniquely references a single fluid from the fluids table. White spaces are allowed in both the name and batchcode/abbreviation fields but are discouraged in the batchcode/abbreviation field. The units of measure for the fluid properties (the gravity and viscosity) are shown in table 2:

Designation	**UOM**
*	specific gravity
*	^{o} API gravity
cs[tokes]	centistokes
s[tokes]	stokes
cp[oise]	centipoises
p[oise]	poise
ss[u]	saybolt universal seconds

* Note that water has an API gravity of 10° and that anything less dense has a higher API gravity. Therefore, no confusion results if either of these two designations is used for lighter hydrocarbons.

Table 2.

3.3 Schedule

The necessary data for description of the schedule for a simple pipeline segment consists of the following set:

a. volume
b. product
c. time

By selecting the 'Edit Schedule' link, shown in the above figures, the following page is presented, shown here after sample data entry:

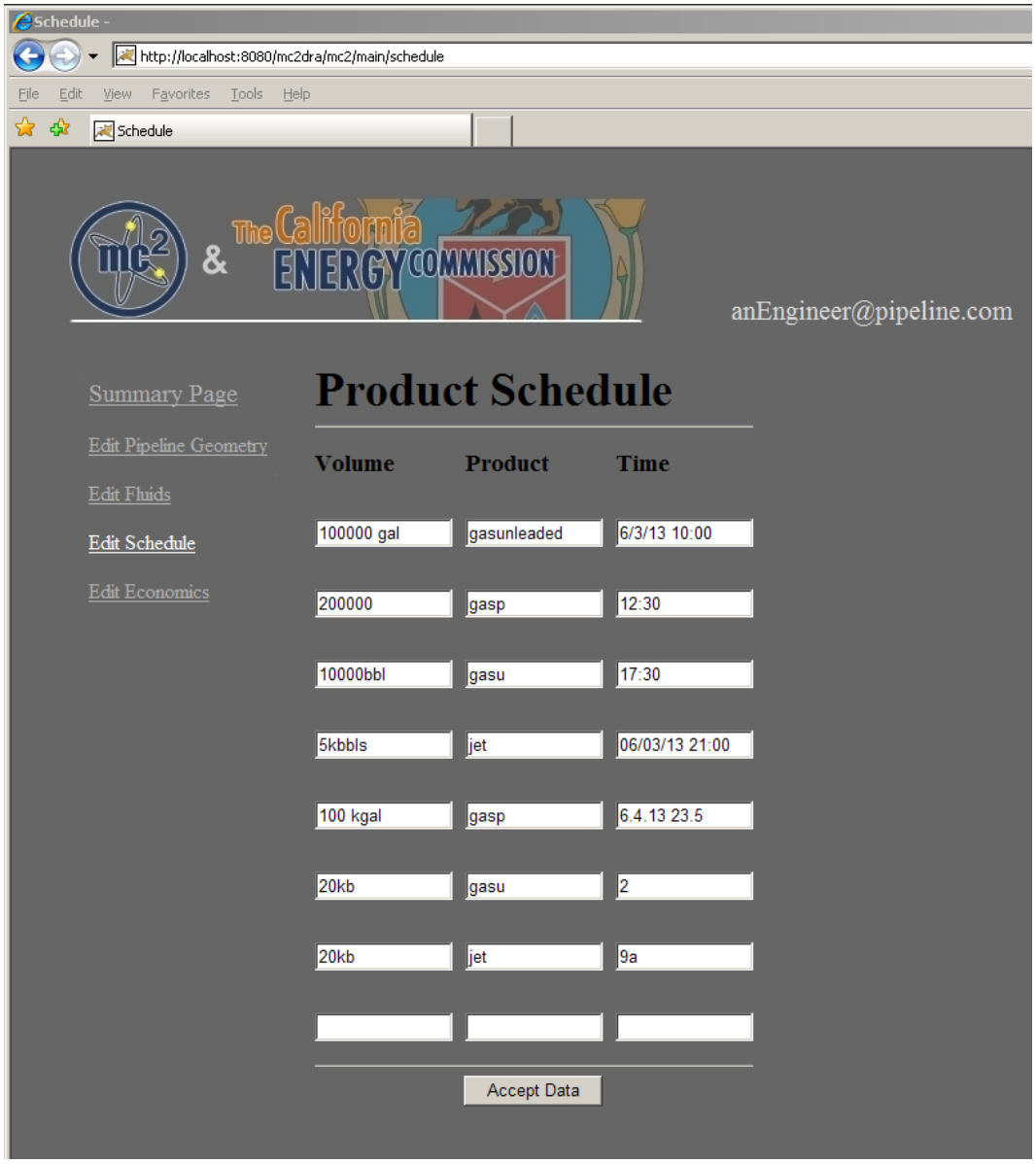

Figure 11.

Clicking on the 'Accept Data' button will return the user to the Case Summary page and the above set of entries will result in the following display:

Figure 12.

The product column can contain any string that uniquely selects one product from among those entered in the property table. Also, DRA concentration and buffering restrictions are specified in this column. For instance, as is typical with jet fuel, DRA is not allowed (0 concentration) and operational rules typically stop DRA injections in neighboring batches such that 0 concentration buffers exist on the both upstream and downstream sides of jet batches. Either time or volume buffers may be specified. Entries in the product column would adhere to syntax described in table 3 below.

Volume data can be entered in either barrels or U.S. gallons, with the single-letter, case-insensitive scientific prefixes k and m accepted for kilo and mega. For consistency, it is suggested that times be entered in a yy/mm/dd hh:mm, 24-hour format, although other formats are available. Table 3 shows the recognized UOM designations for schedule inputs:

Designation	UOM
[k,m]g[allons]	gallons, with optional multiplier
[k,m]b[bls]	barrels, with optional multiplier
[k,m]b[arrels]	barrels, with optional multiplier
[mm/]dd[/yy] hh[:mm]	acceptable date/time format
h[:m] or hh[:mm]	acceptable time format (12/24 hr)
h.m	acceptable time format (decimal minutes)
h[.m]a/p[m]	e.g. 4p, 6am, 3:30a, 10.5p.m., etc
m[onday]	day of week
tu[esday]	day of week
w[ednesday]	day of week
th[ursday]	day of week
f[riday]	day of week
sa[turday]	day of week
su[nday]	day of week
comma separated DOW	multiple days of week (DOW)
two DOW separated by '-'	multiple days of week (DOW)
buffers: productAbb:#UOM	e.g. jet:500b or jet:1h[our] or jet:30m[in]

Table 3.

DRAnalysis analyzes the user's inputs in one of two modes. In survey mode, estimates of consumption and costs are calculated as a function of flow rate and DRA concentration. In simulation mode, a realistic schedule can be entered. Batch start times determine flow rates. Simulation mode calculations must also account for the pipeline contents, or linefill, at the start of the schedule. Without this information, hydraulic power requirements cannot be calculated. DRAnalysis handles this requirement in one of two ways. First, as shown in figures 11 and 12, the initially empty pipeline segment can be filled from the list of products and times shown. Calculations begin when the segment is filled. Alternately, a schedule beginning with a list of volumes and products, with a '*' in the time column, is interpreted as designating the segment contents at the time given by the first schedule entry with a time. Exact volumes need not be given; ratios are taken of the volumes specified and the entire volume expanded or contracted to exactly fill the calculated segment volume. Figure 13 shows an example where a huge volume of unleaded gas is given in the first row, which is interpreted as simply completely filling the pipeline segment, with all excess volume ignored. A value of 1, as opposed to 1 mg, would have resulted in the same initial line fill.

When the economics, discussed in 3.4, depend on days of the week, the first schedule time entered must uniquely specify a day and time in order to correctly identify the economics periods throughout the analysis. This may be accomplished by entering first a date, followed by a time, or by entering a day of the week, again followed by a time. Days or dates and the time field must be separated by a white space character. The month, date, and year must each be separated by a '/'. If just a month and date are entered, the current year is assumed. If both hours and minutes are given, they must be separated by either a ':' or, if using decimal hours, a '.'. Inheritance is used for subsequent dates and times.

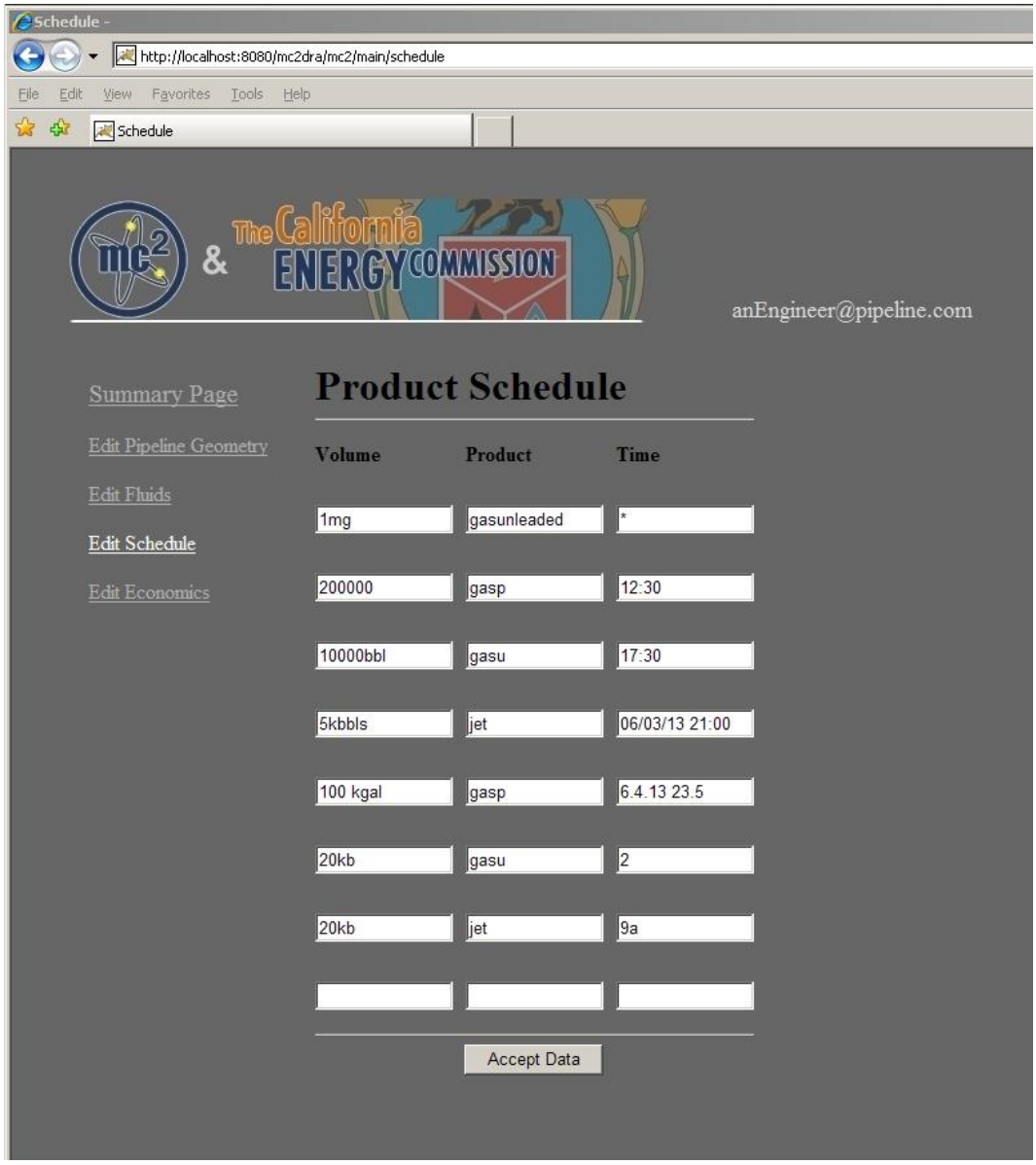

Figure 13.

3.4 Economics

The necessary economic data for cost analysis must permit accurate calculation of marginal utility costs. Time-of-day variations of this cost must be allowed. The data set used to describe the electrical / fuel costs are:

a. Billing KW
b. Billing KWh
c. KW rate
d. KWh rate
e. Start Time
f. Stop Time

By selecting the 'Edit Economics' link, shown in the figures, the following page is presented, shown here after sample data entry:

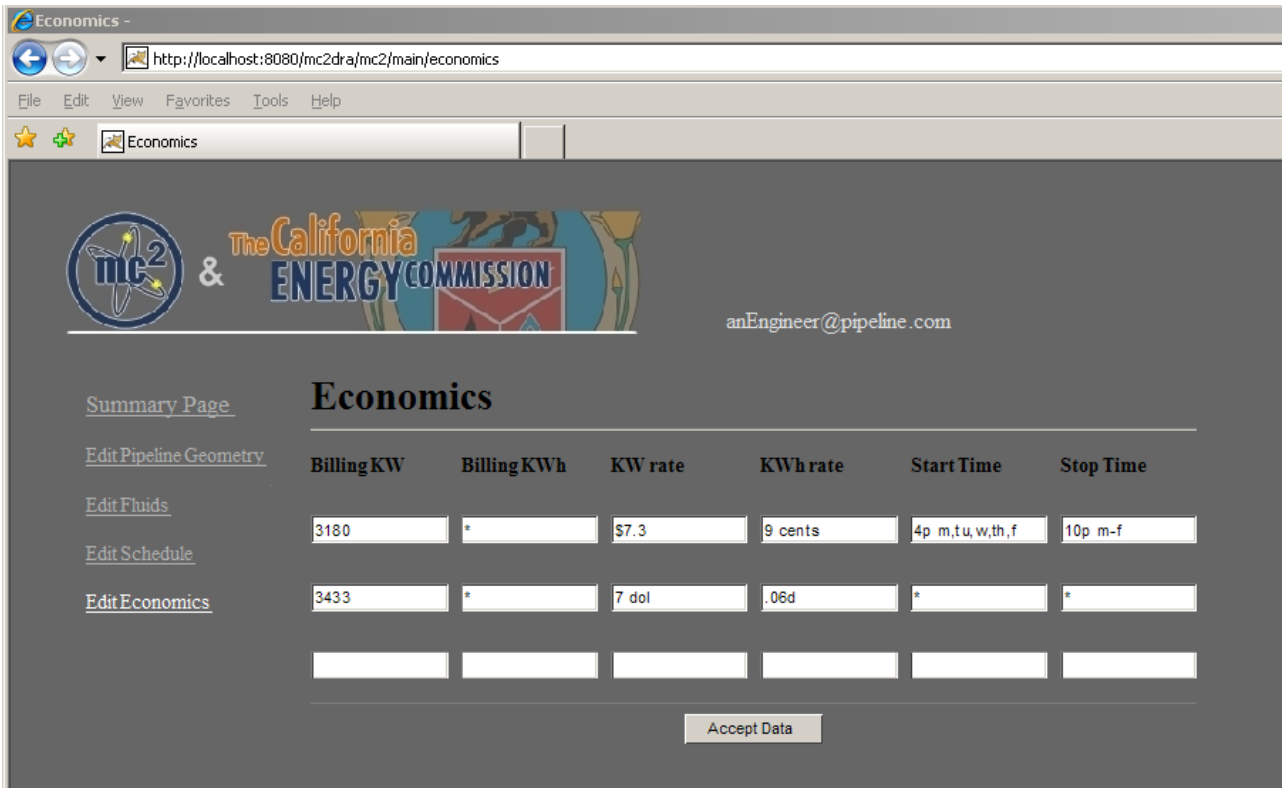

Figure 14.

Clicking on the 'Accept Data' button will return the user to the Case Summary page and the above set of entries will result in the following display:

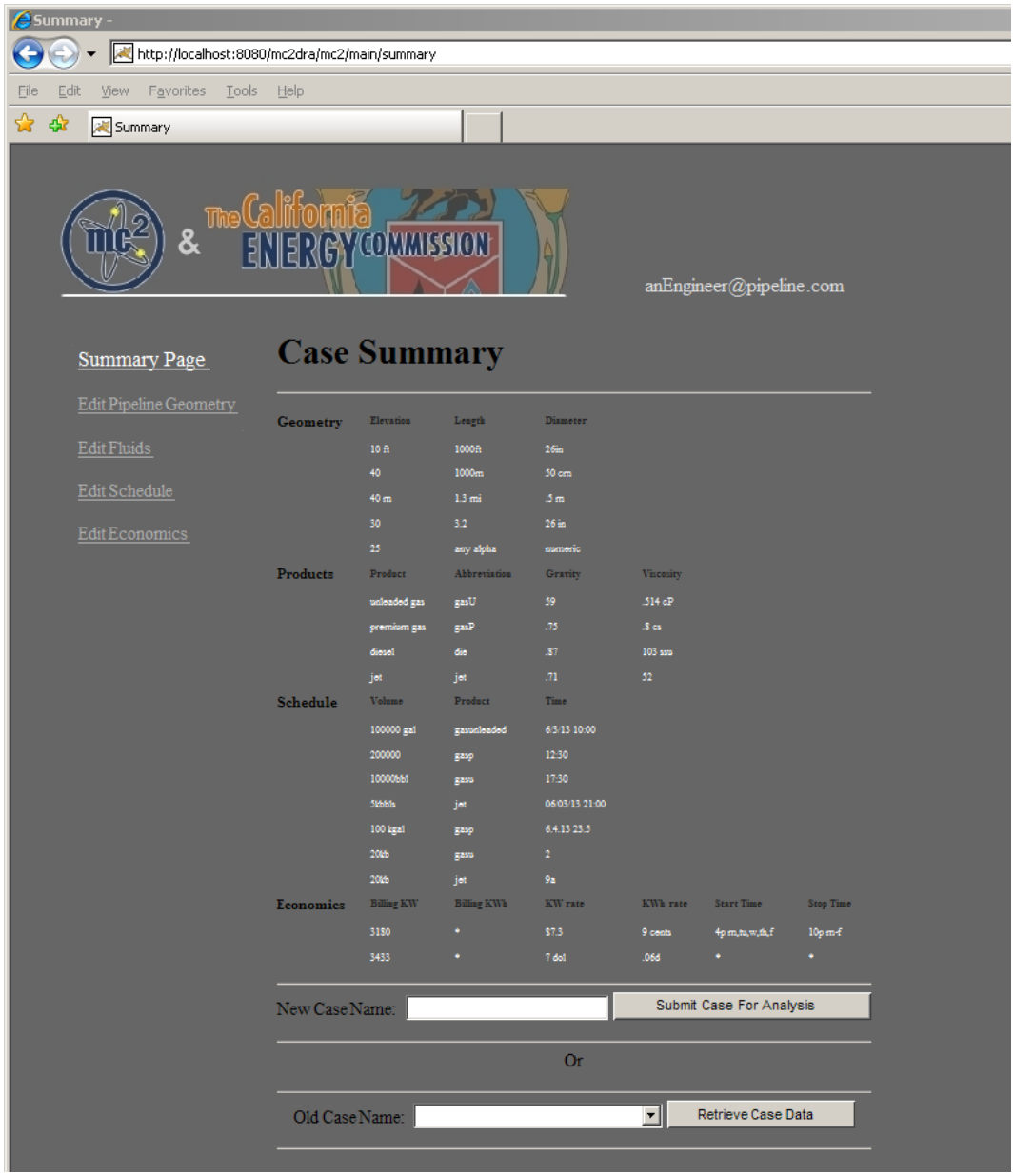

Figure 15.

The first two columns, Billing KW and Billing KWh, obviously have fixed units. The rate columns contain values in either dollars or cents, as shown in table 4. The time columns can use

either day names, spelled out until uniquely specified, or day lists or ranges, or dates (refer to table 3 for day, date, and time formats). For the time columns of the economics tables, a '*' is interpreted as 'all other times', and so is allowed to occur only once in a column. In this example, incremental cost calculations using the rates in the first row are specified for each weekday between 16:00 and 22:00. Otherwise, the rates from the second row are used.

Designation	**UOM**
c[ents]	cents, preceding or following
d[ollars]	dollars, preceding or following
$	dollars, preceding or following

Table 4.

Utility contracts often have seasonal rates, that is, rates which differ from season to season. Transitions between such time/rate periods are not considered in this model.

4. Data Submission and Case Retrieval Procedures

After all data tables have been filled and verified for accuracy, the next step is submission of the case for analysis. The analysis consists of execution of the pipeline schedule, with cost-of-schedule calculations for various DRA concentrations and various DRA costs.

4.1 Data Submission

The case data is sent to the analysis servers for processing when the 'Submit Case for Analysis' button is clicked. The analysis is processed and made available for download, from a link emailed to the user. An optional user-supplied case name, up to 36 characters in length, may be associated with the submission. The default case name is 'active', reflecting the active status of the data. This free-format field can be used to summarize the data set, including segment designation, schedule type, or cost structures. Below is an example where 'case1' was entered as the case name:

Figure 16.

4.2 Case Retrieval

Once a case has been submitted, the user may recall that case, overwriting the database tables with the recalled case data. This feature saves time if analyzing broadly different data sets, when slight modifications are desired from an old submitted case. The next two figures show modification of the product schedule from the submission designated 'case1', followed by resubmission as 'case2'.

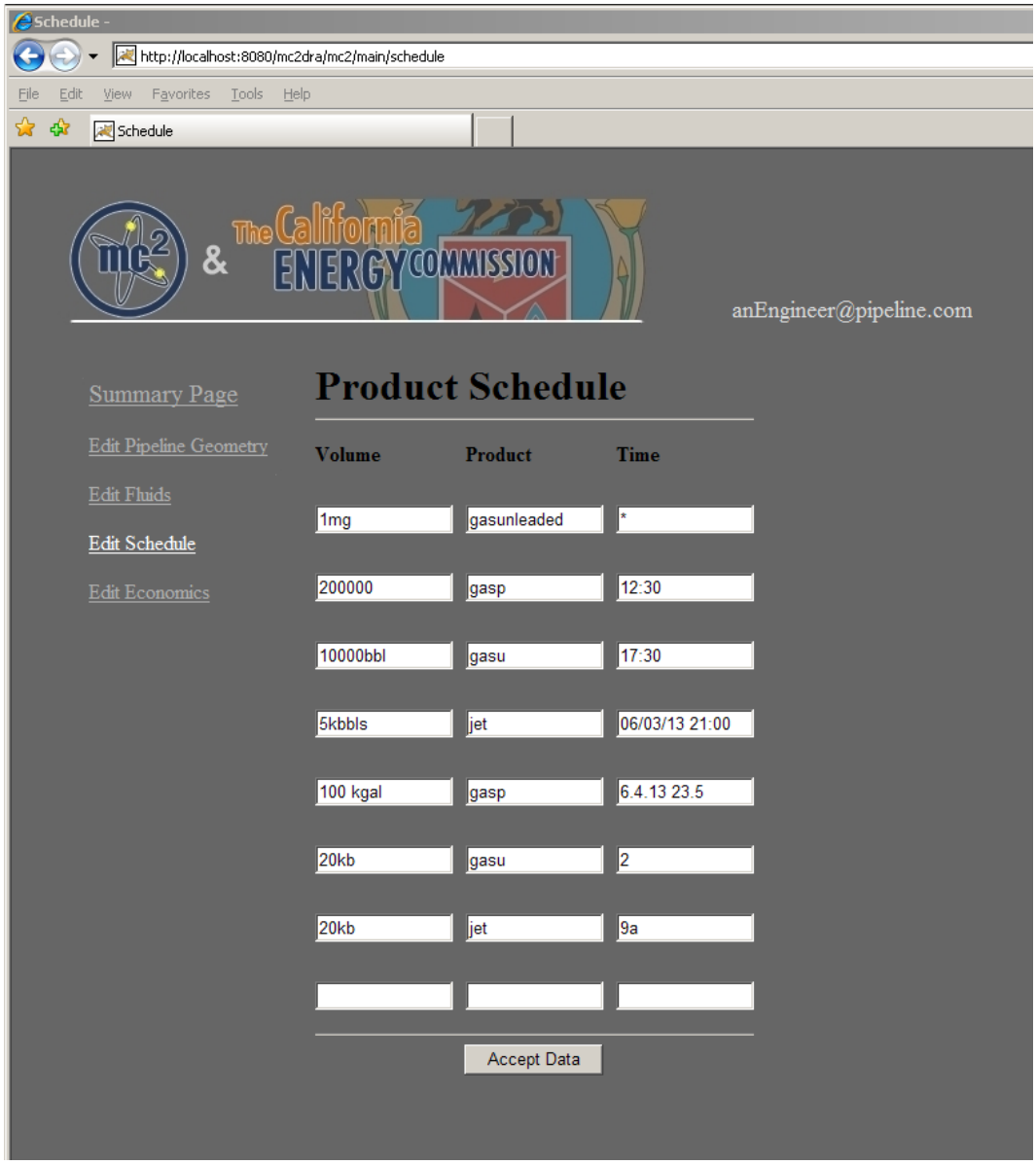
Schedule -
http://localhost:8080/mc2dra/mc2/main/schedule
File Edit View Favorites Tools Help
Schedule
The California ENERGY COMMISSION
anEngineer@pipeline.com
Summary Page
Edit Pipeline Geometry
Edit Fluids
Edit Schedule
Edit Economics
Product Schedule
Volume Product Time
1mg gasunleaded *
200000 gasp 12:30
10000bbl gasu 17:30
5kbbls jet 06/03/13 21:00
100 kgal gasp 6.4.13 23.5
20kb gasu 2
20kb jet 9a
Accept Data

Figure 17.

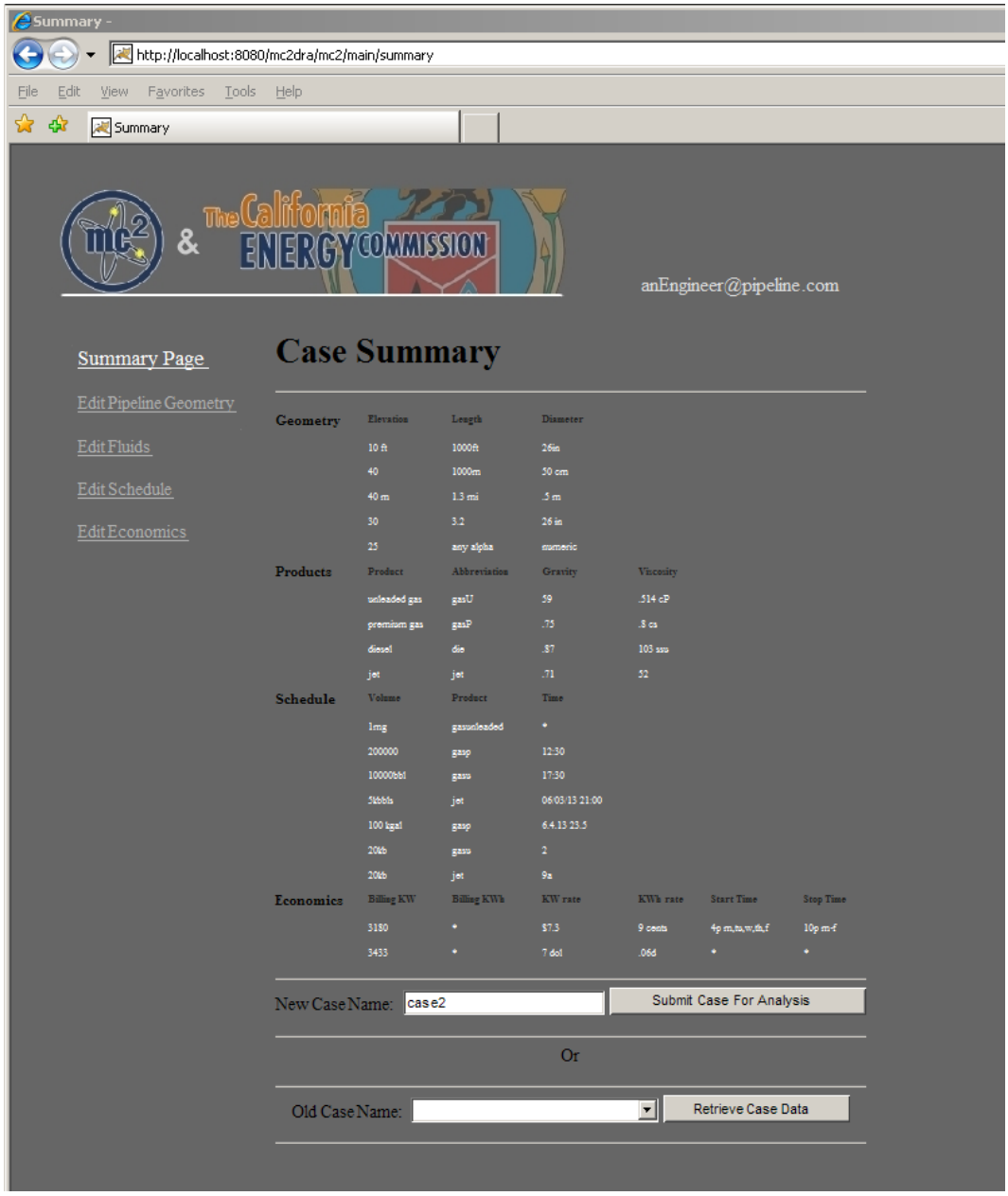

Figure 18.

Figure 19 shows the use of the case selection drop-down list, where, by selecting 'case1' and clicking the 'Retrieve Case Data' button, all 'case1' data is placed in the user's active database tables, and the Case Summary page is refreshed with 'case1' data.

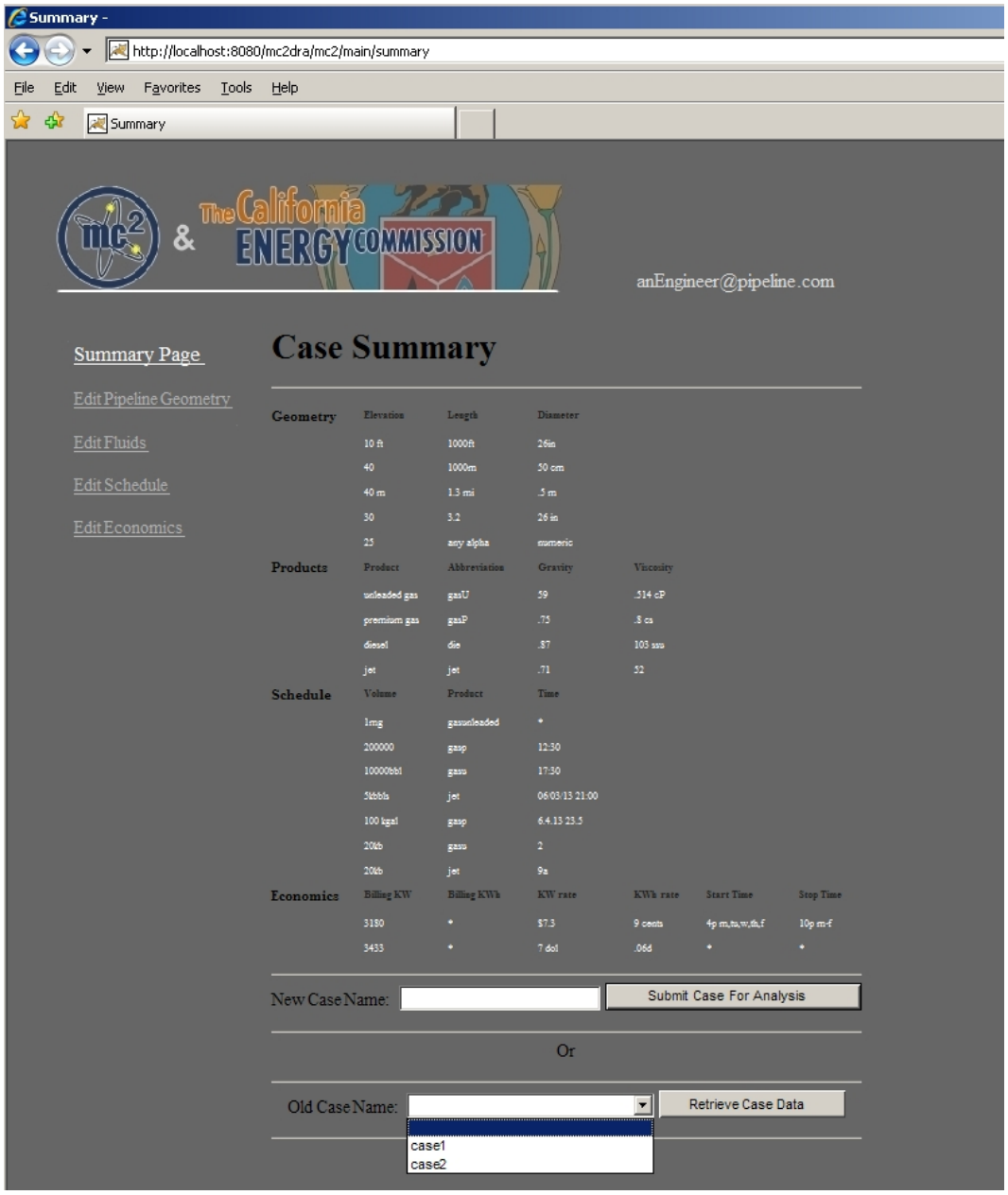

Figure 19.

Depending on data set size and number of simultaneous users, there may be a slight wait while the database tables are reloaded. During this period, the selected old case name will be visible in the selection text box. Upon completion of the table refresh cycle, the text box contents will be erased, indicating that the data is ready for modification using the 'Edit ...' links.

5. Support

Support for use of this package is provided by mc² Consulting, Inc. through the contact information below.

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