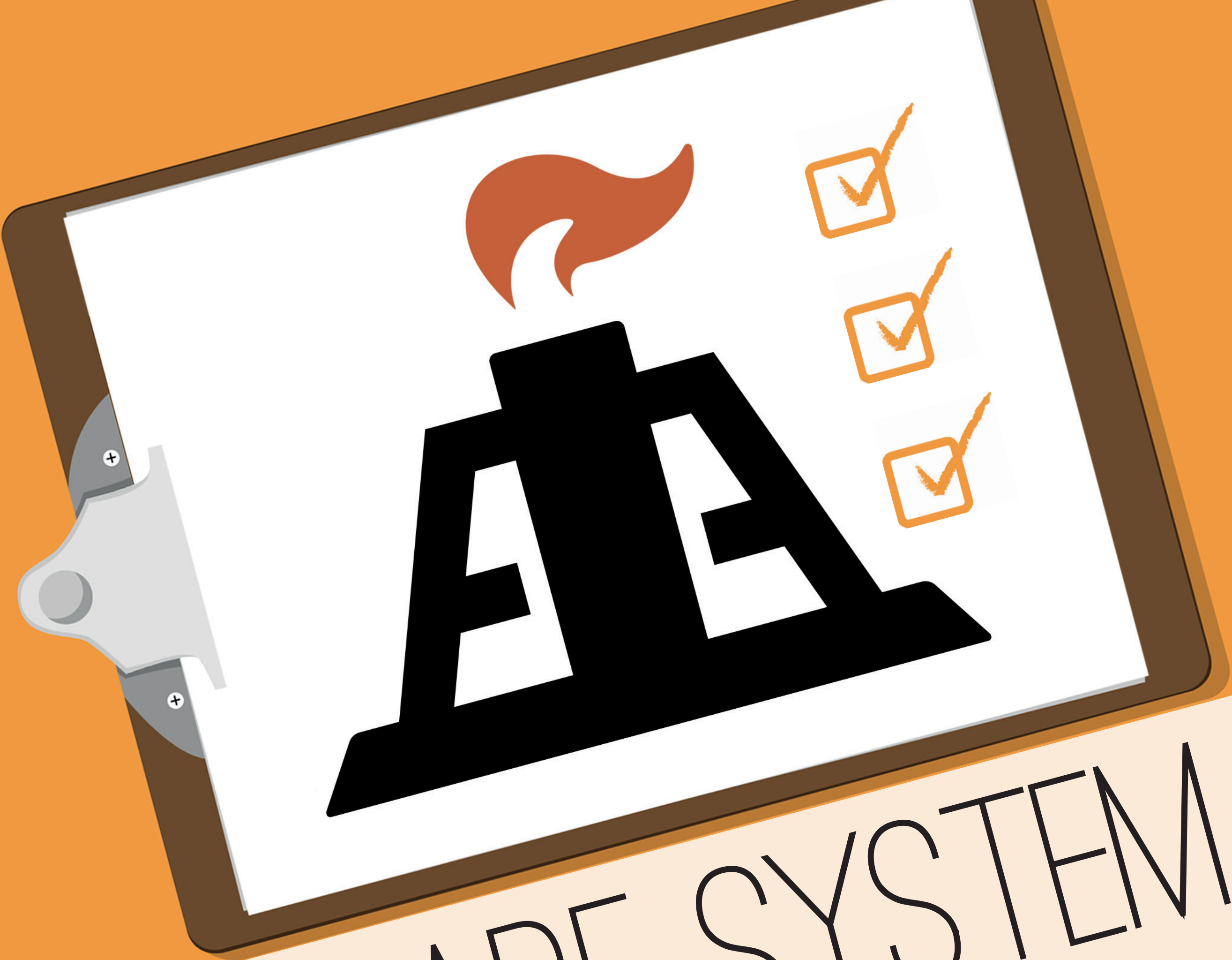

FLARE SYSTEM REGULATIONS

Clayton A. Francis, Zeeco, USA, outlines the potential consequences of proposed legislation to change the laws for flare system design and operation within the US.

In 2020, the US will mark the centennial of one of its greatest social follies, the ratification of the 18th amendment to the US Constitution, or 'Prohibition'. In this social experiment the American government endeavored to legislate what it viewed as moral, appropriate attitudes and behaviour regarding the consumption of alcoholic beverages. While the mission was noble and its aims were pure (healthier, happier, wealthier populace), the complex cascade of reactions and interactions among society, commerce and government caught the country off guard. All kinds of benefits from Prohibition were projected at the removal of this vice, but once the law was enacted the results did not meet expectations. The Prohibition movement and amendment, eventually repealed in 1933, provides a robust case study in unintended consequences. Anecdotes and stories abound where a supposed benefit of the new law led to significant, sometimes overwhelmingly negative, and clearly unanticipated results.

Velocity maximum (in meters/second) for non-air flares

$$H_T = Net\ heating\ value\ of\ gas, MJ/scm$$

$$V_{max} = 10^{(H_T+28.8)/31.7}$$

Velocity maximum for air flares

$$V_{max} = 8.706 + 0.7084(H_T)$$

8.706 = constant

0.7048 = constant

Figure 1. EPA equations relating the heating content of a flare gas to the maximum permitted exit velocity.

Today, the passage of proposed legislation to change the laws for flare system design and operation within the US appears imminent. Its stated intent is to greatly reduce hazardous air pollutant (HAP) emissions and thereby reduce health risks to the populous.[1] Some of the rules will undoubtedly achieve the goal of reducing the amount of uncombusted gases released to the atmosphere. However, many of the requirements will have troubling, negative consequences on the emission of greenhouse gases when compared to current flare design and operation protocols. Initial economic estimations by the government promise no substantial impact on the industry or consumer, but qualitatively those predictions are merely the tip of the iceberg.

It seems apparent when considering the probable, actual outcomes of the proposed legislation that the regulations were prepared without full comprehension of the complexities of combustion systems.

The purpose of a flare

In order to investigate the design principles and operational effects of the proposed legislation, it is appropriate to review the purpose and function of a flare. Anytime combustible gases are being processed, whether at a production well, refinery, or chemical plant, a flare provides a safe means of disposal for gas releases. Instead of an accidental, dangerous gas release into the atmosphere that could harm the employees, the surrounding area, or the facility, potential release sources are collected and routed to a flare. At the flare, the gases are ignited by pilots and destroyed through controlled combustion in a designed for purpose system. While the fire visible from a flare may be alarming, the products of combustion (carbon dioxide and water) are better for the environment, plant and people than the raw gases.

Zeeco's experience in flare design has led to some adages and rules of thumb for flare systems. In general, engineers want to minimise the size and diameter of the flare while still fully combusting the gas. Using the smallest applicable diameter converts the potential energy of the gas (pressure) into kinetic energy (velocity). More velocity means a more erect flame, quicker air inspiration, and less sweep gas, all contributing to lower emissions. Designing for the smallest possible tip while still maintaining good destruction efficiencies lowers capital costs, and extends equipment lifespans due to less destructive flame impingement versus a larger diameter flare tip.

Understanding turndown

Other than a few macho motor enthusiasts, why do commuting drivers not use massive displacement, high horsepower performance engines? While high performance cars may make the drive around town more entertaining, the potential power used is much higher than what is required to haul one or two people to the office. In mechanical terms, the possible peak performance is many, many times greater than what is applied to propel a car down a public road. This lopsided ratio of peak output versus the current, normal usage is known as a high turndown. Operating a racing engine at constant highway speeds is extremely inefficient when it was built for so much more. The optimal car design in terms of fuel consumption, cost, and efficiency is to have the exact amount of power required for normal cruising speed plus a slight safety factor.

By design, flares spend their lifetime operating at an extreme turndown that one does not require of any other equipment in the plant. As the plant safety device, flares are designed to accommodate any emergency upsets up to and including a total plant failure. As one may notice, day to day a properly operating flare has a very petite flame hardly visible on a bright day. When operating at full turndown, this signifies all processes within the plant are normal and safe.

While most mechanical equipment is capable of a turndown of 10:1 and instrumentation of 1000:1, some flares are required to operate at 100 000:1 or greater. Just as in the performance car example, operating at a fraction of overall capacity over time can make flaring equipment prone to inefficiencies, operational difficulties, and even premature failure.

Eliminating SSM: Designing away turndown

Previous Environmental Protection Agency (EPA) operational guidelines recognised the reality of turndown. Abnormal and emergency reliefs to the flare were not subject to the same emission and operating restrictions as day to day or expected process flows. The effective turndown capability of a flare was manageable under this premise since maximum capacity type of releases were not subject to the same rules as extreme minimum flows. In addition to turndowns, many aspects of flare combustion are controlled by the current standards.

The evaluation of a flare's combustion performance is predictable by comparing the flare tip exit velocity to the heating value of the gases being flared. To ensure the flare gas has ample opportunity to combust fully, there should be sufficient heating value to the gas (energy per unit of volume such as BTU/ft^3 or MJ/NM$_3$). In addition to sufficient heating value, the velocity of the gas must be correct to prevent a separation of the combustible zone from the pilot ignition source at the flare tip; this phenomena is known as lift off. Qualitatively, a robust flame not detached from the flare tip and pilots demonstrated ample combustion efficiencies.[2]

Regulations are in place to ensure manufacturers and operators properly combust flare gases. In these regulations, the exit velocity of the tip is the primary operational consideration for the application of EPA standards. To ensure the flare gas has an ample opportunity to combust fully, the following equations determine the applicable velocity as a function of the heating value of the gas flared and the type of flare employed.

Additionally, for any 'normal' flaring release the exit velocity is limited to 400 ft/s, regardless of the results of the previously mentioned equation. This maximum normal flaring velocity is curiously conservative, especially considering testing as far back as the CMA study demonstrated flaring up to sonic velocities is capable of destruction efficiencies in excess of 98.5%.[3] Sonic velocity flare tips are employed successfully around the world with demonstrated smokeless destruction performances above the EPA target minimums. Despite evidence that smaller flares with high exit velocities are fit for purpose, the industry has operated within the parameters successfully. Any foreseeable process output to a flare is accommodated by designing the flare with a tip diameter capable of flowing at lower velocities.

Table 1. Graphic demonstration of the size, utility and emission increase required by proposed rule

	250 000 lb/hr - 40 MW		1 000 000 lb/hr - 25 MW	
	Current design rule	Max 400 ft/s	Current design rule	Max 400 ft/s
Tip diameter (in.)	18	26	38	60
Stack height (ft)	92	103	188	197
Max steam flow (lb/hr)	7000	50 750	19 430	138 690
Purge gas consumption (SCFH)	240	501	1090	2780
Steam cooling rate (lb/hr)	385	525	840	1155
CO_2 production (lb/d)	761	1589	3457	8819
% increase in area	-	220%	-	257%
% increase in CO_2 production*	-	209%	-	255%

*The increase in CO_2 is a straight calculation of the additional percentage produced by the flare. The added amount generation by the production of additional assist air or steam for the 100% smokeless operation and increased utility production should also be considered.

The most impactful, significant proposed change to the rule is the inclusion of exceptional circumstances, startup, shutdown, and malfunction (SSM), into normal operation rules. This change would limit the velocity of all possible outputs including emergency shutdowns to the scientifically vague value of 400 ft/s. During the earliest testing used by the EPA to ascertain the effective destruction performance of flares, tests were conducted primarily for normal releases only. The recommended limitation of 400 ft/s is therefore not derived from an empirical value related to where combustion performance decreased, but instead simply where the data produced at the time of the test ceased. Subsequent tests all demonstrate the stability of flares across all exit speeds including sonic velocity.

The effect of limiting all flare releases to a lower velocity is equivalent to legally limiting a commuter car to only 20% of its power at any given time. The result? A highway commute necessitates a minimum 700 hp vehicle, so 140 hp can be used to get to work.

Impact of SSM elimination

The immediate impact of the change will be an increase in flare tip diameter to lower exit velocity. This change is not as innocuous as it might seem though. Many utilities required in flare use increase in proportion to the flare tip exit area or exponentially to the flare tip diameter.

For example, all flares require measures to prevent oxygen ingress into the flare stack that could result in combustible mixtures in the plant or vessels and ultimately a dangerous explosion. The most common means of protecting the system is maintaining sufficient gas velocity through the tip to prevent the oxygen incursion. A minimum flow of a utility gas, most commonly natural gas or nitrogen, is therefore maintained at all times. Reflecting again on the impact of the new legislation, the resulting diameter increase requires exponential increases in this purge gas. Remember, properly operating plants have flares operating at full turndown nearly 100% of the time, so total emissions from the flare are mostly comprised of the steady running minimum flow of primarily purge gas. Albeit unintentional, an effect of the new rule will actually increase total flare emissions.

As the exit diameter of flare tips increase, the quantity of pilots must increase as well to provide sufficient ignition points around the perimeter of the gas release to ensure proper combustion. Each pilot operates continuously, so increasing the flare tip size has a secondary effect of increasing pilot emissions.

To investigate the effect of eliminating SSM exclusions, several flare systems were studied to demonstrate the changes required. These examples are based on typical systems operating in refineries in the US Gulf Coast region. They are not intended to be comprehensive.

Regardless of the flare technology applied, the revised rules will increase total greenhouse emissions from flares, which is obviously contrary to the primary intent.

Specific impacts of steam assisted flares

When considering specific flare tip technologies, the revised rules continue to have negative environmental consequences. As hydrocarbons become heavier with more complex strains, they require more air for stoichiometric combustion. When ambient air alone is present for mixing, these gases have a tendency to emit smoke when burning due insufficient oxygen and mixing. Many mechanical means are employed to transport additional air to the combustion zone, perhaps the

Figure 2. Integral components of an air flare tip.

most common of which is steam injection via steam flares. The steam itself does not prevent smoking, but instead the injection of steam induces airflow into the flame.

Visible emissions from the flare, namely smoke, were prevented during normal operation but permitted during the extreme SSM conditions. This allowed efficient and effective steam injection system sizing. The high turndown phenomenon applies once again when exceptions under SSM are removed and regulated. The sizing criteria is negatively impacted since:

- Increased flare tip diameter dilutes the effectiveness of the steam injection nozzles. As the nozzles get farther away from the centre of the flare tip, it becomes increasingly difficult to transport air and create mixing through the entire combustion zone. More steam per unit of flare gas is required, increasing the environmental impact associated with producing steam.
- As the perimeter of the flare tip increases to slow the exit velocity, the quantity of steam injection nozzles rises proportionately. The required increase in injection points is necessary since the total smokeless rate must include SSM conditions. Each nozzle requires a minimum flow of steam to remove heat from the devices as well as minimise steam condensation. With more tips, the normal operation of the flare at full turndown requires a higher steam injection rate, thus increasing secondary emission.
- A minimum heating value for the cumulative flow of flare gases and utilities must be maintained to ensure proper combustion may occur. Referred to the combustion zone net heating value, NHV_{CZ}, it requires an enriching gas be added to the flare to offset the injection of inert steam during minimum firing rates. Since this enriching requirement to offset steam affects the regular, turndown operation, it is a major contributor to the overall emissions of the flare. These emissions will increase under the new rule.

In addition to the inefficiencies that will create negative environmental impacts, there are many situations where the best available technology cannot make full flare loads 100% smokeless. A tremendous difference exists between a process upset that can be accommodated smokelessly and a full malfunction release. Very few plants possess the steam capacity to make all flows smokeless, and in some cases, the steam flaring technology does not exist. Requiring operators to install boiler capacity for these mostly theoretical occasions would have a comparatively devastating greenhouse impact.

Specific impacts of air assisted flares

Similar to steam assisted flares, the mechanical injection of air through fans, blowers or compressors can provide the additional air for smokeless combustion of complex hydrocarbons. Just like steam flares, without the SSM exemptions the overall effectiveness of the air injection is certainly strained if it can accomplish the new smokeless rates at all. The performance of air injection systems will be hampered by:

- Most air assisted systems depend on a combined effect of the air injection volume and velocity for smokeless flaring.
- Most air injection tips have a centre gas burner surrounded by an air plenum where the two streams are finally introduced at the tip exit. The gas burner portion of the flare tip will need to increase in exit area to meet the lower velocity requirements. When the gas side increases, total air volume provided by the fan or blower will need to increase as it becomes impossible to maintain the velocity component of the air injection. As the volume requirement increases, power production to drive these devices will increase emissions associated with the flare.
- For air assisted flares utilising perimeter injection systems, more injection points are required as the tip barrel increases to slow the exit velocity. The tips require a minimum constant flow to protect the tip against damage, and therefore the required air volume at turndown increases along with emissions.
- Similar to the effects on steam assisted flares, NHV_{CZ} requirements also mandate the addition of an enriching gas at turndown. As mentioned in the above two points, the inclusion of SSM necessitates larger gas exit areas in turn requiring greater, less efficient air injection volumes at turndown. The rule change results in higher flows of air, so an offsetting increase in enriching gas is required, resulting burgeoning continuous combustion emissions.

Also similar to the limitations of total smokeless capacity via steam injection, there are pragmatic limits to the smokeless capacity of air injection systems. When SSM flow situations must be held to no visible emission standards across all flows, available blower and compressor technologies are quickly surpassed for making many flares smokeless.

Economic impact

As the EPA specifically states, the purpose of the proposed changes is to restrict harmful emissions into the air; the above consequences as noted consider only the unintended greenhouse emissions the changes will cause. Operators need to understand the egregious economic impact as it relates to equipment upgrades, maintenance, and capital cost. The only way to reconcile the EPA's assertion, "[the] proposed standards will have a negligible impact on the costs of petroleum products" is to assume the legislation can be accommodated essentially with purchase of a larger diameter tip. However, this projection seems to fall short when impacts across the entire flare assembly are considered.

Estimations should look beyond initial capital costs and include anticipated longer term operational cost increases as well. Necessary utility flow increases that will result from the change have already been discussed, but what perhaps is not clear to the regulatory body is the decrease in flare tip lifespan that will result from the increased flare tip diameter. The larger a flare tip diameter, the higher the tendency for flame to pull down on the downwind side and impinge directly on the tip barrel and pilots. Damage by flame pull down is often the limiting factor in a tip's life cycle. The required increase in tip diameter will require more frequent tip replacement and increased maintenance costs for the owner.

Equipment modifications

Flare stacks are typically long, slender shapes, and as a result, the governing structural design case is the bending moment enacted by wind effects across the cross sectional profile of the equipment. Any increase in the profile of the equipment adds loading to the stack, guy lines (if applicable) and civil works. Changes in the equipment will result in a weight increase, which will also impact the structural components. As the requirements of the structure increase, remediation measures such as stiffening rings or guy wires will likely need to be employed. However, the additional load that can be accommodated before civil work must be modified is limited. When the foundation becomes insufficient, a new flare installation is likely required.

The revised operation laws will have a cumulative effect on the structure since multiple flare equipment items will change. At minimum, the following impacts must be considered:

- The limitation of the exit velocity for any flaring condition will require an increase in the flare tip size. With the increased diameter, the wind load will be increased at the most critical portion of the stack.
- Where flare tips are being assisted by either steam or air, the utility flows will be increasing because of inefficiencies due to a larger diameter or to accommodate SSM smokeless performance. With the increase in utility flow, the size and quantity of utility pipes will grow as well and place further wind and weight loading on the stack.
- Most stack heights are determined by the permissible flare radiation imparted at ground level or on nearby equipment. Acceptable calculation methods for determining the heat flux applied by a flare take into account the shape of the flame because of exit velocity. In short, a faster exit velocity will have a more erect flame shape that imparts lower radiation to grade. With the limitation of 400 ft/s, the radiation levels of current flares will increase above the original design, perhaps to unacceptable levels. To remedy this, a stack extension may be applied to increase the overall flare height, but this once again increases both wind loading and weight.

New equipment required

Air flares present a particular problem since the majority have a coaxial flow design. The outer diameter of the air plenum is critical for the flow of air transported to the tip, meaning additional airflow though the stack cannot be achieved. Any change in the airflow requirements render the existing equipment obsolete and a new flare will have to be installed. It is doubtful this cost was anticipated in the proposal.

A significant number of sonic tips, including those employed in multi point ground flares, currently use only the velocity of the gas to achieve smokeless flaring. The high exit velocity is integral to meeting the visible emissions criteria, and retrofitting utilities to these flares for smoke suppression at lower exit velocities is probably not possible. The application of the proposed rule will eliminate their use.

In many applications, all of these consequences, inefficiencies, and additions will render the renovation of existing flare equipment to meet the new regulations impossible. What is much more likely to occur is flare relief headers will require a dual system: one flare designed to handle the normal operational and upset flows, and a completely separate isolated second flare structure and tip for emergency release cases. Besides the tremendous capital expenditure required of installing an additional flare and ancillary equipment, this once again will increase overall emissions from the plant. The second flare will require continuously operating pilots and in some cases flows for purging and enriching.

Conclusion

Experiencing unintended consequences of regulatory actions is not unique to America. Old and new operational standards alike in regions all across the globe include counter productive measures. As a flare manufacturer, Zeeco must design and provide equipment according to velocity limitations, sizing restrictions, pilot operating requirements and a myriad of other specifications in contrast to simply providing the best combustion solution for the situation. Since regulations usually exist as a form of legislation, there is little expectation their number will decrease in the future. The company is adept at accommodating regulations and limitations wherever applicable since much of the time they are beyond the control of the customer. This particular proposed change is unique in that never before have operating rules had such a negative impact on equipment performance, durability, economy, or efficiency.

It is understood the government is not a flare or combustion entity, and what may seem like miscues have noble intentions behind them. It is the company's hope they heed the consensus of the industry regarding the best means of protecting delicate and precious air resources. Owners, operators, designers, and manufacturers of flare equipment are all invested in this cause, and offer expertise to ensure a mutually acceptable solution.

References

1. *Environmental Protection Agency: Proposed rule [EPA-HQ-OAR-2010-0682; FRL-9720-4], Petroleum Refinery Sector Risk and Technology Review and New Source Performance Standards.*
2. *40 CFR 60.*
3. *CMA test.*