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, ρ_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

$p_h = p_h$ above stage + p_h to midpoint of stage

Stage No. 1 (top)

$$\begin{aligned} p_{h1} &= 1{,}173 \text{ psi} \\ &\quad + [(\text{Stage number} - 0.5) \times 1{,}100 \text{ ft} \times \rho_1 \times 0.052] \\ &= 1{,}173 \text{ psi} + (0.5 \times 1{,}100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \\ &= 1{,}413 \text{ psi} \end{aligned}$$

Stage No. 2

$$\begin{aligned} p_{h2} &= 1{,}173 \text{ psi} + (1.5 \times 1{,}100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \\ &= 1{,}894 \text{ psi} \end{aligned}$$

Stage No. 3

$$\begin{aligned} p_{h3} &= 1{,}173 \text{ psi} + (2.5 \times 1{,}100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \\ &= 2{,}374 \text{ psi} \end{aligned}$$

Stage No. 4

$$\begin{aligned} p_{h4} &= 1{,}173 \text{ psi} + (3.5 \times 1{,}100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \\ &= 2{,}855 \text{ psi} \end{aligned}$$

Stage No. 5 (bottom)

$$\begin{aligned} p_{h5} &= 1{,}173 \text{ psi} + (4.5 \times 1{,}100 \text{ ft} \times 8.4 \text{ lbm/gal} \times 0.052) \\ &= 3{,}335 \text{ psi} \end{aligned}$$

Nitrogen requirement for each stage based on the midpoint

Nitrogen density, ρ_{N2}:

$$\rho_{N2} = (1.724 \times 10^{-3}) \times K_{N2}. \qquad \text{(C-12)}$$

where

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

Foamed cement quality, Q_{foam}:

$$Q_{foam} = 1 - \frac{\rho_{fc} - \rho_{N2}}{\rho_{bs} - \rho_{N2}}, \qquad \text{(C-13)}$$

where

ρ_{bs} = base slurry density

ρ_{fc} = foamed cement density

ρ_{N2} = nitrogen density.

Foamed cement yield, Y_{fc} (ft^3/sk):

$$= Y_{fc} = \frac{Y_{bs}}{1 - Q_{foam}}. \qquad \text{(C-14)}$$

where

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

Annular volume, V_{ann}:

$$V_{ann} = L \times S_{ann}, \qquad \text{(C-15)}$$

where

L = length

S_{ann} = annular capacity.

Cement requirement, C (sk):

$$C = \frac{V_{ann}}{Y_{fc}}. \qquad \text{(C-16)}$$

Nitrogen requirement at conditions in the annulus, R_{N2}:

$$R_{N2} = V_{ann} \times Q_{foam}. \qquad \text{(C-17)}$$

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):

$$V_{N2} = R_{N2} \times K_{N2}. \qquad \text{(C-18)}$$

Stage No. 1, p_{h1} = 1,413 psi

$$\begin{aligned} \rho_{N2} &= \left(1.724 \times 10^{-3}\right) \times K_{N2} \\ &= 1.724 \times 10^{-3} \times 476 \text{ scf/bbl} \\ &= 0.8206 \text{ lbm/gal} \end{aligned}$$

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}:

$$\begin{aligned} Q_{foam} &= 1 - \frac{8.4 - 0.8206}{14.2 - 0.8206} \\ &= 0.4335. \end{aligned}$$

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_{N2}:

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

Nitrogen volume, V_{N2}, 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.

Stage	**1**	**2**	**3**	**4**	**5**
Hydrostatic pressure (psi)	1,413	1,894	2,374	2,855	3,335
Nitrogen density (lbm/gal)	0.821	1.069	1.291	1.493	1.677
Foamed cement quality	0.4335	0.4417	0.4493	0.4564	0.4631
Foamed cement yield (ft^3/sk)	2.28	2.31	2.34	2.37	2.40
Annular volume (ft^3)	331.9	331.9	331.9	331.9	331.9
Cement requirement (sk)	145.6	143.7	141.8	140.0	138.3
Nitrogen per sack (scf/sk)	83.7	112.6	140.2	166.8	192.5
Nitrogen requirement (scf)	12,192	16,179	19,878	23,353	26,620
Total cement requirement: 943.3 sk (709.4 sk for foamed stages + 233.9 sk for tail)					
Total nitrogen requirement: 98,222 scf					

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 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 × 0.4784 psi/ft = 2,920 psi, and the hydrostatic pressure from the spacer is 745 ft × 0.4472 psi/ft = 333 psi; thus, the total hydrostatic pressure is 2,920 + 333 = 3,253 psi.

- 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 bbl.

2. *Calculate its length based on the annular capacity.*

With an annular capacity of 0.3017 ft^3/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

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

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

$$\rho_{fc} = (1 - Q_{foam})(\rho_{bs} - \rho_{N_2}) + \rho_{N_2}$$
$$= (1 - 0.2755)(14.2 - 1.638) + 1.638 = 10.74 \text{ lbm/gal.}$$

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 psi + 333.1 psi + 479.2 psi = 3,729.1 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

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

Nitrogen and Foamer Rate

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

Conversion Factors

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

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