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NGFAST: A SIMULATION MODEL FOR RAPID ASSESSMENT OF IMPACTS OF NATURAL GAS PIPELINE BREAKS AND FLOW REDUCTIONS AT U.S. STATE BORDERS AND IMPORT POINTS

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ABSTRACT

This paper describes NGfast, the new simulation and impact-analysis tool developed by Argonne National Laboratory for rapid, first-stage assessments of impacts of major pipeline breaks. The methodology, calculation logic, and main assumptions are discussed. The concepts presented are most useful to state and national energy agencies tasked as first responders to such emergencies. Within minutes of the occurrence of a break, NGfast can generate an HTML-formatted report to support briefing materials for state and federal emergency responders. Sample partial results of a simulation of a real system in the United States are presented.

1 INTRODUCTION

High-pressure interstate pipeline systems, carrying large volumes of natural gas (NG) over long distances, crisscross the United States, transporting gas from production fields and import points to consumers nationwide. A pipeline break, especially near the upstream origin point (i.e., pipeline origin point near production fields), could have significant, widespread impacts on downstream consumers and could affect multiple states, sending an entire region into chaos or "emergency mode." Moreover, interdependent infrastructures, such as the electric power sector, are often directly affected because outputs of NG-fired generating units could be significantly curtailed, which could eventually lead to a power supply deficiency in the electric power sector (PCCIP 1997). Because the Department of Energy (DOE) has limited the time for generating briefing materials for the Executive Office during such catastrophic events, an urgent need has emerged for fast-turnaround tools that can quickly estimate the impact of pipeline breaks in both quantitative and qualitative terms. Argonne National Laboratory is experienced in performing NG and petroleum systems analyses for this type of DOE-sponsored, multi-laboratory-supported endeavor.

2 NGfast CAPABILITIES

2.1 Analysis and Data Retrieval Capabilities

Argonne designed NGfast (written in C Sharp language) to be used as both an impact analysis tool and an information retrieval tool. When used as an impact analysis tool, given the name of the affected pipeline, the location of the break, and the month the event occurred, it provides**:**

- A quantitative estimate (tabular) of the impacts to downstream markets
- A graphic overview of impacts, and, thus, insights into possible restoration strategy options
- Options to implement mitigating measures
- An estimate of the net impact after application of mitigation measures (e.g., load shed, states affected, electric megawatts lost

Furthermore, NGfast has the capability of handling multiple breaks involving multiple pipelines across a number of states (Figure 1).

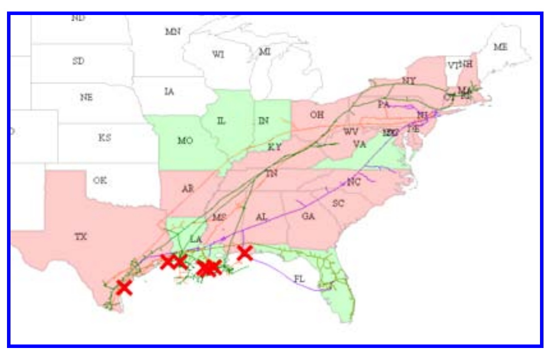

Figure 1: Actual graphical NGfast output ("X" indicates the location of a pipeline break. Affected states are shown in pink.)

When used as an information retrieval tool, given the name of the pipelines of interest and the month the event occurred, it provides the following pre-disruption information:

- Information on normal systems operations, including:
  - Average NG flow and direction of flow at the U.S. state border points
  - Pipeline capacity at the U.S. state border points
- System structure (i.e., commodity flow connectivity) from source to end users, including:
  - States and local distribution companies (LDCs) served by interstate pipelines
  - Configuration of pipelines at U.S. state border points (e.g., number of pipelines, pipeline size)
  - Demand per customer type (e.g., residential, commercial) within each LDC
- Spare mitigating capacity information for each state traversed by pipelines of interest, including:
  - All pipelines delivering to and receiving gas from the states
  - Underground storage (UGS) facilities
  - Liquefied natural gas (LNG) storage facilities
  - Production capacities

2.2 U.S.-wide Tabular and Spatial Database

The NGfast tool is a national model that includes data on more than 80 interstate pipelines, over 1,800 LDCs, and nearly 800 state border points. These data represent approximately 95% of existing pipelines, about 90% of existing LDCs, and 100% of known border crossings. NGfast also contains a database on the technical characteristics and monthly activities of UGS facilities and LNG and production fields. The state border database is the foundational information of the model. NGfast includes data on border points from nearly every state in the contiguous United States. A state border point contains useful information such as magnitude and direction of flow, sending and receiving pipelines, size and capacity of the pipelines, and longitude and latitude of the border point.

All of the data incorporated in NGfast were obtained from publicly accessible sources. All databases supporting the model are in Microsoft Access format. Assigned "primary keys" set up the tables for a dynamic relational computation. Spatial databases in shape files are used for displaying pipeline routes, state border points, and state boundaries via the graphical user interface (GUI) (see Tables 1 and 2).

Table 1: Data sets supporting NGfast.

Name of Data Set	Information Content
State Border	Location, average annual flow, pipeline capacity, number of pipelines, size of each pipeline, sending and receiving pipeline names, etc.
Pipeline to LDC	Relates each of the 80 or so pipelines to all LDCs they serve, including direct-connect loads in all states they traverse
LDC Load Classes	Residential, commercial, industrial, electrical gas use per LDC
UGS Activities and Characteristics	Location, working storage, maximum deliverability, and state-level monthly injections and withdrawal
LNG Facilities and Characteristics	Location, working storage, maximum deliverability, and unit-level monthly injections and withdrawal
Production Profile	State-level monthly marketed production output and maximum output

Table 2: Spatial data sets supporting NGfast.

Name of Data Set	Information Content
State Border Points	Geolocation of state border natural gas meters
Pipelines	Geolocation and routes of more than 80 pipelines
State Boundaries	State boundaries delineated

2.3 GUI, Spatial, and Tabular Outputs

The GUI in NGfast is designed for easy "point, click, and analyze" use. You can point to any state border point, select a pipeline to "break," and execute a simulation run. The break could be total (100% reduction) or partial, in which case you would enter a flow reduction number (in percent). Spatial output includes a picture of the simulated event (Figure 1), which shows the pipelines involved, the locations of the breaks, and the states affected. Tabular output includes detailed inflow-outflow tables that show values for both pre- and post-disruption conditions. All reports and spatial and tabular results are generated in HTML (Hypertext Markup Language) format. A summary tabular result is automatically generated for every run. The summary table includes the following information (Figure 2):

- Amount of gas withheld (lost)

- States affected
- LDCs affected per state
- Load shed per customer class per LDC
- Number of customers affected
- Megawatts of electric power plants affected
- Alternative NG supply sources

View Tabular Results

Disrupted Pipeline:	ABC Gas Transmission Co.
Number of States Affected:	7
Number of LDCs Affected:	15
Total MMcf/D lost:	1541.226
Total MW lost:	878.1553
Total Customers lost:	940242

A. MMcf/D Load Shed per affected state

	MMcf/D Shed					
State	Res	Com	Ind	Elec	Total	% Reduction
TN	8.4723	4.6543	12.2988	0	25.4254	100%
NJ	150.7685	381.441	89.2732	141.8288	763.3115	68.44%
PA	1.331	109.4004	290.777	47.4625	448.9708	39.94%
NY	0	150.8258	0	0	150.8258	27.35%
DE	0	0	0	21.466	21.466	23.34%
MD	0	0	0	0	0	0%
WV	0	0	0	0	0	0%

B. MW Shed per state

State	Total MW	% Reduction
DE	89.4415	63.33%
MD	0	0%
NJ	590.9535	100%

Figure 2: Summary of NGfast analysis report output from a simulation run on an actual pipeline (Note: The company name is deleted to maintain confidentiality. Users "click" the state of interest to see details of pre- and post-disruption loading conditions of LDCs within the state).

3 SIMULATION METHODOLOGY AND ASSUMPTIONS

3.1 Two Modes of Simulation

The model has two modes of simulation: uncompensated and compensated. The former assumes that mitigation measures are not available and that the only way to balance supply and demand after a disruption is to shed load. The latter (i.e., compensated mode), however, provides the user with the option to activate and define a select set of mitigating actions to minimize the impact of the disruption. The uncompensated mode shows the worst-case scenario, whereas the compensated mode simulates the more realistic outcome. Mitigating measures include additional withdrawals from in-state UGS, LNGs, and production fields as well compensating flows from interconnected pipelines.

3.2 Levels of Abstraction (Geographic Computational Granularity)

The load shedding computation in NGfast is performed down to the LDC level. In other words, the load to be shed is allocated to residential, commercial, industrial, and electric power consumers according to a user-defined priority order. When a break occurs at the pipeline level, the volume lost is allocated to all downstream states affected and further to all affected LDCs within the state.

The computation of gas volumes from mitigating agents is performed at the state level. Under such an approach, all UGS facilities within the state are aggregated into a single fictitious composite unit; the output could be used to mitigate the loss of load within that state. The same principle applies to LNGs and production wells. However, compensating volumes from interconnecting pipelines are computed at the pipeline level. This concept is depicted in Figure 3.

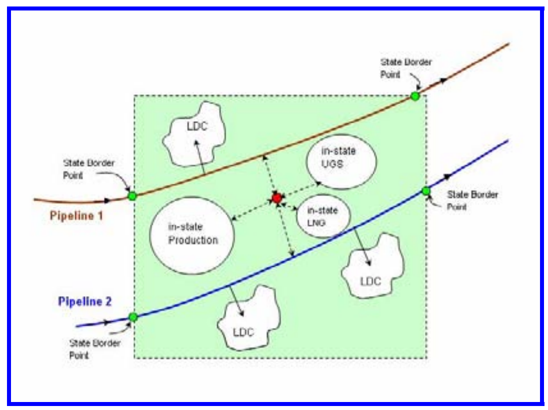

Figure 3: Computational granularity characterized by load shedding at the LDC level.

The red point shown in Figure 3 is called the model's "virtual point of confluence" (VPC). Within the state, four NG infrastructure components – UGS, LNG, production, and pipelines – are assumed to be directly connected to a VPC. Such a configuration makes the following operations possible via the VPC:

- Pipelines can exchange flows.
- UGS facilities can exchange flows with pipelines.
- LNG can be injected into pipelines.
- Production facilities can inject to pipelines.

Figure 3 also shows that each state border point is associated with a unique set of pipelines, and that each pipeline, in turn, is associated with a specific set of LDCs.

3.3 Calculation Logic – General Description

NGfast is a linear model that uses a progressive forward pipeline ownership identification and flow quantification process to track lost flow volumes due to a pipeline break or curtailment in production. Heuristics are used to allocate load to be shed among affected LDCs and various consumer types within those LDCs. Heuristics are also applied to estimate spare capacity from compensating pipelines, UGS facilities, LNG facilities, and production fields (McAllister 1988). The calculation starts at the upstream state most affected by the break and proceeds progressively toward the terminal (most downstream) states. The special structure of the state border database (i.e., "from-state" and "to-state" fields) allows the calculation method to proceed following the flow of gas along the pipeline, analyzing each state in sequence as it is traversed by the pipeline. Figure 4

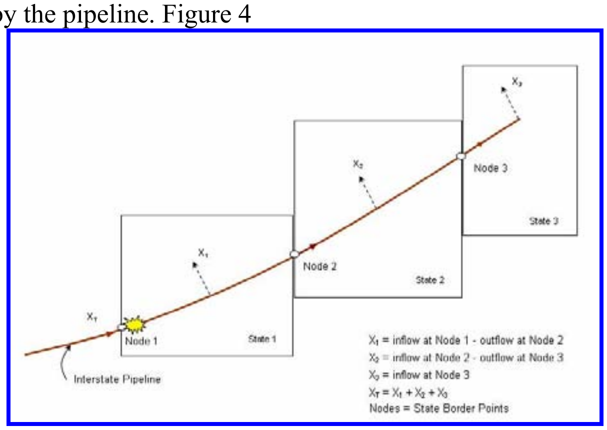

Figure 4: Forward flow and delivery quantification process.

illustrates the forward flow quantification process for a simple single pipeline system traversing several states.

Under the uncompensated mode, when a state border node of a specific pipeline is assumed disrupted, the flow volume through that node (in millions of cubic feet per day [MMcf/d]) is assumed lost. If the pertinent line traverses several states downstream of the disruption point, a multiple-state scenario computation must be performed, and the impacts on all the downstream states must be analyzed.

The forward quantification logic operates by repeatedly applying a recursive flow balance equation to each affected state. The recursive equation simply states:

State Delivery = Inflow – Outflow (MMcf/d)

Because the states traversed by the affected pipeline are in cascade, the output of the upstream state becomes the input into the immediately downstream state.

3.4 Relational Database Operation

Identification of the disruption points starts with the state border data set where the delivering (affected) pipeline is identified, and the magnitude of flow is defined. A series of relational database calculations then ensues to determine the states affected, the affected LDCs in each state, and the corresponding loads in each LDC. Once the magnitude of lost loads is determined for each state, the mitigating measures logic is triggered so that corrective actions from UGS, LNG, production wells, and interconnectting pipelines are set into play. Figure 5 illustrates the relational operation for the compensated case. Operation for uncompensated case would involve only the first three lower boxes.

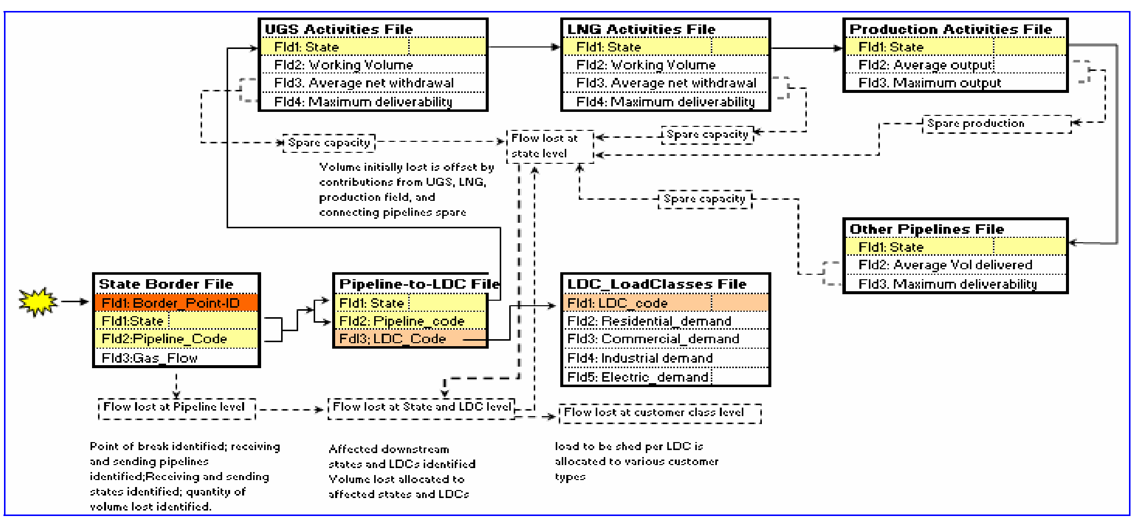

Figure 5: Relational database operation under a compensated simulation mode.

3.5 Varying Pipeline Configuration Complicates Forward Flow Quantification Process

The NGfast calculation logic was formulated to handle the complications presented by varying configurations of the 80 or so interstate pipelines included in the model. Below is the range of complicated cases encountered during the logic development process. Note that a pipeline disruption need not be a break; it could simply be a reduction in flow because of changes in pressure levels (e.g., due to outage of a compressor upstream).

Case 1 Simple single-line system passing through several states. Configuration is similar to that depicted in Figure 4. This case represents the simplest pipeline configuration: the forward flow quantification process proceeds without difficulty. A uniform reduction factor is applied to each of the in-state deliveries by the pipeline as well as the interstate flows.

Case 2 Single-line multiple interstate feed (Figure 6). In Case 2, which is very similar to Case 1, a uniform reduction factor is applied to each of the in-state deliveries by the pipeline as well as the interstate flows.

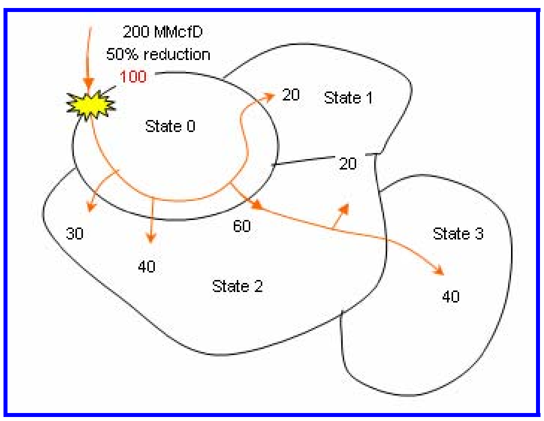

Figure 6: Pre-disruption flow values for Case 2 configuration.

Case 3 Multiple lines at state border and interconnection inside the state (Figure 7). Case 3 is more complicated than either Case 1 or 2. The pipeline system runs through two parallel corridors as it enters state 3, merges at a point within the state, then breaks again into a number of corridors serving several downstream states.

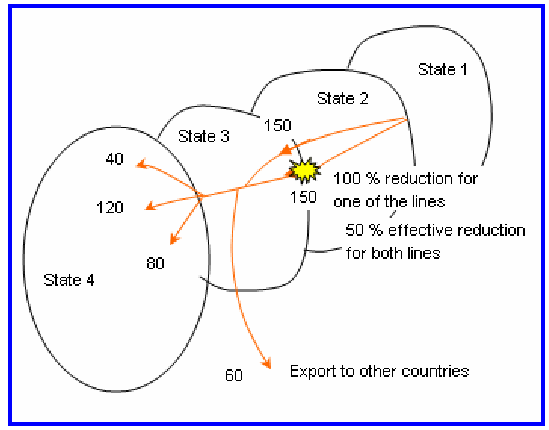

Figure 7: Pre-disruption flow (MMcf/d) for Case 3.

Case 4 Multiple lines at state border with no interconnection inside the state (Figure 8). In Case 4, the analyst would need to draw a "connectivity schematic diagram" (shown as blue broken lines in Figure 8); this "network builder" feature is part of the GUI and makes the connectivity construction task easy and convenient. The connectivity diagram helps to ensure that each input-side state border point identifies the appropriate output-side state border whose flow could be affected by the change in flow in the input-side state border point. Links in the connectivity schematic diagrams are called "lines of influence."

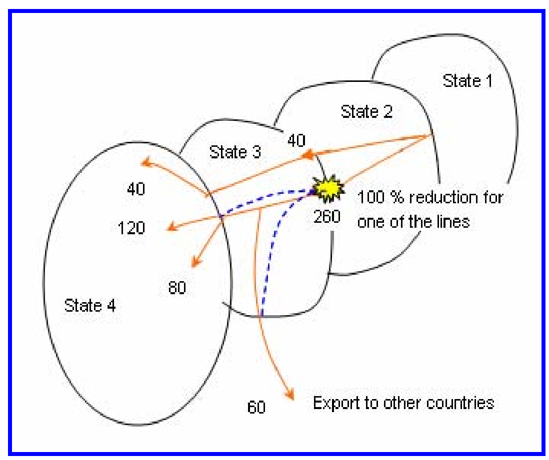

Figure 8: Pre-disruption flow (MMcf/d) for Case 4.

Case 5 Single or multiple lines with outgoing flow greater than incoming flow. In Case 5, the delivery to the state by the pipeline is zero (i.e., on a net flow basis), indicating that the LDCs within this state do not depend on the pipeline for their supply.

3.6 Compensating Action from Mitigation Sources

Compensating actions can be selected and defined via the flexible Policy Editor Window (Figure 9). This window allows you to specify the implementation sequence of the mitigating measures and their magnitudes.

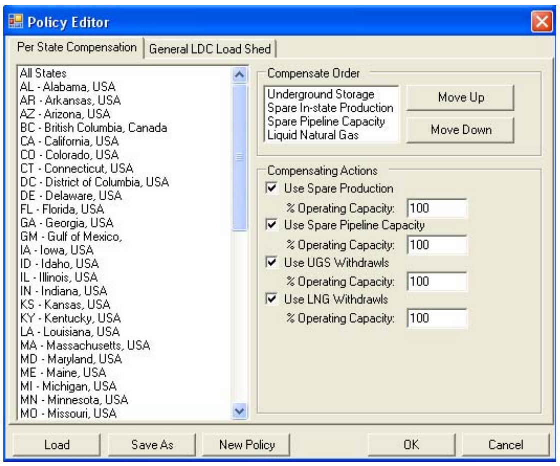

Figure 9: Policy Editor Window that defines the implementation sequence and magnitude of available mitigating measures

3.6.1 Spare Capacity from Surviving Pipelines

For the surviving, or compensating, pipelines, the following rules are observed:

Case 1 Outflow is less than inflow. The estimated compensating capacity for the state can be computed as follows:

Compensating Cap =
(inflow – outflow)/inflow * (pipeline capacity – inflow)

Case 2 Inflow is zero. If inflow is 0, the compensating capacity is also 0.

Case 3. Outflow is greater than inflow. If the inflow-outflow term is 0 or negative, the compensating capacity is also 0.

Whenever the outflow is greater than the inflow, the net delivery into the state is 0, and, from the perspective of the pipeline, the net flow is an injection or a receipt. In this case, there is only a receipt point (no delivery point), so even if the incoming capacity is large, the immediate state cannot use it because the state being considered does not have a delivery point.

3.6.2 Contributions from UGS Facilities

If the composite UGS is in injection mode during the disruption, the UGS should stop injecting, and gas volume intended for storage should be used to mitigate shortfall. Thus, it is assumed that the UGS cannot reverse flow quickly but can stop injection abruptly. If the UGS is in withdrawal mode, the compensating withdrawal rate is set equal to the UGS's deliverability (i.e., maximum rated outflow) less its net withdrawal for the month (EIA 2002).

3.6.3 Contributions from LNG

LNG facilities are assumed to be in injection mode during all non-winter months and in withdrawal mode during the winter months (i.e., November through March). During the winter months, LNG is assumed capable of releasing up to its rated output (gasification rate).

3.6.4 Contributions from Production Fields

Spare production rate is calculated as the difference between the maximum output of the fields during all 12 months of the year, minus the production level during the month when the postulated disruption occurs. This spare capacity could be applied to any residual unbalanced volume (load) resulting from the pipeline break.

4 A CASE STUDY APPLICATION

4.1 Study Description

NGfast was used in a recent study (March 2007) to estimate the impact of a postulated flow reduction in a real interstate pipeline system (fictitious name: ABC PL Co.) crossing the Savannah River at the South Carolina – Georgia border as shown in Figure 10. The reduction in flow was necessitated by an assumed flooding of the Savannah River due to a breach in a large dam upstream of the river.

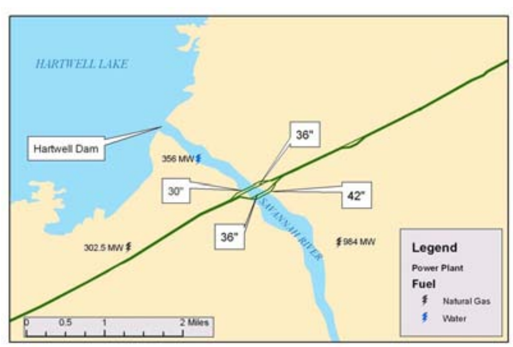

Figure 10: The segment of interstate pipeline system affected by the postulated flooding.

The scenario assumed that the affected pipeline segments are at the river bottom and are weighted. It was also assumed the pipeline operation personnel considered lowering pressure to reduce pipeline stresses. A flow reduction of 25% was subsequently assumed appropriate to meet this objective. The geographical location of the flow reduction point is shown in Figure 11. The characteristics of the pipeline segment where the flow reduction is effected are summarized in Figure 12.

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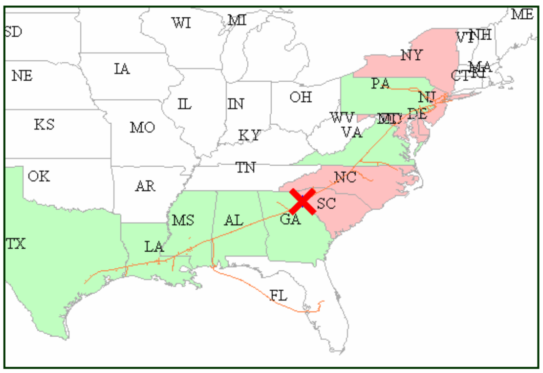

Figure 11: Postulated point of flow reduction is indicated by a red "X" sign.

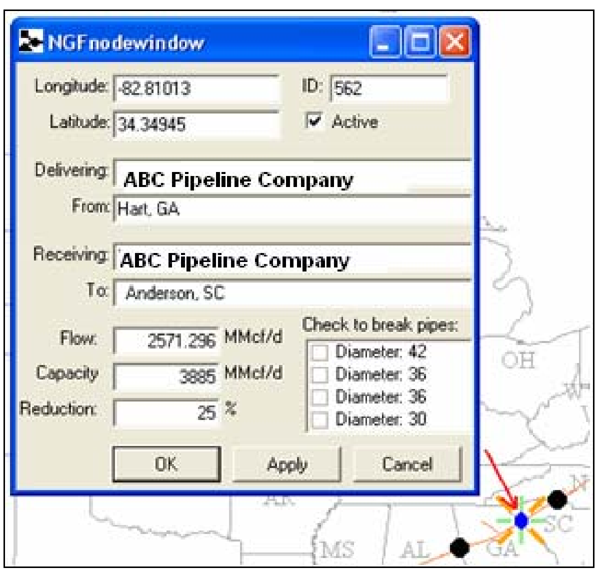

Figure 12: NGfast GUI Window showing characteristics of the affected line segment.

4.2 Results of the Simulations

The simulation results for the uncompensated and compensated cases as generated by NGfast are summarized in Table 4. Tables 5 – 8 show results associated with the uncompensated case. Overall, the results show that with implementation of mitigation measures, a 25 % reduction in flow would have no impact on the downstream markets.

The uncompensated scenario may be considered the worst unrealistic scenario with a probability of occurrence of almost nil. Because of the presence of UGSs in some of the affected states and the interconnected nature of the NG interstate pipelines, there are always options—effective options – to mitigate the impacts resulting from a pipeline break or flow reduction.

Table 4: Summary of NGfast simulation results for the uncompensated and compensated Cases.

Impact Metrics	Uncompensated	Compensated
Number of states affected	6	6
States Affected	SC, NC, DE, NJ, NY, MD	0
Number of LDCs affected	29	0
Total flow lost , MMcf/d	643	0
Estimated total MW capacity lost	1,600	0
Estimated total number of customer lost	21,600	0

Table 5: Summary of load shed (in MMcf/d) per affected state for the uncompensated Case (Note: Res = residential; Com = commercial; Ind = industrial; Elec = Electric; Red = reduction).

State	Res	Com	Ind	Elec	Total	% Red
NJ	0	1.36	58.03	155.97	215.36	14.8%
NY	0	55.82	46.26	94.83	196.91	17.7%
NC	0.02	0.02	66.67	91.94	158.66	26.6%
SC	0	0	15.29	23.13	38.42	16.7%
MD	0	0	17.90	1.56	19.47	7.0%
DE	0	0	0	13.97	13.97	15.2%

Table 6: Summary of MW shed per affected state for the uncompensated case.

State	Total MW
NJ	649.87
NY	395.13
NC	383.10
SC	96.39
DE	58.23
MD	6.51

Table 7: Summary of flow (MMcf/d) lost per affected state for the uncompensated case.

State	Flow (MMcf/d) Lost
NJ	215.36
NY	196.91
NC	158.66
SC	38.42
MD	19.47
DE	13.97

Table 8: Summary of number of customer shed per affected state for the uncompensated case.

State	Res	Com	Ind	Elec	Total
NY	0	15,848	739	5	16,592
NJ	0	669	2,489	334	3,492
NC	124	17	836	15	993
MD	0	0	401	7	408
SC	0	0	101	5	106
DE	0	0	0	0	0

4.3 Relevant Input Data

The entire data set used for the simulation is quite extensive and would require more space than this paper would allow. For this reason, only the relevant input data is presented. Table 9 summarizes the state border point information associated with ABC PL Co.

Table 9: Description of State Border Points associated with ABC PL Co. from GA to NY (Note: Del = Delivering; Rec =receiving; Cap = capacity).

Del PL	State From	Rec PL	State To	Cap (MMcf/D)	Ave Flow (MMcf/D)
ABC	GA	ABC	SC	3,885	2,571
ABC	SC	ABC	NC	3,692	2,418
ABC	NC	ABC	VA	2,870	1,783
ABC	VA	ABC	NC	400	0
ABC	VA	ABC	NC	20	0
ABC	VA	ABC	MD	2,100	1,870
ABC	MD	ABC	PA	2,050	1,789
ABC	PA	ABC	DE	76	61
ABC	PA	ABC	NJ	1,432	969
ABC	PA	ABC	NJ	358	242
ABC	PA	ABC	NJ	885	599
ABC	NJ	ABC	PA	21	0
ABC	NJ	ABC	NY	110	75
ABC	NJ	ABC	PA	400	0
ABC	NJ	ABC	PA	200	0
ABC	NJ	ABC	PA	1,300	0
ABC	NJ	ABC	NY	362	247
ABC	NJ	ABC	NY	190	130
ABC	NJ	ABC	NY	606	413

5 CONCLUSIONS

NGfast is a rapid-response tool intended to assess impacts of a major pipeline break. NGfast maximizes the use of publicly available information to develop relatively straightforward, but insightful, analysis tools. Within minutes of a break, NGfast can generate an HTML-formatted report to support briefing materials for state and federal emergency responders. NGfast is ideal for generating quick, first-stage response.

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