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API 650 EXTERNAL PRESSURE DESIGN APPENDIX

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Introduction:

In the near future, API will publish an appendix to API 650 that will prescribe requirements for the design of tanks that operate at negative pressure (or vacuum).

This paper discusses:

- The background on the development of the new appendix. Why and how did it come about?
- The scope of the document as defined by the Process Industry Practices group.
- The technical basis of the appendix. Where do the rules come from?
- The loading conditions and combinations addressed by the appendix. How is external pressure combined with roof live load and wind load, e.g.?
- The equations and formulas that are provided for the design of tank components. What components are included?
- A design example to illustrate application of the design procedures. What will a typical tank subject to a significant vacuum design pressure look like?
- Guidance for cases where tanks are subject to flooding of the dike area surrounding the tank.

Background:

The request that API 650 include design rules for tanks with external pressure originated with the Process Industry Practices (PIP) group, a consortium of numerous petroleum and chemical companies. In response to PIP's request, API agreed to develop the requested rules and incorporate them in an

appendix to API Standard 650. An API Special Task Group was formed to develop the appendix. Thus in late 1998, the Task Group began work on the appendix.

Fortunately, work on external pressure design of tanks that DuPont had already compiled and implemented in an internal engineering standard was made available to the Task Group with DuPont's permission. This document, together with others that are included in the References section of the appendix, proved to be a great "starting point" in formulating and presenting the rules for API 650 tanks.

Since API 650 already states that tanks designed in accordance with the provisions of the standard can be considered adequate for external pressures up to 1-inch water column, PIP asked that rules be provided for external pressures greater than this amount.

Process Industry Practices Request:

The PIP request was dated April 15, 1998. The effort has taken about five and on-half years to this point. The specific Scope of Work defined for the Task Group by PIP was:

"This task group will develop an appendix to the API Standard 650 for external pressure design. Uniform partial vacuum not to exceed one pound per square inch gage and partial submergence in near-static liquids shall be considered. Closed tanks having both supported and self-supporting roofs, anchored and unanchored, at ambient and elevated temperatures, and of both carbon steel and stainless steel construction shall be considered. Limitations such as

maximum configuration size and magnitude of external pressure may be imposed for specific geometries, materials, and loading combinations.”

The Process Industry Practices (PIP) efforts to “harmonize” specification requirements for storage tanks among many users revealed that there existed a need to rate such tanks for partial vacuum. This need may arise from operational issues such as liquid draw down, rapidly condensing vapors, gas blanket starvation, and external flooding of partially evacuated tanks, in addition to vacuum processing itself. Safety and environmental regulations often require partial vacuum ratings for equipment which might see such service. There appeared to be no industry wide methodology for establishing such ratings.

Technical Basis of Appendix:

The technical bases for the provisions in the appendix are derived from several well-known documents, including:

- DuPont Engineering Standard
- Stability of API 650 Tank Shells
- Guide to Stability Design Criteria for Metal Structures
- ASME Code Case 2286
- Welding Research Council Bulletin 406
- ASME Boiler & Pressure Vessel Code, Section VIII, Division 1
- AISI Steel Plate Engineering Data

The format and organization of the appendix intentionally closely resembles that of the DuPont Engineering Standard. However, closer study will show differences in some equations. These

differences are typically related to nomenclature or safety factors, for example, to make the equations and results consistent with other provisions of API 650.

A brief summary of the technical basis of the appendix is included in the appendix as are references for those who wish to better understand the technical basis.

Loading Conditions and Combinations:

The appendix will prescribe rules for designing a tank for a specified design external pressure and will include rules for combining that specified pressure with other loadings that may occur simultaneously. A recently approved change to API 650 will prescribe rules for load conditions and load combinations and will include these rules in a centralized location in the standard. The new rules are consistent with the philosophy of loading combinations adopted by the major building codes and are also consistent with API 650's level of risk of tank failure. Likewise, the rules in the external pressure appendix will be consistent with the basic part of API 650 with regard to loading conditions and combinations.

Thus, starting with a specified design external pressure, roof live or snow load, and wind pressure (or velocity), the total roof design pressure is calculated as the greater of $DL+(L_r \text{ or } S) + 0.4P_e$ or $DL + P_e + 0.4(L_r \text{ or } S)$, where DL = Dead Load. And the total shell design external pressure is the greater of P_e , excluding wind or $W + 0.4P_e$.

Note that although it is not explicitly stated in the appendix, design external pressure loading should be combined with any specified seismic loading in accordance with load combination criteria prescribed in the main body of the standard.

Roof, Shell & Stiffener Design Equations:

The appendix includes, in both SI and US Customary Units, the equations necessary to calculate the following:

- thickness of self-supporting roofs for both conical and dome roofs
- thickness of shell
- sizes and spacing of end and intermediate circumferential stiffeners
- weld size for stiffener attachment welds

In addition, guidance on bottom evaluation, but not prescriptive equations, is included.

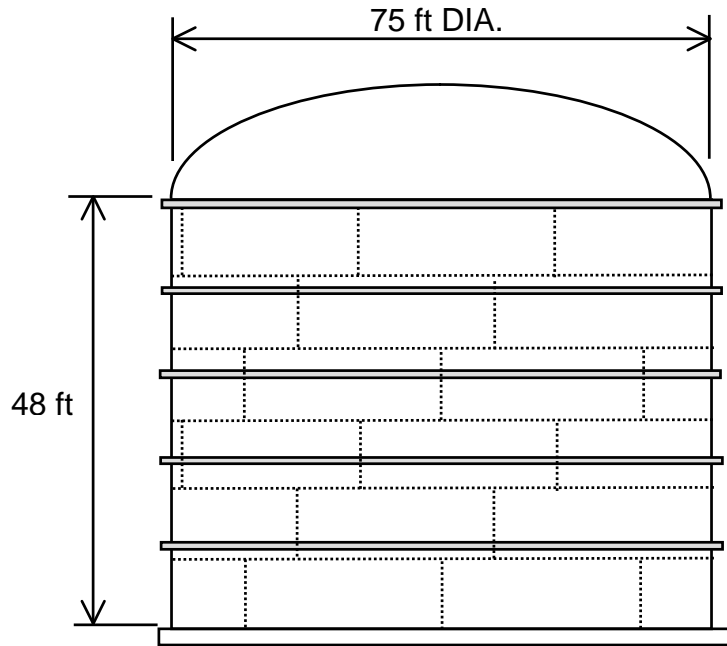
The appendix will not include prescriptive equations for the design of column and rafter-supported cone roofs or supported dome roofs. For relatively low specified design external pressures, where supported cone roofs may be cost-effective, the necessary equations are available in the standard or its references. For more significant design external pressures, supported cone or supported dome roofs are generally not cost-effective compared to self-supporting roofs.

Design Example:

Let us consider what a typical tank design for external pressure might look like. The appendix includes a design example that illustrates the application of the design equations for a 75 foot diameter by 48 foot high tank. This tank would probably be considered large by chemical industry standards, but moderate to small by petroleum industry standards.

If we assume that process conditions dictate that the tank operates at a vacuum of 0.6 psig, and that the design wind velocity for the location of the tank is 100 mph, the result of applying the design equations prescribed in the appendix is the tank pictured below.

$P_e = 0.6$ psig
 Wind = 100 mph
 Shell Thickness = 0.395 in
 Four Intermediate Stiffeners
 One Top End Stiffener
 All Angle Section Stiffeners
 Butt-Welded Dome Roof
 Roof Thickness = 0.529 in
 Roof Dish Radius = 60 ft



In order for this example tank to withstand the specified vacuum loading within safety factors comparable to API 650 safety factors for other types of loading, the tank roof needs to be thickened considerably and the shell needs to be thickened and stiffened with four intermediate circumferential stiffeners.

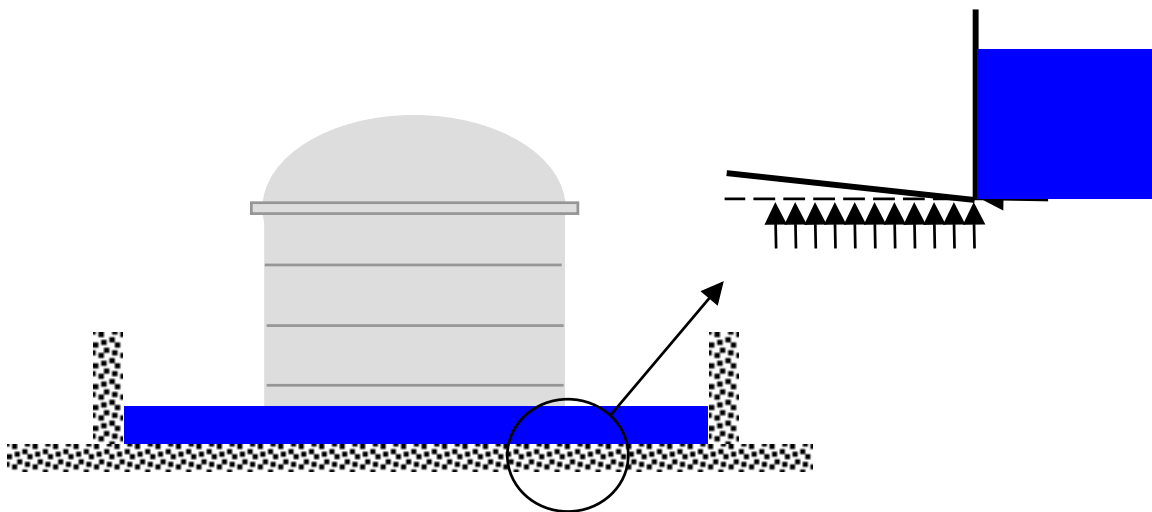
On a tank as large as this one, it was necessary to reduce the dish radius of the dome roof and increase the thickness beyond the limits of lap-welding.

The thickness of the entire shell was increased to the minimum thickness required for the lowest shell course for internal pressure loads for convenience in this example. The appendix allows one to design

stiffening arrangements for shells of varying thickness as well. This allows the most cost-effective combination of shell thickness and stiffening rings to be developed.

Flooded Dike Considerations:

One issue of special importance to the PIP group who requested this appendix was the case where a tank may be subject to periodic flooding of the dike, impoundment, or secondary containment area when the tank is empty of liquid. Such an occurrence tends to uplift the bottom of the tank and to impose hydrostatic pressure against the outside of the shell. Normally, the amount of liquid, usually primarily water, that collects is not sufficient to impose significant hydrostatic pressure on the shell of the tank, but the height of water can be significant enough to “balloon” the bottom of the tank. This is illustrated in the figure below.



The appendix provides guidance on how to evaluate the design of the tank for this condition, including such components as the corner weld of the shell to bottom, tank anchorage, and attached piping and/or bottom fittings such as sumps. One practical method commonly used to mitigate the risk of damage in this event is to maintain a minimum liquid level inside the tank at all times that is high enough, considering the relative specific gravities of the liquids inside and outside the tank, to

balance or offset the pressure causing the bottom to want to balloon. The appendix provides the equations necessary to calculate this minimum liquid level.

Power of External Pressure:

The damage that can be done to tanks by external pressure is similar, whether the damage is caused by wind pressure or by negative internal gas pressure, as the photos that follow will illustrate.

Normally, wind damage tends to be less extreme than negative internal pressure because wind is usually a temporary loading condition whereas vacuum can be sustained over a significant period of time. Of course there are exceptions to both of these generalities. Sometimes the damage done can be repaired by simply pulling out the dents. In other cases, where the shell material has yielded and is plastically deformed, replacement of some material is necessary.

In extreme cases, as shown in Photo 3, the damage is so extreme that the tank may not be salvageable.

Since the damage mechanism for vacuum loading is similar to that for wind loading, it makes sense that the preventative measures in the design for vacuum loading are similar to those for wind loading, i.e. thickened shells with or without circumferential ring stiffeners to increase the buckling resistance of the shell.



Tank Damaged by Negative Internal Pressure (Vacuum)



Tank Damaged by Tornado Winds



Tank Damaged Beyond Repair by Vacuum



Tank Damaged by Wind (Before Pulling Out Dents)



Tank Damaged by Wind (After Pulling Out Dents)



Tank Damaged by Vacuum in Combination with Snow Load



Tank Roof to Shell Connection Damaged by Vacuum