CONFIGURATION OF POSSIBLE INDUSTRIAL SCALE CAVERNS

HYPSTER PROJECT

Deliverable 2.5

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Table of content

1. INTRODUCTION

Within the HyPSTER project several simulation tools are tested and verified for the modeling of hydrogen storage in salt caverns. The simulation tools can be used to design and develop the best possible plant configurations on both a technical and a commercial point of view.

Furthermore, various requirements for hydrogen storage as an essential link in the supply chain of future hydrogen economies were developed (HyPSTER, Deliverables D1.1 [1] and D1.2). From these figures (required working gas quantities, turnover cycles and injection and withdrawal rates) the following questions arise:

- How many caverns are needed?
- What is the spatial volume of an individual cavern?
- Which depth is most appropriate?
- What is the best operating pressure range?

All these questions will be investigated in the further course of the project with the help of suitable numerical models. Parameters that may vary from different salt deposits (e.g. rock properties) and/or individual cavern configurations (e.g. height/volume ratio) will be sensitively examined. As a result of this work, a general overview will be given of how the different requirements for H2 storage in terms of volume and rate capacities can best be met by which cavern configuration. The present document describes the set of cavern configurations that will be used for these investigations.
The first industrial scale hydrogen storage caverns are likely to be converted former natural gas caverns, as new caverns require multiple years to be leached out. But, from a current perspective, there is no reason to assume that new hydrogen storage caverns will have significantly different configurations than the existing natural gas storage caverns.

The data in this document is beeing published according to the « Open Research Data Pilot ». Thus, this data should be open access and should allow to be reused by third parties. It consists of two pillars, the projects Data Management Plan (Deliverable D7.2 [2]) and making the data available in a structured way (open access journal or repository).

2. INDUSTRIAL SCALE CAVERNS

2.1. Cavern configurations

The cavern properties, which have the strongest impact on the storage performance, are:

- Spatial cavern volume
- Depth of the last cemented casing shoe
- Inner diameter of the production tubing
- Ratio of cavern height to diameter

Therefore, the upcoming investigations should be focused on variations of these parameters within typical ranges for caverns in Europe. The set of parameters is defined in Table 1.
The cavern geometry should be considered cylindrical for these investigations.

In addition to the parameter definition, Table 1 lists several exemplary representations, where similar caverns can be found throughout Europe (see also [3]). This listing is not complete, nor can the typical caverns in a certain region fully match with the defined cases, as these had to be idealized to some level. For comparison, some publications on current hydrogen cavern projects, which are also reflected in the case definition, should be noted [4-8].

TABLE 1: DEFINITION OF INDUSTRIAL SCALE CAVERNS – VARIATION OF THE MAIN PARAMETERS.

Parameter	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Depth of last cemented casing shoe [m]	600	900	900	900	1400	1400	1400
Geometrical cavern volume [m³]	350.000	200.000	500.000	800.000	200.000	500.000	800.000
Cavern height (roof to sump) [m]	70	70	140	300	70	140	300
Exemplary representations	Western UK	Eastern Germany, Western Germany	Denmark, Central France, Eastern Germany, Netherlands, Portugal	Northern Germany, Netherlands	Western Germany	Denmark, Central France, Western Germany	Northern Germany

Each of these configurations can be equipped with different production tubing configurations. In the current natural gas storage business, the most common tubings are either 8 5/8'' or 9 5/8'' in outer diameter. Both of them should be included in the simulations of the industrial scale hydrogen storage.

2.2. Additional parameters and information

All wells should be regarded as fully vertical.
For simplicity, the production tubing should have a constant diameter and the depth of the tubing shoe should be regarded identical to the last cemented casing shoe.
The roughness of the inner surface of the tubing should be 0,1 mm.
Each cavern should have a chimney of 0,2 m diameter and 30 m length.
A heat transfer coefficient of 30 W/m² K should be applied for the heat exchange between storage inventory and salt rock. The rock surface should be considered flat.
The salt top depth is set to 500 m for all cases.
The geothermal gradient is 3°C/100 m in the overburden and 1,5°C/100 m in the salt rock. The surface temperature is 10°C.
The maximum allowable pressure at the well head should be 110 bar for Case 1, 165 bar for the cases with 900 m casing shoe depth and 250 bar for the cases with 1400 m casing shoe depth.
The minimum allowable pressure at the well head should be 40 bar for Case 1, 60 bar for the cases with 900 m casing shoe depth and 80 bar for the cases with 1400 m casing shoe depth.
The allowable pressure range is defined for well head pressures. Nevertheless, should be noted, that for operating caverns the pressure limits are often defined with respect to the cavern pressure or the pressure at

the last cemented casing shoe. As for hydrogen storage, the pressure differences between cavern and well head are in the range of a few bar, this has no relevant impact on the modeling work within HyPSTER.
The density of overburden and salt rock should be 2.200 kg/m³.
The specific heat capacity of overburden and salt rock should be 1 J/g K.
The heat conductivity should be 3 W/K m for the overburden and 6 W/K m for the salt rock.

The geomechanical properties of the cavern models will be specified in a subsequent document (Deliverable D2.7 – Set up of possible industrial scale models [9]). Typical creep closure rates (volume loss) for orientation could range from 0,05 %/year (shallow caverns) to 1 %/year (deeper caverns). However, it is worth noting that these depend strongly on the rock parameters and on the operational cycles and also values beyond this range have been observed in certain cases. Furthermore, creep closure is typically higher in the first years of operation due to the stronger influence of the transient creep.

3. OPERATING CYCLE

The cavern operation should be modeled for 30 years to obtain relevant results regarding the long-term volume, temperature and pressure behavior. A yearly operating cycle is defined for common years (365 days) and for leap years (366 days, see Figure 1 and Annexes A and B). These operating cycle should be repeated and combined accordingly to form a continuous 30 year operating schedule (i.e. 3 common years, 1 leap year, 3 common years, 1 leap year etc., see Figure 2). As commonly applied in the natural gas industry, each yearly cycle starts on the 1st of October and ends on the 30th of September of the following calender year.

As the caverns defined above have highly different gas contents and operating pressure ranges, the operational cycles are defined in terms of the relative well head pressure. For each cavern the cycle has to be transformed linearly to obtain the individual well head pressure evolution, where 0 corresponds to the minimum allowable well head pressure and 1 corresponds to the maximum allowable well head pressure. Please note that for hydrogen the pressure difference between well head and casing shoe is low, so the specified well head pressure evolution is similar to the geomechanically relevant casing shoe or cavern pressure.
From natural gas storage it is known that not the full working gas capacity is utilized each year, but only during long, cold winter seasons. To represent this, only 60 % of the working gas is withdrawn in the operating cycle for common year, while more than 90 % of the working gas is withdrawn in leap years.
The overall shape of the operating cycle is derived from the case « Salt cavern storage with wind generation for gas grid demand » in the previous deliverable D1.1 « H 2 production and consumption profiles ».

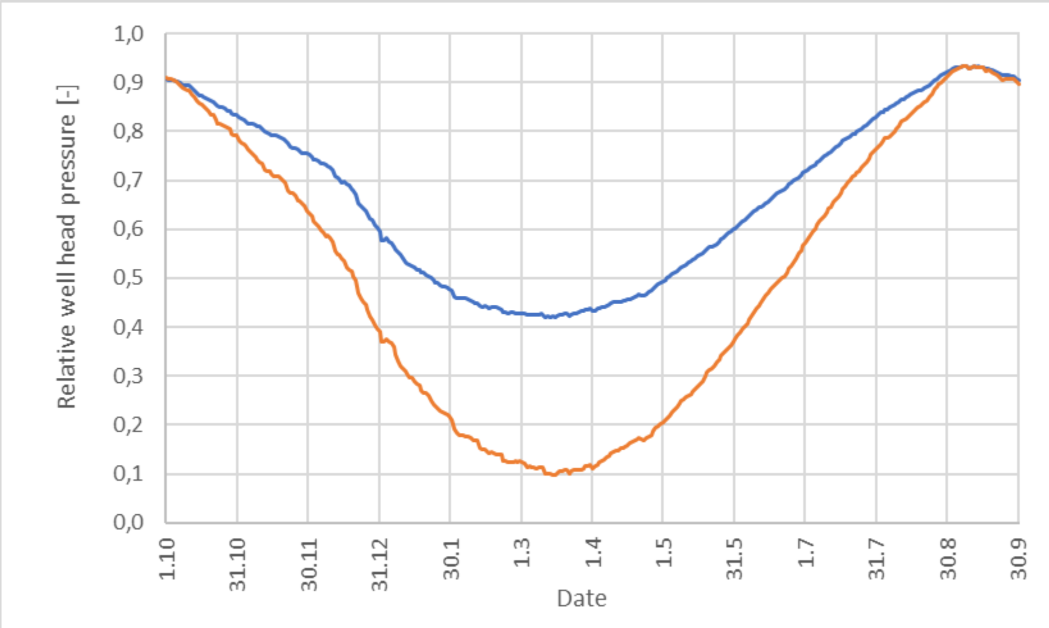

FIGURE 1: OPERATING CYCLE FOR COMMON YEARS (BLUE) AND LEAP YEARS (ORANGE).

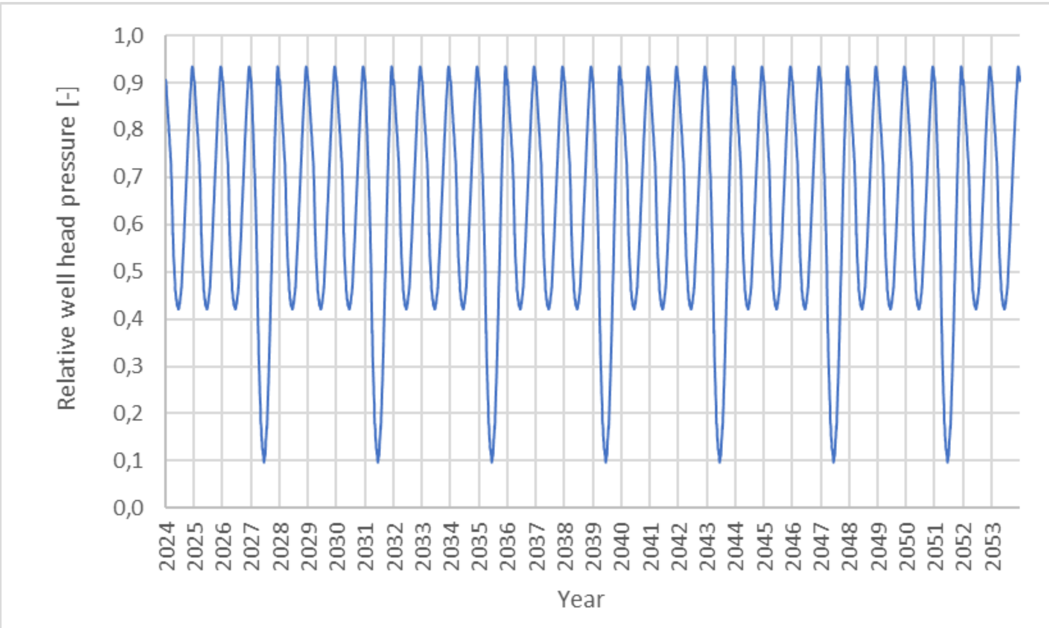

FIGURE 2: EXEMPLARY 30 YEAR OPERATING SCHEDULE STARTING WITH THE 1ST OF OCTOBER 2024.

4. REFERENCES

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[8] Krummhoern project (Germany) ; https://www.uniper.energy/news/funding-decision-for-hydrogen-pilot-project-in-krummhoern-natural-gas-storage-facility-received (retrieved 26/08/2022)

[9] *Set up of possible industrial scale models* ; HyPSTER (Deliverable D2.7) ; in preparation

5. ANNEXES

ANNEX A – OPERATING CYCLE FOR COMMON YEARS

Date (dd.mm)	Relative well head pressure
1.10	0,9061
2.10	0,9046
3.10	0,9047
4.10	0,9044
5.10	0,9024
6.10	0,9018
7.10	0,8992
8.10	0,8949
9.10	0,8944
10.10	0,8940
11.10	0,8936
12.10	0,8893
13.10	0,8834
14.10	0,8795
15.10	0,8737
16.10	0,8718
17.10	0,8700
18.10	0,8675
19.10	0,8649
20.10	0,8620
21.10	0,8604
22.10	0,8549
23.10	0,8520
24.10	0,8507
25.10	0,8493
26.10	0,8470
27.10	0,8419
28.10	0,8409
29.10	0,8352
30.10	0,8342
31.10	0,8347
1.11	0,8296
2.11	0,8264
3.11	0,8236
4.11	0,8214
5.11	0,8165
6.11	0,8149
7.11	0,8141
8.11	0,8116
9.11	0,8105
10.11	0,8099
11.11	0,8057
12.11	0,7992
13.11	0,7960
14.11	0,7937
15.11	0,7928
16.11	0,7919
17.11	0,7917
18.11	0,7882
19.11	0,7859
20.11	0,7848
21.11	0,7815
22.11	0,7752
23.11	0,7694
24.11	0,7665
25.11	0,7659
26.11	0,7624
27.11	0,7616
28.11	0,7564
29.11	0,7556
30.11	0,7538
1.12	0,7517
2.12	0,7474
3.12	0,7420
4.12	0,7408
5.12	0,7395
6.12	0,7352
7.12	0,7344
8.12	0,7323
9.12	0,7284
10.12	0,7273
11.12	0,7198
12.12	0,7084
13.12	0,7044
14.12	0,7017
15.12	0,6959
16.12	0,6964
17.12	0,6932
18.12	0,6886
19.12	0,6821
20.12	0,6785
21.12	0,6708
22.12	0,6531
23.12	0,6471
24.12	0,6415
25.12	0,6374
26.12	0,6328
27.12	0,6228
28.12	0,6178
29.12	0,6088
30.12	0,6029
31.12	0,5957
1.1	0,5778
2.1	0,5779
3.1	0,5815
4.1	0,5746
5.1	0,5706
6.1	0,5646
7.1	0,5588
8.1	0,5534
9.1	0,5470
10.1	0,5416
11.1	0,5328
12.1	0,5291
13.1	0,5269
14.1	0,5249
15.1	0,5216
16.1	0,5174
17.1	0,5161
18.1	0,5127
19.1	0,5106
20.1	0,5076

21.1	0,5032
22.1	0,4998
23.1	0,4951
24.1	0,4919
25.1	0,4897
26.1	0,4858
27.1	0,4836
28.1	0,4835
29.1	0,4798
30.1	0,4770
31.1	0,4749
1.2	0,4626
2.2	0,4592
3.2	0,4587
4.2	0,4583
5.2	0,4593
6.2	0,4581
7.2	0,4567
8.2	0,4539
9.2	0,4521
10.2	0,4489
11.2	0,4496
12.2	0,4433
13.2	0,4418
14.2	0,4428
15.2	0,4421
16.2	0,4389
17.2	0,4414
18.2	0,4419
19.2	0,4411
20.2	0,4383
21.2	0,4365
22.2	0,4312
23.2	0,4295
24.2	0,4286
25.2	0,4298
26.2	0,4292
27.2	0,4278
28.2	0,4280
1.3	0,4283
2.3	0,4277
3.3	0,4271
4.3	0,4260
5.3	0,4254
6.3	0,4250
7.3	0,4252
8.3	0,4257
9.3	0,4261
10.3	0,4269
11.3	0,4252
12.3	0,4208
13.3	0,4213
14.3	0,4207
15.3	0,4218
16.3	0,4208
17.3	0,4236
18.3	0,4247
19.3	0,4254
20.3	0,4268
21.3	0,4275
22.3	0,4236
23.3	0,4252
24.3	0,4280
25.3	0,4284
26.3	0,4316
27.3	0,4329
28.3	0,4341
29.3	0,4358
30.3	0,4361
31.3	0,4376
1.4	0,4325
2.4	0,4340
3.4	0,4370
4.4	0,4379
5.4	0,4402
6.4	0,4415
7.4	0,4444
8.4	0,4462
9.4	0,4477
10.4	0,4501
11.4	0,4513
12.4	0,4506
13.4	0,4514
14.4	0,4527
15.4	0,4531
16.4	0,4553
17.4	0,4571
18.4	0,4590
19.4	0,4609
20.4	0,4636
21.4	0,4674
22.4	0,4645
23.4	0,4655
24.4	0,4681
25.4	0,4718
26.4	0,4749
27.4	0,4778
28.4	0,4828
29.4	0,4867
30.4	0,4905
1.5	0,4938
2.5	0,4966
3.5	0,5007
4.5	0,5036
5.5	0,5090
6.5	0,5124
7.5	0,5149
8.5	0,5187
9.5	0,5229
10.5	0,5250
11.5	0,5281
12.5	0,5314
13.5	0,5349
14.5	0,5376
15.5	0,5414
16.5	0,5455
17.5	0,5475
18.5	0,5511
19.5	0,5558
20.5	0,5596
21.5	0,5627
22.5	0,5639
23.5	0,5667
24.5	0,5705
25.5	0,5737
26.5	0,5789
27.5	0,5831
28.5	0,5871
29.5	0,5918
30.5	0,5965
31.5	0,6001
1.6	0,6018

2.6	0,6063
3.6	0,6116
4.6	0,6160
5.6	0,6198
6.6	0,6234
7.6	0,6268
8.6	0,6309
9.6	0,6364
10.6	0,6399
11.6	0,6440
12.6	0,6462
13.6	0,6487
14.6	0,6527
15.6	0,6560
16.6	0,6603
17.6	0,6653
18.6	0,6692
19.6	0,6732
20.6	0,6771
21.6	0,6801
22.6	0,6831
23.6	0,6881
24.6	0,6921
25.6	0,6953
26.6	0,6989
27.6	0,7022
28.6	0,7058
29.6	0,7097
30.6	0,7147
1.7	0,7189
2.7	0,7217
3.7	0,7261
4.7	0,7291
5.7	0,7326
6.7	0,7360
7.7	0,7407
8.7	0,7439
9.7	0,7489
10.7	0,7525
11.7	0,7563
12.7	0,7585

13.7	0,7620
14.7	0,7671
15.7	0,7721
16.7	0,7762
17.7	0,7801
18.7	0,7838
19.7	0,7872
20.7	0,7901
21.7	0,7934
22.7	0,7948
23.7	0,7987
24.7	0,8021
25.7	0,8061
26.7	0,8096
27.7	0,8139
28.7	0,8183
29.7	0,8215
30.7	0,8253
31.7	0,8296
1.8	0,8326
2.8	0,8379
3.8	0,8401
4.8	0,8443
5.8	0,8442
6.8	0,8484
7.8	0,8515
8.8	0,8542
9.8	0,8579
10.8	0,8610
11.8	0,8654
12.8	0,8659
13.8	0,8697
14.8	0,8728
15.8	0,8762
16.8	0,8777
17.8	0,8808
18.8	0,8835
19.8	0,8840
20.8	0,8869
21.8	0,8889
22.8	0,8909

23.8	0,8949
24.8	0,8987
25.8	0,9040
26.8	0,9076
27.8	0,9106
28.8	0,9145
29.8	0,9163
30.8	0,9196
31.8	0,9224
1.9	0,9256
2.9	0,9284
3.9	0,9298
4.9	0,9313
5.9	0,9319
6.9	0,9329
7.9	0,9342
8.9	0,9330
9.9	0,9288
10.9	0,9299
11.9	0,9324
12.9	0,9318
13.9	0,9324
14.9	0,9308
15.9	0,9301
16.9	0,9278
17.9	0,9275
18.9	0,9261
19.9	0,9244
20.9	0,9220
21.9	0,9210
22.9	0,9174
23.9	0,9145
24.9	0,9146
25.9	0,9138
26.9	0,9142
27.9	0,9125
28.9	0,9117
29.9	0,9080
30.9	0,9038

ANNEX B – OPERATING CYCLE FOR LEAP YEARS

Date (dd.mm)	Relative well head pressure
1.10	0,9087
2.10	0,9077
3.10	0,9064
4.10	0,9045
5.10	0,9015
6.10	0,8994
7.10	0,8946
8.10	0,8891
9.10	0,8865
10.10	0,8842
11.10	0,8827
12.10	0,8749
13.10	0,8692
14.10	0,8633
15.10	0,8560
16.10	0,8545
17.10	0,8513
18.10	0,8475
19.10	0,8411
20.10	0,8338
21.10	0,8325
22.10	0,8236
23.10	0,8164
24.10	0,8142
25.10	0,8137
26.10	0,8095
27.10	0,8067
28.10	0,8041
29.10	0,7937
30.10	0,7907
31.10	0,7912
1.11	0,7823
2.11	0,7755
3.11	0,7723
4.11	0,7703
5.11	0,7620
6.11	0,7582
7.11	0,7521
8.11	0,7462
9.11	0,7416
10.11	0,7375
11.11	0,7351
12.11	0,7205
13.11	0,7191
14.11	0,7182
15.11	0,7123
16.11	0,7078
17.11	0,7071
18.11	0,7078
19.11	0,7028
20.11	0,6981
21.11	0,6943
22.11	0,6797
23.11	0,6734
24.11	0,6747
25.11	0,6690
26.11	0,6587
27.11	0,6583
28.11	0,6524
29.11	0,6480
30.11	0,6382
1.12	0,6311
2.12	0,6267
3.12	0,6172
4.12	0,6107
5.12	0,6048
6.12	0,5991
7.12	0,5921
8.12	0,5860
9.12	0,5862
10.12	0,5810
11.12	0,5748
12.12	0,5563
13.12	0,5481
14.12	0,5483
15.12	0,5407
16.12	0,5362
17.12	0,5233
18.12	0,5163
19.12	0,5143
20.12	0,5035
21.12	0,4961
22.12	0,4708
23.12	0,4597
24.12	0,4515
25.12	0,4452
26.12	0,4356
27.12	0,4230
28.12	0,4149
29.12	0,4052
30.12	0,3972
31.12	0,3908
1.1	0,3703
2.1	0,3713
3.1	0,3761
4.1	0,3705
5.1	0,3668
6.1	0,3595
7.1	0,3434
8.1	0,3309
9.1	0,3193
10.1	0,3161
11.1	0,3086
12.1	0,3034
13.1	0,2967
14.1	0,2976
15.1	0,2886
16.1	0,2829
17.1	0,2801
18.1	0,2708
19.1	0,2664
20.1	0,2659
21.1	0,2591
22.1	0,2504
23.1	0,2420

24.1	0,2385
25.1	0,2349
26.1	0,2293
27.1	0,2274
28.1	0,2233
29.1	0,2215
30.1	0,2178
31.1	0,2114
1.2	0,1918
2.2	0,1838
3.2	0,1785
4.2	0,1795
5.2	0,1785
6.2	0,1765
7.2	0,1764
8.2	0,1727
9.2	0,1687
10.2	0,1683
11.2	0,1684
12.2	0,1525
13.2	0,1510
14.2	0,1491
15.2	0,1461
16.2	0,1421
17.2	0,1458
18.2	0,1435
19.2	0,1392
20.2	0,1396
21.2	0,1383
22.2	0,1278
23.2	0,1263
24.2	0,1251
25.2	0,1229
26.2	0,1237
27.2	0,1257
28.2	0,1249
29.2	0,1253
1.3	0,1229
2.3	0,1213
3.3	0,1146
4.3	0,1147
5.3	0,1134
6.3	0,1142
7.3	0,1112

8.3	0,1123
9.3	0,1126
10.3	0,1125
11.3	0,1015
12.3	0,1008
13.3	0,0992
14.3	0,0968
15.3	0,0966
16.3	0,1000
17.3	0,1043
18.3	0,1065
19.3	0,1085
20.3	0,1089
21.3	0,1016
22.3	0,1044
23.3	0,1072
24.3	0,1088
25.3	0,1078
26.3	0,1093
27.3	0,1099
28.3	0,1154
29.3	0,1162
30.3	0,1198
31.3	0,1120
1.4	0,1148
2.4	0,1195
3.4	0,1230
4.4	0,1254
5.4	0,1299
6.4	0,1340
7.4	0,1372
8.4	0,1427
9.4	0,1459
10.4	0,1468
11.4	0,1467
12.4	0,1518
13.4	0,1525
14.4	0,1560
15.4	0,1585
16.4	0,1627
17.4	0,1647
18.4	0,1677
19.4	0,1703
20.4	0,1746

21.4	0,1699
22.4	0,1681
23.4	0,1734
24.4	0,1759
25.4	0,1801
26.4	0,1859
27.4	0,1940
28.4	0,1980
29.4	0,2015
30.4	0,2057
1.5	0,2097
2.5	0,2141
3.5	0,2178
4.5	0,2255
5.5	0,2308
6.5	0,2374
7.5	0,2434
8.5	0,2486
9.5	0,2533
10.5	0,2570
11.5	0,2590
12.5	0,2632
13.5	0,2678
14.5	0,2738
15.5	0,2781
16.5	0,2845
17.5	0,2898
18.5	0,2984
19.5	0,3066
20.5	0,3124
21.5	0,3155
22.5	0,3211
23.5	0,3274
24.5	0,3340
25.5	0,3410
26.5	0,3474
27.5	0,3517
28.5	0,3574
29.5	0,3636
30.5	0,3713
31.5	0,3745
1.6	0,3838
2.6	0,3893
3.6	0,3960

4.6	0,4009
5.6	0,4074
6.6	0,4148
7.6	0,4218
8.6	0,4296
9.6	0,4378
10.6	0,4446
11.6	0,4498
12.6	0,4570
13.6	0,4637
14.6	0,4704
15.6	0,4779
16.6	0,4822
17.6	0,4865
18.6	0,4905
19.6	0,4963
20.6	0,5006
21.6	0,5034
22.6	0,5126
23.6	0,5185
24.6	0,5257
25.6	0,5337
26.6	0,5412
27.6	0,5502
28.6	0,5572
29.6	0,5658
30.6	0,5723
1.7	0,5798
2.7	0,5869
3.7	0,5947
4.7	0,6008
5.7	0,6076
6.7	0,6157
7.7	0,6221
8.7	0,6269
9.7	0,6341
10.7	0,6413
11.7	0,6455
12.7	0,6543
13.7	0,6606

14.7	0,6664
15.7	0,6750
16.7	0,6811
17.7	0,6870
18.7	0,6939
19.7	0,7004
20.7	0,7074
21.7	0,7106
22.7	0,7151
23.7	0,7196
24.7	0,7251
25.7	0,7311
26.7	0,7376
27.7	0,7457
28.7	0,7514
29.7	0,7575
30.7	0,7628
31.7	0,7674
1.8	0,7745
2.8	0,7810
3.8	0,7857
4.8	0,7858
5.8	0,7892
6.8	0,7935
7.8	0,7992
8.8	0,8050
9.8	0,8109
10.8	0,8193
11.8	0,8221
12.8	0,8256
13.8	0,8305
14.8	0,8335
15.8	0,8391
16.8	0,8445
17.8	0,8496
18.8	0,8512
19.8	0,8561
20.8	0,8608
21.8	0,8638
22.8	0,8706

23.8	0,8766
24.8	0,8854
25.8	0,8917
26.8	0,8953
27.8	0,8996
28.8	0,9051
29.8	0,9093
30.8	0,9155
31.8	0,9201
1.9	0,9230
2.9	0,9248
3.9	0,9271
4.9	0,9296
5.9	0,9336
6.9	0,9345
7.9	0,9322
8.9	0,9279
9.9	0,9302
10.9	0,9328
11.9	0,9303
12.9	0,9308
13.9	0,9317
14.9	0,9300
15.9	0,9237
16.9	0,9254
17.9	0,9236
18.9	0,9195
19.9	0,9176
20.9	0,9147
21.9	0,9099
22.9	0,9052
23.9	0,9072
24.9	0,9070
25.9	0,9078
26.9	0,9063
27.9	0,9065
28.9	0,9016
29.9	0,8961
30.9	0,9024

ANNEX X – ELECTRONIC FILLING IDENTIFER

Document Name and version	<Configuration of possible industrial scale caverns (Deliverable D2.5, final version)>
Description	<This document contains the definition of the cavern configurations and the operating cycle that will be used to further investigate the optimum cavern configurations for industrial scale applications of salt caverns for hydrogen storage. The defined parameter ranges represent a majority of the relevant storage caverns in Europe.>
Location	<Project sharepoint\WP2\Task2.3>
Filing date	<16/09/2022>

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