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A NATURAL GAS MODELING FRAMEWORK FOR CONDUCTING INFRASTRUCTURE ANALYSIS STUDIES

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ABSTRACT

Increased emphasis on national critical infrastructure protection has accelerated the need to respond to infrastructure assessment requests in a timely manner with reasonable certainty of system consequences following either natural or deliberate system disruptions. Natural gas supply, transmission, and distribution networks provide an important capability to dependent electric power, industrial, commercial, military, and residential customers. This paper describes the natural gas infrastructure analysis and modeling framework (NGtools) at Argonne National Laboratory that directly supports the analysis of the natural gas transmission network given various system disruptions. Infrastructure analysts, given the task to assess the resiliency of the natural gas infrastructure under various disruption scenarios, efficiently respond with increased certainty to various requests by using the in-house-developed analytical suite of tools within NGtools. Analysts use NGtools to identify critical system components and equipment, assess potential network-wide impacts, and suggest measures to mitigate undesirable system responses.

1 OVERVIEW OF NATURAL GAS INFRUSTRUCTURE ANALYSIS

1.1 Problem Statement

The natural gas supply, transmission, and distribution networks have always been regarded as an important asset to its electric power, industrial, commercial, military, and residential customers. However, in recent years, the natural gas sector has been affected by its increasing importance to electric power production. This strong interdependence between the electric and natural gas sectors bolsters the importance of a sustained, reliable natural gas system even during traditional non-peak summer months. Therefore, a simplified and efficient method to evaluate the natural gas network response to either natural or deliberate disruptions is increasingly important. This paper describes the natural gas infrastructure analysis and modeling capabilities at Argonne National Laboratory (Argonne) that directly support the analysis of the natural gas transmission network given these potential disruptions. In particular, this paper describes the capabilities of the integrated environment provided by NGview, which is a subset of the analytical suite of tools that is available in NGtools.

System analysts at Argonne are responsible for assessing natural gas infrastructure impacts on specific facilities or regions of interest. Facilities may be military bases or assets that are critical to military missions and/or national interests or to other sectors that serve the public (e.g., energy, public health, or telecommunications). Once facilities are identified, the analysis focuses on identifying supporting infrastructures and critical infrastructure assets that are required to sustain the deliverability of necessary goods or services. In the context of natural gas, assuring a reliable supply of the commodity becomes the goal of these assessments.

Two types of natural gas analyses are conducted at Argonne: isolation and system analyses. *System analysis* considers the effects that changes in normal operating conditions can have on the sustained delivery of natural gas and pressures at the facility of interest, while *isolation analysis* identifies the critical nodes and links that are required to sustain or interrupt the natural gas supply to the facility of interest. The objective of isolation analysis is achieved by examining the connectivity and organization of pipelines between available natural gas supply sources and the facility. Models that address the concerns of isolation analysis are often based on graph theory.

Three basic natural gas modeling approaches are available for system analysis studies, which focus on the analysis of pipeline network flows and pressures. Table 1 identifies each modeling approach and compares its expected precision and data requirements. Modeling precision ranges from low to high, while data requirements needed to support each approach range from minimal to maximal. Two steady-state (i.e., system conditions do not vary with respect to time) modeling approaches ignore the dynamics of natural gas flows, while the transient model treats time-sensitive characteristics explicitly. The application of each modeling approach has specific advantages and disadvantages.

Table 1: Comparison of Various Modeling Approaches and Their Expected Precision and Data Requirements.

Modeling Approach	Precision	Data Requirements
Mass flow steady-state model	Low	Minimal
Mass flow and pressure steady-state model	Medium	Extensive
Mass flow and momentum transient model	High	Maximal

Because large natural gas networks are often encountered during system analysis, large amounts of network data are routinely required to specify the characteristics and capabilities of various network components. This data can represent an exorbitant amount of information. In many cases, required data may be only available from transmission pipeline companies through established company contacts, where the procurement of proprietary data is often unlikely given the sensitivity of the required network parameters. Data readily available from the Federal Energy Regulatory Commission or Energy Information Agency often lacks the completeness needed to support the data requirements of large-scale natural gas networks represented by using commercial models. The lack of accessibility to critical detailed data often impedes the construction and credibility of highly detailed network representations.

1.2 Need for Models and Tools

Adequate assessment of natural gas pipeline networks requires fast response with a reasonable degree of certainty in estimated results. Knowing that tools are used to support analysis efforts and to improve customer response, there are tradeoffs associated with tool development and analysis tasks. Primary tradeoffs in tool development are characterized by the tradeoff between simulation accuracy and data availability. To address these concerns, the Argonne team adopted an in-house model development effort that supports the specification, development, testing, and verification of a model that provides multilevel network specification according to the data constraints described in Table 1. Development efforts have produced integrated models that are capable of addressing the first two steady-state modeling approaches identified in Table 1 on a regular basis, while addressing limited aspects of transient behavior by using approximations outside of the integrated paradigm on an infrequent basis. In this regard, effort and resources are directed to tool development that best benefits the needs of Argonne system analysts.

2 NGTOOLS AND THE INTEGRATED NGVIEW ENVIRONMENT

Argonne has developed a suite of natural gas modeling tools, called NGtools, to support various natural gas infrastructure analyses identified above. A subset of these tools uses the common operating environment provided by NGview, which supports the construction and modification of representative natural gas pipeline networks used in the analyses. In addition, NGview provides the interface to the NGflow and NGcut models. NGflow consists of two models used to determine steady-state pipeline flows and operating pressures, and NGcut is used to determine critical network components. Figure 1 illustrates the organization of the natural gas analysis tools under the direct control of NGview.

The NGview collection of models, which includes the NGflow and NGcut models, significantly reduces the effort required to conduct system and isolation analysis studies. In addition, the application of NGview reduces the time required to perform system analysis tasks—an essential characteristic to ensure a prompt analytical response with results that exhibit the highest level of practical confidence. This paper introduces the characteristics and features of the models identified in Figure 1 and provides details of the NGflow Mass/Pressure Model.

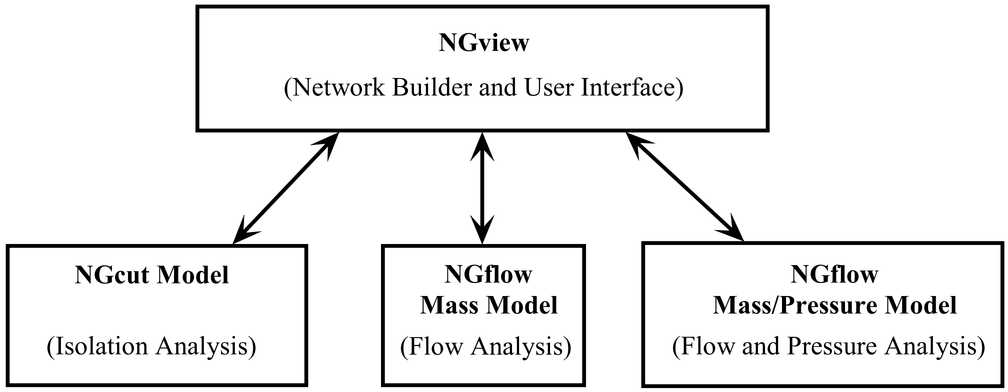

Figure 1: Subset of NGtools Integrated using the NGview Environment

3 SUMMARY OF NGVIEW

3.1 Purpose

NGview is a Windows-based, graphical user interface (GUI) and user-friendly modeling tool that enables the user to construct a schematic representation of physical natural gas supply, transmission, and distribution systems via its convenient point-and-click feature. NGview provides windows and menus to create and modify components of pipeline networks. As the abstract network is created on the screen, a connectivity file defining the relationship of various network components is automatically generated in the background. That file provides input data for NGflow simulations and NGcut calculations.

Natural gas networks expressed in NGview consist of various system components. Most notably, however, these networks consist of a series of pipelines and connection points where pipelines join. In addition, some of these connection points can either consume natural gas from (i.e., indicate *deliveries* to a customer) or supply natural gas to (i.e., indicate *receipts* from a supplier) the interconnected network of pipelines. In modeling terms, pipelines are often called *links*, whereas pipeline connection points (with or without natural gas deliveries or receipts) are called *nodes*. Nodes must be unique; however, multiple links can connect two nodes.

NGview validates a completed network before passing the associated data to the NGflow or NGcut models. Execution of the NGflow or NGcut models is triggered from NGview through options on its menu bar. NGview automatically generates a graphical display of NGflow simulation results and NGcut-derived critical components to provide seamless data exchanges among the three models.

3.2 Typical Applications

NGview has been used to construct natural gas distribution and transmission networks ranging in size from 10 to 20 nodes and links to networks consisting of several hundred nodes and links. Networks used for analysis of specific critical facilities typically consist of 20 to 30 nodes and links. However, studies that focus on the adequacy of a metropolitan regional gas supply network may model hundreds of nodes and links. Although construction of NGview models is not always feasible or required in all analysis situations (e.g., limited data, data sensitivity complications, insufficient time, unknown operating conditions), NGview-constructed gas networks provide very convenient and complementary support for NGflow simulations and NGcut calculations.

The following figures introduce the representation of a 110-node, 116-link natural gas pipeline system. A portion of the natural gas transmission system in northwest Washington is shown in Figure 2. A nongeospatial view of the same pipeline system represented in NGview is shown in Figure 3.

Figure 2: Graphic Showing Natural Gas Transmission Pipeline Serving Northwest Washington.

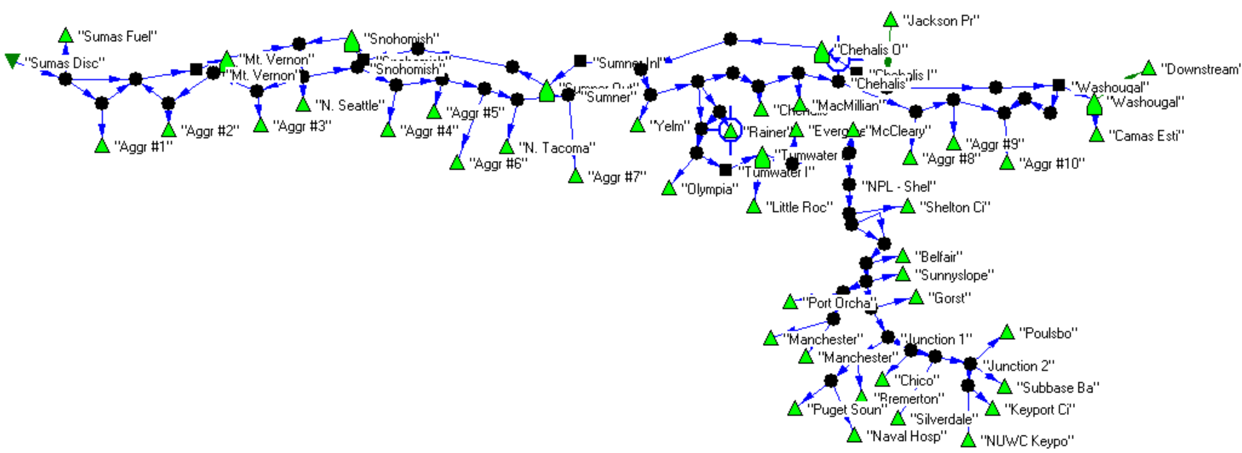

Figure 3: NGview Nongeospatial Representation of Natural Gas System shown in Figure 2.

3.3 Features

A summary of NGview features follows:

- The Microsoft (MS) Windows-based GUI permits a convenient point-and-click feature.
- NGview provides single-point user access to natural gas models.
- Network parameters are stored in a MS Access database.
- Network construction can be automated via prepopulated, structured MS Access tables or accomplished manually via the NGview user interface.
- NGview supports geospatial and nongeospatial alternate user views.
- NGview provides an integrated environment for NGcut and NGflow.
- Data import capabilities are used to simplify network component characterization.
- Network validation code detects questionable network parameters and invalid network component specifications.
- A map print option can be used to assist mapping and analysis requirements.

4 SUMMARY OF NGCUT

4.1 Purpose

An option available from within NGview is NGcut, which is based on classic network theory algorithms. However, speed enhancements have been applied to reduce the computational intensity of the algorithms and to improve performance and efficiency. NGcut requires a network description that consists of various interconnected nodes and links. Nodes function as delivery, receipt, and/or pipeline terminating points. Links function as gas pipelines that transport natural gas between nodes. Once a particular demand node of interest is selected, NGcut determines the critical network components required for sustained natural gas service to the node. Results obtained from NGcut are automatically exported to NGview, where they can also be displayed.

4.2 Typical Applications

Most isolation analysis studies do not require the application of NGcut, because isolation analysis is generally intuitive and can be accomplished readily by observation. NGcut, however, is applied in situations where critical components cannot be easily inferred via visual inspection of network components. This situation typically arises when pipelines are highly interconnected, yielding many alternative pathways for delivery to occur.

4.3 Features

A summary of the NGcut features follows:

- NGcut is used to support isolation analysis efforts.
- Single- and multiple-component outages are illustrated on the NGview GUI.
- Critical components are easily identified by using the NGview GUI.

5 NGFLOW OVERVIEW

The NGflow models are part of the overall NGview modeling environment. NGflow simulates pipeline flows (flow rates) and nodal pressures present in natural gas networks under various supply and demand conditions and fault scenarios. System analysts combine information determined by NGflow with other system-specific information to determine the network conditions that could potentially impact the natural gas deliverability in the region of interest.

NGflow is composed of two specific models: NGflow Mass Model and NGflow Mass/Pressure Model. Selection from the two options is primarily driven by the available types of network data. NGflow Mass Model is generally used when natural gas consumption and supply information is known, while specific pressure and pipeline characteristics are unknown. NGflow Mass/Pressure Model is used when all required data parameters are known, which includes gas consumption and supply data as well as pressure and pipeline characteristic parameters and compressor station attributes. Because more types of network-specific data are used to describe the natural gas network, NGflow Mass/Pressure Model supports improved simulation accuracy. Both NGflow models are solved by using General Algebraic Modeling System (GAMS) (Rosenthal 2008). NGflow is the shortened name used as a substitute for either of the full model names.

6 SUMMARY OF NGFLOW MASS MODEL

6.1 Purpose

NGflow Mass Model, which is selected from within NGview, is designed to assist system analysts with assessing natural gas infrastructure supply impacts on specific facilities or regions of interest. Although the application of the NGflow Mass/Pressure Model is preferred in systems analysis studies, some situations may occur in which NGflow Mass Model is the only model that can be applied to a specific analysis. NGflow Mass Model is generally used when natural gas consumption and supply information is known, but specific pressure and pipeline characteristics are unknown.

NGflow Mass Model determines natural gas flows through pipelines of a network without characterizing or accounting for the effects of pressure. In NGflow Mass Model networks, system nodes can function as delivery, receipt, compressor, and/or pipeline terminating points. Links function as gas pipelines that transport natural gas between nodes. The combination of nodes and links describes the network topology used to simulate network flow rates (in million cubic feet per day [MMcf/d]).

The set of nodes and their associated gas receipts, deliveries, and fuel usage amounts are all represented as fixed values (i.e., fixed mass). These values drive the estimations of natural gas flows in network pipelines. Each pipeline must transport the net amount of natural gas required to support the nodes to which it connects and any other nodes located downstream to achieve mass balance throughout the network. On the basis of total network balance equations, the model determines the flows in each pipeline. These flows provide information on the condition of the system prior to any postulated disturbance and are essential starting points in determining available capacities in the pipelines. NGflow Mass Model is implemented as a linear program by using GAMS.

6.2 Typical Applications

NGflow Mass Model is designed to assist system analysts with assessing natural gas infrastructure supply impacts on specific demand nodes or facilities. For example, system analysis considers the effects that changes in normal operating conditions can have on the flow of natural gas and pressures at the facility. However, NGflow Mass Model can only simulate pipeline network flows. NGflow Mass Model results are essential for establishing preoutage conditions (i.e., loading levels of pipelines before any postulated outage scenario). NGflow also simulates likely pipeline flows (flow rates) present in natural gas networks under various gas usage conditions and failure scenarios. System analysts then combine information determined by NGflow Mass Model with other system-specific information to determine the network conditions that could potentially impact the deliverability of natural gas to any given facility. In situations where NGflow Mass Model simulations are required and feasible, NGflow Mass Model results improve the quality of analysis efforts.

6.3 Features

A summary of the NGflow Mass Model features follows:

- Each node is capable of being a supplier and/or consumer of a fixed amount of natural gas.
- Compressors can be placed at any node, and the associated fuel usage is assumed fixed for all possible flow conditions. Compressor pressure attributes are not used as part of the simulation.
- The model determines pipeline flow rates without considering the effects of pressures at pipeline nodes.
- The effects of pressure in parallel pipeline configurations are represented through the use of distribution factors, which are used to generally represent the flow in individual pipelines within a parallel group of pipelines.
- The effects of load curtailments on pipeline flows can be easily explored.
- Model variables can be modified to conduct various what-if scenarios. Similarly, supplies, demands, and compressor fuel usage values also can be modified as required.

7 SUMMARY OF NGFLOW MASS/PRESSURE MODEL

7.1 Purpose

NGflow Mass/Pressure Model, which is selected from within NGview, is designed to assist system analysts with assessing natural gas infrastructure supply impacts on specific regions of interest or on specific delivery points at facilities. Although the application of NGflow Mass/Pressure Model is preferred in systems analysis studies, there may be situations in which only the NGflow Mass Model can be applied.

NGflow Mass/Pressure Model requires a network description that is composed of various interconnected nodes and links. However, the network data requirements are more extensive than the data requirements for NGflow Mass Model network descriptions. In NGflow Mass/Pressure Model, nodes function as delivery (fixed-mass or fixed-pressure), receipt (fixed-mass or fixed-pressure), and/or pipeline terminating points. Contrary to fixed-mass nodes, fixed-pressure nodes provide constant pressure requirements. Links function as gas pipelines that transport natural gas between nodes. In addition, links (and their associated originating and terminating nodes) can have compressor or regulator characteristics associated with their individual attributes. The combination of nodes and links describes the network topology used to simulate network flow rates (MMcf/d) and pressures in pounds per square inch, absolute (psia). Nodes must be unique; however, multiple links can connect two nodes.

The set of nodes and their associated gas receipts and deliveries are either represented as fixed-mass or fixed-pressure values. Initial receipt and/or delivery values drive the estimations of natural gas flows in network pipelines and pressures at system nodes. Given these initial values, each pipeline must transport the net amount of natural gas (i.e., mass balance) required to support the nodes to which it is connected and any other nodes located downstream. In addition, the pressures at the originating and terminating ends of each pipeline (i.e., nodal pressures) must satisfy pipeline loss equations. Considering mass balance, pipeline pressure relationships, and network equipment operating equations and constraints (including compressors and regulators), NGflow Mass/Pressure Model determines the flows in each pipeline and the corresponding network nodal pressures. These steady-state flows and pressures play a critical role in subsequent system analyses.

In summary, NGflow Mass/Pressure Model simultaneously estimates steady-state pipeline flow rate and nodal pressure values given the initial operating parameters of the natural gas network and equipment operating constraints. The nonlinear solver determines the steady-state pressure and pipeline flow rate values and compressor horsepower values for the given network by minimizing the pipeline error function and other mathematical residuals used to achieve nontrivial convergence. The details of NGflow Mass/Pressure Model are provided in the following section.

7.2 Typical Applications

NGflow Mass/Pressure Model is designed to assist system analysts with assessing natural gas infrastructure supply impacts on specific demand nodes, specific facilities, or on a larger region of interest. NGflow Mass/Pressure Model results are essential for establishing preoutage conditions (i.e., loading levels of pipelines and pressures at network nodes before any postulated outage scenario). NGflow Mass/Pressure Model also simulates likely pipeline flows (flow rates) and nodal pressures present in natural gas networks under various gas usage conditions and failure scenarios. Figure 4 shows the preoutage (left) and postoutage (right) flow and pressure system conditions for a postulated pipeline outage (designated as a dashed pipeline). System analysts can combine information determined by NGflow with other system-specific information to determine the network conditions that could potentially impact the natural gas deliverability to any given facility or region. In situations where NGflow Mass/Pressure Model simulations are required and feasible, NGflow Mass/Pressure Model results contribute to the credibility and certainty of system analysis results and improve the quality of analysis efforts.

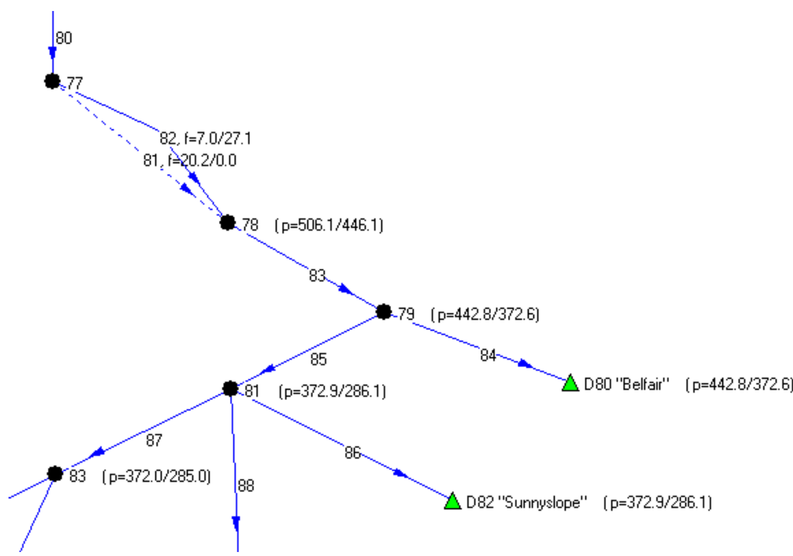

Figure 4: NGflow Mass/Pressure Model Results for Preoutage/Postoutage System Conditions of a Pipeline Disruption.

7.3 Features

A summary of the NGflow Mass/Pressure Model features follows:

- Each node is capable of being a fixed-mass or fixed-pressure supplier and/or consumer of natural gas.
- Compressors can be placed along any unidirectional link, and their associated fuel usage is assumed fixed for all possible flow conditions. Discharge pressures are attributed to the terminating node of the link.
- Pressure regulators can be placed along any unidirectional link. The regulated pressure is attributed to the terminating node of the link.

- The model simultaneously determines pipeline flow rates, nodal pressures, and compressor horsepower values in an integrated formulation.
- The effects of load curtailments on pipeline flows and nodal pressures can be easily explored.
- Model variables can be modified to conduct various what-if scenarios. Similarly, supplies, demands, compressor fuel usage values, and compressor and pressure regulator characteristics also can be modified as required.

8 NGFLOW MASS/PRESSURE MODEL FORMULATION

The NGflow Mass/Pressure Model formulation uses a nonlinear solver within GAMS to minimize an error function to simultaneously solve the system of nonlinear network equations. The model formulation is described below in terms of its sets, network parameters, variables, and equations.

8.1 Sets

Sets are used to define the domain of various model parameters, variables, and equations. Because the natural gas network is described by using nodes and links, these two fundamental entities represent ideal set candidates. The set of all N nodes exists, where node, $n \in N$. Similarly, the set of all L links (i.e., pipelines that model frictional pipeline losses, compressors, or regulators) exists, where link, $l \in L$. These two sets are used as building blocks to define the basic description of the network topology.

Additional sets are required to control the application of system-specific equations, which are triggered by the presence of certain physical network elements or conditions. Four such sets are *IL* (to track in-service pipelines), *RN* (to track fixed-mass nodes), *RL* (to track pipelines without associated compressors or regulators), and *CL* (to track network links that represent compressors). For example, pipelines that are out-of-service require special treatment, because pipelines that are inoperable exhibit no flow and zero pressure values. The set *IL*, where $IL \subset L$, is used to indicate all in-service pipelines. Similarly, links that do not have compressors or regulators associated with them are denoted by the set *RL*, where $RL \subset L$. Because the Mass/Pressure Model distinguishes between fixed-mass (typically, delivery nodes) and fixed-pressure nodes (typically, receipt nodes), the set *RN*, where $RN \subset N$, is used to indicate all fixed-mass nodes. Inversely, $\overline{RN}$ denotes the set of all fixed-pressure nodes. The set *CL*, where $CL \subset L$, is used to indicate network links that represent compressors.

8.2 Network Parameters

The existence of nodes and pipelines without any data describing their connectivity is futile in describing the natural gas network topology. The association among various pipelines and their originating and terminating nodes is given in the network incidence matrix, A_{nl}, where $n \in N$ and $l \in L$. A_{nl} contains elements having values of 1, -1, and 0. For example, pipelines leaving a node are represented by using a value of -1, while pipelines entering a node are represented by using a value of 1. This numbering convention defines the positive flow direction (from –1 to 1) in a pipeline. If a pipeline has a flow in the direction opposite to that defined in A_{nl}, the pipeline flow is negative. Pipelines that do not connect to a particular node are represented in A_{nl} by using a value of 0.

Fixed-mass nodes have a constant flow rate (MMcf/d) associated with them. The fixed flow rate injected or received at node, n, denoted by Q_n, where $n \in RN$, can be either a positive (under constant delivery conditions) or negative value (under constant receipt conditions). On the other hand, fixed-pressure nodes have a constant pressure designated in psia. The nodal pressure at node, n, denoted by p_n, where $n \in \overline{RN}$, is assigned a constant value to indicate that the node is operating as a fixed-pressure node. Nodal pressures are also assigned fixed values to specify the operating characteristics of compressors. For example, p_n can be assigned a constant pressure to represent the desired downstream discharge pressure (denoted as P_{Out}) of a compressor station. Other compressor and regulator parameters are defined by setting fixed values to either pipeline or nodal variables.

In addition to parameters for network nodes, each pipeline, $l \;\forall\; l \in (RL \cap IL)$, has two associated parameters: its length (L_l) and diameter (D_l). Pipeline diameters are specified in inches, and lengths are specified in miles.

8.3 Variables

When p_n is not fixed to a specific value, it acts as a variable that must be determined by the model. The nodal pressure at each node is related to the flow rate of natural gas, denoted as Q_l, in its incident pipeline(s). As a result, both variables, p_n and Q_l, are determined simultaneously.

The model supports two high-pressure pipeline loss equations: Weymouth and Panhandle "A". Both equations are expressed as a relationship of several constants, the pipeline flow rate (Q_l) and the difference of the pipeline inlet and outlet squared pressures, denoted as Δp_l, where $l \in (RL \cap IL)$.

In addition to Δp_l, each pipeline in $RL \cap IL$ has an associated error value (epsilon), designated as ε_l. The model objective function attempts to minimize this error value for all network pipelines below some predetermined error threshold.

Another variable to represent compressor horsepower (hp_l) at a particular compressor station is related to the flow through the compressor and the station inlet (or suction) (P_{In}) and outlet (or discharge) (P_{Out}) pressures. Compressors play a significant network support role under high-volume pipeline flow conditions.

8.4 Equations

The NGflow formulation simultaneously solves five primary equations: (1) mass balance, (2) difference of squared pipeline inlet and outlet pressures, (3) pipeline loss, (4) compressor horsepower, and (5) error minimization equations. All five equations are: (a) expressed in terms of the sets, parameters, and variables defined above; (b) subject to various network pressure and flow constraints; and (c) subject to the data parameters specified at model initialization.

The mass balance equation governs the conservation of all incoming and outgoing gas flows at every network node. Potential flows at every node include all connected pipeline flow rates and fixed-mass deliveries or receipts. This constraint ensures that the balance of natural gas at each fixed-mass node is preserved. The mass balance equation is

$$\sum_{l \in IL} A_{nl} * Q_l - Q_n = 0 \quad \forall \quad n \in RN \quad . \tag{1}$$

The second equation specifies the difference of pipeline inlet and outlet squared pressures for all pipelines in the network. Equation (2) is the first of two equations that specifies the pressure loss across a particular pipeline. The determination of Δp_l and its relationship to ε_l for each pipeline is described in

$$\sum_{n \in N} -A_{nl} * p_n^2 = \Delta p_l + \varepsilon_l \quad \forall \quad l \in (RL \cap IL) \quad . \tag{2}$$

Along with (2), either (3a) or (3b) is required to fully specify the pipeline loss for each network pipeline (Gulf Publishing Company 1996). Equation (3a) represents the Weymouth loss equation:

$$\Delta p_l = K_W * \frac{L_l}{D^{16/3}} * Q_l^2 \quad \forall \quad l \in (RL \cap IL) \quad , \tag{3a}$$

and (3b) represents the Panhandle "A" loss equation:

$$\Delta p_l = K_{PA} * \frac{L_l}{D^{4.854}} * Q_l^{1.8539} \quad \forall \quad l \in (RL \cap IL) \quad . \tag{3b}$$

K_W and K_{PA} represent a collection of constants that include the mean absolute temperature and pressure of the pipeline at standard conditions, specific gravity and compressibility factors of natural gas, and the pipeline efficiency factor. The assumptions regarding the constant natural gas compressibility and high-pressure (300 psia and above) operating conditions that are representative of transmission pipelines are taken into account in the application of (2), (3a), and (3b) in the NGflow model.

Equation (4) is used to determine the compressor horsepower at various compressor stations throughout the network given the simultaneous solution of the flow through the compressor and the station inlet and outlet pressures. P_{In} and P_{Out} correspond to the p_n of link l by using the network incident matrix, A_{nl} for each l. K_C represents a collection of constants that include the base atmospheric pressure and temperature conditions, suction-side temperature of the natural gas, compressor efficiency, and compressibility factor of natural gas. Compressor horsepower is defined in

$$hp_l = K_C * Q_l * \left[\left(\frac{P_{Out}}{P_{In}} \right)^{3/13} - 1 \right] \qquad \forall \quad l \in CL \ \ and \ \ P_{Out}, P_{In} \in A_{nl} \quad . \tag{4}$$

The fifth equation provides the error minimization characteristics (or objective function) required to solve the set of simultaneous equations. The individual pipeline error losses are squared (to remove the effects of negative error values) and summed to arrive at a total error value for the entire pipeline network. An additional term involving Δp_l and hp_l is included to achieve nontrivial convergence. The resulting objective function describing the total error, E, is

$$\mathrm{E} = \sum_{l \in IL} \left[10^{-5} * \varepsilon_l^2 \; + \; 10^{-16} \left(\Delta p_l^2 + hp_l \right) \right] \quad . \tag{5}$$

9 CONCLUSIONS

NGview and the NGflow Mass/Pressure Model have been used to support Argonne natural gas pipeline system analysis efforts and have greatly improved the confidence in system analysis efforts conducted at the laboratory. To gain general acceptance of the model, model results for two particular case studies were validated with industry results and natural gas experts. The performance of the model by using publicly available data was within 10% of industry-provided results obtained by using commercial simulation models. These modeling error margins were considered acceptable knowing the potential error in industry reported data and network parameters. Model performance and simulation result accuracy were also considered adequate given the resources used to develop the modeling capabilities and the degree of precision needed in typical and anticipated applications.

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