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Transient Optimization – Examples and Directions

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ABSTRACT

Transient pipeline optimization is in much the same immature state as pipeline simulation was 30 years ago. Both started with new technologies, and glimmers of ideas about how the technical advances could actually be used in practice. Ideas currently abound on ways to use transient optimization. Just as in the early days of pipeline simulation, it seems certain that some of our current ideas will pass the test of time, while other ideas may prove less useful. Conversely, it is also certain that we will find novel ways beyond what is already conceived.

In this talk we hope to educate the audience on some current projected uses of transient optimization, and at the same time encourage discussion among potential users of the technology on what they need and what they do not, and why.

1. GOALS OF THIS PAPER

When transient pipeline simulation began to become available a few decades ago, two questions immediately arose. First, given the fledgling state of the art, what pipeline features and operations could we actually, technically, simulate? Second, were any of the things we could simulate actually useful? At the start, only a limited amount of thought had been given to either of these matters, because they were brand new. But with time, practitioners advanced the technical art of simulation, and pipeline companies thought of a widening variety of practical uses for these technical capabilities. These two processes were complementary; as operators thought of new practical uses they spurred new development within the simulation community. And as the simulation community enhanced the scope of simulation, these enhancements encouraged pipeline operators to be even more creative in using said enhancements.

Transient optimization is in a similar position. A variety of remarkable technical capabilities have been demonstrated, many aimed at helping with known issues that arise at real pipelines. (E.g. [1]-[7]) However every pipeline is different and the actual range of potential uses is certainly broader than the examples so far published. Continued industry-wide feedback is needed to guide technical development. Conversely, many potential industry users of this technology would benefit from thinking outside the box and applying the technologies in ways not currently envisioned.

This paper was originally envisioned as a workshop wherein potential users and developers could have spirited discussion regarding what is needed and what is possible. Although the material is instead being presented as a paper/presentation, our goal remains to provide a base for general discussion rather than to promote particular capabilities or methodologies.

To provide this basis, in this paper we first explore some of the mathematical problems that Transient Optimization can solve. We show some ways this might be used, and how this differs from both simple transient simulation and from steady state optimization. We will skim through uses suggested in the literature.

To give our discussions some grounding in reality, we go into much more depth on one real example from OMV. Our intent is to give enough background to start discussion, without giving so much as to predispose the audience with our own preconceptions.

Recognizing that each pipeline is different, we encourage further discussion of 3 questions.

- Do the ranges of described uses seem pertinent to real pipelines?
- Which are most useful and under what circumstances?
- Are there any enhanced capabilities that would increase the usefulness further?

2. COMPARISON BETWEEN TOOLS

2.1 Pipeline Simulation

A pipeline simulation is a computer model of what is occurring, or what hypothetically could occur, in a pipeline system. A broad variety of modeling methods can be used depending on what quantities we are interested in, and how much accuracy we need to do our work. At one end of the gamut, a simulation might just be a spreadsheet showing mass balances of flows in and out of a system. Such simulation is too grossly oversimplified to be much use in an engineering context, but might be of use in simplified financial planning.

A somewhat better simulation method is one that computes a steady-state balance that simultaneously satisfies mass balance and also algebraic simplifications of pressure drop equations. By steady state we mean that mass flowing into each pipe always matches mass flowing out. A broad variety of pressure drop approximations have been used over the years in this sort of analysis, ranging from old equations optimized for slide rule computation, up to the highly accurate “fundamental equation” including accurate representations of nonlinear friction factor and equation of state terms. Compressor stations and other non-pipe elements can also be modeled in either trivial or excruciatingly accurate detail.

With good modeling practices and adequate pipeline measurements, steady state simulation can give extremely accurate models on what is going on in a pipeline, *provided* the pipeline is in steady state. Gas distribution systems, even large ones, tend to satisfy this criterion, and steady state simulation is the gold standard for these systems. Gas *transmission* lines most often do not unless loads are unusually steady. Steady state modeling of transmission lines must therefore be very carefully interpreted. It is valid and often useful to consider such a simulation as producing an instantaneous “*representative*” flow/pressure model for use in planning purposes. The simulation output can also be interpreted as establishing that a given operation is *sustainable* provided boundary conditions remain the same.

Transient simulation raises the bar and considers conditions where the pipeline loads and line pack may be continually changing. Again there are a variety of ways of doing this sort of modeling, the most accurate (and expensive) being the numerical solution of the coupled time-dependent system of nonlinear partial differential equations describing pressure changes and mass flow in the pipes.

2.2 Steady State Optimization

Pipeline simulation can be an enormously useful tool but it isn't the whole story. It can tell you what happens if you choose to operate a pipeline in a certain way, but doesn't provide any direct suggestions on how to operate the pipeline better. Still, people will often run simulators repeatedly to investigate how to improve operation, and sometimes will even run large "case studies" that scan over a grid of possible operation. Benefits can be had from those approaches, and sometimes an humble simulator will even be called an "optimizer" in marketing literature for this reason.

However for most interesting problems the number of variables to manipulate is far too high for the case study approach to be practical. Consequently many mathematical tools have been developed to do a vastly better job of optimization.(E.g. [8])

For steady state optimization, people most often ask the following questions:

- How much can I increase my outlet flow and still find a valid, coordinated way of operating the compressors and pipeline. (E.g. Throughput optimization.)
- For given deliveries, how can I choose the best, system-wide, coordinated combination of compressor operation so as to minimize operational cost? (E.g. Fuel and or Power cost optimization.)

Various approaches exist for optimizing these quantities, and for the most part it is a mature field. Large real-world benefits can often be accrued by using this approach. However, we are still assuming the system is at steady state. Solutions must therefore always be considered representative, instantaneous examples, or, in the case of throughput, examples of maximum attainable sustainable operation.

2.3 Transient Optimization

In cases where pipelines are in significant flux, steady state optimization tells us too little about how to operate the pipeline. However significant flux is exactly the situation where an operator needs the most help.

To address this situation, transient optimization tools are the only real help. These tools are not limited to optimizing single operational snapshots in time, but instead can manipulate line pack distribution continually over a designated interval in time. For instance, if a large upcoming load is expected midway through the day, transient optimization can tell you how best to *pre-position* line pack to meet that load efficiently and safely. The best that steady state optimization could do is tell you whether there is a sustainable way of operating at the time of the load; it can tell you nothing about a preparation strategy before the load or a recovery strategy after the load.

For brevity, in the remainder of the paper we will use the acronym TOM to refer to "transient optimization method" or methods. We do not necessarily refer to any particular tool; by TOM we refer to any tool that can automatically compute a pipeline operating plan. Specifically, a tool that manipulates user-specified controls such as compressor setpoints in time, that satisfies user designated constraints, and that optimizes some user-designated quantity of interest. This is a purposefully broad definition; the fun comes in seeing what a user might accomplish by selection of what sort of things should be included in the "user-specified" clauses above.

Let us next consider some of the circumstances for which TOM might be a useful set of tools.

3. Arenas of Use

3.1 Use in Operations

The most obvious uses of TOM involve its use by gas controllers in regional or local pipeline control rooms.

- **Quick response to changed situations**

Pipeline operators are frequently presented with unanticipated changes with little or no warning. For example, they may get notification that a peaking electric power plant will be coming online in an hour, or that a large industrial client is temporarily shutting down operation. Compressor equipment outages, supply outages, and similar system upsets can occur. For the largest upsets it may be necessary for an operator to take coordinated action over several stations in a time varying manner to gracefully deal with the upset. TOM can automatically recommend new operating plans to meet the new situation, and thus can be an attractive tool to help operators deal with unexpected changes.

- **Reliable response to challenging conditions**

Operators are often faced with challenging conditions. Sometimes operation is difficult because of an unanticipated event, such as described in the previous section. Sometimes operation is difficult because we are already close to a feasibility boundary, such as maintaining max throughput at a main delivery while side loads are fluctuating. TOM can be useful to assist the operator in keeping pipes and compressors within their allowed operational limits. If there is some warning of upcoming events, the methodology can also help prepare by getting line pack resources into the right spots, and if there is no warning it can help quickly decide how to use existing line pack resources optimally in time and space.[6]

- **Rapid transition between desired states**

Some pipelines use a methodology of normally attempting to keep steady operation, but at fixed intervals or when circumstances dictate, transitioning to a new pre-designated state. When the decision is made to transition, it is often important to do it rapidly. (It might be a limited-time spot market sale for instance.) Operators typically have good schemes they have learned for doing such transitions if they are familiar with both the initial and target states (which may have quite different linepack distributions.) If they are not familiar with the particular transition, they may be forced to choose “seat of the pants” transition plans which may take much longer than could have been achieved with TOM.

- **Efficient operation**

Similarly, an operator may know his desired starting state and ending state, but may not care about getting there rapidly. (For example, the target might even be the same as the ending state if the operator just wants to get back to a designated line pack at the end of each day.) Under these circumstances TOM could be a good tool for finding daily operational plans that minimize operational cost (such as fuel or electric power) while maintaining time-dependent deliveries throughout the system and still getting to the end-time target state. [4]

- **Operating under situations beyond the operator’s experience**

Experienced operators are usually very good at dealing with situations that they have frequently seen before. However as described in a previous example, in today’s environment they may be unexpectedly confronted by entirely new load patterns dictated by a changing marketplace, new industries, or sudden changes in equipment availability. Also not all operators are experienced; new operators are trained all the time. Finally, even experienced operators can face uncharted territory when pipeline expansion projects and mergers come online. TOM can be a great tool for dealing with such situations as they occur in the control room.

- **Initial state**

In control room contexts, a TOM run will almost always need to start with an estimate of the pipeline’s current state at every point in the system, regardless of whether the point is instrumented. Under steady state conditions, such “state estimation” can be done simplistically: by plugging available SCADA information into a simple simulation and letting a balancer fill in estimated data at the un-instrumented points. However, for transient circumstances this will give poor results. Specialized state finding software is far preferable. We note that the techniques of TOM can themselves be used to do state finding in a variety of ways.

3.2 Use in Financial Settings

In the previous section we discussed use of TOM in the control room. Such uses are often called “on-line optimization” and it is usually assumed that all runs are executed starting from the estimated current state, and performed using best known estimates for such quantities as upcoming load profiles.

There is not necessarily a clear distinction between “financial” settings and “control room settings.” For instance, we discussed fuel cost optimization as a control room application. However, in this section, we focus on uses that maximize profits by also considering *hypothetical modified load patterns*, rather than just changes to compressor setpoint operating plans. These applications may still start from the best estimate of the current state (on-line applications), or may be completely offline and use hypothetical starting states as well as hypothetical load patterns.

- **The “Well Informed Broker” problem.**

Some pipeline load profiles are (for the most part) outside the control of operators and short term planners. For example, if a pipeline has contracted with a municipality to supply gas for heating, that load will be determined by what the municipality takes, which in turn is dictated by weather and other factors. For both heating and industrial deliveries, these loads often vary dramatically with time of day. This time profile is also not typically under control of the pipeline. We will refer to the collection of loads that are outside the control of the pipeline as “predetermined loads.”

In other contexts in the US and Europe there is a certain level of choice regarding some possible transportation contracts. Selection of contracts can be similar to a stock exchange or spot market, wherein a broker can offer or accept transportation deals beyond the predetermined loads. If accepted, it is up to the pipeline to make the delivery. Large amounts of money can be made by selecting the right combination of contracts.

Obviously, it is possible for the broker, driven by the laws of *economics*, to create a contract that breaks the laws of *physics*. That is, he can propose a contract that cannot physically be delivered without compromising other contracts, or even pipeline integrity. Missing a contract delivery can incur large financial penalties.

Brokers can perform well *only if we provide them with adequate information* for their decision process. One way of keeping the broker’s actions in line with the laws of physics is to use a system where for each extra contract he proposes, a simulation is run to determine whether the contract is reasonable.

The difficulty with that approach is that meeting the new load pattern will often require a revised control plan. A human operator can be tapped to provide such a plan for each simulation, but if there are a significant number of potential contracts to be individually evaluated, too much skilled manpower will be required. Furthermore by the time the all the analyses have been made, the contract opportunities may be gone. And if in any instance the human operator cannot find a plan, there is always the nagging possibility that with more effort or cleverness, he could have.

TOM neatly fills this void. It can be used to *automatically* find a control scheme to meet both the predetermined load and the proposed extra load, rather than calling on a human to find a valid control scheme for the simulation. Conversely, if TOM cannot find a valid operational plan that makes all deliveries, the proposed contract can be rejected. This validated/rejected information is passed back to the broker.

- **Characterization of spare capacity**

Another approach to the "well informed broker" problem is to provide him up-front with an estimate of *spare capacity*. Spare capacity is hypothetical gas that could be delivered above and beyond predetermined loads. If such a quantity can be properly defined and computed, the value can then be passed on to the broker. He then knows that he can make any combination of deals that do not exceed this excess capacity.

The concept of spare capacity is well defined for steady-state, particularly for pipelines with only one supply and one delivery point. Simple generalizations can be made to do weighted optimization of more than one supply and/or delivery point, although proper use and interpretation of results becomes more complex. Steady state "throughput maximization" optimization tools have long been used in situations of this nature.

In transient and/or networked pipelines, the question of spare capacity is more complex. Suppose we use steady state tools to show that a pipeline can deliver 500 MMSCF/D average flow and we know that predetermined industrial loads average 400 MMSCF/D. Can we safely say that any arbitrary contract averaging 100 MMSCF/D can be accepted? No, because the deliveries are not necessarily constant in time. The industrial loads which average 400 MMSCF/D may actually have a peak of 500 MMSCF/D although the daily average is only 400. If the proposed extra contract draws 100 MMSCF/D constantly, that makes the actual peak load 600 MMSCF/D. So this combination of loads may be impossible to deliver even though the daily average satisfies the steady state limit.

On the other hand, an extra contract of 50 MMSCF/D would give total average 450 and worst instantaneous peak of 550. In a transient environment where line pack distribution can be manipulated as a resource, short term peaks can often be met even if they are well in excess of sustainable capacity. Suppose that by using line pack, the 550 instantaneous peaks can actually be met. Steady state analysis based on daily average would correctly say that the contract is feasible, but use incorrect logic in reaching that conclusion. Steady state analysis based on comparing maximum combined instantaneous peaks to steady state maximum sustainable capacity will be overly pessimistic and reject the contract.

Clearly, steady state analysis is not adequate for this sort of analysis. TOM can be better tool, using its capabilities in various ways.

First, either of the proposed contracts can be validated or rejected as described in the last section. This is good, but only gives the broker information *in reaction* to his proposed contracts.

Second, TOM can be configured to compute a *generalized definition of spare capacity*. That is, it can directly compute the maximum attainable size of a proposed contract, rather than just validating or rejecting a specific contract size suggested by the broker. For instance, take the previous example, and suppose we may wish to make a spot market sale in the afternoon to a power plant, and want to know in advance how much we can sell. Mathematically, we just define an optimizable contract profile between say 1PM and 6PM, and ask the TOM software for the operating plan that maximizes average deliveries of the optimizable contract. TOM then computes how large we can make this contract, while simultaneously ensuring that the fluctuating predetermined loads can be met. It also presents us with the detailed operating plan that allows us to achieve these loads. The computed spare capacity will automatically be as large as possible given the potentially conflicting predetermined loads, and this will all be computed in a fully transient sense. This definition of spare capacity is much more meaningful that steady state limits, and can be given to the broker as a limit.

For pipelines that have more than one supply/delivery point pair, the concept of spare capacity is more complicated.

Accepting a contract between points A and B obviously affects spare capacity for future additional contracts between A and B, but also hydraulically can affect spare capacity between A and C, and D and E, etc. The methods above can be run repeatedly to generate if-then contingency tables to be given to brokers, but the combinatoric complexity grows at an intractably rate. The pipeline simulation industry needs to give more thought to supporting decisions in this situation.

- **Load Shedding**

Unfortunately, sometimes equipment can unexpectedly fail, brokers can oversell, blizzards can hit the cities you supply, and a pipeline can find itself unable to deliver contracts. Sometimes interruptible loads can be shed, but in the worst case firm loads must be curtailed. These situations are generally very expensive for the pipeline.

In finding the optimal operating plan, TOM may help an operator avoid shedding loads in the first place, provided it is possible. If shedding is unavoidable, TOM may help in containing the damage.

Sometimes there is a predefined formula specifying the order in which loads are shed. This leaves little room for optimization to help. However if there is any freedom of choice, optimization may be quite useful. The “spare capacity” technique in the last section can be easily reconfigured to minimize integrated delivery volume shed. If each curtailed contract has an associated price/unit, TOM can select the least expensive curtailment plan.

Rules regarding curtailment are complex and seem to be very different in different countries. Applicability of the simple price/unit scheme in the last paragraph may be limited due to cost-per-incident sort of fines as opposed to cost-per-total-curtailed-volume. This is another area where more activity in the pipeline simulation community is merited.

- **Selection of best combination of sources and deliveries**

Circumstances sometimes exist where a contract can be written with a flexible combination of supplies and/or deliveries. Each supply will have a direct cost/SCF and each delivery will have a direct profit/SCF. Since the various supplies and various delivery points are geographically separated, implicitly there are different transportation costs independent of gas prices at the different locations. Other time-varying loads within a system can compete with the various contract flow points in complex, time dependent ways. The task is to pick the ideal combinations of volumes to get from each supply, and the ideal combinations to give to each delivery.

The techniques of the previous two sections apply directly to cases like this. One merely needs to make each supply or delivery flow profile an optimizable quantity, and assign the appropriate price to each one. The optimization will pick the best flow combination and best operating plan to maximize profit.

3.3 Use in Strategic Settings

TOM can also be used for strategic analysis. Some such applications involve completely hypothetical studies and may not require initialization to an accurate “current state”.

- **Analysis of lost opportunity costs**

Rachford et al. [7] shows how TOM can allow one to quantify lost opportunity costs to the pipeline if one of their clients insists on taking their entire load in a brief interval rather than spread out over the day.

- **Linepack positioning for uncertain load**

Carter et al.[6] show how to use TOM to create operational plans that automatically position line pack to prepare for uncertainty in upcoming loads. This is a “strategic” use of

TOM, but it would most likely be applied as a control room tool starting from an accurate state estimation.

- **Fair use of linepack changes**

Some transport systems consist of several sub networks operated by different companies, containing different pipe sizes and gas volumes. In case of some major dropout pressure and overall linepack might decrease gradually. In this case the allocation of gas in each subsystem needs to be done in a fair way. An extra constraint can be added to TOM formulations to handle such situations. The constraint could simply be: "distribute linepack changes in proportion to the pipe volumes of the subsystems."

- **Storage**

TOM manipulates line pack mass and energy as a resource to meet fluctuating loads. [4] Hypothetically, TOM could manage mass within storage fields as a resource in much the same way. Longer time scales would be necessary of course. This is another area where more activity in the pipeline simulation community is merited.

- **Pipeline design**

Pipelines are often designed using steady state tools despite the fact that most pipelines seldom operate for long at steady state. The methodology is often to create a hypothetical pipeline design, analyze its performance, repeat those 2 steps many times, and pick the best design from among all the cases based on some measure of “best performance.”

Transient simulation is sometimes also used to help assess the various designs. (Ideally it should always be used.) Selected hypothetical transient events are simulated to see how well the pipeline performs. One difficulty is that for each transient event, a pipeline operation plan also needs to go into the simulation. If a good pipeline design happens to be given a bad operational plan for the test, or vice versa, the wrong pipeline design can easily be selected.

This pitfall is not unique to transient simulation based design, and it has a simple solution. A venerable method in steady state design is to always use steady state *optimization* to create an operational plan for each potential pipeline design and its associated test cases, rather than relying on a simple simulation. That way when test cases are compared, they will be on an even footing.

TOM can be used in exactly the same way to regularize design comparisons when doing transient performance assessment.

- **Establishing best practices for running new networks**

Human operators can be extremely good at running pipelines, but this is often a function of experience. New pipelines can behave very differently than the pipelines operators trained on. And new pipelines don’t yet have a training manual or “playbook” that tells how to operate the pipeline under various conditions.

Repeated transient simulations can be used to investigate the behavior of a new pipeline over a broad variety of circumstances, without the inconvenient possibility of destroying the pipeline during real world experimentation. These results can be used to create documentation, manuals, and “to train the trainers.”

This is a powerful technique but TOM can make it much better. First, it can directly quantify the limits of operation (throughput, etc.), rather than just providing a range of case studies some of which worked and some of which failed.

More importantly, for hypothetical situations, it can not only say whether or not the situation can be managed, it also generates the precise operational plan one should use. These plans can be collected and can provide the start of a "best practices user manual" or "operator's playbook".

3.4 Challenges

- **Uncertainty**

Many things going into any simulation or optimization are typically uncertain. Pipe roughness, precise operating characteristics of aging compressors, and inaccurate measurements from instrumentation are all factors. Uncertainty in load forecasts is also an important thing to consider. This last item has been partially addressed in [6] but this is another area where more activity in the pipeline simulation community is merited.

- **Complexity (understanding, problem formulation, data)**

Pipeline simulations can be arbitrarily complex, so much so that it may be difficult to fully understand how to best formulate a simulation, and understanding what the simulation is doing, let alone formulating and understanding an optimization. But interpreting optimization results rely on knowing what the limitations of the methods are, what TOM is allowed to change, level of accuracy of data, etc.

Intelligently designed interfaces, and lots of operator training, is the traditional way to mitigate some of these issues. However, this is another area where more activity in the pipeline simulation community is merited. One should use enough complexity to do the job.

- **Computational time**

Results need to be computed quickly enough to be of practical use. Given the magnitude of computation needed for larger systems, very aggressive attention needs to be given to computational speed in any computer implementation of TOM.

- **Extra task for the operator instead of help?**

Computer implementations also need to be easy to use. They need to be written so that operators and users see the program as a *useful daily tool*. Poorly written interfaces, no matter how good the underlying mathematical method, can create an extra chore for an operator as opposed to a helping hand. Interfaces need to present the right data, and they need to present it in a way that makes it easier for operators to make informed decisions, rather than making it harder. This is a *crucially important* area where more activity in the pipeline simulation community is merited.

- **Technological limitations (e.g. global vs. local optimum)**

Although TOM is enormously powerful in principle, make no mistake: transient optimization is computationally difficult. Various TOM approaches have different strengths and weaknesses in what can be easily formulated. Also, just as in steady state optimization, results must be interpreted carefully. Just as one should not treat a steady state simulation as a valid picture of a pipeline in flux, one should also be aware that TOM results are not oracular. Some examples of this are as follows.

TOM is only as good as the data it is given. It will run slower on more complex models, so the dictum "model it as simple as you can for your requirements" is very true for TOM. Conversely it will give misleading answers if the model is *too* simple. It cannot optimize all possible parameters that a user might be able to change within a *simulation*, it can only optimize those that match the TOM framework.

And, for problems of this complexity, methods that are fast enough to be useful tend to have their own pitfalls. They always recommend *improvements* to the default operation, sometimes large, sometimes small. Even if TOM finds a very different operating plan from the default, with great performance improvement, this plan still may be a “local optimum”. A local optimum is a spot where the software has stopped because its current answer is better than it can get by any incremental modification to the operating plan over any combination of variables. However, there is no guarantee that if TOM somehow searched broadly enough with radical changes that it might find a “global optimum” better than the local one returned. Optimization methods which provably “always find global solutions” to hard problems abound, and are actually quite easy to create, but the fine print of their convergence proof always has the words “given an infinite amount of time.” What matters in the real world is whether a method can give you a useful improvement fast enough for it still to be useful.

Users who are happy with a tool that consistently recommends improvements to their own guesses, in time to be usefully applied, are likely to be happy with TOM results. Users who insist that there be no possible better answer anywhere may be disappointed.

4. Specific Examples

In the last section we discussed a very broad range of expected useful applications, but only in general terms.

In this section we examine an example in much greater detail, and point out where it fits within the taxonomy of Section 3.

4.1 OMV – WAG Performance Test

4.1.1 Steady State Planning

OMV has implemented a practical example that fits into the “Reliable response to challenging conditions” category, and almost all other aspects named in Section “3.1 Operations”.

The WAG network is a simple transmission system that generally transports gas from Slovakia to Germany in East/West direction and simultaneously supplies deliveries within Austria. There are cases however when the normal flow direction is violated, bringing gas from Germany into Austria (Figure 1).

During a time when normal flow was very low planners where challenged to carry out a performance test. The main goal of this test was to confirm the design capacity of the WAG System for East/West flow. For several reasons it was expected that the pipeline system offers more capacity than previously calculated. One of the suspected reasons was a lower roughness of the pipes. For reaching a transparent and clear conclusion, this maximum flow situation had to be carried out practically.

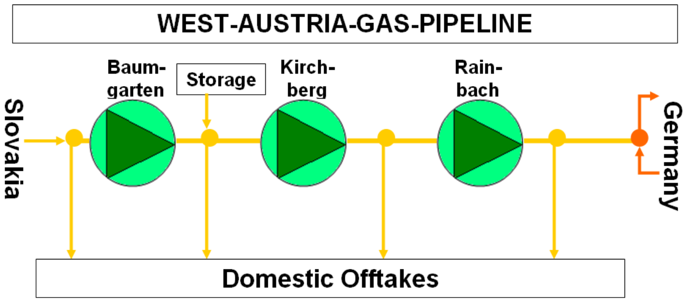

Figure 1: Scheme of the WAG system

It was necessary to fulfill the daily regime for all shippers within Austria without any interruptions or restrictions. Therefore the performance test had to be well organized and coordinated with the adjacent upstream and downstream Transport System Operators.

Nominated flow rates for all offtake points were estimated in advance. Furthermore it was not certain in which direction the system would be operated at the time the performance test would start. We assumed West/East flow, the usual direction for that season. Starting from that point a schedule for increasing main flow rate was developed consisting of 6 steps based on the operators’ previous experience on the WAG system (Figure 2).

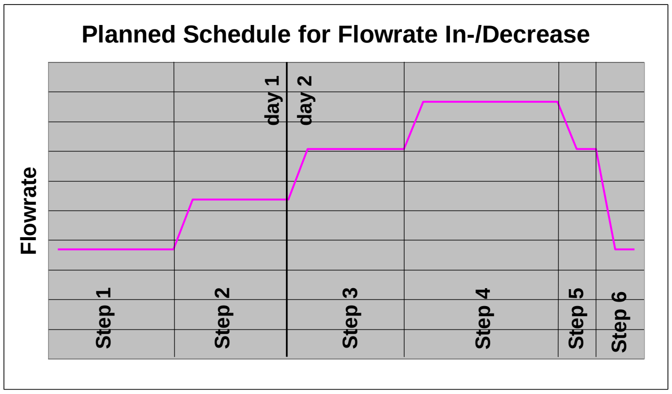

Figure 2: Scheduled steps for increasing flowrate

It was necessary to prepare the schedule for the required main flow rate for the TSOs in Slovakia and Germany in order to balance the surplus at the beginning of the test on the one hand and the shortage after the test on the other hand. Additionally it required performing the schedule without any influences on the domestic supply or domestic market. Differences had to be compensated by domestic storage gas only.

Furthermore we had to organize additional manpower at the compressor stations for checking instruments and change settings in station control systems.

The six steps of the original schedule were developed via a sequence of steady state optimization runs. The length of each period was chosen manually, long enough for reaching steady state conditions and for having good data for later verification of the hydraulic model. The length of each period was originally planned for six hours.

4.1.2 Practical execution of the performance test

Transition periods between the steps have been the unknown variables. Without transient calculations those dynamic operations had to be done according to the operator’s previous experience.

During the first step of flow reversal it became obvious that the transition periods from step to step were estimated longer than necessary. So we decided to shorten the periods - one of the first results of the performance test, as described in the next section.

During the test we had to face several unexpected situations. Outages within all three compressor stations interrupted flow at different periods of time. The stations are relatively new and had never faced such high performing situations until the performance test. In CS Baumgarten, the intake station for gas import from Slovakia, the recirculation valve opened and the performance dropped. In the next station, CS Kirchberg, the internal station control system shut the station down because of a temperature high alert in the exhaust system. The third station, CS Rainbach, dropped out shortly due to a wrong placement of the transmitter for discharge pressure. Figure 3 indicates the chronology of events.

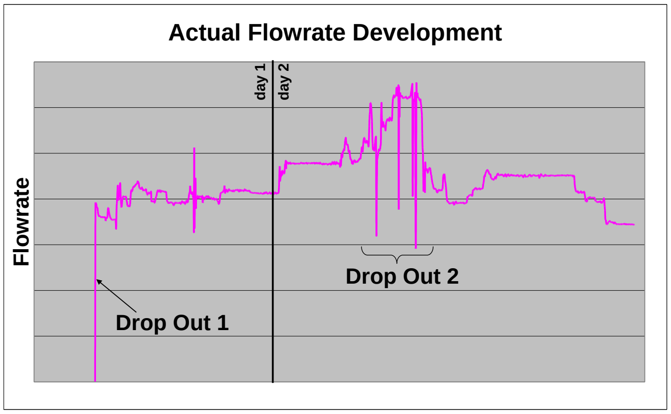

Figure 3: Actual flow rate with unexpected problems

For changing the flow direction from West/East to East/West it was necessary to provide additional gas quantities for keeping the period as short as possible. The amount of approx. 200,000Nm³ (~7MMSCF) corresponds to the difference of gas volume between initial and design capacity state.

Due to the above mentioned problems within the compressor stations there was hardly enough time to achieve steady state periods at all. Nevertheless it was possible to obtain 3 short periods which have been nearly constant.

The most important goal was reached. It was possible to operate the system at the desired maximum for a short period of time. The steady state design capacity was confirmed. Furthermore it was possible to detect a spare capacity of approx. 100,000 Nm³/h (~85MMSCF/D).

To get back to the initial situation as it was before the performance test it was necessary to change flow direction back to West/East. This transition could be done much faster than at the beginning of the performance test.

After the performance test the recorded pressure and flow rate data were used to fine tune the hydraulic model used for optimization.

4.1.3 Use of Transient Optimization in the above

Highly dynamic situations like the change of flow direction had occurred several times in the past. The operators had some experience and usually performed this delicate operation very cautiously. Confidence in TOM had not yet been established however.

After the steady state planning stage several offline studies using a Transient Optimizer were made to support the performance test operations and to find out, whether better control regimes could be obtained.

Supporting the performance test:

First transient results indicated that the entire performance test could be done much faster than originally planned. This didn’t seriously contradict to the operators’ experience. So as a first consequence of transient calculations the decision was taken to split the operation into the two phases:

- Change of flow direction to be completed on day one by the end of day shift. Steady flow over night.
- Increase of flow rate starting at 6 a.m. day two, reaching design capacity flow between 12 and 2 p.m. and returning to initial conditions till the end of day shift.

Optimizing the control schedule:

Only after completion of the performance test the transient studies were continued to find out more efficient strategies with respect to

- Time for reaching design flow rate
- Amount of storage gas
- Fuel consumption.

An optimization scenario is roughly characterized by a given initial state, some constraints on the final state, given boundary flows and pressures and a number of internal control settings to be optimized.

Step 1 defines the steady state initial conditions with West-East flow from Germany and only the first compressor station running. The domestic deliveries remain constant over time, while main input and output flow are being raised and lowered simultaneously according to steps two to six. The final state is characterized by one additional constraint: the total gas volume must be the same as initially, which practically restores initial state.

The task of TOM is to obtain the most efficient and dynamically correct answers for questions like this:

- When are the other compressor stations needed and what are the flow rate set points?
- When is extra storage gas needed, how much, and when can it be returned?
- Pressure development throughout the network

Three optimization scenarios are being discussed, all based on fuel minimization. To keep the model small only a small number of eight periods is used, representing relatively large time steps (hours). All the transient dynamics occur in periods two to seven, design flow must be maintained in periods five and six. Changing the lengths of time steps changes the overall time for the entire operation.

The resulting pressure values in period 6 show how well the steady state requirement is met during design flow, deviations are given in units of 1 bar ~ 14 psi. Gas volumes are specified in units of 1000 Nm3, equivalent to ~ 35 MSCF.

1. **Run T1** more or less corresponds to the original “steady state” schedule with slow build up of flow, but now correctly respecting the transient effects. Equal time steps

of 4 hours lead to a 24 hour period from initial to final state. It serves as a base run for later comparisons.

Time steps: 4 4 4 4 4 4 4 4 hours.
Time to reach design state: 20 hours
Design state: steady within 0.1 bar ~ 1 psi
Storage gas (1000 Nm3): 0 -528 24 409 0 0 98 0
~ MMSCF: 0 -19 1 14 0 0 3 0
Total fuel: 217 (1000 Nm3) ~ 7 MMSCF

2. **Run T2** successfully finds a faster approach to reaching design flow rate. Using the same flow regime as T1 the time steps were reduced in length. Within a significantly shorter time of only 10 hours it is possible to perform the entire transient operation, reaching practically the same steady state at design capacity, see Figure 5. Compressor Stations 2 and 3 are started much later causing a large reduction of fuel gas, see Figure 6. Less storage gas can be considered as another pleasant side effect. The main advantage however: the entire test could be performed within one work day.

   Time steps: 1 1 1 1 2 2 3 1 hours
   Time to reach design state: 7 hours (vs. 20 in T1)
   Design state: steady within 0.3 bar ~ 4 psi
   Storage gas (1000 Nm3): 0 -254 0 179 0 0 75 0
   ~ MMSCF: 0 -9 0 6 0 0 3 0
   Total fuel: 93 (1000 Nm3) ~ 3.2 MMSCF

3. **Run T3** uses the same approach as run T2, but shows further benefits from using the optimizer. OMVs storage department will soon become an independent company, so the question should be answered, whether a control regime could be found which needs less storage gas. Putting cost factors on the storage source resulted in an interesting alternative strategy. A solution was found which hardly requires any extra gas, thus achieving all the line pack changes via compressor operations only, however at the cost of more fuel gas.

   Time steps: 1 1 1 1 2 2 3 1 hours
   Time to reach design state: ~7 hours
   Design state: steady state achieved approximately, within
   0.9 bar ~ 13 psi
   Storage gas: 0
   Total fuel: 97 (1000 Nm3) ~ 3.4 MMSCF

4.1.4 Conclusions from OMV study

The positive experiences around the performance test for this small WAG network encouraged users to make transient analysis available for regular use in everyday operations for the entire gas transport system. A project has been started to set up an

- **Online Transient Optimization System**

This is currently in its final implement phase. Every hour a “look ahead” optimization run calculates the most efficient control strategy, based on a new set of future nominations as well as all operational restrictions known for the planning period. Main goal: fuel minimization.

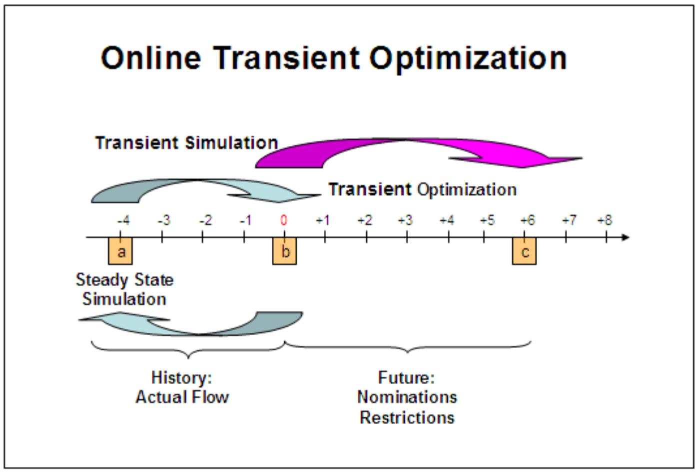

Figure 4: Principle of transient optimization

The complete knowledge of the current state is essential for transient analysis; a delicate matter since no state finding software is used by OMV. However, a “backdoor solution” for state finding has been developed which is solely based on the TOM tool according to the following procedure:

It starts with going back in time searching for the first near steady state, point “a” in the figure above. A steady state simulation run determines a complete set of pressures at “a”, which in turn serves as the initial state for a transient simulation rerunning history from “a” to present time “b”. Measured control flow rates are used for this simulation run, which returns a complete transient current state at point “b”, the initial state for the actual look ahead optimization.

- **Expectations**

Future demands of the gas market will require a variety of transient applications. The next step for OMV Gas will be the implementation of the Entry/Exit-Model. This market model offers shippers the possibility to feed gas into the Austrian system at one point and put it out at any other point. The main difference is that the shipper does not have to buy a capacity over a certain length of transportation, but he buys a certain capacity at any intake or off take point in the whole Austrian system. From one hour to the other significant amounts of gas might have to be transferred to another transport line which can even cause flow reversal along the WAG line. So highly dynamic conditions will have to be dealt with gracefully.

The focus for a Transport System Operator, such as OMV Gas, will be to cover the higher demand on flexibility by higher developed optimization programs.

Summary

Transient optimization can be used to address an extremely broad range of pipeline problems. We encourage discussion and feedback between industry practitioners and industry operators and engineers, particularly as regards to our “three questions.”

- Do the ranges of described uses in this paper seem pertinent to real pipelines?
- Which are most useful and under what circumstances?
- Are there any enhanced capabilities or reformulations that would increase the usefulness further?

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FIGURES

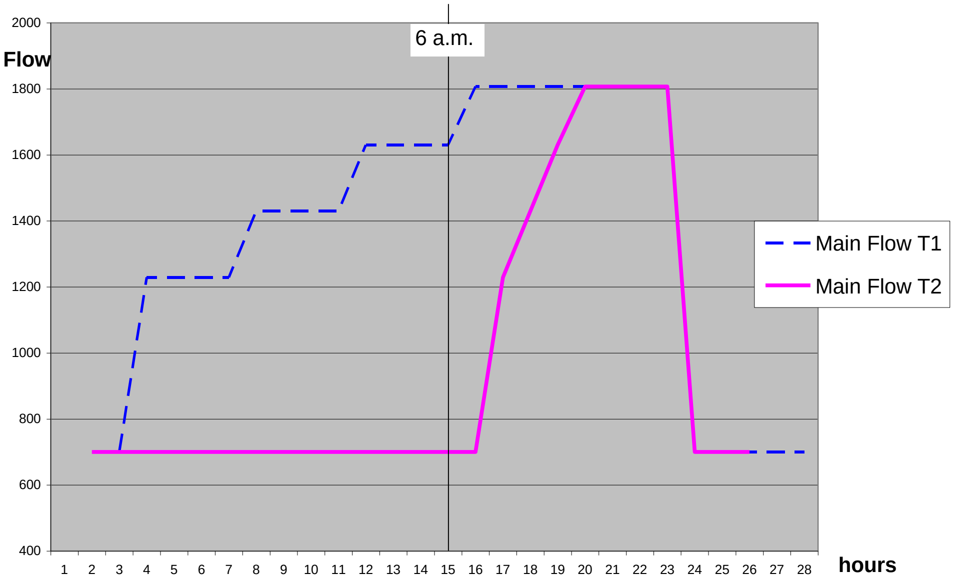

Figure 5. WAG Input Flow rate for Optimization Runs T1 and T2

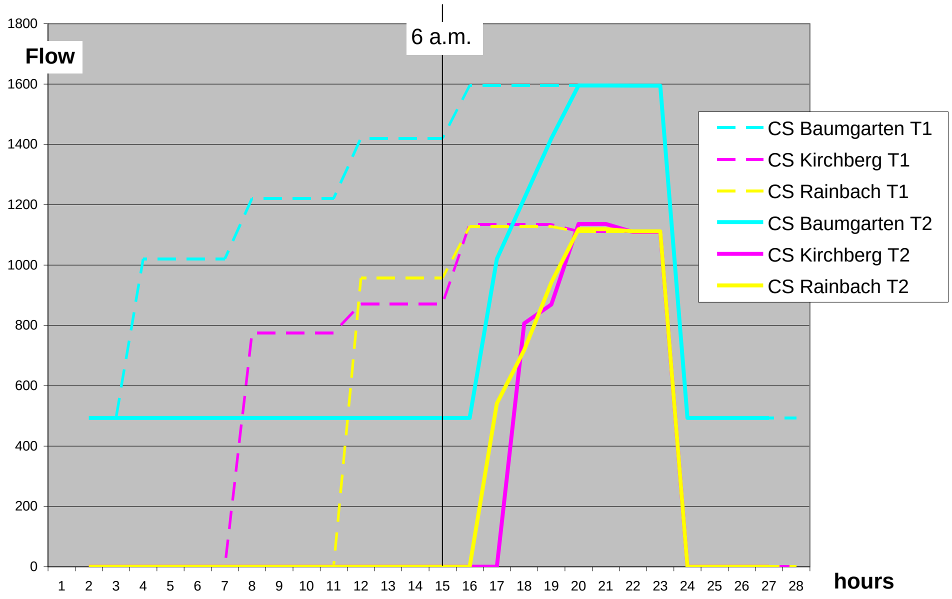

Figure 6. WAG Compressor Flow rates for Optimization Runs T1 and T2

Author Biographies

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- **Erwin Sekirnjak** holds a Ph.D in Physics from the University of Vienna. For 27 years he had been working for the Austrian Oil and Gas Company, OMV in various areas of computer applications with emphasis on operations research methods. His responsibilities covered simulation and optimization in the areas of reservoir engineering, refinery planning, long-term company investments, and gas transportation systems. Since 1998 he worked as a scientific consultant in the area of gas network optimization first for PSI AG, Berlin and now for ADES, Vienna.