Bismuth based barrier materials – Initial Results from 3rd party testing in SWIPA

OFFSHORE NORGE

10th Norwegian Plug & Abandonment Seminar

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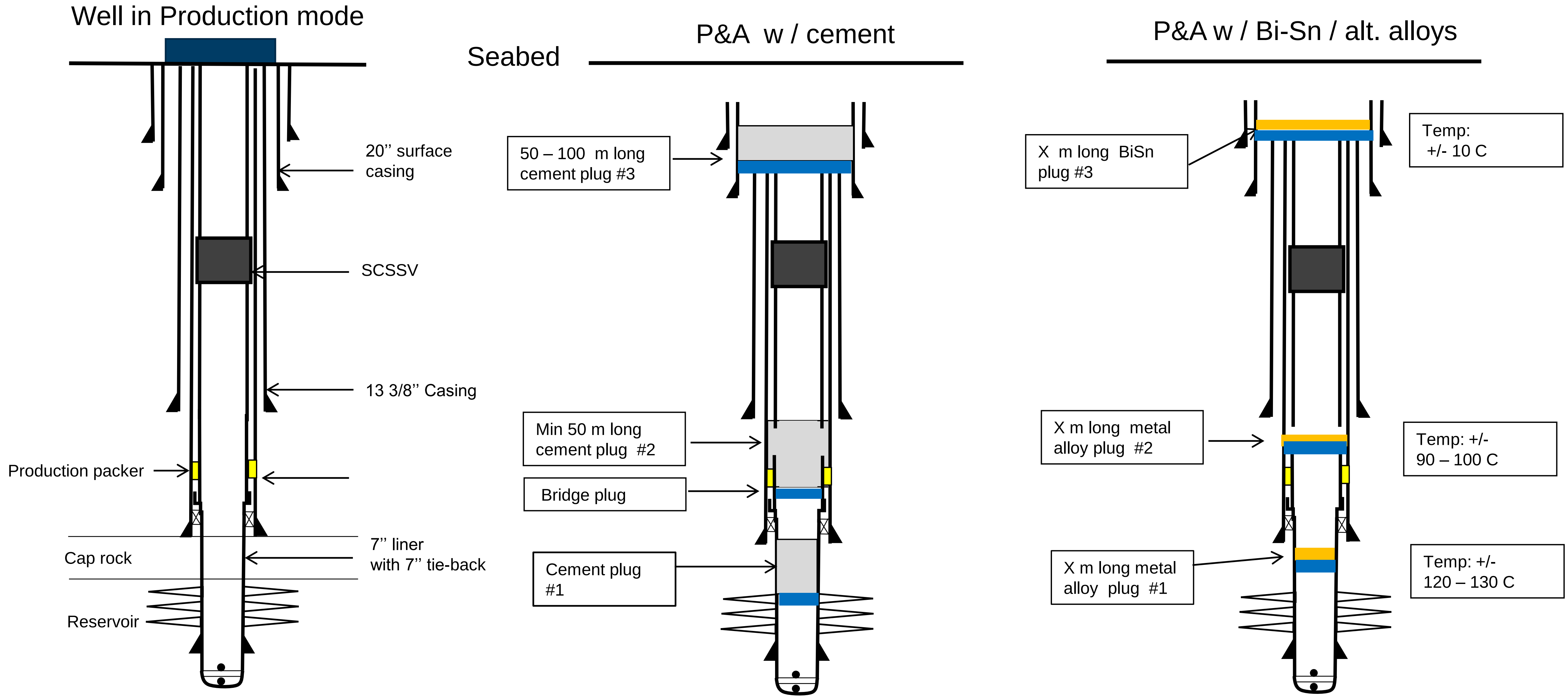
Well Plugging – Potential options using low-temperature melting alloys (Bismuth)



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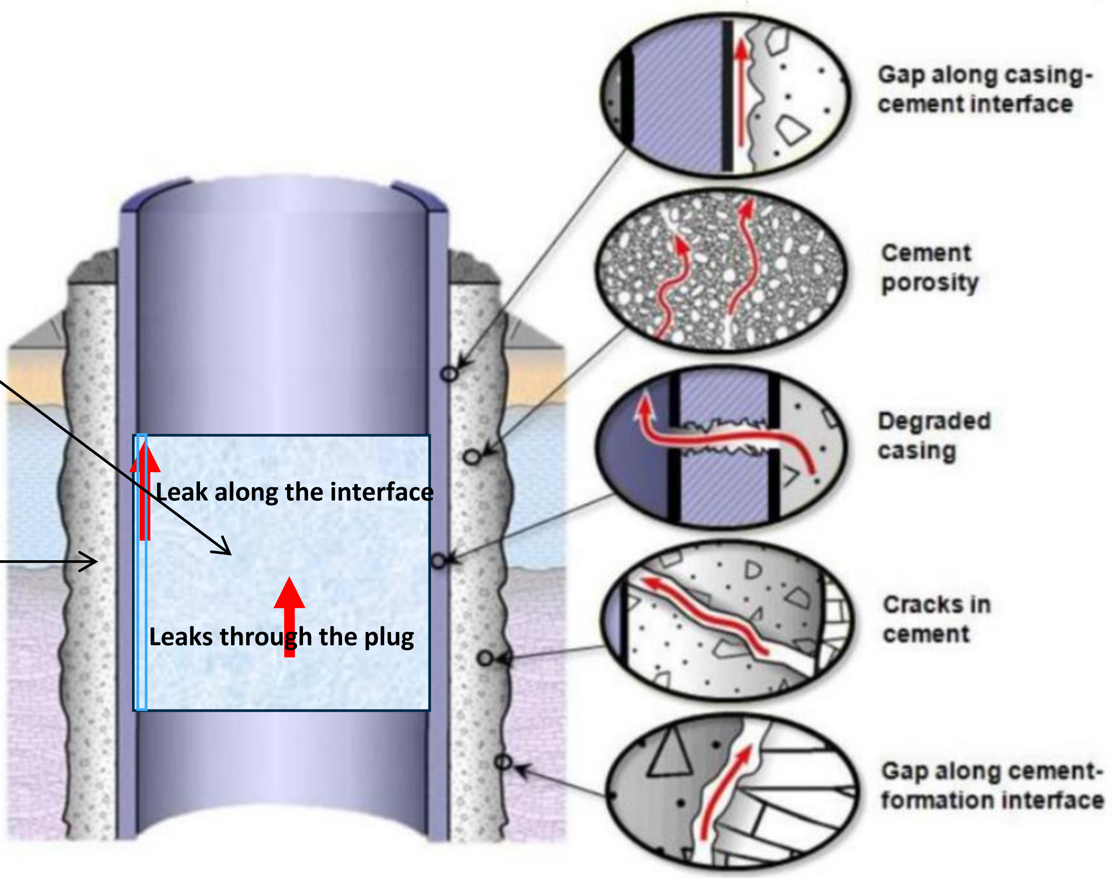
Potential use of Bismuth in P&A

Casing plug

Annulus plug/

Cement repair



Modified after Celia et al. 2005

Requirements for P&A

Ref. NORSOK D-010, Chapter 9.6.

Several requirements including point f) "Ensure bonding to steel“

- BiSn alloys has no or limited bonding to steel, but
- Volume / radial expansion of BiSn may provide friction and sealing capabilities equivalent to “bonding to steel”

Ongoing /planned activities using Bismuth

Laboratory tests and modelling:

1. Expansion performance in pipes (casing) and friction tests in casing (bonding).

2. Interaction between bismuth/casing/(cement or settled baryte, cement chunks)/formation, and how the interaction is affecting sealing along the bore hole section

Bismuth Alloys

- ✓ Bismuth and its combination with other metals, form alloys with different melting points
- ✓ Alloys of bismuth can expand, shrink, or remain dimensionally stable on solidification and this depends on the composition of each chemical element of the alloy.

Growth and Shrinkage of Low-Melting Alloys

	Alloy			
Time after Casting	47°C	70°C	138°C	138/170°C
6 min	−0.00025	0.00490	−0.00010	0.00030
20 min	−0.00030	0.00565	.00000	0.00035
1 h	−0.00025	0.00570	0.00015	0.00060
8 h	−0.00020	0.00600	0.00045	0.00095
1 day	−0.00015	0.00615	0.00060	0.00105
1 month	0.00025	0.00635	0.00090	0.00120

[a] Cumulative changes, inches per inch relative to cold mold dimensions. Test bar $\frac{1}{2}\times\frac{1}{2}\times10$ in. ($1.27\times1.27\times25.4$ cm).

Encyclopedia of Chemical Technology, Kirk Othmer

Properties of Bismuth Alloys

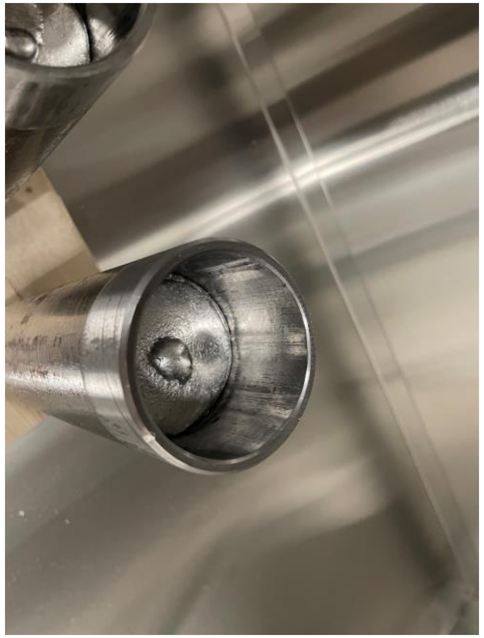
Properties of Low-Melting Bismuth Alloys

Property	Alloy 47°C	70°C	138°C	138/170°C
melting point or range, °C (°F)	47.5 (117)	70 (158)	138.5 (281)	138.5–170 (281–338)
density, lb/in.^{3} (g/cm^3)	0.34 (9.36)	0.35 (9.67)	0.31 (8.58)	0.30 (8.21)
specific heat, cal/g·C[a]				
solid	0.039	0.035	0.040	0.043
liquid	0.047	0.044	0.048	0.051
heat of fusion, cal/g	8.8	9.5	10.7	10.6
coefficient of thermal expansion, 1×10^{-6} °C	25	22	15	15
thermal conductivity	0.035	0.043	0.044	0.071
electric conductivity (% of pure copper)	3.09	3.54	2.88	5.00
resistivity, μΩ·cm	55.0	48.0	59.0	34.0
Brinell hardness (2-mm ball, 4-kg load)	14.5/16.5	13/14.5	23/23	23.5/24
tensile strength, lb/in.^{2} (Pa)[b]	4868–5337	2668–3775	8701–9013	8459–9041
maximum sustained load, lb/in.^{2} (Pa)[b]				
30 s	NA[c]	10,000	15,000	15,000
300 s	NA[c]	4,000	9,000	9,500

[a]To convert calories to joules, multiply by 4.184.
[b]To convert pounds force per square inch to pascals, multiply by 6.895×10^3.
[c]Not available.

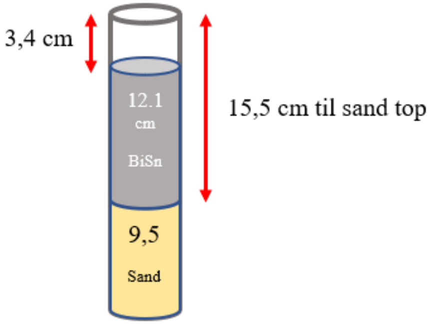
Encyclopedia of Chemical Technology, Kirk Othmer

Bismuth Alloy Plug Set-up



Pipe Properties (X-52)	Value
Length	25 cm
Inner Diameter	5,77 cm
Outer Diameter	6,080 cm

Plug Properties (MCP 137)	Value
Melting Point	135 °C
Density	8,58 g/cm3



Laboratory tests

- Plug testing
  - *Mechanical Push-Out Test*
  - *Hydraulic Push-Out Test*
  - *Leakage Testing using Nitrogen gas*

Plug Testing Specifications

Plug Length	Cement	Pure Bismuth	Bismuth Alloy
cm	18.5	12.1	12.1

Shear Bond Strength Calculations:

$$\text{Shear Bond Strength} = \frac{\text{Force}}{\text{Contact area}}$$

$$\tau_{av} = \frac{F}{\pi * D_i * L_c}$$

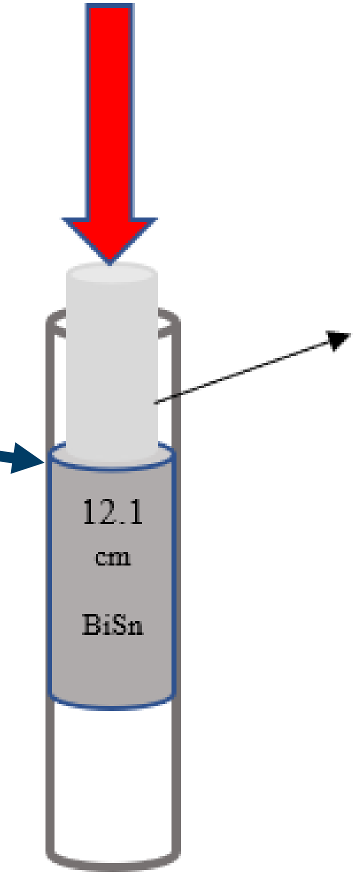
Where:

F: failure load applied

D_i: inner diameter of the pipe, or outer diameter of the plug

L_c: length of the plug

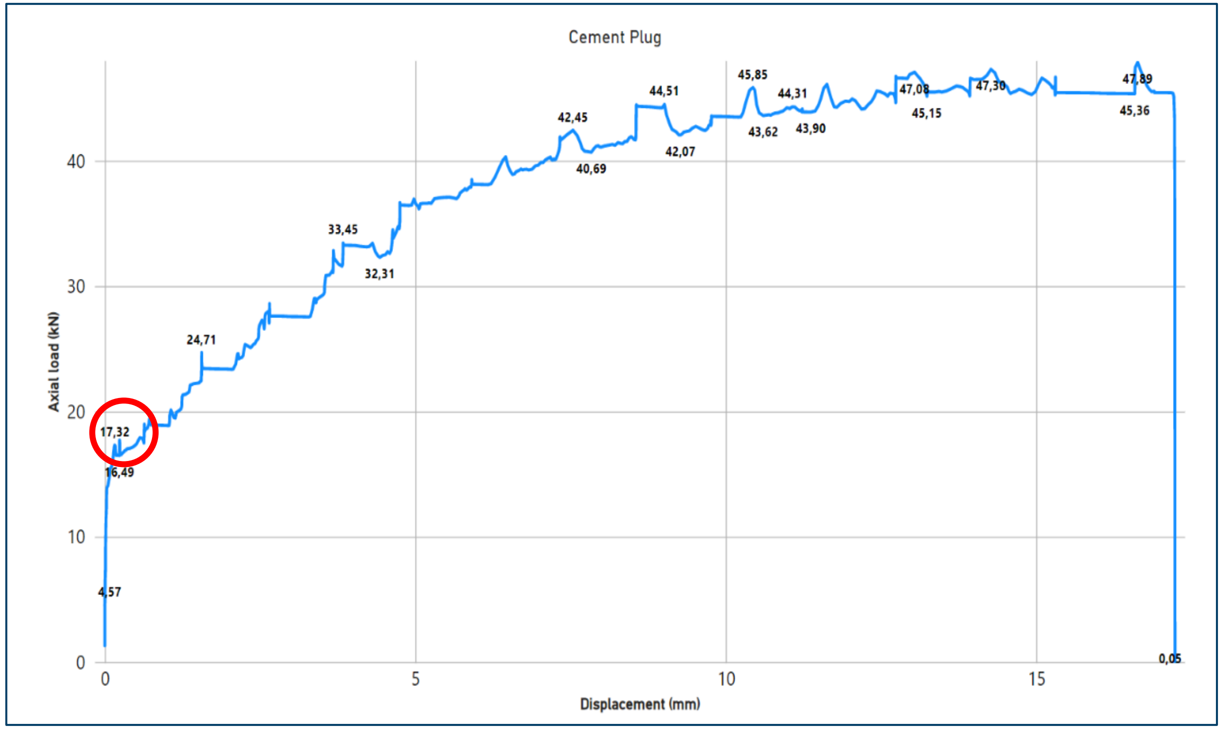
Mechanical Push-Out Test - Setup

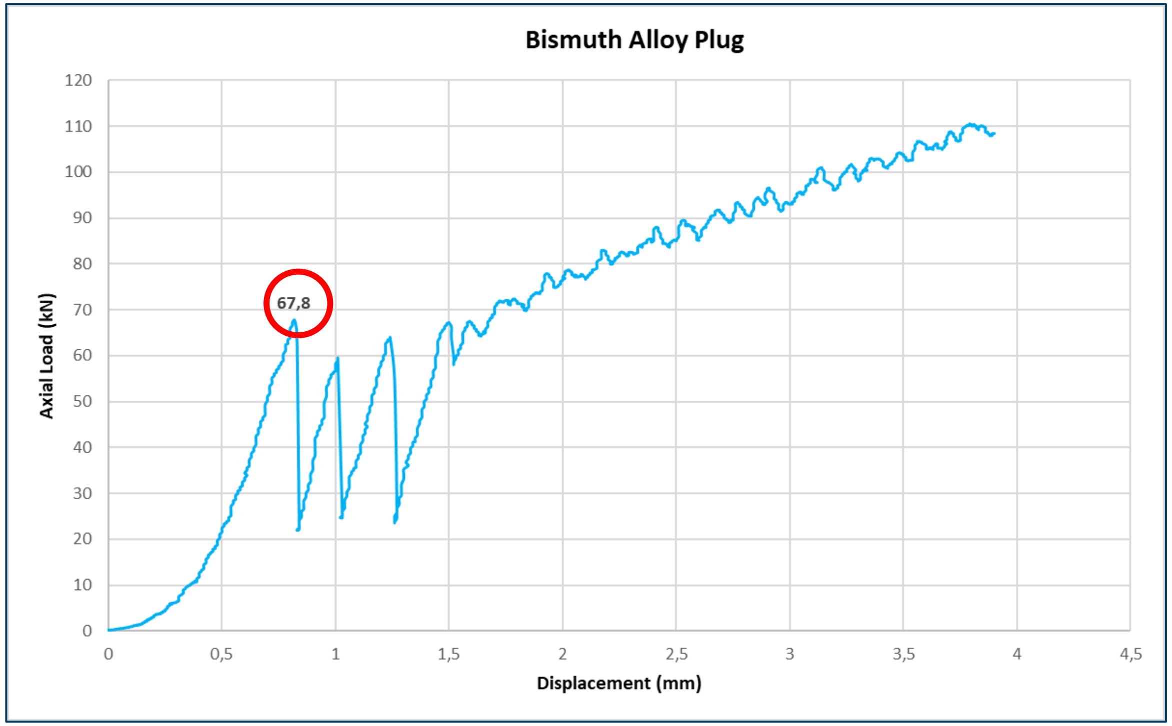


Rapid Triaxial Rock Testing system (RTR)

- Load Cell Capacity: 0 – 400 tons (≈ 4000 kN)

Mechanical Push-Out - Results





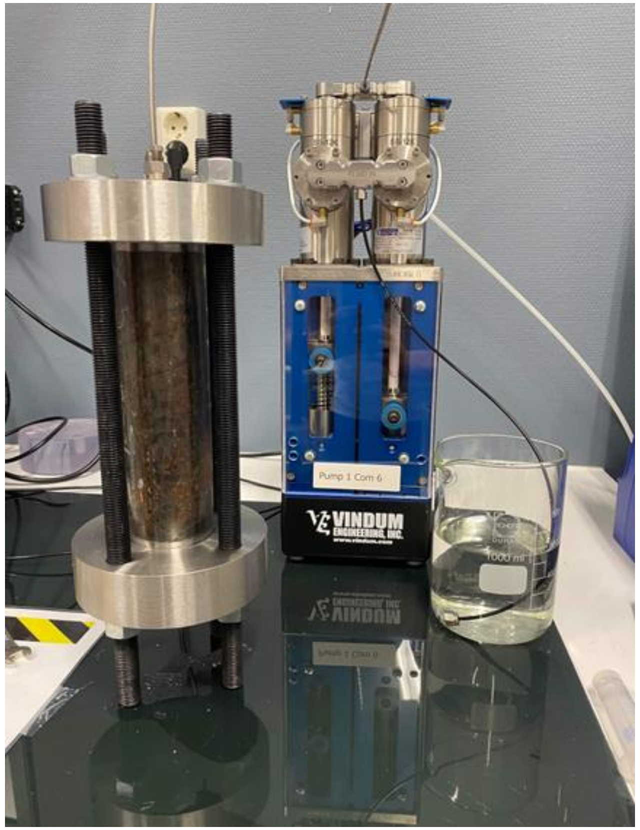
Mechanical Push-Out

Material	Avg. Roughness [µm] - Ra	Length [cm]	Contact Area [cm2]	Axial Load [kN]	Shear Bond Strength [MPa]
Portland G- Cement	1,2	18,5	335,3	17,71	0,53
Bismuth Alloy-137	0,855	12,1	219,3	67.8	3,09

Comments:

- *Bismuth alloy shows a higher resistance to axial load compared to cement*

Hydraulic push out test- Setup



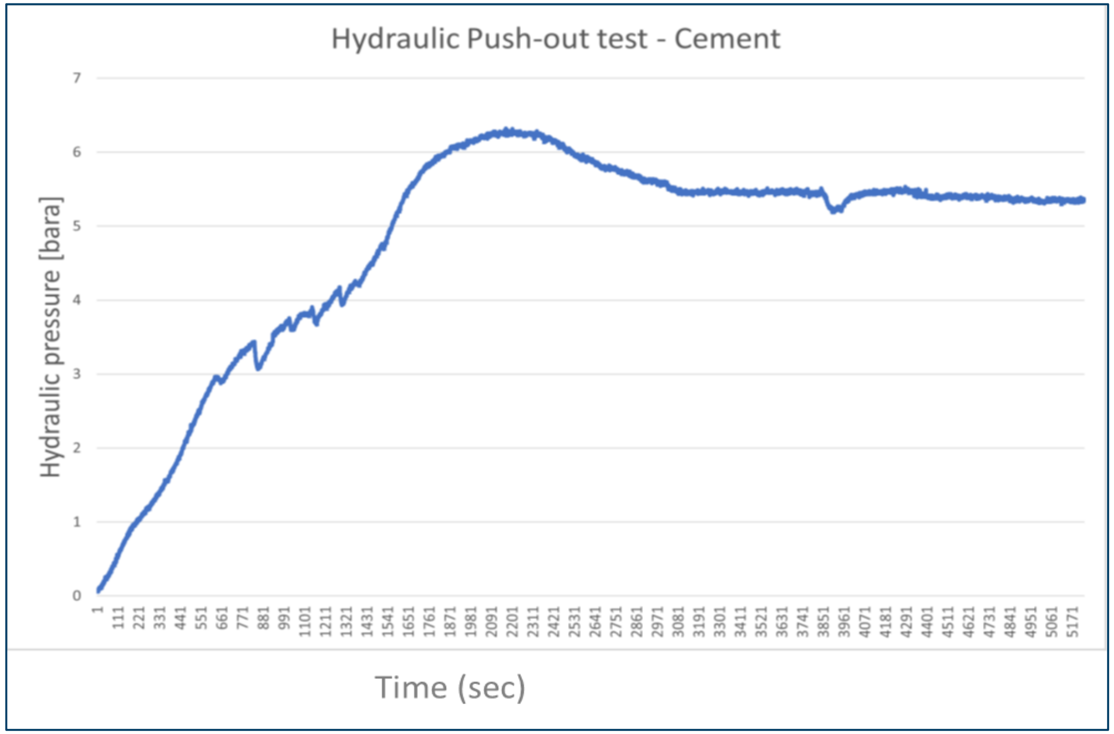
Test cylinder and pump

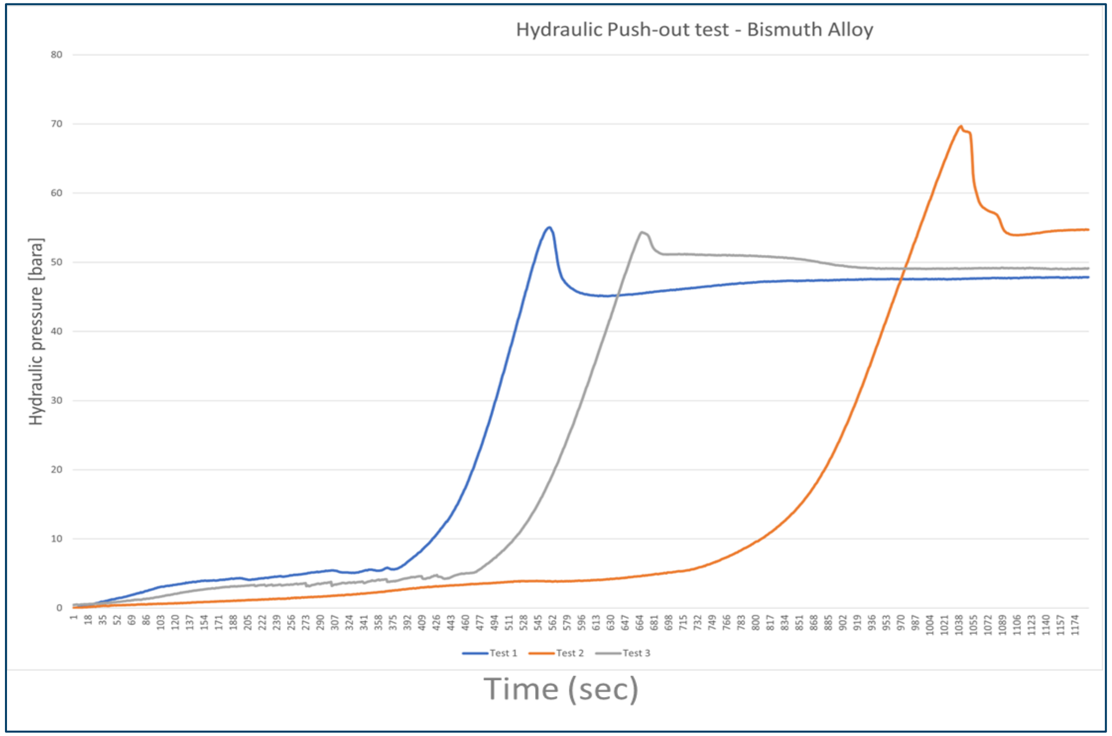
The pump used delivers ultra-precise, pulse-free, continuous flow in either constant-pressure or constant-rate modes, at up to 25,000 psi.

Pump	Max Pressure, psi	Flow Rate, ml/min	Hi-Temp Available?
VP-3K	3,500	0.0001 - 97	YES
VP-6K	6,500	0.0001 - 54	YES
VP-12K	12,000	0 0001 - 29	YES
VP-20K	20,000	0.0001 - 12	NO
VP-25K	25,000	0.0001 - 12	NO

Operating Conditions	Value
Flow Conditions	Continuous Flow
Flow Rate Set	0.4 ml/min
Safety Pressure Set	200 bar

Hydraulic Push-Out Test- Results





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Hydraulic Push-Out Test

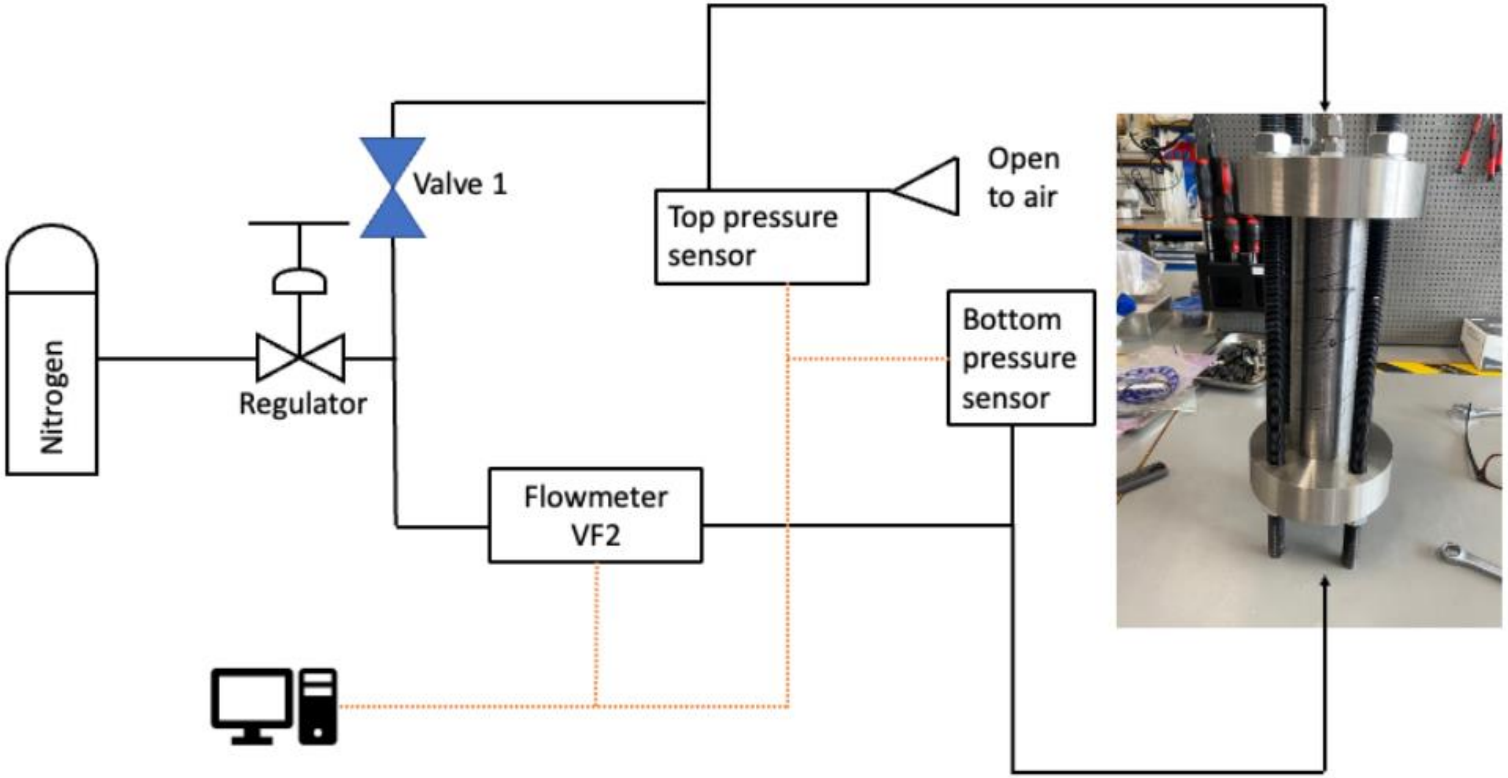
Test	Hydraulic bond strength [MPa]
Cement	0,632
Bismuth 1	5,551
Bismuth 2	6,968
Bismuth 3	5,435

The shear bond strength of bismuth alloys ranges between 2.07-26.2 MPa. On an average the bismuth alloys have a shear bond strength of 8.44 MPa *(Ref. MatWeb,2022)*

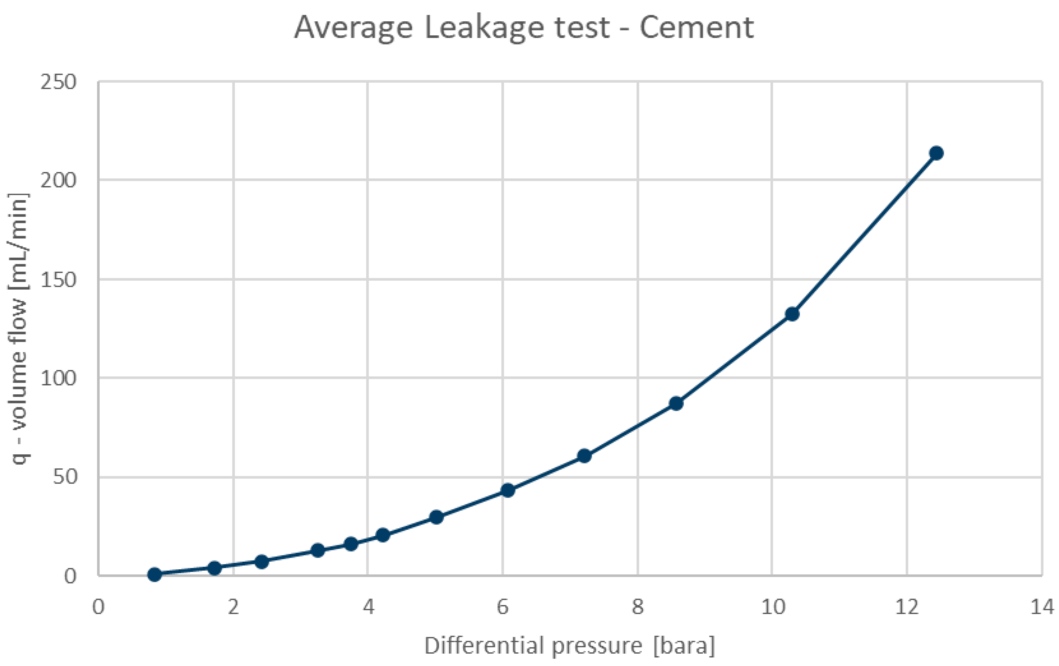
Comments:

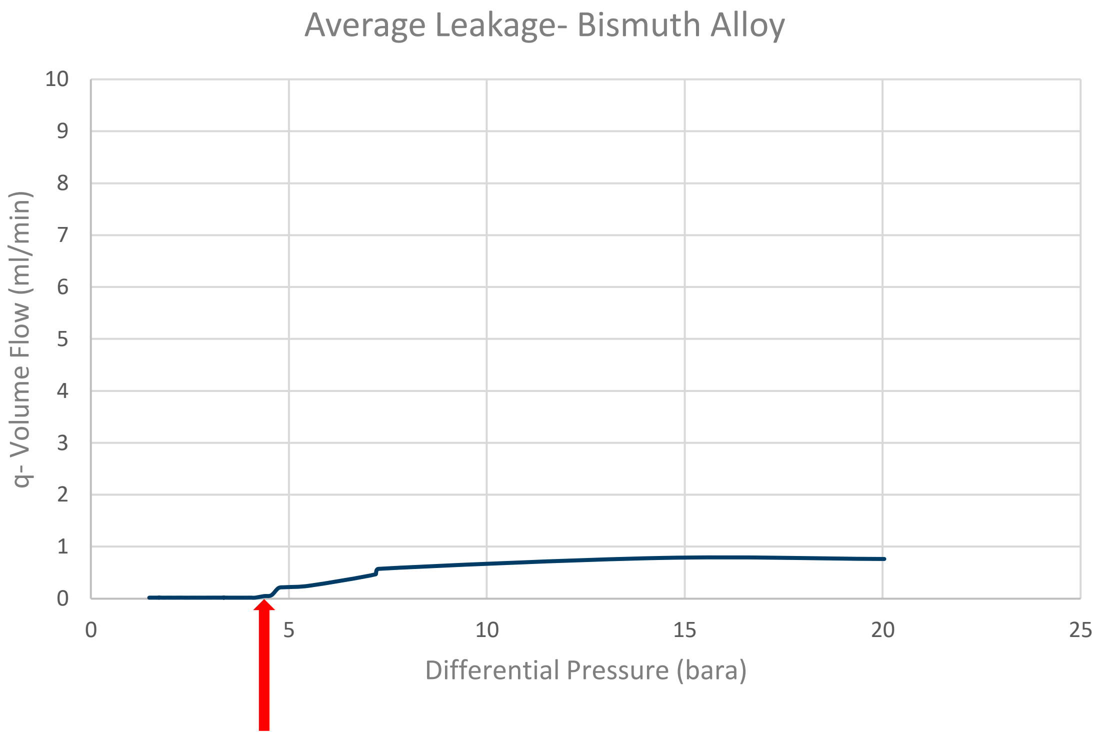
- *Bismuth alloy shows significant greater strength compared to cement*
- *Plug shear/hydraulic bond failure were clearly detected during this test*

Leakage Testing using N2 Gas - Setup



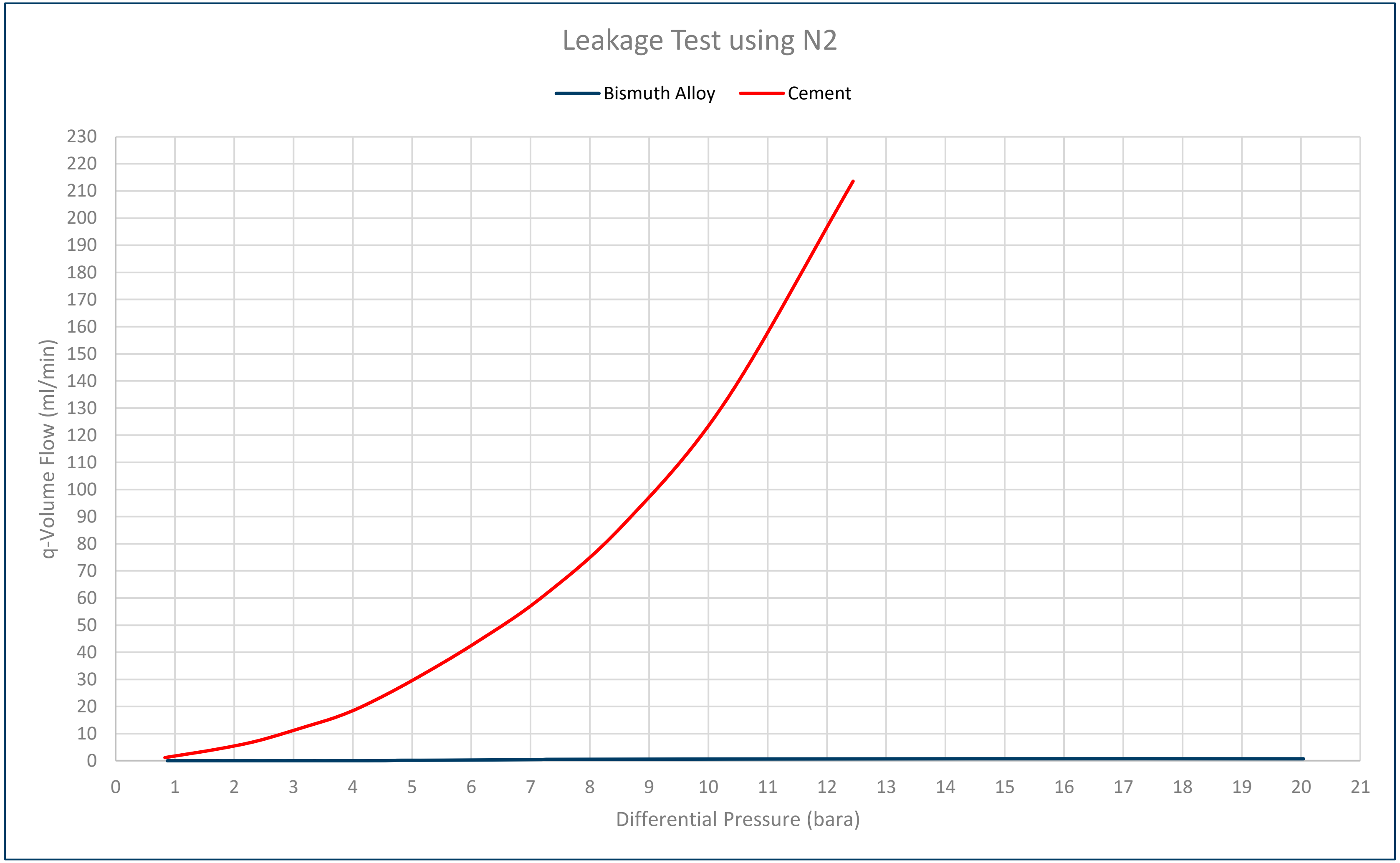
Leakage Testing using N2 Gas – Initial Results





Leakage detected at 4.74 bara

Leakage Testing using N2 Gas – Results Combined



Conclusions:

- *Bismuth alloy plugs show higher resistance to gas migration in the micro-annuli compared to cement, see details in previous slide*

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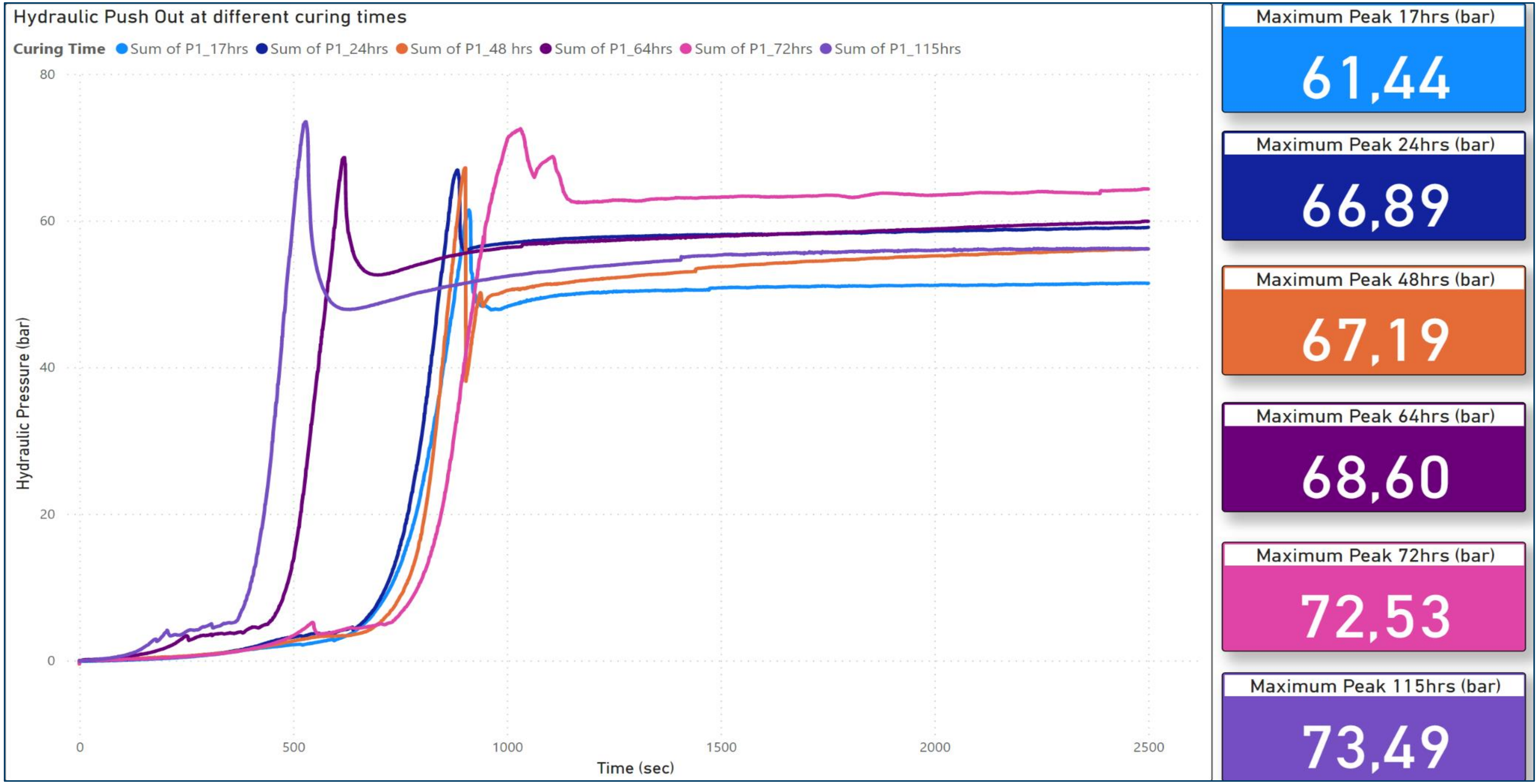
Hydraulic Plug Testing- Effect of Curing time



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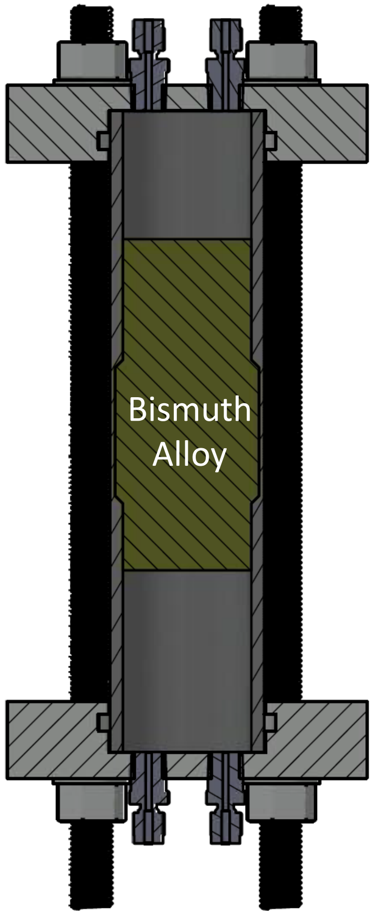
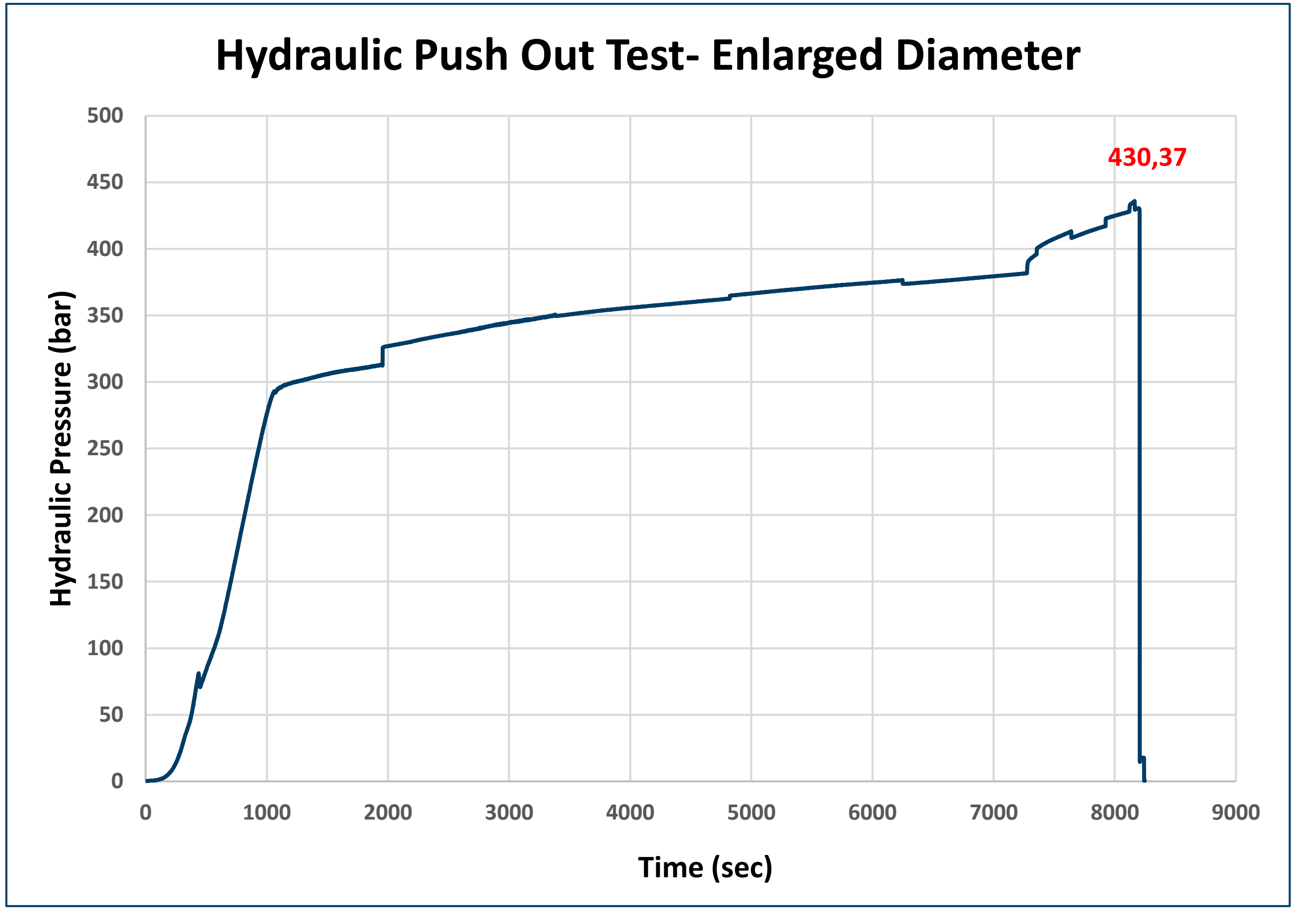
Hydraulic Plug Testing- Enlargement of Pipe Diameter





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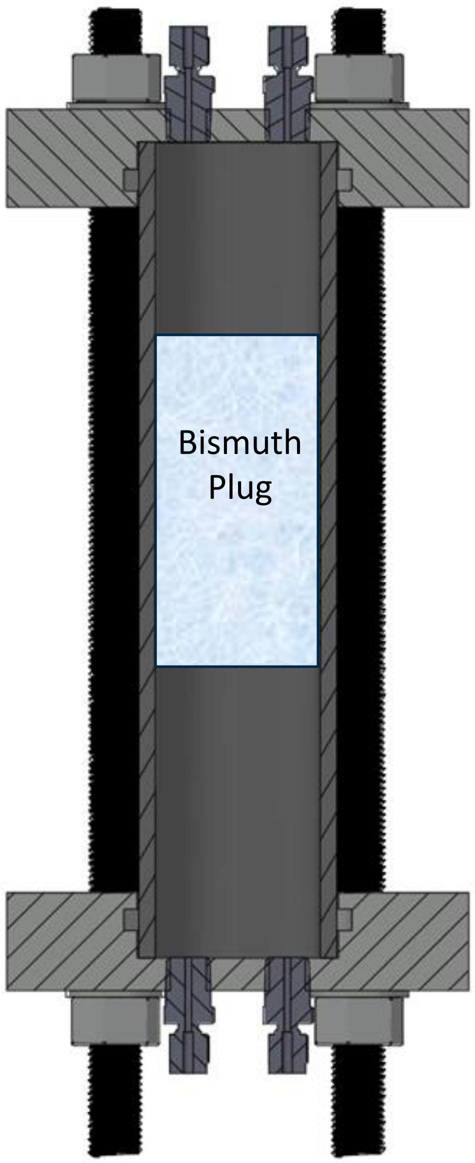
Plug Testing (continuation)

- *Gas leak tests*
- *Effect of increased plug length*
- *Effect of pipe inner surface*
- *Increased inner pipe diameter (forced local corrosion)*
- *Restricted axial expansion / re-enforcement*
- *Alternative Bismuth alloys*
- *Standard casing size (5 inch)*
- *Testing using high pressure gas (30 MPa)*



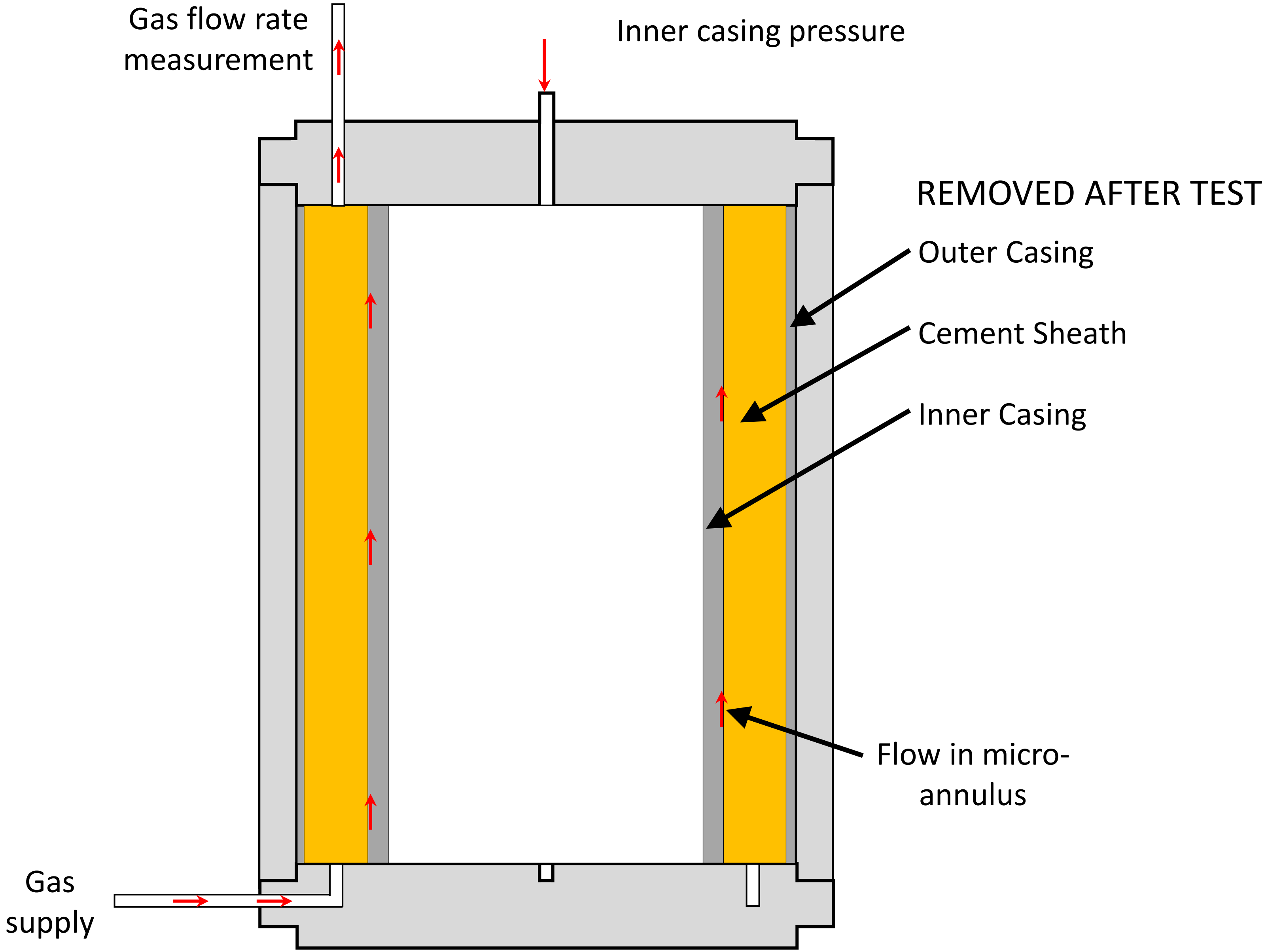
Annular Sealing Experiments – Cement w/ micro-annulus /Settled baryte

Sealing tests

- *Effect of inner casing pressure to close/reduce micro annulus, or compress settled baryte (micro baryte) for proper sealing*

For P&A

- *Expanding Bi-Sn alloy plug in the inner casing may provide the radial force / pressure needed*



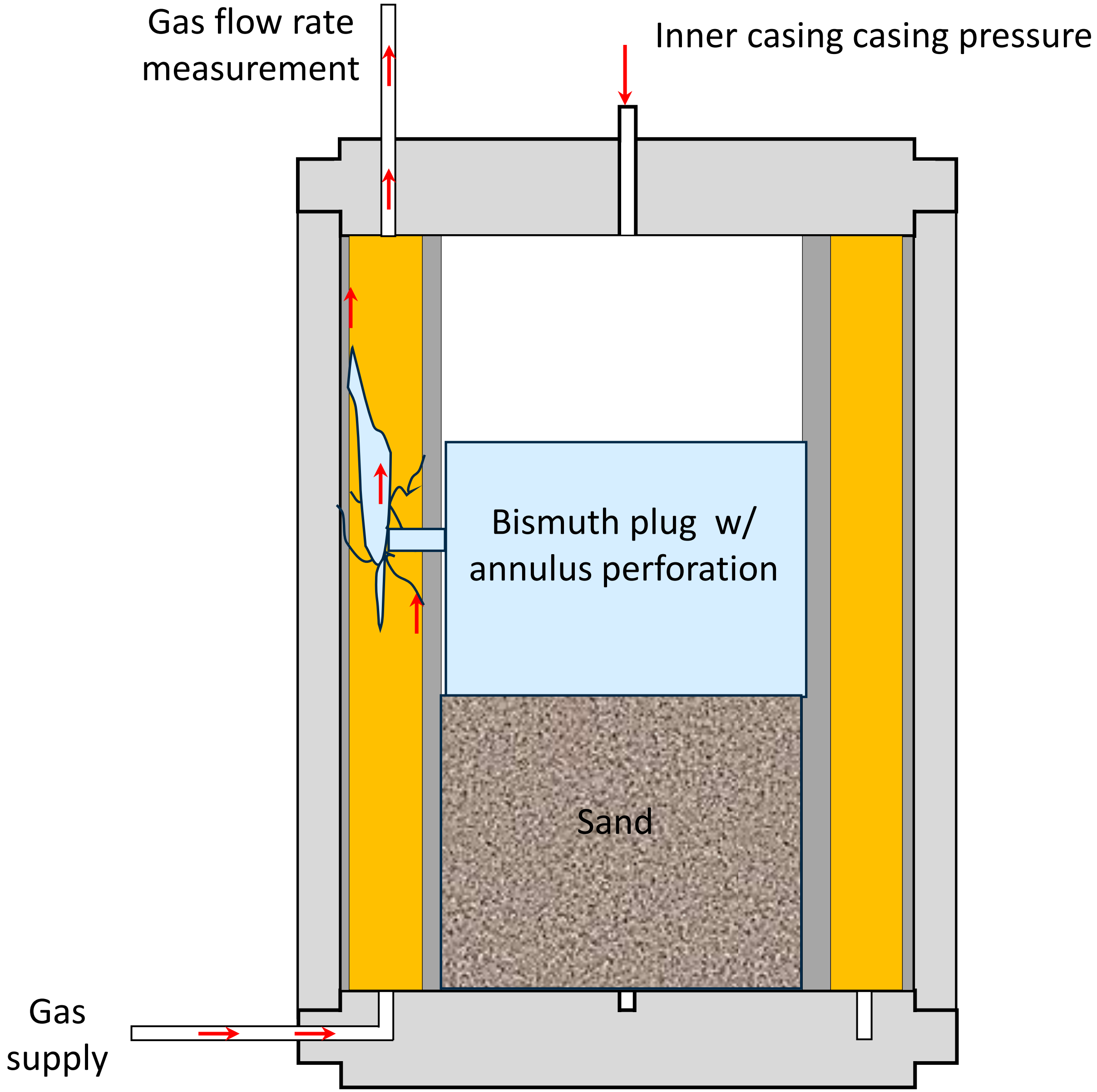
Annular Sealing Experiments – cement chunks/ poor-quality cement

Sealing tests

- *Place / Inject Bismuth alloy in annulus w/ or wo/ additional pressure to repair annulus sealing*

For P&A

- *Expanding Bismuth alloy plug in the inner casing may provide the radial force / pressure needed for proper sealing*

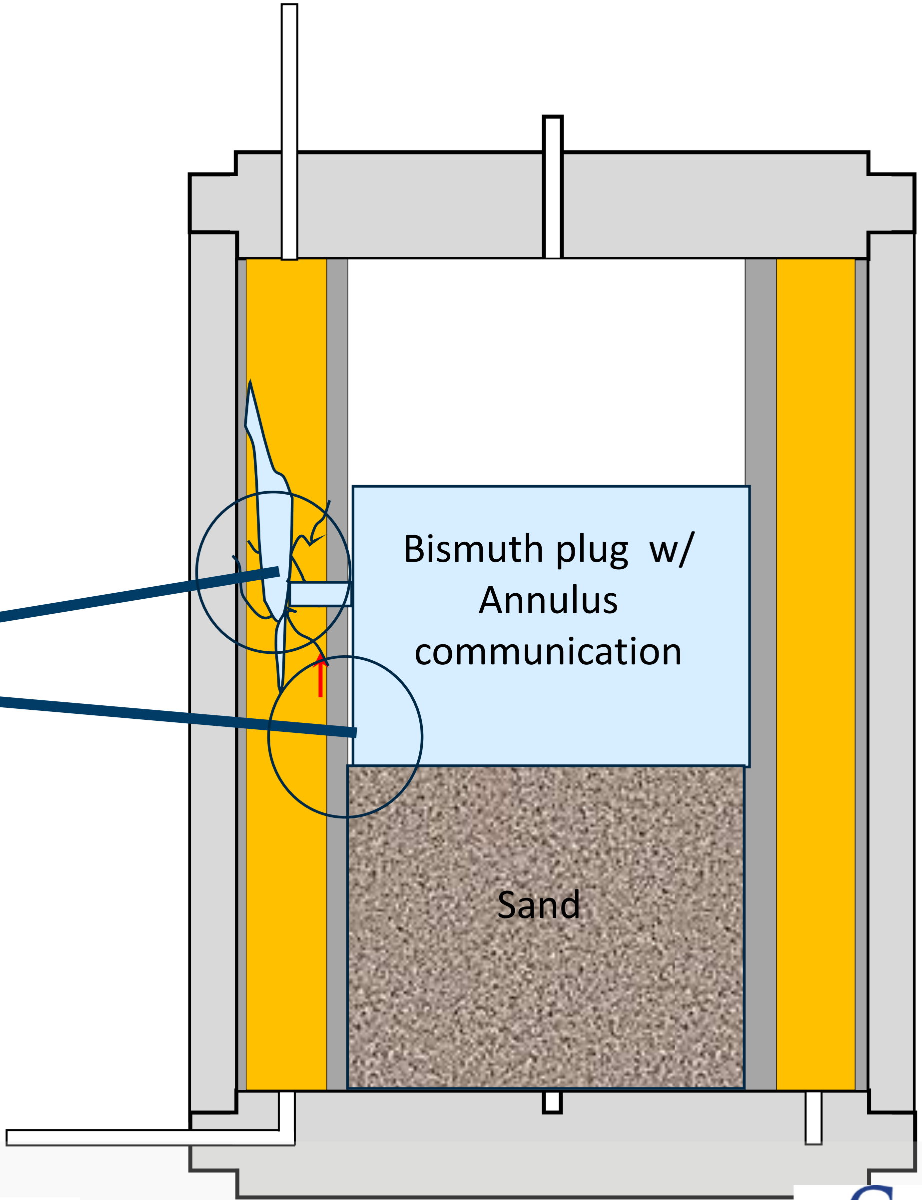


Investigation of Interaction between Bismuth and cement, casing & formation

SEM analysis

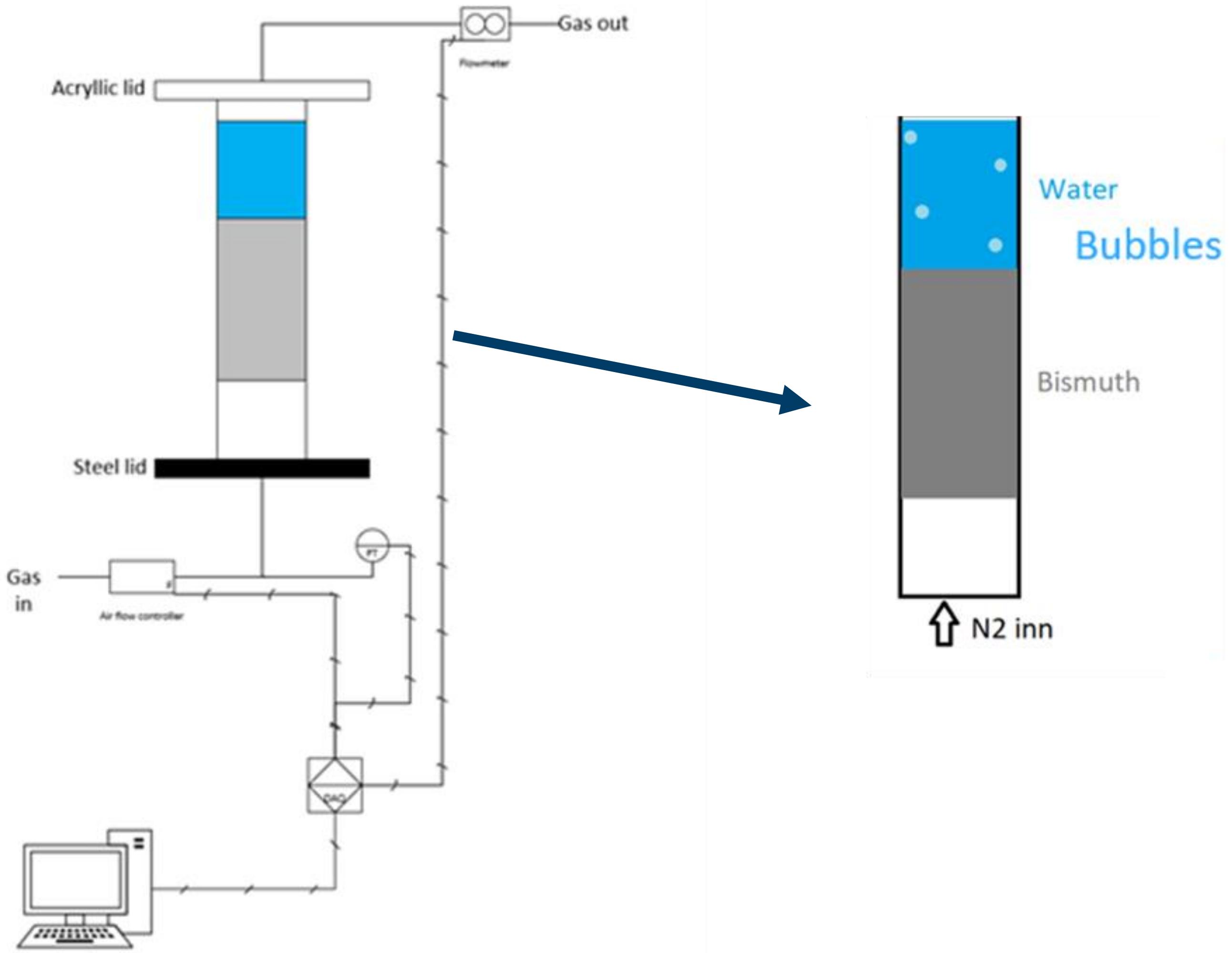
https://serc.carleton.edu/research_education/geochemsheets/techniques/SEM.html

Polishing/ preparation of the samples



Bubble Test

Goal:
Investigate how flow of gas through a column of Bismuth with low melting point (60°C) will affect the sealing during solidifications



3rd party verification tests in SWIPA

Test facilities available and specific test cells used for the study:

NorPALabs
Norwegian P&A Laboratories

Research Council grant MNOK 77, period 2020-2023

- Existing test cells (2 – 5) inches
- Heat chamber size, small and large (1,5 x 1,5 x 2,5) m, 250 °C
- Hydraulic pressure: 827 bar (12k Psi)
- Push-out test: 400 tons
- Gas pressure test: 300 bar max (require small gas volume in test sample)
- New test cells – Standard casing sizes (limited by the size of heat chamber)

Thank You!

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