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812 MURIEL STREET WOODSTOCK, ILLINOIS 60098 815-338-8579



TITLE:

Natural Gas Storage Project at Ll. Torup, Denmark

RESPONDING AUTHOR:

Ole Bernt Frydenberg DANSK OLIE & NATURGAS A/S Agern Allé 24-26 DK - 2970 Hoersholm, Denmark

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0. SUMMARY

The salt diapir at Ll. Torup was investigated by D.O.N.G. in 1978 to 1981 for the possible use as base rock for development of caverns. The geological and geophysical investigations consisted of a 12-fold reconnaissance seismic survey, to supplement previous seismic surveys, a densely spaced surface - gravity survey and the drilling of 8 boreholes of which the 6 were prepared for a subsequent leaching. A geological model has been developed based on the oriented drill cores taken in each drill hole. The inclination (dip and strike) of the salt structure was measured to 70° C - 90° C leading to reduced compression yield stress, when loading the cores uniaxial and made further triaxial test necessary.

The Danish Authorities (DEA) participated in the interpretation of the initial results and a set of guidelines were issued as a frame of regulations for the design of caverns. Based on extensive laboratory test programmes the caverns were designed, using Finite Element Calculation Programmes and a set of material laws, (S. Krenk, Menzel/ Schreiner, Burger's modified). Presentation of the major findings are that no stability rupture will occur but substantial creep is to be suspected if internal pressure falls to around 8 MPa.

The layout of the gas plant includes intake pump station and dilution station at Virksund, leaching water and brine discharge pipelines, high pressure leaching facilities and blanket gas installations. A thorough design procedure has been followed through basic design, technical notes on detail investigations and latest detailed design.

1. INTRODUCTION

The Danish natural gas project was initiated with the formation of the limited company "DANSK OLIE & NATURGAS" in 1972 for the commercial use of the natural gas production at the "DAN-feltet". However, the feasibility studies and the technical viability of the project as part of the Government's energy plan of 1976 permitted the design of the system to start only in 1978. In March 1979 a contract between D.O.N.G. and D.U.C. was signed on a gas volume of 55 mia. m³ to be delivered from 1/10 1984 to 1/10 2009. For the gradual introduction of gas into the Danish market D.O.N.G. signed with Ruhrgas AG for the delivery of approximately 200 mio. m³ from 1/10 1982 to 30/9 1986.

The time schedule for the construction phases are the following:

- 1982 Land pipelines and regulator stations on the Frøslev-Egtved alinement (D.O.N.G.). Distribution net works in region south (Naturgas Syd I/S). Laying of marine pipelines from Tyra in the North Sea to land. Laying of pipelines between Jylland and Fyn and between Fyn and Sjælland.
- 1983 Land pipelines and regulator stations on the Egtved Storebælt alinement.
- 1984 Land pipelines and regulator stations on the Storebælt - Copenhagen alinement and the Egtved-Nybro alinement. Completion of the gas treatment plant at Nybro.
- 1985 Partial completion of the Egtved Ll. Torup alinement and first cavern leached for gas storage at Ll. Torup.

1986 Land pipelines and regulator stations on the Egtved -Ll. Torup alinement. Completion of the gas handling plant Ll. Torup.

2. INITIAL STORAGE INVESTIGATIONS

Investigations of a salt diapir at Ll. Torup (Tostrup salt dome) the well To-3 and To-4 gave negative results as to the leachability of the salt. The strength of the salt was further questioned for the To-5 well as uniaxial strength for the Danish salt was far below the strength of German salt from the same formations.

While the well drilling programme was continued, the initial discouraging results gave reason for alternatives being considered at Pårup in a similar salt diapir or at Tønder in a nitrogen filled reservoir.

3. GEOLOGICAL MODEL

The Tostrup salt dome is one in a group of around 25 salt structures discovered in middle- and northern Jutland by geophysical investigations and test drilling. Of these structures 16 can be named genuine salt diapirs, the rest have not reached the diapiric stage remaining as salt pillows at a depth beyond 2000 meters. The locations of the salt diapirs are shown on Fig. 1.

The nomenclature used for describing the salt layers are the German for the North German Zechstein bassin. They are from the oldest to the youngest:

Zechstein 1 (Z-1), the Werra-Series

- Werra rocksalt (Na 1)
- Deckanhydrit (A 1r)

Zechstein 2 (Z-2), the Stassfurt-Series

- Hauptanhydrit, Stinkschiefer, Anhydritknotenschiefer (Ca 2)
- Basalanhydrit, Flaseranhydrit (A2)
- Stassfurt rocksalt (Na 2)
- Potash layer Stassfurt (Veggerby) (K2).

Zechstein 3 (Z-3), The Leine - Series

- Grauer Salzton (salt clay) T3
- Leine rocksalt (Na3)

The youngest layer the Z-4 has not yet been found at the Tostrup salt diapir.

The surface of the caprock was registered by a 3-line 6fold reconnaissance seismic survey in 1973-74 supplemented with a 2-line 12-fold reconnaissance seismic survey in June 1981.(1). The flanks and the overhang of the structure was determined from a densely spaced surface-gravity measurement (2). The evaluation of the structure is based on a Bouguer Anomally Map and six Residual Gravity Maps. The dome is elliptical with the main axis of 6 km almost northsouth and the little axis of 4 km west-east. Overhang is non-existent on the southern and northern flank according to the gravimetric survey and reaching its maximum of appr. 600 meters on the eastern flank. The crest of the caprock is situated 1,5 km south-west of the drilled area, approximately 100 meters below surface. (Coordinates $9^{\circ}25'$, $56^{\circ}38'$) (Fig. 2 and 3).

The thickness of the salt dome caprock consisting of anhydrite dolomite and gypsum varies between 33 meters at To-1 and 99 meters at TO-2 near the crest of the dome. The overburden of the salt dome is chalk and limestone from Upper Cretaceous overlaid with around 30 m loose sediments of mainly glacial sand. The To-1 and To-2 were drilled as exploration wells for hydrocarbons in the year of 1951. The To-1 well encountered a pocket of high pressure gas released when drilling in the salt at a depth of 503 m. The To-3 to To-10 have been drilled by D.O.N.G. when exploiting the possibilities for high pressure natural gas storage (To-3 and To-4 in 1978/79 and To-5 to To-10 in 1980/81).

The geological profiles of the wells are shown on Fig. 4 and Fig. 5 (3). The To-3 and To-4 wells drilled to a depth of 1593 meters and 1610 meters penetrated sequences of the Zechstein 1-3, potash salts, salt clay, "Stinkschiefer", dolomites and anhydrites. The To-3 well stuck residual gas in the dolomite - stinkschiefer in the transition zone from Z-1 to Z-2 at a depth of 359 to 394 meter.

The detection of rocksalts, potash salts, salt clays, anhydrites and dolomites of 3 Zechstein cycles (21 to 23) in the relatively small area in which To-5 to To-10 are situated picture the intensive internal techtonics of the salt dome. The plastic saltrock masses have followed their own deformation laws, leading to the typical phenomena of flow folding. The normal salt lay thicknesses are thinned out by the flow process on anticlinal and synclinal flanks and accumulated far above the normal thickness in the anticlinal and synclinal (normal thickness for the Stassfurt rocksalt layer is 400-500 m and for the Veggerby potash layer 6-8 m). Brittle rocks, such as anhydrite and dolomite have not normally withstood the deformation of the salt and are broken up into individual blocks isolated in the rock salt. Major anticlines and synclines have been subdivided by special folds with axes dipping at random. The dip of the layers can be horizontal, steep and the layers can even be turned upside down.

In all the wells To-3 to To-10 oriented cores were taken (Fig. 6 to 8). The To-5 to To-10 cores show intensive folding with steepy dipping fold axes finally forming the folds typical for salt domes ("Kulissen Falten"). When combining the results from all 6 wells the geological model suggested (3) is a steep almost vertical large anticline opening to the SW with the Werra-salts Z-1 at the center.

4. ROCK MECHANICAL INVESTIGATIONS

Rock mechanical laboratory test on cores extracted from the TO-5 well showed unexpected low uniaxial strength.

While continuing the exploration drilling program changes were introduced into the overall organization of the evaluation of the feasibility of cavern construction in the Tostrup Salt dome. The Danish Energy Agency, executing agency on behalf of the Ministry of Energy, was joined by the Research Institute Risø and the Consultant Dr. E. Passaris in issuring Guidelines for design of caverns, (4). On the other side KBB with Professor Dreyer, Dr. Rokahr and Dr. Lux acted as consultants to D.O.N.G.

Uniaxial compression test were made on app. 10 cores in each executed well based on these and on model tests performed by professor Dreyer it was concluded that caverns could be constructed at the TO-5 to TO-10 locations. A theoretical approach to approval of cavern design was further requested by the Danish Energy Agency in the Guidelines.

Laboratory test made by Dr. Rokahr and Dr. Lux on the TO-6 rock-salt material parameters showed equally low uniaxial strength (5) (and Fig. 9 to 11). However, when applying a confining pressure on the cores as expected the compression strength raised considerably (Fig. 12 to 14). At a confining pressure of app. 9 MPa the failure strength was as for other known North German Salt types (Fig. 15). Qualitatively it is further seen form TO-5 to TO-10 that increasing the dip of the rock salt layers when bedding planes coinsided with this gives decreasing uniaxial failure strength (compare Fig. 6 to Fig. 8 with Fig. 11). The experience gained on Tostrup cores confirms the general experience that the influence on failure strength from stratification deminishes as the isotropic stress increases.

According to the Guidelines the caverns should be designed to withstand the load conditions as stated below:

- Cavern during leaching period , Pinternal = h 0,012
 MPa.
- Cavern during operation period, ${\tt P_{min}}$ and ${\tt P_{max}}$ to be determined.
- Long term Cavern Operation, (creep calculated for mean pressure of 12 MPa and 15 MPa.)
- Cavern in Repair State.
- Cavern under Cyclic stress.

The design criterias to fulfil specified are to eliminate partly to totally the following consequences:

- Loss of load bearing capacity due to failures (Spalling, brittles fractures) of limited rock formation area in the cavern vicinity.
- Loss of load bearing capacity due to failures in a large rock mass as a sequence of continuous fractures (progressive fracture).
- Loss of serviceability due to high rate of convergence.

These criteria are translated into (Fig. 16):

- tensile stresses are not recommendable (as tensile strength is only around $\sigma_{t} < 1.5$ MPa).
- multiaxial failure strength must not be exceeded.
- plasticity zones around the cavern shall be limited (yield limit stress of* to be reached only in the vicinity of the cavern, 10 MPa < of* < 15 MPa for TO-6), and influence from adjacent caverns shall be limited (deviation of stress half way between caverns 10% of initial stress).
- creep failure not to occur by surpassing a viscose limit strain ($\boldsymbol{\varepsilon}_{eff} = 20 30$ %).
- cavern convergence and convergence rate to be minimized (convergence rate $\ddot{K} = 1-2$ % year).

The calculations of the stress and strain expected in the rock were calculated using a time-independent elastic/nonlinear-plastic material law Krenk - Ottosen as this gives conservative results compared to actual conditions. Where as the calculation of the deformations were determined by a time dependent non-linear viscose material law the Menzel/ Schreiner material law and the Burgers material law (modified), as an vicous material law likewise provides conservative (overestimated) prognosis of the creep.

The planned shape of the cavern at TO-6 is cylindrical with a height of 380 m and a diameter of 55 m or with a volume of theoretically 788,000 m³, but in practise limited to only 450,000 m³. (Fig. 17).

The geometrical model used for the stress-strain calculations were an infinitely extended disc with a circular shaped hole in the plane strain state. (Fig. 18).

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The geometrical model used for the creep calculations were a cylindrical cavern model and displacements calculated by finite element method (FEM). Calculations on more simple as disc rings showed considerable overestimation of creep (Fig. 19 and 20).

The results obtained were:

- No tensile stesses occur.
- By Pi = O MPa stresses are around 0,75 of short term failure strength causing failure in cavern wall. (Fig. 21).
 By P_i = 8 MPa stresses are around 0,5 of short term failure strength (Fig. 22).
- Plasticity zones are as shown on (Fig. 23), and deviation in initial stresses 200 m from cavern below 10% (Fig. 24).
- Creep failure using the Krenk-Ottosen time independent elastic, non-linear plastic law gave creep strain rate
 = 0,12 % d⁻¹ or rupture at *E*_{eff} = 20% after a period of 5 months at 8 MPa. However, this conclusion is considered very conservative.
- The creep strains calculated for $P_i = 12$ MPa at $22^{\circ}C$ were for Menzel/Schreiner on 1.7% and for Burger 9.2% over 10 year period. For the design evaluation of cavern life time the law of Burger was adopted giving calculated convergence at temperature $22^{\circ}C$ and $42^{\circ}C$ as shown on (Fig. 25). Convergence is calculated without taking the leaching history into consideration which gives an overestimation of creep. (6).

Conclusion:

- minimum pressure not to decrease below 8 MPa, period at low pressure to be monitored and compared to regular sonar measurements of cavern when in operation.
- cavern diameter up to 55 m. Cavern volume approximately 450,000 m³.
- distance between caverns 400 m or above.

further:

- maximum pressure not to exceed h • 0.0175 MPa.

5. LEACHING PLANT

The water for the leaching of caverns is taken at the VIRK-SUND located 10 kilometers from the cavern site at Ll. Torup. Investigations were made for ground water withdrawal of the site and delivery of the brine to Dansk Salt at Mariager 25 kilometers from the site. This solution was deferred as feasibility of the project and a time schedule depending on the salt production rate at Mariager was unattractive. The water at the Virksund dam is slightly brakkish water on the side of HJARBÆK FJORD and salt water with a salinity around $22^{\circ}/_{\circ\circ}$ on the side of LOVNS BREDDING. The leaching water is taken in from HJARBÆK FJORD and when returned as saturated brine diluted with brakkish water until the salinity is around $22^{\circ}/\circ\circ$ or below. The pump station is equipped with 4 leaching water pumps with a yield of 200 m^3/h and 3 dilution pumps with a yield of 4000 m^3/h . The station is remote controlled from Ll. Torup.

The pipelines are laid in a trench which follows the standard from the gasproject. The pressure classification of the pipes are PN 16 and PN 10 and the material is P.V.C. The system is protected against pressure chock waves by a hydrophore system. Of the 6 caverns 2 to 3 are leached at a time. The caverns are situated at different depth determined from geological conditions and each cavern has consequently its own pipe installation fed by individual pumps. As energy costs are a substantial part of the implementation costs, selection of leaching plant contractor was made on a combined evaluation of construction cost and capitalized energy cost.

The construction of the intake and the pipelines was commenced on the 1st September, the leaching plant is scheduled started on the 1st November, 1982, and terminated one year later when leaching will start. Overall construction cost for leaching plant surface installations are estimated at D.kr. 55 million. These costs cover neither consultant fees nor the construction of administration building, the gas plant and the caverns.

6. CONCLUSION

Extensive geological surveys were necessitated by the complex structure of the Tostrup Salt dome before 6 wells were selected for subsequent leaching. The final geological model in the drilled area of the salt dome was a large anticline fold, practically vertical.

Uniaxial compression strength on salt cores from the TO-5 and TO-6 was below normal for North German Salt and a rock mechanical test program on cores from TO-6 was undertaken. Results from the theoretical evaluations of results using elastic/nonlinear plastic time independent and nonlinear viscose time dependent material laws are judged of a sufficient quality for establishing a set of design parameters which secure a safe cavern construction. Due to the complex geological structure the caverns are situated at different depth. The design of the pump configuration secures a maximum flexibility at minimum cost. The leaching of the caverns are scheduled to start in the late autumn 1983.

- (1) The Tostrup Salt Dome, Geophysical Investigations and Interpretation.
 J.C. Baartman,
 Dansk Olie & Naturgas A/S, Dec., 1981.
- (2) Interpretation of gravimetric observations at the Tostrup Salt Dome.
 Steen Agerlin Petersen,
 Århus University, Nov., 1981.
- (3) Structural Evaluation of the Tostrup Saltdome, Ll. Torup Area.
 Fritz Lyngsie Jacobsen,
 D.G.U., May, 1982.
- (4) Guidelines for the Design of Underground Caverns in Salt for Natural Gas Storage.
 Danish Energy Agency - 1981.
- Rock Mechanical Investigations for Cavern Well TO-6
 Part 1: Laboratory test
 Part 2: Theoretical Investigations.
 LUB, Hannover University, Feb. 1982.
- (6) The Effects of Leaching, Plasticity and Creep on the Behaviour of a Gas Storage Cavity in Rock Salt. Risø, N.S., Ottosen, O. Gumeskov, P. Engbæk, April, 1982.
- (7) Danish Natural Gas Transmission System, Cavern Storage, Leaching, Detail Design Report, Naturgasgruppen - March 1982.









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Legend

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Κ Potnssium bed.

¥ Gas.

FIG. 5

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Tos	trup	3
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Tostrup 5

Core	Depth	Salt	Strike and dip (avg.)	Core	Depth	Salt	Strike and dip (avg.)	Core No.	Depth	Salt	Strike and dip (avg.)
10.				1	524.0-25.3	T3	50 ⁰	1	449.0-58.2	ZI	122-415W 117-36N 0/120 hori
				2 3	648.3-55.5 747.o-56.o	Z3 Z3	44 ⁰ 107-53S ✔ 228-50SW	2 3	627.0-36.0 797.0-806.0		79 ⁰ 71-515
1 2	no recovery lo78.9-87.9	к2	lo-85W	4	1003-12	23	90-75N 6 303-68NW	4	979.3-88.3	Z2	5-41E
3	1243.8-52.8	Z2	8-71W	5	1229-38	K2	0-40W & 220-285W	5 6	1194.3-1204.7 1271.3-80.3	Z2 Z2	67-58SE 88-80S
4	1352.9-61.8	22	160-64W	6	1363-72	к2	118-50N 50-40NE	7 8	1346.4-55.4 1421.7-30.4	Z2 Z2	62-82SE 52-72NW
5	1463.9-73.0	 Z2	17-59W	7	1497-1506	Т3	var. ♂3o2-2o₩	9	1496.8-1505.8	Z2	20-67E
6	1584.0-93.0	. 22	13-46W	8	1601-09.9	T3/Z3	var. 284-20W	10	1600.5-09.4	Z2	37-51 SE
											FIG. 6

	No. 1 2 3 4 5	329,8- 31 549 - 58 747,4- 49 804,3- 13	,9 Z1 Z1 ,4 Z1 ,2 Z1	31 ⁰ 88-82N 120-90 107-86N	1 2 3	374,0- 82,9 556,0- 65,2 753,762,1	Z1 ?	65 [°] 65 [°]			
	1 2 3 4 5	329,8- 31 549 - 58 747,4- 49 804,3- 13	,9 Z1 Z1 ,4 Z1 ,2 Z1	31 ⁰ 88-82N 120-90 107-86N	1 2 3	374,0- 82,9 556,0- 65,2 753,762,1	ZI ? 72	65 [°] <u>152-12SW</u>			
	2 3 4 5	549 - 58 747,4- 49 804,3- 13	Z1 ,4 Z1 ,2 Z1	88-82N 120-90 107-86N	3	<u>556,0-65,2</u> 753,762,1	?	152-12SW			
	3 4 5	747,4- 49 804,3- 13	,4 Z1 ,2 Z1	120-90 107-86N	3	753,762,1	72			1	1
	4 5	804,3- 13	,2 Z1	107-86N	1	1		120-15NE 08-12W			
	5	07- 2 70		1 1	4	818,0- 27,2	Z2	25 ⁰			
	Ì	8/0,3- /9	,2 Z1	114-90	5	896,0-905,1	Z2	0 ⁰ ?			
	6	946,2- 55	,o Z1	85 ⁰	6	961,0-970,0	Z2	86 ⁰			
	7	1022,0- 30	,9 Z1	88 ⁰	7	1028,3- 37,3 1079,3- 88,2	Z2 Z2	27 ⁰ 125-41NE			
	8	1097,5-1166	,7 Z1	79 ⁰	9	1151,6- 60,6	Z2	170-73E			
	9	1154,2- 59	,8 ZI	139-66NE	10	1206,3- 15,3	Z2	. 45 ⁰			
	lo	1210,9- 20	0 Z1-	158-75NE	11	1246,2- 55,4	Z2	151-62NE			
]	1	1267,8- 77	,o Z1	74 ⁰	12	1281,0- 90,0	Z1/ Z2	166-22E			ľ
1	2	1333,6- 42,	,6 Z1	164-77E	13	1341,0- 50,2	ZI	170-82W			
•1	3	1377,0- 85,	5 ZI	0-80E	14	1414.3-23.3	22	· 78 ⁰			
1	4	1454,0- 62,	,9 Z1	175-79W	15	1500,0- 09,0	Z1	174-54E			
 }	15	1604,8- 13,	8 Z1	153-79NE	16	1575,4- 84,4	ZI	86 ⁰			
					17	1651,7- 60,7	Z1	27-63E			
	•	- -			18	1736,5- 45,5	Z1	96-67N	·	FIG. 7	

Tostrup 7

Tostrup 6

. Tostrup 8	
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Tostrup 9

Tostrup lo

Care lia,	Depth	Salt	Strike and dip (avrg.)	Core No.	Depth	Salt	Strike and dip (avrg.)	Core No.	Depth	Salt	Strike and dip (avrg.
}	283.0- 292.0	22	45 ⁰	1	305,0- 313,8	ZI	61 ⁰	1	287,6- 297,0	Z2	46 ⁰
2	578,5- 587,5	Z2	1.	2	546,7- 555,8	<u>72</u>	113-845	2	544,6- 553,8	22	108-5311
3	759,0- 768,0	Z2	132-090	3	745,0- 754,0	Z2	74-30N	3	752,0- 761,0	Z2	133-705W
4	821,0- 829,8	Z2	15-075E	4	828,o- 837,o	Z2	47 ⁰	4	819,4- 828,5	Z2	890
5	891,0- 899,8	Z2	50-54 SE	5	895,0- 904,0	Z2	48-66SE	5	886,4- 895,2	Z2	112-625
6	960,0- 969,0	Z2	47 ⁰	6	960,0- 969,0	Z2	48 ⁰	6	961,4- 970,4	Z2	75 ⁰
7	1041,0-1050,0	Z2	90 ⁰	7	1040,0-1049,0	Z2	o6-54E	7	1036,4-1045,4	Z2	120-535
в .	1120,0-1129,0	22	35-74NW	8	1123,0-1132,0	Z2	81 ⁰	8	1115,4-1124,4	Z2	44 ⁰
9	1101.0-1170.0	Z2	82 ⁰	9	1161,0-1170,0	Z2	57-64NW	9	1160,4-1169,5	Z2	70-24N
10	1199,0-1208,0	22	var.	10	1198,9-1208,0	Z2	78 ⁰	lo	1197,4-1206,5	Z2	24 ⁰
п	1250,1-1259,4	22	47 ⁰	11	1256,0-1264,9	22	38-41 SE	11	1253.0-1262.0	<u>Z2</u>	45-44SE
12	1300,0-1309,0	22	04-65E	12	1304,0-1313,0	Z2	c.90 ⁰	12	1301,0-1310,0	Z2	570
13	1350.0-1359.0	22	c.75 ⁰	13	1352,0-1361,0	Z2	73 ⁰	13	1349,0-1357,3	к2	70-655
14	1400.0-1409.0	22	o5-75E	14	1399,0-1408,0	Z2	156-76E	14	1399,0-1408,0	72	45-555F
15	1426,0-1435,0	K2	67 ⁰	15	1447,0-1456,0	Z2/ Z1	145-54NE	15	1490,0-1499,0	T3	41-59SE
		i						16	1585,0-1594,0	Z3	36-72SE
			, 1								
											FIG. 8



Gu [MPa] • test results from August 1980 O test results from July 1981 I L CORE 2 3 4 9 10 11 12 13 14 0+ DEPTH (m)

TO6 UNIAXIAL COMPRESSION TESTS



UNIAXIAL COMPRESSION STRENGTH

FIG. 11,



TD6 TRIAXIAL COMPRESSION TESTS

sample signification	short signification	° €1 [8 • min ⁻¹]	-σ ₃ [MPa]	^{-σ} ļu [MPa]	-0 ^C 1u	- ^e tu [%]
T06-1/1-1024 T06-1/2-1024 T06-1/3-1024 T06-1/4-1024 T06-2/1-1026	1/1 1/2 1/3 1/4 2/1	0,25 0,25 0,25 0,25 0,25 0,25	0,0 3,0 6,0 9,0 12,0	16,1 49,1 71,5 88,8 106,9	15,9 44,2 57,4 65,4 68,3	1,5 9,9 19,7 26,4 36,1
T06-26/1-1456 T06-26/2-1456 T06-26/3-1456 T06-26/4-1456 T06-26/5-1457	26/1 26/2 26/3 26/4 26/5	0,25 0,25 0,25 0,25 0,25 0,25	0,0 3,0 6,0 9,0 12,0	16,2 47,2 67,6 88,8 105,0	15,9 42,8 55,8 65,4 67,4	1,6 9,4 17,5 26,4 35,8

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TO6 TRIAXIAL STRENGTH (COMPRESSION)













TO-6 Comp. Disc-Model /Cavern-Model



TO-6 Nonlinear Zones around the Cavern







TO-6 Material Law KRENK – Stress Distribution for $p_i = 0.0$ MPa



Convergence due to internal pressure

FIG. 25

4