Minimum fracture pressure

Hydrostatic pressure of the fluids (mud and spacer) ahead of the foamed cement

Allowable average density of the foamed cement
The allowable average density of the foamed cement in the annulus, $\rho_1$, is calculated as below.
Number of stages
Divide into intervals of 1,000 to 1,500 ft
Total interval is 8,000 – 2,500 ft = 5,500 ft
Divide into 5 stages of 1,100 ft each

Hydrostatic pressure at the midpoint of each stage
\[ p_h = p_h \text{ above stage} + p_h \text{ to midpoint of stage} \]

Stage No. 1 (top)
\[ p_{h1} = 1,173 \text{ psi} \]
\[ + [(\text{Stage number} - 0.5) \times 1,100 \text{ ft} \times \rho_1 \times 0.052] \]
\[ = 1,173 \text{ psi} + (0.5 \times 1,100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \]
\[ = 1,413 \text{ psi} \]

Stage No. 2
\[ p_{h2} = 1,173 \text{ psi} + (1.5 \times 1,100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \]
\[ = 1,894 \text{ psi} \]

Stage No. 3
\[ p_{h3} = 1,173 \text{ psi} + (2.5 \times 1,100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \]
\[ = 2,374 \text{ psi} \]

Stage No. 4
\[ p_{h4} = 1,173 \text{ psi} + (3.5 \times 1,100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \]
\[ = 2,855 \text{ psi} \]

Stage No. 5 (bottom)
\[ p_{h5} = 1,173 \text{ psi} + (4.5 \times 1,100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \]
\[ = 3,335 \text{ psi} \]

Nitrogen requirement for each stage based on the midpoint
Nitrogen density, \( \rho_{N2} \):
\[ \rho_{N2} = (1.724 \times 10^{-3}) \times K_{N2} \].

where
\( K_{N2} = \) nitrogen volume factor (scf/bbl).

Foamed cement quality, \( Q_{foam} \):
\[ Q_{foam} = 1 - \frac{\rho_{foam} - \rho_{N2}}{\rho_{bs} - \rho_{N2}} \],

where
\( \rho_{bs} = \) base slurry density
\( \rho_{fc} = \) foamed cement density
\( \rho_{N2} = \) nitrogen density.

Foamed cement yield, \( Y_{fc} \) (ft\(^3\)/sk):
\[ Y_{fc} = \frac{Y_{bs}}{1 - Q_{foam}} \].

where
\( Y_{bs} = \) base slurry yield (ft\(^3\)/sk).

Annular volume, \( V_{ann} \):
\[ V_{ann} = L \times S_{ann} \],

where
\( L = \) length
\( S_{ann} = \) annular capacity.

Cement requirement, \( C \) (sk):
\[ C = \frac{V_{ann}}{Y_{fc}} \].

Nitrogen requirement at conditions in the annulus, \( R_{N2} \):
\[ R_{N2} = V_{ann} \times Q_{foam} \].

The nitrogen requirement refers to the volume required at circulating temperature and pressure. For job-design purposes, this value must be converted to the equivalent volume of nitrogen in standard cubic feet (at standard temperature and pressure [STP]).

Nitrogen volume, \( V_{N2} \), at STP (scf):
\[ V_{N2} = R_{N2} \times K_{N2} \].

Stage No. 1, \( p_{h1} = 1,413 \text{ psi} \)
\[ \rho_{N2} = (1.724 \times 10^{-3}) \times K_{N2} \]
\[ = 1.724 \times 10^{-3} \times 476 \text{ scf/bbl} \]
\[ = 0.8206 \text{ lbm/gal} \]

The nitrogen volume factor can be calculated based upon pressure and bottomhole circulating temperature or more easily looked up in standard tables published by most cementing companies.

Foamed cement quality, \( Q_{foam} \):
\[ Q_{foam} = 1 - \frac{8.4 - 0.8206}{14.2 - 0.8206} \]
\[ = 0.4335 \].
Foamed cement yield, \( Y_{fc} \):

\[
Y_{fc} = \frac{1.29 \text{ ft}^3/\text{sk}}{1 - 0.4335} = 2.28 \text{ ft}^3/\text{sk}.
\]

Annular volume, \( V_{ann} \):

\[
V_{ann} = 1,100 \text{ ft} \times 0.3017 \text{ ft}^3/\text{ft} = 331.9 \text{ ft}^3.
\]

Cement requirement, \( C \) (sk):

\[
C = \frac{331.9 \text{ ft}^3}{2.28 \text{ ft}^3/\text{sk}} = 145.6 \text{ sk}.
\]

Nitrogen requirement, \( R_{N_2} \):

\[
R_{N_2} = 331.9 \text{ ft}^3 \times 0.4335 = 143.9 \text{ ft}^3.
\]

Nitrogen volume, \( V_{N_2} \), at STP:

\[
V_{N_2} = 143.9 \text{ ft}^3 \times 0.178 \text{ bbl/ft}^3 \times 476 \text{ scf/bbl} = 12,192 \text{ scf}.
\]

Similarly, the requirements for the other stages are calculated, and the following table can be built.

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrostatic pressure (psi)</td>
<td>1,413</td>
<td>1,894</td>
<td>2,374</td>
<td>2,855</td>
<td>3,335</td>
</tr>
<tr>
<td>Nitrogen density (lbm/gal)</td>
<td>0.821</td>
<td>1.069</td>
<td>1.291</td>
<td>1.493</td>
<td>1.677</td>
</tr>
<tr>
<td>Foamed cement quality</td>
<td>0.4335</td>
<td>0.4417</td>
<td>0.4493</td>
<td>0.4564</td>
<td>0.4631</td>
</tr>
<tr>
<td>Foamed cement yield (ft³/sk)</td>
<td>2.28</td>
<td>2.31</td>
<td>2.34</td>
<td>2.37</td>
<td>2.40</td>
</tr>
<tr>
<td>Annular volume (ft³)</td>
<td>331.9</td>
<td>331.9</td>
<td>331.9</td>
<td>331.9</td>
<td>331.9</td>
</tr>
<tr>
<td>Cement requirement (sk)</td>
<td>145.6</td>
<td>143.7</td>
<td>141.8</td>
<td>140.0</td>
<td>138.3</td>
</tr>
<tr>
<td>Nitrogen per sack (scf/sk)</td>
<td>83.7</td>
<td>112.6</td>
<td>140.2</td>
<td>168.8</td>
<td>192.5</td>
</tr>
<tr>
<td>Nitrogen requirement (scf)</td>
<td>12,192</td>
<td>16,179</td>
<td>19,878</td>
<td>23,353</td>
<td>26,620</td>
</tr>
<tr>
<td>Total cement requirement: 943.3 sk (709.4 sk for foamed stages + 233.9 sk for tail)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total nitrogen requirement: 98,222 scf</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hydrostatic pressure as each stage of foamed cement enters the annulus

Actually, hydrostatic pressure should be calculated for the position of each stage immediately above the weak formation(s). Because a job designed for constant density uses a slurry with the lowest concentration of nitrogen in the first stages, these initial stages will be significantly more dense when they pass the weaker formations below. Therefore, to ensure the integrity of the well, the hydrostatic pressure exerted on the weak formations must be calculated and compared to the fracturing pressure of these formations. To do this, the following steps must be followed.

1. Determine the volume occupied by each stage at the weak zone.
2. Calculate its length based on the annular capacity.
3. Calculate the hydrostatic pressure of the fluids in the annulus above.
4. Calculate the hydrostatic pressure of the foamed cement stage(s).
5. Add the results of Steps 3 and 4 to obtain the total hydrostatic pressure.
6. Compare this value to the fracturing pressure of the weak formation.
7. If the results indicate a risk of formation fracturing, consider a constant-nitrogen-rate or a hybrid job. A hybrid job involves several stages of foamed cement with different designed densities.

From the preceding example, this calculation is performed as shown below.

1. Determine the volume occupied by each stage at the weak zone.
   - For Stage No. 1, 145.6 sk or \((145.6 \times 1.29 \text{ ft}^3/\text{sk} \times 0.178 \text{ bbl/ft}^3) = 33.4 \text{ bbl of cement slurry are required.}"
   - The nitrogen requirement is 12,192 scf.
   - The weak zone is at 7,700 ft.
   - The fluids ahead of the cement are 9.2-lbm/gal mud (0.4784 psi/ft), and 745 ft of spacer at 8.6 lbm/gal (0.4472 psi/ft).
   - Assuming the foamed cement occupies 850 ft (because of compression), the length of the mud column is 7,700 – 850 (cement) – 745 (spacer) = 6,105 ft.
   - The hydrostatic pressure from the mud is 6,105 ft \(\times 0.4784 \text{ psi/ft} = 2,920 \text{ psi, and the hydrostatic pressure from the spacer is 745 ft} \times 0.4472 \text{ psi/ft} = 333 \text{ psi; thus, the total hydrostatic pressure is } 2,920 + 333 = 3,253 \text{ psi.}"

### Stage 1
- Hydrostatic pressure: 1,413 psi
- Nitrogen density: 0.821 lbm/gal
- Foamed cement quality: 0.4335
- Foamed cement yield: 2.28 ft³/sk
- Annular volume: 331.9 ft³
- Cement requirement: 145.6 sk
- Nitrogen requirement: 83.7 scf/sk
- Total cement requirement: 145.6 sk

### Stage 2
- Hydrostatic pressure: 1,894 psi
- Nitrogen density: 1.069 lbm/gal
- Foamed cement quality: 0.4417
- Foamed cement yield: 2.31 ft³/sk
- Annular volume: 331.9 ft³
- Cement requirement: 143.7 sk
- Nitrogen requirement: 112.6 scf/sk
- Total cement requirement: 143.7 sk

### Stage 3
- Hydrostatic pressure: 2,374 psi
- Nitrogen density: 1.291 lbm/gal
- Foamed cement quality: 0.4493
- Foamed cement yield: 2.34 ft³/sk
- Annular volume: 331.9 ft³
- Cement requirement: 141.8 sk
- Nitrogen requirement: 140.2 scf/sk
- Total cement requirement: 141.8 sk

### Stage 4
- Hydrostatic pressure: 2,855 psi
- Nitrogen density: 1.493 lbm/gal
- Foamed cement quality: 0.4564
- Foamed cement yield: 2.37 ft³/sk
- Annular volume: 331.9 ft³
- Cement requirement: 140.0 sk
- Nitrogen requirement: 168.8 scf/sk
- Total cement requirement: 140.0 sk

### Stage 5
- Hydrostatic pressure: 3,335 psi
- Nitrogen density: 1.677 lbm/gal
- Foamed cement quality: 0.4631
- Foamed cement yield: 2.40 ft³/sk
- Annular volume: 331.9 ft³
- Cement requirement: 138.3 sk
- Nitrogen requirement: 192.5 scf/sk
- Total cement requirement: 138.3 sk
Reading from the nitrogen tables, the volume occupied by 12,192 scf of nitrogen is 12.7 bbl at 160°F. Thus, the volume of the foamed cement slurry is 

\[ 12.7 + 33.4 = 46.1 \text{ bbl} \]

2. Calculate its length based on the annular capacity.
With an annular capacity of 0.3017 ft³/ft and 46.1 bbl of slurry, the fill-up is

\[ \frac{46.1 \text{ bbl}}{0.3017 \text{ ft}^3/\text{ft} \times 0.178 \text{ bbl/ft}^3} = 858 \text{ ft} \]

If this result had not been close to the assumed foamed cement length of 850 ft (Step No. 1), the calculation would be repeated using an adjusted length.

3. Calculate the hydrostatic pressure of the fluids in the annulus above.
The height of the mud column is 7,700 – 745 – 858 = 6,097 ft. Therefore, the hydrostatic pressure is 6,097 ft × 0.4784 psi/ft = 2,916.8 psi. For the spacer, the hydrostatic pressure is 745 ft × 0.4472 psi/ft = 333.1 psi.

4. Calculate the hydrostatic pressure of the foamed cement stage(s).

\[ \rho_{N_2} = 1.724 \times 10^{-3} \times \text{nitrogen volume factor (scf/bbl)} \]

\[ = 1.724 \times 10^{-3} \times 950 \text{ scf/bbl} \]

\[ = 1.638 \text{ lbm/gal} \]

The foam quality can be calculated by

\[ Q_{\text{foam}} = \frac{V_{N_2}}{V_{bs} + V_{N_2}} = \frac{12.7 \text{ bbl}}{12.7 \text{ bbl} + 33.4 \text{ bbl}} = 0.2755 \]

The previous equation for foamed cement quality can be rearranged to calculate foamed cement density,

\[ \rho_{fc} = (1-Q_{\text{foam}})(\rho_{bs} - \rho_{N_2}) + \rho_{N_2} \]

\[ = (1-0.2755)(14.2 - 1.638) + 1.638 = 10.74 \text{ lbm/gal} \]

Therefore, the hydrostatic pressure from foamed cement is 10.74 lbm/gal × 0.052 psi/ft/lbm/gal × 858 ft = 479.2 psi.

5. Add the three hydrostatic pressures to obtain the total hydrostatic pressure.

\[ 2,916.8 \text{ psi} + 333.1 \text{ psi} + 479.2 \text{ psi} = 3,729.1 \text{ psi} \]

6. Compare this value to the fracturing pressure of the weak formation.
The fracturing pressure of the weak formation is 3,942 psi.

Note that the pressure calculated in the previous step does not exceed the fracturing pressure of the weak formation but does exceed the safety margin set in the first step. This is what would be expected based on the method for calculating the foamed cement density, based on the fracturing pressure less the safety margin. This calculation should be repeated as each stage passes the weak formation.

Job execution tables
It is helpful for control of the job to construct tables of the pumping schedule containing the following information.
- Base slurry volume
- Nitrogen ratio
- Nitrogen volume
- Nitrogen pump rate
- Foamer pump rate

### Job Schedule per Stage

<table>
<thead>
<tr>
<th>Stage</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base slurry volume (bbl)</td>
<td>33.4</td>
<td>33.0</td>
<td>32.6</td>
<td>32.1</td>
<td>31.8</td>
</tr>
<tr>
<td>Nitrogen ratio (scf/bbl base slurry)</td>
<td>365</td>
<td>490</td>
<td>610</td>
<td>728</td>
<td>837</td>
</tr>
<tr>
<td>Nitrogen volume (scf)</td>
<td>12,192</td>
<td>16,179</td>
<td>19,878</td>
<td>23,353</td>
<td>26,620</td>
</tr>
</tbody>
</table>

### Nitrogen and Foamer Rate

<table>
<thead>
<tr>
<th>Base Slurry Rate (bbl/min)</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen rate (scf/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stage No. 1</td>
<td>1,095</td>
<td>1,460</td>
<td>1,825</td>
<td>2,190</td>
<td>2,555</td>
</tr>
<tr>
<td>Stage No. 2</td>
<td>1,470</td>
<td>1,960</td>
<td>2,450</td>
<td>2,940</td>
<td>3,430</td>
</tr>
<tr>
<td>Stage No. 3</td>
<td>1,830</td>
<td>2,440</td>
<td>3,050</td>
<td>3,660</td>
<td>4,270</td>
</tr>
<tr>
<td>Stage No. 4</td>
<td>2,184</td>
<td>2,912</td>
<td>3,640</td>
<td>4,368</td>
<td>5,096</td>
</tr>
<tr>
<td>Stage No. 5</td>
<td>2,511</td>
<td>3,348</td>
<td>4,185</td>
<td>5,022</td>
<td>5,859</td>
</tr>
<tr>
<td>Foamer rate (gal/min)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All stages</td>
<td>1.31</td>
<td>1.74</td>
<td>2.18</td>
<td>2.61</td>
<td>3.05</td>
</tr>
</tbody>
</table>
C-7 Acronym list

- API: American Petroleum Institute
- BWOB: By weight of blend
- BWOC: By weight of cement
- BWOW: By weight of water
- ISO: International Organization for Standardization
- SI: Système International
- STP: Standard temperature and pressure
- TVD: True vertical depth

### Conversion Factors

<table>
<thead>
<tr>
<th>Customary Unit</th>
<th>Multiply by</th>
<th>To Obtain SI Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>in.</td>
<td>2.54 (25.4)</td>
<td>cm (mm)</td>
</tr>
<tr>
<td>ft</td>
<td>0.305</td>
<td>m</td>
</tr>
<tr>
<td>ft^3</td>
<td>0.0283</td>
<td>m^3</td>
</tr>
<tr>
<td>bbl</td>
<td>0.159</td>
<td>m^3</td>
</tr>
<tr>
<td>U.S. gal</td>
<td>3.785 (3.785 × 10^-3)</td>
<td>L (m^3)</td>
</tr>
<tr>
<td>ft^3/ft (capacity)</td>
<td>0.0929</td>
<td>m^3/m</td>
</tr>
<tr>
<td>bbl/ft (capacity)</td>
<td>0.522</td>
<td>m^3/m</td>
</tr>
<tr>
<td>gal/sk (94 lbm sack)</td>
<td>88.78</td>
<td>L/t</td>
</tr>
<tr>
<td>ft^3/sk (94 lbm sack)</td>
<td>0.301</td>
<td>m^3/t</td>
</tr>
<tr>
<td>lbm</td>
<td>0.454</td>
<td>kg</td>
</tr>
<tr>
<td>lbm/gal</td>
<td>120</td>
<td>kg/m^3</td>
</tr>
<tr>
<td>lbm/ft (pipe weight)</td>
<td>1.49</td>
<td>kg/m</td>
</tr>
<tr>
<td>psi</td>
<td>6.895 (6.895 × 10^-3)</td>
<td>kPa (MPa)</td>
</tr>
<tr>
<td>psi/ft</td>
<td>22.7</td>
<td>kPa/m</td>
</tr>
<tr>
<td>°F</td>
<td>(°F – 32)/1.8</td>
<td>°C</td>
</tr>
</tbody>
</table>