CONSTRUCTION ENHANCEMENTS

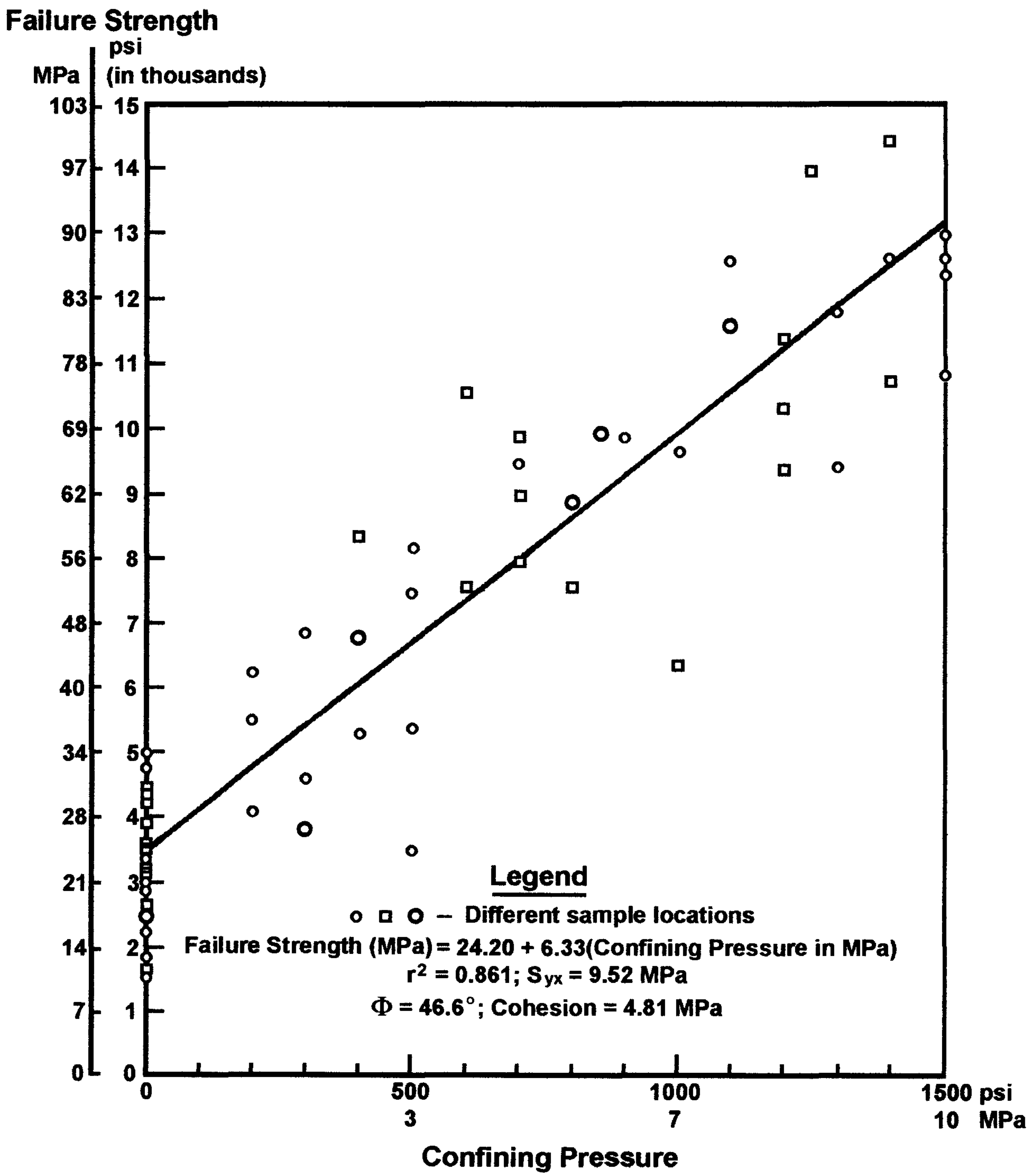
The remaining panel closure enhancements relate primarily to the resulting strength of the concrete in the panel closure bulkheads, over the minimum operational period of 35 years. The strength of the concrete is critical to the strength of the panel closure bulkheads.

The proposal to allow the mass concrete to utilize any rock salt in the mix depends on the ability to consistently meet the strength specification. The unconfined compressive strength of the 16 Permian evaporite beds tabulated in Appendix F ranges from 2300 psi to 5880 psi and the cohesion from 540 to 1580 psi. The unconfined compressive strength of the evaporite beds tabulated in Appendix G, including the Permian beds in Appendix F, ranges from 2260 psi to 7510 psi and the cohesion from 540 to 1790 psi. The random selection of the salt from any tested salt bed should be capable of providing equivalent strength properties. In addition, the strength variation across a single evaporite bed in the Salado formation is significant. The unconfined compressive strength of the Mississippi Potash Company's Cycle 7 bed (> 85% salt) ranged from 1610 psi to 4950 psi, as shown on Figure 17. The important factor would appear that the salt component of the mix be consistent, i. e. well mixed from one source.

Aggregate strength is a minor concrete strength factor which can be compensated for, if necessary, by increasing the cement in the mix and verified by testing. In addition, carbonate aggregate concrete probably has a lower coefficient of thermal expansion that quartz aggregate. Figure 8 indicates that concrete with quartz aggregate has a higher coefficient of expansion (approximately 6.6 millionths per °F) than either limestone aggregate concrete (approximately 3.8 millionths per °F) or dolomite aggregate concrete (approximately 5.3 millionths per °F). It should be possible to use either the Pennsylvanian Atoka limestone or the Permian, Guadalupian, Bell Canyon limestone river rock for concrete aggregate. Rounded river rock should facilitate slick line pumping and form filling.

Surface or underground mixing of the concrete is of no significance. Sunnyside Cold Corp. has constructed five water impoundment bulkheads using underground mixing and pumping stations, four using supersacks, surface mixing and pumping and one with surface mixing and transporting by rail in Moran cars. The critical factor is limiting the time between mixing and placement in the form. Troxell, et. al. (1968) state:

Figure 17. Strength of Mississippi Potash Co.'s Cycle 7 bed



Strength of Mississippi Potash Co.'s Cycle 7 bed (Abel and Djahanguiri, 1984)

> Current specifications for ready-mixed concrete require that the concrete be discharged from the truck within 1-1/2 hr or before the drum has had 300 revolutions (whichever comes first) after the water is added to the batch, or the cement to the moist aggregate. Under specially favorable conditions, periods up to 2 and 3 hr may be allowed. Conversely, under unfavorable conditions where air temperatures are unusually high, or the ingredients of the concrete are such that an unusually quick time of set or loss of plasticity may occur, it may be necessary to substitute a shorter period.

If the water is added to the bulkhead concrete on the surface, it will be difficult to meet the time limitation. Transporting supersacks underground and adding the water and mixing close to the bulkhead sites would appear to be the most reasonable method.

Replacing freshwater grout with salt-based grout should be done in order to minimize salt dissolution in the adjacent rock salt and in the salt-based concrete. Salt dissolution could weaken the contact zone and potentially provide a leakage path for brine, methane explosion pressure and closure compressed gas pressure behind the panel closure bulkheads.

It should be expected that the best contractor bid will result from the least restrictive specification. There is no apparent reason to require panel closure construction within six months rather than one year.

CONCLUSIONS AND RECOMMENDATIONS

The most important of the specific enhancements proposed, allowing flexibility in the bulkhead forming practices is troubling because the planned bulkhead design contains multiple potential leakage paths within cells, between cells and through the panel closure bulkheads. It is recommended that the panel bulkhead specifications:

1) provide an incentive for the contractor to minimize the number of cells (preferably to one),
2) require that each cell be filled as a continuous monolithic concrete pour,
3) require the contractor support the fluid concrete in all cells with external structures,
4) require the contractor to remove the support structures and forms between internal cells,
5) provide for a rough form surface between internal cell walls, (possibly with a layer of burlap),
6) assure that some grout points are located at the roof concrete/rock salt contact and
7) prevent the use of all internal form spacer supports.

If built as recommended, the panel closure bulkheads should be capable of providing more than the required 35 years of protection from brine migration, 480 psi of methane explosion pressure and 100 psi of panel closure pressure.

The planned 12-ft thick explosion-isolation masonry walls should not be built. The methane concentration will take more than 17 years to rise to the 5% lower explosive limit after stopping panel ventilation. If built, the planned 12-ft thick explosion-isolation masonry walls would probably be incapable of resisting the design 480 psi methane explosion pressure.

The 4-ft thick construction-isolation wall is recommended to isolate the panel closure construction areas. The 4-ft thick construction-isolation walls are more than adequate to support the potential roof fall overpressure.

Generic salt-based concrete should be equally as effective as Salado-based concrete.

It should be possible to use local limestone or dolomite river rock for concrete aggregate. Limestone aggregate concrete should have a lower coefficient of thermal expansion than crushed quartz aggregate concrete. River rock should pump more readily than crusher product.

The contractor should be allowed to use either surface or underground mixing of the concrete. However, underground mixing of supersacks is recommended to assure sufficient time for placing the concrete in the forms.

Salt-based grout is recommended to eliminate the possibility of weakening the salt-based concrete along the rock salt/concrete contact by dissolution. Grouting across the roof contact is essential to assure that voids are filled.

There does not appear to be a time imperative requiring a 180-day construction period rather than a one year period.

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APPENDIX A. INTAKE DRIFT BULKHEAD DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = concrete shear strength $\left(2\sqrt{f'_c} = 126 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft•lb)
S = section modulus (in^3)
T_e = effective bulkhead thickness (28 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain concrete strength reduction factors
0.65 plain concrete flexure, compression
shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = concrete comp strength (4,000 psi)
f_{cl} = concrete tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{4000} = 206 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft•lb)
M_u = factored beam moment (ft•lb)
T = overall bulkhead thickness (36 ft)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_S = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d = dynamic pressure head (240 psi)
γ_c = concrete density (151PCF)
γ_S = salt density (140 PCF)
σ_S = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of concrete-rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Required bulkhead thickness with low pressure grouting on concrete/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Appendix A. Intake Drift bulkhead design calculations (Continued)

Pressure gradient along minimum effective bulkhead thickness T_e= 28 ft

$$\rho_g = \frac{\rho}{28} = \frac{480}{28} = 17.1 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along concrete/rock salt contact around 28-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{17.1} = \underline{2.40}$$

Allowable concrete shear on Intake Drift perimeter:

$$f_s' = 2\sqrt{f_c'} = 2\sqrt{4000} = 126 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f_s'}$$

$$\rho_a = \frac{2T(h+\ell)f_s'}{h\ell} = \frac{2(36)(13+20)126}{13(20)} = \frac{299400}{260} = 1152 \text{ psi}$$

$$W = \rho_d h\ell = 480(13)20(144) = 17{,}970{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{17970000}{[2(13+20)]36(144)} = \frac{17970000}{342100} = 52.5 \text{ psi}$$

Factor of Safety against concrete shear failure $= \frac{f_s'}{v_s} = \frac{126}{52.5} = 2.40$

Allowable rock salt shear force along concrete/rock salt contact, Intake Drift bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to concrete/rock salt contact:

$$L_{rs} = \sqrt{8^2 + 8^2} + 0.5 + 9.75 + 9.75 = 31.3 \text{ ft}^2\text{/ft of perimeter}$$

Minimum rock salt perimeter = 2(13+20) = 66 ft

Total effective bulkhead shear area = 2,066 ft^2

Maximum rock salt shear resistance = 2066(1070)144 = 318,300,000 lb

Appendix A. Intake Drift bulkhead design calculations (Continued)

Maximum shear force on panel side bulkhead face and outward inclined panel side concrete/rock salt contact potentially opened by explosion gas pressure:

Face area = 13(20) = 260 ft^2

Vertical component of sloping area = $2(13+20)8 + \frac{\pi 8^2}{4} = 528 + 50 = 578$ ft^2

Design maximum thrust = (578+260)(480)144 = 57,920,000 lb

Factor of Safety against rock salt shear failure = $\frac{318{,}300{,}000}{57{,}920{,}000} = 5.50$

Plain concrete deep beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 480 psi design dynamic pressure head:

$$\omega = U = 2\rho_d(144) = 2(240)144 = 69{,}120\left(\frac{\text{lb}}{\text{ft}^2}\right)$$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(20^2)}{24} = 1{,}152{,}000 \text{ ft}\cdot\text{lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{1152000}{0.65} = 1{,}772{,}000 \text{ ft}\cdot\text{lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{1772000}{\frac{144T^2}{6}} = \frac{73830}{T^2}$$

$T = \sqrt{\frac{73830}{206}} = \sqrt{358.4} = 18.9$ ft thick plain concrete bulkhead is required for worst-case rib to rib fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{1772000}{\frac{144(36^2)}{6}} = \frac{1772000}{31100} = 57.0 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{57.0} = 3.61$$

Therefore, a 36-ft thick plain-concrete bulkhead worst-case griped at both ribs of the 20-ft wide Intake Drift, is acceptable as a panel closure bulkhead.

Appendix A. Intake Drift bulkhead design calculations (Continued)

Bulkhead deep beam griped at Intake Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega\ell^2}{24} = \frac{69120(13^2)}{24} = 486{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{486700}{0.65} = 748{,}800 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{748800}{\frac{144T^2}{6}} = \frac{31200}{T^2}$$

$T = \sqrt{\frac{31200}{206}} = \sqrt{151.5} = 12.3$-ft thick plain concrete bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{748800}{\frac{144(36^2)}{6}} = \frac{748800}{31100} = 24.1 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{24.1} = 8.55$$

Therefore, a 36-ft thick plain-concrete bulkhead, best-case griped at roof and floor of the 13-ft high Intake Drift, is acceptable as a panel closure bulkhead.

APPENDIX B. EXHAUST DRIFT BULKHEAD DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = concrete shear strength $\left(2\sqrt{f'_c} = 126 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Exhaust Drift width (14 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
T_e = effective bulkhead thickness (18 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain concrete strength reduction factors
0.65 plain concrete flexure, compression
shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = concrete comp strength (4,000 psi)
f_{cl} = concrete tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{4000} = 206 \text{ psi}\right]$
h = Exhaust Drift height (12 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (26 ft)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d = dynamic pressure head (240 psi)
γ_c = concrete density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of concrete-rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Exhaust Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Required bulkhead length with low pressure grouting on concrete/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Pressure gradient along minimum effective bulkhead thickness T = 18 ft

$\rho_g = \frac{\rho}{18} = \frac{480}{18} = 26.7$ psi/ft

Factor of Safety against leakage of explosion gasses along concrete/rock salt contact around 18-ft effective bulkhead thickness is:

$\underline{FS} = \frac{41}{26.7} = \underline{1.54}$

Allowable concrete shear on Exhaust Drift perimeter:

$f'_s = 2\sqrt{f'_c} = 2\sqrt{4000} = 126$ psi (ACI 318-95, Sec 11.3.1.1)

$$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(36)(12+14)126}{12(14)} = \frac{235900}{168} = 1404 \text{ psi}$$

$W = \rho_d h\ell = 480(12)14(144) = 11{,}610{,}000$ lb

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{11610000}{[2(12+14)]36(144)} = \frac{11610000}{269600} = 43.1 \text{ psi}$$

Factor of Safety against concrete shear failure $= \frac{f'_s}{v_s} = \frac{126}{43.1} = 2.92$

Allowable rock salt shear force along concrete/rock salt contact, Exhaust Drift bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to concrete/rock salt contact:

$L_{rs} = \sqrt{8^2 + 8^2} + 0.5 + 4.75 + 4.75 = 21.3$ ft²/ft of perimeter

Minimum rock salt perimeter = 2(12+14) = 52 ft

Total effective bulkhead shear area = 1,108 ft^2

Maximum rock salt shear resistance = 1108(1070)144 = 170, 700, 000 lb

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Maximum shear force on panel side bulkhead face and outward inclined panel side concrete/rock salt contact potentially opened by explosion gas pressure:

Face area = 12(14) = 168 ft^2

Vertical component of sloping area = $2(12+14)8 + \frac{\pi 8^2}{4} = 416 + 50 = 466\ ft^2$

Design maximum thrust = (466+168)(1070)144 = 97,690,000 lb

Factor of Safety against rock salt shear failure = $\frac{170{,}700{,}000}{97{,}690{,}000} = 1.75$

Plain concrete deep beam bending stress design, Exhaust Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 480 psi design dynamic pressure head:

$$\omega = U = 2\rho_d(144) = 2(240)144 = 69{,}120\ \left(\frac{lb}{ft^2}\right)$$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(14^2)}{24} = 564{,}500\ ft \cdot lb$$

$$M_u = \frac{M_n}{0.65} = \frac{564500}{0.65} = 868{,}500\ ft \cdot lb$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206\ psi$$

$$f'_{cl} = 206 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{868500}{\frac{144T^2}{6}} = \frac{36190}{T^2}$$

$T = \sqrt{\frac{36190}{206}} = \sqrt{175.7} = 13.3$ ft thick plain concrete bulkhead is required for worst-case rib to rib fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{868500}{\frac{144(26^2)}{6}} = \frac{868500}{16220} = 53.5\ psi$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{53.5} = 3.85$$

Therefore, a 26-ft thick plain-concrete bulkhead, worst-case griped at both ribsides of the 14-ft wide Exhaust Drift, is acceptable as a panel closure bulkhead.

Appendix B. Exhaust Drift bulkhead design calculations (Continued)

Bulkhead deep beam griped at Exhaust Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(12^2)}{24} = 414{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{414700}{0.65} = 638{,}000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{4000} = 206 \text{ psi}$$

$$f'_{cl} = 190 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{638000}{\frac{144T^2}{6}} = \frac{26580}{T^2}$$

$T = \sqrt{\frac{26580}{206}} = \sqrt{129.0} = 11.4$-ft thick plain concrete bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{638000}{\frac{144(26^2)}{6}} = \frac{638000}{16220} = 39.3 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{206}{39.3} = 5.24$$

Therefore, a 26-ft thick plain-concrete bulkhead, best-case griped at roof and floor of the 12-ft high Exhaust Drift, is acceptable as a panel closure bulkhead.

APPENDIX C. INTAKE DRIFT EXPLOSION-ISOLATION MASONRY WALL DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain masonry strength reduction factors
  0.65 plain concrete flexure, compression
    shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{cl} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
  $\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (12 ft)
V_c = masonry shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (480 psi)
ρ_d = dynamic pressure head (240 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
  Static fluid load factor (F) = 1.4;
  Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
  Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Required bulkhead thickness with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 12 ft

$$\rho_g = \frac{\rho}{28} = \frac{480}{12} = 40.0 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 12-ft effective bulkhead thickness is:

$$\underline{FS} = \frac{41}{40.0} = \underline{1.03}$$

Allowable masonry shear on Intake Drift perimeter:

$$f_s' = 2\sqrt{f_c'} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h\ell}{2(h+\ell)f_s'}$$

$$\rho_a = \frac{2T(h+\ell)f_s'}{h\ell} = \frac{2(12)(13+20)100}{13(20)} = \frac{79200}{260} = 304.6 \text{ psi}$$

$$W = \rho_d h\ell = 480(13)20(144) = 17{,}970{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{17970000}{[2(13+20)]12(144)} = \frac{17970000}{114000} = 157.6 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f_s'}{v_s} = \frac{100}{157.6} = \mathbf{\underline{0.63}}$

Required masonry wall thickness to resist design methane explosion pressure

$$T = \frac{\rho h\ell}{2(h+\ell)f_s'} = \frac{480(13)20}{2[13+20]100} = \frac{124800}{6600} = 18.9 \text{ ft}$$

Allowable rock salt shear force along masonry/rock salt contact, Intake Drift explosion-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

L_{rs} = 12 ft^2/ft of perimeter

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Minimum rock salt perimeter = 2(14+21) = 70 ft
based on perimeter hitched 6-in into roof, ribs and floor of Intake Drift

Total effective bulkhead shear area = 840 ft^2

Maximum rock salt shear resistance = 840(1070)144 = 129,400,000 lb

Maximum shear force on masonry/rock salt contact potentially opened by explosion gas pressure:

Face area = 14(21) = 294 ft^2

Design maximum thrust = (294)(480)144 = 20,320,000 lb

Factor of Safety against rock salt shear failure = $\frac{129{,}400{,}000}{20{,}320{,}000} = 6.37$

Masonry explosion-isolation beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1) for 480 psi design dynamic pressure head:

$$\omega = U = 2\rho_d(144) = 2(240)144 = 69{,}120\ \left(\frac{lb}{ft^2}\right)$$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(20^2)}{24} = 1{,}152{,}000\ ft\cdot lb$$

$$M_u = \frac{M_n}{0.65} = \frac{1152000}{0.65} = 1{,}772{,}000\ ft\cdot lb$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5\ psi$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{1772000}{\frac{144T^2}{6}} = \frac{73830}{T^2}$$

$T = \sqrt{\frac{73830}{162.5}} = \sqrt{454.3} = 21.3$ ft thick masonry bulkhead is required for worst-case rib to rib fixed explosion-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{1772000}{\frac{144(12^2)}{6}} = \frac{1772000}{3456} = 512.7\ psi$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{512.7} = \underline{\mathbf{0.32}}$$

Appendix C. Intake Drift explosion-isolation masonry wall design calculations (Continued)

Therefore, 12-ft thick cement-mortared masonry block bulkhead, worst-case griped at both ribsides of the 20-ft wide Intake Drift, is NOT acceptable as an explosion-isolation bulkhead.

Masonry bulkhead deep beam griped at Intake Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega \ell^2}{24} = \frac{69120(13^2)}{24} = 486{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{486700}{0.65} = 748{,}800 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{748800}{\frac{144T^2}{6}} = \frac{31200}{T^2}$$

$T = \sqrt{\frac{31200}{162.5}} = \sqrt{192.0} = 13.8$-ft thick concrete block masonry bulkhead is required for best-case roof to floor fixed bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{748800}{\frac{144(12^2)}{6}} = \frac{748800}{3456} = 216.7 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{216.7} = \underline{\mathbf{0.75}}$$

Therefore, 12-ft thick cement-mortared masonry block bulkhead, best-case griped at roof and floor of the 13-ft high Intake Drift, is NOT acceptable as an explosion-isolation bulkhead.

APPENDIX D. EXHAUST DRIFT EXPLOSION-ISOLATION MASONRY WALL DESIGN CALCULATIONS

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Exhaust Drift width (14 ft)
M_n = nominal beam moment (ft•lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_a = allowable pressure head (psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w = water density (62.4PCF)
ϕ = plain masonry strength reduction factors
0.65 plain concrete flexure, compression
shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{ct} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$
$\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Exhaust Drift height (12 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft•lb)
M_u = factored beam moment (ft•lb)
T = overall bulkhead thickness (12 ft)
V_c = masonry shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (480 psi)
ρ_d = dynamic pressure head (240 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
σ_s = flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Exhaust Drift bulkhead, design dynamic pressure head = $L\rho_d = 2(240) = 480$ psi

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Required bulkhead length with low pressure grouting on masonry/rock salt bulkhead contact:

$$T = \frac{\rho}{41} = \frac{480}{41} = 11.7 \text{ ft}$$

Pressure gradient along bulkhead thickness T = 12 ft

$$\rho_g = \frac{\rho}{12} = \frac{480}{12} = 40.0 \text{ psi/ft}$$

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 12-ft effective bulkhead thickness is:

$$FS = \frac{41}{40.0} = 1.03$$

Allowable masonry shear on Exhaust Drift perimeter:

$$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100 \text{ psi} \qquad \text{(ACI 318-95, Sec 11.3.1.1)}$$

$$T = \frac{\rho_a h \ell}{2(h+\ell) f'_s}$$

$$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(12)(12+14)100}{12(14)} = \frac{62400}{168} = 371.4 \text{ psi}$$

$$W = \rho_d h\ell = 480(12)14(144) = 11{,}610{,}000 \text{ lb}$$

$$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{11610000}{2(12+14)12(144)} = \frac{11610000}{89860} = 129.2 \text{ psi}$$

Factor of Safety against masonry shear failure $= \frac{f'_s}{v_s} = \frac{100}{129.2} = \underline{\mathbf{0.77}}$

Required masonry wall thickness to resist design methane explosion pressure

$$T = \frac{\rho h\ell}{2(h+\ell)f'_s} = \frac{480(12)14}{2[13+20]100} = \frac{81640}{6600} = 12.2 \text{ ft}$$

Allowable rock salt shear force along masonry/rock salt contact, Exhaust Drift explosion-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

L_{rs} = 12 ft^2/ft of perimeter

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Minimum rock salt perimeter = 2(13+15) = 56 ft
based on perimeter hitched 6-in into roof, ribs and floor of Exhaust Drift

Total effective bulkhead shear area = 672 ft^2

Maximum rock salt shear resistance = 672(1070)144 = 103, 500, 000 lb

Maximum shear force on panel side bulkhead face and outward inclined panel side masonry/rock salt contact potentially opened by explosion gas pressure:

Face area = 13(15) = 195 ft^2

Design maximum thrust = (195)(480)144 = 13,480,000 lb

Factor of Safety against rock salt shear failure = $\frac{103,500,000}{13,480,000} = 7.68$

Masonry explosion-isolation beam bending stress design, Exhaust Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1) for 480 psi design dynamic pressure head:

$$\omega = U = 2\rho_d(144) = 2(240)144 = 69,120\left(\frac{lb}{ft^2}\right)$$

Bulkhead deep beam griped at rock salt ribs by creep pressure (worst-case)

$$M_n = \frac{\omega\ell^2}{24} = \frac{69120(14^2)}{24} = 564,500 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{564500}{0.65} = 868,500 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{868500}{\frac{144T^2}{6}} = \frac{36190}{T^2}$$

$T = \sqrt{\frac{36190}{162.5}} = \sqrt{222.7} = 14.9$ ft thick masonry bulkhead is required for worst-case rib to rib fixed explosion-isolation bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{868500}{\frac{144(12^2)}{6}} = \frac{868500}{3456} = 251.3 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{251.3} = \underline{\mathbf{0.65}}$$

Appendix D. Exhaust Drift explosion-isolation wall design calculations (Continued)

Therefore, 12-ft thick cement mortared masonry block wall, worst-case griped at both ribsides of the 14-ft wide Exhaust Drift, is NOT acceptable as an explosion-isolation bulkhead.

Masonry bulkhead deep beam griped at Exhaust Drift rock salt roof and floor (best-case)

$$M_n = \frac{\omega\ell^2}{24} = \frac{69120(12^2)}{24} = 414{,}700 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{414700}{0.65} = 638{,}000 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{638000}{\frac{144T^2}{6}} = \frac{26580}{T^2}$$

$T = \sqrt{\frac{26580}{162.5}} = \sqrt{177.2} = 13.3$-ft thick concrete block masonry bulkhead is required for best-case roof to floor fixed beam bulkhead.

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{638000}{\frac{144(12^2)}{6}} = \frac{638000}{3456} = 184.6 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{184.6} = \underline{\mathbf{0.88}}$$

Therefore, 12-ft thick cement mortared masonry block wall, best-case griped at roof and floor of the 12-ft high, Exhaust Drift is NOT acceptable as an explosion-isolation bulkhead.

APPENDIX E. INTAKE DRIFT CONSTRUCTION-ISOLATION WALL DESIGN CALCULATIONS (ROOF FALL PRESSURE)

Notation:

C = compressive bending force (lb)
D = dead load $\left(\frac{lb}{ft}\right)$
FS = factor of safety
$\sqrt{f'_c}$ = square root of f'_c
f'_s = masonry shear strength $\left(2\sqrt{f'_c} = 100 \text{ psi}\right)$
H = depth below surface (2150 ft)
I = moment of inertia (in^4)
ℓ = Intake Drift width (20 ft)
M_n = nominal beam moment (ft·lb)
S = section modulus (in^3)
U = required strength $\left(\frac{lb}{ft}\right)$
V_n = nominal shear force (lb)
v_s = shear stress (psi)
ω = uniform bulkhead load $\left(\frac{lb}{ft}\right)$
ρ_d= dynamic pressure head (0.035 psi)
γ_c = masonry density (151PCF)
γ_s = salt density (140 PCF)
ϕ= plain concrete strength reduction factors
0.65 plain concrete flexure, compression shear and bearing

c = centroidal distance (in)
F = fluid load $\left(\frac{lb}{ft}\right)$
f'_c = masonry comp strength (2,500 psi)
f_{ct} = masonry tensile strength $\left(5\phi\sqrt{f'_c} \text{ psi}\right)$ $\left[5(0.65)\sqrt{2500} = 162 \text{ psi}\right]$
h = Intake Drift height (13 ft)
L = live, dynamic, load $\left(\frac{lb}{ft}\right)$
M = bending moment (ft·lb)
M_u = factored beam moment (ft·lb)
T = overall bulkhead thickness (4 ft)
V_c = concrete shear strength (lb)
V_u = factored shear force (lb)
W = bulkhead load (lb)
ρ = design pressure head (0.070 psi)
ρ_g = pressure gradient $\left(\frac{psi}{ft}\right)$
γ_w= water density (62.4PCF)
σ_s= flexure stress (psi)

Load factors (ACI 318-95, Sec 9.2.1)
Static fluid load factor (F) = 1.4;
Live (dynamic) load factor (L) = 1.7

Load factor (DOE, 1996, Appendix PCS: 2.2.3.1)
Live (dynamic) load factor (L) = 2

Allowable pressure gradient:

Low pressure grouting of masonry/rock salt contact but not rock salt, gradient allowable = 41 psi/ft (Garrett & Campbell-Pitt, 1958, Chekan, 1985, p11), with factor of safety of 4

Intake Drift bulkhead, 10 psf design dynamic pressure head = $L\rho_d = 2(0.035) = 0.070$ psi

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Required bulkhead thickness with low pressure grouting on masonry/rock salt bulkhead contact:

$T = \frac{\rho}{41} = \frac{0.070}{41} = 0.0002$ ft

Pressure gradient along bulkhead thickness T = 4 ft

$\rho_g = \frac{\rho}{T} = \frac{0.070}{4} = 0.0175$ psi/ft

Factor of Safety against leakage of explosion gasses along masonry/rock salt contact around 28-ft effective bulkhead thickness is:

$\underline{FS} = \frac{41}{0.0175} = >2300$

Allowable masonry shear on Intake Drift perimeter:

$f'_s = 2\sqrt{f'_c} = 2\sqrt{2500} = 100$ psi (ACI 318-95, Sec 11.3.1.1)

$T = \frac{\rho_a h\ell}{2(h+\ell)f'_s}$

$\rho_a = \frac{2T(h+\ell)f'_s}{h\ell} = \frac{2(4)(13+20)100}{13(20)} = \frac{26400}{260} = 101.5$ psi

$W = \rho_d h\ell = 0.070(13)20(144) = 2621$ lb

$v_s = \frac{W}{[2(h+\ell)]T(144)} = \frac{2621}{[2(13+20)]4(144)} = \frac{2621}{38020} = 0.0689$ psi

Factor of Safety against masonry shear failure = $\frac{f'_s}{v_s} = \frac{100}{0.0689} = >1450$

Allowable rock salt shear force along masonry/rock salt contact, Intake Drift constructon-isolation bulkhead:

Rock salt cohesion (C_{rs})approximately 1070 psi (See appendix F.)

Length of minimum shear path in rock salt (L_{rs}) adjacent to masonry/rock salt contact:

$L_{rs} = 4$ ft^2/ft of perimeter

Minimum rock salt perimeter = 2(14+21) = 70 ft
(6-in inset in roof, walls and floor)

Total effective bulkhead shear area = 280 ft^2

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Maximum rock salt shear resistance = 2(14 + 21)12(1070)144 = 129,400 lb
based on perimeter hitched 6-in into roof, ribs and floor of Intake Drift

Maximum shear force on masonry/rock salt contact potentially opened by roof fall overpressure:

Face area = 14(21) = 294 ft^2

Design maximum thrust = (294)(0.070)144 = 2,964 lb

Factor of Safety against rock salt shear failure = $\frac{129,400}{2,964} = 43.7$

Masonry construction-isolation beam bending stress design, Intake Drift (ACI 318-95, Sec 9.3.5, Sec 10.5; ACI318.1-89, Sec 6.2.1)

for 0.070 psi design dynamic roof fall pressure head:

$$\omega = U = 2\rho_d(144) = 2(0.035)144 = 10.1 \left(\frac{lb}{ft^2}\right)$$

Simply supported 4-ft thick bulkhead beam supported at rock salt ribs by contact grout pressure (worst-case)

$$M_n = \frac{\omega\ell^2}{8} = \frac{10.1(21^2)}{8} = 556.8 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{556.8}{0.65} = 856.6 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 150 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{856.6}{\frac{144T^2}{6}} = \frac{35.69}{T^2}$$

$T = \sqrt{\frac{35.69}{162.5}} = \sqrt{0.220} = 0.47$ ft thick masonry concrete bulkhead is required for worst-case rib to rib simply-supported construction-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{856.6}{\frac{144(4^2)}{6}} = \frac{856.6}{384.0} = 2.23 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{2.23} = >73$$

Appendix E. Intake Drift construction-isolation wall design calculations (Continued)

Therefore, 4-ft thick cement-mortared concrete block masonry bulkhead, worst-case, simply-supported at both ribsides of the hitched in 21-ft wide Intake Drift, is acceptable as a construction-isolation bulkhead.

Simply supported 4-ft thick bulkhead beam supported at roof and floor by contact grout pressure (best-case)

$$M_n = \frac{\omega \ell^2}{8} = \frac{10.1(13^2)}{8} = 213.4 \text{ ft·lb}$$

$$M_u = \frac{M_n}{0.65} = \frac{213.4}{0.65} = 328.3 \text{ ft·lb}$$

$$S = \frac{I}{c} = \frac{\frac{bT^3}{12}}{\frac{T}{2}} = \frac{\frac{1(T^3)(12^3)}{12}}{\frac{T(12)}{2}} = \frac{144T^2}{6}$$

$$f'_{cl} = 5\phi\sqrt{f'_c} = 5(0.65)\sqrt{2500} = 162.5 \text{ psi}$$

$$f'_{cl} = 162.5 = \sigma = \frac{M_u c}{I} = \frac{M_u}{S} = \frac{328.3}{\frac{144T^2}{6}} = \frac{13.68}{T^2}$$

$T = \sqrt{\frac{13.68}{162.5}} = \sqrt{0.0842} = 0.29$ ft thick masonry bulkhead is required for best-case rib to rib simply-supported construction-isolation bulkhead

$$\sigma_s = \frac{M_u}{S} = \frac{M_u}{\frac{144T^2}{6}} = \frac{328.3}{\frac{144(4^2)}{6}} = \frac{328.3}{384.0} = 0.855 \text{ psi}$$

$$FS = \frac{f'_{cl}}{\sigma_s} = \frac{162.5}{0.855} = >190$$

Therefore, 4-ft thick cement-mortared concrete block masonry bulkhead, best-case simply-supported at roof and floor of the hitched 13-ft high Intake Drift, is acceptable as a construction-isolation bulkhead.

APPENDIX F. TRIAXIAL PROPERTIES OF PERMIAN EVAPORITES

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
AEC-7 & ERDA-9 boreholes, rock salt	3230	29.6°	940	0-3000	8
from 1900 to 2800 ft, Carlsbad, NM (GCR, Chapter 4)					
Mississippi Chemical Corp., Carlsbad, NM					
Cycle 7, Potash salt (CSM Lab, 1982)	3520	46.6°	700	0-1500	64
Cycle 5, Potash salt (CSM Lab, 1991)	2880	36.9°	720	0-1500	34
Cycle 5, Roof rock salt	3170	39.3°	750	0-2000	25
Cycle 5, Floor clayey rock salt (CSM '92)	3580	38.1°	870	0-2000	20
PCS Mining, Ltd., Rocanville Div., Saskatchewan (Molavi & Wooley, 1986)					
Esterhazy potash salt mbr.	2300	27.3°	700	Unknown	??
RE/SPEC, Inc., Paradox Basin, UT (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 6, Rock salt	4970	33.7°	1330	0-2200	4
Cycle 6, Carnalite	5660	32.0°	1570	0-2200	4
Cycle 7, Rock salt	5880	33.5°	1580	0-2200	4
RE/SPEC, Inc., Permian Basin, TX (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 5, Rock salt	5000	31.2°	1410	0-2200	10
Cycle 4, Rock salt	4150	30.8°	1180	0-2200	4
Dettin Well, Rock salt, 1900-ft depth	4640	33.8°	1240	0-2200	6
Dettin Well, Rock salt, 2250-ft depth	4280	36.0°	1090	0-2200	6
Zeeck Well, Rock salt, 28-2900-ft depth	4750	33.4°	1280	0-2200	9
Carey Salt Co., Hutchinson, KS (CSM Lab, 1985)					
Rock salt	2900	49.1°	540	0-1000	24
Independent Salt Co., Kanapolis, KS (CSM Lab, 1987)					
Roof rock salt	4330	31.2°	1220	0-3000	16
Averages	4080	35.2°	1070		
Standard Deviations	1040	5.9°	330		

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (CSM & Adv Terra Testing Labs 1992)					
Grueso Brecha Domo Sal, Barreno30	3630	48.4°	690	0-2000	9
Intermedio Brecha Domo Sal, Bar 30	3180	49.3°	590	0-2000	7
Fino Brecha Domo Sal, Barreno 30	3150	48.8°	600	0-2000	9
All Barreno 30 Brecha Sal Pruebas	3340	48.7°	630	0-2000	25
Upper Brecha Sal, Barreno 36	7510	44.9°	1560	0-2000	5
Lower Brecha Sal, Barreno 36	5230	47.8°	1010	0-2000	5
All Barreno 36 Brecha Sal Pruebas	6350	46.4°	1270	0-2000	10
ALL BRECHA SAL PRUEBAS, Bars 30-36	4110	48.4°	780	0-2000	35
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (ATT Lab 1992)					
Yeso, Caliza y Anhidrita Brecha Barreno 36	5050	47.2°	990	0-2000	5
Minerales Para La Industria, Sal-Gema, Hidalgo, N.L., Mexico (ATT Lab 1992)					
Red Brecciated Salt, Barreno 20	2260	20.0°	790	0-2000	3
AEC-7 & ERDA-9 boreholes, rock salt from 1900 to 2800 ft, Carlsbad, NM (GCR, Chapter 4)	3230	29.6°	940	0-3000	8
Cote Blanche Mine, Cote Blanche, LA (Hansen, 1977)					
Cote Blanche, dome salt	4130	40.1°	960	0-1500	9
Cote Blanche, yellow dome salt	6840	34.5°	1800	0-1500	3
German Democratic Republic (Menzel, et al, 1972)					
Rock salt	5590	34.8°	1460	0-4250	8
"Hartsalz"	6950	35.5°	1790	0-4250	8
Carnolite	4730	30.6°	1350	0-4250	8
"Sylinit"	6730	34.0°	1790	0-4250	8

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES (Continued)

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Mississippi Chemical Corp., Carlsbad, NM					
Cycle 7, Potash salt (CSM Lab, 1982)	3520	46.6°	700	0-1500	64
Cycle 5, Potash salt (CSM Lab, 1991)	2880	36.9°	720	0-1500	34
Cycle 5, Roof rock salt	3170	39.3°	750	0-2000	25
Cycle 5, Floor clayey rock salt (CSM Lab, 1992)	3580	38.1°	870	0-2000	20
PCS Mining, Ltd., Rocanville Div., Saskatchewan (Molavi & Wooley, 1986)					
Esterhazy potash salt mbr.	2300	27.3°	700	Unknown	??
RE/SPEC, Inc., Paradox Basin, UT (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 6, Rock salt	4970	33.7°	1330	0-2200	4
Cycle 6, Carnalite	5660	32.0°	1570	0-2200	4
Cycle 7, Rock salt	5880	33.5°	1580	0-2200	4
RE/SPEC, Inc., Permian Basin, TX (Pfeifle, Mellegard & Senseny, 1982)					
Cycle 5, Rock salt	5000	31.2°	1410	0-2200	10
Cycle 4, Rock salt	4150	30.8°	1180	0-2200	4
Dettin Well, Rock salt, 1900-ft depth	4640	33.8°	1240	0-2200	6
Dettin Well, Rock salt, 2250-ft depth	4280	36.0°	1090	0-2200	6
Zeeck Well, Rock salt, 28-2900-ft depth	4750	33.4°	1280	0-2200	9
RE/SPEC, Inc., LA salt domes (Pfeifle, Mellegard & Senseny, 1982)					
Richton Dome	3280	35.7°	840	0-2200	4
Vacherie Dome	3340	36.6°	840	0-2200	4
RE/SPEC, Inc., Avery Island, LA (Hansen & Mellegard, 1979)					
Dome rock salt	3640	35.4°	940	0-3000	7
Meadowbank Mine, Cheshire, Great Britain (Sen, 1962)					
Rock salt	4640	40.9°	1060	0-1000	3

APPENDIX G. TRIAXIAL PROPERTIES OF SELECTED EVAPORITES (Continued)

Source, Cycle etc. and testing lab or reference	Unconfined Compression Strength (psi)	Angle of Internal Friction (degs)	Cohesion (psi)	Confining Pressure Range (psi)	Number Samples Tested
Carey Salt Co., Hutchinson, KS (CSM Lab, 1985)					
Rock salt	2900	49.1°	540	0-1000	24
TG Chemicals, Inc., Granger, WY (CSM Lab, 1985)					
Bed # 21, Trona	3900	43.9°	830	0-2000	49
General Chemical Corp., Green River, WY (CSM Lab, 1987)					
Bed # 17, Trona	5860	42.8°	1280	0-3000	72
Independent Salt Co., Kanapolis, KS (CSM Lab, 1987)					
Roof rock salt	4330	31.2°	1220	0-3000	16
Morton Salt Co., Fairport Harbor Mine, Painesville, OH (CSM Lab, 1987)					
Rock salt	4020	39.0°	960	0-4000	30
Gold Bond Building Products Co., Shoals Mine, IN, (CSM Lab 1988-89)					
Gypsum	2880	34.0°	765	0-1300	22
Averages	4390	36.2°	1100		
Standard Deviations	1320	6.3°	350		