Originally appeared in:
February 2011, pgs 85-89.
Used with permission.
HYDROCARBON PROCESSING®

Circumvent design issues when adding new hydrotreating units

Follow these guidelines for substantial capital cost savings with existing flare systems

M. H. MARCHETTI, A-Evangelista, S.A., Buenos Aires, Argentina

Due to higher global demand for gasoil and gasoline along with strict environmental regulations, refineries are incorporating new hydrotreating units into their existing facilities. Just in the southern cone of Latin America (Argentina, Chile and Uruguay) at least five hydrotreating units have been projected and/or built in the last five years. These hydrotreating units aim to lower the sulfur content to 20 ppm–50 ppm on final products.

Project attention focuses on these new hydrotreating units, while utilities and other services are evaluated later in the project cycle. Verifying the existing refinery flare systems has to be performed as early as possible during the detail engineering project phase to answer key questions, such as: Would the existing crude distillation unit pressure-relief valve (PSV) open with the new backpressure introduced from the new hydrotreating unit's PSV? Is the existing flare tall enough that it doesn't exceed the radiation limits at ground level? Are the emission contaminants changing compared to the previous refinery operations?

Method description and best practice tips. The proposed methodology is used as a multi-tier approach to compress project schedules, determine PSV requirements earlier in the project and purchase those PSVs early, if it's economical; assess alternatives to improve design and save on capital costs without compromising safety.

To quickly identify possible problems, relief loads are first calculated using a simple approach. The different concurrent contingency loads can be calculated with the basic material and energy balance engineering data. A conservative enthalpy balance approach can be used. For example, in a column with a cooling failure, power failure or reflux failure, the energy balance is:

$$F \times h_F + Q_R = B \times h_B + P \times h_P + V \times h_V + Q_A + Q_I + L \times h_L \qquad (1)$$

where:

F = Feed flow
h_F = Feed enthalpy
Q_R = Reboiler duty
B = Bottom liquid flow
h_B = Bottom liquid enthalpy
P = Product flow
h_P = Product enthalpy
V = Vapor flow
h_V = Vapor enthalpy
L = Relief load
h_L = Relief load enthalpy
Q_A = Air cooler (condenser) duty
Q_I = Trim cooler (condenser) duty
$\lambda_{reboiler}$ = Latent heat of vaporization or, for multicomponent systems, the difference between the vapor and liquid specific enthalpies.

The reboiler duty is recalculated for relieving conditions. For an air-cooler contingency (or power loss), Q_A in relieving conditions would be 20% of operating Q_A. For cooling water loss, Q_I would be 0. To evaluate a reflux failure, the top tray vapor less the operating vapor to the condenser is a good approximation to calculate L.[1–4,7]

Example. With a new gasoline stabilizer column without an air-cooler condenser (Q_A = 0), the following quick calculations were considered to estimate the relief load for a loss of cooling in the condenser:

- A steady-state simulation model was used (Fig. 2), setting the column pressure as the opening valve pressure and Q_I = 0. The relief load is calculated as L = 3,732 kg/hr.
- For normal vapor flow to the condenser from the material and energy balance (V_1), the relief load is calculated as L = 2,923 kg/hr.
- As an approximation, using $(Q_I + Q_A)/\lambda_{reboiler}$, the relief load is L = 3,035kg/hr.

Once the preliminary relief loads are calculated, the new pressure-relief valves are sized, and the new flare system lines are designed and routed into a new unit subheader. While calculating the concurrent PSV contingency loads, most coming from columns, towers or pressure separators, other process engineers can work on calculating all the single-contingency PSV loads, such as blocked outlet loads, control valve full-open cases, etc.

HAZOP analyses and relief scenarios. A hazardous operation (HAZOP) analysis of the new process enables assessment of the number of PSVs that might be triggered to open in various scenarios. In a new gasoline hydrotreating unit, the number of PSVs involved in a multivalve opening contingency, other than fire, that could impact the existing flare design rating are shown in Table 1.

Out of 30 PSVs, only two were involved in concurrent PSV discharge scenarios—a cooling water and general power failure—

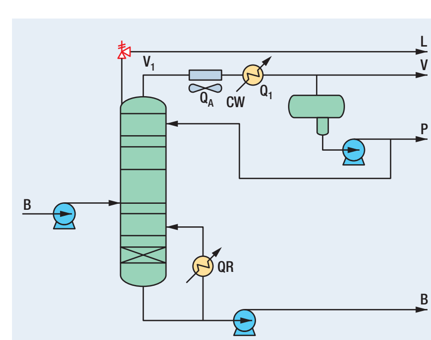

FIG. 1 Material and energy balance in a column.

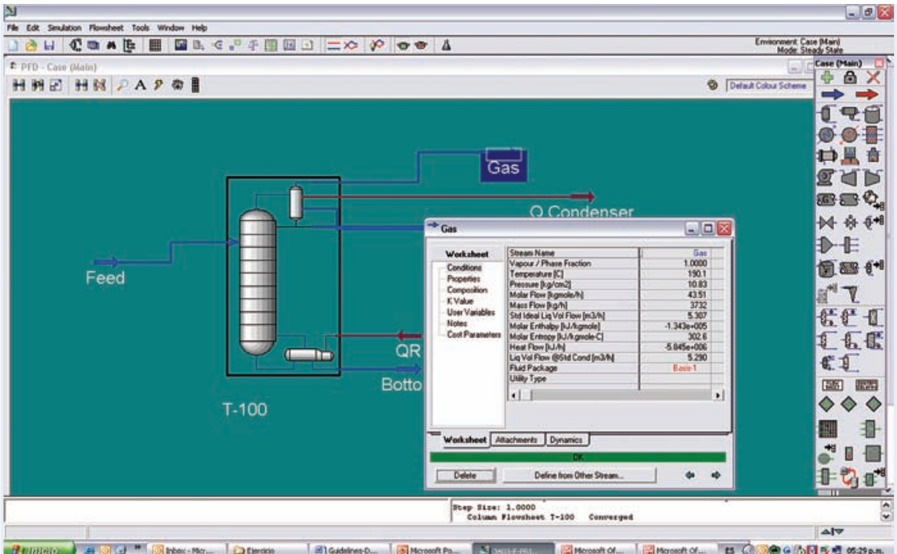

FIG. 2 A steady-state simulation model.

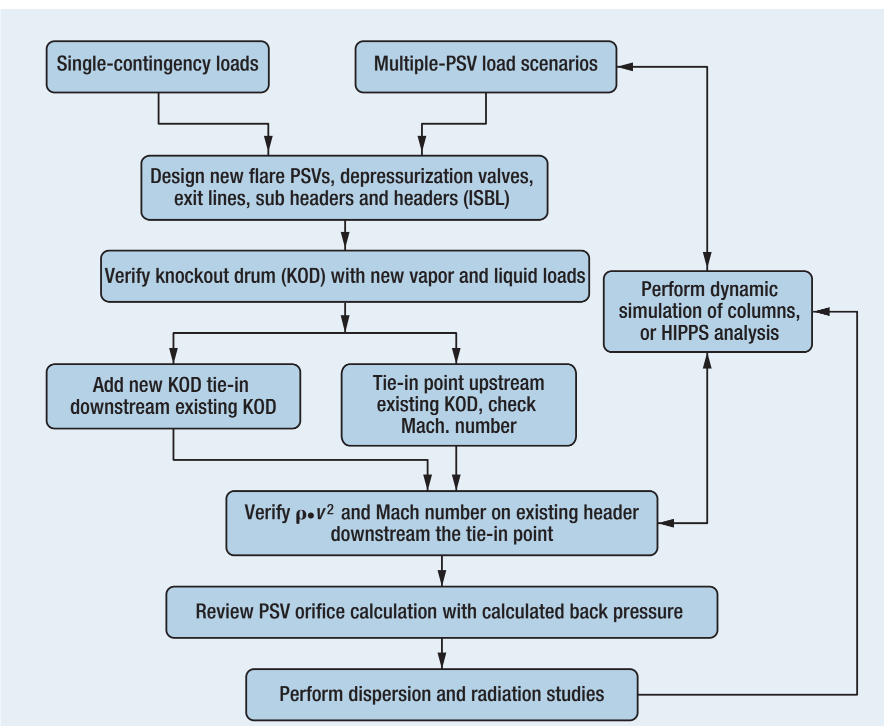

FIG. 3 Flare system rating method workflow.

TABLE 1. Gasoline hydrotreating unit relief scenarios

Contingency	Fire	Concurrent other than fire	Single contingency only
Number of PSVs involved	25	2	4

and these potentially affect the existing flare header performance. All other contingencies, including fire, were unit-wide scenarios but not plant- or refinery-wide scenarios. The number of plant-wide scenarios that might affect existing flare backpressure, radiation intensity and contaminant dispersion was reduced to two. Only these two scenarios had to be studied further at a plant-wide level. All other new-unit scenarios were studied separately to size the new unit main header, which in this example was determined to be governed by one of the fire cases.

Engineering workflow and guidelines. Fig. 3 represents the workflow of the flare-system rating method. The various steps are described as follows:

- Workflow starts with a parallel evaluation of multiple PSV load contingencies and single or unit-wide contingencies, using a flare-system analyzer model.
- New flare network is designed. At this stage in the detailed engineering project, the new units' isometrics are not available. To complete the flare header design and rating, basic routing of PSV exits are made over the plot plan of the plant or layout of new and existing units. Choosing the tie-in point and knockout drum verification will be discussed in detail later.
- The network is designed and rated to project-specific values of $\rho \cdot v2$ and Mach number. Good engineering practice uses $\rho \cdot v2$ for gases of less than 150,000 Pa and Mach numbers of 0.3 to 0.7. If these parameters are not met in the existing main header, then a better understanding of the existing relief loads can be achieved through dynamic simulation. Once the hydraulic calculations comply with the design parameters, the PSV orifice calculations for the multi-PSV opening cases are reviewed. Dispersion and radiation studies are performed and, if all studies comply with international and local regulations, the flare-system rating is completed.

Unfortunately, flare-system analysis does not always follow a straight path. Sometimes a more detailed analysis and additional problem-solving solutions are required, and these will be discussed further.

Tie-in point and final disposal design. The tie-in location choice is generally made as close to the flare stack as possible, taking into consideration whether the existing knockout drum can handle the worst case vapor and liquid loads. When a PSV has a high setpoint and the volumetric flow for the design case is high, the Mach number at the tie-in point tends to be high as well. In these cases, having a higher backpressure at the tie-in point can reduce the Mach number. For example, moving the tie-in point upstream in the existing flare header helps reduce the Mach number; the consequence is a slight increase in the backpressure.

Fig. 4 illustrates an example of a flare system analyzer simulation with a stabilizer PSV that has a high set pressure with its tie-in point in the unit's 16 in. subheader and in a 30-in. main header. The 30-in. tie-in point resulted in high Mach numbers while the resulting Mach numbers using the

16 in. subheader were lower without excessively elevating the PSV's exit backpressure. The resulting hydraulic performance for both situations is shown in Fig. 4.

The existing knock-out drum rating can be performed in parallel with the flare-header rating and later checked by the final simulation model. The various flare-header scenarios are loaded into the simulation tool, and the PSV sizing and flare calculations are performed. The flare-tip pressure drop can be simulated, using the old design data and extrapolated to new loads, using a Bernoulli Equation approximation:

$$\frac{v^2 \times \rho}{2} + P + \rho \times g \times z = K$$

The process engineer can consider the backpressure problems that might arise from these calculations on existing PSVs, especially on the crude unit PSVs that have low pressure settings. For the new units, the project team can select the PSV types, conventional or balanced, and purchase these early if there are cost savings.

The radiation intensity methods described in API 521, a simple radiation method, and Brzustowski and Sommer, can be used to determine the radiation intensity based on the worst case heat of combustion calculations.[1] Finally, the contaminant dispersion into the atmosphere can be calculated using the US EPA Screen 3 models.[9]

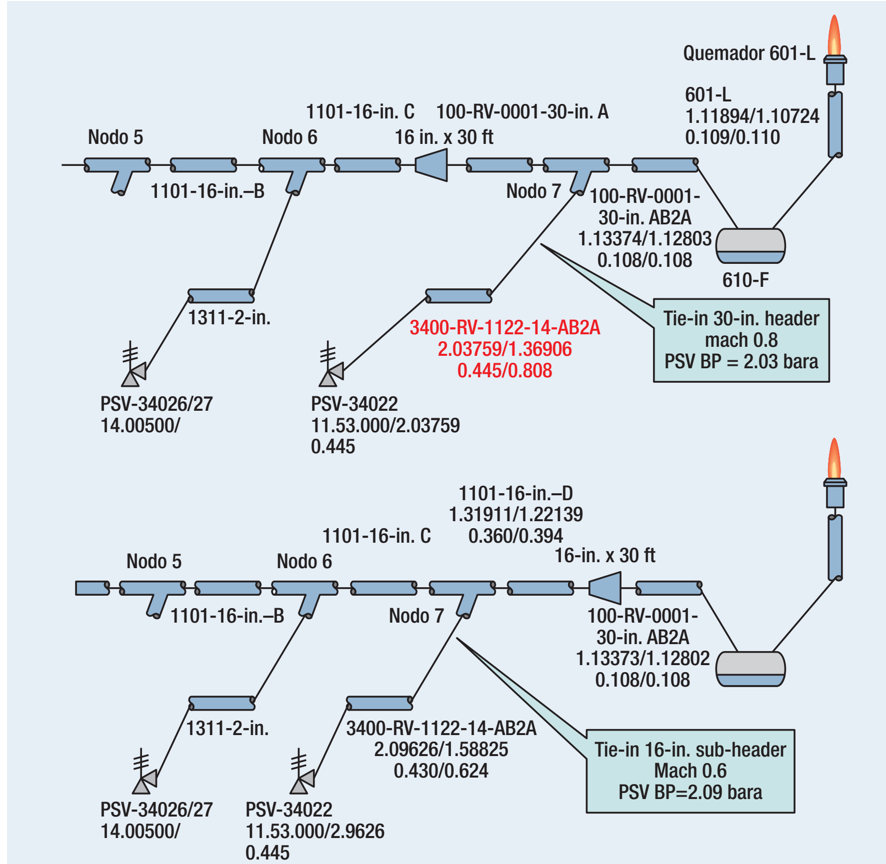

FIG. 4 Tie-in point diagram.[10]

TABLE 2. Gasoline hydrotreating unit PSV changes between revisions

	Rev. A Project's Month 5		Rev. 0 Project's Month 11	
	Number of PSVs	API orifice	Number of PSVs	API orifice
	12	D	13	D
	0	E	2	E
	2	F	0	F
	3	G	3	G
	1	H	1	H
	1	K	1	K
	1	P	0	P
	1	Q	0	Q
	0	R	2	R
Total	**21**		**22**	

When to use dynamic simulation and relief considerations. The relief load calculation is a difficult task when rating or designing a flare system. The API 521 standard gives general guidelines on estimating relief loads but leaves the calculation details to the process engineer's judgment.[1] This is due to the different approaches a process engineer can take to perform relief-load calculations.

As previously discussed, typical scenarios to consider for a column are related to reflux, cooling or power loss. A dynamic modeling approach has been used and documented, and it helped the engineers gain additional insight on what happened during a relief event.[5] Often, this confirms that traditional methods are conservative, allowing engineers to use reduced relief loads while still focusing on safety. However, dynamic simulation takes time and tight project schedules may make it difficult to use this approach. Dynamic simulation benefits are clear and project teams are encouraged to consider it when the situation requires it.

A dynamic simulation (Fig. 5) was performed for the new gasoline stabilizer, resulting in a relief load of L = 2,200 Kg/hr. This load represented a 24% reduction of the lowest load estimation using steady state calculations.

One way to decide when to use dynamic simulation and when to apply the standard steady-state calculations is to analyze if the contingency being studied impacts the whole flare system, involving multiple units across the plant or refinery. If this contingency is limited to a single unit and does not impact the whole flare system, and if the pressure drop does not increase substantially, and there are no radiation or dispersion problems, then dynamic calculations can be avoided.

Guidelines for hydrotreating unit flare analysis. Specifically for hydrotreating units, the guidelines to rate and design a flare system comprise the following load calculations and possible solutions, including dynamic simulation, to

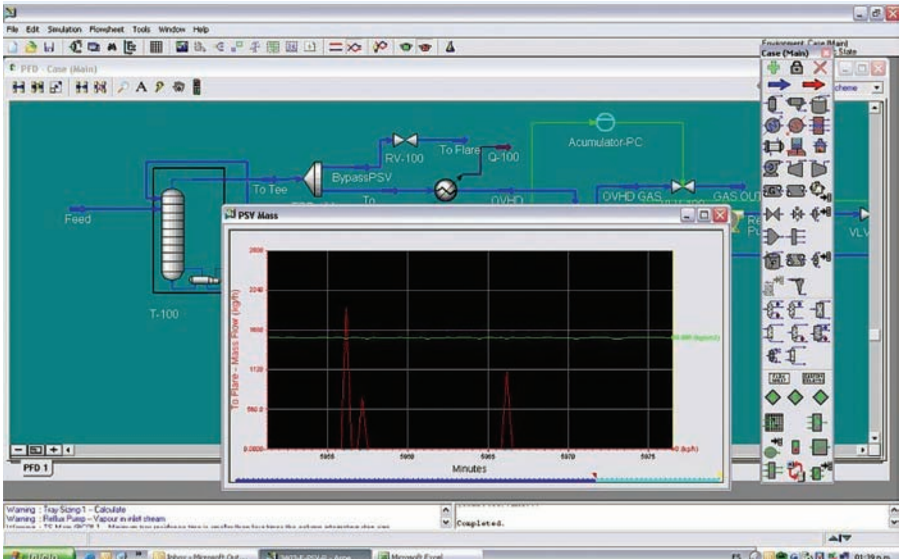

FIG. 5 Dynamic relief load calculations using a simulation model.

TABLE 3. Gasoil hydrotreating unit PSV changes between revisions

	Rev. A Project's Month 5 Number of PSVs	 API orifice	Rev. 0 Project's Month 11 Number of PSVs	 API orifice
	9	D	7	D
	3	E	4	E
	3	F	4	F
	4	G	4	G
	4	H	4	H
	1	J	1	J
	0	K	0	K
	1	M	1	M
	0	P	0	P
	0	Q	0	Q
	0	R	0	R
Total	**25**		**25**	

problems that may be encountered. These guidelines include the usual analysis of relief loads, but also additional consideration of new acid loads, etc.

Evaluate existing loads. Determine if, for a plant-wide concurrent contingency (cooling or power loss, etc.), the new relief loads added to existing loads resulted in any of the following effects or conditions being violated:

- Substantial backpressure changes on existing PSVs
- Radiation intensity at ground level corresponding to API 521 radiation limits
- Air contaminant dispersion complying with EPA and local environmental regulations.

If any of the verification steps fail, the solution is to change the existing conventional PSVs to a balanced (bellow or pilot) type. If the existing PSVs are a balanced type, then it is advisable to perform a dynamic analysis of the PSVs that participate in that design contingency. This would typically involve PSVs with greater volumetric loads and usually concurrent scenarios involving topping columns, absorbers, stabilizers and FCC's safety valves.

New acid loads. The new hydrotreating units concentrate H_2S in the top vapor streams of unit operations. Most of the H_2S is extracted in an amine contactor and then sent to the amine and sour-water unit strippers, which then have the flare loads rich in H_2S and NH_3. If the refinery doesn't already have a sour-flare system, then the company should consider building one when adding the new hydrotreating unit. Dispersion constraints are key in designing this system with concentration limits for SO_2 that are defined by the World Health Organization and other local regulatory authorities.

New sweet-loads evaluation: Hydrotreating unit reactors usually work at high temperatures and when the system is evaluated at opening pressure for a fire relief, the hydrocarbon/H_2 mixture usually enters in a critical flow regime. In these cases API 521 recommends using depressuring systems and dry fire calculations. The loads calculated using API dry formulas are very conservative. A more accurate approach is presented by Ouderkirk.[8]

The new flare-header design for hydrotreating units is often governed by one of these cases:

- Depressurization loads
- Fire loads
- Electrical failure loads (considering that most condensers are air coolers and relief loads for cooling-water failure is minimal compared to an electrical failure).

If the multiple concurrent PSV design scenarios do not comply with the conservative API 521 radiation limits or environmental regulations, it is worth calculating the relief loads using dynamic simulation. Most column relief loads can be calculated with a more rigorous model, and the revised loads are used to rate the overall flare system including recalculating the flare main header, the radiation intensity and the dispersion levels.

While the rigorous models are being developed, the piping engineers might have also completed the isometrics using the first non-rigorous simulation diameters. By the time the more rigorous load calculations are being done, these final flare simulations can be performed, putting all the pieces of the puzzle together (isometrics, revised multiple-contingencey loads, existing PSV pressures, etc.). This provides the most complete, accurate and rigorous analysis.

If radiation intensity, back pressure or contaminant dispersion issues cannot be resolved using the methodology presented, other alternatives may be considered:

1. Perform a high-integrity pressure protection system (HIPPS) project to identify which units control the relief loads, and perform a permutation analysis of the individual relief loads by their probability of occurrence and determine the applicable safety integrity level (SIL). SIL is a measure of the reliability of a safety instrumented system to function as designed. There are

three possible discrete integrity levels (SIL 1, SIL 2 and SIL 3) of safety instrumented systems defined in terms of probability of failure on demand (PFD). SIL 3 has the highest reliability, SIL1 has the lowest. API 521 Fifth Edition allows you to take load credits for the use of HIPPS.[1] The benefit of this approach is the avoidance of having to build a complete new flare. The downside is the operational constraints on the degree of turndown or the possibility even having to shutdown a unit to avoid overloading the flare system, and the capital investment needed to enhance the control systems of existing units.

2. Increase existing flare height. The radiation intensity and dispersion concentration at ground level will improve but the support structures may have to be revamped or new structures added.

3. Change the existing main flare header. Sometimes backpressure problems persist in existing PSVs and the only option is to replace portions of the existing network. Obviously, this will require additional capital investment.

4. Add a gas-recovery facility. When a dispersion analysis results in high contaminant concentration, this approach could partially solve the problem, but it also might increase the backpressure on the PSVs and increase capital cost.

5. Change the flare tip. Sometimes, high Mach numbers at the flare tip can be avoided by simply changing the flare tip.

Results obtained by applying this method. The results of applying this approach to flare-system analysis in a project involving the addition of two new hydrotreating units to an existing refinery are discussed below.

Tables 2 and 3 show the number of PSVs that changed from one type to a different type as the project progressed. This resulted from the simulation model being improved as various engineering tasks were completed, and as the overall design evolved and improved.

Even though many load calculations changed and PSV sizes were revised during the project, the unit's main header diameter, the tie-in point and the knockout-drum calculations remained unchanged between design revisions.

This experience demonstrates that some tasks can be performed in parallel. Later in the project cycle all pieces of the flare system can be quickly recalculated using process simulator and flare system analysis software.

Benefits of using this method. Many benefits can be obtained using the approach presented in this article, as validated by experience on several projects:

- Compressed project schedules by performing PSV calculations and flare system calculations in parallel. For the example cited previously, these calculations resulted in achieving a three-month reduction in the project schedule.
- Project man-hour savings by performing the appropriate level of modeling as required by the project-specific design. The example cited represented saving 160 engineering man-hours of modeling time.
- Early definition of header sizing and the PSVs required. There may be cost savings in procuring these supplies early.
- Material capital cost savings in accurate header sizing.
- New flare cost savings in performing more accurate dynamic-load calculations when needed. **HP**

LITERATURE CITED

1 ANSI/API Standard 521 (ISO 23251), "Pressure-relieving and Depressuring Systems," Fifth Edition, January 2007.

2 ANSI/API Standard 520, "Sizing, Selection and Installation of Pressure-Relieving Devices in Refineries. Part I: Sizing and Selection," Seventh Edition, January 2000.

3 K. Banjee, N. P. Cheremisinoff and P. N. Cheremisinoff, *Flare Gas Systems Pocket Handbook,* Gulf Publishing Company, 1985.

4 Kister, H. Z., "Distillation Operation," MacGraw-Hill, Inc, Chapter 9.

5 Gruber, D., D.-U. Leipnitz, P. Seturaman, M. Alos, J. M. Nougues and M. Brodcorb, "Are there alternatives to an expensive overhaul of a bottlenecked flare system?, *Petroleum Technology Quarterly*, Q1 2010.

6 Marshall, B., "Improve Flare System Design to Reduce Cost and Enhance Safety," AspenTech Webinar, November 2009.

7 Crosby, T. *Pressure Relief Valve Engineering Handbook,* Technical Document, May 1997.

8 Ouderkirk, R., "Rigorously Size Relief Valves for Supercritical Fluids," *CEP Magazine,* August 2002.

9 US Environmental Protection Agency, "Guía del usuario del Modelo SCREEN3," EPA454/B95-004, September 2000.

10 Simulation performed with Aspen Flare System Analyzer V7.1, Aspen Technology, 2009.

Mayra Marchetti is a process engineer at A. Evangelista S.A. She has 10 years´ work experience in process simulation and industrial projects, with a special focus in relief system design and evaluation studies, revamps and new designs. She graduated as a chemical engineer from Buenos Aires University and holds an MS degree in engineering management from Florida International University.