APPENDIX L - SEISMIC DESIGN OF API 620 STORAGE TANKS
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L.1 SCOPE

This Appendix provides minimum requirements for the design of welded storage tanks that may be subject to seismic ground motion and are designed and constructed to the API 620 standard. These requirements represent accepted practice for application to welded steel flat-bottom tanks supported at grade. This Appendix is based on the requirements of API 650 Appendix E. The design procedures contained in this Appendix are based on Allowable Stress Design (ASD) methods

All tanks designed and constructed to the requirements defined in API 620 Section 1.2 shall meet the requirements of API 650 Appendix E unless specifically modified or augmented herein. All of the requirements contained in API 650 Appendix E are not duplicated here, but are wholly incorporated by reference. Special provisions for tanks designed and constructed in accordance with Appendices Q and R are included in this Appendix.

Application to tanks supported on a framework elevated above grade is beyond the scope of this Appendix.

Optional design procedures are included for the consideration of the increased damping and increase in natural period of vibration due to soil-structure interaction for mechanically anchored tanks.

Tanks located in regions where S_1 is less than or equal to 0.04 and S_S less than or equal to 0.15, or the peak ground acceleration for the ground motion defined by the regulatory requirements is less than or equal to 0.05g, need not be designed for seismic forces; however, in these regions, tanks in SUG III shall comply with the freeboard requirements of this Appendix.

Dynamic analysis methods incorporating fluid-structure and soil-structure interaction are permitted to be used in lieu of the procedures contained in this Appendix with Purchaser approval and provided the design and construction details are as safe as otherwise provided in this Appendix.

The provisions for outer tanks of double walled tank systems are limited to tanks designed and constructed in accordance with API 650 or API 620. Outer tanks designed and constructed of other materials such as reinforced or prestressed concrete outer tanks or containments are outside the scope of this standard.

L.2 – DEFINITIONS and NOTATIONS

L.2.1 Definitions

h_s Additional shell height required above the sloshing wave height, mm (ft)

W_{ns} Effective weight of insulation acting on the tank shell for lateral seismic load, N (lbf)

W_{nr} Effective weight of insulation acting on the tank roof for lateral seismic load, N (lbf)

X_{ns} Height from the bottom of the shell to the center of action for the insulation load on the tank shell, m (ft)

X_{nsr} Height from the bottom of the shell to the center of action for the insulation load on the tank roof, m (ft)

L.3 SPECIAL PROVISIONS FOR TANKS DESIGNED AND CONSTRUCTED TO APPENDIX Q and R

For storage tanks designed constructed to meet the requirements of API 620 Appendices Q and R, the Provisions of API 650 Appendix E shall be modified and augmented as shown in this section. If the requirements of Appendix E or L, conflict with those of Appendix Q or R, the more conservative requirements shall apply.

Special provisions for tanks storing refrigerated liquefied natural gas (LNG) storage are contained in Section L.4.

L.3.1 Response Modification Factor

The response modification factor for ground supported, liquid storage tanks designed and detailed to these provisions shall be less than or equal to the values shown in Table L-4Q or L-4R, as applicable.

Table L-4Q, Response Modification Factors for ASD Methods, Appendix Q Tanks

Anchorage system	R_{wi}, (impulsive),	$R_{wc,}$ (convective)
Inner (primary) Tank:		
Steel (nickel, or stainless)		
Self–anchored	1.5	1.0
Mechanically-anchored	1.75	1.0
Aluminum		
Self–anchored	1.25	1.0
Mechanically-anchored	1.5	1.0
Outer (secondary) Tank:		
Self–anchored	2.0	n/a
Mechanically-anchored	2.0	n/a

[*editorial note: values of 2.0 for outer tank are conservative given that these are used for CLE events. Committee may want to discuss these values in view of acceptable damage and cost.]*

Table L-4R, Response Modification Factors for ASD Methods, Appendix R Tanks

Anchorage system	R_{wi}, (impulsive),	$R_{wc,}$ (convective)
Inner (primary) Tank:		
Self–anchored	2.25	1.5
Mechanically-anchored	2.5	1.5
Outer (secondary) Tank:		
Self–anchored	2.0	n/a
Mechanically-anchored	2.0	n/a

[*editorial note: values of 2.0 for outer tank are conservative given that these are used for CLE events. Committee may want to discuss these values in view of acceptable damage and cost.]*

The inner and outer tanks may be decoupled for seismic design of the tank and anchorage and assumed to act independently. However, if the inner and outer tanks are founded upon or are anchored to a common foundation, the seismic foundation loading shall be calculated using the lesser response modification values for the inner tank for both tanks and a dynamic analysis shall be performed to determine the combined effect.

L.3.2 Resistance to Design Loads

L.3.2.1 Allowable Stresses
For Appendix R tanks, design allowable stresses shall be per API 620 Appendix R, Section R.3.3.

For Appendix Q tanks, design allowable stresses shall be per API 620 Appendix Q, Section Q.3.3.

L.3.2.2 Annular Bottom Plates
For self-anchored tanks, the butt-welded annular plate width shall be the greater of that required in Section R.3.4 (for Appendix R tanks), Section Q3.4.1 (for Appendix Q tanks), or the width required for seismic anchorage as defined in API 650 Appendix E, Section E.6.2.1.1.2. The minimum annular bottom plate thickness shall be the greater of that required in Table R-6 (for Appendix R tanks), Table Q-4A or B (for Appendix Q tanks), or API 650 Appendix E.

L.3.2.3 Resistance to Sliding
The tank system, whether self-anchored or mechanically-anchored, shall be configured such that the overall horizontal shear force at the base of the tank does not exceed the friction capacity as defined in API 650 Appendix E, Section E.7.6. Mechanical anchorage shall not be used to resist sliding.

L.3.2.4 Insulation Load

1. For tanks designed and constructed with an outer tank containing loose fill insulation in the annular space between the tanks, the insulation weight shall be divided equally to the inner and outer tank wall for seismic lateral loads unless a more rigorous analysis is performed to determine the distribution. The insulation within the annular

space shall not be used as to calculate resistance to overturning. Insulation on the roof or suspended deck shall be applied to the tank supporting the load at the point or center of gravity of attachment and may be used to resist overturning.

2. For single wall tanks with insulation or double wall tanks with the insulation adhered to the plate surface, the additional weight of the insulation shall be included and may be included in the tank weight, w_t, used to resist overturning. The insulation weight shall also be included in the definition of the terms, W_T and W_{rs}.

3. Modify eqn ( ) of API 650 Appendix E as shown in eqn (L-1):

$$V_i = A_i(W_s + W_r + W_f + W_i + W_{ns} + W_{nr}) \qquad \text{Eqn (L-1)}$$

Modify eqns (xx and xx) of API 650 Appendix E as shown in eqns (L-2 and L-3)

Ringwall Moment, M_{rw}:

$$M_{rw} = \sqrt{\left[A_i(W_i X_i + W_s X_s + W_r X_r + W_{ns} X_{ns} + W_{nr} X_{nr})\right]^2 + \left[A_c(W_c X_c)\right]^2} \qquad \text{Eqn (L-2)}$$

Slab Moment, M_s:

$$M_s = \sqrt{\left[A_i(W_i X_{is} + W_s X_s + W_r X_r + W_{ns} X_{ns} + W_{nr} X_{nr})\right]^2 + \left[A_c(W_c X_{cs})\right]^2} \qquad \text{Eqn (L-3)}$$

L.3.2.5 Additional Roof Loads

When $S_{DS} > 0.33g$ and the tank is classified as SUG III; and equipment loads such as pumps, platforms, piping platforms supported directly by the roof exceed 25% of the combined weight of the roof and shell, W_r+W_s, a dynamic analysis shall be performed to determine the effective roof load and the amplified roof acceleration for the design of the roof, roof supports and superstructure supported by or suspended from the roof.

L.3.2.6 Alternate Performance Basis Design

If the governing regulations or project documents require the tank system to be designed for an operating level earthquake or to consider aftershocks, the provisions in Section L.4 may be used. Adjustment may be required to the definition of the ground motion (i.e. different recurrence interval).

If base isolation of the tank system is permitted, the requirements of Section L.4.5 shall apply.

L.4 SPECIAL PROVISIONS FOR LNG TANKS

This section is applicable to refrigerated LNG tanks built to API 620 Appendix Q with supplemental seismic design methods addressing an operating level earthquake (OLE), sometimes referred to as OBE, a contingency level earthquake (CLE), sometimes referred to as SSE, and an aftershock level earthquake (ALE) when required by regulations.

The performance basis objectives for the ground motions are:

OLE – the tank system will remain operational with only minor repair required. The tank system should be capable of withstanding multiple events with this ground motion without significant damage.

CLE- the tank system will survive and contain the liquid to protect the public but extensive damage may occur and the tank system may not be repairable after this event. This is assumed to be a singular event in the design life of the tank system.

ALE- the tank system is assumed to be damaged by the CLE event and the secondary containment system is containing the liquid. The secondary containment is intended survive multiple aftershocks of the ALE ground motion which containing the liquid with minor damage and leaks.

The requirements of API 650 Appendix E, and sections L.3 of this standard apply unless modified herein.

L.4.1 Ground motions

The definition of the ground motions to be used with the OLE, CLE and ALE events may vary depending on regulations for the specific location. Within the US, federal regulations 49 CFR 193 and NFPA 59A are the primary regulatory and standard documents for LNG storage tanks. The user is referred to those documents or similar regulatory documents when the tank is located outside the US, for ground motion definitions to be used with this Appendix.

Vertical earthquake shall be considered.

A site-specific response spectrum is required for LNG tanks located in regions where peak ground acceleration is greater than 0.15g or Ss is greater than 0.3g unless otherwise specified.

The exception in API 650 Appendix E, Section E.4.9.1.1 limiting the upper value of the spectral acceleration, S_a^* under specific tank configurations is not applicable to LNG storage tanks.

Current US requirements are based on a response spectrum with 5% damping. If the site specific regulations require a different damping value, and a site-specific spectrum is not required, the following factors may be applied to the impulsive spectral component to adjust the 5% damped values to other values of damping. The convective multiplier, K, from API 650 Appendix E is unchanged and equal to 1.5. Alternative adjustment factors to damping ratios are permitted providing they are based on local geotechnical data and rational analysis.

Table L-5 Impulsive Damping Ratio Adjustment

Damping ratio	Adjustment factor, K_i
20%	0.45
10%	0.6
5%	1.0
2%	1.65
1%	2.0
0.5%	2.2

L.4.2 Operating Level Earthquake (OLE)

Unless otherwise defined by the governing local regulations, the operating level earthquake ground motion shall be defined as the motion due to an event with a 10% probability of exceedence within a 50 year period (a 475 year recurrence interval).

L.4.2.1 OLE Definition Based on Appendix E, ASCE 7 Method

To utilize API 650 Appendix E Section E.4 to define the OLE ground motion, the following modifications shall be made based on the provisions in this Appendix:

1. Re-define the following terms for OLE only:

   S_S Mapped, 10%PE50 earthquake from the USGS data, 5-percent-damped, spectral response acceleration parameter at short periods (0.2 sec), %g.

   S_1 Mapped, 10%PE50 earthquake from the USGS data, 5-percent-damped, spectral response acceleration parameter at a period of one second, %g.

1. The scaling factor, Q, is not applicable.
2. API 650 Appendix E, eqn (E-5) and (E-6), do not apply.
3. Eqn (E-4) shall be modified:

$$A_i = K_i F_a S_s$$

4. Eqns (E-7 and E-8) shall be modified:

When, $T_C \leq T_L$

$$A_c = KS_{D1}\left(\frac{1}{T_C}\right) = 2.5KF_vS_0\left(\frac{T_S}{T_C}\right) \leq A_i$$

When, $T_C > T_L$,

$$A_c = K\ S_{D1}\left(\frac{T_L}{T_C^{\ 2}}\right) = 2.5KF_vS_0\left(\frac{T_ST_L}{T_C^{\ 2}}\right) \leq A_i$$

L.4.2.2 Adjustment factors
Unless specifically permitted by the regulations, the OLE design forces shall not be adjusted by an importance factor, I, or force reduction factor, R as shown in API 650 Appendix E. Nor shall the forces be reduced by the 0.7 multiplier (1/1.4) commonly applied to convert contingency level events to ASD methods.

L.4.2.3 Damping
Unless otherwise defined by regulatory requirements, the damping ratio for the impulsive spectral accelerations shall be 5%.

L.4.2.4 Soil Structure interaction
Soil structure interaction per API 650 Appendix E, Section E.6.1.6 may be used for OLE design providing the damping ratio does not exceed 10%.

L.4.2.5 Allowable stresses
Design allowable stresses shall be per API 620 Appendix Q, Section Q.3.3, including the 33% increase permitted for earthquake loads.

L.4.2.6 Self-anchored inner tank
The anchorage ratio for a self-anchored inner tank, J, shall not exceed 1.0 for the OLE design combination to limit uplift and stresses in the annular plate and corner weld.

L.4.2.7 Foundation stability
The overturning ratio defined in API 650 Appendix E.6.2.3, Eqn () shall be equal to or greater than 3.0 for the defined OLE event.

L.4.2.8 Inner Tank Freeboard
Freeboard shall be provided for the OLE event in accordance with the following where the terms are as defined in API 650 Appendix E:

$$\delta_s = 0.42Da_f + h_s$$

An additional shell height, h_s, shall be added to the calculated value above the sloshing height as required by the governing regulations. The minimum value of h_s for the OLE event shall be 300mm (1ft).

If provided, the site-specific response spectrum may be used to determine the effective spectral acceleration, A_f, in lieu of using the T_L values in API 650 Appendix E.

Alternative sloshing height calculation methods may be used if approved by the regulatory body providing the calculated sloshing height is not less than 80% of the value required by these provisions.

L.4.2.9 Piping flexibility

Piping, piping supports, support foundations and superstructures supporting piping attached to the tank shall be designed for the piping displacements in Table E-8 of API 650 Appendix E. A 33% increase in stress is permitted.

L.4.2.10 Sliding Resistance

The calculated sliding force at the base of the tank shall not exceed V_s. The maximum coefficient of friction, μ, shall be (tan 30^o/1.5) where 1.5 is the factor of safety against sliding. The coefficient of friction selected shall consider the materials underlying the tank bottom. Anchorage may not be used to resist sliding. If the sliding force exceeds the allowable, the tank shall be re-configured.

L.4.2.11 Connections with adjacent structures

The calculated or tabular displacements in API 650 Appendix E.7.8 shall be amplified by 1.25 for OLE.

L.4.2.12 Bottom and shell support

The tank under-bottom insulation shall be designed to resist the combined pressures from the product load, the overturning seismic load and the vertical seismic load. These pressures may be combined by SRSS.

The bearing ring under the shell shall be designed to resist the calculated OLE peak compressive force in the tank shell due to overturning (see Appendix E.6.2.2), including dead and live loads. A 33% increase in allowable bearing stress is permitted.

L.4.3 Contingency Level Earthquake (CLE)

Unless otherwise defined by the governing local regulations, the contingency level earthquake ground motion shall be defined as the motion due to an event with a 2% probability of exceedence within a 50 year period (a 2475 year recurrence interval) which is the maximum considered earthquake in API 650 Appendix E and ASCE 7.

L.4.3.1 CLE Definition Based on API 650 Appendix E, ASCE 7 Method

To utilize API 650 E Section E.4 to define the CLE ground motion, the following modifications shall be made based on the provisions in this Appendix:

1. The scaling factor, Q, is not applicable and may be set equal to a value of 1.0.
2. The response modification factor shall be as defined in Table L4-Q.
3. The importance factor, I, shall be taken as 1.0.

L.4.3.2 Inner Tank Freeboard

Freeboard shall be provided in accordance with Section L.4.2.8 except the value of h_s shall be taken as zero unless required by the governing regulations.

L.4.3.3 Sliding Resistance
The calculated sliding force at the base of the tank shall not exceed V_s. The maximum coefficient of friction, μ, shall be tan 30^o. The coefficient of friction selected shall consider the materials underlying the tank bottom. Anchorage may not be used to resist sliding. If the sliding force exceeds the allowable, the tank shall be re-configured.

<u>L.4.4 Aftershock Level Earthquake (ALE)</u>

This design case shall be applicable only when regulations or project documents specifically require the tank system to be designed or evaluated for aftershocks.

Unless otherwise defined by the governing local regulations, the aftershock level earthquake (ALE) ground motion shall be defined as the motion due to an event with a 2% probability of exceedence within a 50 year period (a 2475 year recurrence interval), which is the maximum considered earthquake in API 650 Appendix E and ASCE 7, with the spectral values reduced by 50%.

If the outer tank is not designed as a secondary containment (i.e. it serves as vapor barrier and pressure boundary only and is not constructed of API 620, Appendix Q material suitable for the inner tank), then no design or evaluation for ALE is required by these Provisions for the inner or outer tank.

If the outer tank is designed as the secondary containment (i.e. constructed of API 620, Appendix Q materials suitable for the inner tank and designed for the product hydrostatic pressure), the outer tank, foundation and anchorage shall be designed for the ALE assuming the inner tank no longer exists and all of the liquid is contained by the outer tank system and the following provisions apply.

L.4.4.1 Modification Factors
The secondary containment shall be designed for ALE while containing liquid using an importance factor equal to 1.0 and response modification values in Table L-4Q for the inner tank.

L.4.4.2 Damping
Unless otherwise defined by regulatory requirements, the damping ratio for the impulsive spectral accelerations shall be 5%.

L.4.4.3 Soil Structure interaction
Soil structure interaction per API 650 Appendix E, Section E.6.1.6 may be used for ALE design.

L.4.4.4 Allowable stresses
Design allowable stresses shall be per API 620 Appendix Q, Section Q.3.3, including the 33% increase permitted for earthquake loads.

L.4.5 Base isolation

Base isolations systems may be used to alter the tank response to the design ground motions providing:

1. The inner and outer tanks are both isolated on a common foundation to avoid excessive differential displacements between the tanks and connecting internals.
2. The anchorage, internal and external piping , insulation and other attached equipment are designed for the larger differential deformations associated with an isolated system.
3. A site-specific response spectrum is mandatory and includes the long term periods necessary to define the system response.
4. All external piping connections to the isolated system are designed for the calculated displacements for the actual ground motions (no I or R modifications).
5. The design is peer reviewed for technical adequacy by an independent party knowledgeable in the design and behavior of base-isolation systems; or, the design is verified by scaled shake-table tests.