COMPUTER MODELING OF THE INITIAL CAVERN FOR BEYPAZARI TRONA ORE ON THE BASIS OF LEACHING RATES, INSOLUBLE CONTENTS AND THICKNESS OF TRONA LAYER

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ABSTRACT

COMPUTER MODELING OF THE INITIAL CAVERN FOR BEYPAZARI TRONA ORE ON THE BASIS OF LEACHING RATES, INSOLUBLE CONTENTS AND THICKNESS OF TRONA LAYER

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Trona ore located in Beypazarı is extracted by solution mining method with well pair connected by directional drilling technology. This thesis covers the determination of the dimensions of the initial (vertical) caverns formed in underground by use of a computer modeling (trademark: WinUbro/Poland) on the basis of horizontal and vertical leaching rates. The leaching rates were determined using the trona core samples from the ore deposit. The effect of insoluble content and the thickness of trona layer and solvent temperature on the initial cavern dimension were studied. The outcome of this study showed that the better the trona layer quality from the point of view of thickness and insoluble content, the wider the vertical cavern size is. In 1 m thick trona layer with 20% insolubles, it is possible to develop caverns of 6 m width, which is the minimum size for well pair connection. On the other hand, it is determined that the effective leaching time depends mainly on solvent temperature.

Keywords: Solution Mining, Leaching, Cavern, Trona

ÖZ

BEYPAZARI TRONA CEVHERİNDE BAŞLANGIÇ KAVERNASININ ÇÖZÜNME HIZLARINA, SAFSIZLIK İÇERİĞİNE VE TRONA DAMARI KALINLIĞINA BAĞLI OLARAK BİLGİSAYAR MODELLEMESİ

TUNÇAY SAYGUN, İlkay
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Mart 2008, 107 sayfa

Beypazarı'nda bulunan Trona cevheri, yön kontrollü sondaj teknolojisi kullanılarak birleştirilmiş kuyu çiftlerinden oluşan çözelti madenciliği yöntemi ile işletilmektedir. Bu tez, yeraltında oluşan başlangıç kavernası (dik kaverna) boyutlarının yatay ve düşey çözünme hızlarına bağlı olarak bilgisayar modellemesi (marka: WinUbro/Polonya) ile belirlenmesini kapsamaktadır. Çözünme hızları maden yatağından alınan trona karot numuneleri kullanılarak belirlenmiştir. Trona damarları safsızlığı ve kalınlığının, çözücü sıcaklığının başlangıç kavernası üzerine etkileri irdelenmiştir. Bu çalışmanın sonucu, kalınlık ve safsızlık bakımından daha kaliteli trona damarlarında, daha büyük kavernalar oluşturmanın mümkün olduğunu göstermiştir. %20 safsızlık içeriğine sahip 1 m kalınlığındaki trona damarında kuyu çifti birleşmesinin sağlanabilmesi için gerekli olan 6 m çapında kaverna oluşturmanın mümkün olduğu görülmüştür. Diğer taraftan, etkin çözündürme zamanının esas olarak çözücü sıcaklığına bağlı olduğu tespit edilmiştir.

Anahtar Kelimeler: Çözelti Madenciliği, Çözündürme, Kaverna, Trona

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CHAPTER 1

INTRODUCTION

The molecular formula of the chemical compound known as “soda ash” is Na_2CO_3. Soda ash is currently produced from natural soda ores or synthetically with rock salt and limestone being the main raw materials. It is called to be natural or synthetic soda ash depending on the production method.

The synthetic production process and plants are increasingly criticized due to high energy consumption and thus high production cost as well as generation of environmentally hazardous wastes. Yet most of world soda ash production is carried out by synthetic method. The most important reason for this phenomenon is that the natural soda minerals are not common throughout the world. USA having the largest trona reserves in the world has already abandoned the synthetic process.

Trona is a natural form of sodium sesquicarbonate, having the formula of $Na_2CO_3.NaHCO_3.2H_2O$. Its formation is the result of very specific geologic and climatic conditions. For this reason, trona is a rare mineral.

Trona is very important mineral for natural soda ash production. In this context, it is clearly apparent that exploitation of Beypazarı Trona Deposit thus serving it to merits of the country is strictly indispensable.

Eti Soda A.Ş. utilizes Beypazarı Trona Reserves located in Turkey by using solution mining method to produce natural soda ash. It is estimated that there are 237 million tons of trona in the Beypazarı Reserve. The grade of Beypazarı Trona is quite high (84 % on the avarage) and its impurity level is rather low (relatively free of chlorides and sulfates).

Being a deeply deposited ore trona is extracted by two different methods in the world:

(i) Conventional mining method, by using excavator (mechanized mining),

(ii) Solution mining method, dissolving the trona and extracting it as brine (in-situ leaching)

Solution mining method was chosen for exploitation of trona in the Beypazarı reserve.

Solution mining is a highly sophisticated mining method allowing exploitation of not only evaporite type deposits but also some oxidized ones and even other types at low investment costs, without taking serious operational and environmental risks and, ensuring high productivity, thus it has recently been emphasized. The idea principally covers drilling a production well to reach orebody and taking out the pregnant solution of the leached ore by means of injecting a solvent medium which is adequate for the nature of ore itself. Means of well development, field practices and other applications may vary from field to field in the point of approach.

Eti Soda A.Ş. has adopted the "Double Well Solution Mining Technique" for exploiting the trona reserves in Beypazarı. Within this solution mining technique, the well pairs are connected to each other by means of directional drilling. The solvent is sent through one of the wells (the injection well) to the underground (cavern) thus dissolving the ore. The dissolved ore is taken from the other well (production well).

The object of this thesis was to determine the dimensions of **initial caverns** formed in underground on the basis of horizontal and vertical leaching rates by using a computer modeling. The leaching rates were determined using the trona core samples from the ore deposit. The effect of insoluble content and the thickness of trona layer and solvent temperature on the initial cavern dimension were studied.

CHAPTER 2

GEOLOGICAL STRUCTURE OF BEYPAZARI TRONA DEPOSIT

2.1 Location and Geography of the Study Area

Beypazarı Trona Field is located on a coverage area of 8 km^2 limited by Çakıloba, Zaviye (Bağözü) and Başören villages, which is 20 km northwest of Beypazarı town centre as shown in Figure 2.1. Beypazarı is about 100 km to the NW from Ankara and is accessible through asphalt paved Ankara-Beypazarı state road.

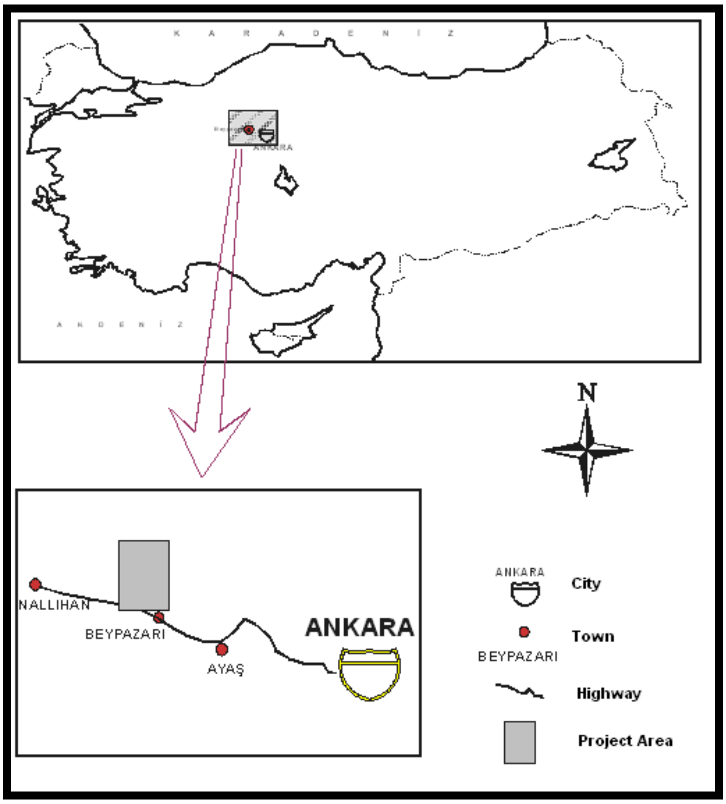


Figure 2.1 Location of the Beypazarı Basin and adjacent settlements (Özgür et al., 2002)

Large part of the area is hilly and undulating (Figure 2.2). Average elevation and the prominent hills in the deposit vicinity which are located at the northern part of the site range is between 850-880 meters and 810-1100 m, respectively. The hills are mostly bare and rarely covered with vegetation. The plains are used for agricultural purposes (Onargan et al., 2001).

Figure 2.2 General view of the Beypazarı Trona Field

There are no permanent streams in the basin. A few periodic creeks in the basin are: Gürağaç Creek in the western part, Başağaç Creek in the middle part, Başören Creek in the eastern part. They are fed by sources whose flow range from 10 l/s to 20 l/s. The water of these creeks is entirely used for irrigation purposes. At 2.5 km of the deposit, to the east, flows the İnözü stream, the only perennial water of the area. More important rivers are found at some 10 km to 20 km: Aladağ River to the West, Kirmir River to the South (CdFI et al., 1991).

Anatolian climate prevail throughout the field, which features hot and dry in summer, cold and rainy in winter. The rainy season mainly visits the area in December, January, April and May.

2.2 Sedimentary Process of Beypazarı Trona Deposit

Trona is a mineral with the natural form of sodium sesquicarbonate. Its formation is the result of many time repeated rapid evaporation cycle of an ancient lake, approximately 50-60 million years ago. The original lake contained fresh water and supported abundant flora and fauna. When the climate changed from humid to arid, lake evaporated and trapped the remnants of the once abundant life. The lake bottom became a mixture of mud and organic sediments that formed oil shale. Runoff water from the nearby mountains continued to supply sodium, alkaline earth, and bicarbonate to the lake.

The most likely source of sodium for the formation of trona deposit is from the weathering of rocks in the source area (granites and Paleocene and Cretaceous volcanics); leaching of the tuffs interbedded with the sediments; and the extensive Teke Volcanics (from coeval volcanic activity) interfingered with the sediments in northeastern part of the Beypazarı Basin (Figure 2.3). The Teke Volcanics were probably the major source of sodium for the trona and other sodium carbonate salts. The sodium entered the playa-lake system through surface and underground waters and thermal springs (Helvacı, 1998).

Since the rate of evaporation was high, the clear waters changed to brine that finally precipitated as sodium carbonate-bicarbonate compound known as the mineral “trona” (chemical formula: $Na_2CO_3 \cdot NaHCO_3 \cdot 2H_2O$). Alternating climates prevailed for about two million years. Periods of rains washed mud into the lake to cover previously formed carbonate type precipitates while interim periods of arid climate produced new precipitates. This caused numerous beds of trona to be formed. The tropical rains eventually returned to expand the lake. This washed sand and mud from the surrounding mountains into the lake waters. Sediments of clay and shale built new formations and these sediments buried the trona beds.

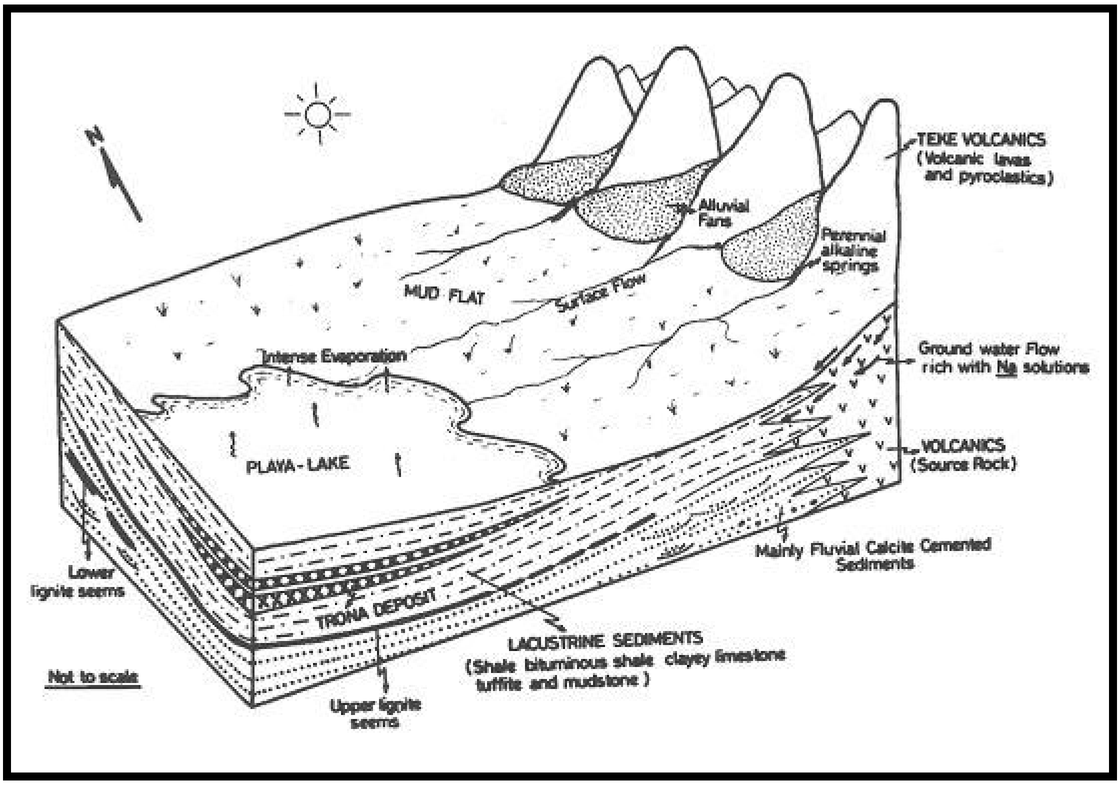


Figure 2.3 Depositional model of the Beypazarı Trona Deposit (Helvacı, 1998) (not to scale)

2.3 Stratigraphy

The trona field is characterized by the Pliocene and Miocene aged formations consisting of sedimentary and volcano-sedimentary lithological units deposited in the lake facies, and the alluvium. The Miocene aged formations are called as Beypazarı Group with a thickness of 1000 m and uncomformably overlie the older units (CdFI et al., 1991). A generalized stratigraphic sequence of the Beypazarı trona basin with details of underlying Neogene and older basement rocks are illustrated in Figure 2.4. The general features of the formations from the oldest to the youngest are summarized in the following paragraphs (Onargan et al., 1999).

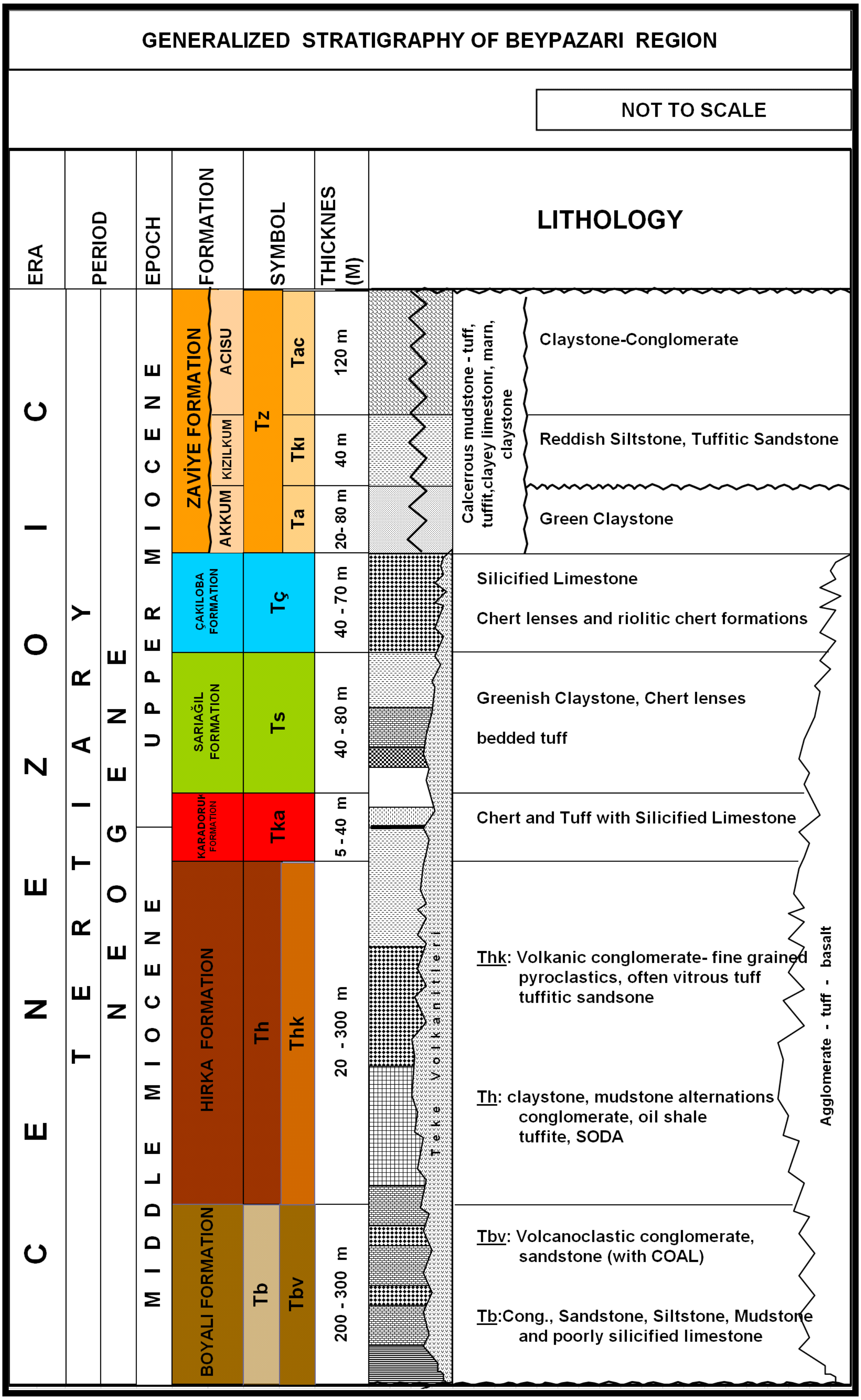


Figure 2.4 Generalized Stratigraphy of Beypazarı Region

Boyalı Formations (Tb):

The formation crops out in a very limited area in the west of the trona field and is composed of conglomerate and sandstone with claystone alternations. At its uppermost levels two lignite seams and conglomerates including volcanic fragments can be observed. The thickness of the formation is about 200 to 300 m.

Hırka Formation (Th) – containing trona deposit:

This formation involves trona zones and consists of bituminous shales, claystones and siltstones below the trona zone, and alternation of claystone, bituminous shale and tuffite above the trona zone. Brecciated tuffites below the upper trona zone are typical. At the central part of the field, the thickness of the formation reaches to about 300 m, but decreases towards north and northeast.

Karadoruk Formation (Tk):

This formation is represented by dark gray limestones with chert levels and is the closest aquifer to the upper trona zone. It is concordant with the Hırka and Sarıağıl Formations at its lower and upper levels, respectively. The thickness of the formation is about 15 to 20 m, however, occasionally reaches to 40 meters and drops down to 5 meters.

Sarıağıl Formation (Ts):

It outcrops in the vicinity of Sarıağıl village in the northern part of the field and mainly consists of greenish gray claystone and tuffite alternations. In some levels, medium bedded limestones can also be observed. Its thickness ranges between 40 and 80 m.

Çakıloba Formation (Tç):

This formation is composed of limestones with chert, and alternations of tuffite, claystone and marl at the upper and lower levels, respectively. It also forms the second aquifer above the trona zone. The rock units in the formation have a fractured structure and involve solution features. The thickness of the formation through the field ranges between 40 and 70 m.

Zaviye Formation (Tz):

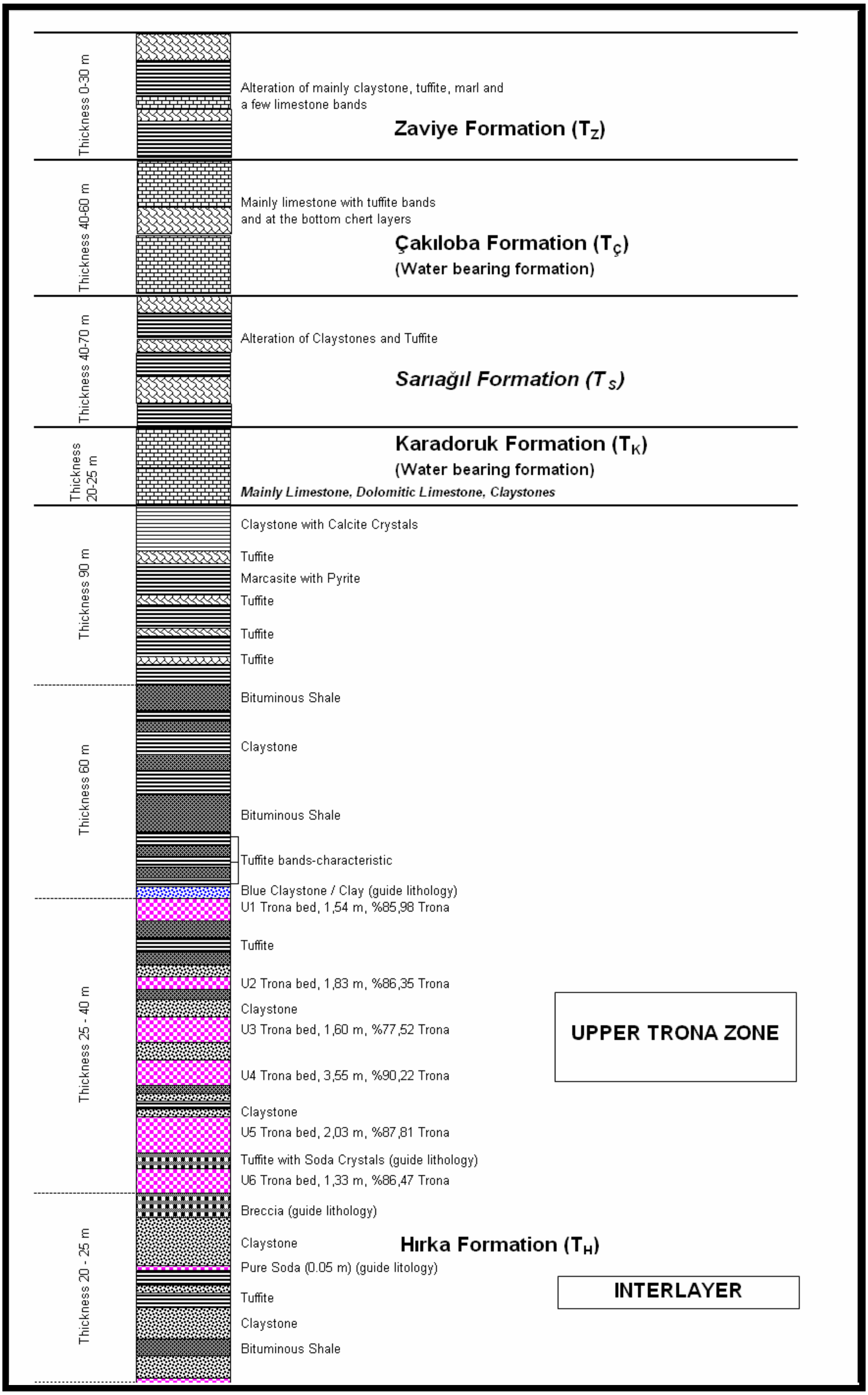
It largely crops out in an important part of the Arıseki Sector and in the south. The formation mainly consists of marl, claystone and tuffite alternations. However, limestone layers are observed towards the upper levels. While its thickness reaches up to 200 m at the south of the Zaviye Fault, it becomes thinner towards north. The formation discordantly overlies the Çakıloba Formation.

2.4 Trona Bearing Zones in Hırka Formation

Trona zone is located in the middle and lower zone part of Hırka formation. The formation above Hırka with their limestone levels have been rigidly turned and faulted between the two major longitudinal wrench-faults which limit the trona basin. Compression efforts produced the Kanlıceviz thrust. The plastic Hırka formation does not show trace of these fracturations (CdFI et al., 1991).

The orebody appears as two trona bearing bodies, upper trona zone and lower trona zone, gently dipping towards N and NE. Data indicates that the upper and lower trona zone is buried in the depth of 250-430 m. The thickness of the lens type trona zone is 70-100 m, including 33 sublayers and each is 0.4-2 m thick. Total thickness of the trona is 2.5m at the edge of the bed and 34 m at the centre (YIKE, 2002)

The general characteristics of the upper and lower trona zone and interbeddings between them are summarized in the following paragraphs (CdFI et al., 1991). Generalized stratigraphy of Hırka Formation and guide lithologies are illustrated in Figure 2.5.



(not to scale)

Figure 2.5 Generalized Stratigraphy of Hırka Formation and Guide Lithologies (İnceefe et al., 2002)

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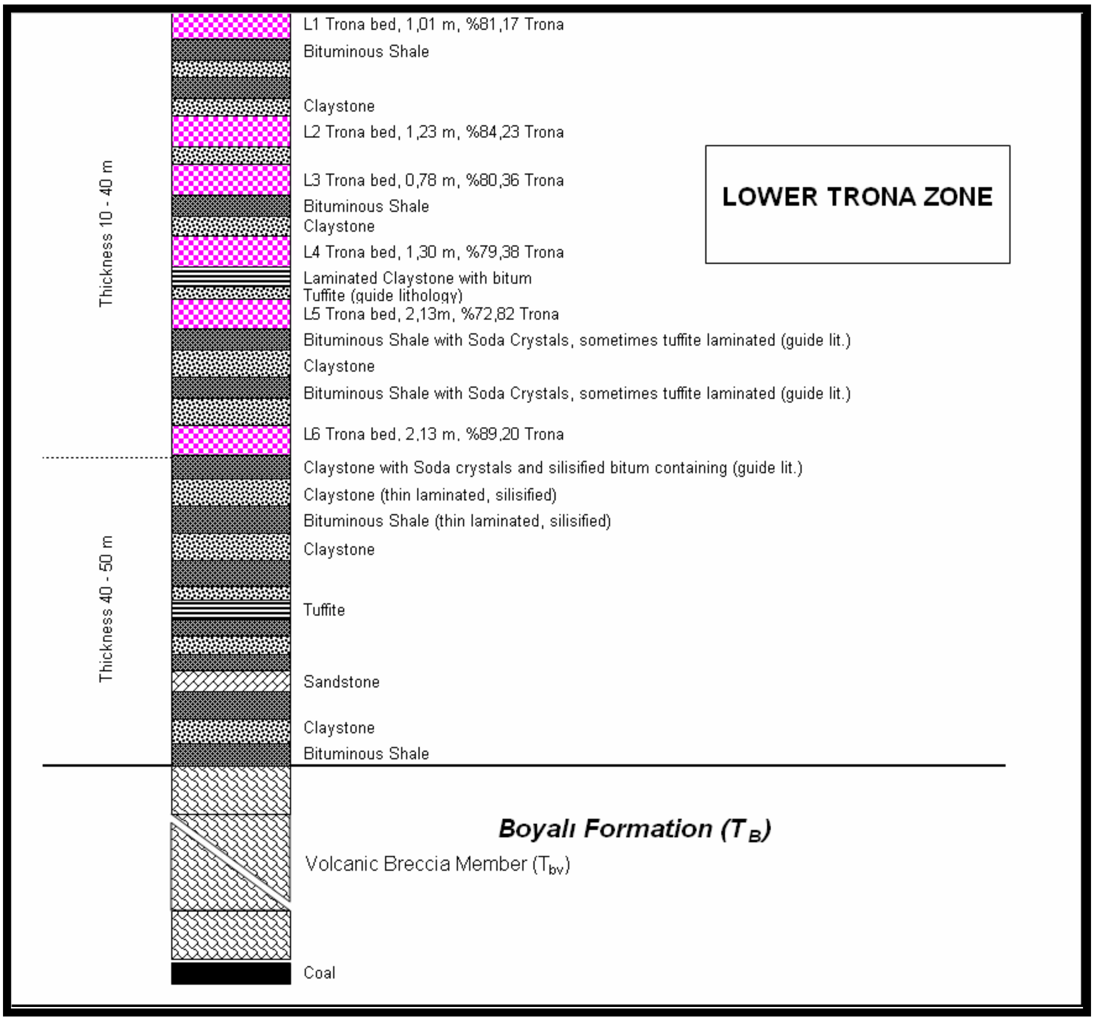


(not to scale)

Figure 2.5 Generalized Stratigraphy of Hırka Formation and guide lithologies (İnceefe et al., 2002)

<u>Upper Trona Zone:</u>

The upper trona zone covers all the deposit with a thickness between 5 to 40m. This zone has totally 17 seams but 6 of them are main ore beds named, from top to bottom, upper 1 (U1) to upper 6 (U6). Seam thickness varies from some centimetres to 10m.

Interbeds are bituminous shales and claystone. Their thickness is generally between 2 to 5m with the exception of U3 and U4 separated with an interbed of some 7 – 8 m.

Interlayer Between Upper and Lower Zones:

There is a layer of 20-25m between upper and lower part of trona zone. Bituminous shales and claystones constitute this interlayer with some tuffs and scarce sandstones.

Lower Trona Zone:

The lower zone is much more irregular in thickness and composition than the upper zone. The zone thickness containing ore is 40-60m. There are 16 seams and 6 of them are main ore beds named, from top to bottom, lower 1 (L1) to lower 6 (L6).

Trona seams are very irregular in this zone. Between seams are found bituminous shales, claystones and siltstones. In some occasion, sandstones may appear.

2.5 Structural Geology

The Trona Field has been affected by a number of major discontinuity systems, namely (Onargan et al., 1999);

1 – Zaviye, Kanlıceviz and Elmabeli Faults,
2 – Çakıloba Fold System consisting of anticlines and synclines,
3 – Secondary faults developed parallel to and/or intersecting the major fault systems, and,
4 – Bedding planes generally dipping towards southeast.

Zaviye Fault striking N 60º E and the Çakıloba Fold System striking N 73º E bound the trona field from the south and north, respectively. About 5 kilometers long section of the Zaviye Fault can be observed on the surface. Its dip is approximately 80º – 85º. It is a wrench fault and occurred parallel to the west part of the area, and can be considered as a strike-slip fault at the east. No trona zones were penetrated through the boreholes drilled in the south part of this fault.

The other major discontinuity in the area is the Kanlıceviz Fault which separates the trona field into two sectors, namely Arıseki Sector and Elmabeli Sector, in the east and the west, respectively (Figure 2.6 and Figure 2.7). This fault striking N 20º W dips towards southwest with an inclination of 35^o – 60^o and is a thrust fault. During the field observations it was noted that this fault cuts the Zaviye Fault and the Çakıloba Fold.

Figure 2.6 General views of Arıseki Sector and Çakıloba Fold

Figure 2.7 General view of Elmabeli Sector

Elmabeli Fault, approximately striking E-W direction can be recognized from the sharp variations in the inclination of the bedding planes observed on the both sides of Elmabeli Stream. According to CdFI et al 1991, it can be considered as a thrust fault.

The Çakıloba Fold system can be observed 7.5 km. long on the surface in the northern part of the trona field. It is a system of anticlines and synclines. Dips on the south flank are about 5º – 6º to southwest, while 55º-60º on the north flank. Although the fold system is also considered as a probable strike-slip fault system, there isn't any evidence to prove this (CdFI et al., 1991).

2.6 Hydrologic Conditions

Over the trona layer are the aquifers distributed in Karadoruk and Çakıloba formations. Within the space between every two aquifers and between the aquifer and trona layer are water resisting layers composed of tuff, clayrock and mudstone, etc.

CHAPTER 3

EXISTING METHOD OF SALT SOLUTION MINING

Underground solution mining technology has been applied for more than hundred years. It represents an alternative to mechanical extraction and is applicable to a wide range of minerals that are soluble in water or in aqueous solvent.

The basic schema of the technology applied in solution mining is simple (Kunstman et al, 2007):

- the deposit is made accessible by wells drilled in the suitable distance, depending on the geology of the deposit, geomechanical calculations and surface conditions,
- the leaching medium (water or semi-brine) is introduced into the salt deposit through leaching tubings in the wells,
- in the bare zone of the borehole, the dissolution of the salt takes place, and the concentration of the brine increases,
- as a result of leaching, the opening (the cavern) is developed around this zone,
- the brine, as an exploitation product, is taken out through tubings up to the surface, under the pressure of the leaching medium pumped into the cavern (Figure 3.1).

Since most of the waste components in the salt are not soluble, the dissolution residues tend to remain in the cavern, while the valuable components are dissolved and removed to the surface for processing. As a result, in situ operations are characterized by the absence of waste brines and tailing piles (KBB, 2001).

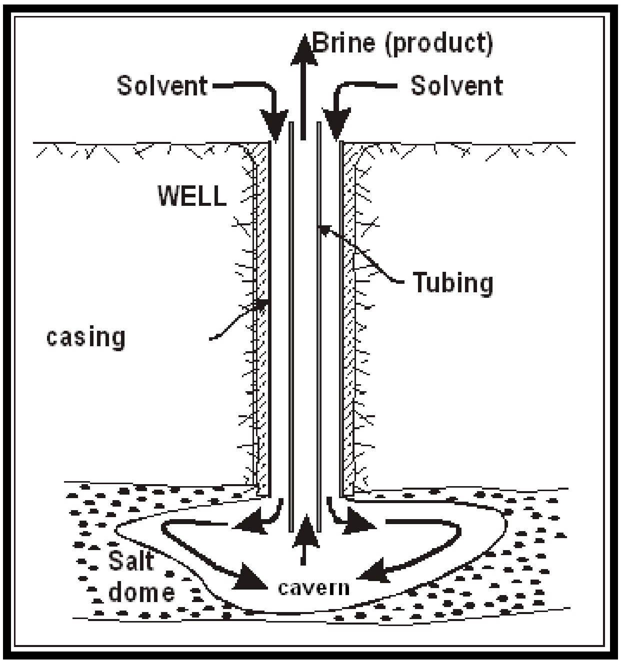


Figure 3.1 Generalized outline of solution mining (Çakmakçı et al, 2002)

Similarly, as in other methods of mining operations, it is possible to distinguish:

- stage of accessing works - the boreholes drilling
- stage of development – casing and well completion for leaching, preparing suitable arrangements on the surface (pumps, pipelines, tanks) and preliminary stages of the leaching
- stage of operation work (exploitation) – leaching for obtaining a brine with required saturation

Salt reserves can be deposited in the form of salt domes having a thickness over 1000 m or layers having the thickness varying from some centimetres to few hundred meters. Depending on the characteristic of the deposit, different type of the leaching method was developed resulting in different shapes of the cavern.

Among salt leaching technologies applied in the world, following classification can be done to make it easy to describe and analyse:

- leaching using single wells,
- leaching using wells connected by hydraulic fracturing,
- leaching using wells connected by drilling.

3.1 Leaching Using Single Wells

Leaching using single wells is applicable in salt domes and also in thick salt layers. Basis of this method is entering into contact with the ore deposit by drilling a single borehole, dissolving the ore by injecting hot or cold water or any other solvent and extracting the ore as brine.

The solvent is pumped into the borehole via the inner tubing string or the inner annulus. When pumped solvent reach the ore bed, it dissolves salt from the walls, becoming more or less saturated. The resulting brine is then forced back to the surface through the annulus or inner tubing string by the force of solvent being pumped in (Figure 3.2).

In order to force and control the expansion of the cavern in the horizontal direction, the contact between solvent and roof of the ore is prevented by oil or pressurized air blanketing. Especially for the thin seam, oil or air blanket is also used for preventing the loosening and spilling of the overlayer.

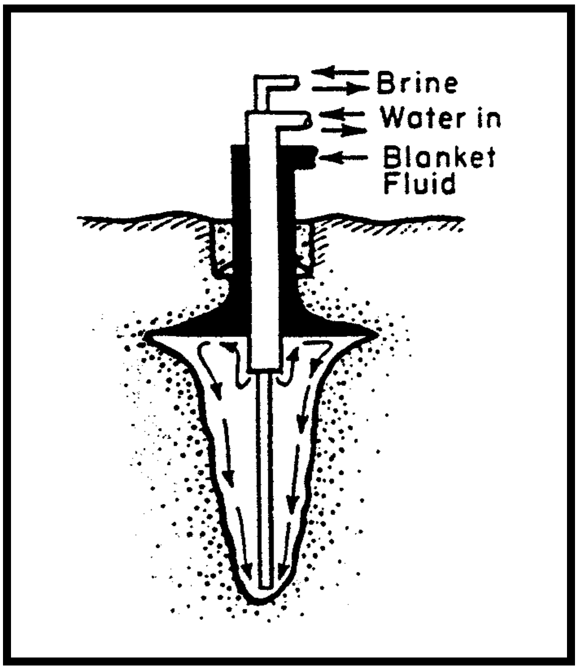
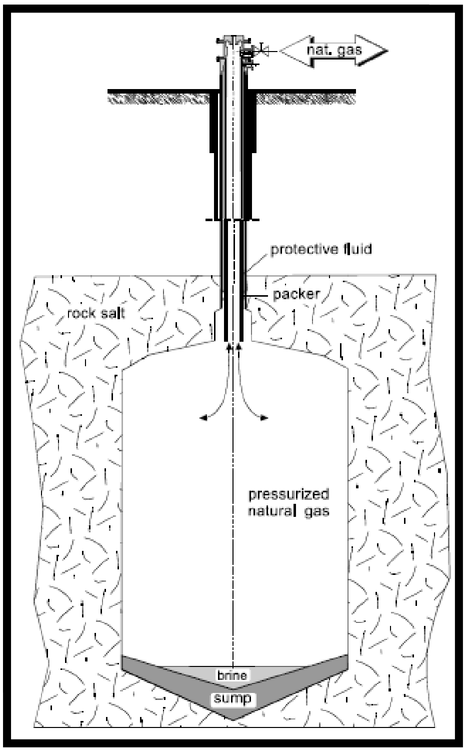
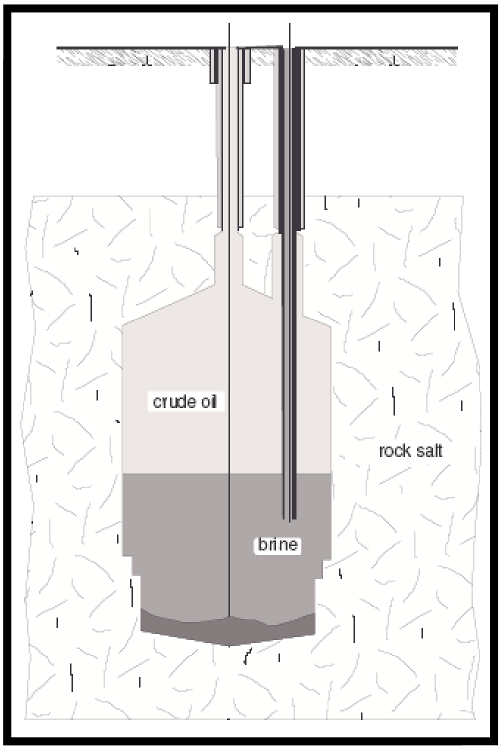


Figure 3.2 Single well leaching method (Remson et al, 1965)

Basic products of the solution mining are: ***brine***, which can be saturated or unsaturated and ***cavern*** made during leaching, which can be used for storing the usable liquid or gaseous substances like crude oil, liquid or gaseous hydrocarbons, natural gas, etc., and for disposal of hazardous waste. These operating characteristics make salt cavern extremely valuable.

Storage of both liquids and gases in solution mined salt caverns was reportedly first conceived in Canada in the early 1940's, during World War II (Bays, 1963). Storage in salt caverns of liquid petroleum gas (LPG), and other "light hydrocarbons" spread rapidly in the early 1950's in North America and several European countries. Storage of crude oil reportedly occurred first in England, also in the early 1950's, during the "Suez Crisis" (Joachim, 1994). Natural gas storage followed storage of liquid hydrocarbons by about a decade in the U.S. and Canada (Thoms and Gehle, 2000). Currently, storages of the crude oil, petroleum products, liquid hydrocarbons or natural gas in salt caverns are in operation in many countries worldwide: USA, Germany, France, UK, Denmark, Canada, Poland, Russia, Iraq and China (Figure 3.3).





(a)
crud

e oil storage in cavern PMRİP "Gora" (b) natural gas storage cavern KMPG "Mogilno"

Figure 3.3 Scheme of storage cavern application in Poland (Kunstman et al., 2007)

The same conditions which make salt caverns favorable for storage purposes are also favorable for disposal of waste to strictly isolate it from the biosphere. Because of the great public concern about waste disposal, the problem has been analyzed for a few dozen years, especially in regard to the group of the radioactive waste and so called hazardous waste. The disposal caverns operating nowadays have still formally the status of an experiment (Kunstman et al., 2007).

Cavern shape is very important in view of employing it as an underground storage and waste disposal purposes. On the other hand, productivity of the cavern is depending on its shape. For this reason, a method of cavern construction is extremely important. A number of leaching technologies was developed to construct a cavern of demanded parameters.

The most important technique of the leaching process is direct and indirect (reverse) leaching system. By changing the injection manner, cavern shape to be obtained can be arranged.

The circulation of the liquid in the well, when water flows inside the inner tubing and the brine flows through the annular space between both tubings, is called the **direct circulation** (Figure 3.4). In this method there is a flow of water in upward direction. This results in quick turbulent mixing of brine from the point of injection to the point of discharge, and from the central axis of the cavern to the salt walls. In direct circulation, the whole part of the cavern above the lower tubing shoe (injection point) develops during leaching more or less regularly, but the produced brine concentration is generally lower, than the so-called industrial concentration level (around 310 g/l).

The circulation of the liquid in the well, when the water flows through the annular space between both tubings, and the brine flows inside the inner tubing, is called the **indirect (reverse) circulation** (Figure 3.5, 3.6). In this technology, only a part of the cavern is developed regularly, namely the part above the outer (upper) tubing shoe (injection point). Between the upper and lower tubing shoes, the cavern walls lean over in the form of a reversed cone. The produced brine concentration is generally high and it is possible to reach the industrial concentration level.

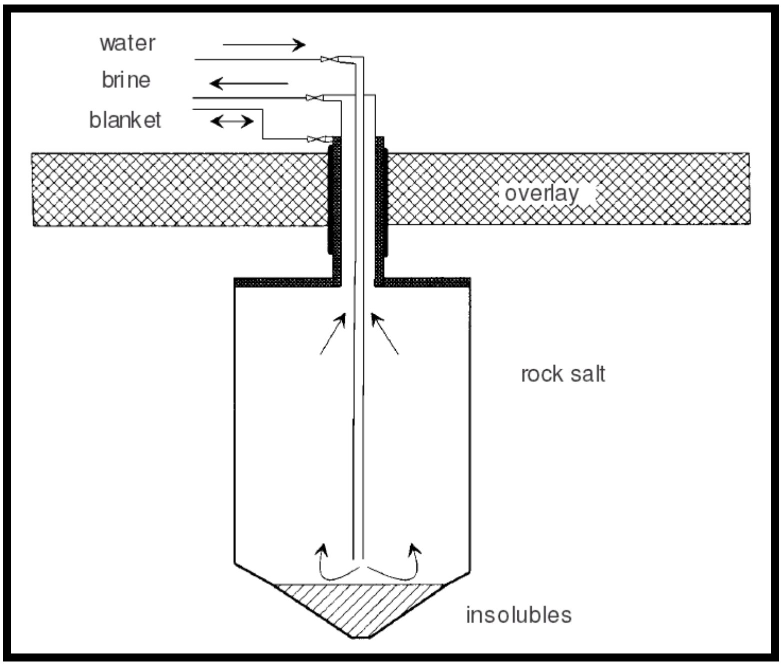


Figure 3.4 Diagram of leaching in direct circulation (Kunstman et al., 2007)

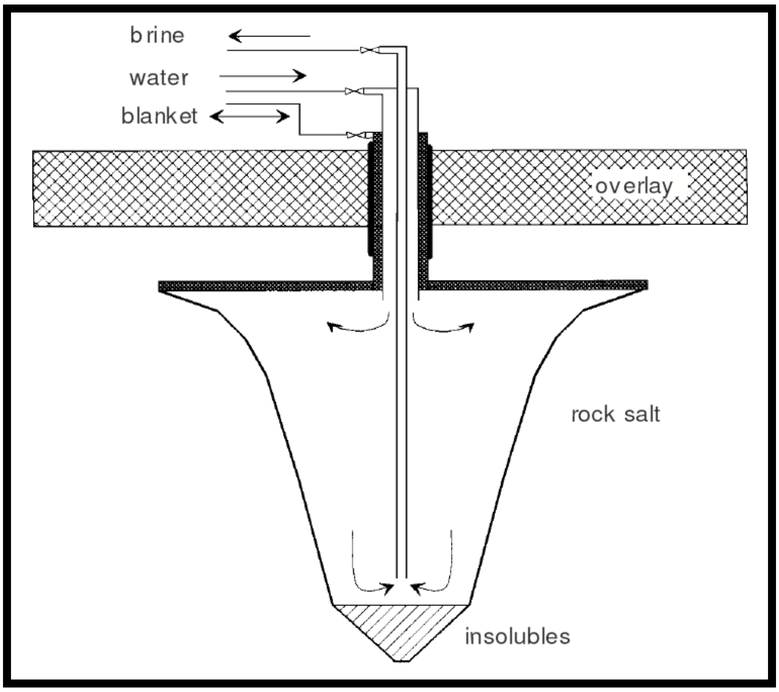


Figure 3.5 Diagram of leaching in reverse circulation – classical variant (Kunstman et al., 2007)

To sum up, a regularity of the shape is the main advantage of the direct circulation and a high concentration is the main advantage of the reverse circulation. In order to seize both these advantages at the same time, reverse circulation is applied in the so-called “close tubing shoes” version (Figure 3.6).

The technique of “close tubing shoes” consists in locating both shoes in the lower part of the cavern, at a small distance from each other (15 - 30 m) , using reverse circulation.

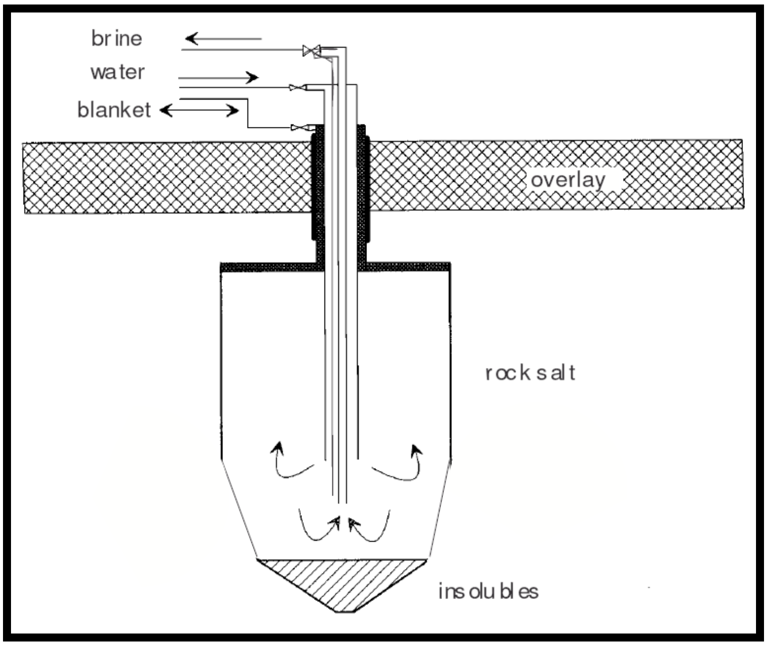


Figure 3.6 Diagram of leaching in reverse circulation – close tubing shoes version (Kunstman et al., 2007)

Cavern developed by using direct circulation has larger diameter at the bottom than indirect circulation. This large diameter supply bigger volume for insoluble accumulation. For this reason this method is applied mostly for creating the initial or so-called preparatory stage in the cavern shape forming purposes.

Applying the "classic reverse circulation", relying on pumping the water just under the roof of the cavern and producing the brine at the bottom of the leaching zone

(Figure 3.5), always leads caverns to the unfavourable shape of a reversed cone, undercutting the pillars at the top of the leaching zone and losing the deposit at its bottom. Using of such a technology during longer time is sensible only for intentional over-cutting of the salt deposit, e.g. to connect two or more initial caverns (Figure 3.7) because, in the indirect circulation, cavern diameter at the top is bigger than in direct circulation. Interconnected wells results in tunnel like cavern and gives brine of higher concentration than in single well leaching operation.

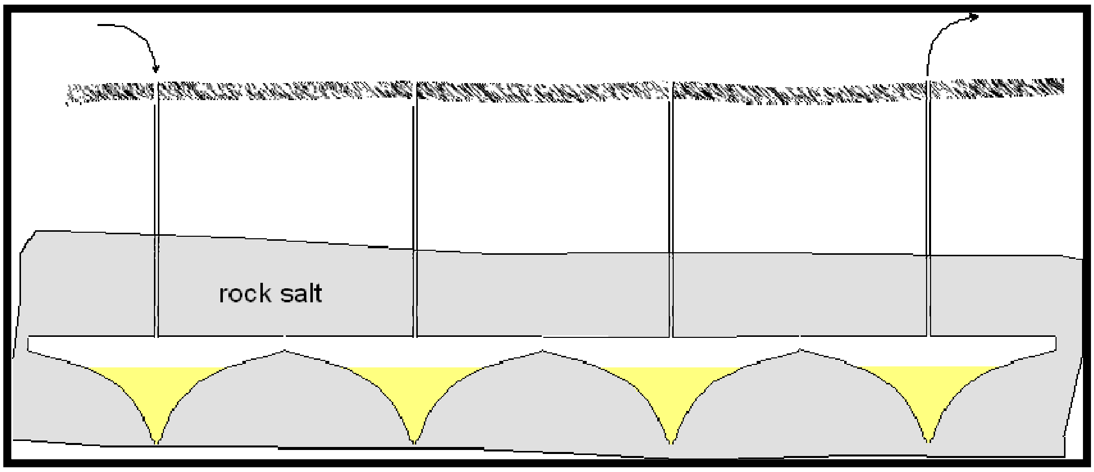


Figure 3.7 Production stage of wells connected by reverse circulation

The other important technique for developing predetermined shaped cavern is changing the setting depth of the suspended tubings. The number of the tubings can be one or two according to desired cavern shape and characteristics of salt deposit. Figure 3.8 depicts the progression of cavern by changing the tubing depth.

In this method, inner tubing remains bottomed at the total depth throughout the process and outer tubing is always positioned so that the point of injection coincides very closely with the position of the blanket-water interface.

One of the complexities of this procedure arises from the fact that the final cavity configuration is the result of the alteration of each leaching stage by every successive stage. Therefore, cavity shape is greatly affected by the uniformity of the salt, flow and pipe setting. This renders precise control very difficult (Remson et al., 1965).

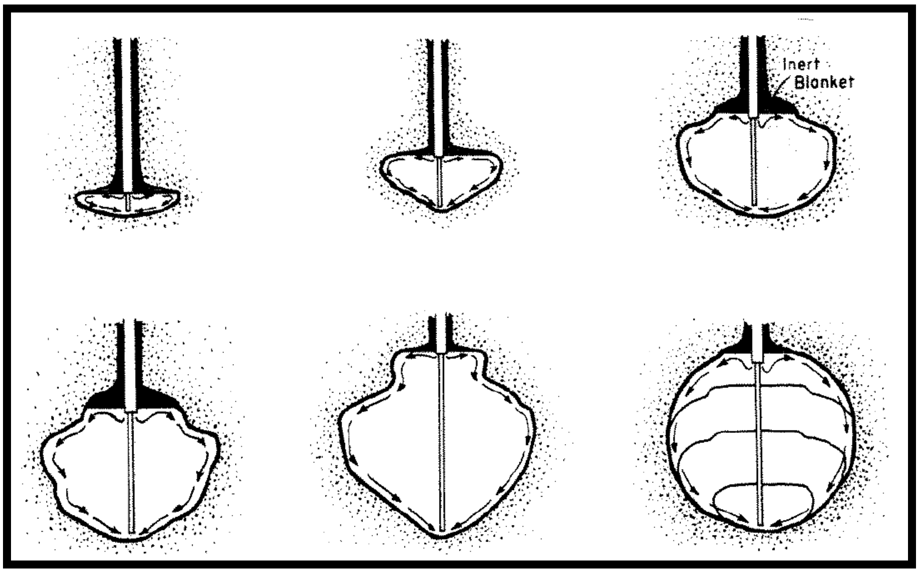


Figure 3.8 Progression of cavern by changing the tubing depth (Remson et al., 1965)

3.2 Leaching Using Wells Connected by Hydraulic Fracturing

By taking the field stress conditions and seam alignment into consideration, two or more wells can be connected within the same ore seam by the help of the hydraulic pressure. Wells should be spaced according to geological and structural properties of the deposit field, preferably 80-150 m. Cavity development is started immediately after connection and high pressure circulation is carried until low pressure corridor in fractured zone is obtained. After a while, normal production is carried out from the expanded connection corridor. When the connection is achieved, one of the well serves for solvent injection and the other serves for brine taken as product (Figure 3.9).

Obtained cavern shape using this leaching method is different from single well leaching systems. In this method, tunnel-like caverns are obtained and leaching surface opened in the deposit is big enough to saturate the brine flowing between wells.

Among the joining techniques, fracturing can be least expensive; however, many problems can arise to increase the costs.

In this method, the main problem is how to determine the development of fracturing patterns. Some specialists believe that almost all induced fractures are vertical. Others believe that almost all induced fractures will follow the pattern of natural fractures. Still others believe that fractures remain horizontal. Fracture patterns are governed by the rock and associated conditions in which they develop and do not conform to standard rule (Henderson, 1973).

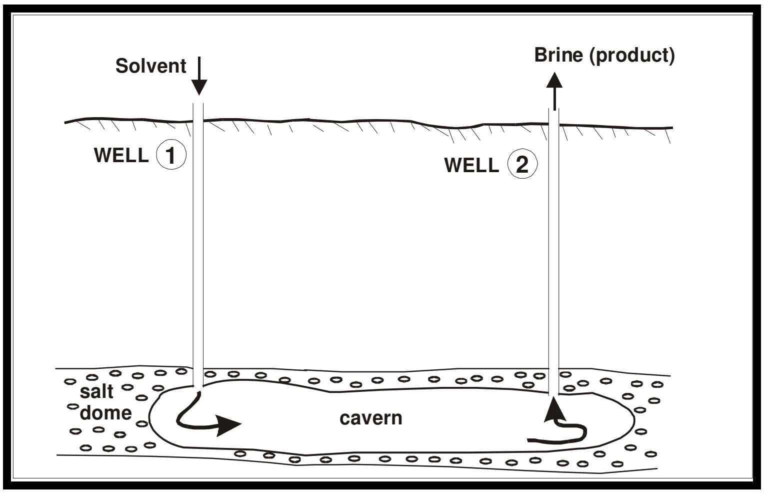


Figure 3.9 Production stage of well pair connected by hydraulic fracturing

In hydraulic fracturing method, main purpose is connecting two or more borehole through the bottom part of the deposit. But connection path can not be determined precisely because it depends on rock mechanic properties of the deposit and adjacent rocks, and structural conditions of them. When fracture initiates from the fracturing well, its developing tendency will be toward to the weakest zone. For this reason, if there is a natural fracture or interface between layers, obtained fracture path will be different from the planned. Figure 3.10 and 3.11 depict the diagram of probable problems encountered while hydraulic fracturing method is used.

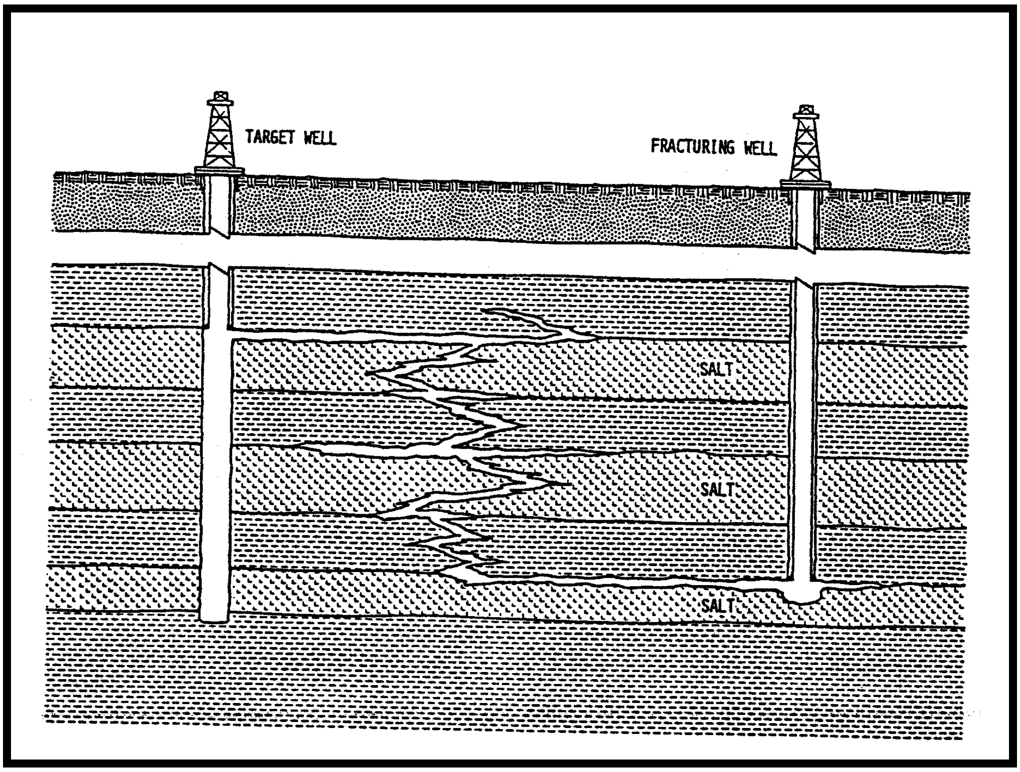


Figure 3.10 Fracture connection through insoluble lenses (Henderson, 1973)

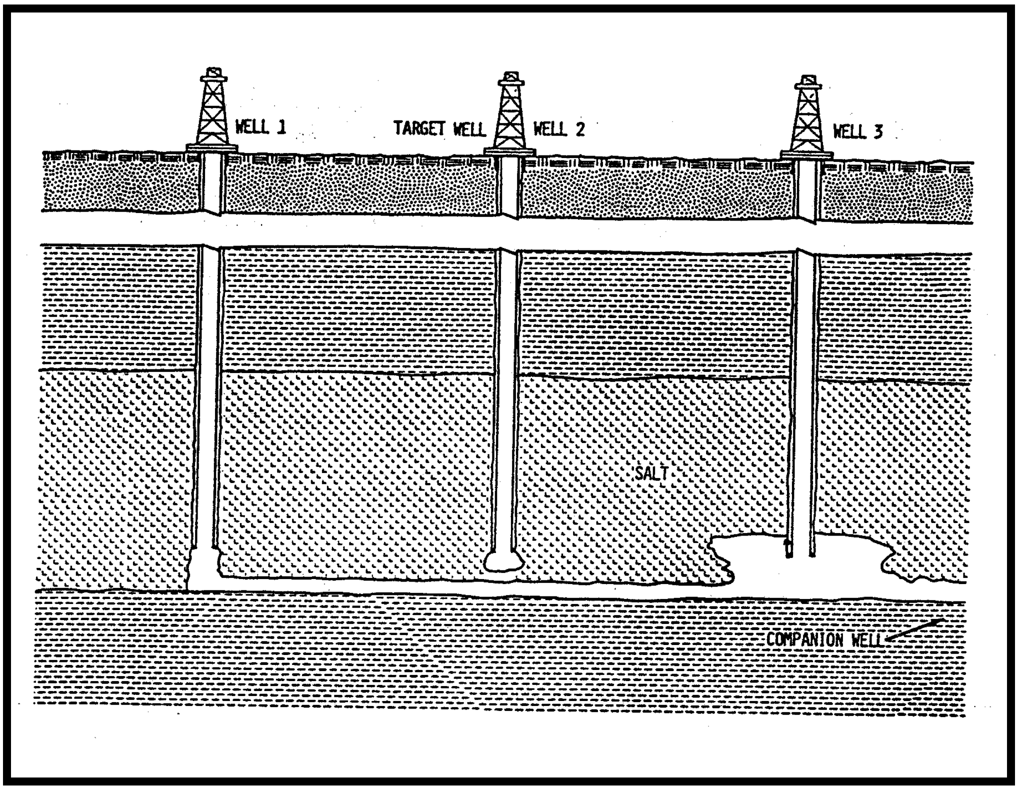


Figure 3.11 Fracture connection that missed target well (Henderson, 1973)

To sum up, whenever the site is structurally feasible, the hydraulic fracturing method for well connection in salt zone is recommended, because fracturing is the most economical way of well connection (Haimson, 1973). This is a fact, however it is offset by several disadvantages including following:

- fracturing path can not be directionally controlled
- applicable only in some areas

On the other hand, obtaining well saturated brine and large volume cavern are the main advantages of this method.

3.3 Leaching Using Wells Connected by Directional Drilling

The directional drilling technique is especially used in petroleum industry and this technique is state of art in the drilling technology. For this reason, it is a very expensive application. But, this technique supplies maximum control of the cavern geometry and by developing the long cavity, we can obtain more recovery from one well unit. Also, in order to get on to the production stage as soon as possible, this method is very useful. For the deposits of small thickness, this technique is a unique method to obtain high recovery.

Leaching system of wells connected by directional drilling technique is very similar to wells connected by hydraulic fracturing. One well is used for solvent injection, the other for brine extraction and, obtained cavern shape will be tunnel-like again. The only difference comes from the connection method.

In this method one well is drilled with conventional drilling technique. The other well, called horizontal well, is located in a certain distance from vertical well and drilled by directional drilling technique within the ore seam. The connection of the horizontal well with the vertical well is obtained directly, using low drilling pressure (Figure 3.12).

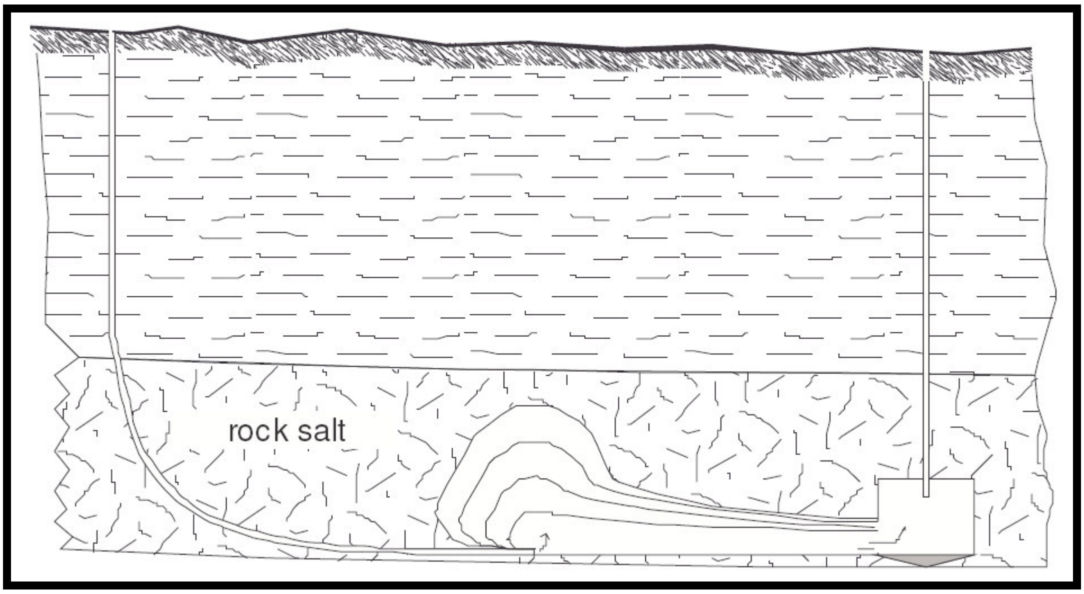


Figure 3.12 Wells connected via directional drilling and tunnel like cavern (Kunstman et al., 2007)

While directional drilling is already applied extensively in the world drilling technology, the leaching of horizontal caverns is still a new technology, involving a number of technical problems, not finally solved so far. However, it is certainly the technology of the future for the deposits of small thickness.

CHAPTER 4

ADAPTATION OF A SOLUTION MINING METHOD FOR BEYPAZARI TRONA DEPOSIT

Researches made between 1998-2002 showed that, traditional underground mining method is not applicable for Beypazarı Trona field due to different reasons. Main and supplementary factors can be listed as follows (ETI SODA, 2006):

- Ore recovery of trona deposit characterized by multiple thin layers will be very low (~15%) even with the full mechanized equipment.

- Unexpected operating cost will be high due to various environmental conditions in underground mine. Factors which may result in high operating cost can be listed below:

    - ***Weak parent rocks:*** Rock mass will create strata control problem and the need to use a special support system.

    - ***Aquifer zone overlying trona bed:*** Water is entering the mine excavations because of this aquifer zone, and mine dewatering system increases the operating costs.

    - ***Gas and brine formation in trona:*** The subject of gas which have been included in trona and associated rocks was studied. Result of this study showed that gas mixture composed of dominantly methane and denser other hydrocarbons has a potential of explosion (Didari, 2003). For this reason, mine ventilation and monitoring system will increase cost accordingly. On the other hand, brine trap formation in the trona layer and in the contact zone of trona and associated rocks may cause mine accident and flood in the mine during production stage.

- In the case of underground mining, even not considering the unexpected costs mentioned above, cost of ore exploitation and cost of process to produce soda ash was quite high for such specific project. The main reason for high operating cost are listed below:
  - High mining investment (100 million USD approx., KVAERNER, 2001)
  - High labour requirement
  - Extensive waste generation and waste management cost
  - High energy consumption
  - High logistics cost

  Such additional economic burdens would significantly decrease the competitiveness of the product at the market.

Due to technical, logistics and management issues mentioned above, traditional longwall mining method is not feasible for Beypazarı Trona deposit. Hence, research about in-situ solution mining methods was initiated. Considering its characteristics, a double-well system connected via directional drilling techniques was found to be the most suitable system for Beypazari trona field.

In this method, considering the thickness, grade and continuity of the layers, ore deposit can be exploited starting from bottom layer. Connected well pairs in the suitable lowermost layers will continue to leach in upward direction with raising the cavern roof up to next layer. Well pair will continue leaching operation up to completely dissolving the higher trona layers and then service life of well pair is completed. Well pair (cavern) in which leaching operation was finished is plugged and pressurised and then closed.

The opening formed in underground strata due to leaching of trona and disintegration of parent rocks under water action is full of brine. In the double-well leaching system preferred for this project, cavern formed in the vertical well is called an **initial cavern (vertical cavern)** and cavern formed in between vertical and horizontal well obtained via directional drilling is called an **production cavern (horizontal cavern)** (Figure 4.1).

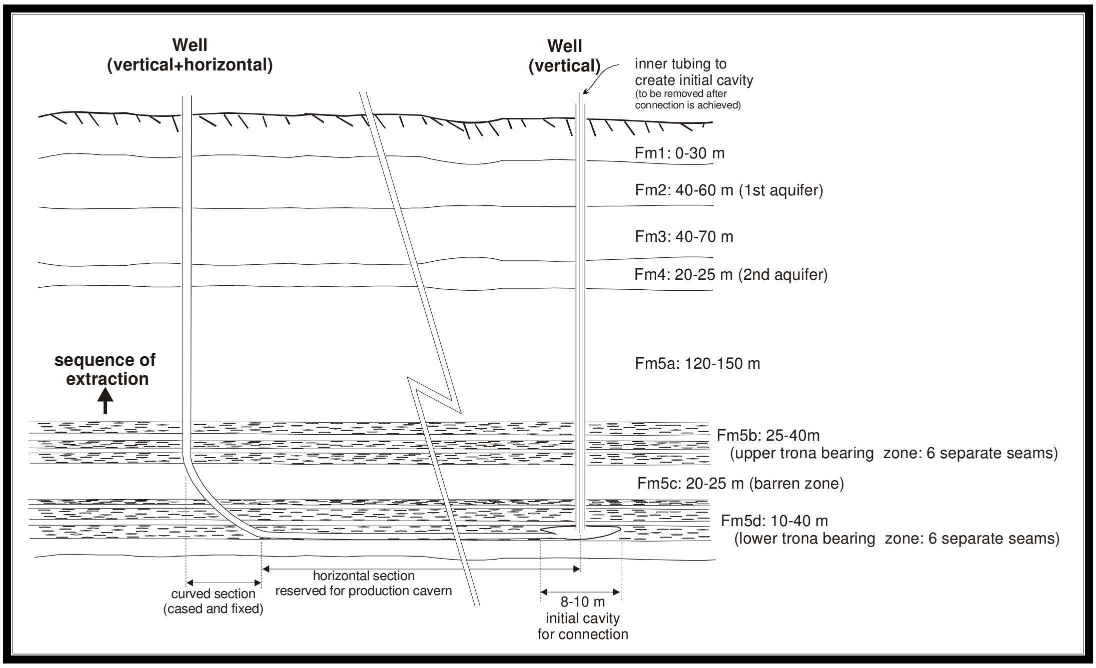


Figure 4.1 Schematic view of a well pair

The details regarding considered system has been designed in accordance with the following issues (ETI SODA, 2004):

- Orientation of the well pair in the deposit: Alignment of the wells connection axis is parallel to the strike of trona layer floor (Figure 4.2). Dip of the Beypazarı Trona Deposit is around 9-10° in the ESE direction excluding the border of the mineralization zone and some specific locations having flexure-monoclinal formation. For this reason, well pair connection axes are in the NEN-SWS direction according to the plan which considers the low dipping zones (<15°).

- Production unit length: Layer morphology allows the horizontal cavern length up to 300-350 m. Technical efficiency of the contractor, CMEC-YIKE, limited the cavern length to 250 m. Curved radius of wells drilled with directional drilling technique is around 200 m. This part is not included in cavern length. According to the direction change capacity of horizontal drilling technique, maximum interval between horizontal and vertical well was designated as 450 m (CMEC-YIKE, 2004) (Figure 4.3).

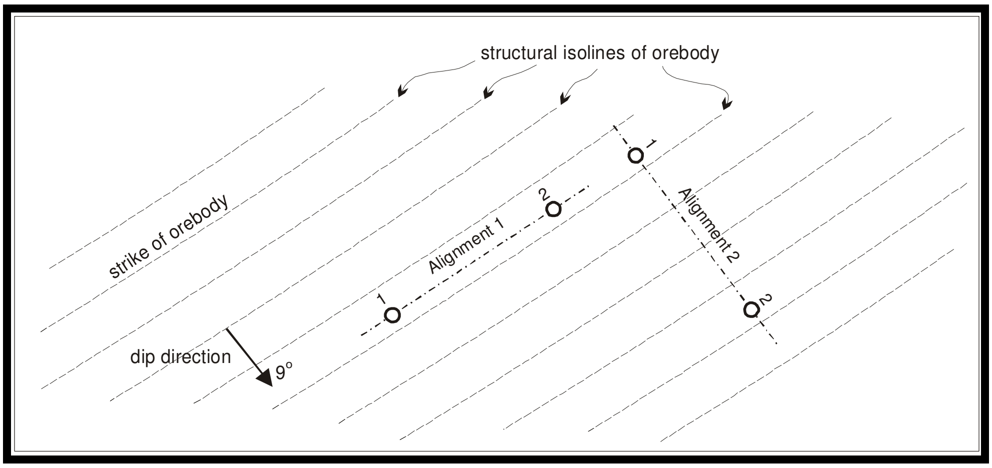


Figure 4.2 Alignment of well pair

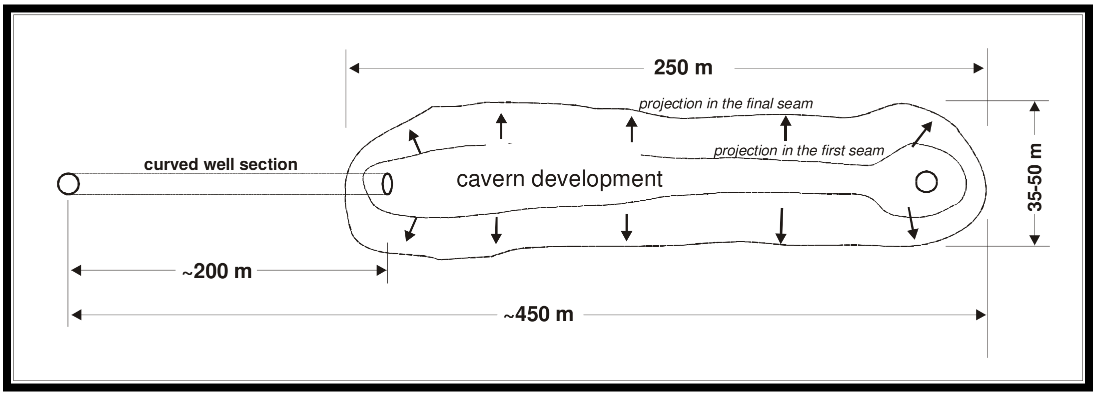


Figure 4.3 Well pair plan view – in the lower (starting) layer and in the uppermost layer

- Initial vertical cavern: For initial cavern development, called as undercutting, lower most trona layer should have a minimum thickness of 1.2 m and maximum amount of insolubles 20%. When upper and lower trona layers were investigated, L6, L5, L3 and U6 layers were found as suitable for undercutting.
- Pillars: For each well pair, group spacing and row spacing was determined as 90 m. If the initial cavern development layer is chosen in U series, this spacing will be 70 m (Figure 4.4). Maximum cavern width at the uppermost trona layer should not exceed 35-50 m to remain 35-40 m pillar in between connection axis of the wells. Cavern width can be controlled as mentioned in the next item. Remained pillars are in trapezoidal shape. Insolubles in the

trona and associated rocks are falling down during the leaching and are accumulated at the bottom of the cavern forming sump. It was calculated that, when cavern fulfilled its service time, almost 90% of cavern height will be full of sump (Çakmakçı et al., 2005). This creates an advantage for cavern stability as well as clear product recovery providing significant decrease in amount of insoluble wastes.

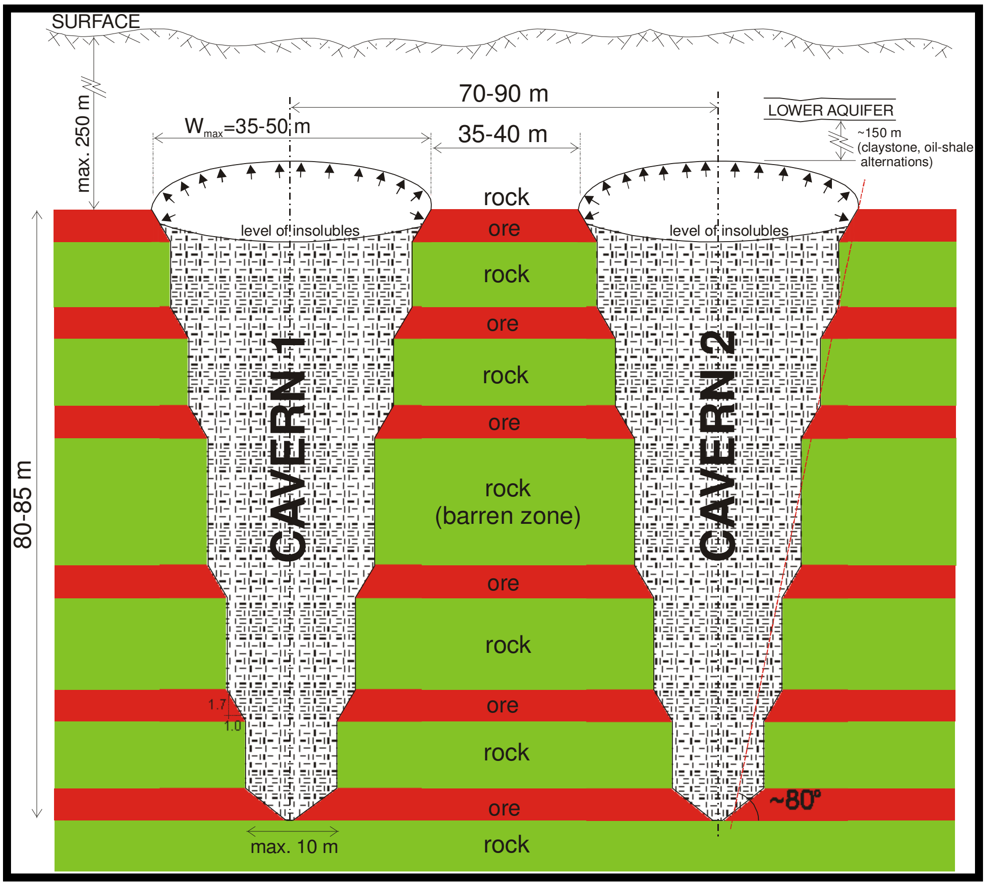


Figure 4.4 Cross-section across two neighbouring pairs of wells (Çakmakçı et al., 2005)

Design of the well pair layout was done according to these parameters mentioned above and site properties. Figure 4.5 shows well pair layout for Beypazarı Trona Deposit. In the figure colour indicates the starting trona layer. Bars show the horizontal cavern to be developed and lines show the curved section of horizontal well.

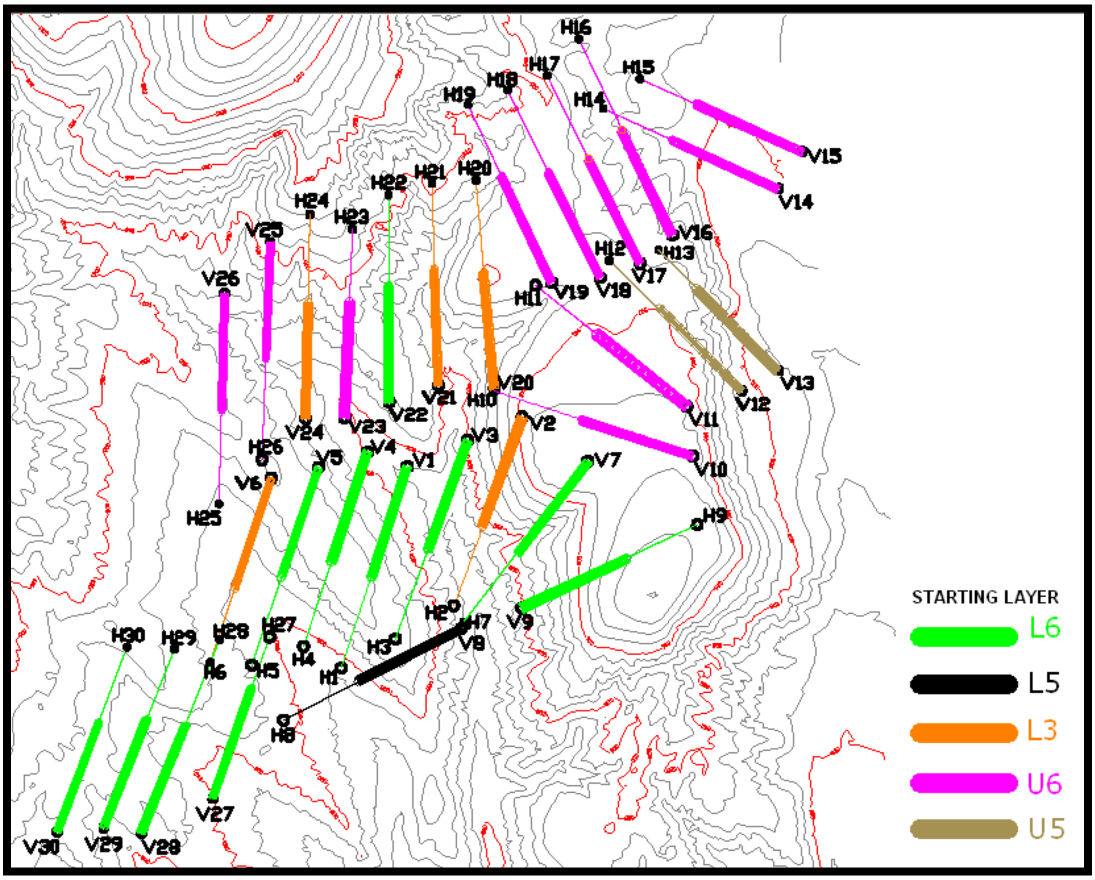


Figure 4.5 Well pair layout for Beypazarı Trona Deposit

- Leaching control: Leaching rate of trona layers is higher in the vertical direction of deposit (vertical leaching rate) than in horizontal direction of deposition (horizontal reaching rate). The reason of that is mainly influence of gravity, but also a macro scale surface roughness and leaching surface differences formed during crystal growth. For this reason, if the leaching in vertical direction will not be controlled, the cavern will grow in upward direction very quickly and interlayers will fall down and leaching surface will be blocked with sump. Consequently, service life of production cavern and leaching efficiency will decrease. To overcome this problematic issue, roof isolation operation has been adopted to this system by injecting oil blanket. The oil blanket should be a fluid having lower density than brine, not mixing with brine and also not polluting. For this purpose, diesel oil is preferred as an isolating medium.

- Passing to upper layer: Main method for passing to the upper trona layers is recovering the injected isolation medium and waiting for the interlayer falling down to expose the floor of overlying trona layer. If the interlayer is tight and thick, hydraulic fracturing from the interlayer or directional drilling through the upper trona layer can be applicable.

- Solvent and brine characteristic: Trona is not a simple (single) salt as halite. Carbonate and bicarbonate salts in trona show different dissolution characteristic. Both carbonate and bicarbonate can be dissolved into a water-based solvent. However, as dissolution proceeds, more and more carbonate ions tend to dissolve as the dissolved bicarbonates tend to precipitate. Achieving maximum dissolution yield is possible by providing a well-balanced dissolution of both carbonate and bicarbonate. For this purpose, carbonate dissolution rate is partly hindered by adding some amount of carbonate to the solvent. In this project, recovered brine from the well pairs should have minimum 15% equivalent carbonate content (12% sodium carbonate, 6% sodium bicarbonate). In this case, as it is seen in Figure 4.6, solvent having 3-5% carbonate content is suitable for recovering brine having 15% equivalent carbonate content. As such a solvent, in the exploitation process, waste soda brine from the soda process plant can be used. This brine will have not only enough amounts of carbonates, but also a high temperature.

- Starting leaching and obtaining mature cavern: Leaching and cavern development is started by injecting the solvent having proper temperature and chemical composition from interconnected well pair through trona layer. The cavern providing the necessary flowrate and having enough leaching surface and volume to recover desired brine quality (15% equivalent carbonate concentration) is called as “mature cavern”. Considering the geological conditions (i.e. thickness, quality of trona layer), a cavern should reach a volume of at least 400-600 m^3 to be called as a mature cavern.

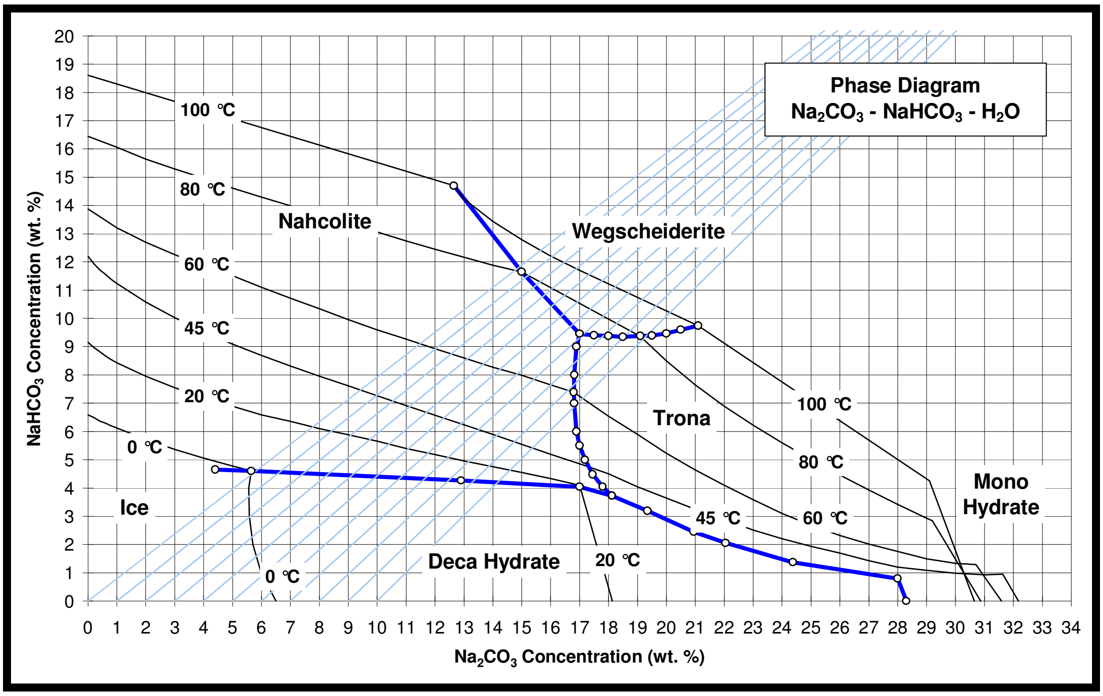


Figure 4.6 Phase diagram of trona solution (Garret, 1992)

4.1 Vertical Well

4.1.1 Drilling, construction, and completion

The depth of the trona deposit and presence of the two aquifer zones above the deposit requires special construction techniques for the wells. A typical cross-section of leaching well constructed for dissolving the trona is presented in Figure 4.7. Wells are constructed using multiple cemented casings through the aquifer zones to prevent any water leakage between the trona zones and the overlying aquifer zones.

Boreholes were drilled starting with 311.1 mm diameter and this diameter was utilized down to around 200-250 m depth (which is 10 m below the Karadoruk aquifer) and then 9⅝″ casing (API grade, J55-244.47×8.94mm) was inserted into the borehole, just before the first cementation was carried out. Cement injection parameters were: 8 MPa injection pressure and 1.85 g/cm^3 slurry density. The injection was continued till the cement slurry overflowed from the collar. The curing period allowed was 48 hours.

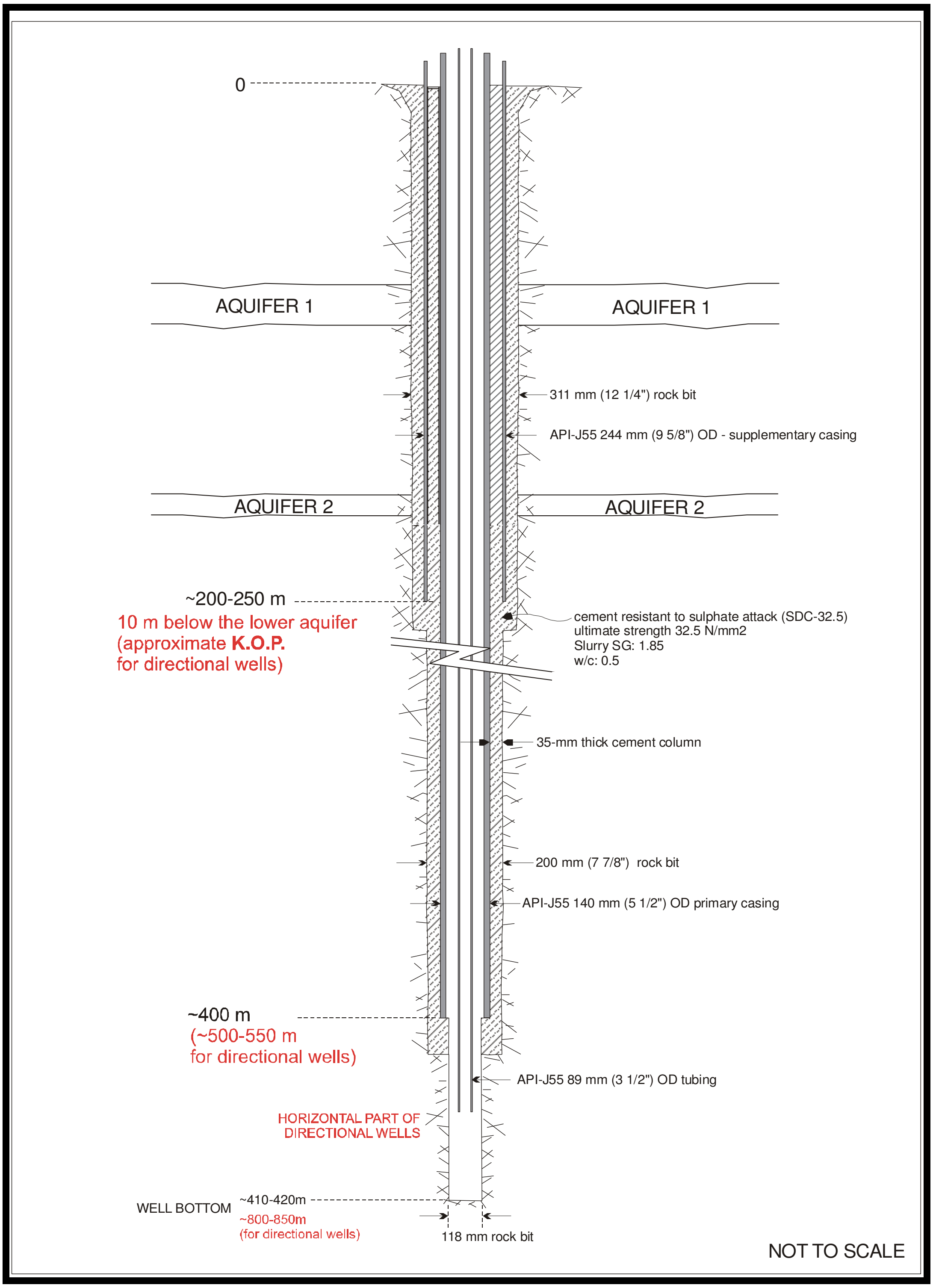


Figure 4.7 Columnar section of a typical in-situ leaching well.

The final application in this first stage was a hydro-pressure test at 5 MPa. Half an hour was allowed under the specified pressure and the pressure level was observed not to drop more than 0.5 MPa, which was satisfactory.

A rockbit of 200 mm diameter was utilized in the borehole after first cementation. It was used till 20 m above the roof of U1 layer, beyond which the coring was started. Coring bit had 110 mm in diameter and coring operation was continued down to 10 m below L6 layer. The borehole was redrilled with a 200-mm rockbit after the coring.

The well reached its bottom at the depth around 400-450 m (in the case if L6 layer was chosen for the initial cavern development). Afterwards electrical and in-hole surveys were carried out in order to figure out the exact position of each trona layer and well deviations. After finishing the in-hole surveys, lower most trona layer in which the initial cavern will be formed was selected.

Selecting the initial cavern development trona layer, 5½″ production casing (API J55-139.7×7.72mm) was suspended in the borehole at about 20 cm below the roof of the selected trona layer and consequently cementation was made again. The injection lasted till the slurry was overflowed from the collar and then 72-hours of curing period was allowed. Another pressure test in the well followed the curing time to check the cementation tightness. The cement plug set at the well bottom was drilled out and cleaned with a 118-mm rockbit.

The production tubing 3½″ (API J55-88.9×6.45mm) was then suspended into the well, reaching 10-20 cm below the last casing and injection tubing 1¾″ was suspended inside the production tubing, reaching the bottom of trona layer. Thus, the vertical well was completed in this way. The completion works was finished by installing the well head and make the necessary transfer pipe connections. Figure 4.8 and 4.9 show the drilling works and constructed wellhead and pipeline after completion of drilling respectively.

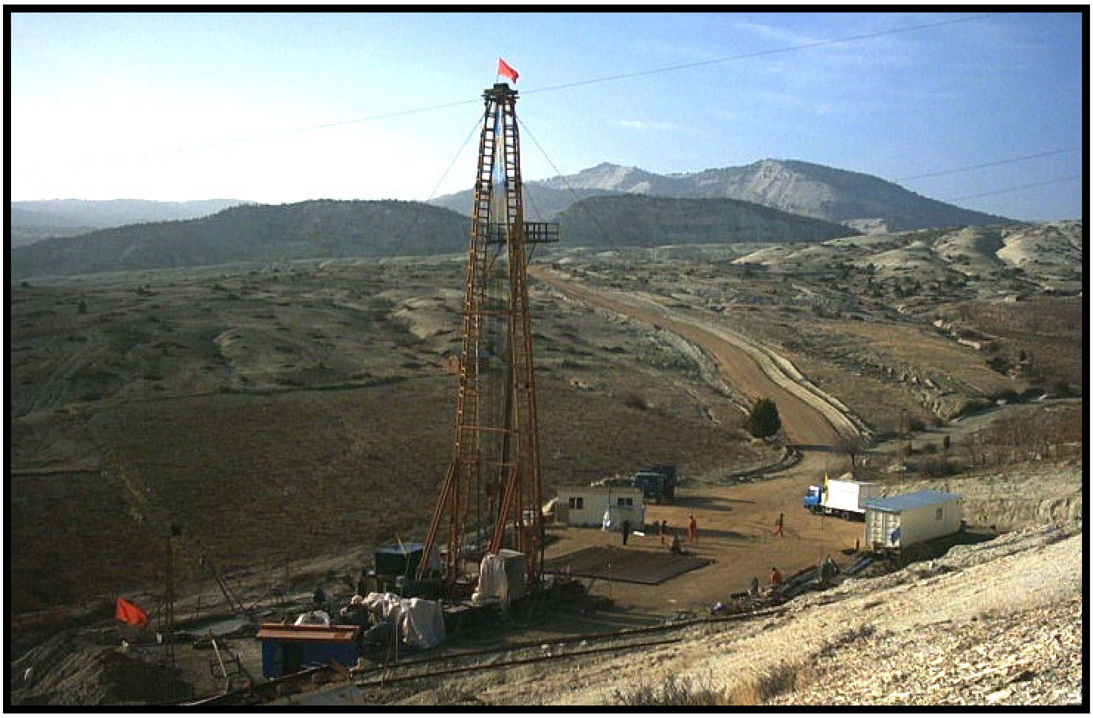


Figure 4.8 Drilling works

Figure 4.9 Constructed well head and pipeline

4.1.2 Leaching of initial cavern and its significance for further leaching

Drilling and completion of vertical well take nearly one month. After finishing the drilling and construction of vertical wells, solvent circulation is started immediately to develop the initial cavern. During the cavity development, roof control is carried out by oil isolation. Initial cavern development takes nearly one month. At the end of one month, nominal diameter of the cavity reaches 5-6 m. In this period, cavern development is measured by ultrasonic in-hole survey (trademark: ECHOSONDA /Poland). For this purpose, leaching is stopped, the cavern decompressed, inner tubing usually removed and the sonar tool lowered on the cable to the cavern, through the outer tubing. The measurement of the cavern shape is made by registration of the delay time of the ultrasonic signal, sent by the tool emitter and reflected from the cavern wall. In Figure 4.10, cavern profile of V009 drawn through by ultrasonic surveys is given.

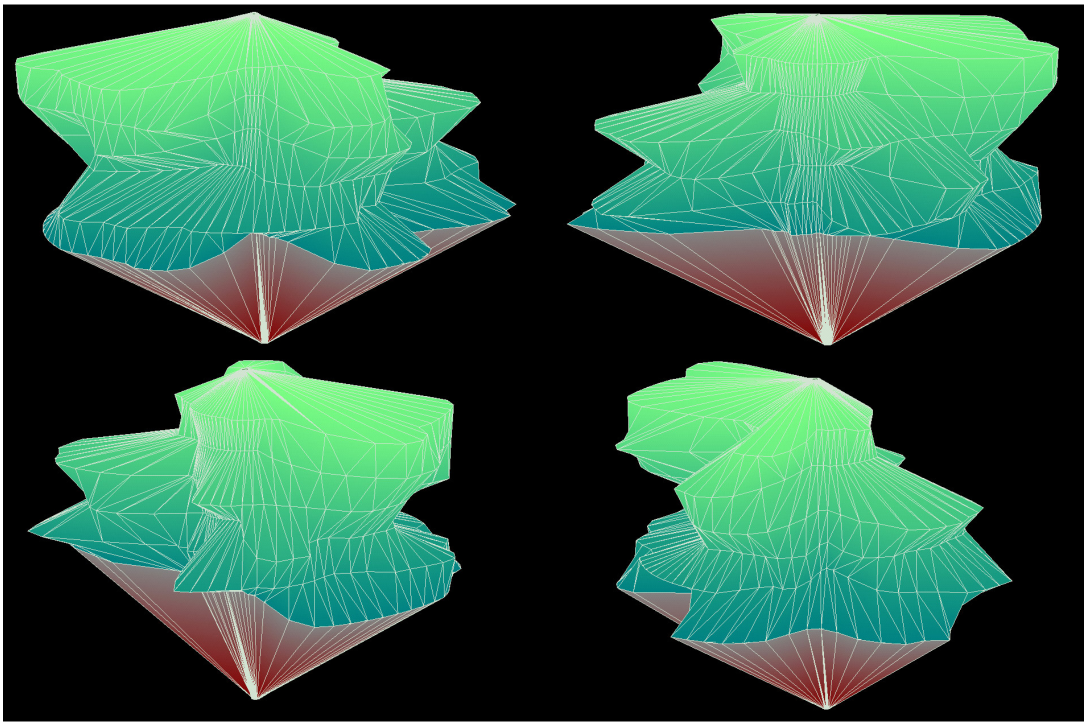


Figure 4.10 Cavern 3-D view of V009 from different angles

Developing the initial cavern is very important for the following reasons given below:

- This cavity provides a target for the horizontal well. For achieving successful connection of horizontal and vertical well pairs, initial vertical cavity should reach minimum 6 m of nominal diameter.
- Developing the initial cavern in good shape and having adequate volume is important, because this volume will serve as empty space for insolubles accumulation during the horizontal cavern development as well as during the production stage.

4.2 Directed Horizontal Well

During the initial vertical cavern development, drilling and completion of horizontal well is carried out. When the initial cavern would reach nominal diameter, drilling of the horizontal well should be completed and it should be ready for pair connection.

4.2.1 Drilling, construction, and connection with the initial cavern

Drilling of the horizontal wells was done in the following manner. Horizontal drilling started as vertical well and first cementation was held at the same depth (10 m below the lower aquifer). After that, the borehole started to deviate at 0.5°/m by using special drilling string equipped with mud turbo motor and a 200 mm rockbit. The depth in which the borehole was started to deviate is called the “Kick Off Point” (KOP). Determination of KOP is done according to the formation and expected depth of trona layer in which connection will be achieved. Curve radius of wells drilled with directional drilling technique is around 200 m.

When the curved part of the borehole reached the total length of 500-550 m and the bit was inserted about 1.0 m into lowermost trona layer, the well logging is completed in the horizontal well. Afterwards the 5½″ (API J55-139.77×7.72mm) casing is fixed by cementing procedure.

Then drilling is continued up to the floor of trona layer. After this point the borehole became completely horizontal and the vertical well bottom was targeted. Measuring While Drilling system (MWD) was utilized for surveying the horizontal borehole direction.

This horizontal drilling was continued following the floor of trona layer up to 40-50 m remaining for connection. Connection of the well pairs requires the precise survey. For this purpose Rotating Magnet Ranging Service (RMRS) system was utilized.

The Rotating Magnet Ranging Service is designed for directional drilling companies as a complement to their MWD instruments because; MWD is unable to provide the accuracy necessary to maintain this precise connection. The kit consists of a Rotating-magnet sub, approximately 18.5˝ in length, which is located between the bit and the motor. This sub contains stacks of powerful rare earth magnets that create an A/C magnetic field when rotating with the bit. This magnetic field is monitored by the RMRS probe located on wireline in the target cavern, with a usable distance of up to 50 m and provides a distance and direction from the probe to the drill bit (Figure 4.11). In the target vertical well, ready for connection, the inner 1¾˝ tubing is removed, and from this moment it is not used in the pair leaching anymore.

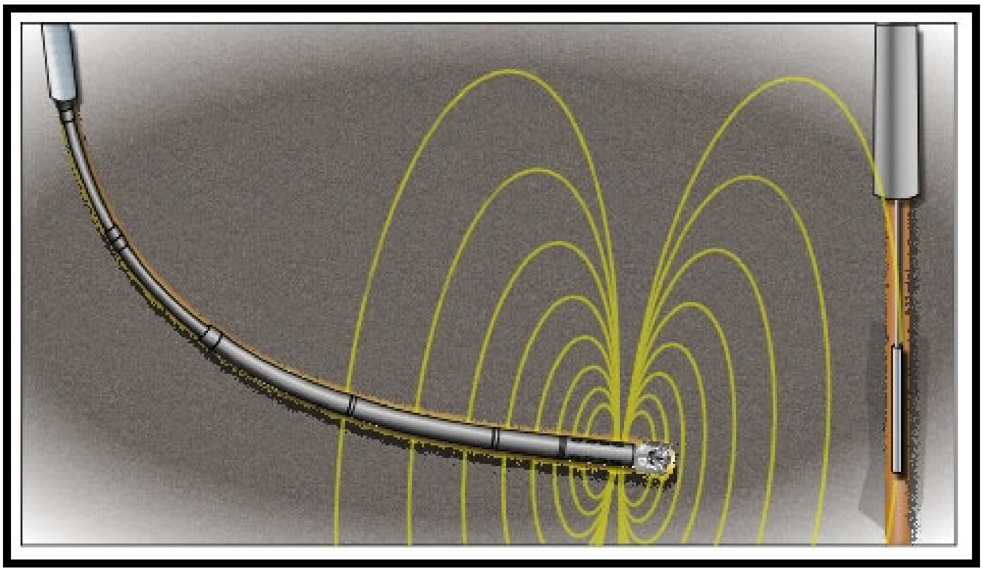


Figure 4.11 Intersecting a vertical well with a horizontal well using RMRS (www.vectormagnetics.com/intersections_hdd.htm)

Once the connection was managed, the central tubing 3½″ (API J55-88.9×6.45mm) was suspended down the horizontal well to the bottom of connection layer. Afterwards the well tree was installed and pipeline connection was finished with necessary valve and/or elbows.

4.2.2 Leaching in the connected pair of wells

After the connection of horizontal well with vertical one, production unit become completed and solvent-brine circulation is carried out within this well pair (Figure 4.12). The solvent having 3-5% sodium carbonate content is sent through one of the wells (injection well) to the underground cavern, thus dissolving the ore through the connection corridor. The dissolved ore is taken from the other well (production well), as trona brine.

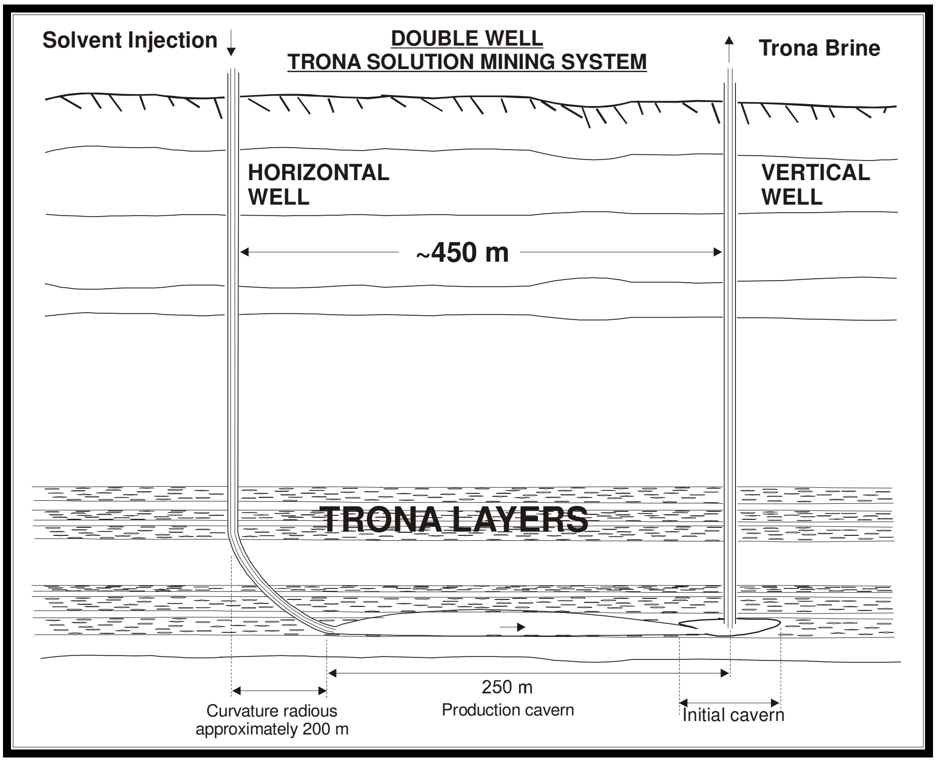


Figure 4.12 Double well trona solution mining system

At the beginning, brine with minimum 15% equivalent carbonate content is not achievable because; the leaching surface is not enough to yield desired brine content. Horizontal cavern became mature approximately after one month leaching operation and then well pair has become ready for production stage.

Whichever vertical well for initial cavern development purposes or horizontal and vertical well pair for production purposes taken into the leaching operation, some operational data are recorded in 2-4 hour interval including flowrate, temperature, density, pressure for both solvent and brine. On the other hand chemical composition and carbonate content of solvent and brine is determined from the taken sample while operational data recorded. In this time interval, dissolved trona amount can be calculated from the carbonate content difference between solvent and brine depending on the flowrate. This approach is useful just for determination of cavern volume developed in underground but it is incapable for determination of developed cavern geometry.

Ultrasonic in-hole survey held in vertical well gives the initial cavern shape exactly. But it is impossible to say anything about the geometry of horizontal cavern called as production cavern by using today’s technology.

CHAPTER 5

DESCRIPTION OF LEACHING PROCESS

Leaching process consists in dissolving the surface of a heterogeneous solid body - rock salt, containing solubles and insolubles. Soluble parts pass into the solution, insoluble ones are washed out from the rock. Some of them partially fall down producing the sump in the bottom part of the cavern; the remaining creates a suspension inside the solution.

The leaching process of the salt caverns includes the following physical phenomena:

- **Passing of salt** from rock salt to the solution (dissolving). During dissolving, the cavern wall moves, depending on its inclination and on the dissolving brine concentration,
- **Transport of salt** from the cavern wall to the brine deeper inside the cavern. This is caused by the molecular and turbulent diffusion overlapping the average flow through the cavern.
- **Flow through the cavern** resulting from water injection and brine production overlapped by the flow caused by the phenomena of convection and turbulence connected with a diversified distribution of the concentration.
- **Washing out**, crushing up and peeling off **insoluble** additions to rock salt and filling the lower part of the cavern (sump) with them.

A full description of the leaching process consists of a dozen or so partial, highly nonlinear, differential equations with boundary conditions on the moving surface of a cavern wall. It looks perhaps paradoxical that such a common phenomenon as salt dissolving in water is so complicated from mathematical - physical point of view and so difficult for quantitative approach (Kunstman et al, 2007).

5.1 Thermal Effects

The original temperature of a salt body, existing in the region of the cavern leached in the salt deposit, can be quite substantial, from about 30°C for shallow caverns, to about 70°C for deeper ones.

In Beypazarı Trona Deposit, caverns are developed 400-450 m deep. The original temperature of trona body at that depth is about 33-35°C. During the cavern leaching, the temperature of injected brine is 40-60°C for initial cavern development and 70-75°C for production purpose. Produced brine temperature changes from 35 to 50°C respectively for both cases. In both cases heat transfer occurs in the cavern between solvent and surrounding trona body and in the well between injected solvent and produced brine. Because of this heat transfer and solvent flow in the cavern, the zones of various brine temperature are created inside the cavern.

At present no model can take the above effects into account. Nevertheless, temperature of the leaching medium influences leaching rate, and this can be included into a model.

5.2 Insoluble Content

The rock salt contains some quantity of insoluble particles. It is most often anhydrite sand or anhydrite layers of various thickness, clay, gypsum etc. The purest rock salts contain these additions in limits of 1% - 3%, but it happens that caverns are leached in the salt containing 30% of the insolubles parts, and sometimes even more.

During leaching, the insolubles are released and fall down onto the cavern bottom. The smallest particles remain suspended in the brine and are taken away to the surface with it. Coarser particles settle at the bottom with some loosening, occupying a larger volume than the volume which they occupied before in the rock salt. Depending on their sizes and shapes, they are able to occupy about 50% of volume more than originally. It corresponds to the **loosening factor of 1.5** (Kunstman et al, 2007).

Insolubles fall onto all cavern walls, where inclination is less than 90° (vertical). If the wall inclination is steep enough, they slide down the wall, falling lower. If, however, the inclination is low, there is no sliding, and insolubles cover the wall, and in result – stop leaching. Because of that, there are no flat horizontal surfaces on the caverns walls.

The inclination angle of the salt wall, for which the sliding of insoluble parts ceases, is called a **limiting dissolution angle**. For the majority of salt deposits it is around 15° (Kunstman et al, 2007).

Insolubles in Beypazarı trona deposit is mostly tuffite, claystone, oil shale, sandstone and the amount of insoluble content varies from 0% to 23%.

5.3 Relation between Salt Production and Cavern Net Volume

The quantity of the produced salt (production) is the basic and most exact method of determining the cavern volume. However, the relation between the salt production and the cavern volume is not as simple as it looks at the first sight, because it is necessary to take into account the salt included in the brine filling the cavern and the insoluble content. All these lead to the formula given in Equation-1 (Urbanczyk and Kunstman, 1997):

$$\frac{M}{V_e} = \frac{(\rho - C)(100 - P_{ins})}{1000\,(100 - \alpha\, P_{ins})} \qquad [1]$$

where:

M - total salt production from the cavern [ton]

V_e - net volume of the cavern (without sump) [m^3]

P_{ins} - per cent of insoluble parts in the rock salt

C - mean concentration of the brine remaining in the cavern [kg/m^3]

ρ - density of rock salt [kg/m^3]

α - loosening factor for insolubles in the sump.

For trona leaching, taking 2140 kg/m^3 as trona density and 1.5 as the loosening factor for insolubles in the cavern, the following table of quotients M/V_e was obtained:

Table 5.1 Quotients of trona production to the net cavern volume depending on concentration of brine in the cavern and amount of insolubles

P_{ins}, % C, kg/m^3	0	1	5	10	15	20	30
150	1.990	2.000	2.044	2.107	2.183	2.274	2.533
155	1.985	1.995	2.039	2.102	2.177	2.269	2.526
160	1.980	1.990	2.034	2.096	2.172	2.263	2.520
165	1.975	1.985	2.028	2.091	2.166	2.257	2.514
170	1.970	1.980	2.023	2.086	2.161	2.251	2.507
175	1.965	1.975	2.018	2.081	2.155	2.246	2.501
180	1.960	1.970	2.013	2.075	2.150	2.240	2.495
185	1.955	1.965	2.008	2.070	2.144	2.234	2.488
190	1.950	1.960	2.003	2.065	2.139	2.229	2.482
195	1.945	1.955	1.998	2.059	2.133	2.223	2.475
200	1.940	1.950	1.992	2.054	2.128	2.217	2.469

Example: if the trona rock contains 10% of insolubles, and mean concentration of brine remaining in the cavern is estimated as 175 kg/m^3, the quotient M/V_e for such conditions is 2.081. So, if the production from the cavern is 250 tons of trona, the net volume (without sump) of this cavern will be 120 m^3.

5.4 Leaching Rate

Leaching rate, i.e. the rate of leaching front displacement deeper into the salt wall, depends on:

- brine concentration,
- petrography of the rock salt,
- inclination angle of the salt wall,
- temperature.

The dependence of the leaching rate on the type of rock salt has to be determined empirically, by laboratory tests on the rock salt samples taken from the deposit. But the dependence on concentration, the inclination angle and temperature is of a general character and can be described by suitable mathematical formulae (Urbanczyk and Kunstman, 1997).

In Poland, systematic theoretical and laboratory research on the leaching process for computer modeling has been led since 1978 in CHEMKOP Krakow by Kunstman and Urbanczyk. This research together with laboratory tests (laboratory leaching of minicaverns in big blocks of rock salt), led in the eighties to the original UBRO model. This model, extended in the nineties and known as **WinUbro** has currently become the basic commercial leaching model, sold to various companies and applied in various countries (among others Germany, USA, France, Great Britain, the Netherlands, Belgium, China) (Kunstman et al, 2007).

An original, well documented formula given in Equation-2 was applied to the WinUbro model for the leaching rate (Kunstman, A., et al, 2007):

$$\omega(C,T,\psi,h) = k(\psi,h)\ (1+\beta(T-T_0))\left(\frac{C_S(T)-C}{C_S(T_0)}\right)^{3/2}\left(\frac{C_S(T)}{C_S(T_0)}\right)^{1/2} \quad [2]$$

where:

$\omega(C, T, \psi, h)$ - leaching rate with brine at concentration C and temperature T of leached wall with inclination ψ having the leaching parameters detected on the depth h, [mm/h],

$k(\psi, h)$ - leaching rate with fresh water at temperature T_0 for cavern wall with inclination ψ having the leaching parameters detected on the depth h, [mm/h],

β - temperature coefficient, determined experimentally

$\beta = 0.0262$ [°C^{-1}] (for $T_0 = 20$°C, determined for domal rock salt),

T - brine temperature in the cavern [°C],

T_0 - temperature, for which β was determined ($T_0 = 20$°C),

C_S (T) - concentration of saturation, dependent on temperature; the form of this dependency is connected with the chemical compound of soluble rock and brine,

C - brine concentration in the cavern (mass - volume) on the depth h

Leaching rate, as the function of the wall inclination angle, has to be calculated in laboratory. In the practice, it can be limited to the leaching rate measurements for: vertical wall (horizontal leaching) and horizontal roof (vertical leaching). It can be assumed, that a different mechanism is for roof leaching, and another for side leaching, and both mechanisms have their participation for intermediate angles. A limiting dissolution angle is also being calculated, indicating the limit, below which the insoluble parts are covering the cavern wall, making impossible the further leaching.

For any angle between 0 and π, the leaching rate will be determined according to the interpolation formula given in Equation-3(Kunstman et al, 2007):

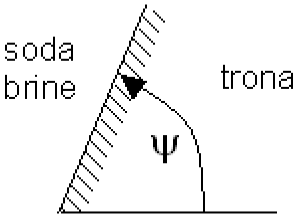
$$k(\psi) = \begin{cases} 0 & 0 \le \psi \le \psi_B \\ k_h \dfrac{\sin^2\psi - \sin^2\psi_B}{1-\sin^2\psi_B} & \psi_B \le \psi \le \dfrac{\pi}{2} \\ k_v \sin^2\psi + k_h \cos^2\psi & \dfrac{\pi}{2} \le \psi \le \pi \end{cases} \qquad [3]$$

where:

k_h - horizontal leaching rate [mm/h]

k_v - vertical leaching rate [mm/h]

ψ_B - limiting dissolution angle.



An angle ψ is measured from the flat level, so it equals:

for flat bottom	0
for vertical wall	π/2
for flat roof	π.

5.5 Alkalinity Definition of Soda Brine

To apply formula [2] for trona leaching process, it must be decided that, which physical quantity is to be used in place of concentration, as soda brine is a two component solution, containing sodium carbonate and sodium bicarbonate.

The best decision is to use total sodium carbonate equivalent alkalinity for the purpose. After here, instead of sodium carbonate equivalent alkalinity, just alkalinity term will be used.

Total alkalinity takes into account the reaction:

$$2\,NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2 \qquad [4]$$

where sodium bicarbonate converts into sodium carbonate. Two molecular masses of sodium bicarbonate give one molecule of sodium carbonate; in moles:

$$2*84 \rightarrow 106 + ...$$

$$106 / 168 = 0.631$$

This coefficient of 0.631 can be used in recalculations from concentrations of both components into alkalinity. For example; the brine containing 132.5 kg/m^3 Na_2CO_3 and 71.0 kg/m^3 $NaHCO_3$ has the total alkalinity of:

$$132.5 + (71.0 * 0.631) = 177.3 \text{ kg/m}^3.$$

Alkalinity can be in mass percentage or in kilograms per cubic meter. They are connected by the relation given in Equation-5:

$$A = 0.01\,\rho\,A_p \qquad [5]$$

where:

ρ – density

A – alkalinity in kilograms per cubic meter

A_p – alkalinity in mass percentage

5.6 Temperature and Alkalinity Relation

The most important quantity in formula [2] when applied to soda solutions is total alkalinity of saturated solutions in different temperatures.

Phase diagram given in Figure 5.1 shows the obtained brine concentration according to the temperature through the W-line and B-line. W-line is in the case of water injected as solvent and B-line is in the case of the solvent having 2.5 % sodium carbonate injected

Using values read from phase diagram (for the *W-line* and *B-line,* Figure 5.1)

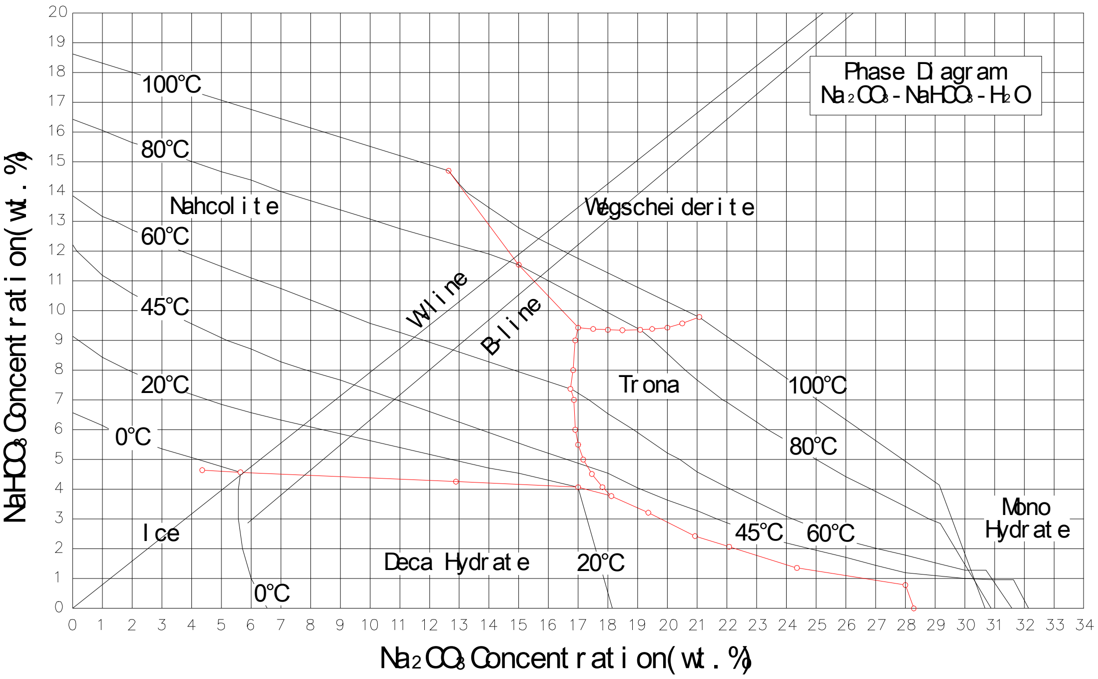


Figure 5.1 Phase diagram (Garret, 1992)

the relationgiven in Equation-6 was fitted for the temperature range 10-80°C (Urbanczyk et al, 2005).

$$A_S(T) = 106.4747421 + 1.031197019 * T + 0.012608736 * T^2 \qquad [6]$$

where:

$A_S(T)$ – alkalinity of saturation, dependent on temperature [kg/m^3]

T – brine temperature [°C],

The above formula was derived using least square method.

The relation in graphical form has the following shape:

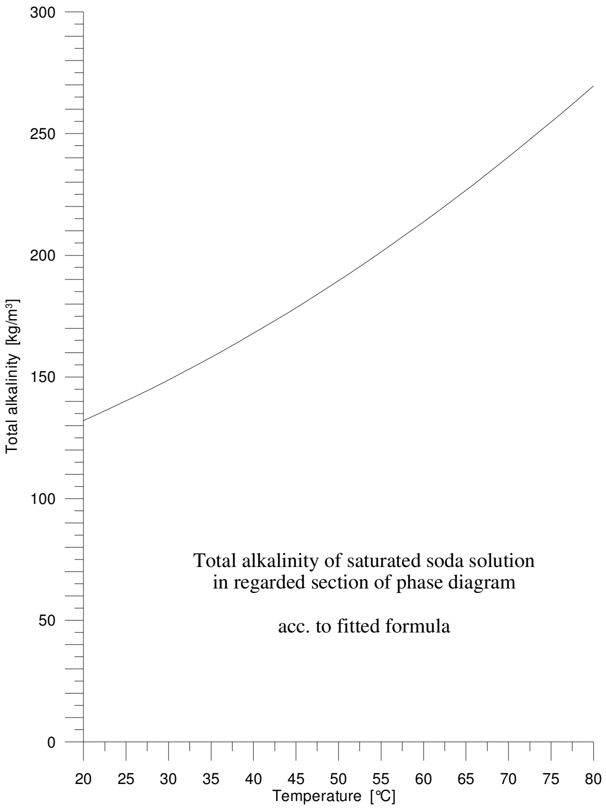


Figure 5.2 Graph of alkalinity vs. temperature relation

CHAPTER 6

LABORATORY TESTS OF CORE SAMPLES FOR MODELING PURPOSE

Determination of leaching properties of trona rocks, in which the leaching of the initial vertical cavern is foreseen, is necessary to design the leaching technology, i.e. to determine the leaching time, the cavern shape and the amount and the location of the isolating medium. Determination of trona leaching parameters is performed in laboratory, using core samples obtained during drilling the vertical borehole.

Usually, a complete set of laboratory leaching tests include:

- determination of the leaching rate in the horizontal and vertical directions,
- determination of the insoluble content,
- determination of density,
- and determination of the chemical composition of trona rock.

This study is aimed at leaching rates and insoluble content determination of trona samples.

6.1 Description of Trona Leaching Tests Methodology

Methods of performing the leaching tests for salt rock samples were developed in Chemkop especially for the needs of designing the leaching technology using computer simulation software. The method developed for trona and described below is based on the stationary dissolution of trona samples in fresh water. Determination of the leaching rate for pure trona rock, as well as for trona with addition of some impurities of different kind (i.e. clay or shale) is possible by this method (Kasprzyk and Branka, 2005).

6.1.1 Choice of the core samples

For the leaching tests, the samples should be taken from these parts of the core, which are within the depth interval of the initial leaching cavern. The parts of the core with traces of mechanical damage during drilling, with loose crystal grains, with fractures or with uneven side walls, should be omitted. The amount of the core taken as the leaching test samples should correspond to the foreseen number of tests.

Usually, the vertical leaching rate is determined on the separate sample with the leaching surface perpendicular to borehole axis. The horizontal rate is determined on the separate sample with the leaching surface parallel to the borehole axis. In both cases, the natural orientation of the sample in the trona deposit should be maintained, so during sample selection, their origin location and their natural orientation should be visibly and persistently marked on the samples.

To make one complete set of leaching tests for trona rock it is necessary to have trona core with minimum 20 cm of length with even walls. For determining the amount of insolubles, trona rock pieces obtained during cutting off the ends of the core in preparation of the samples for leaching tests can be used. These pieces can be used also for determining the density and chemical composition. This determination can be done using one of the classical methods.

6.1.2 Preparation of the samples

For the leaching tests, the core samples should be prepared, obtaining the necessary shapes. During this shaping, the cutting procedure should be made slowly and carefully by mechanical dry (waterless) cutting using saw-blade disk. Rotary disks should have slow rotation (100-200 r.p.m.) and medium grain –diamond disk can be used also. Some part of the cutting can be also made manually by hand saw used together with bench vice.

During procedure of cutting vertically to the core axis, the core should be placed inside a piece of tight PVC tube to avoid the destruction of the cutting's edges. PVC tube should have the internal diameter corresponding to core diameter and have the 8mm wide cut along all its length to make easier the location of the core inside the tube, and the proper fixing of both before cutting. On "to be cut off" part of the core, protruding from the tube, the 80mm long ring of PVC tube is located and also fixed on the same level as the whole core. Figure 6.1 shows the outline of sample for vertical leaching test.

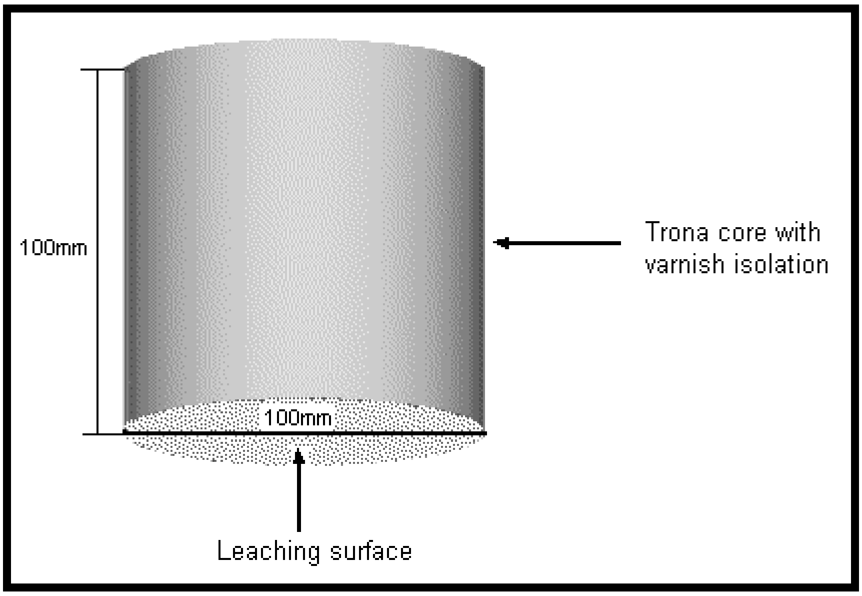


Figure 6.1 Outline of sample for vertical leaching test

For the horizontal tests, the samples should be prepared first by cutting off ca. 100mm of the core vertically to its axis, and afterwards by cutting once more this 100mm cylinder parallel to its axis. The cutting plane should go then about 3-5mm away from the core axis and the bigger part is taken as a sample. Figure 6.2 shows the outline of sample for horizontal leaching test.

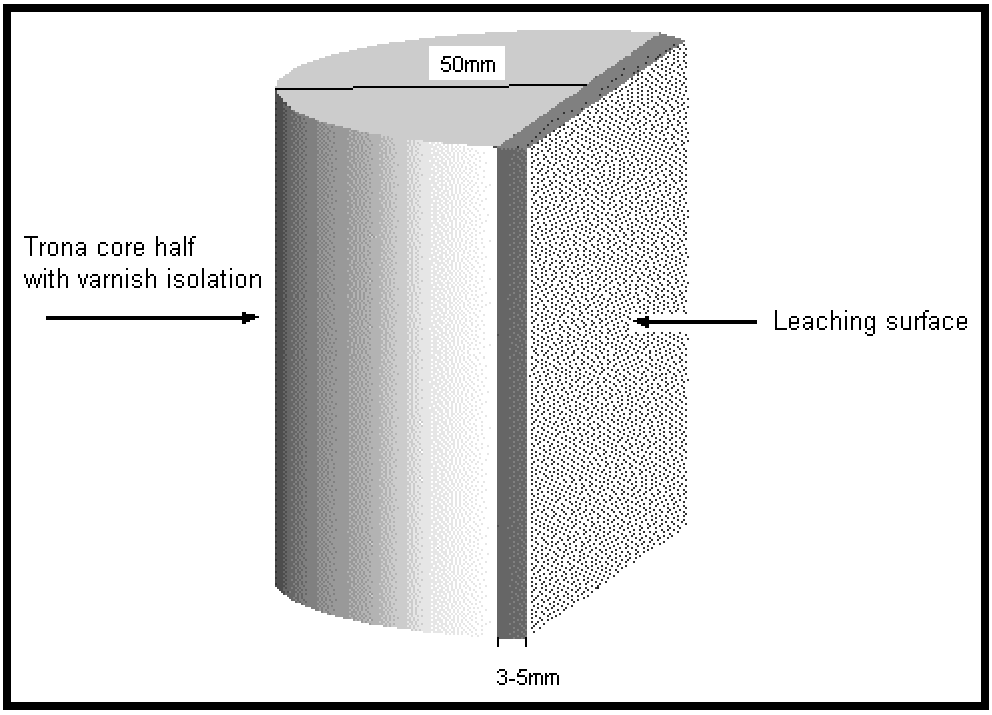


Figure 6.2 Outline of sample for horizontal leaching test

The second part of the core, cut parallel to its axis, should be kept as an archive material needed in some cases to verify the results.

The sample surfaces foreseen to be leached should be ground using abrasive paper (or abrasive cloth). First grinding to remove roughness and dirt is made using 350 – 400 grain, and the final smoothing is made using 500 – 600 grain. After grinding, the samples should be carefully dry-cleaned from the dust. If a sample has visible cracks or dents, should be removed from the testing.

All cutting and grinding procedures should not last too long to maintain the natural humidity of trona samples.

The surface foreseen to be leached should be carefully measured using Venier caliper for calculating their exact surface dimension. If the surface is irregular, its photo-scan on the computer scanner should be taken.

Afterwards, the samples are isolated from all sides, leaving clean only the surface foreseen to be leached. The isolation can be made using acrylic lacquer resistant in the water until 80ºC. Another water resistant lacquer can also be used. The isolation can be made using brush or by immersion.

The samples should be carefully cleaned before the isolation, as the lacquering on the dusty or wet samples can make the isolation untight and falling-out.

When the isolation is dry, the surface foreseen to be leached is cleaned and lightly ground once more to remove dirt and possible remains of lacquer.

During all preparation works with the samples, it is very important to keep visible the labeling of their origin location and their natural orientation marked on the samples.

Then, the samples are dried in 30ºC drier, and all are separately and precisely weighed.

6.1.3 Main equipment for trona leaching test

1. Thermostat box: capacity ~80 liter, operating temperature range 15-90ºC. Inside box dimensions: width and depth bigger than width and length of the leaching tank. Minimum height: 25 cm higher than leaching tank height Good thermo-isolation of the walls (Figure 6.3 and 6.4).
2. Leaching tank: capacity ~40 liter, operating temperature range 15-90ºC. Leaching tank will be nested in the thermostat box during test (Figure 6.3 and 6.4).
3. Sample holder (Figure 6.3 and 6.4)
4. Laboratory balance: capacity 2000 g, readability 0.1g, pan minimum 12cm
5. Electrical water boiler: temperature control to 90ºC, capacity: 80 liter or bigger
6. Laboratory oven: range to 150°C
7. Thermometer: 0 - 100°C, readability 1°C
8. Stop-watch

Figure 6.3 (a) thermostat box, (b) leaching tank, (c) sample holder

Figure 6.4 Leaching test equipment set up

6.1.4 Tests

Water:

Water used for testing can be the tap water and must have the required testing temperature. To provide constant testing temperature during the whole test, the thermostat box is necessary. The tank filled with water should be put into a thermostat box some time sooner to stabilize water temperature. Temperature must be measured inside the water. After finishing the leaching test, the water must be totally removed from the tank. A control sample of this water may be taken if necessary.

Performing the leaching:

A sample after precise measurement of its surface and weight is placed in the tank, in the water of testing temperature. Only one sample can be tested at the same time. Special holders are used to fasten the sample in horizontal (or vertical) position of the leached surface, below the water level. The water should have the testing temperature during all the testing time and no mixing is allowed.

During the leaching test, observations should be done to notice such phenomena as: falling down not dissolved trona crystals or insoluble particles, etc. Horizontal leaching progress can be observed directly; while vertically leached samples can be observed with the help of a mirror.

At the end of testing, the sample must be taken out of the water quickly and carefully and put aside for drying. The leached surface should be upright during drying.

Time of leaching:

Leaching time should be precisely measured using stop-watch from the moment of submersion of the sample in the water until taking it out. Duration of the test should be adapted to the leaching progress, and normally should be taken between 15-45 minutes. Resultant leaching rate is dependent on the leached surface, thus this surface should remain relatively flat and it is usually observed in the macro scale, if the sample is not internally damaged. For the samples taken from damaged core, the leaching can lead to development of deep holes, streaks, edges and protrusions which can significantly affect the actual mass loss used to calculate the leaching rate.

Measurements after leaching:

To determine the mass loss during the test, the samples must be dried at 30ºC. As preparation, the samples may be washed with alcohol of 96% before drying.

The samples must be treated very carefully to avoid crumbling away the isolation, insoluble parts, or sample edges.

The dried samples must be precisely weighted. After that the leached surface must be studied and its quality analyzed. Bad mark must be assigned to the samples where damage of its internal structure is suspected, i.e. with large deep holes, or with visibly loosen structure. Such samples should be eliminated from further interpretation.

Area of single pinholes and area of single islands of unsolved clays or shales must be measured for determining their contribution in the leached surface. The leached sample surface must be scanned once more using scanner of high depth of focus.

6.1.5 Calculation of the leaching rate

To calculate the leaching rates, besides the salt mass decrease, the leached surface and the density of salt are necessary.

Horizontal and vertical leaching rates are obtained for the tested samples with the use of the formula given in Equation-7 (Kasprzyk and Branka, 2005):

$$\mathrm{v} = \frac{10 \cdot (Q_1 - Q_2)}{\gamma_0 \cdot S \cdot t} \qquad [7]$$

where;

v - leaching rate [mm/h]

Q_1 - weight of the sample before the leaching [g]

Q_2 - weight of the sample after the leaching [g]

γ_0 - density of the sample [g/cm^3]

S - effective surface of leaching [cm^2]

t - leaching time [h]

If some pinholes or unsolved islands (protrusions) are observed, the area of leached surface should be modified to have a leaching rate adequate to the average trona composition.

Estimation of effective leaching area can be made by the way of photo-scanning the sample with attached millimeter scale. Obtained computer images can be rescaled using appropriate software tool and values of selected area can be calculated by computer.

6.1.6 Calculation of the insoluble contents

The amount of insolubles in the trona rock usually varies substantially and it can also differ from visual estimation of impurities in the trona rock. As the amount of insolubles influences the whole leaching process, especially the sump formation, leaching rate and the cavern shape, the amount of insolubles is to be specially determined in the laboratory on core samples using a “technological” method without crushing the sample before testing.

Routine chemical analysis cannot be applied here, as it is performed on totally pulverized samples and leads to taking only the amount of silicate as insoluble, because other chemical substances are to be dissolved during analysis, to make possible analytically evaluate the total amount of calcium, magnesium and sulphate. These substances will surely not dissolve during the real leaching in the cavern – they will fall down to the sump and there they will never dissolve, surrounded by the saturated lye.

The trona sample taken to the test is 200 – 400 g of the core fragments obtained during cutting off the ends of the core in preparation of samples for leaching tests. These fragments are dried at 30°C, weighed and placed on a net in the water where they were completely dissolved. That means, the dissolution time should be long enough (e.g. one day). All solution with suspended and settled particles is filtered by filter paper on filtering funnel. The gathered settlings are rinsed using distillated water to remove the carbonate ions and afterwards dried at 105°C, and finally the dry insoluble parts are precisely weighed.

Amount of insolubles (in percent) is calculated using formula given in Equation-8 (Kasprzyk and Branka, 2005):

$$I = \frac{G_n}{G_s} \cdot 100 \qquad [8]$$

where;

I – amount of insolubles	[%]
G_n – weight of insoluble remain	[g]
G_s – weight of trona sample before dissolution	[g]

6.2 Leaching Tests and Results

When required equipment was supplied and preparation work was finished, trona leaching test operation was started. Leaching operation was held in between 07/07/2005 and 16/07/2005 including sampling, preparation of samples, leaching test and evaluation.

For leaching test, the samples are taken mainly from the drilling core of two vertical wells named as V004 and V005. According to sampling places, samples are grouped as pairs. In each pair, one sample would be taken for horizontal leaching test, the other would be vertical. Table 6.1 given below shows the information about samples.

After the sampling and preparation of the samples were completed, dimensions of the samples and their weight were measured. Thus, their volumes and densities were calculated. By following the leaching tests methodology given in Chapter 6.1, leaching rates were determined. Table 6.2 given below shows the leaching rate results. In Appendix photos of samples taken after leaching were given.

Table 6.1 Samples used for leaching test

Sampling Date	Sample Name	Sampling Place	Leaching Axis
07.07.2005	TR-2	Taken from heap stored during decline driving	horizontal
07.07.2005	TR-1	Taken from heap stored during decline driving	vertical
11.07.2005	4/U-2/1	Taken from V004 vertical well U-2 seam core sample	horizontal
11.07.2005	4/U-2/3	Taken from V004 vertical well U-2 seam core sample	vertical
11.07.2005	4/U-2/4	Taken from V004 vertical well U-2 seam core sample	horizontal
11.07.2005	4/U-2/5	Taken from V004 vertical well U-2 seam core sample	vertical
11.07.2005	4/U-5/1	Taken from V004 vertical well U-5 seam core sample	horizontal
12.07.2005	4/U-5/2	Taken from V004 vertical well U-5 seam core sample	vertical
12.07.2005	4/U-6/1	Taken from V004 vertical well U-6 seam core sample	horizontal
12.07.2005	4/U-6/2	Taken from V004 vertical well U-6 seam core sample	vertical
12.07.2005	4/U-6/4	Taken from V004 vertical well U-6 seam core sample	horizontal
12.07.2005	4/U-6/3	Taken from V004 vertical well U-6 seam core sample	vertical
15.07.2005	4/L-6/2	Taken from V004 vertical well L-6 seam core sample	horizontal
15.07.2005	4/L-6/1	Taken from V004 vertical well L-6 seam core sample	vertical
15.07.2005	4/L-6/4	Taken from V004 vertical well L-6 seam core sample	horizontal
15.07.2005	4/L-6/3	Taken from V004 vertical well L-6 seam core sample	vertical
15.07.2005	5/L-6/1	Taken from V005 vertical well L-6 seam core sample	horizontal
15.07.2005	5/L-6/2	Taken from V005 vertical well L-6 seam core sample	vertical
15.07.2005	5/L-6/3	Taken from V005 vertical well L-6 seam core sample	horizontal
15.07.2005	5/L-6/4	Taken from V005 vertical well L-6 seam core sample	vertical

Table 6.2 Test of leaching rate results

Rock Samples

Sample Name	Leaching Axis	Rock Mass (g)	diameter (cm)	height (cm)	length a (cm)	length b (cm)	Volume (cm^3)	Density (g/cm^3)	Leaching Surface Area (cm^2)	Weight Before Leaching (g)	Weight After Leaching (g)	Weight Loss (g)	Leaching Temp. ºC	Leaching Duration (h)	Leaching Rate (mm/h)
TR-2	horizontal	910.70	irregular shape				446.42	2.040	62.40	885.60	869.40	16.15	20	0.50	2.54
TR-1	vertical	617.40	irregular shape				291.25	2.120	53.76	611.00	582.40	28.60	20	0.50	5.02

Core Samples

Sample Name	Leaching Axis	Rock Mass (g)	diameter (cm)	height (cm)	length a (cm)	length b (cm)	Volume (cm^3)	Density (g/cm^3)	Leaching Surface Area (cm^2)	Weight Before Leaching (g)	Weight After Leaching (g)	Weight Loss (g)	Leaching Temp. ºC	Leaching Duration (h)	Leaching Rate (mm/h)
4/U-2/1	horizontal	1009.68	7.48	10.12	7.48	10.12	444.71	2.270	75.33	571.10	523.80	47.30	40	0.50	5.53
4/U-2/3	vertical	981.20	7.75	9.84			464.18	2.114	47.05	984.70	938.70	46.00	40	0.50	9.25
4/U-2/4	horizontal	998.50	7.71	10.05	7.71	10.05	469.21	2.128	76.99	608.40	584.70	23.70	40	0.37	3.91
4/U-2/5	vertical	896.80	7.74	8.98			422.52	2.122	47.02	903.60	870.67	32.93	40	0.50	6,60
4/U-2/1	horizontal	1023.86	7.90	9.86	7.90	9.86	483.30	2.118	77.89	685.84	597.20	88.64	60	0.30	17.91
4/U-5/1'	horizontal	1023.86	7.72	9.88	7.72	9.88	483.40	2.118	76.80	568.60	523.26	45.34	60	0.25	11.15
4/U-5/2	vertical	953.30	7.88	9.28			452.57	2.106	47.78	952.80	910.33	42.47	60	0.30	14.07
4/U-6/1	horizontal	985.93	7.66	10.16	7.61	10.16	468.21	2.106	76.30	518.36	484.90	33.46	60	0.30	6.94
4/U-6/2	vertical	853.76	7.63	8.83			403.74	2.115	45.72	851.80	811.50	40.30	60	0.30	13.89
4/U-6/4	horizontal	968.70	7.65	9.95	7.58	9.95	457.34	2.118	75.40	533.80	506.10	27.70	60	0.30	5.78
4/U-6/3	vertical		7.65					2.118	45.96	788.10	773.00	15.10	60	0.30	5.17
4/L-6/2	horizontal	1016.60	8.07	9.58	7.96	8.26	490.41	2.073	65.51	478.80	465.40	13.40	40	0.25	3.95
4/L-6/1	vertical	776.50	7.93	7.59			374.58	2.073	49.07	776.70	754.80	21.90	40	0.25	8.61
4/L-6/4	horizontal	1009.30	7.97	9.77	7.97	9.73	487.42	2.071	77.55	572.30	554.70	17,60	40	0.25	4.38
4/L-6/3	vertical	851.10	7.98	8.20			409.71	2.077	49.96	853.10	829.50	23.60	40	0.30	7.58
5/L-6/1	horizontal	875.50	8.07	8.15	8.07	8.18	416.69	2.101	66.01	516.30	502.10	14.20	40	0.25	4.10
5/L-6/2	vertical	828.20	8.11	7.70			398.13	2.080	51.68	829.10	806.10	23.00	40	0.25	8.56
5/L-6/3	horizontal	1033.60	8.08	9.75	7.86	9.7	500.18	2.066	76.24	496.30	475.90	20.40	40	0.28	4.62
5/L-6/4	vertical	1065.17	7.98	10.07			503.48	2.116	50.01	1065.50	1037,40	28.10	40	0.28	9.48

* Weight loss amount of 4/U-5/1 was too big than the other samples, and it was thought that this is a measurement error. For this reason test was repeated with the same sample (4/U-5/1').

Core fragments obtained during cutting off the ends of the core in the preparation of the samples for leaching test was used for determining the insoluble contents. For insoluble content determination, test procedure given in Chapter 6.1 was followed. Test results were given in Table 6.3..

Table 6.3 Test of insoluble content results

Rock Samples

Sample	Weight (g)	Insoluble (g)	Insoluble (%)
TR-1	209.46	1.45	0.69
TR-2	415.80	10.06	2.42

Core Samples

Sample	Weight (g)	Insoluble (g)	Insoluble (%)
4/U-2/3	644.08	19.13	2.97
4/U-2/1			
4/U-2/4	475.18	1.57	0.33
4/U-2/5			
4/U-5/1	352.34	16.81	4.77
4/U-5/2			
4/U-6/1	435.76	25.32	5.81
4/U-6/2			
4/U-6/3	410.60	16.88	4.11
4/U-6/4			
4/L-6/3	414.50	6.34	1.53
4/L-6/4			
5/L-6/1	334.80	7.83	2.34
5/L-6/2			

6.3 Evaluation of Test Results

It was observed that vertical leaching rate is greater than the horizontal leaching rate at the same leaching temperature. When leaching temperature was increased, both horizontal and vertical leaching rates also increased in more or less the same ratio.

At the same leaching temperature, very wide range of leaching rates was obtained. This shows that leaching temperature is not a unique factor affecting the leaching rate. At the same leaching temperature, leaching rates of sample having more insoluble content is generally greater than sample having less insoluble content. This means that insolubles in the trona are easily crumbling away during the leaching.

From the leaching test results given in Table 6.2, average of horizontal and vertical leaching rate was calculated separately according to testing temperature (Table 6.4 and Table 6.5).

Table 6.4 Average of horizontal leaching rates

Sample Name	Leaching Axis	Leaching Temp. ºC	Leaching Rate (mm/h)
TR-2	horizontal	22	2.54
		Average	**2.54**
4/U-2/1	horizontal	40	5.53
4/U-2/4	horizontal	40	3.91
4/L-6/2	horizontal	40	3.95
4/L-6/4	horizontal	40	4.38
5/L-6/1	horizontal	40	4.10
5/L-6/3	horizontal	40	4.62
		Average	**4.42**
4/U-5/1'	horizontal	60	11.15
4/U-6/1	horizontal	60	6.94
4/U-6/4	horizontal	60	5.78
		Average	**7.96**

Table 6.5 Average of vertical leaching rates

Sample Name	Leaching Axis	Leaching Temp. ºC	Leaching Rate (mm/h)
TR-1	vertical	22	5.02
		Average	**5.02**
4/U-2/3	vertical	40	9.25
4/U-2/5	vertical	40	6.60
4/L-6/1	vertical	40	8.61
4/L-6/3	vertical	40	7.58
5/L-6/2	vertical	40	8.56
5/L-6/4	vertical	40	9.48
		Average	**8.35**
4/U-5/2	vertical	60	14.07
4/U-6/2	vertical	60	13.89
4/U-6/3	vertical	60	5.17
		Average	**13.98**

6.4 Nominal Leaching Rate Calculation

Nominal leaching rate can be defined as leaching rate in fresh water at 20°C. Nominal leaching rate is calculated from the laboratory leaching test results.

For nominal leaching rate calculation of trona formula given in Equation-9 is used (Urbanczyk et al, 2005).

$$\omega = \omega_{20}\left(1+\beta(T-T_0)\right)\left(\frac{A_S(T)-A}{A_S(T_0)}\right)^{3/2}\left(\frac{A_S(T)}{A_S(T_0)}\right)^{1/2} \qquad [9]$$

where:

ω – leaching rate with trona brine [mm/h],

ω_{20} – nominal leaching rate with fresh water at the temperature 20ºC [mm/h],

β – temperature coefficient, determined experimentally

$\beta = 0.005$ [°C^{-1}] (for $T_0 = 20$°C, determined for trona rock),

T – brine temperature in the cavern [°C],

T_0 – temperature, for which β was determined ($T_0 = 20$°C),

$A_S(T)$ – alkalinity of saturation, dependent on temperature [kg/m^3], (from formula [5])

A – alkalinity of brine in the cavern [kg/m^3]

This formula is derived from formula [2] for trona leaching calculation by CHEMKOP.

With determined temperature factor, the nominal leaching rates were calculated from the leaching test results by using formulae [5] and [9]. Taking $T_0 = 20°C$ and $A = 0$ as nominal conditions, their values are as follows:

Table 6.6 Nominal leaching test rates for 20ºC

Temperature [°C]	**Vertical [mm/h]**	**Horizontal [mm/h]**
22	4.74	2.40
40	4.70	2.49
60	4.45	2.53

The average values from the tests are:

roof: 4.63 mm/h

wall: 2.47 mm/h

CHAPTER 7

USE OF COMPUTER MODELING IN DESIGNING INITIAL CAVERN

Computer models of the salt cavern leaching process allow numerically simulate the course of the process, basing on its description in terms of mathematical and physical equations and on finite difference approximation of the three-dimensional host rock salt medium. From the IT point of view, these models are highly advanced software tools, which have to combine very complicated numeric calculations (solving the set of partial differential and integral equations) with simplicity of use and user-friendly graphical options.

Such models enable to simulate the selected cavern leaching technology and analyze how technological items influence the cavern shape development. "User-friendly" interface allows quick checking of many technological variants, by using different leaching scenarios. A decision, which variant is the best, is left to a specialist performing computer modeling.

Many computer models of the leaching process have been developed worldwide for the last 40 years. The majority of these models are used only by companies where they were developed but few of them (e.g. Salgas, Sansmic developed by Sandia National Laboratories in New Mexico, sponsored by SMRI) available in the commercial form, are commonly applied in many countries. The WinUbro model, developed at CHEMKOP (Krakow, Poland) is one of such models, purchased and applied by many companies around the world for modeling the caverns in rock salt for brine production or storage purposes (Kunstman et al, 2007).

7.1 Basis of WinUbro Model

Basis of the computer modeling with WinUbro and its approach on cavern development can be summarized as follows (CHEMKOP, 2003):

The basic idea is dividing the cavern and the surrounding salt body into 8 or 16 azimuthal sectors, (45°/22.5° each), with edges at the cavern axis (Figure 7.1). Each sector has its own cavern wall profile which evolves in time depending on leaching properties assigned to this sector, independently of cavern shape in the other sectors. The cavern wall profile in each sector is sector-equivalent, i.e. at any depth, the area of circle sector of 45° (or 22.5°) with the sector-equivalent radius at this depth is the same as the area of real cavern section at this depth.

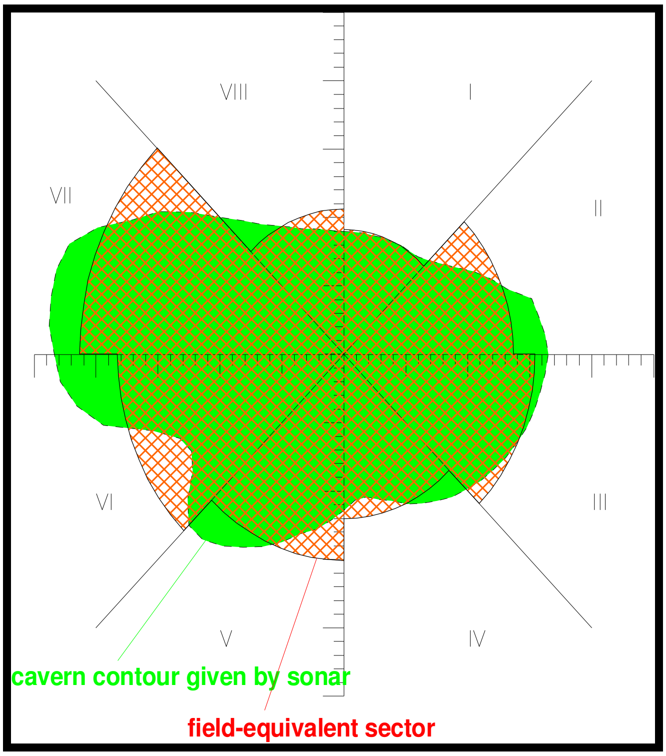


Figure 7.1 Approximation of cavern wall profile azimuthal sectors (CHEMKOP, 2003)

The conversion from a real, irregular cavern horizontal contour to 8 or 16 sector-equivalent radii is simple and obvious. However, if the model working with sectors is created, a reverse procedure is necessary; converting 8 or 16 circle sectors to a continuous irregular contour. This can be done by interpolation that satisfies following two conditions (Figure 7.2):

- sector-equivalent radii obtained from the interpolated contour must be the same as the starting equivalent radii,
- at the boundary between two sectors, radius must have the average value of these two sectors.

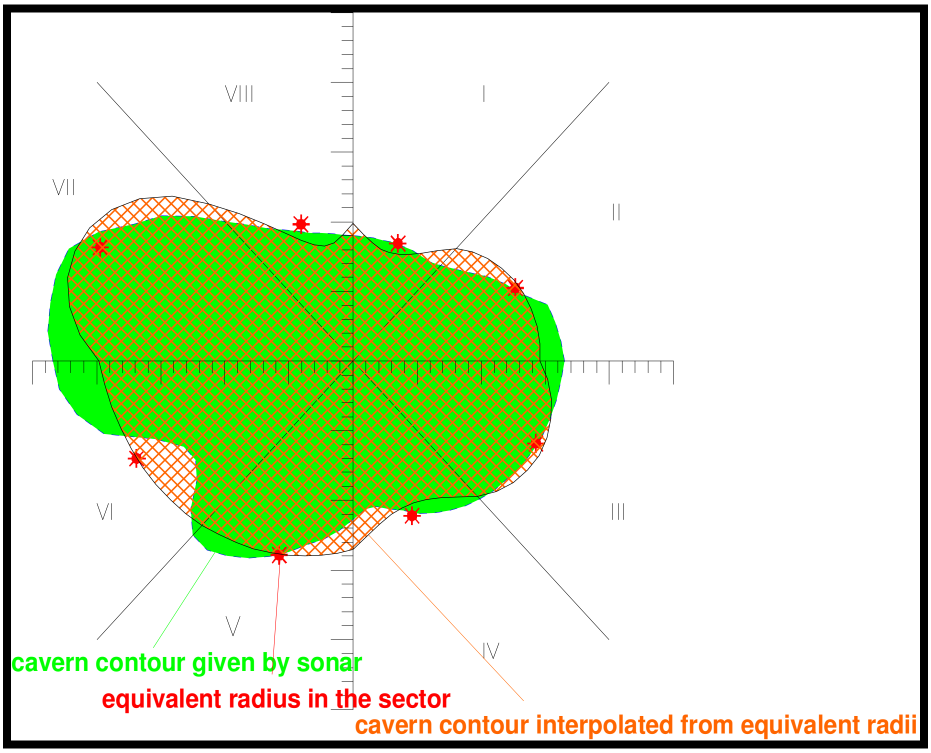


Figure 7.2 Cavern contour interpolation from equivalent radii (CHEMKOP, 2003)

The wall profile of each cavern sector is treated using the following rules of the model:

- cavern vertical contour (profile) can be described as radius being a function of depth (Figure 7.3) - so it can be assumed that the depths of points at the profile are monotone, the possibility that a profile of non-monotone depths can occur is excluded, (no so-called "fingers" or "pockets" can be modeled) (Figure 7.4 and Figure 7.5).

- cavern profile is approximated by an open polygon (broken line), independently of depth approximation inside the cavern,
- inhomogeneous, time-dependent step is applied to profile approximation, where the vertices (approximation nodes) follow the cavern boundary and change their depths with time, and during simulation new vertices may be created as well as old ones may disappear,
- for cavern horizontal section at any depth, each sector of azimuthal approximation is represented by a single radius value that gives the area corresponding to area cavern section element within this sector and at this depth; this representing value is equal to the radius of polygon vertex if a vertex lies at given depth, otherwise it is interpolated between neighboring vertices.

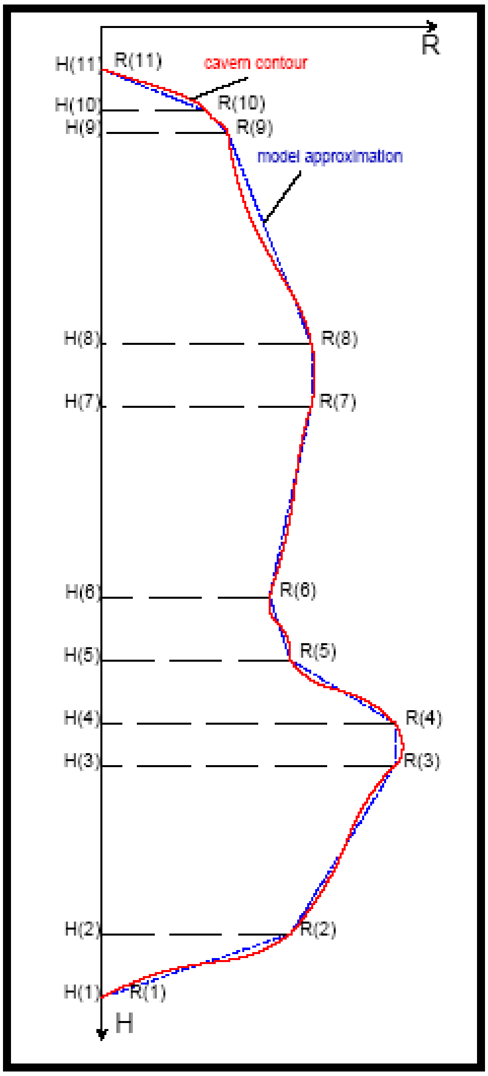


Figure 7.3 Approximation of cavern profile in a sector by {H(i), R(i)} sequence (CHEMKOP, 2003)

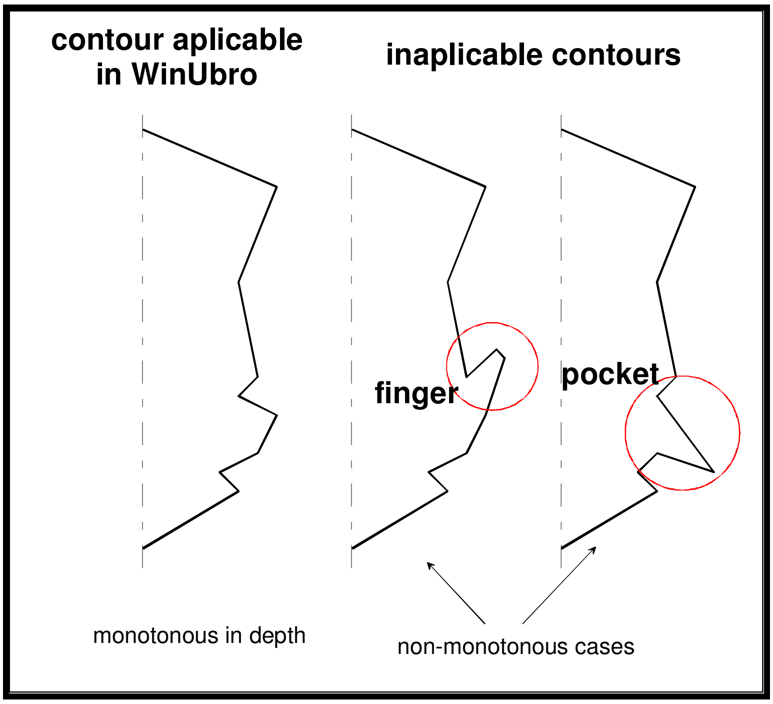


Figure 7.4 Cavern profile in monotonous and non-monotous cases in depth (CHEMKOP, 2003)

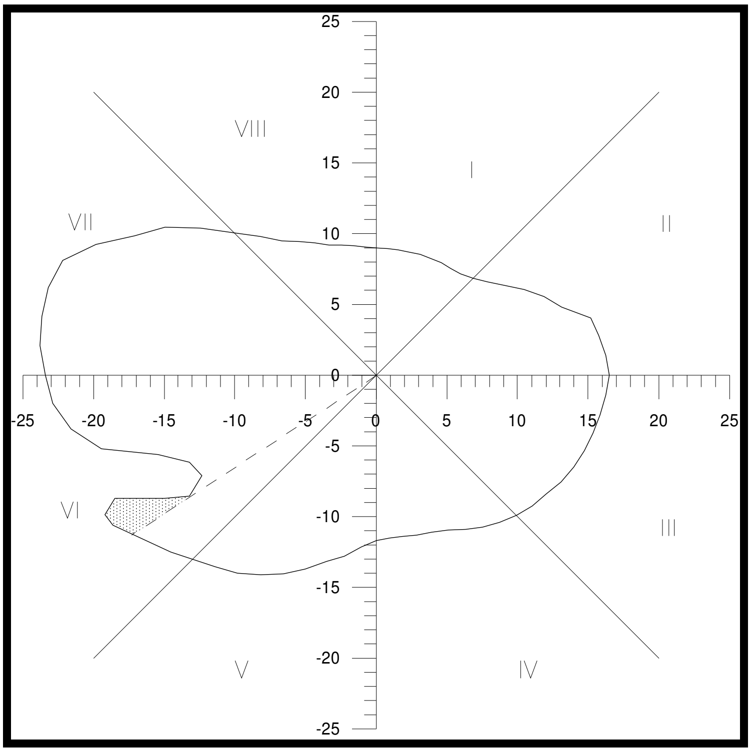


Figure 7.5 Cavern contours in non-monotonous in azimuth (CHEMKOP, 2003)

During every time step the algorithm determining the cavern profile movement is called eight times, i.e. for each sector successively. To determine the displacement of individual sides of the cavern sector profiles, the algorithm takes leaching coefficients values corresponding to the sector and depth where the relevant profile side belongs (Figure 7.6).

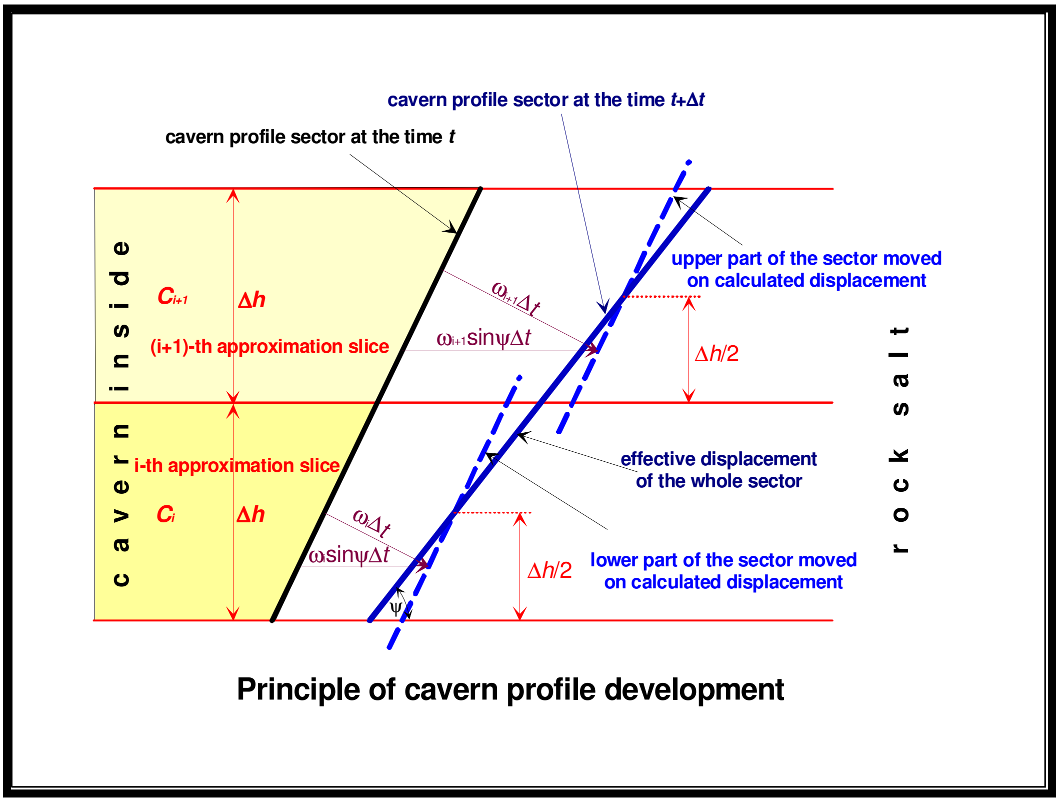


Figure 7.6 Principle of cavern profile development (CHEMKOP, 2003)

When new cavern profile (after time step interval) is determined in every of 8 cavern sectors, the volumes of successive cavern slices are calculated. Slice volume is a sum of 8 pies, i.e. 45° sectors of truncated cones approximating the cavern in successive sectors. Then new level of insolubles in sump is determined basing on the balance of mass and volume for brine, water and insolubles.

7.2 WinUbro Model Adaptation for Trona Specificity

The CHEMKOP experts, being WinUbro authors, working as leaching consultants in ETI Soda in 2005 - 2007 during the drilling and leaching of wells for trona exploitation, adapted their WinUbro software for trona specificity and used this software for prognoses and designs of vertical caverns development.

The fact that trona brine is a two-component solution, containing sodium carbonate and sodium bicarbonate was the specificity needed to take into account during adapting the software for trona leaching modeling. The alkalinity of soda solutions in different temperatures and their densities, which were measured in ETI Soda laboratory, were used to find the polynomial approximation of this dependence, which was afterwards used in the adapted model.

In addition, the formula describing the total alkalinity of saturated soda solutions in different temperatures were derived from laboratory measurements and introduced into the model.

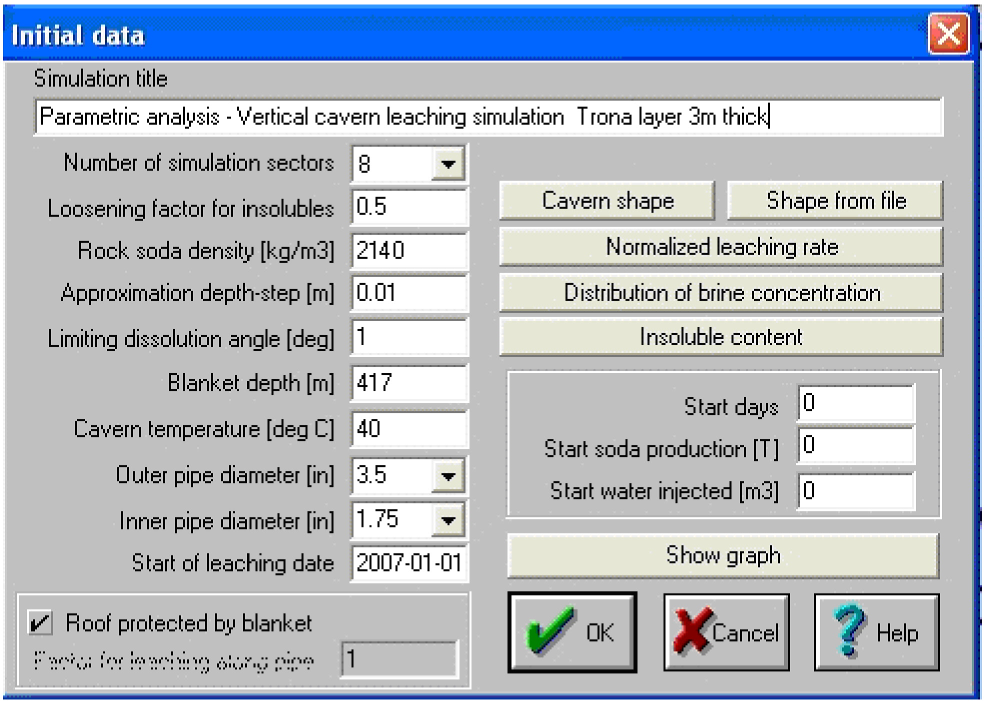
Leaching rate formula used in the WinUbro model was compared with the leaching laboratory tests results made in ETI Soda on trona core samples, and the proper for trona case coefficients for this formula were chosen – especially the coefficient responsible for leaching rate dependency on temperature of the leaching solvent.

As a result of this work, unique software – WinUbroTrona was constructed and afterwards used for modeling vertical caverns development.

7.3 Input Data for Modeling with WinUbroTrona

Input data must be entered to create the numeric initial model of the given cavern. The input data consist of (Figure 7.7):

- ***Initial shape of the cavern from which the modeling starts:*** It can be either bare section of the borehole (drilled in the salt and prepared for leaching), or any shape of the cavern already in leaching. Such a shape can be entered from the keyboard, or automatically read from the numeric file containing the results of the sonar survey. In this study, a bare section of the borehole drilled in trona layer was taken as initial shape – there are three different sizes of staring shape – trona bare layer 1 m thick, 2 m thick and 3 m thick with oil isolation of this layer roof. Initial diameter of the bare borehole was 0.22 m.



Simulation title: Parametric analysis - Vertical cavern leaching simulation Trona layer 3m thick
Number of simulation sectors: 8
Loosening factor for insolubles: 0.5
Rock soda density [kg/m3]: 2140
Approximation depth-step [m]: 0.01
Limiting dissolution angle [deg]: 1
Blanket depth [m]: 417
Cavern temperature [deg C]: 40
Outer pipe diameter [in]: 3.5
Inner pipe diameter [in]: 1.75
Start of leaching date: 2007-01-01
Start days: 0
Start soda production [T]: 0
Start water injected [m3]: 0
☑ Roof protected by blanket
Factor for leaching along pipe: 1

Figure 7.7 Example of WinUbroTrona window to introduce initial data

- ***Approximation steps for space and time in the cavern model:*** For numerical purposes it is necessary to divide space and time into approximation steps, which will be used during solving the model equations. The recommended approximation depth step for the big caverns in rock-salt is 1 m and the approximation step of the leaching time is 1 hour, but it is possible to apply other steps, provided, that the whole height of the cavern is contained within 500 vertical steps. Azimuth is divided into eight or sixteen sectors. It allows also describing the “axial asymmetry”. In the case of presented here calculations, as caverns in trona are very small, the depth approximation step is 1 cm, the approximation step of the leaching time is 30 minutes, and the axial symmetry of the case was assumed.

- ***Limiting dissolution angle:*** Limiting dissolution angle of trona is 15º as the majority of the salt deposit which is determined from laboratory analysis made in Poland. But at the beginning of the leaching process most of the insolubles will be taken out from the cavern with brine. For this reason, according to cavern diameter reached during leaching simulation stages, different dissolution angles were assumed (Table 7.1).

Table 7.1 Limiting dissolution angle value according to cavern diameter

Cavern diamater (m)	Limiting dissolution angle (deg)
1	1
2	5
3	15

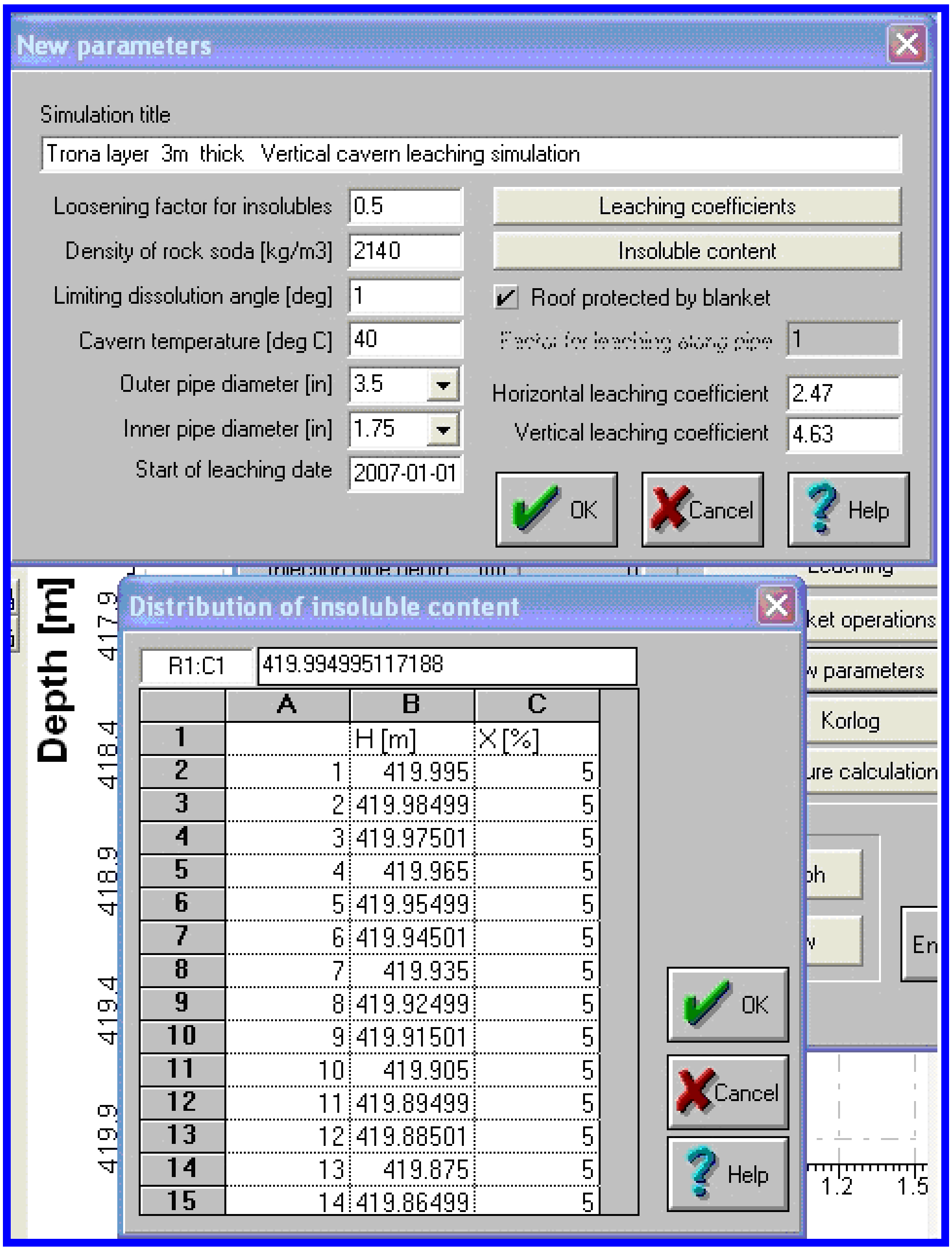
- ***Loosening factor of insolubles:*** Loosening factor for insolubles is 1.5. In this study, cavern is too small so it will never reach that value. For this reason, according to cavern diameter reached during leaching simulation stages, different loosening factor of insolubles were assumed (Table 7.2).

Table 7.2 Loosening factor of insolubles value according to cavern diameter

Cavern diamater (m)	Loosening factor of insolubles
1	0.5
2	0.9
3	1.2

- ***Distribution of leaching properties and insoluble content in every depth-approximation step:*** Theoretically their values in each step can be different, in practice (as number of laboratory tested samples is limited) values are entered corresponding to layers identified in the cavern section of the well profile. Usually, for the big caverns the more detailed differentiation of leaching coefficients can be obtained later, when sonar survey is done in the modeled cavern. The WinUbro software can modify leaching coefficients automatically by adjustment to sonar. In the case of presented here calculations, as the modeling goal was to compare leaching results for different layer thicknesses, different temperatures and different insoluble contents in the kind of parametric analysis – the leaching properties of trona rock was taken uniformly as a medium value measured in leaching tests, namely 4.63 mm/h for horizontal leaching and 2.47 mm/h for vertical leaching. Amount of insolubles in the trona rock was considered in three cases: 5%, 10% and 20% (Figure 7.8).

- ***Temperature in the cavern:*** In this study two different temperatures of solvent in the cavern were considered: 40°C and 60°C.



Simulation title: Trona layer 3m thick Vertical cavern leaching simulation

Loosening factor for insolubles: 0.5

Density of rock soda [kg/m3]: 2140

Limiting dissolution angle [deg]: 1

Cavern temperature [deg C]: 40

Outer pipe diameter [in]: 3.5

Inner pipe diameter [in]: 1.75

Start of leaching date: 2007-01-01

☑ Roof protected by blanket

Factor for leaching along pipe: 1

Horizontal leaching coefficient: 2.47

Vertical leaching coefficient: 4.63

R1:C1 419.994995117188

	A	B	C
1		H [m]	X [%]
2	1	419.995	5
3	2	419.98499	5
4	3	419.97501	5
5	4	419.965	5
6	5	419.95499	5
7	6	419.94501	5
8	7	419.935	5
9	8	419.92499	5
10	9	419.91501	5
11	10	419.905	5
12	11	419.89499	5
13	12	419.88501	5
14	13	419.875	5
15	14	419.86499	5

Figure 7.8 Example of WinUbroTrona windows to introduce changes in model parameters (below the input window for insoluble content)

7.4 Data Describing the Leaching Scenario to be Simulated

These data are necessary to inform the program which process is to be modeled. If several possible leaching variants are desired to test, a few scenarios can be prepared and then run them in turn on the same model. All scenarios contain basic technological parameters describing intervals and stages of the cavern leaching process. For each of these stages it is obligatory to describe in the scenario the data listed below:

- depths of both tubing shoes,
- injection rate of leaching medium (solvent),
- concentration of injected solvent.
- conditions of the stage ending – they are checked by the computer each time-step and if any of them is satisfied, the computer ends the stage and passes to the next step (if any) or waits for the command from the keyboard. It is possible to define several conditions. They can be the following:
    - limit of leaching time (duration in days or final date of the given stage),
    - limit of cavern radius at the given depth,
    - limit of salt production (in the given stage or total),
    - limit of cavern volume (in the given stage or total).

Change of the blanket level (up or down) is treated in the scenario as a separate stage. Between stages it is possible to save all data of the model to enable future restart of the modeling for other variants precisely from this moment and this cavern state.

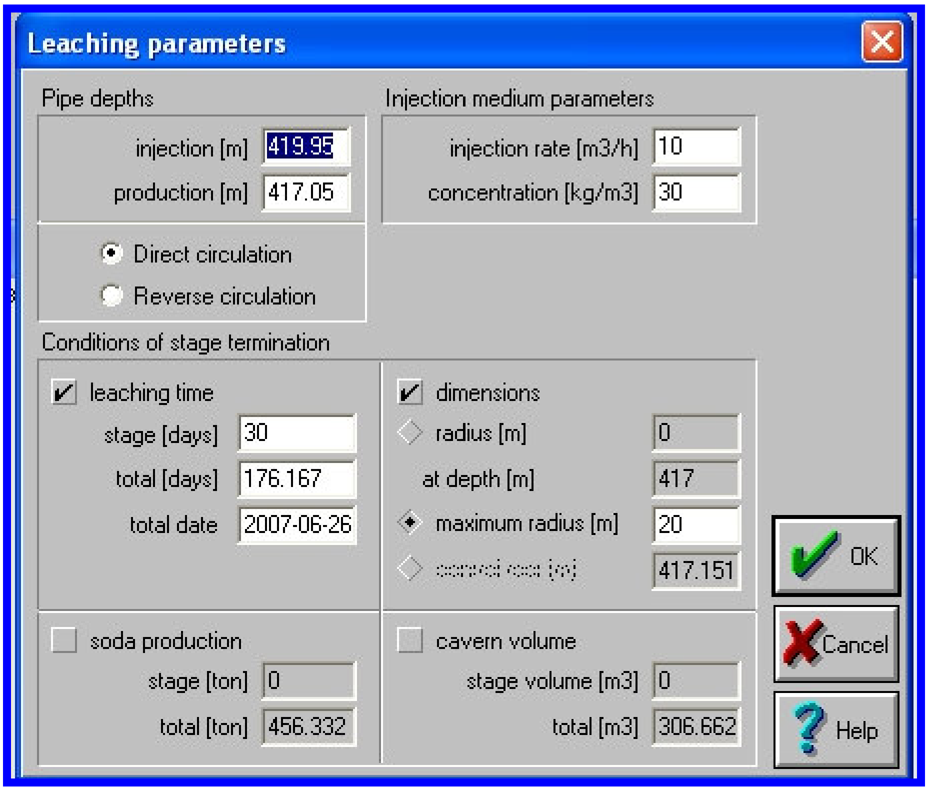
In this study, the leaching was modeled in following conditions (Figure 7.9):

- **direct circulation**, injecting point just over the bottom of the trona layer, production point just below the roof of the bare trona layer. Leaching tubings diameters were **3 ½”** and **1 ¾”.**
- **isolation of the cavern roof** constantly just over the production point.
- solvent injection rate - **10 m^3/h**

- solvent concentration (total alkalinity) - 30 kg/m^3 (both these values are corresponding to mean conditions during vertical cavern leaching in ETI Soda Beypazari field)

Modeling can be made manually, stage after stage, attentively watching simulation results and on this basis defining and entering data for the next stage. Such a situation usually takes place when designing the leaching technology for a new cavern, when it is still unknown which technology proves optimal to be used. For caverns already in leaching, modeling of their further development usually goes automatically, according to the prepared scenario, which allows achieving the purpose much more quickly.

In this study, the leaching was modeled using 3 scenarios: for the cavern leaching in trona layer 1m thick, 2 m thick and 3 m thick (Figure 7.10).



Pipe depths
injection [m] 419.95
production [m] 417.05
● Direct circulation
○ Reverse circulation

Injection medium parameters
injection rate [m3/h] 10
concentration [kg/m3] 30

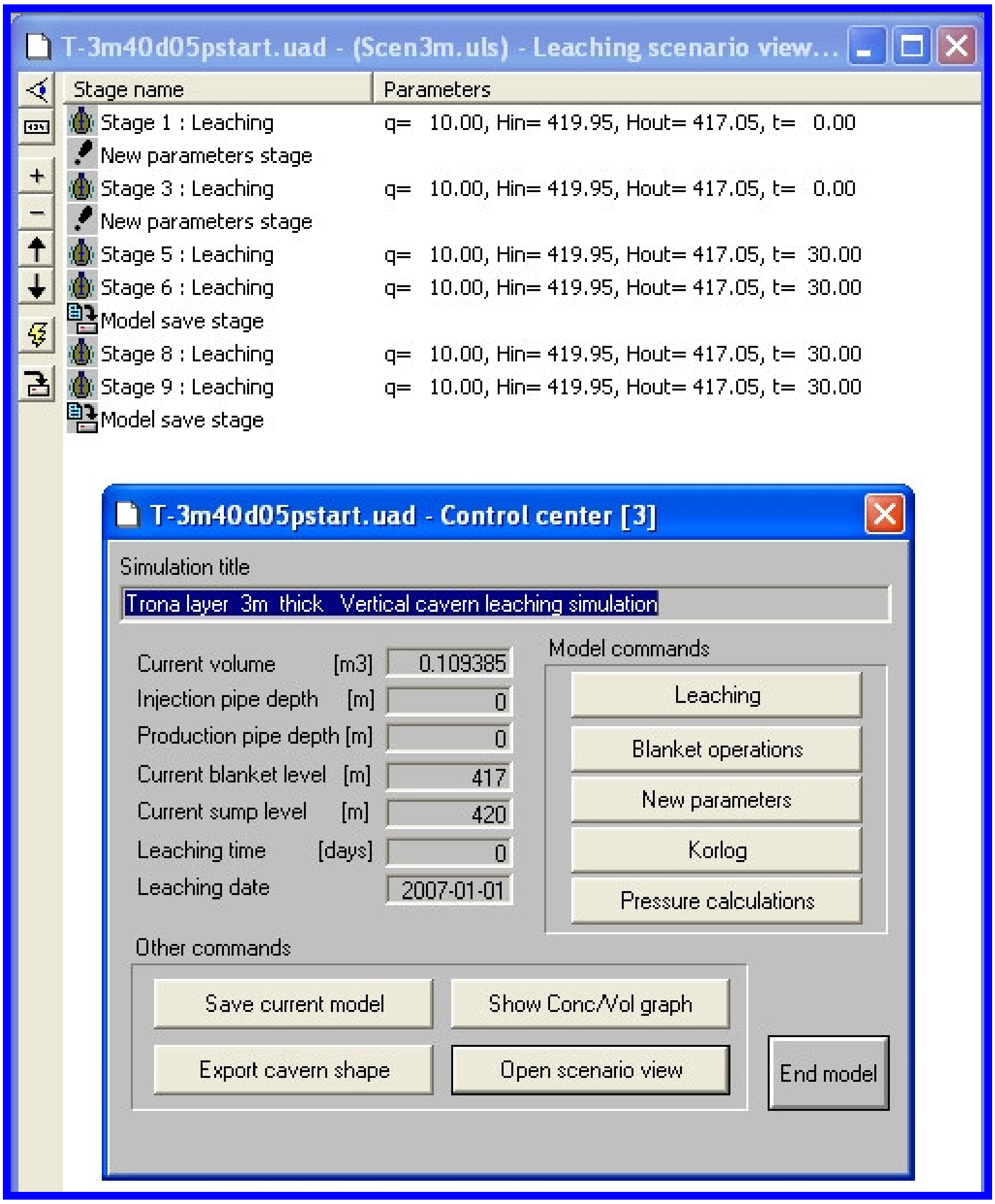
Conditions of stage termination
☑ leaching time
stage [days] 30
total [days] 176.167
total date 2007-06-26

☑ dimensions
◇ radius [m] 0
at depth [m] 417
◆ maximum radius [m] 20
◇ [illegible] 417.151

☐ soda production
stage [ton] 0
total [ton] 456.332

☐ cavern volume
stage volume [m3] 0
total [m3] 306.662

Figure 7.9 Example of WinUbroTrona window to introduce leaching data


T-3m40d05pstart.uad - (Scen3m.uls) - Leaching scenario view...

Stage name	Parameters
Stage 1 : Leaching	q= 10.00, Hin= 419.95, Hout= 417.05, t= 0.00
New parameters stage	
Stage 3 : Leaching	q= 10.00, Hin= 419.95, Hout= 417.05, t= 0.00
New parameters stage	
Stage 5 : Leaching	q= 10.00, Hin= 419.95, Hout= 417.05, t= 30.00
Stage 6 : Leaching	q= 10.00, Hin= 419.95, Hout= 417.05, t= 30.00
Model save stage	
Stage 8 : Leaching	q= 10.00, Hin= 419.95, Hout= 417.05, t= 30.00
Stage 9 : Leaching	q= 10.00, Hin= 419.95, Hout= 417.05, t= 30.00
Model save stage	

T-3m40d05pstart.uad - Control center [3]

Simulation title: Trona layer 3m thick Vertical cavern leaching simulation

Current volume [m3]	0.109385
Injection pipe depth [m]	0
Production pipe depth [m]	0
Current blanket level [m]	417
Current sump level [m]	420
Leaching time [days]	0
Leaching date	2007-01-01

Figure 7.10 Example of WinUbroTrona windows for scenario run (below the window for simulation control)

7.5 Way of Presentation of Simulation Results in WinUbro Software

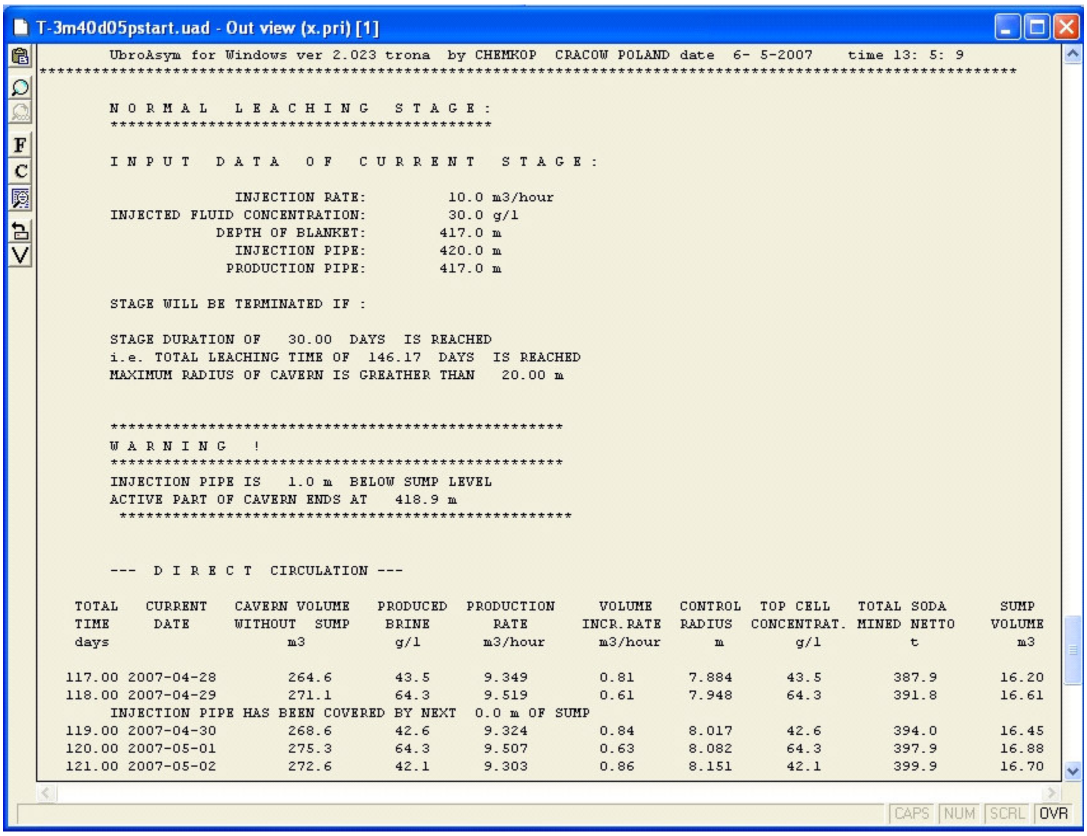
Modeling results are presented in the text and graphic form and the user can select the most convenient graphic options. The basic results of the modeling are assembled in the table which is displayed during simulation. The user can specify the frequency of the table lines printout (e.g. every 10 leaching days or every 1 day if the process is fast-variable).

The table contains the following data (Figure 7.11):

- leaching time in days (from the beginning of the leaching) and as the date,
- current cavern volume (without the sump),
- concentration of produced brine,
- current radius of the cavern at the assigned depth,
- current salt production from the cavern, (counting from the beginning of the leaching),
- sump volume.

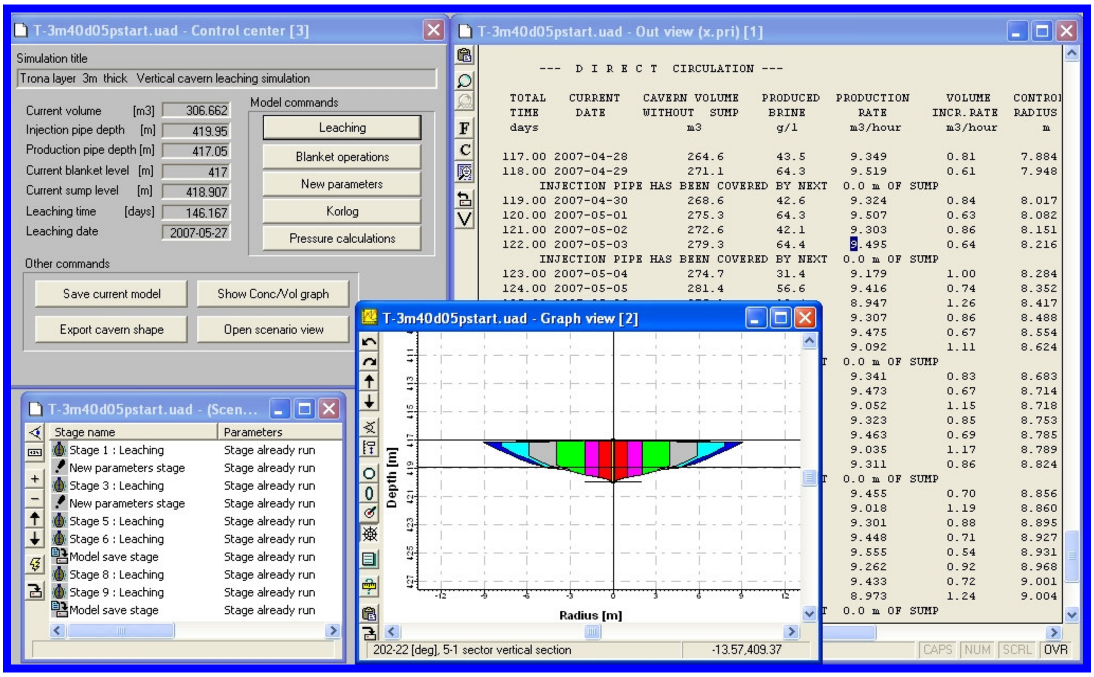
Presentation of simulation results in graphic form includes:

- vertical sections of the cavern through given angle-sectors with history of the shape development in the previous stages (Figure 7.12, Figure 7.13),
- horizontal sections of the cavern on given depth with history of the shape development in the previous stages (Figure 7.13),
- three-dimensional shape of the cavern in the perspective view from the selected point (Figure 7.14),
- graphs of the produced brine concentration as a function of time and graphs of the growing cavern volume.



```
        UbroAsym for Windows ver 2.023 trona  by CHEMKOP  CRACOW POLAND date  6- 5-2007    time 13:  5:  9
**********************************************************************************************************

        N O R M A L   L E A C H I N G   S T A G E :
        *******************************************

        I N P U T   D A T A   O F   C U R R E N T   S T A G E :

                      INJECTION RATE:         10.0 m3/hour
        INJECTED FLUID CONCENTRATION:         30.0 g/l
                    DEPTH OF BLANKET:        417.0 m
                      INJECTION PIPE:        420.0 m
                     PRODUCTION PIPE:        417.0 m

        STAGE WILL BE TERMINATED IF :

        STAGE DURATION OF    30.00  DAYS  IS REACHED
        i.e. TOTAL LEACHING TIME OF  146.17  DAYS  IS REACHED
        MAXIMUM RADIUS OF CAVERN IS GREATHER THAN   20.00 m


        ***************************************************
        W A R N I N G   !
        ***************************************************
        INJECTION PIPE IS   1.0 m  BELOW SUMP LEVEL
        ACTIVE PART OF CAVERN ENDS AT   418.9 m
         ***************************************************


        ---  D I R E C T  CIRCULATION ---

    TOTAL   CURRENT   CAVERN VOLUME   PRODUCED  PRODUCTION     VOLUME   CONTROL  TOP CELL   TOTAL SODA    SUMP
    TIME     DATE     WITHOUT  SUMP    BRINE      RATE      INCR.RATE  RADIUS  CONCENTRAT. MINED NETTO  VOLUME
    days                   m3           g/l      m3/hour     m3/hour     m        g/l          t          m3

   117.00 2007-04-28         264.6       43.5      9.349       0.81      7.884     43.5        387.9       16.20
   118.00 2007-04-29         271.1       64.3      9.519       0.61      7.948     64.3        391.8       16.61
        INJECTION PIPE HAS BEEN COVERED BY NEXT  0.0 m OF SUMP
   119.00 2007-04-30         268.6       42.6      9.324       0.84      8.017     42.6        394.0       16.45
   120.00 2007-05-01         275.3       64.3      9.507       0.63      8.082     64.3        397.9       16.88
   121.00 2007-05-02         272.6       42.1      9.303       0.86      8.151     42.1        399.9       16.70
```

Figure 7.11 Example of WinUbroTrona window with simulation results: Table



Simulation title
Trona layer 3m thick   Vertical cavern leaching simulation

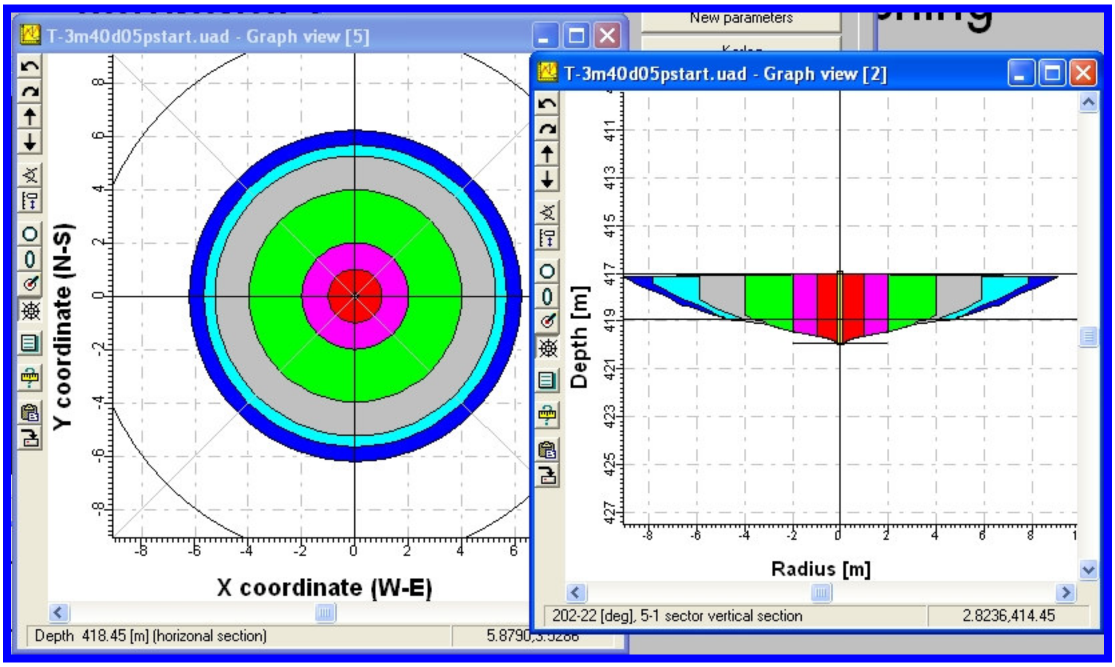
Current volume [m3] 306.662
Injection pipe depth [m] 419.95
Production pipe depth [m] 417.05
Current blanket level [m] 417
Current sump level [m] 418.907
Leaching time [days] 146.167
Leaching date 2007-05-27

Stage name	Parameters
Stage 1 : Leaching	Stage already run
New parameters stage	Stage already run
Stage 3 : Leaching	Stage already run
New parameters stage	Stage already run
Stage 5 : Leaching	Stage already run
Stage 6 : Leaching	Stage already run
Model save stage	Stage already run
Stage 8 : Leaching	Stage already run
Stage 9 : Leaching	Stage already run
Model save stage	Stage already run

```
      ---  D I R E C T  CIRCULATION ---

  TOTAL   CURRENT   CAVERN VOLUME  PRODUCED  PRODUCTION    VOLUME   CONTROI
  TIME     DATE     WITHOUT  SUMP   BRINE      RATE      INCR.RATE  RADIUS
  days                  m3          g/l      m3/hour      m3/hour     m

 117.00 2007-04-28        264.6      43.5      9.349        0.81      7.884
 118.00 2007-04-29        271.1      64.3      9.519        0.61      7.948
      INJECTION PIPE HAS BEEN COVERED BY NEXT  0.0 m OF SUMP
 119.00 2007-04-30        268.6      42.6      9.324        0.84      8.017
 120.00 2007-05-01        275.3      64.3      9.507        0.63      8.082
 121.00 2007-05-02        272.6      42.1      9.303        0.86      8.151
 122.00 2007-05-03        279.3      64.4      9.495        0.64      8.216
      INJECTION PIPE HAS BEEN COVERED BY NEXT  0.0 m OF SUMP
 123.00 2007-05-04        274.7      31.4      9.179        1.00      8.284
 124.00 2007-05-05        281.4      56.6      9.416        0.74      8.352
                                               8.947        1.26      8.417
                                               9.307        0.86      8.488
                                               9.475        0.67      8.554
                                               9.092        1.11      8.624
                                         T  0.0 m OF SUMP
                                               9.341        0.83      8.683
                                               9.473        0.67      8.714
                                               9.052        1.15      8.718
                                               9.323        0.85      8.753
                                               9.463        0.69      8.785
                                               9.035        1.17      8.789
                                               9.311        0.86      8.824
                                         T  0.0 m OF SUMP
                                               9.455        0.70      8.856
                                               9.018        1.19      8.860
                                               9.301        0.88      8.895
                                               9.448        0.71      8.927
                                               9.555        0.54      8.931
                                               9.262        0.92      8.968
                                               9.433        0.72      9.001
                                               8.973        1.24      9.004
                                         T  0.0 m OF SUMP
```

202-22 [deg], 5-1 sector vertical section -13.57,409.37

Figure 7.12 Example of WinUbroTrona windows with simulation results:
scenario run, tables, vertical cross-section

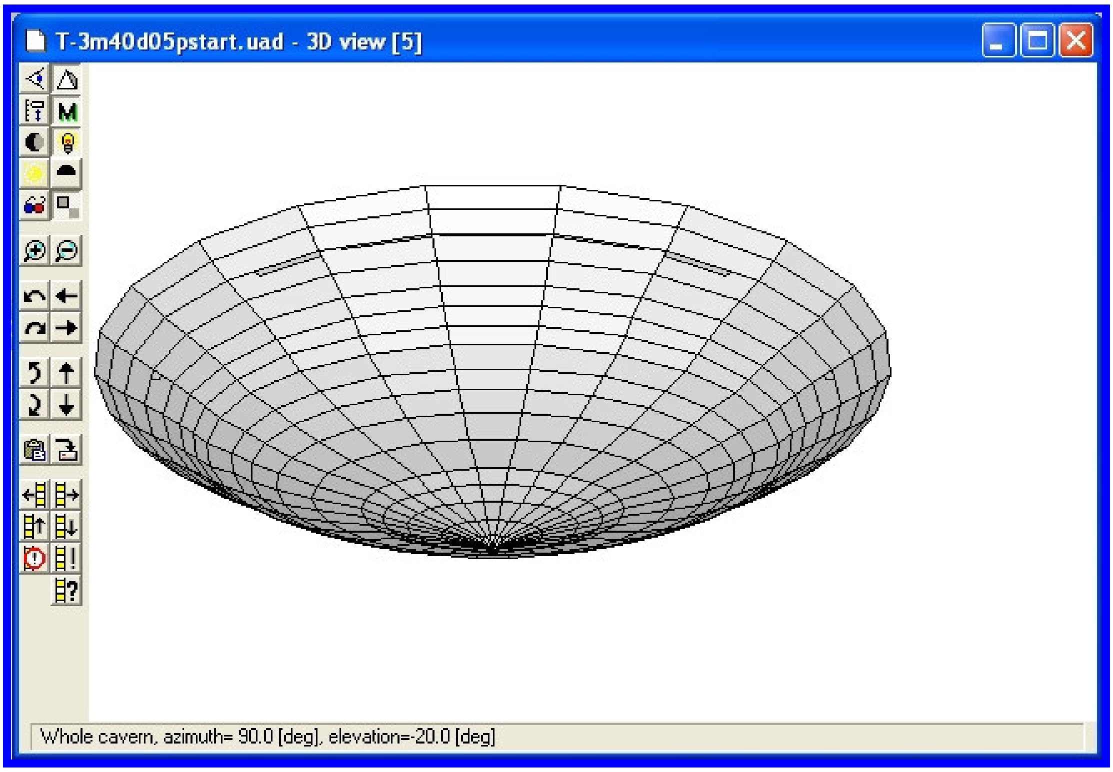


Depth 418.45 [m] (horizonal section)

202-22 [deg], 5-1 sector vertical section

2.8236,414.45

Figure 7.13 Example of WinUbroTrona windows with simulation results: horizontal and vertical cross-section



Whole cavern, azimuth= 90.0 [deg], elevation=-20.0 [deg]

Figure 7.14 Example of WinUbroTrona window with simulation results: 3D view

7.6 Results of Simulations

As it was mentioned in Chapter 7.3, the leaching simulations of vertical caverns in trona layers were made for following cases:

3 layer thicknesses : 1 m, 2 m, 3 m,
3 insoluble contents : 5%, 10%, 20%,
2 temperatures in cavern : 40°C, 60°C.

Together it was **18 leaching cases** to simulate.

The results of all 18 simulations were obtained during software runs in the form of tables and graphs described in the Chapter 7.5. As it was a lot of outputs and only part of them are the final results necessary for parametric analysis, which is the main goal of this thesis, the simulation results are presented here in the form of processed tables and graphs, being not the direct output from the software. The examples of original WinUbroTrona software outputs are presented in Figure 7.11, Figure 7.12, Figure 7.13, and Figure 7.14

Table 7.3 and the graphs Figure 7.15, Figure 7.16 are presenting the numeric and graphic results of the leaching simulation for vertical cavern in trona layer 1 m thick.

Table 7.4 and the graphs Figure 7.17, Figure 7.18 are presenting the numeric and graphic results of the leaching simulation for vertical cavern in trona layer 2 m thick.

Table 7.5 and the graphs Figure 7.19, Figure 7.20 are presenting the numeric and graphic results of the leaching simulation for vertical cavern in trona layer 3 m thick.

The main results, characterizing all 18 cases and allowing to compare them with each other and to deduce conclusions, are:

- final cavern radius,
- final cavern net volume (without sump),
- final height of the net cavern (distance roof-sump),
- total leaching time (this time is partially ineffective in the last part of cavern),
- time to reach cavern radius of 3 m (in all cases effective)

Table 7.3 Simulation results of WinUbroTrona software for cavern in 1 m thick trona layer

Insolubles	Solvent temperature [deg C]	Leaching time [days]	Cavern volume [m3]	Cavern radious [m]	Total trona extracted [t]	Sump volume [m3]	Time till R=3m [days]	Roof-sump height [m]
5%	40	85	34.0	4.86	50.0	1.97	39	0.7
10%	40	55	15.7	3.72	23.2	1.76	38	0.5
20%	40	48	10.0	3.44	14.5	2.39	37	0.4
5%	60	73	35.9	5.15	52.9	2.09	21	0.7
10%	60	43	19.6	4.17	28.9	2.27	20	0.6
20%	60	43	10.7	3.50	15.5	2.59	20	0.4

Table 7.4 Simulation results of WinUbroTrona software for cavern in 2 m thick trona layer

Insolubles	Solvent temperature [deg C]	Leaching time [days]	Cavern volume [m3]	Cavern radious [m]	Total trona extracted [t]	Sump volume [m3]	Time till R=3m [days]	Roof-sump height [m]
5%	40	117	117.7	6.88	170.5	7.06	40	1.3
10%	40	85	79.6	6.10	118.1	10.08	39	1.0
20%	40	73	34.5	4.90	51.2	9.22	38	0.7
5%	60	69	198.4	8.40	294.7	12.20	22	1.4
10%	60	64	84.4	6.56	125.4	10.63	21	1.0
20%	60	64	34.6	4.98	51.3	9.30	20	0.7

Table 7.5 Simulation results of WinUbroTrona software for cavern in 3 m thick trona layer

Insolubles	Solvent temperature [deg C]	Leaching time [days]	Cavern volume [m3]	Cavern radious [m]	Total trona extracted [t]	Sump volume [m3]	Time till R=3m [days]	Roof-sump height [m]
5%	40	127	288.9	8.55	417.2	17.75	42	1.9
10%	40	115	178.4	7.84	261.1	23.01	40	1.4
20%	40	110	86.3	6.89	130.1	24.80	39	0.8
5%	60	75	295.2	8.91	424.4	18.14	23	2.0
10%	60	65	183.1	8.00	270.9	23.64	22	1.5
20%	60	65	100.5	7.27	151.8	29.59	21	0.9

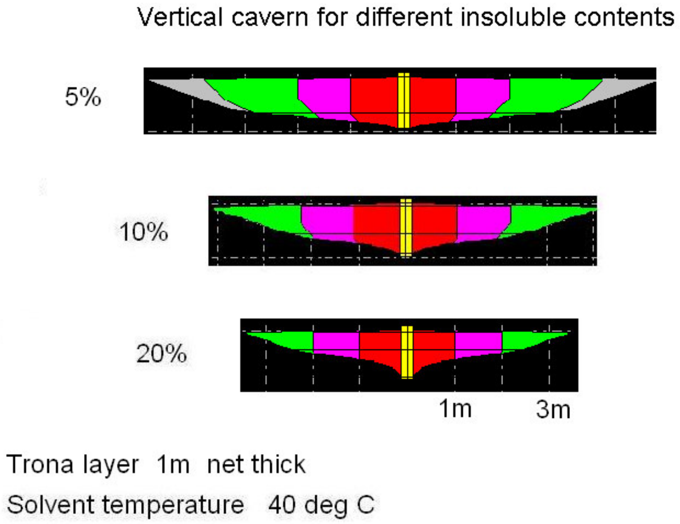


Figure 7.15 Vertical caverns for different insoluble contents in trona layer of 1m net thick at 40°C solvent temperature

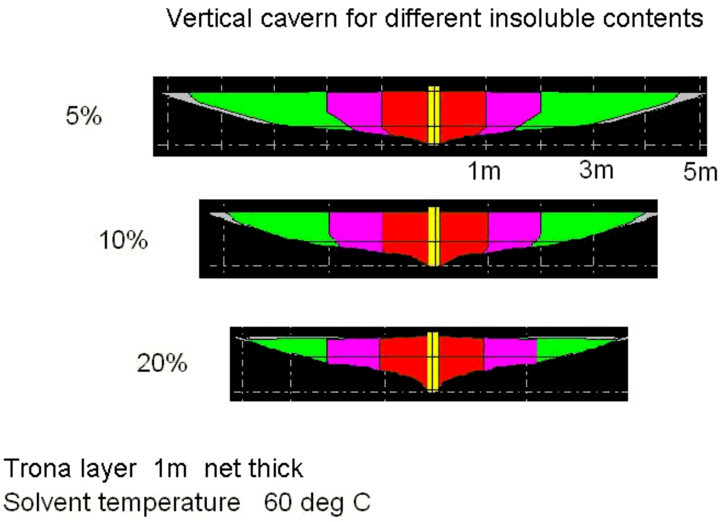


Figure 7.16 Vertical caverns for different insoluble contents in trona layer of 1m net thick at 60°C solvent temperature

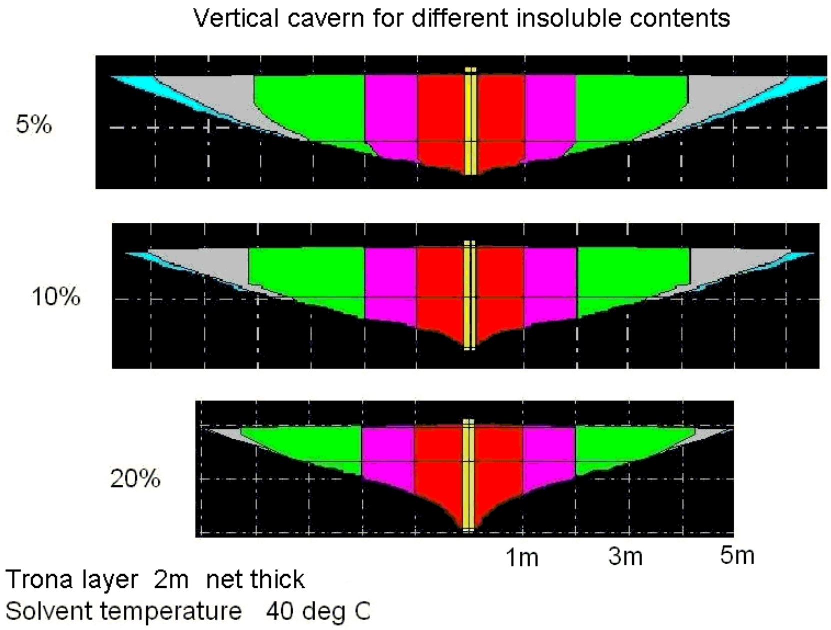


Figure 7.17 Vertical caverns for different insoluble contents in trona layer of 2m net thick at 40°C solvent temperature

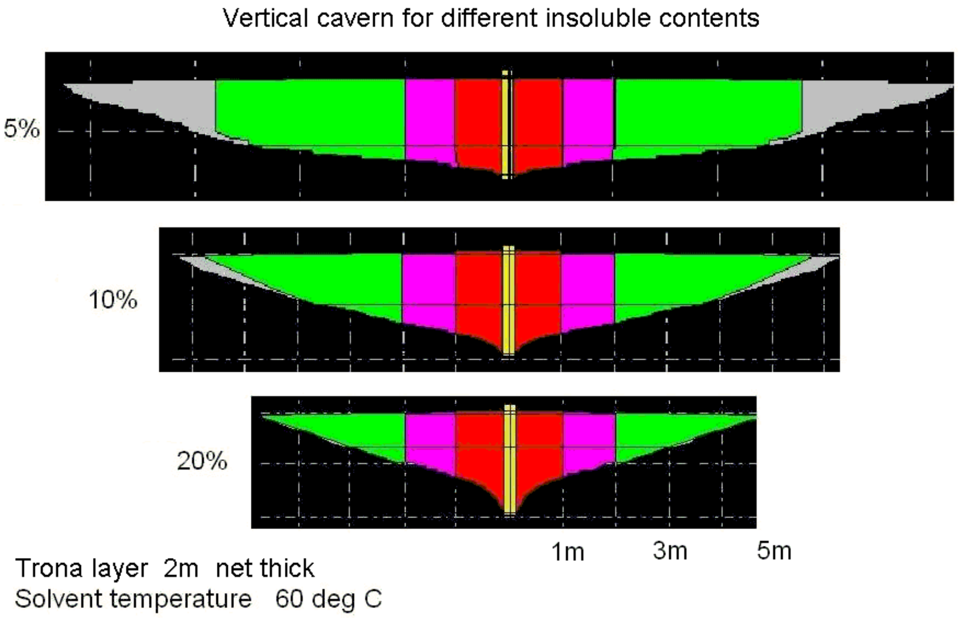


Figure 7.18 Vertical caverns for different insoluble contents in trona layer of 2m net thick at 60°C solvent temperature

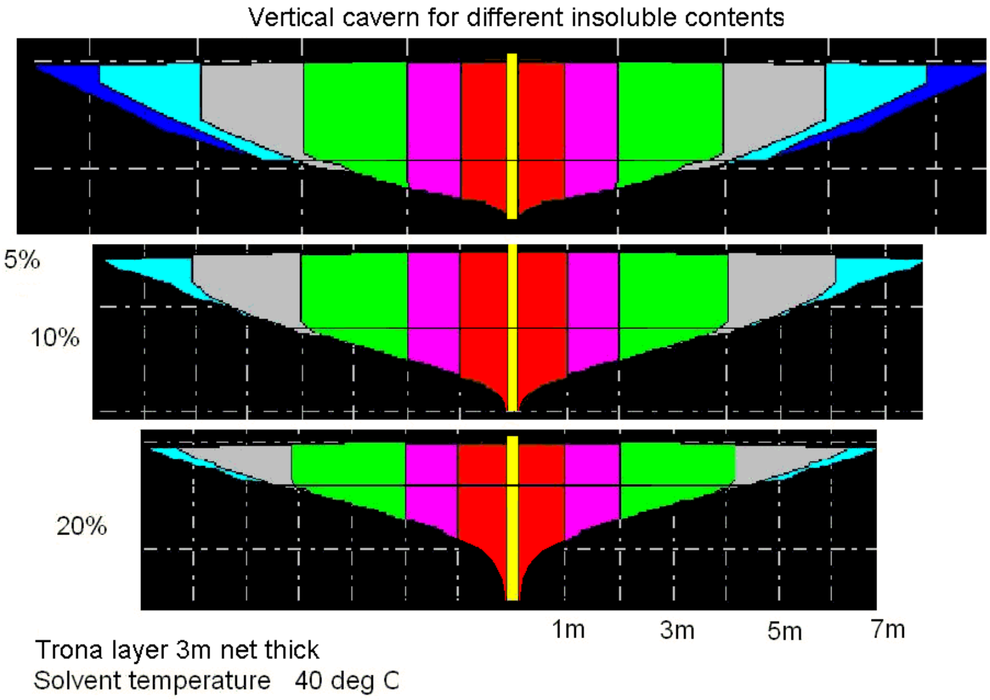


Figure 7.19 Vertical caverns for different insoluble contents in trona layer of 3m net thick at 40°C solvent temperature

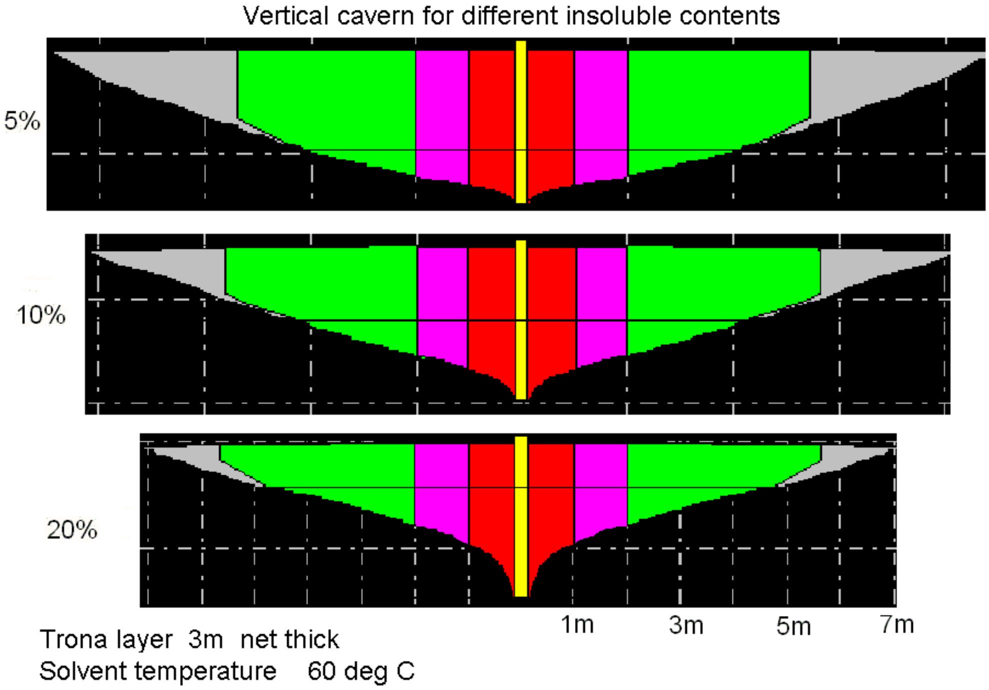


Figure 7.20 Vertical caverns for different insoluble contents in trona layer of 3m net thick at 60°C solvent temperature

Ineffectiveness of the leaching time during last part of each cavern leaching is connected with a declining leaching surface of cavern wall. The cavern edges, between the isolated roof and the bottom partially covered by insolubles, are becoming very sharp and narrow, when cavern is big enough. In such conditions leaching is going slower and slower and finally it stops. So, a total leaching time encompasses an effective leaching time during first part of vertical cavern development and ineffective leaching time during second part of vertical cavern development. To properly compare these figures for different cavern sizes, one should eliminate ineffectiveness, as it is blurring the comparison. For this purpose, in the Tables 7.3, 7.4 and 7.5 additional time was shown – time to reach during leaching, a radius 3 m, as such a radius is attainable for all studied cases of caverns, even these smallest.

CHAPTER 8

CONCLUSIONS

1. Vertical caverns are developed not directly for trona exploitation purposes. They are a target to be reached by horizontal wells, made using directional drilling, and they are supplying the volume inside trona layer for easy intake and output the production soda brine, coming from horizontal well.

2. Vertical caverns of considerable diameter can be properly leached out in trona layers of even small thickness. In Figure 7.15 and 7.16 it is seen that, even in trona layer 1 m thick (net thickness for leaching), a cavern with 6 m or 10 m of diameter could be developed, depending on trona insoluble content.

3. The fundamental condition for proper vertical cavern leaching is proper cavern roof isolation. If there is no isolation, or only part of the roof is isolated, the cavern will be quickly over-leached up in vertical direction through thin protective remaining layer of trona in the roof and as a result of this, covered by insolubles from overlaying spoil layer.

4. The proper leaching technology during vertical cavern development is direct circulation (injection near the bottom of layer, production near the roof), using two tubing columns. The annulus space between outer tubing and casing is used for oil isolation. Oil should be added in small amounts continuously during all leaching period.

5. The better trona layer quality, the bigger vertical cavern is possible to leach. By quality one should consider both – trona layer thickness and insoluble content in trona. In thin trona layer with 20% of insolubles only a 6 m of diameter cavern is possible to leach (Figure 7.15), but in 3 m thick trona layer with 5% of insolubles as big as 18 m of diameter cavern is possible to leach (Figure 7.20).

6. The leaching time (effective one) is depending mainly on temperature of the solvent (Tables 7.3, 7.4, 7.5). For 40°C it is between 37 and 42 days to reach 3m of cavern radius, with a weak dependency on layer thickness or insolubles. For 60°C it is between 20 and 23 days to reach 3m of cavern radius, with the same weak dependency on layer thickness or insolubles.

7. The conclusion from the above time-dependencies is that a minimum time to develop a vertical cavern is 25 days (if hot enough solvent is supplied) or 40 days (if solvent temperature is around 40°C) and that this time could be more or less similar for all caverns. The further possible development of vertical caverns (for better trona layer quality) can be made during preparatory leaching of connected wells (horizontal – vertical). The mean leaching time for Beypazari field vertical caverns was about 1 month (with solvent temperature between 40°C and 60°C), but some caverns were switched off too early, and some were in inefficient leaching too long.

8. The concentration of soda brine (total alkalinity) during vertical cavern leaching never will be high – for the best cases analyzed here, it is below 80 kg/m^3 (with solvent TA 30 kg/m^3) and similar low concentrations were observed also during vertical cavern leaching in ETI Soda Beypazari field. As such brine is not good enough for production; it should be stored and re-used as solvent for further saturation.

9. If the thickness of trona layer is more than 3 m (and such conditions are occurring locally in the Beypazari deposit), the vertical cavern leaching should start in the bottom part of this layer not higher than 3 m. Upper part of the layer should be isolated and left for future cavern development upwards, if the pair exploitation will be well advanced. If not – if one starts to leach a higher vertical cavern, the lower part of trona deposit will be lost and quickly covered by insolubles, especially if there is higher insoluble content. One can see the sharp angle of the cavern bottom covered by the sump even on the Figure 7.19 and 7.20 (20%). This angle will be much sharper for caverns higher than 3 m.

10. The vertical cavern should be finally as big as possible, as its main role in the further exploitation of the pair of wells is to keep safe empty volume around the production tubing and do not allow to cover it by insolubles coming from horizontal well.

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APPENDIX

Figure 1 Leaching surfaces of samples taken from heap stored during decline driving

Figure 2 Leaching surfaces of samples taken from V004 vertical well U-2 seam

Figure 3 Leaching surfaces of samples taken from V004 vertical well U-5 seam

Figure 4 Leaching surfaces of samples taken from V004 vertical well U-6 seam

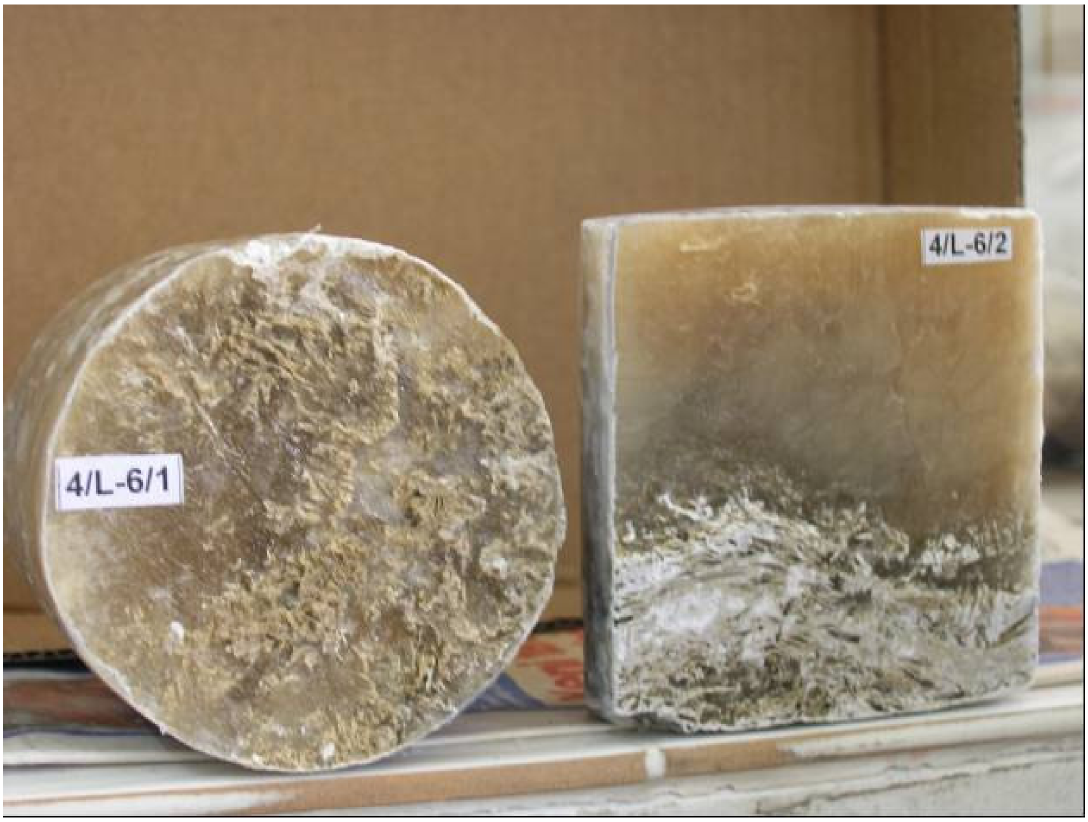

Figure 5 Leaching surfaces of samples taken from V004 vertical well L-6 seam

Figure 6: Leaching surfaces of samples taken from V004 vertical well L-6 seam

Figure 7: Leaching surfaces of samples taken from V005 vertical well L-6 seam

Figure 8 Leaching surfaces of samples taken from V005 vertical well L-6 seam