ASSESSMENT OF LOW TEMPERATURE

GEOTHERMAL RESOURCES

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ABSTRACT

ASSESSMENT OF LOW TEMPERATURE GEOTHERMAL RESOURCES

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One of the most applicable methods of low-temperature geothermal resource assessment is volumetric method. While applying volumetric method, the values of uncertain parameters should be determined. An add-in software program to Microsoft EXCEL, @RISK, is used as a tool to define the uncertainties of the parameters in volumetric equation. In this study, Monte Carlo simulation technique is used as the probabilistic approach for the assessment of low-temperature Balçova-Narlıdere geothermal field.

Although Balçova-Narlıdere geothermal field is being utilized for several direct heat applications, there exists limited data for resource assessment calculations. Assessment studies using triangular and uniform distribution type functions for each parameter gave the mean values of recoverable heat energy of the field as 25.1 MW_t and 27.6 MW_t, respectively. As optimistic values (90%), those values were found as 43.6 MW_t and 54.3 MW_t. While calculating these numbers, a project life of 25 years with a load factor of 50% is used.

Key Words: Assessment, Low temperature, Geothermal Reservoir, Monte Carlo Simulation, Risk Analysis, Volumetric Method

ÖZ

DÜŞÜK SICAKLIKTAKİ JEOTERMAL KAYNAKLARIN DEĞERLENDİRİLMESİ

Arkan, Serkan

Yüksek Lisans, Petrol ve Doğal Gaz Mühendisliği Bölümü

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Hacimsel metot düşük sıcaklıktaki jeotermal kaynakların değerlendirilmesinde en çok uygulanmakta olan yöntemdir. Hacimsel metodu uygularken, belirsiz parametrelerin değerleri belirlenmelidir. Microsoft EXCEL'e ek bir yazılım programı olan @RISK hacimsel denklemdeki parametrelerin belirsizliklerini tanımlamak için bir araç olarak kullanıldı. Bu çalışmada, düşük sıcaklıktaki Balçova-Narlıdere jeotermal sahasının değerlendirilmesi için Monte Carlo simulasyon tekniği tahmini bir yaklaşım olarak kullanıldı.

Balçova-Narlıdere jeotermal sahası doğrudan sıcaklık uygulamalarında kullanılıyor olmasına rağmen jeotermal kaynağın hesaplanması için gereken verilerden sınırlı sayıda mevcuttur. Her bir parametre için, üçgen ve tek bidüze dağılım fonksiyonları kullanılarak yapılan değerlendirme çalışmaları, sahanın ısı enerjisi olarak sırasıyla ortalama 25.1 MW_t ve 27.6 MW_t değerlerini vermiştir. İyimser değerlere göre (% 90) bu veriler 43.6 MW_t ve 54.3 MW_t olarak bulunmuştur. Bu sayılar hesaplanırken, % 50 lik bir yük faktörüyle 25 yıllık proje ömrü kullanıldı.

Anahtar kelimeler: Değerlendirme, Düşük Sıcaklık, Jeotermal Rezervuar, Monte Carlo Simulasyonu, Risk Analizi, Hacimsel Metot

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CHAPTER 1

INTRODUCTION

Geothermal energy is heat energy originating deep in the earth's molten interior. It is this heat energy, which is responsible for tectonic plates, volcanoes and earthquakes. The temperature in the earth's interior is as high as 7000 °C, decreasing to 650 – 1200 °C at depths of 80km-100km (Wright, 1998). Through the deep circulation of groundwater and the intrusion of molten magma into the earth's crust to depths of only 1km-5km, heat is brought closer to the earth's surface. The hot molten rock heats the surrounding groundwater, which is forced to the surface in certain areas in the form of hot steam or water, e.g. hot springs and geysers. The heat energy close to, or at, the earth's surface can be utilized as a source of energy, namely geothermal energy.

The total geothermal resource is vast. An estimated 100PW (1×10^{17} W) of heat energy is brought to the earth's surface each year (World Energy Council, 1994). However, geothermal energy can only be utilized in regions where it is suitably concentrated. These regions correspond to areas of earthquake and volcanic activity, which occur at the junctions of the tectonic plates that make up the earth's crust. It is at these junctions that heat energy is conducted most rapidly from the earth's interior to the surface, often manifesting itself as hot springs or geysers.

Resource assessment can be defined as the broad-based estimation of future supplies of minerals and fuels. This assessment requires not only the estimation of the amount of a given material in a specified part of the Earth's crust, but also the fraction of that material that might be recovered and used under certain assumed economic, legal, and technological conditions.

Furthermore, resource assessment includes not only the quantities that could be produced under present economic conditions, but also the quantities not yet discovered or that might be produced with improved technology or under different economic conditions.

Geothermal resources consist primarily of *thermal energy*, and thus geothermal resource assessment is the estimation of the thermal energy in the ground, referenced to mean annual temperature, coupled with an estimation of the amount of this energy that might be extracted economically and legally at some reasonable future time. Geothermal resource estimation also includes estimates of the amount of *byproducts* that might be produced and used economically along with the thermal energy. These byproducts can be metals or salts dissolved in saline geothermal fluids or gases such as methane dissolved in geopressured fluids.

Assessment of geothermal resources involves determination of the location, size, and geologic characteristics of each resource area to calculate the accessible resource base (*thermal energy* stored in the reservoir) and the resource (*thermal energy* recoverable at the wellhead).

Methodologies used for geothermal resource assessment were reviewed by Muffler and Cataldi (1977; 1978) and divided into four main categories: *Surface thermal flux method, Volume method, Planar fracture method and Magmatic heat budget method*, among which the volume method is the most suitable for many low-temperature reservoirs.

The *volume method* involves the calculation of the thermal energy contained in a given volume of rock and water and then the estimation of how much of this energy might be recoverable. The *thermal energy* in the ground can readily be calculated as the product of the volume of a geothermal reservoir, the *mean temperature*, the *porosity*, and the *specific heats* of rock and water. Most of the variables in the equation of volume method (aerial extension, thickness, porosity, etc.) exhibit some uncertainty. These uncertainties are overcome by probabilistic approach using Monte Carlo techniques to construct cumulative probability curves for a given geothermal reservoir.

In this study, stored energy and producible heat energy of a low-temperature geothermal reservoir of Turkey, Balçova-Narlıdere, were determined by applying volume method. An add-in software to Microsoft EXCEL, @RISK, was used to carry out Monte Carlo simulation studies.

CHAPTER 2

GEOTHERMAL ENERGY

The presence of volcanoes, hot springs, and other thermal phenomena must have led our ancestors to guess that parts of the interior of the Earth were hot. However, it was not until a period between the sixteenth and seventeenth century, when the first mines were excavated to a few hundred meters below ground level that man deduced, from simple physical sensations that the Earth's temperature increased with depth.

The first measurements by thermometer were probably performed in 1740, in a mine near Belfort, in France (Bullard, 1965). By 1870 modern scientific methods were being used to study the thermal regime of the Earth, but it was not until the twentieth century, and the discovery of the role-played by *radiogenic heat*, that we could fully comprehend such phenomena as heat balance and the Earth's thermal history. All modern thermal models of the Earth, in fact, must take into account the heat continually generated by the decay of the long-lived radioactive isotopes of uranium (U238, U235), thorium (Th232) and potassium (K40), which are present in the Earth (Lubimova, 1968). Added to *radiogenic heat*, in uncertain proportions, are other potential sources of heat such as the primeval energy of planetary accumulation. Realistic theories on these models were not available until the 1980s, when it was demonstrated that there was no equilibrium between the *radiogenic heat* generated in the Earth's interior and the heat dissipated into space from the Earth, and that our planet is slowly cooling down (Dickson and Fanelli, 1995).

The cooling process is, however, very slow. The temperature of the *mantle* (Figure 2.1) has decreased no more than 300-350 °C in three billion years, remaining at about 4000 °C at its base. Estimates from more than twenty years ago gave the total heat content of the Earth, reckoned above an assumed average surface temperature of 15 °C, in the order of 12.6 x 10^{24} MJ, and that of the *crust* in the order of 5.4 x 10^{21} MJ (Armstead, 1983). So far our utilization of this energy has been limited to areas in which geological conditions permit a carrier to transfer the heat from deep hot zones to or near the surface, thus giving rise to geothermal resources, but innovative techniques in the near future may offer new perspectives in this sector. In the early part of the nineteenth century the geothermal fluids were already being exploited for their energy content.

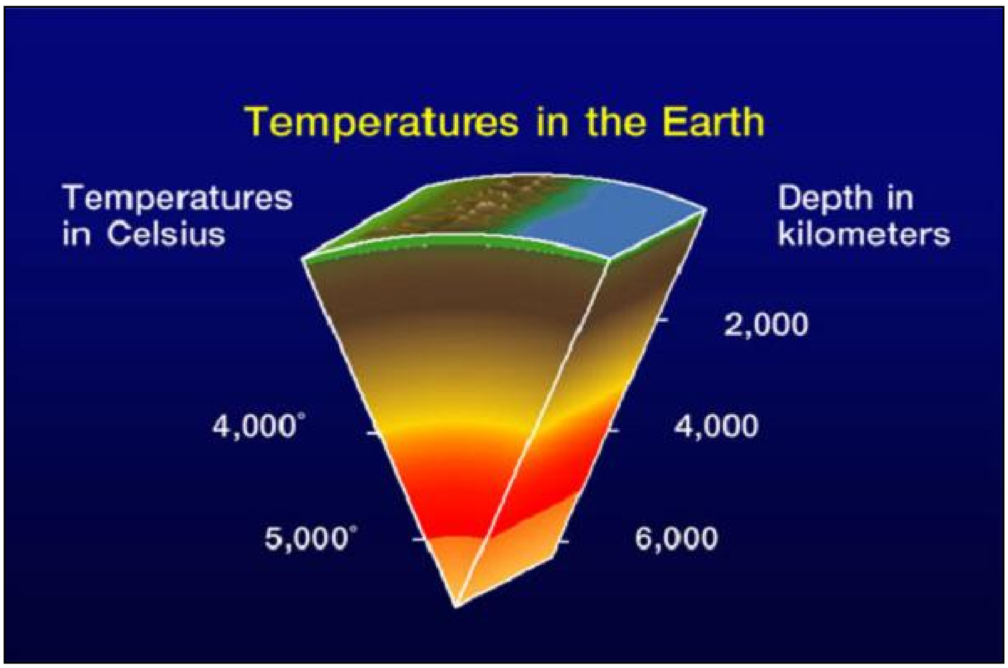


Figure 2.1 Temperatures in the earth (Geothermal Education Center http://geothermal.marin.org/)

The *geothermal gradient* expresses the increase in temperature with depth in the Earth's crust. Down to the depths accessible by drilling with modern technology, the average geothermal gradient is about 2.5-3 °C/100 m. For example, if the temperature within the first few meters below ground-level, which on average corresponds to the mean annual temperature of the external air, is 15 °C, then we can reasonably assume that the temperature will be about 65 °C -75 °C at 2000 m depth, 90 °C - 105 °C at 3000 m and so on for a further few thousand meters. There are, however, vast areas in which the geothermal gradient is far from the average value.

In areas in which the deep rock basement has undergone rapid sinking, and the basin is filled with geologically very young sediments, the geothermal gradient may be lower than 1 °C/100 m. On the other hand, in some geothermal areas the gradient is even higher than ten times the average value.

The temperature increase with depth, as well as volcanoes, geysers, hot springs etc., are in a sense the visible or tangible expression of the heat in the interior of the Earth, but this heat also generates other phenomena that are less noticeable by man, but of such magnitude that the Earth has been compared to an immense thermal engine. These phenomena will be described, referred to the *plate tectonics* theory, and their relationship with geothermal resources.

Our planet consists of a *crust*, which reaches a thickness of about 20-65 km in continental areas and about 5-6 km in oceanic areas, a *mantle*, which is roughly 2900 km thick, and a *core*, about 3470 km in radius (Figure 2.2).

The physical and chemical characteristics of the crust, mantle and core vary from the surface of the Earth to its center. The outermost shell of the Earth, known as the *lithosphere*, is made up of the crust and the upper layer of the mantle. Ranging in thickness from less than 80 km in oceanic zones to over 200 km in continental areas, the lithosphere behaves as a rigid body. Below the lithosphere is the zone known as the *asthenosphere*, 200-300 km in thickness, and of a less rigid or more plastic behavior. In other words, on a geological scale, where time is measured in millions of years, this part of the Earth behaves in much the same way as a fluid in certain processes.

Because of the difference in temperature between the different parts of the *asthenosphere*, convective movements and, possibly, convective cells were formed some tens of millions of years ago. Their extremely slow movement (a few centimeters per year) is maintained by the heat produced continually by the decay of the radioactive elements and the heat coming from the deepest parts of the Earth. Immense volumes of deep, hotter rocks, less dense and lighter than the surrounding material, rise with these movements towards the surface, while the colder, denser and heavier rocks near the surface tend to sink, re-heat and rise to the surface once again; very similar to what happens to water boiling in a pot or kettle (Figure 2.3).

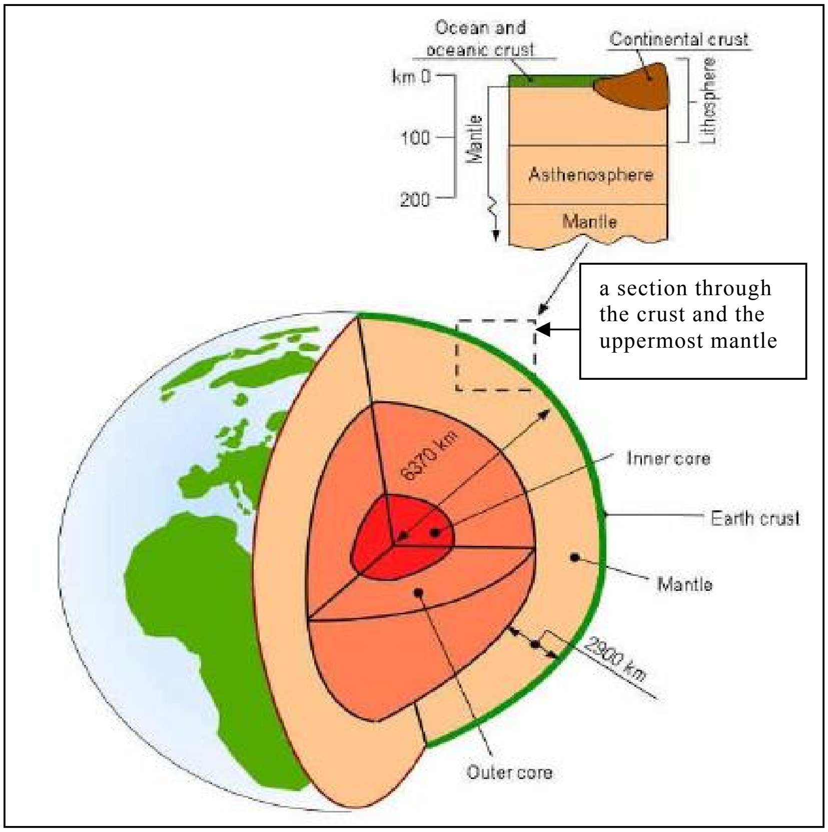


Figure 2.2 The earth's crust, mantle, and core (Dickson and Fanelli, 1995)

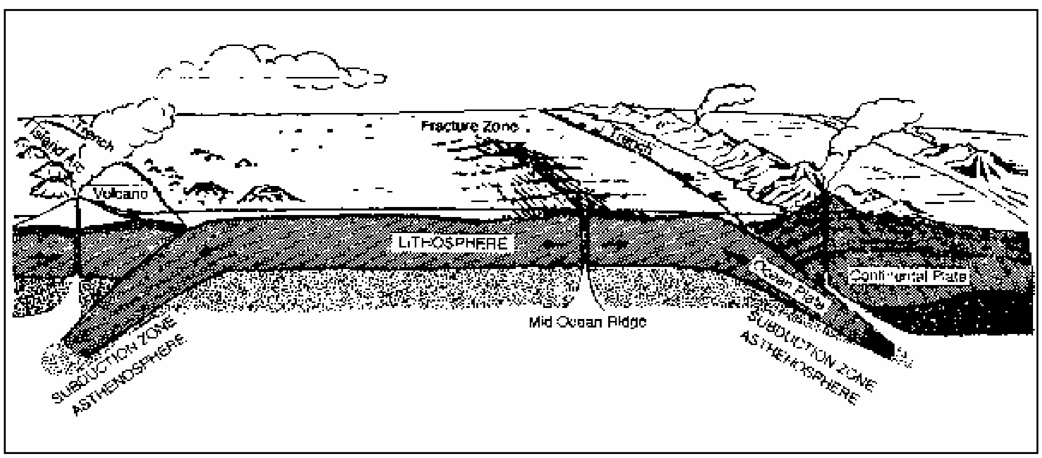


Figure 2.3 Schematic cross-section showing plate tectonic processes (Dickson and Fanelli, 1995).

In zones where the lithosphere is thinner, and especially in oceanic areas, the lithosphere is pushed upwards and broken by the very hot, partly molten material ascending from the asthenosphere, in correspondence to the ascending branch of convective cells. It is this mechanism that created and still creates the *spreading ridges* that extend for more than 60,000 km beneath the oceans, emerging in some places (Azores, Iceland) and even creeping between continents, as in the Red Sea. A relatively tiny fraction of the molten rocks upwelling from the asthenosphere emerges from the crests of these ridges and, in contact with the seawater, solidifies to form a new oceanic crust. Most of the material rising from the asthenosphere, however, divides into two branches that flow in opposite directions beneath the lithosphere. The continual generation of new crust and the pull of these two branches in opposite directions have caused the ocean beds on either side of the ridges to drift apart at a rate of a few centimeters per year.

Consequently, the area of the ocean beds (the oceanic lithosphere) tends to increase. The ridges are cut perpendicularly by enormous fractures, in some cases a few thousand kilometers in length, called *transform faults*. These phenomena, commonly referred as *plate tectonics*, lead to a simple observation. Since there is apparently no increase in the Earth's surface with time, the formation of new lithosphere along the ridges and the spreading of the ocean beds must be accompanied by a comparable shrinkage of the lithosphere in other parts of the globe. This is indeed what happens in *subduction zones*, the largest of which are indicated by huge ocean trenches, such as those extending along the western margin of the Pacific Ocean and the western coast of South America. In the subduction zones the lithosphere folds downwards, plunges under the adjacent lithosphere and re-descends to the very hot deep zones, where it is digested by the mantle and the cycle begins all over again. Part of the lithosphere material returns to a molten state and may rise to the surface again through fractures in the crust. As a consequence, *magmatic arcs* with numerous volcanoes are formed parallel to the trenches, on the opposite side to that of the ridges. Where the trenches are located in the ocean, as in the Western Pacific, these *magmatic arcs* consist of chains of volcanic islands; where the trenches run along the margins of continents the arcs consist of chains of mountains with numerous volcanoes, such as the Andes.

Spreading ridges, transform faults and subduction zones form a vast network that divides our planet into six immense and several other smaller lithosphere areas or *plates* (Figure 2.4). Because of the huge tensions generated by the Earth's thermal engine and the asymmetry of the zones producing and consuming lithosphere material, these plates drift slowly up against one another, shifting position continually. The margins of the plates correspond to weak, densely fractured zones of the crust, characterized by an intense seismicity, by a large number of volcanoes and, because of the ascent of very hot materials towards the surface, by a high terrestrial heat flow. As shown in Figure 2.4, the most important geothermal areas are located around plate margins.

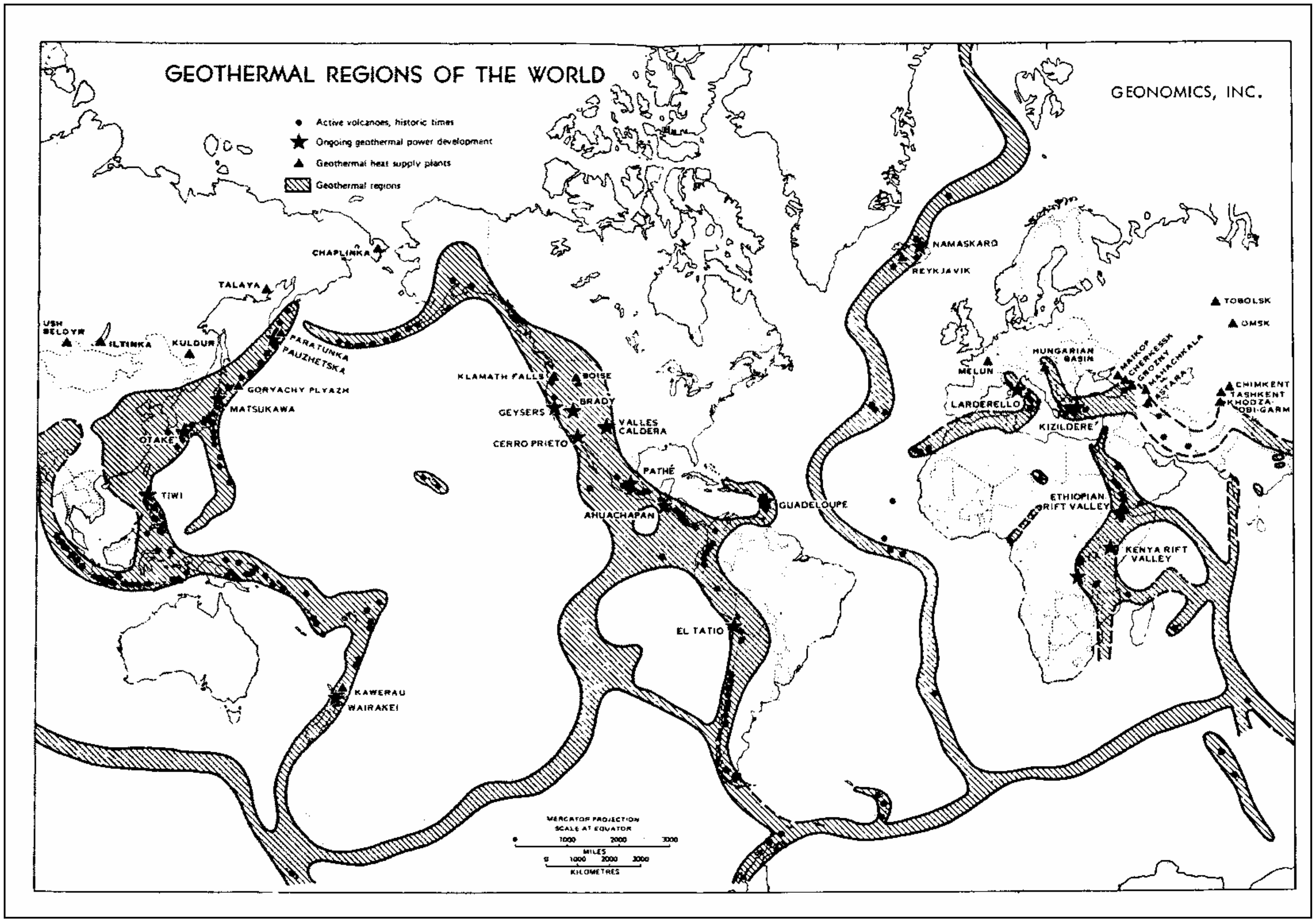


Figure 2.4 World pattern of plates and location of geothermal fields (Wahl, 1977).

2.1 GEOTHERMAL SYSTEMS

Geothermal systems can therefore be found in regions with a normal or slightly above normal geothermal gradient, and especially in regions around plate margins where the geothermal gradients may be significantly higher than the average value. In the first case low temperatures, usually no higher than 100 °C at economic depths, will characterize the systems; in the second case the temperatures could cover a wide range from low to very high, and even above 400 °C.

What is a *geothermal system* and what happens in such a system? It can be described schematically as "convecting water in the upper crust of the Earth, which, in a confined space, transfers heat from a heat source to a heat sink, usually the free surface" (Hochstein, 1990). A geothermal system is made up of three main elements: a *heat source*, a *reservoir* and a *fluid*, which is the carrier that transfers the heat. *The heat source* can be either a very high temperature (> 600 °C) magmatic intrusion that has reached relatively shallow depths (5-10 km) or, as in certain low temperature systems, the Earth's normal temperature, which increases with depth. *The reservoir* is a volume of hot permeable rocks from which the circulating fluids extract heat. The reservoir is generally overlain by a cover of impermeable rocks and connected to a surfacial recharge area through which the meteoric waters can replace or partly replace the fluids that escape from the reservoir by natural means (e.g. through springs) or are extracted by boreholes. *The geothermal fluid* is water, in the majority of cases meteoric water, in the liquid or vapor phase, depending on its temperature and pressure. This water often carries with it chemicals and gases such as CO_2, H_2S, etc. Figure 2.5 is a simple representation of an ideal geothermal system.

The mechanism underlying geothermal systems is governed by *fluid convection*. Figure 2.6 describes schematically the mechanism in the case of an intermediate temperature hydrothermal system. Convection occurs because of the heating and consequent thermal expansion of fluids in a gravity field; heat, which is supplied at the base of the circulation system, is the energy that drives the system. Heated fluid of lower density tends to rise and to be replaced by colder fluid of high density, coming from the margins of the system. Convection, by its nature, tends to increase temperatures in the upper part of a system as temperatures in the lower part decrease (White, 1973).

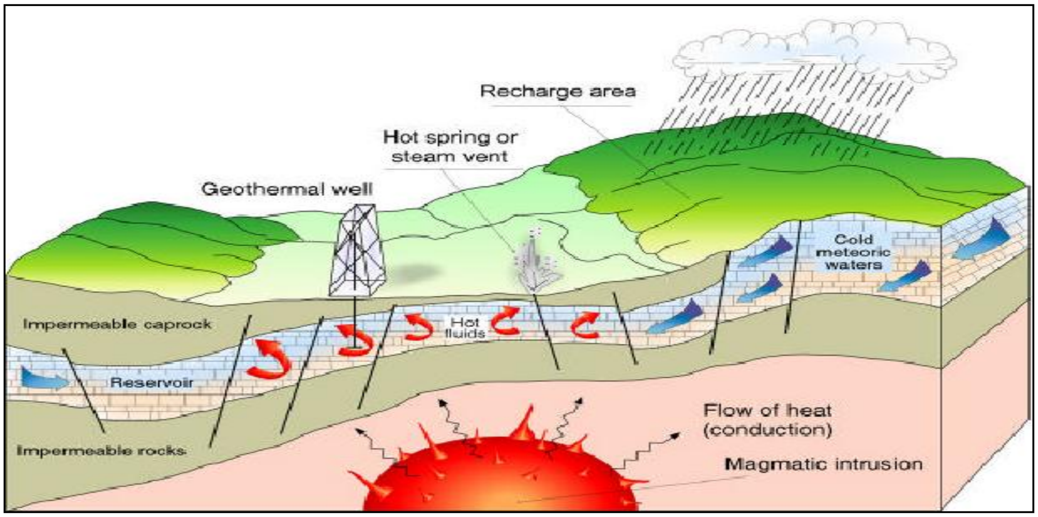
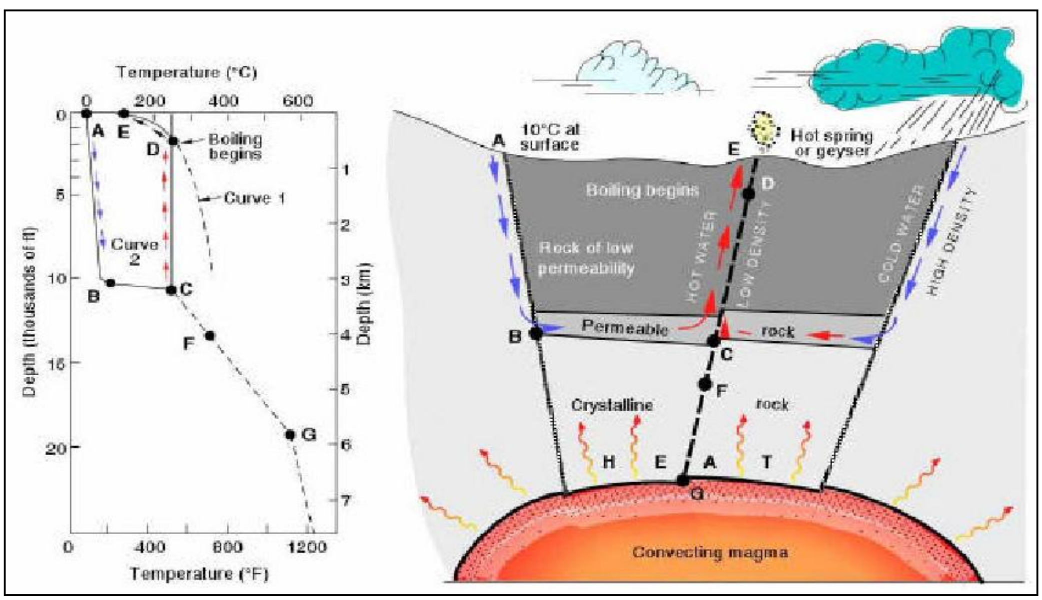


Figure 2.5 Schematic representation of an ideal geothermal system (Dickson and Fanelli, 1995).



Curve 1: reference curve for the boiling point of pure water

Curve 2: the temperature profile along the typical circulation route from point A (recharge) to point E (discharge)

Figure 2.6 Model of a geothermal system (White, 1973).

The phenomenon that has already described may seem quite a simple one but the reconstruction of a good model of a real geothermal system is by no means easy to achieve. It requires skill in many disciplines and a vast experience, especially when dealing with high temperature systems. Geothermal systems also occur in nature in a variety of combinations of geological, physical and chemical characteristics, thus giving rise to several different types of system.

Of all the elements of a geothermal system, the heat source is the only one that needs to be natural. Providing conditions are favorable, the other two elements could be artificial. For example, the geothermal fluids extracted from the reservoir to drive the turbine in a geothermal power plant could, after their utilization, be injected back into the reservoir through specific *injection wells*. In this way the natural recharge of the reservoir is integrated by an artificial recharge. For many years now re-injection has been adopted in various parts of the world as a means of drastically reducing the impact on the environment of power-plant operations.

There are four types of geothermal resources: *hydrothermal*, *geopressured*, *hot dry rock* and *magma*. Of the four types, only hydrothermal resources are currently commercially exploited.

2.1.1 Magma

Magma, the largest geothermal resource, is molten rock found at depths of 3000 km-10000 km and deeper, and therefore not easily accessible. It has a temperature, which ranges from 700 - 1200 °C. The resource has not been well explored to date.

2.1.2 Hydrothermal

Hydrothermal, resources arise, when hot water and/or steam is formed in fractured or porous rock at shallow to moderate depths (100m to 4.5km) as a result of either the intrusion in the earth's crust of molten magma from the earth's interior, or the deep circulation of water through a fault or fracture (World Energy Council, 1994) (Figure 2.7). *High temperature* hydrothermal resources, with temperatures from 180 °C to over 350 °C, are usually heated by hot molten rock. While *low temperature* resources, with temperatures from 100 °C to 180 °C, can be produced by either process (Wright, 1998).

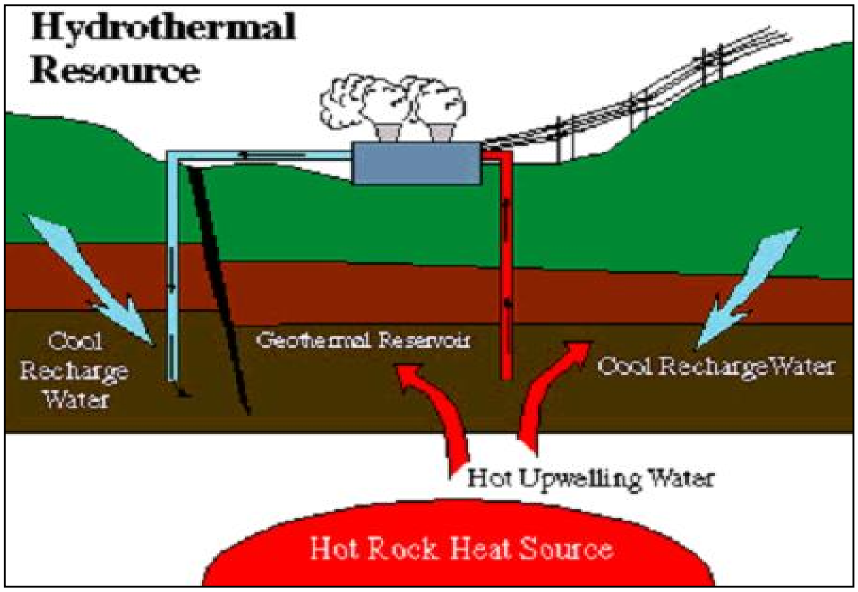


Figure 2.7 Hydrothermal resource (Geothermal Education Center http://geothermal.marin.org/)

Hydrothermal resources come in the form of either steam or hot water depending on the temperatures and pressures involved. *High-temperature* resources are usually used for electricity generation (Figure 2.8), while *low-temperature* resources are used mostly in direct heating applications.

Hydrothermal resources require three basic components a *heat source* (e.g. crystallized magma), *aquifer* containing accessible water, and an impermeable *cap rock* to seal the aquifer. You can see the representation of these basic components in Figure 2.9, which is a simplified cross section of a geothermal site. These terms will be explained specifically in the section 2.2. Drilling into the aquifer, and extracting the hot water or steam usually tap the geothermal energy.

Figure 2.8 Electricity generation from a high-temperature reservoir in New Zealand (ACRE, 2003).

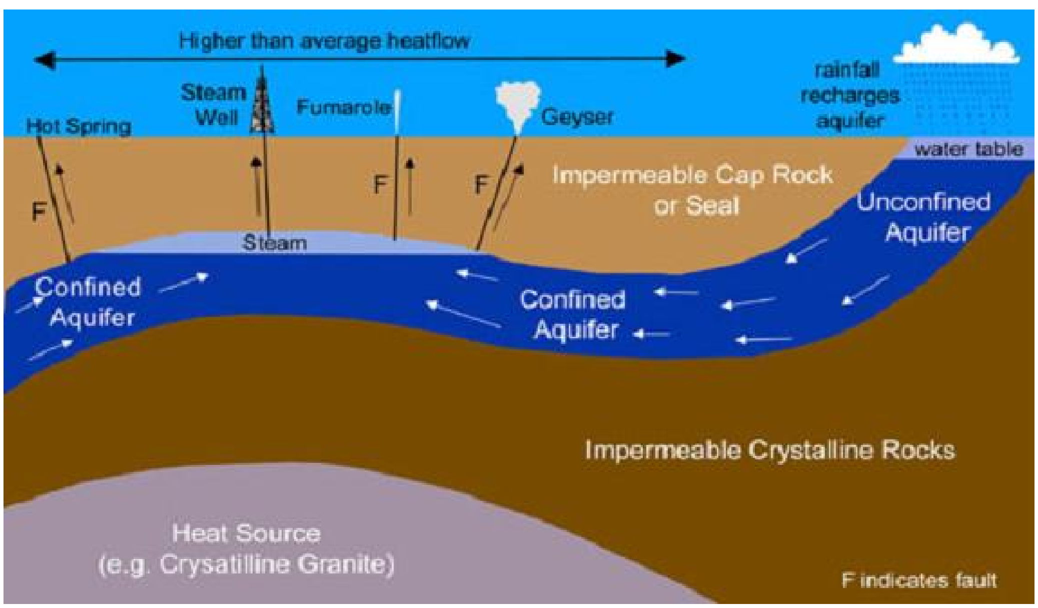


Figure 2.9 Simplified cross section of the second characteristics of a geothermal site (ACRE, 2003).

2.1.3 Geopressured

Geopressured geothermal resources consists of hot brine saturated with methane, found in large, deep aquifers under high pressure. The water and methane is trapped in sedimentary formations at a depth of about 3km-6km (World Energy Council, 1994). The temperature of the water is in the range of 90 °C- 200 °C. Three forms of energy can be obtained from geopressured resources: thermal energy, hydraulic energy from the high pressure and chemical energy from burning the dissolved methane gas. The major region of geopressured reservoirs discovered to date is in the northern Gulf of Mexico.

2.1.4 Hot Dry Rock

Hot dry rock (HDR) is a heated geological formation formed in the same way as hydrothermal resources, but containing no water as the aquifers or fractures required to conduct water to the surface are not present. This resource is virtually limitless than hydrothermal resources. (Figure 2.10)

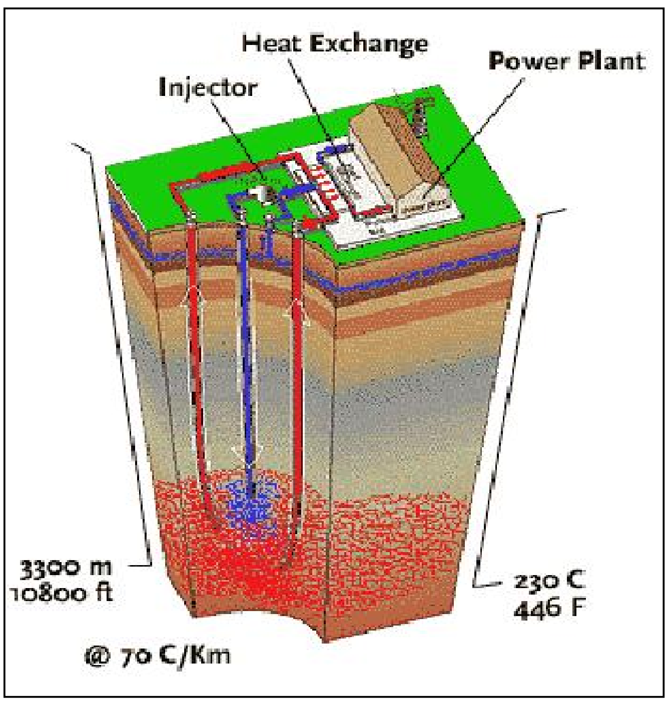


Figure 2.10 Hot dry rock technology (ACRE, 2003).

2.2 BASIC MODEL OF A HYDROTHERMAL RESERVOIR

The basic features of a hydrothermal reservoir are shown in Figure 2.11.

These features are:

- A source of natural heat of great output;
- An adequate *water supply*;
- An *aquifer*, or permeable reservoir rock;
- A *cap rock*.

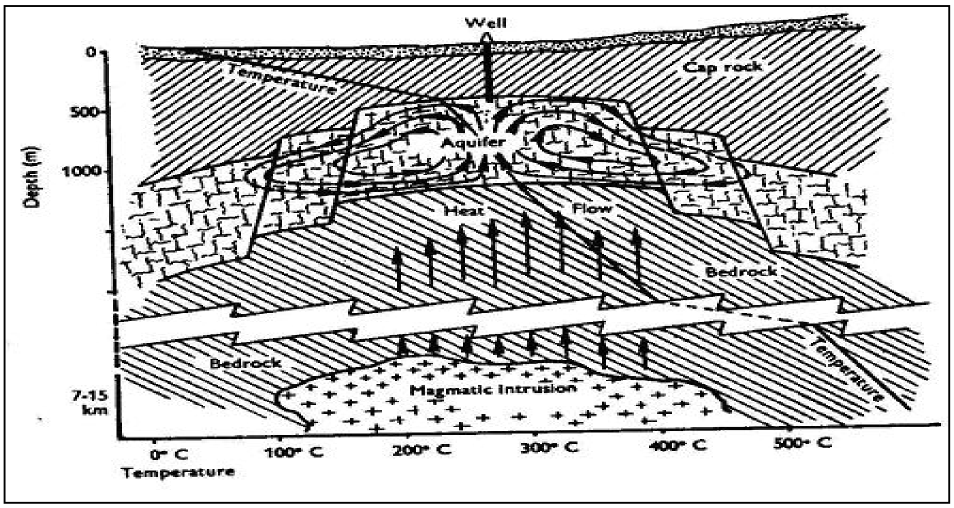


Figure 2.11 Basic model of a steam field (Christopher and Armstead, 1973).

2.2.1 The Source of Heat

There is general agreement that the source of heat is a *magmatic* intrusion into the earth's crust, having a temperature of 600 to 900 °C, often at depths of the order of 7 to 15 km. This view is supported by various facts and reasons notably that all the known commercial fields are in regions where volcanic activity has occurred during recent Miocene Quaternary times, or is still occurring. Some fields are actually situated on, or close to volcanoes (e.g. Japan and Central Mexico), whereas others (e.g. Larderello) are not directly linked with a centre of recent volcanic activity. Larderello is nevertheless located within the northern part of the large Tyrrhenian volcanic province.

2.2.2 Water Supply

Early hypotheses about geothermal fluids suggested that they were of *magmatic*, or juvenile origin, that is, water vapor and gases released from solution in the magma when the pressure is reduced. This may still be partially true it is now believed that at least 90 % of the water in a geothermal reservoir is *meteoric*, originating from rainwater. Thus, referring to Figure 2.11, it would appear that most of the water in the aquifer is of meteoric origin and that it is heated conductively through a largely impermeable base rock, even though some relatively small quantity of magmatic steam may penetrate this base rock through faults and fissures.

As hot fluid is withdrawn from bores or from surface vents, the hydrological balance of the system is restored, or partially restored, by the inflow of new water. There are often clearly visible *recharge areas*, where the permeable reservoir terrain outcrops, permitting the ingress of rainwater. At *Larderello* there are outcrops of the Mesozoic carbonatic and evaporitic series. Here, it is possible to calculate from observed rainfall and run-off the quantity of meteoric water entering the reservoir each year. In other geothermal fields matters are not always so simple. Many hydrothermal systems are dynamic, with water entering at some high level and leaving at some low level. Our knowledge of water movements in deep aquifers is very limited especially where these lie below sea level, as is so often the case.

2.2.3 The Aquifer

A wet well may produce some hundreds of tons per hour of mixed fluid. The maintenance of such high flow rates implies a high degree of permeability in the aquifer, with porosity playing only a secondary part. Any permeable rock can serve as a good geothermal reservoir. At the *Geysers* it is greywacke with fissure permeability; at *Larderello* a carbonate rock with karstic permeability; at *Wairakei*, fissured ignimbrite overlain with rhyolite and pumice breccia; at *Otake*, a permeable volcanic tuff; at *Cerro Prieto*, deltaic sands.

2.2.4 Cap Rock

A *cap rock* is a layer of rock of low permeability overlying the *aquifer*. All steam-producing fields have a *cap rock*. Some have been formed as original impervious rocks, such as the *flysch* formation at *Larderello*, the *lacustrine Huka* formation at *Wairakei*, the *deltaic clay* in the *Imperial Valley* and *Cerro Prieto* fields. Elsewhere, the cap rock may have become impervious as a direct result of thermal activity. For example, at *The Geysers* and at *Otake*, the shallow rocks are hard fractured formations. It is probable that before the beginning of thermal activity these rocks had fissure permeability, but that this activity itself has caused the sealing of the permeable passages. This could have occurred by two geochemical processes:

- The deposition of minerals from solution, mainly silica;
- The hydrothermal alteration of rock, causing kaolinisation.

Deposition of silica can easily be observed in The Geysers field: fractures of one-inch width, completely filled and sealed by silica and calcite are common features. Kaolinisation, associated with other more complicated hydrothermal rock alteration, is also widespread and prominent. Hydrothermal alteration can be recognized by the bleaching of greywacke, and in places by the lack of vegetation. Hydrothermal alteration is a very complicated, and not fully understood, geochemical process that changes from place to place.

Sometimes a hot *aquifer* may intercalate in places with the cap rock. Where such zones have been exploited they have been productive only for a limited time and it has been necessary to deepen the bores into the main convective reservoir.

A *low temperature* hot water field may sometimes occur in an environment similar to that shown in Figure 2.11. It can also occur in fields devoid of cap rock, in which case the model is drafted somewhat in the manner of Figure 2.12, where the *thermal gradient* and depth of the permeable aquifer are sufficient to maintain a convective circulation. The temperature in the upper part of the reservoir will not exceed the boiling point at atmospheric pressure, partly because water brought up convectively from depth will lose pressure (and temperature) as it rises, and partly because there may be mixing with cool ground waters (Armstead, 1973).

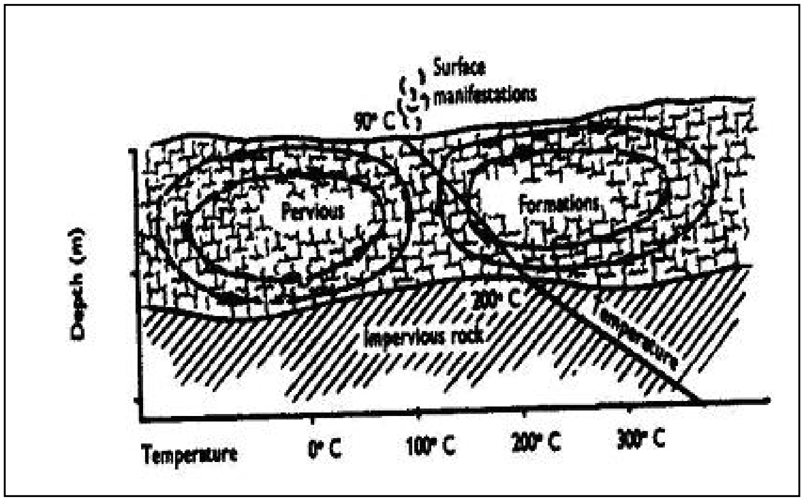


Figure 2.12 Basic model of a low temperature hot water field
(Christopher and Armstead, 1973).

CHAPTER 3

RESOURCE ASSESSMENT

Resource assessment can be defined as the broad-based estimation of future supplies of minerals and fuels. This assessment requires not only the estimation of the amount of a given material in a specified part of the Earth's crust, but also the fraction of that material that might be recovered and used under certain assumed economic, legal, and technological conditions. Furthermore, resource assessment includes not only the quantities that could be produced under present economic conditions, but also the quantities not yet discovered or that might be produced with improved technology or under different economic conditions.

Geothermal resources consist primarily of *thermal energy*, and thus geothermal resource assessment is the estimation of the thermal energy in the ground, referenced to mean annual temperature, coupled with an estimation of the amount of this energy that might be extracted economically and legally at some reasonable future time. Geothermal resource estimation also includes estimates of the amount of *byproducts* that might be produced and used economically along with the thermal energy. These byproducts can be metals or salts dissolved in saline geothermal fluids or gases such as methane dissolved in geopressured fluids.

A *resource assessment* is a statement made at a given time using a given data set and a given set of assumptions concerning economics, technology, etc. With respect to most commodities, both the data and the assumptions can change rapidly, the former primarily in response to exploration activities, the latter in response to technology development, economics, environmental constraints, social policy, etc. Consequently, a resource assessment is of only transitory value and must be updated periodically. This is particularly so for a resource like geothermal energy, for which exploration, development, and use are increasing rapidly and where the world-wide energy picture is in a state of flux as countries try to come to grips with finite fossil fuel resources, environment pollution, nuclear waste disposal, etc.

3.1 RESOURCE TERMINOLOGY

The need for explicit terminology concerning geothermal energy was emphasized by Muffler and Cataldi (1977; 1978). This terminology must be uniform and comparable from country to country and also must be compatible with the resource terminology used for other energy sources. A primary goal of energy resource estimation is the comparison of different energy sources, and to do this, the terminology used in the various disciplines must be coherent. An internally consistent geothermal terminology is of little value if it is incompatible with petroleum, uranium, and coal terminology. For a general description of mineral and fuel resource assessment see Schanz (1975a,1975b).

In building a classification of geothermal energy, *resource base* is the starting point and a general definition of *resource base* given by Schurr and Netschert (1960). "*Resource base* is all of a given material in the earth's crust within a given geographic area, whether its existence is known or unknown and regardless of cost considerations and of technological feasibility of extraction". *Resource base* thus provides an upper limit to any estimates of valuable materials in the earth and is obviously far greater than the amounts extractable and usable at any future time. Explicity excluded from resource base are materials in the mantle.

Resource was defined by Netschert (1958) and by Schurr and Netschert (1960): "*Resource* is the part of the resource base (including *reserves*) which seems likely to become available given certain technologic and economic conditions."

And finally, *reserve* was defined by Flawn (1966): "*Reserve* is the quantities of minerals that can be reasonably assumed to exist and which are producible with existing technology and under present economic conditions." The term resource base refers to material in the ground. The terms resource and reserve, however, refer only to the fraction of the material that can be recovered.

When dealing with specific concentration of material such as an ore deposit, a petroleum reservoir, or a geothermal reservoir, the ratio of the material (or energy) that can be recovered to the material (or energy) in place is termed the recovery factor. This factor is termed as the *reserve recovery factor* or the *resource recovery factor*, depending on whether it is used in the determination of reserves or resources.

Muffler and Cataldi (1977; 1978) recommended that geothermal energy terminology be made compatible with the terminology for other energy sources and that the term *geothermal resource* be restricted to that part of the thermal energy in the ground (referenced to mean annual temperature) that can be extracted economically and legally at some specified future time. This figure, expressed in terms of energy, is the only figure that can be compared meaningfully to the thermal energy equivalent of barrels of recoverable oil, cubic meters of gas, tons of coal, or kilograms of uranium. It is the recoverable geothermal energy that is useful and meaningful to an engineer and therefore should be termed the geothermal resource.

In recent years, it has become common to depict resources, reserves, and similar terms on rectangular diagrams that depict the degree of economic feasibility on the vertical axis and the degree of geological assurance on the horizontal axis. These diagrams were introduced by *McKelvey* (1968) and have come to to be termed *McKelvey diagrams*. As adopted by the U.S. Bureau of Mines and the U.S. Geological Survey (1976), the *McKelvey* diagram encompasses *total resources*, with the major vertical subdivisions being *economic* and *subeconomic* and the major horizontal subdivisions being *identified* and *undiscovered* (Figure 3.1).

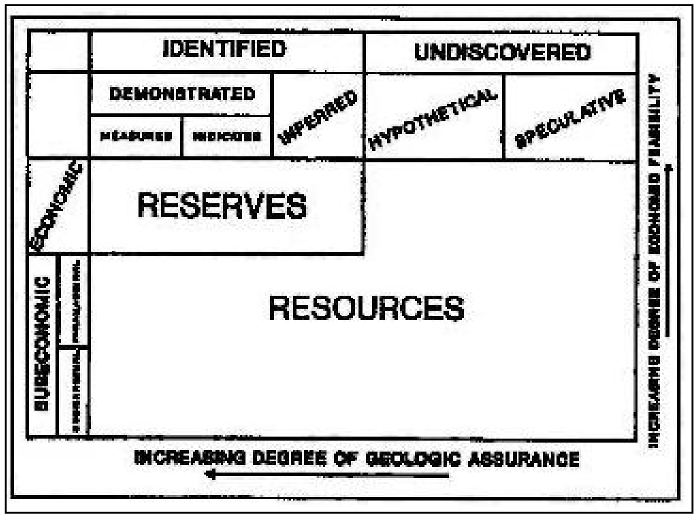


Figure 3.1 Classification of minerals resources (McKelvey, 1968).

It has been pointed out by Schanz (1975b) that this *McKelvey* diagram of the U.S. Geological Survey is open-ended and does not encompass all of a given material. Schanz further emphasizes that, in using this *McKelvey* diagram, one must continually keep in mind the physical existence of materials and energy beyond resources (i.e. materials and energy which we may not use until far into the future; Schanz, 1975b). As an example, there is no question that there is an immense quantity of aluminum in almost all types of crustal rocks. But aluminum resources are not considered to include all this aluminum, but only that aluminum in specific, restricted rock types where the aluminum occurs in such a concentration and such a form that it can be extracted under reasonable economics and technology (i.e., bauxite or laterite).

3.2 GEOTHERMAL RESOURCE TERMINOLOGY

Muffler and Cataldi (1977; 1978) attempted to develop a logical resource terminology specifically for geothermal energy. Adapting the general definition for resource base, *geothermal resource base* is defined as “all the heat in the Earth’s crust beneath a specific area, measured from local mean annual temperature”. The *accessible resource base* is the thermal energy at depths shallow enough to be tapped by drilling. In the forseeable future, whereas that fraction of the accessible resource base that might be extracted economically and legally at some reasonable future time is the *geothermal* *resource.* Both the accessible resource base and resource include *identified* and *undiscovered* components. Finally, the *geothermal reserve* is identified as geothermal energy that can be extracted legally today at a cost competitive with other energy sources.

McKelvey diagram whose vertical axis is extended to include the residual *accessible resource base* and the *inaccessible resource base* can depict these terms (Figure 3.2). This diagram depicts all the important categories of geothermal energy, illustrates the cumulative nature of *reserves*, *resources*, and *resource base* (Schanz, 1975b), emphasizes that reserves are only those resources that are *identified* and *economic* today. It should be emphasized that all categories are measured in units of energy and referenced to *mean annual temperature.* A synthesis of the geothermal definitions and of their attributes and corollaries is given in Table 3.1.

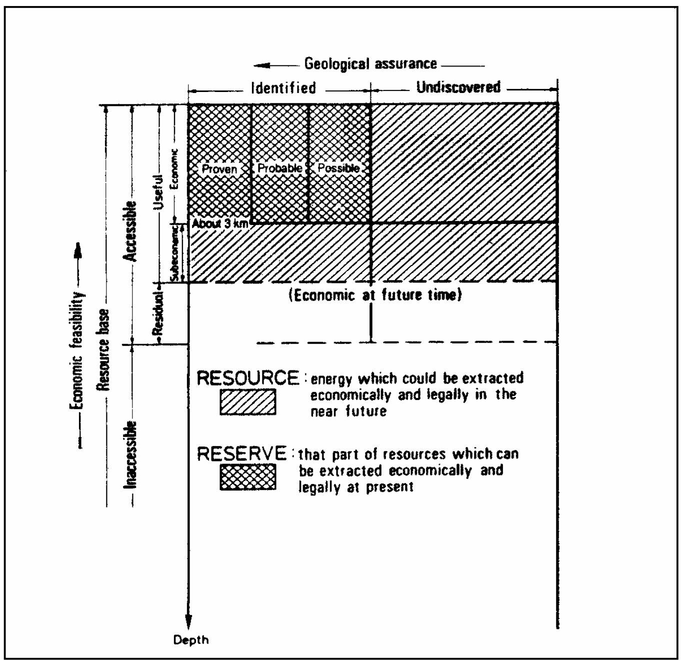


Figure 3.2 McKelvey diagram for geothermal energy (Muffler and Cataldi, 1978)

Table 3.1 Geothermal Resource Terminology

Name	Definition	Attributes and Corollaries
Resource base	All of the geothermal energy in the earth's crust beneath a specified area, referenced to local mean annual temperature	Refers to an instant in time Neglects transfer of heat from mantle Takes no regard of whether or not it would ever be technically or economically feasible to recover the geothermal energy
Inaccessible resource base	All of the geothermal energy stored between the base of the crust and a specified depth in the crust, beneath a specified area and referenced to local mean annual temperature	Refers to an instant in time Neglects transfer of heat from mantle Depth chosen for the upper limit is a matter of convenience, but must be specified in each case Implies that geothermal energy beneath the specified depth is unlikely to be tapped by production drilling at a reasonable time in the future
Accessible resource base	All of the geothermal energy between the earth's surface and a specified depth in the crust, beneath a specified area and referenced to local mean annual temperature	Refers to an instant in time Neglects transfer of heat from deeper levels Depth chosen for the lower limit is a matter of convenience, but must be specified in each case Implies that geothermal energy within the specified depth might be tapped by production drilling at some reasonable time in the future
Residual accessible resource base	That part of the accessible resource base unlikely to be extracted economically and legally at some specified time in the future	Criterion for subdivision of accessible resource base is a subjective aggregate of predicted technology and economics at some reasonable and specified future time
Useful accessible resource base RESOURCE	That part of the accessible resource base that could be extracted economically and legally at some specified time in the future	Criterion for subdivision of accessible resource base is a subjective aggregate of predicted technology and economics at some reasonable and specified future time (≤100 years)
Subeconomic resource	That part of the resource of a given area that cannot be extracted legally at a cost competitive with other commercial energy sources at the time of determination, but might be extracted economically and legally at some specified time in the future	
Economic Resource	That part of the resource of a given area that can be extracted legally at a cost competitive with other commercial energy sources at the time of determination	
Undiscovered economic resource	That part of the economic resource in unexplored parts of regions known to contain geothermal resources, or in regions where geothermal resources are suspected but not yet discovered	
Identified economic resource RESERVE	That part of the economic resource known and characterized by drilling or by geothermal, geophysical and geological evidence	

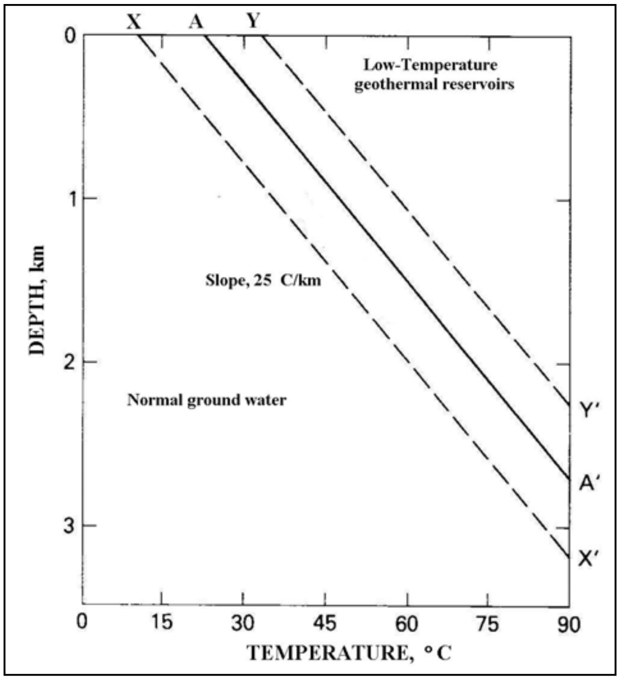
CHAPTER 4

METHODOLOGY

4.1 LOW TEMPERATURE GEOTHERMAL RESOURCES

Low-temperature geothermal resources exists in systems dominated by *hydrothermal convection* and by *heat conduction*. Most identified *low-temperature* geothermal resource areas occur in *hydrothermal-convection* systems that were delineated solely on the basis of a single thermal spring or well, and for resource assessment purposes a standard reservoir volume was assigned to these areas. Other types of *low-temperature* geothermal resource areas for which actual reservoir volumes could be determined occur in *conduction-dominated* systems within sedimentary basins and beneath coastal plains.

Assessment of geothermal resources involves determination of the location, size, and geologic characteristics of each resource area to calculate the accessible resource base (*thermal energy* stored in the reservoir) and the resource (*thermal energy* recoverable at the wellhead). Identified *low-temperature* geothermal resource areas must meet the criteria that a reservoir with sufficient permeability to supply long-term production exists and that reservoir temperatures exceed a defined temperature depth relation (Figure 4.1). In this chapter, the types of *hydrothermal-convection* and *conduction-dominated* systems within which *low-temperature* geothermal resources occur are discussed, and the methods used to estimate accessible resource base are described.



X-X[1] and Y-Y[1] show minumum geothermal-resource temperatures required for mean annual air temperatures of 0° and 23°C.For a mean annual air temperature of 12°C, the minumum surface spring temperature is 22°C (Point A), and the line A-A[1] gives the minumum temperature at any depth.

Figure 4.1 Temperature-versus-depth relations used to define low-temperature geothermal resources. (Marshall, 1982)

Identified *low-temperature* geothermal resources occur mostly in areas where subsurface temperatures in permeable rock layers are above the normal or background temperatures at corresponding depths. At any given locality, one or more of the following factors may give rise to such a geothermal resource:

- High regional *heat flow*,
- *Young magmatic intrusions*,
- A thick sequence of *low-thermal-conductivity* rocks overlying an *aquifer*,
- Upward circulation of thermal fluid along *faults*, or
- Up dip flow within really extensive *aquifers*.

In areas where these factors are unimportant, the temperature gradient is generally so low that drilling to resource temperatures is either uneconomical or impractical.

A useful distinction can be made between a geothermal reservoir and a geothermal system. A *geothermal reservoir* is considered to be a geometrically defined volume of permeable rock from which thermal energy in water can be extracted. Reservoirs containing *low temperature* (and *high temperature*) geothermal resources commonly are surrounded by cooler rocks that are also permeable and hydraulically connected to the reservoir; thus, water may flow between the reservoir and surrounding rocks in the natural state. Such reservoirs exist as parts of larger *geothermal systems* involving circulation of meteoric water downward from recharge areas and upward toward discharge areas, commonly with lateral leakage of thermal water into permeable formations adjacent to the up flow conduits. In the broadest sense, a geothermal system could also be interpreted to include a heat source of either magmatic or nonmagmatic origin. Although the reservoir is the producible part of the geothermal system, the response of the reservoir to development may be significantly affected by the nature of its connection with the rest of the geothermal system.

4.1.1 Categories of Low-Temperature Areas

Low temperature geothermal resources occur in two types of geothermal systems *hydrothermal-convection* and *conduction-dominated*. In *hydrothermal-convection* systems, upward circulation of water transports thermal energy to reservoirs at shallow depths or to the surface. These systems commonly occur in regions of active tectonism and above normal heat flow. In *conduction-dominated* systems, upward circulation of fluid is less important than the existence of high vertical temperature gradients in rocks that include aquifers of significant lateral extent. These conditions occur beneath many deep sedimentary basins.

For each type of geothermal system, two categories of *low temperature* geothermal resource areas are recognized (Table 4.1). Each *low-temperature* geothermal resource area identified is assigned to one of these four categories. Figure 4.2 through 4.4 illustrate conceptual models of geothermal systems related to all these categories. Additional discussions of the various types of geothermal systems, including those in which *low-temperature* geothermal resources occur, are presented by Muffler et al, 1979.

Table 4.1 Categories of low temperature geothermal resource areas (Marshall, 1982)

CATEGORY	SETTING
Hydrothermal-convection systems	
1	Isolated thermal spring and wells
2	Delineated thermal reservoirs
Conduction-dominated systems	
3	Sedimentary basins
4	Coastal plains

Most of the identified *low-temperature* geothermal resource areas associated with *hydrothermal-convection* systems fall into category 1 (isolated thermal springs and wells). In such areas, the only evidence that a geothermal reservoir exists at depth is a single thermal spring or group of closely spaced springs, or a well that produces thermal water. Figure 4.2 shows three possible models of fluid circulation.

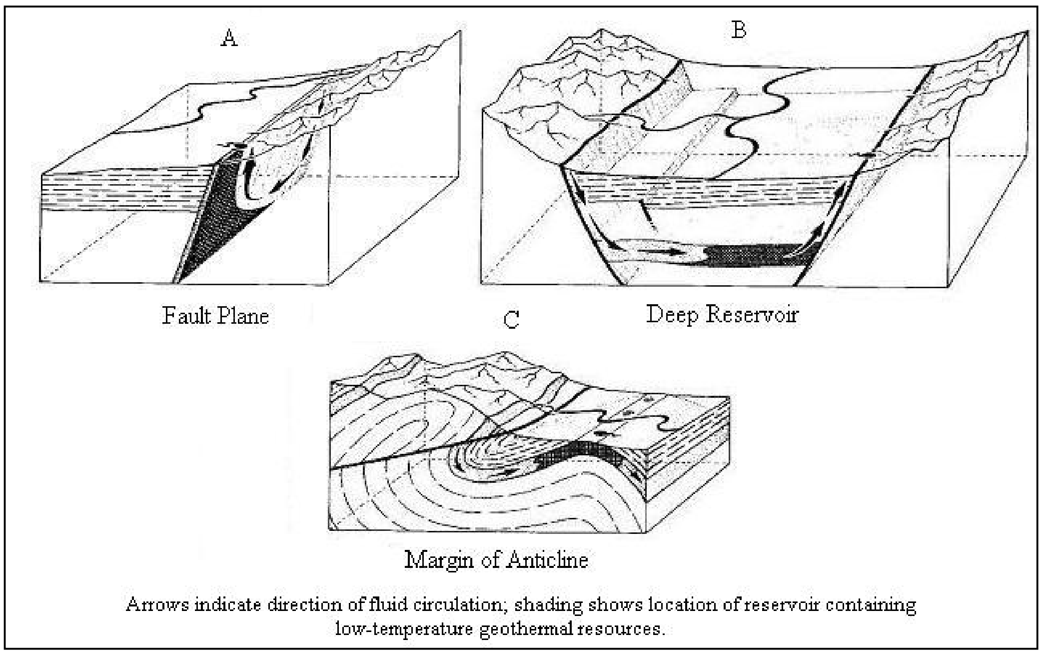


Figure 4.2 Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal resource areas in category 1. (Marshall, 1982)

Low-temperature geothermal resource areas in category 2 (delineated thermal reservoirs in *hydrothermal-convection* systems) are generally characterized by the up flow of thermal water along faults and its subsequent lateral movement into aquifers at relatively shallow depths (Figure 4.3). There may or may not be an associated discharge of thermal springs at the surface, and the shallow thermal aquifer may be underlain by a hotter reservoir at greater depths. Temperature profiles in wells drilled in such areas generally show high gradients above the thermal aquifer and temperature reversals below; Figure 4.5.A illustrates such a temperature profile along with the 25 °C/km minimum gradient criterion used in this assessment to identify *low-temperature* geothermal resource areas. For resource areas in category 2, reservoir volumes are estimated from available data on reservoir areas and thicknesses; such data are provided by test drilling, geophysical surveys, or simply by the distribution of thermal springs within the same geologic province.

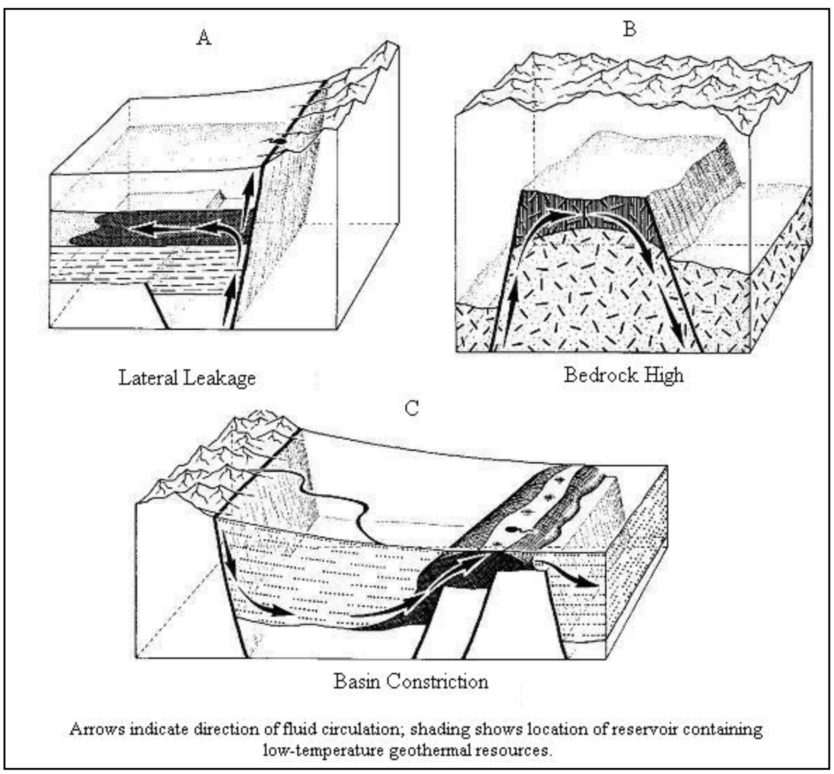


Figure 4.3 Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal resource areas in category 2 (Marshall, 1982).

Low-temperature geothermal resources in *conduction-dominated* systems occurs within *sedimentary basins* (category 3) and beneath *coastal plains* (category 4). Identified geothermal resource areas in category 3 exist where thick layers of low thermal conductivity shale and relatively high temperature gradients occur above regionally continuous carbonate and sandstone aquifers (Figure 4.4.A). An idealized temperature profile within a *sedimentary basin* (Figure 4.5.B) illustrates that aquifers must occur at depths sufficient for temperatures to exceed the minimum temperature criterion.

The conceptual model shown for category 4 (Figure 4.4.B) involves a thick sedimentary layer underlain by an intrusive body that generates an elevated heat flow by radioactive decay.

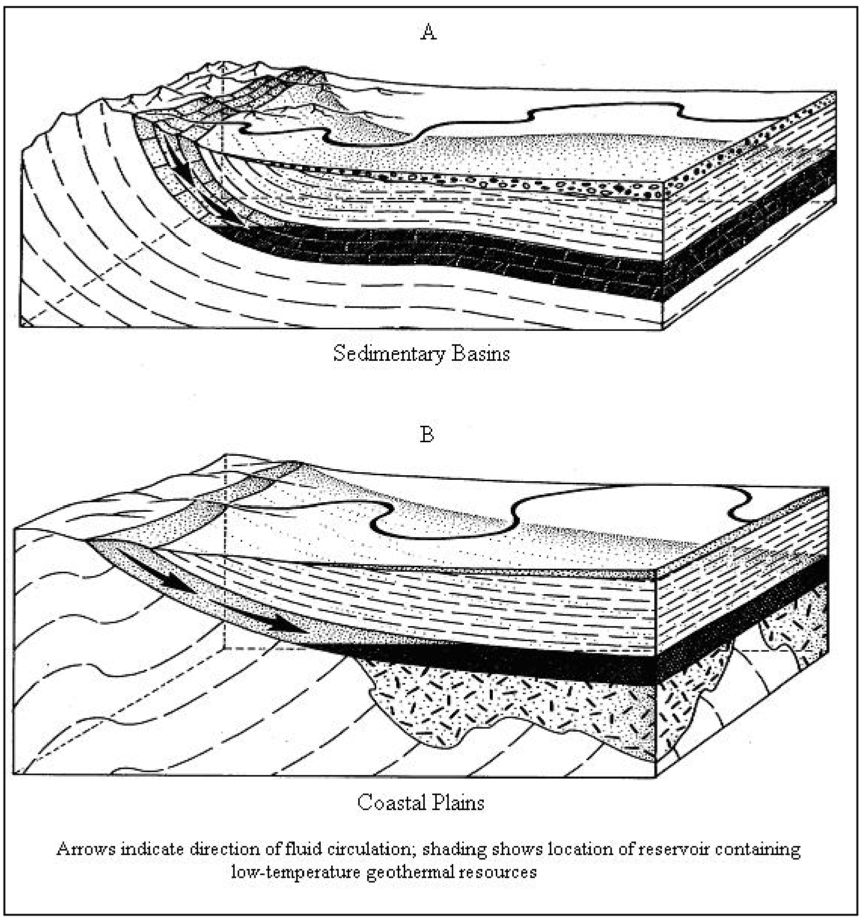


Figure 4.4 Conceptual models for types of conduction-dominated systems in which low-temperature geothermal resource areas in category 3 and 4. (Marshall, 1982)

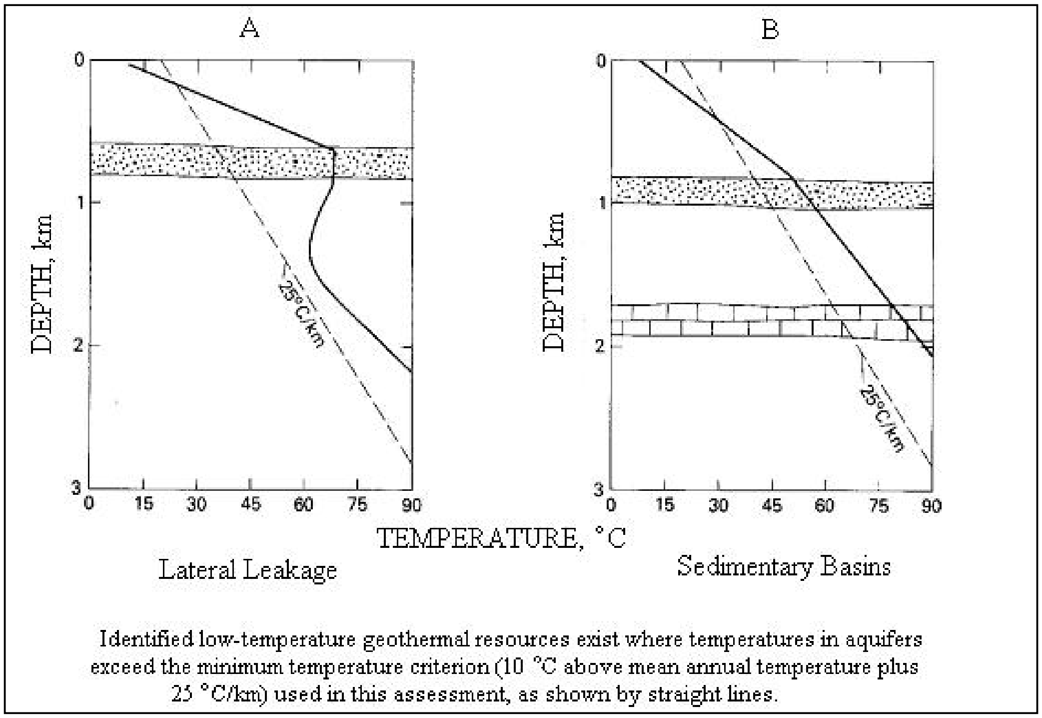


Figure 4.5 Idealized temperature profiles in hydrothermal-convection systems. (Marshall, 1982)

4.2 METHODOLOGIES FOR GEOTHERMAL RESOURCE ASSESSMENT

Methodologies used for geothermal resource assessment prior to 1977, were reviewed by Muffler and Cataldi (1977; 1978) and divided into four main categories:

- *Surface thermal flux*
- *Volume*
- *Planar fracture*
- *Magmatic heat budget.*

4.2.1 Surface Thermal Flux Method

The method of *surface thermal flux* consists of measuring the rate of thermal energy loss at the ground surface by conduction, steaming ground, hot springs, fumaroles, and discharge of thermal fluids directly into streams.

Experience from already developed geothermal fields is then used to relate this rate of energy loss to the rate at which thermal energy might be produced through drill holes.

4.2.2 Volume Method

The *volume method* involves the calculation of the thermal energy contained in a given volume of rock and water and then the estimation of how much of this energy might be recoverable. The *thermal energy* in the ground can readily be calculated as the product of the volume of a geothermal reservoir, the *mean temperature*, the *porosity*, and the *specific heats* of rock and water. Alternatively, one can calculate the thermal energy approximately as the product of just volume, temperature, and an assumed volumetric specific heat (White, 1965; Renner et al, 1975). Calculation of the amount of recoverable thermal energy is more complex, however, and requires knowledge of reservoir properties such as *permeability*. In most cases, the recovery factor can be specified only approximately (Nathenson, 1975).

4.2.3 Planar Fracture Method

The *planar fracture method* involves a model wherein thermal energy is extracted from *impermeable rock* by flow of water along a planar fracture. The calculations are based on conductive transfer of heat to the fracture and require estimation of *fracture area*, *fracture spacing*, *initial rock temperature*, *minimum acceptable outflow temperature*, and the *thermal conductivity* of the rock. The method does allow the direct calculation of *recoverable thermal energy* without going through the intermediate step of calculating thermal energy in place. However, the method is strictly applicable only to terrains such as the unfolded flood basalts of Iceland and is of questionable use in the complex, three-dimensional fracture systems that characterize most *hydrothermal-convection systems*.

4.2.4 Magmatic Heat Budget

The method of *magmatic heat budget* involves calculating the *thermal energy* still remaining in young igneous intrusions and adjacent country rock, as a function of *emplacement temperature*, *size*, *age*, and *cooling mechanism*. Although the method is very useful for giving an indication of the order of magnitude of geothermal energy to be expected in young volcanic terrains, it is not an inventory of geothermal energy, and the estimates cannot be translated directly into geothermal resources.

Muffler and Cataldi (1978) concluded that the *volume method* appeared to be the most useful because;

- It was applicable to virtually any geologic environment;
- The required parameters could in principle be measured or estimated;
- The inevitable errors were in part compensating;
- The major uncertainties (the recovery factor and the resupply of heat) were suitable to resolution in the foreseeable future. The recovery factor was deemed to be a major weakness that required substantial investigation, both in terms of modeling and in terms of field reservoir engineering. Several simple models suggested that resupply of heat is significant only for hot-water systems of high natural discharge, as indicated previously by Nathenson (Nathenson, 1975).

4.3 VOLUME METHOD

For the estimation of the thermal energy at *low temperature* geothermal fields, the *volumetric method* which was described in Section 4.2.2 was used.

The stored heat is computed by using the following volumetric equation (Muffler and Cataldi,1977, 1978);

$$\begin{gathered} H_{Total}=H_R+H_F \\ H_{Total}=(1-\varphi)c_R\rho_R V(T_R-T_U)+\varphi c_F\rho_F V(T_F-T_U) \end{gathered} \qquad (4.1)$$

where;

$H =$ heat energy, kJ

$\phi =$ porosity, fraction

$c =$ specific heat, kJ/kg-°C

$\rho =$ density, kg/m^3

$V =$ hot rock volume, m^3

$T =$ temperature, °C

and subscripts R, F and U stand for rock, fluid and utilized, respectively. H_{Total} can actually be referred as the *accessible resource base* of the low-temperature reservoir under study.

In case of a direct heat application from a low-temperature geothermal reservoir, the accessible resource base (kJ) can be converted to recoverable heat energy (kW_t) by using the following equation;

$$H_{Recoverable} = \frac{H_{Total} \times RF \times Y}{LF \times t} \tag{4.2}$$

where;

$H_{Recoverable}$ = Recoverable heat energy, kW_t

H_{Total} = Accessible resource base, kJ

RF = Recovery factor for the given reservoir, fraction

Y = Transformation yield. It takes into account the efficiency of transferring heat energy from geothermal fluid to a secondary fluid, fraction

LF = Load factor. Most of the direct heat applications (space heating, greenhouse heating etc.) of geothermal energy are not continuous throughout the year. This factor takes into account the fraction of the total time in which the heating application is in operation, fraction

t = Total project life, sec

Some of the variables of the volumetric equations (Equation 4.1 and 4.2) exhibit uncertainties. Those variables are aerial extension, reservoir temperature, formation thickness, porosity, formation rock and fluid density, specific heat of rock and formation fluid in Equation 4.1 and accessible resource base, recovery factor and transformation yield in Equation 4.2.

Monte Carlo simulation is a powerful tool to simulate the systems having variables with uncertainty. An add-in software for Microsoft EXCEL, @ RISK, is capable of running Monte Carlo simulations and will be used throughout this study.

The Monte Carlo simulation and @Risk Software program will be explained in the following sections.

4.3.1 Monte Carlo Simulation

Numerical methods that are known as *Monte Carlo* methods can be loosely described as statistical simulation methods, where statistical simulation is defined in quite general terms to be any method that utilizes sequences of random numbers to perform the *simulation*. *Monte Carlo* methods have been used for centuries, but only in the past several decades has the technique gained the status of a full-fledged numerical method capable of addressing the most complex applications. The name *Monte Carlo* was given because of the similarity of statistical simulation to games of chance, and because the capital of Monaco was a centre for gambling and similar pursuits. *Monte Carlo* is now used routinely in many diverse fields including oil well exploration.

Statistical simulation methods may be contrasted to conventional numerical discretization methods, which typically are applied to ordinary or partial differential equations that describe some underlying physical or mathematical system. In many applications of *Monte Carlo*, the physical process is simulated directly, and there is no need to even write down the differential equations that describe the behavior of the system. The only requirement is that the physical (or mathematical) system be described by *probability density functions* (pdf's), which will be discussed in Section 4.3.2. For now, we will assume that the behavior of a system can be described by pdf's. Once the pdf's are known, the *Monte Carlo simulation* can proceed by random sampling from the pdf's. Many simulations are then performed (multiple trials or histories) and the desired result is taken as an average over the number of observations (which may be a single observation or perhaps millions of observations). In many practical applications, one can predict the statistical error (the *variance*) in this average result, and hence an estimate of the number of *Monte Carlo* trials that are needed to achieve a given error.

Assuming that the evolution of the physical system can be described by probability density functions (pdf's), then the *Monte Carlo* simulation can proceed by sampling from these pdf's, which necessitates a fast and effective way to generate random numbers uniformly distributed on the interval [0,1]. The outcomes of these random samplings, or trials, must be accumulated in an appropriate manner to produce the desired result, but the essential characteristic of *Monte Carlo* is the use of random sampling techniques to arrive at a solution of the physical problem. In contrast, a conventional numerical solution approach would start with the mathematical model of the physical system, discretizing the differential equations and then solving a set of algebraic equations for the unknown state of the system.

Given our definition of *Monte Carlo*, let us now describe briefly the major components of a *Monte Carlo* method. These components comprise the foundation of most *Monte Carlo* applications, and the following sections will explore them in more detail. An understanding of these major components will provide a sound foundation for the reader to construct his or her own *Monte Carlo method*. The primary components of a Monte Carlo simulation method include the following:

- *Probability density functions (pdf's)*: the physical (or mathematical) system must be described by a set of pdf's.
- *Random number generator:* a source of random numbers uniformly distributed on the unit interval must be available.

- *Sampling rule:* a prescription for sampling from the specified pdf's, assuming the availability of random numbers on the unit interval, must be given.

- *Scoring (or tallying)*: the outcomes must be accumulated into overall tallies or scores for the quantities of interest.

- *Error estimation*: an estimate of the statistical error (*variance*) as a function of the number of trials and other quantities must be determined.

- *Variance reduction techniques*: methods for reducing the variance in the estimated solution to reduce the computational time for *Monte Carlo simulation*

- *Parallelization and vectorization*: algorithms to allow *Monte Carlo* methods to be implemented efficiently on advanced computer architectures.

The essential component of a *Monte Carlo simulation* is the modeling of the physical process by one or more *probability density functions* (pdf's). By describing the process as a *pdf*, which may have its origins in experimental data or in a theoretical model describing the physics of the process, one can sample an *outcome* from the pdf, thus simulating the actual physical process. The graphs and the equations of the probability density functions are given in Appendix A. While applying these density functions, some statistical terms such as mean, variance, etc. are utilized. The brief definitions of these terms are also given in the Appendix A.

For each uncertain variable (one that has a range of possible values), one may define the possible values with a *probability distribution*. The type of distribution that can be selected is based on the conditions surrounding that variable. The common distribution types can be seen in Figure 4.6. The equations of the distribution types were given in Appendix B.

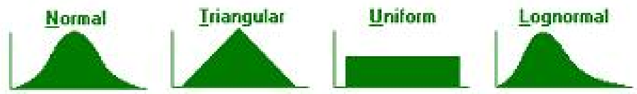


Figure 4.6 Distribution types

To add this sort of functions to an EXCEL spreadsheet, it is needed to know the equation that represents this distribution. @RISK can automatically calculate these equations or even fit a distribution to any historical data that one might have.

4.3.2 @ RISK

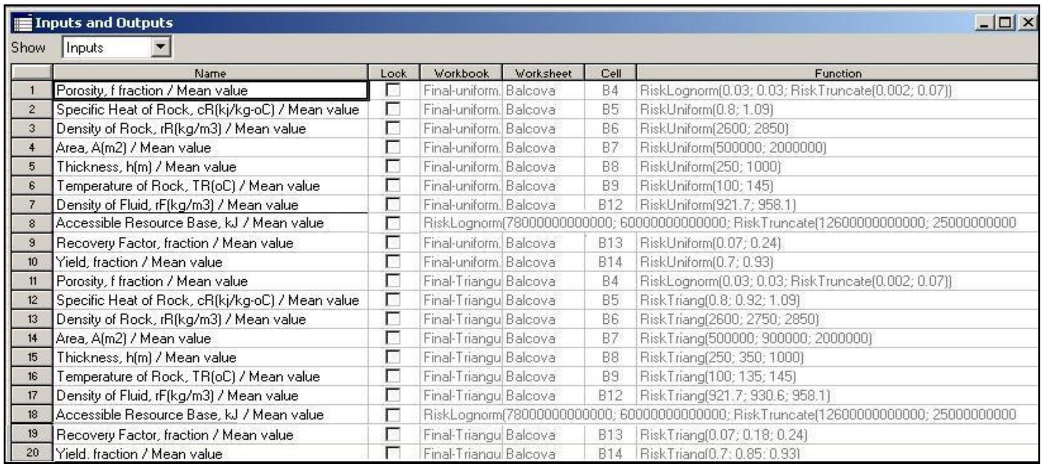
In most of the cases, the decisions are based on whatever the data available on hand. But how often the available data is full and the information is complete? In the subject of this study the aerial and vertical change of rock properties such as porosity, formation rock density should be known. Due to limited data source on these properties, it's easy to make wrong decision if all possible scenarios are not taken into account. Making the best decisions means performing risk analysis.

@RISK is an add-in to Microsoft EXCEL, which can add risk analysis to your existing models. @RISK uses a technique known as *Monte Carlo simulation* to show all possible outcomes. Running an analysis with @RISK involves three simple steps:

- Define Uncertainty for Input Variables

The first step of running an analysis with @RISK is to define all the variables that are uncertain in the model. The nature of the uncertainty of a given variable is described with probability distributions, which give both the range of values that the variable could take (minimum to maximum), and the likelihood of occurrence of each value within the range. In @RISK, uncertain variables and cell values are entered as probability distribution functions for example: RiskNormal (10;100), RiskUniform (20;30), or RiskTriangular(100;135; 145). The numbers in normal and uniform type distributions in brackets indicate the minimum and maximum values of the variable that it could take while the numbers in triangular type distribution indicate minimum, most likely and maximum values of the variable, respectively.

Thus the first step is defining all uncertain variables as inputs and assigning distribution functions for them (Figure 4.7).


Inputs and Outputs

Show Inputs

	Name	Lock	Workbook	Worksheet	Cell	Function
1	Porosity, f fraction / Mean value		Final-uniform.	Balcova	B4	RiskLognorm(0.03; 0.03; RiskTruncate(0.002; 0.07))
2	Specific Heat of Rock, cR(kj/kg-oC) / Mean value		Final-uniform.	Balcova	B5	RiskUniform(0.8; 1.09)
3	Density of Rock, rR(kg/m3) / Mean value		Final-uniform.	Balcova	B6	RiskUniform(2600; 2850)
4	Area, A(m2) / Mean value		Final-uniform.	Balcova	B7	RiskUniform(500000; 2000000)
5	Thickness, h(m) / Mean value		Final-uniform.	Balcova	B8	RiskUniform(250; 1000)
6	Temperature of Rock, TR(oC) / Mean value		Final-uniform.	Balcova	B9	RiskUniform(100; 145)
7	Density of Fluid, rF(kg/m3) / Mean value		Final-uniform.	Balcova	B12	RiskUniform(921.7; 958.1)
8	Accessible Resource Base, kJ / Mean value		RiskLognorm(78000000000000; 60000000000000; RiskTruncate(12600000000000; 25000000000			
9	Recovery Factor, fraction / Mean value		Final-uniform.	Balcova	B13	RiskUniform(0.07; 0.24)
10	Yield, fraction / Mean value		Final-uniform.	Balcova	B14	RiskUniform(0.7; 0.93)
11	Porosity, f fraction / Mean value		Final-Triangu	Balcova	B4	RiskLognorm(0.03; 0.03; RiskTruncate(0.002; 0.07))
12	Specific Heat of Rock, cR(kj/kg-oC) / Mean value		Final-Triangu	Balcova	B5	RiskTriang(0.8; 0.92; 1.09)
13	Density of Rock, rR(kg/m3) / Mean value		Final-Triangu	Balcova	B6	RiskTriang(2600; 2750; 2850)
14	Area, A(m2) / Mean value		Final-Triangu	Balcova	B7	RiskTriang(500000; 900000; 2000000)
15	Thickness, h(m) / Mean value		Final-Triangu	Balcova	B8	RiskTriang(250; 350; 1000)
16	Temperature of Rock, TR(oC) / Mean value		Final-Triangu	Balcova	B9	RiskTriang(100; 135; 145)
17	Density of Fluid, rF(kg/m3) / Mean value		Final-Triangu	Balcova	B12	RiskTriang(921.7; 930.6; 958.1)
18	Accessible Resource Base, kJ / Mean value		RiskLognorm(78000000000000; 60000000000000; RiskTruncate(12600000000000; 25000000000			
19	Recovery Factor, fraction / Mean value		Final-Triangu	Balcova	B13	RiskTriang(0.07; 0.18; 0.24)
20	Yield, fraction / Mean value		Final-Triangu	Balcova	B14	RiskTriang(0.7; 0.85; 0.93)

Figure 4.7 Defining the input variables and their uncertainties in @RISK.

These "distribution" functions can be placed in worksheet cells and formulas just like any other EXCEL function. (Figure 4.8).

- Define Output Variables

Next, output cells in which the values of the variables that are interested in will be recorded are defined. For the current study, these variables are accessible resource base and recoverable heat energy (Figure 4.9).

- Simulate

Simulate is the option of @RISK which recalculates the spreadsheet model hundreds or thousands of times (Figure 4.10). The number of different scenarios that can be looked at is limited by 10000 iterations. @RISK samples random values for each iteration from the @RISK functions that were entered and records the resulting outcome. The overall result is a look at a whole range of possible outcomes, including the probabilities that will occur. Almost instantly, it is possible to see what critical situations to seek out or avoid.

The power of *Monte Carlo simulation* lies in the distributions of possible outcomes it creates. Simply by running a simulation, @RISK takes the spreadsheet model from representing just one possible outcome to representing thousands of possible outcomes.

Thus, @RISK makes it possible to see all possible outcomes in a given situation and tells how likely they are to occur. What this means for a decision maker is that he/she finally has, if not perfect information, the most complete picture possible.

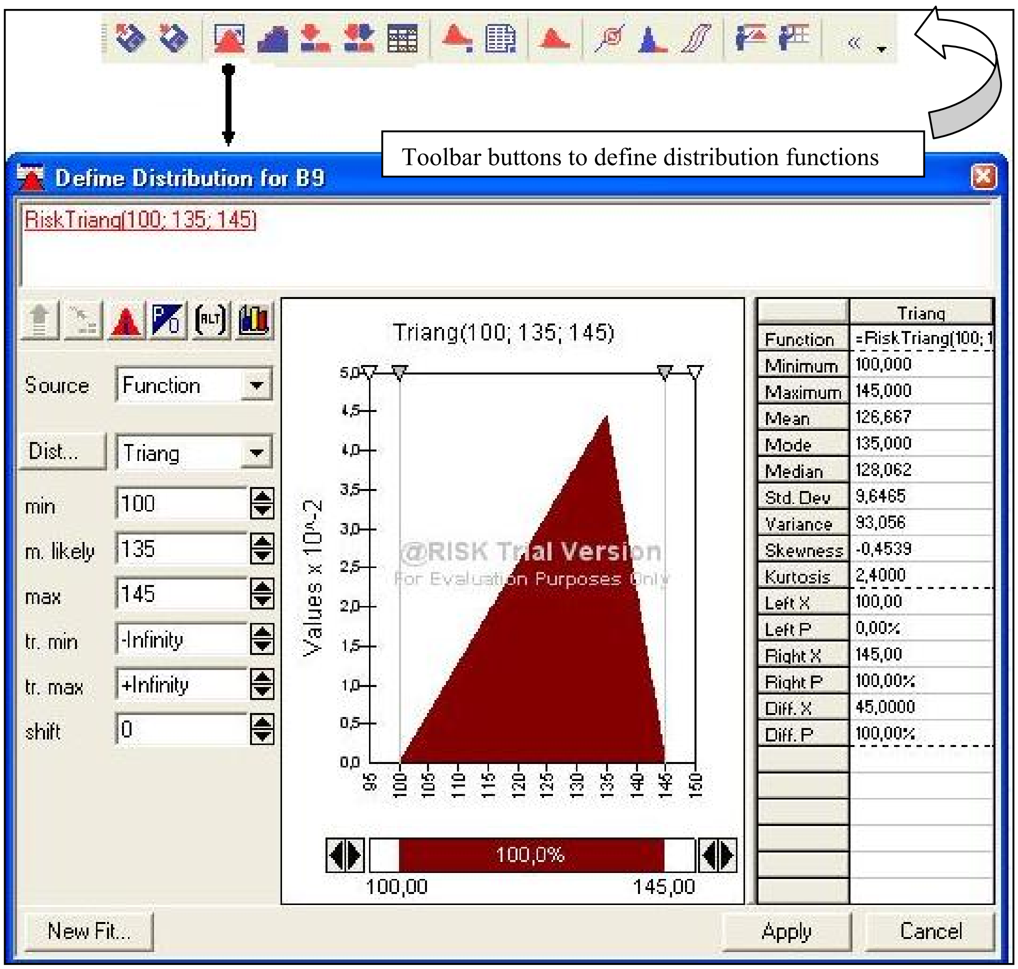


Figure 4.8 Defining the distribution function for a variable.

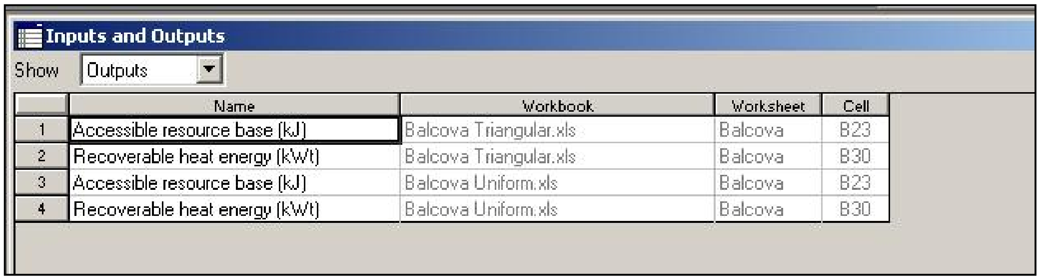


Figure 4.9 Defining output cells in @RISK.

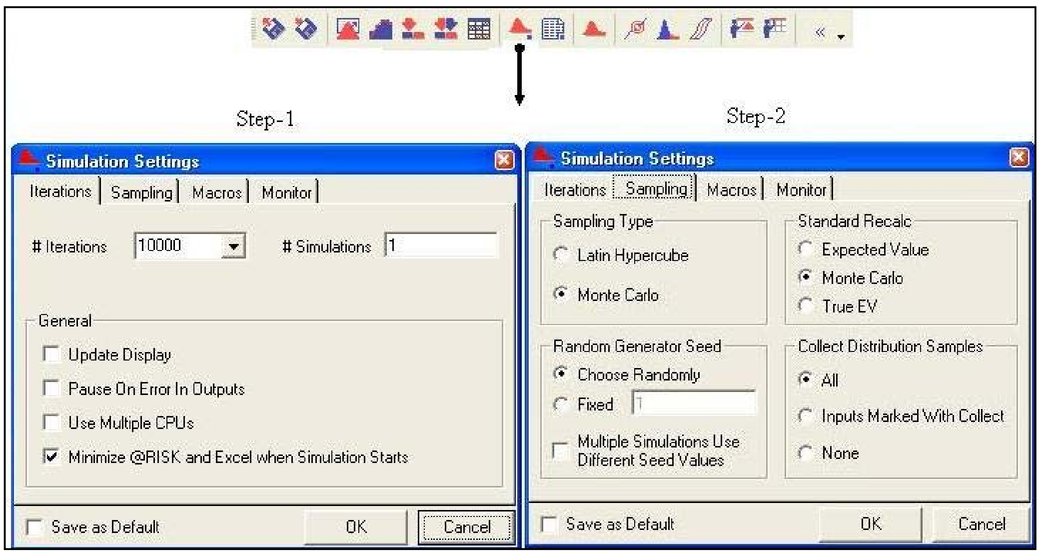


Figure 4.10 Steps of Simulation in @RISK.

@RISK provides a wide range of graphing options for interpreting and presenting the results. It creates histograms, cumulative curves, area and line graphs (Figure 4.11). Using overlay graphs to compare several results on one graph. It can even create summary graphs that display risk over a range of time or across outputs.

@RISK also gives a full statistical report of simulations, as well as access to all the data generated. Plus it is possible to generate a one-page, pre-formatted and ready to print Quick Report. Quick Reports include *cumulative graphs*, *regression charts* for sensitivity analysis, *histograms*, and summary statistics.

In addition to this, the availability of data in EXCEL gives the opportunity to present data in the format other than @RISK has.

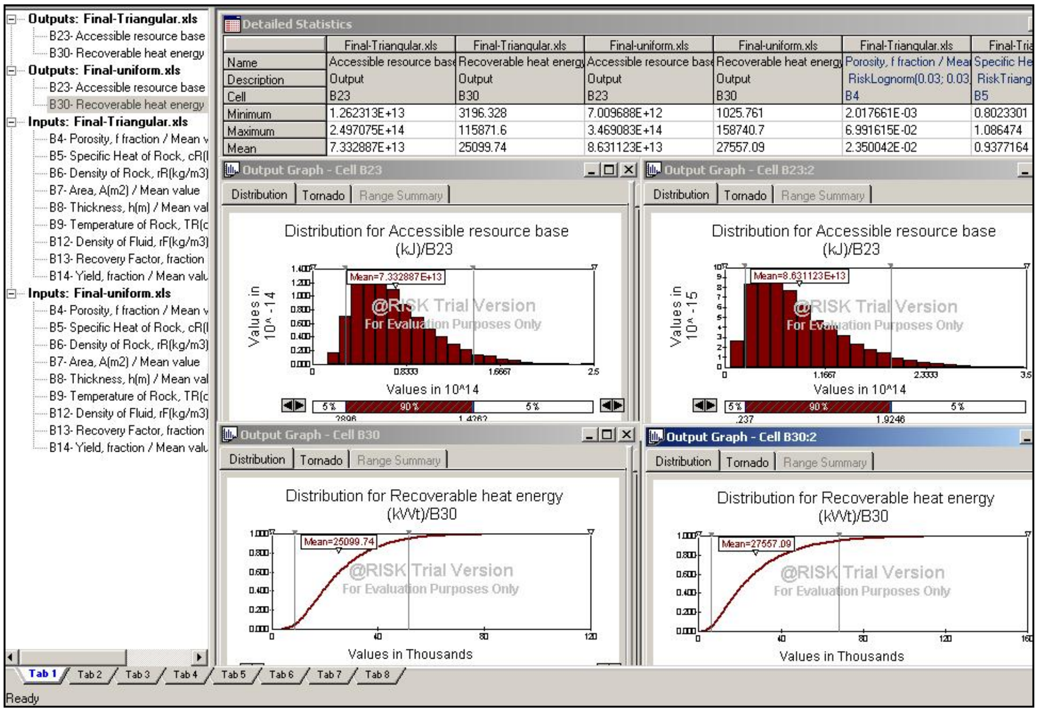


Figure 4.11 Graphical options of @RISK.

CHAPTER 5

STATEMENT OF THE PROBLEM

Turkey is one of the richest countries regarding the geothermal resources. More than 170 geothermal fields were identified. Few of these fields are high enthalpy (temperature) fields suitable for electricity generation. There exists substantial low-temperature geothermal energy capacity of Turkey, which can be used for several direct heat applications, such as space heating, greenhouse heating, balneology, thermal tourism etc.

Assessment of resource is one of the important stages of the development studies of low-temperature geothermal resources. Among the several methods of assessment, volume method gained importance. In this study, assessment of Balçova-Narlıdere low-temperature geothermal field of Turkey is realized by the use of volume method. Probabilistic approach, through the use of Monte Carlo simulation technique, is applied to overcome the uncertainties of the variables of the volumetric method.

CHAPTER 6

RESULTS AND DISCUSSION

The accessible resource base and recoverable heat energy of Balçova-Narlıdere low-temperature geothermal field of Turkey are estimated by probabilistic approach. Monte-Carlo simulation method is used through an add-in software (@RISK) to Microsoft EXCEL. The following sections discuss the results of this study in detail.

6.1 BALÇOVA-NARLIDERE GEOTHERMAL FIELD

Balçova-Narlıdere geothermal field is the first field of Turkey utilized for direct heat application of geothermal energy. It is located 11 km southwest of the city of İzmir in western Anatolia (38.2º latitude, 27.0º longitude) (Figure 6.1). The geology of the field is rather complicated, however it is known that the deeper parts of the system are composed of an impermeable and a thick unit called İzmir flysch. The upper Cretaceous aged İzmir flysch is a member of the İzmir-Ankara Suture Zone and consists of mainly sandstones, siltstones, shales and carbonates, including exotic blocks of some magmatic units such as; serpentinites, diabases, rhyolites, and granodiorites. İzmir flysch outcrops on a NNE-SSW trending horst and the field lies at the northern slope of the mountain nearby İzmir Bay. The young sediments that fill İzmir Bay cover the field at further north (Öngür, 2001).

İzmir Bay and İzmir Fault occurred together with graben systems in Western Anatolia due to extensional tectonics during the Late Tertiary. Balçova-Narlıdere geothermal system lies on Agamennon Fault, which is an extension of İzmir Fault. In addition to E-W trending Agamennon Fault, the field is dissected by several faults parallel to Agamennon fault. Except Agamennon, all other faults are buried in the alluvium but their existence was observed in the drillings. Figure 6.2 shows the fault system and the locations of the wells in Balçova-Narlıdere geothermal system (Satman, et al., 2001).

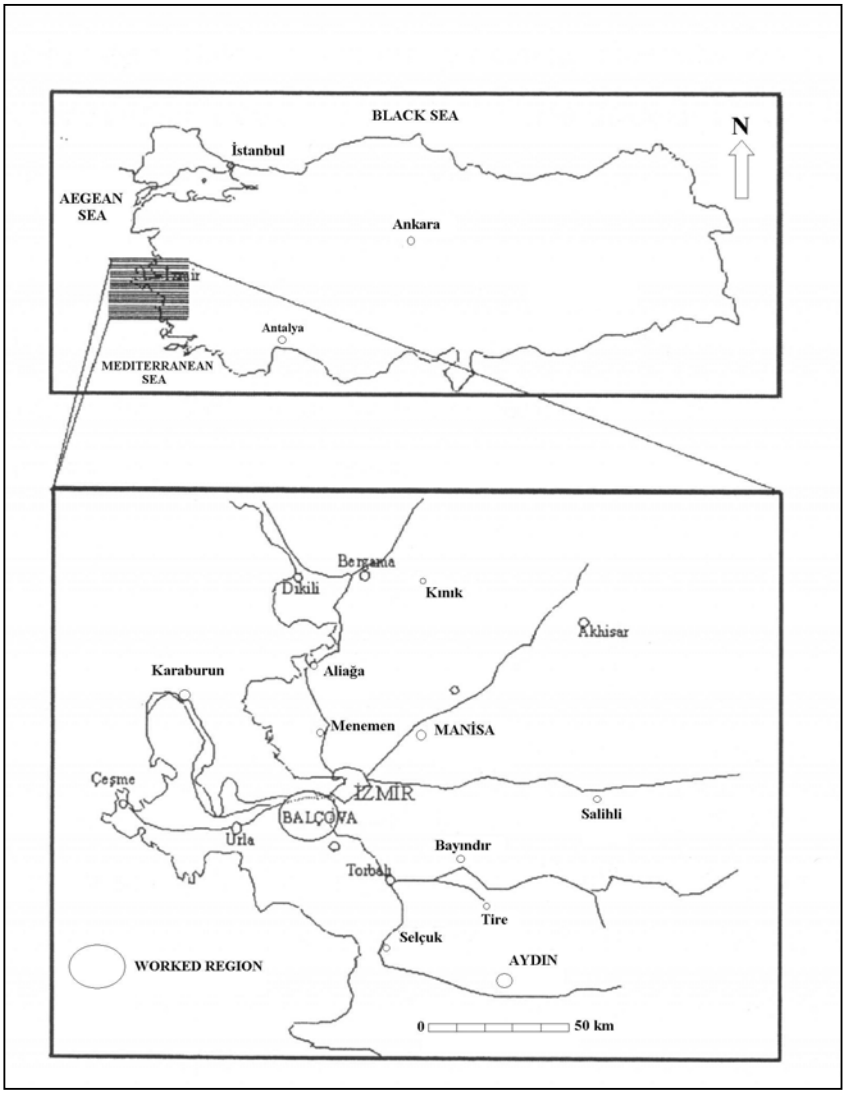


Figure 6.1 Location map of Balçova-Narlıdere geothermal field (Aksoy and Filiz, 2001)

Mineral Research and Exploration General Directorate of Turkey (MTA) did the first geothermal drilling studies in the region at 1963. Resistivity, thermal probing, and self-potential surveys conducted (the first time a geothermal area received systematic, scientific delineation in Turkey). 3 wells were drilled including the first geothermal exploratory well in Turkey. First well (S-1) resulted with a mixture of hot water and steam at 124 ºC at a depth of 40 m. S-2 and S-3/A were drilled to 100 m and 140 m, with downhole temperatures of 102 ºC, and 101 ºC, respectively. S-3/A did not flow. From 1981 to 1983, 16 wells, including 7 thermal gradient and 9 production wells (100-150 m), were drilled. They encountered temperatures of 50 ºC to 126 ºC with flow rates of 4-20 kg/s. In 1982, system of geothermally heated hotels, curing center, swimming pools, and hot water began operation. 9 wells produce 4500000 kcal/h for surrounding hotels, buildings, and greenhouses. A district heating system with a total capacity of 2.2 MW_t began operation in 1983 for heating offices, hospital and dormitories of Dokuz Eylül University (~30000 m^2). Heating for Turkey's largest indoor swimming pool, which has capacity of 1600000 kcal/h, began operation in February 1987. In 1989, 2 new wells (B-10 and B-11) were drilled to 125 m that encountered temperatures of 109 ºC and 114 ºC and flow rates of 5 kg/s and 3 kg/s. Geothermal heating of a 11000 m^2 curing center became operational with a capacity of 1200000 kcal/h on September in 1989. Heating system for an additional 110000 m^2 (1100 dwellings) plus hot water for the Hospital of Faculty of Medicine at Dokuz Eylül University was installed on February in 1992. Additional system with capacity of 6900000 kcal/h (9.3 MW_t) began running on November in 1992. The most important stage was realized by starting the operation of the Balçova Geothermal Center Heating System in 1996 and Narlıdere Geothermal Center Heating System in 1998.

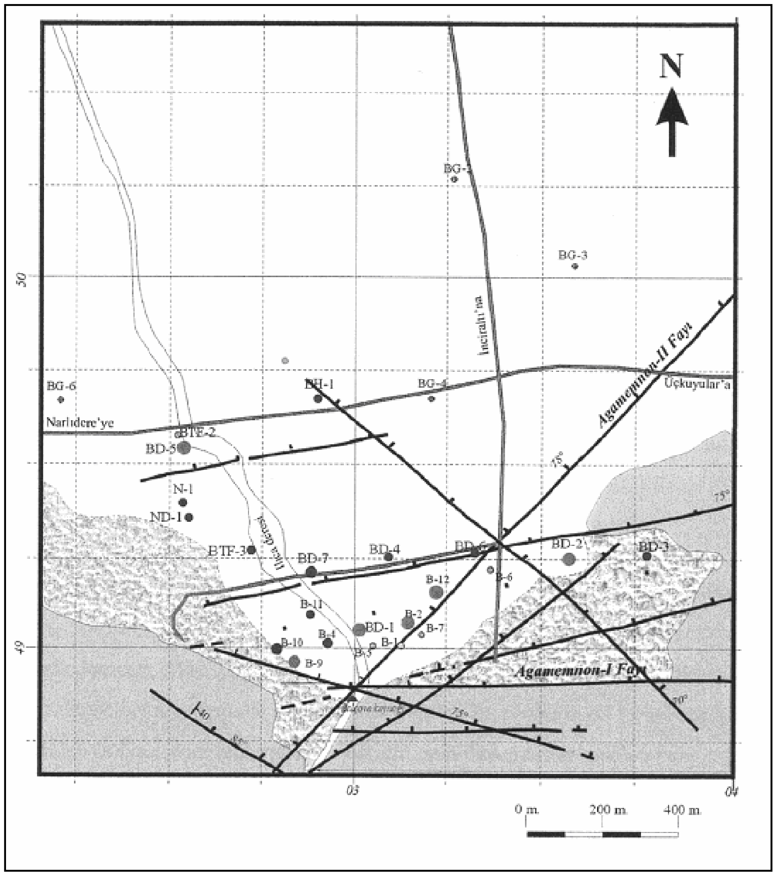


Figure 6.2 Fault systems and well locations of Balçova-Narlıdere geothermal field (Satman et al. 2001)

6.2 ACCESSIBLE RESOURCE BASE CALCULATION

Volumetric method described by Muffler and Cataldi (1977; 1978) is used to estimate the accessible resource base of Balçova-Narlıdere geothermal field. Equation 4.1 is the basic equation of the method:

$$\begin{aligned} H_{Total} &= H_R + H_F \\ H_{Total} &= (1-\varphi) c_R \rho_R V (T_R - T_U) + \varphi c_F \rho_F V (T_F - T_U) \end{aligned} \quad (4.1)$$

where;

H = heat energy, kJ

ϕ = porosity, fraction

$c =$ specific heat, kJ/kg-°C

$\rho =$ density, kg/m^3

$V =$ hot rock volume, m^3

$T =$ temperature, °C

and subscripts R, F and U stand for rock, fluid and utilized, respectively. H_{Total} can actually be referred as the *accessible resource base* of the low-temperature reservoir under study.

Except the constant values such as, the utilization temperature (T_U), specific heat of rock and fluid (c_R, c_F) in Equation 4.1 all other variables do not have a known an exact value but a range of possible occurrence. This brings the uncertainty for the evaluation of accessible resource base. In order to overcome this uncertainty probabilistic approach of *Monte Carlo* method is generally used. In the method of *Monte Carlo* each variable is assigned to a distribution function representing the behavior of the variable.

There are several distribution types that can be used in *Monte Carlo* method. Newendrop (1975), who conducted risk analysis projects on Petroleum investments, suggests using triangular distribution in the risk analysis simulation if the number of data is limited. This is the case in this simulation study; although several wells have been drilled in the area, the collected data is very limited, thus it was decided to use triangular distribution for most of the variables in Equation 4.1.

Satman et al. (2001) presents porosity values obtained from neutron logs taken in Balçova-Narlıdere field (Figure 6.3). The most frequent porosity is found to be 1% with a frequency of 166 among 401 samples; therefore it was assigned as the most likely value of porosity. The maximum and minimum porosity values were taken as 7% and 0.2%, respectively.

Analysis of Table 6.1 indicated the minimum, most likely and maximum values of specific heat of rock as 0.80 kJ/kg-°C for Granite, 0.92 kJ/kg-°C for Sandstone and 1.09 kJ/kg-°C for Serpentine, respectively.

Table 6.1 Specific Heat of Rocks (http://www.engineeringtoolbox.com/24_154.html)

Product	Specific Heat Capacity, kJ/kg-°C
Calcite 32- 212 F	0.84
Clay	0.92
Dolomite Rock	0.92
Granite	0.80
Limestone	0.84
Marble	0.88
Sandstone	0.92
Serpentine	1.09

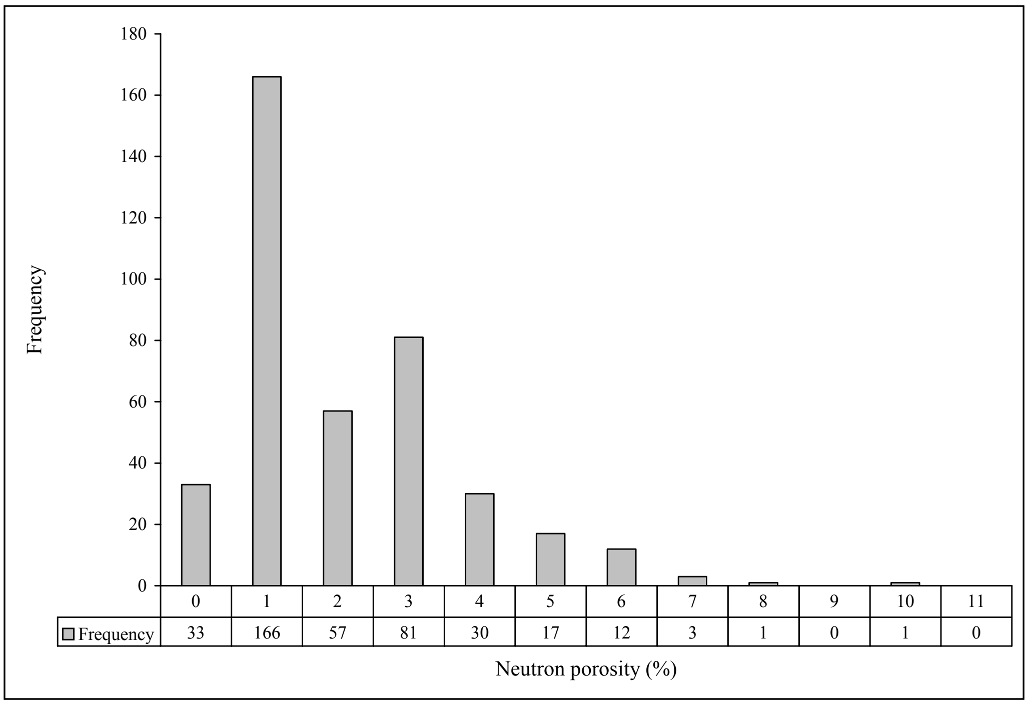


Figure 6.3 Histogram showing the neutron porosity values from Wells BG-4, BG-8, BG-9 and BG-10 (adapted from Satman et al. 2001).

Normalized rock densities obtained from density logs are presented in Figure 6.4 (Satman et al., 2001). Analysis of Figure 6.4 indicated the minimum, maximum and most likely values of rock density as 2600 kg/m^3, 2850 kg/m^3 and 2750 kg/m^3, respectively.

The temperature profiles from shallow and deep wells of Balçova-Narlıdere field (Figure 6.5) (Satman et al., 2001) were used to determine the ranges of rock temperature and thickness of formation. The well BD-5 is the deepest well at which the temperature profile was taken. This profile shows a maximum temperature of about 115 °C in the depth interval of 700-820 m and then a reversal in deeper sections with a constant temperature profile of 100 °C. This behavior indicates a lateral movement of geothermal fluid in the interval of 700-820 m, but at the deeper sections constant temperature behavior also shows the existence of permeable zones. Therefore the deepest point of the reservoir can be taken as high as 1000 m. The other deep wellbores (BD-1; BD-7) show thicknesses of 250 m and above. Therefore the thickness data are taken as 250, 350 and 1000 m for minimum, most likely and maximum values, respectively.

Figure 6.5 is also used to determine the possible values of temperature to be used in triangular distribution. The highest recorded temperature is about 145 °C (BD-1), and the minimum is taken as 100 °C while the most likely is 135 °C all deduced from Figure 6.5.

The density of fluid data for triangular distribution correspond to the density of pure water obtained from steam tables for the temperatures 100, 135 and 145 °C as 958.1, 930.6 and 921.7 kg/m^3, respectively (Mayhew and Rogers, 1977).

Triangular distribution values for reservoir area are obtained from Satman et al. (2001).

The remaining variables of Equation 4.1 (utilized temperature, specific heat of fluid) are taken as constant values. Utilized temperature is assigned to the return temperature of the primary loop of the heat exchanger. The specific heat of fluid is taken as 4.18 kJ/kg-°C, which is the specific heat capacity for pure water. Table 6.2 lists the values of variables of Equation 4.1.

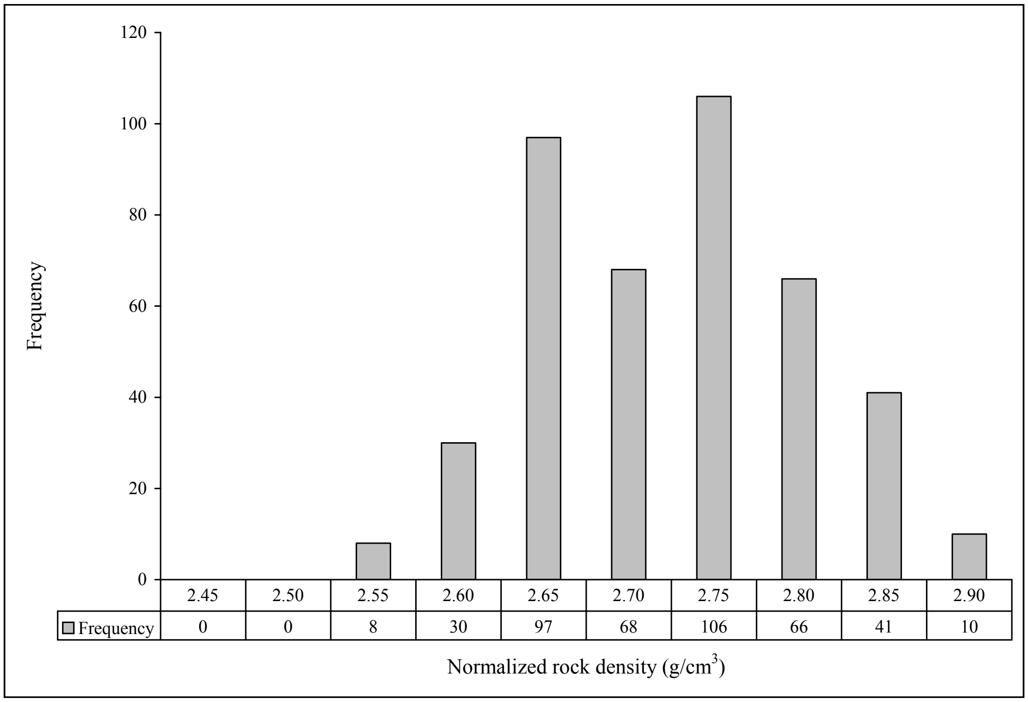


Figure 6.4 Histogram showing the normalized rock density values from Wells BG-4, BG-8, BG-9 and BG-10 (adapted from Satman et al. 2001).

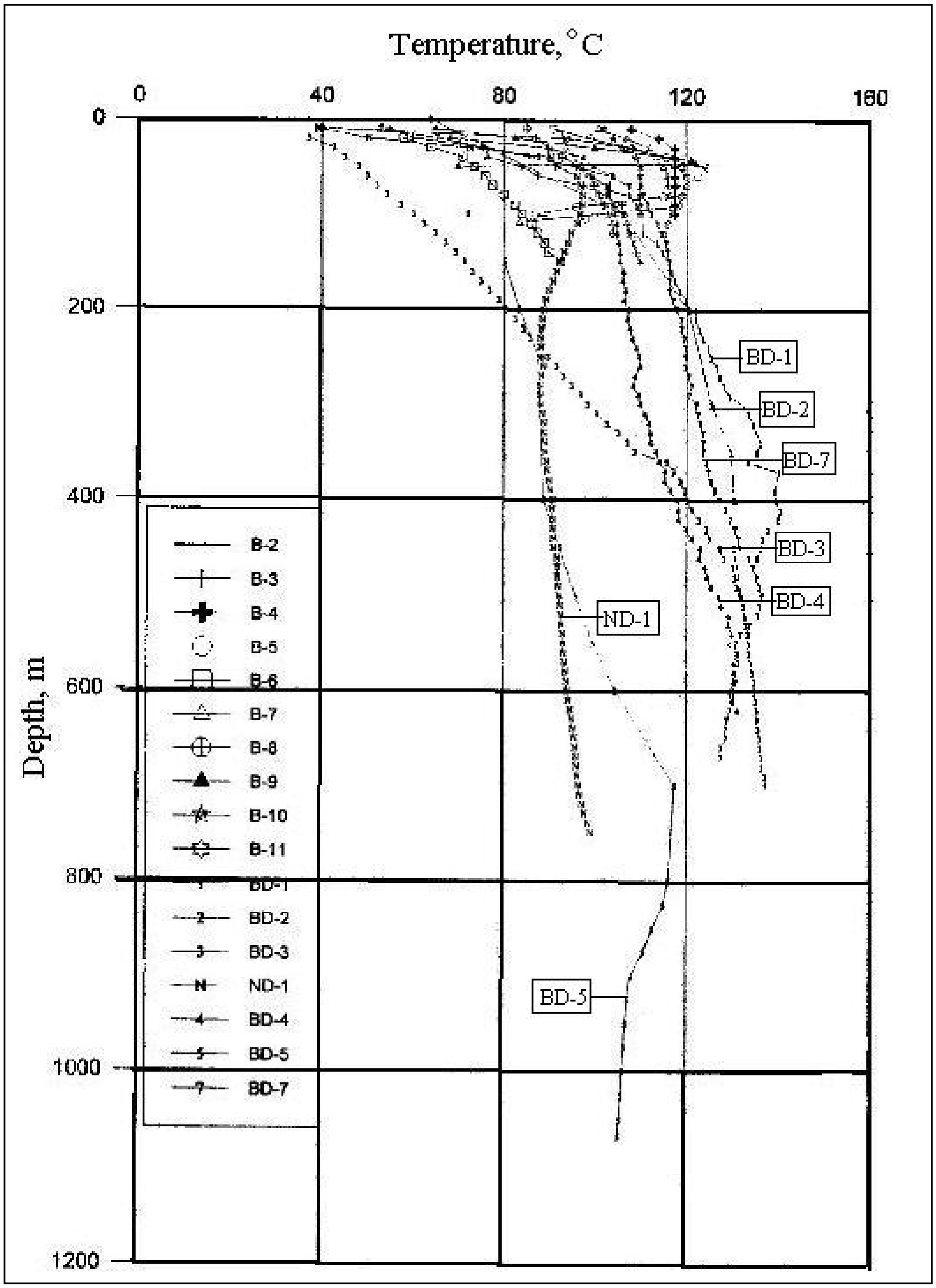


Figure 6.5 Temperature profiles of shallow and deep wells (adapted from Satman et al. 2001).

Table 6.2 Values of the variables in Equation 4.1 with Triangular Distribution

İzmir Balçova-Narlıdere Geothermal Region				
Accessible Resource Base				
Parameters	**Most Likely**	**Type of Distribution**	**Minimum**	**Maximum**
Porosity, ϕ (fraction)	-	Lognormal	0.002	0.07
Specific Heat of Rock, c_R (kJ/kg-°C)	0.92	Triangular	0.80	1.09
Density of Rock, ρ_R (kg/m^3)	2750	Triangular	2600	2850
Area, A (m^2)	9.00 E+05	Triangular	5.00 E+05	2.00 E+06
Thickness, h (m)	350	Triangular	250	1000
Temperature of Rock, T_R (°C)	135	Triangular	100	145
Density of Fluid, ρ_F (kg/m^3)	930.6	Triangular	921.7	958.1
Utilized Temperature, T_U (°C)	80	Constant	-	-
Specific Heat of Fluid, c_F (kj/kg-°C)	4.18	Constant	-	-

While applying simulation, the number of iterations was chosen as 10000, which is the maximum number that can be applied in @RISK. Then the @RISK software program assigns random numbers to each variable based on the type of distribution and limits.

By dragging the delimiters (p1, p2) displayed on a histogram or cumulative graph, target probabilities may be calculated. Calculated probabilities (x1 and x2) of the indicated delimiters (p1 and p2) are shown both in the delimiter bar beneath the graph and in the displayed statistics report. This is useful for graphically displaying answers to questions such as “What is the value for an optimistic approach (90% probability). In this study p1 and p2 are chosen as 10% and 90% respectively for easy calculation of pessimistic and optimistic values.

Table 6.3 lists the mean, minimum and maximum values of the variables of Equation 4.1 as the result of simulation study of @RISK. Figures 6.6 – 6.13

give the histograms of the output of @RISK. According to the summary statistics of @RISK (Appendix C, Table C.4), the mean value for accessible resource base of Balçova-Narlıdere field is 7.33 E+13 kJ. On the other hand, the most likely accessible resource base was found to be 5.53 E+13 kJ (Figure 6.13). The most likely resource base has the probability of 37% (approximately from Table C.4).

Table 6.3 Simulation Summaries for Accessible Resource Base

Simulation Summary							
Summary Information							
Number of Simulations					1		
Number of Iterations					10000		
Number of Inputs					7		
Number of Outputs					1		
Sampling Type					Monte Carlo		
Input	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Porosity, ϕ (fraction)	0.0020	0.0235	0.0699	0.0073	10%	0.0467	90%
Specific Heat of Rock, c_R (kJ/kg-°C)	0.80	0.94	1.09	0.86	10%	1.02	90%
Density of Rock, ρ_R (kg/m^3)	2601	2734	2848	2661	10%	2801	90%
Area, A (m^2)	5.03E+05	1.13E+06	2.00E+06	7.44E+05	10%	1.59E+06	90%
Thickness, h (m)	251	534	997	336	10%	779	90%
Temperature of Rock, T_R (^{o}C)	100	127	145	112	10%	138	90%
Density of Fluid, ρ_F (kg/m^3)	921.8	936.8	958.0	927.3	10%	948.1	90%
Output	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Accessible resource base (kJ)	1.26E+13	7.33E+13	2.50E+14	3.47E+13	10%	1.22E+14	90%

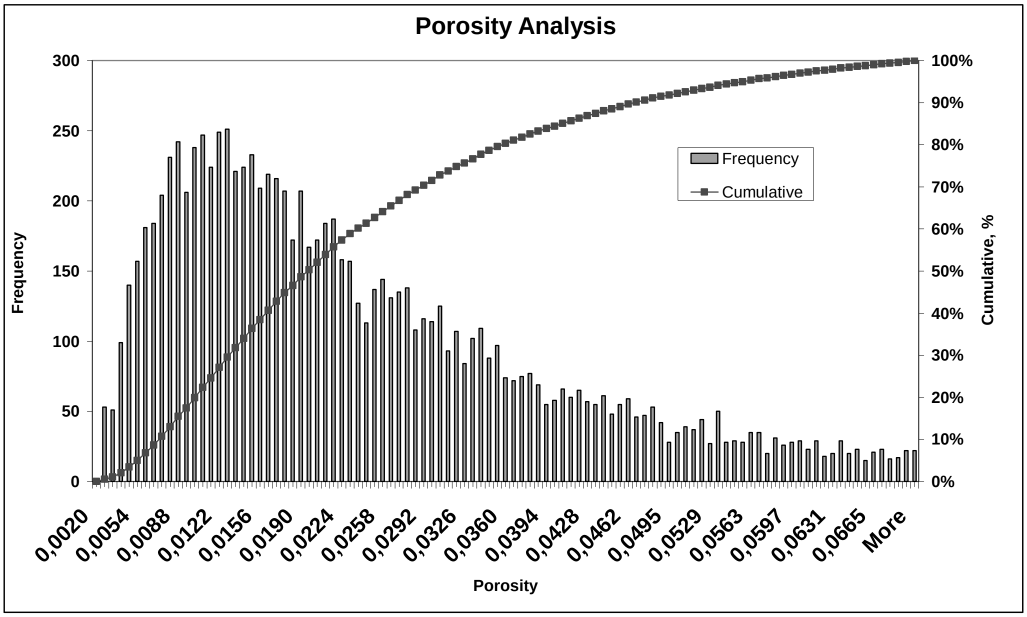


Figure 6.6 Histogram and Cumulative Graphs for Porosity

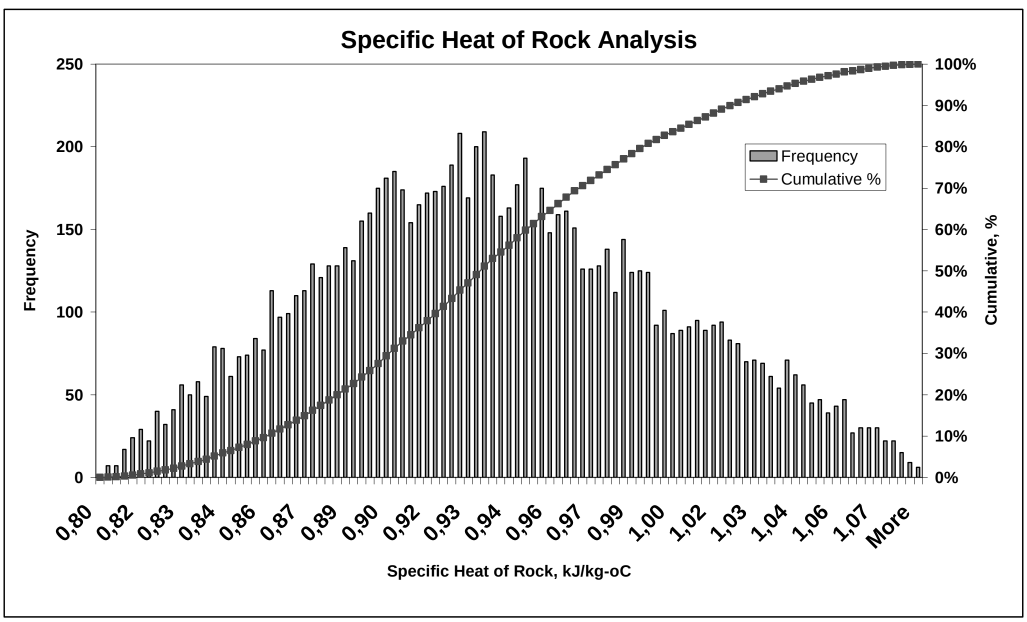


Figure 6.7 Histogram and Cumulative Graphs for Specific Heat of Rock

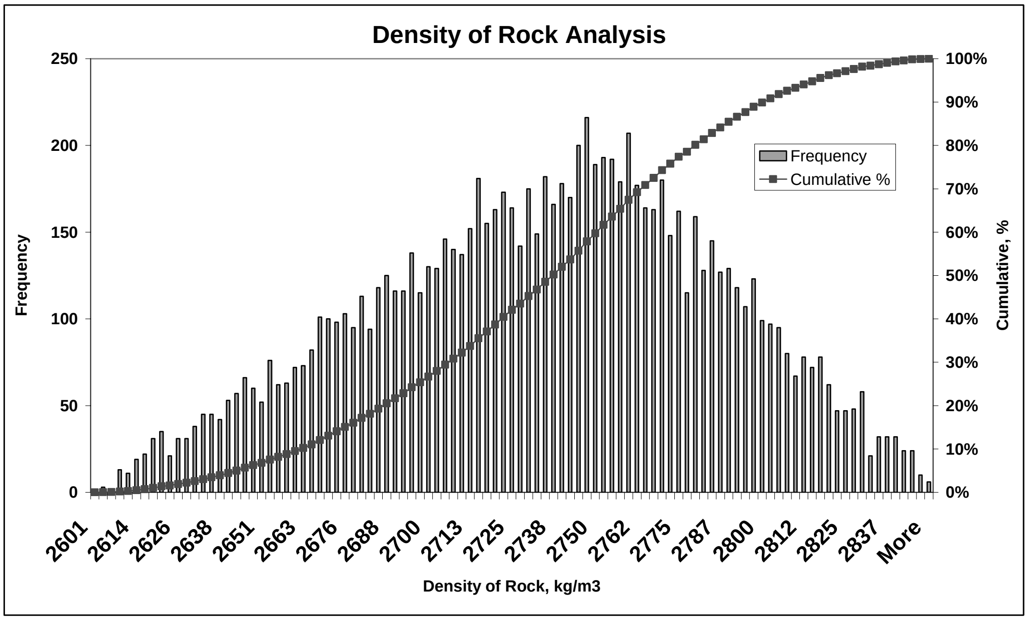


Figure 6.8 Histogram and Cumulative Graphs for Density of Rock

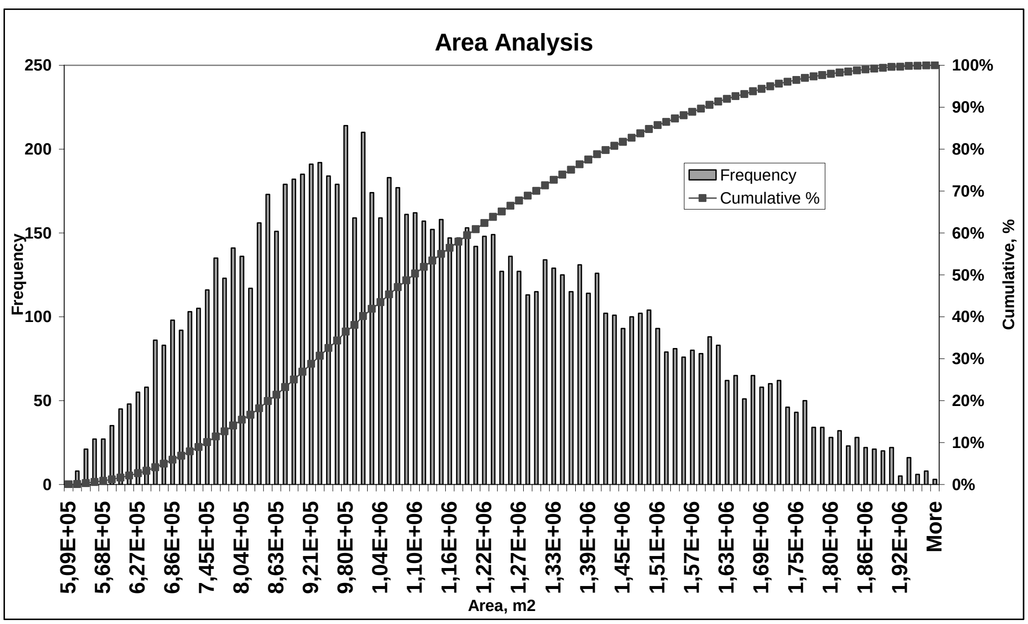


Figure 6.9 Histogram and Cumulative Graphs for Area

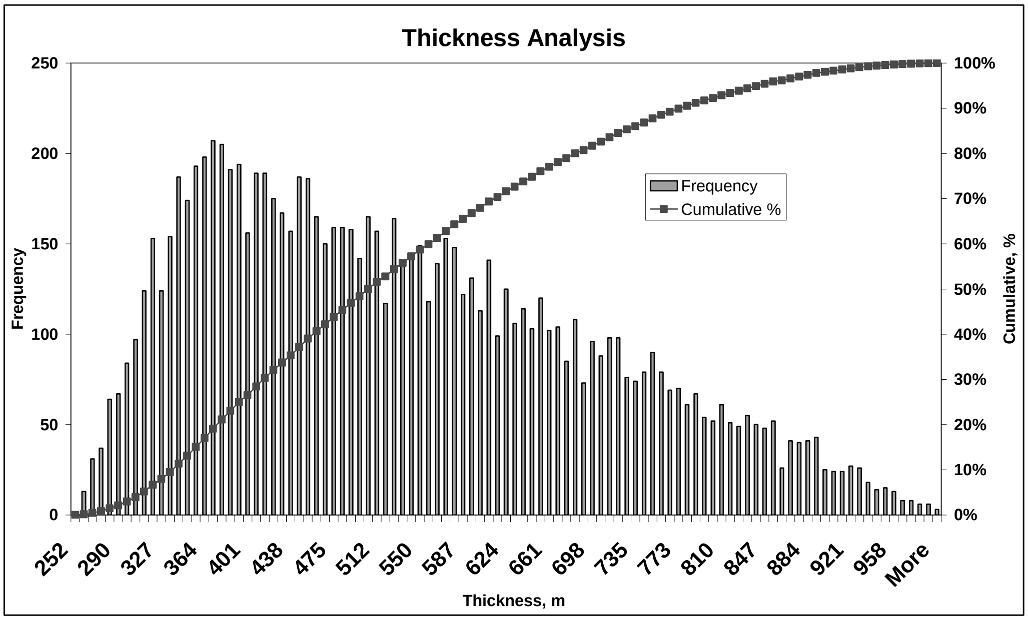


Figure 6.10 Histogram and Cumulative Graphs for Thickness

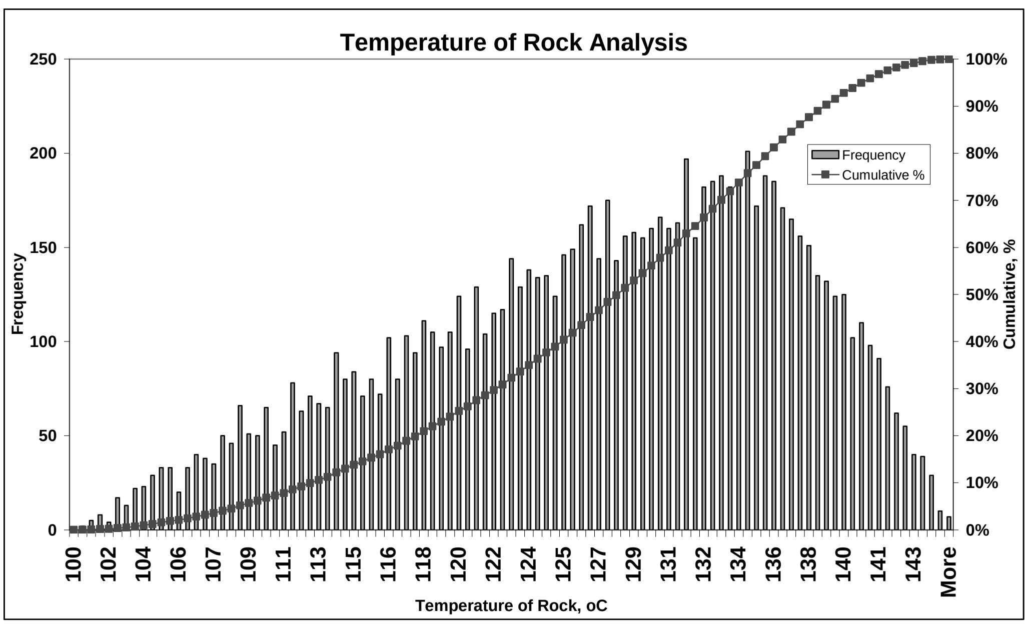


Figure 6.11 Histogram and Cumulative Graphs for Temperature of Rock

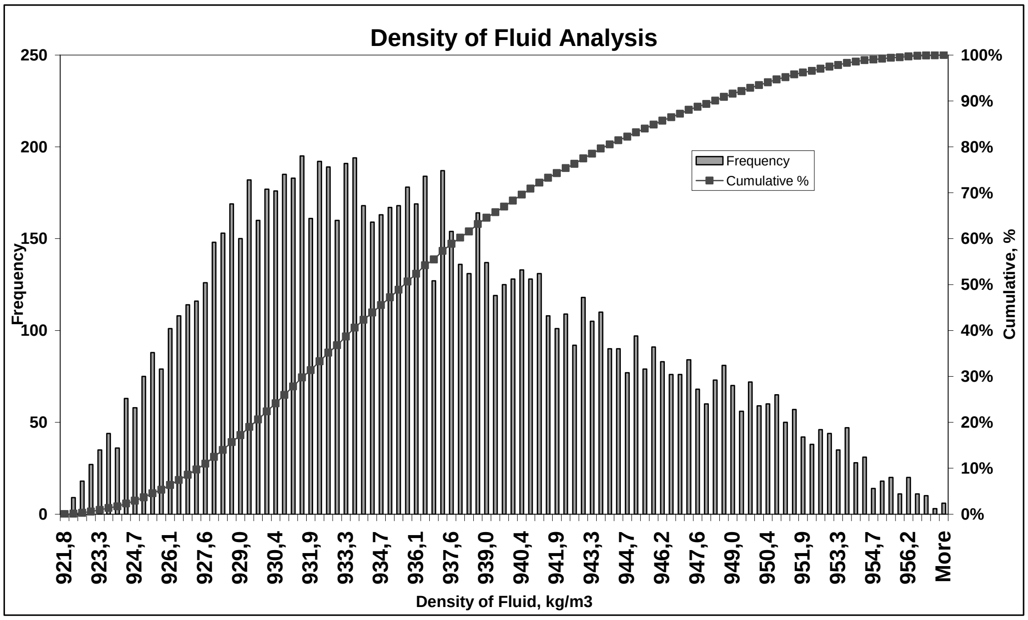


Figure 6.12 Histogram and Cumulative Graphs for Density of Fluid

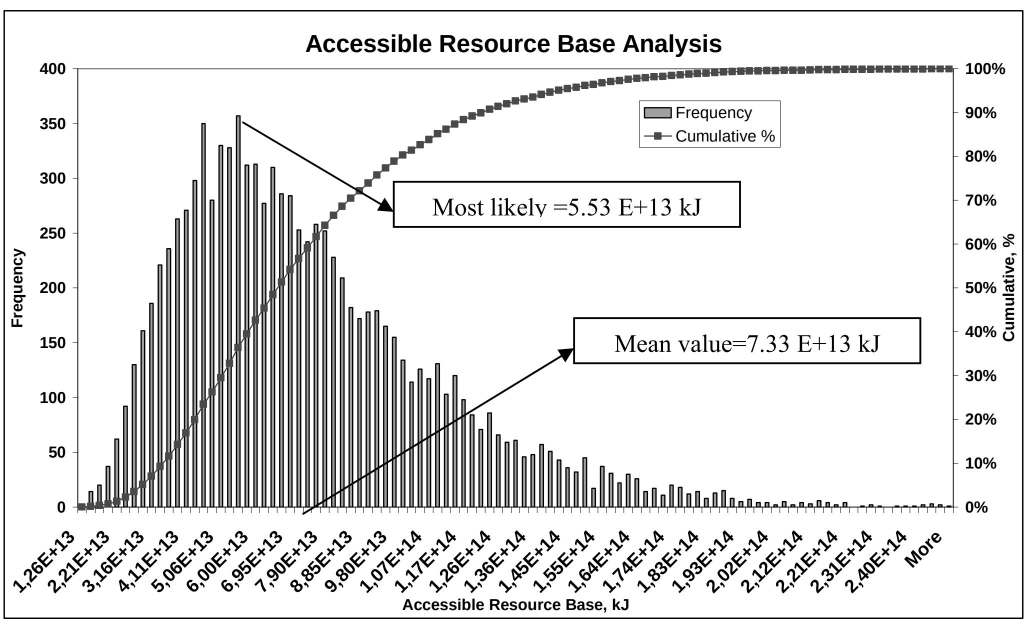


Figure 6.13 Histogram and Cumulative Graphs for Accessible Resource Base

6.3 RECOVERABLE HEAT ENERGY CALCULATION

In case of a direct heat application from a low-temperature geothermal reservoir, the accessible resource base (kJ) can be converted to recoverable heat energy (kW_t) by using Equation 4.2.

$$H_{Recoverable} = \frac{H_{Total} \times RF \times Y}{LF \times t} \qquad (4.2)$$

where;

$H_{Recoverable}$ = Recoverable heat energy, kW_t

H_{Total} = Accessible resource base, kJ

RF = Recovery factor for the given reservoir, fraction

Y = Transformation yield. It takes into account the efficiency of transferring heat energy from geothermal fluid to a secondary fluid, fraction

LF = Load factor. Most of the direct heat applications (space heating, greenhouse heating etc.) of geothermal energy are not continuous throughout the year. This factor takes into account the fraction of the total time in which the heating application is in operation, fraction

t = Total project life, sec

In this model the most critical parameter is recovery factor, which represents the produced percentage of accessible resource. White and Williams (1975), Muffler and Cataldi (1978), and Sorey et al. (1982) discussed this parameter in their studies and they accepted this parameter in the range of 18-25% for the water-dominated systems. On the other hand Nathenson and Muffler (1975) used a value of 24% for recovery factor in their study while modeling hot water systems. World Energy Council, WEC, (1978) used a value of 7% for recovery factor. This is a fairly low value and it is thought that it represents only the heat energy that water has. For this reason a triangular distribution is formed and for the minimum, most likely and the maximum values, 7%, 18% and 24% are chosen, respectively.

The range for transformation yield was defined between 0.7 and 0.93 with a value of 0.85 as most likely.

H_{Total} can actually be referred as the *accessible resource base* of the low-temperature reservoir under study. For the minimum, most likely and the maximum values, 1.26E+13, 5.53E+13 and 2.50E+14 are obtained respectively for *accessible resource base* from the output of Equation 4.1 after running @RISK.

The remaining variables of Equation 4.2 (total project life and load factor) are taken as constant values. The value of 7.88 x 10^8 seconds for total life represents 25 years production time and the value of 50% for load factor represents 183 days production in a year for a comfort temperature of 18 °C (Figure 6.14).

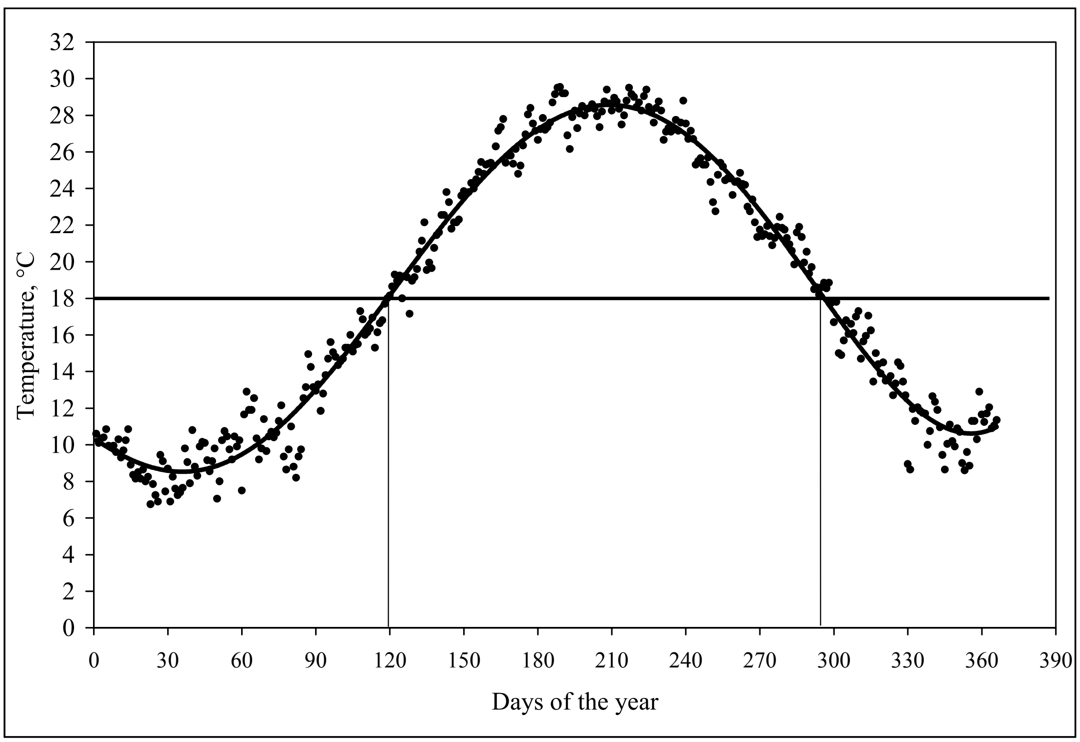


Figure 6.14 Daily temperature change in İzmir.

Table 6.4 lists the values of variables of Equation 4.2.

Table 6.4 Values for the variables in Equation 4.2 with Triangular Distribution

İzmir Balçova-Narlıdere Geothermal Region				
Recoverable Heat Energy				
Parameters	**Most Likely**	**Type of Distribution**	**Minimum**	**Maximum**
Accessible Resource Base, (kJ)	5.53E+13	Lognormal	1.26E+13	2.50E+14
Recovery Factor, (fraction)	0.18	Triangular	0.07	0.24
Yield, (fraction)	0.85	Triangular	0.7	0.93
Total Life, (sec)	7.88E+08	Constant	-	-
Yearly Production, (fraction)	0.50	Constant	-	-

Table 6.5 lists the mean, minimum and maximum values of the variables of Equation 4.2 as the result of simulation study of @RISK. Figures 6.15 – 6.18 give the histograms of the output of @RISK. According to the summary statistics of @RISK (Appendix C, Table C.6), the mean value for recoverable heat energy of Balçova-Narlıdere field is 2.51 E+04 kW_t. On the other hand, the most likely recoverable heat energy was found to be 2.12 E+04 kW_t (Figure 6.18). The most likely resource base has the probability of 47% (approximately from Table C.6).

Table 6.5 Simulation Summaries for Recoverable Heat Energy

Simulation Summary							
Summary Information							
Number of Simulations					1		
Number of Iterations					10000		
Number of Inputs					3		
Number of Outputs					1		
Sampling Type					Monte Carlo		
Input	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Accessible Resource Base, (kJ)	1.26E+13	7.33E+13	2.50E+14	3.47E+13	10%	1.22E+14	90%
Recovery Factor, (fraction)	0.07	0.16	0.24	0.11	10%	0.21	90%
Yield, (fraction)	0.70	0.83	0.93	0.76	10%	0.89	90%
Output	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Recoverable heat energy (kWt)	3.20E+03	2.51E+04	1.16E+05	1.08E+04	10%	4.36E+04	90%

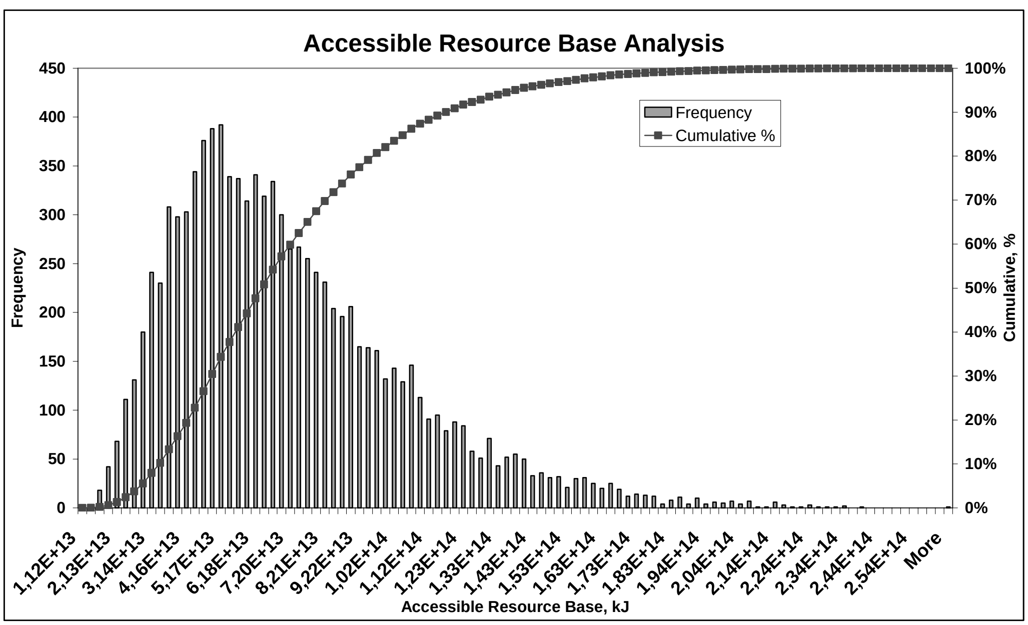


Figure 6.15 Histogram and Cumulative Input Graphs for Accessible Resource Base

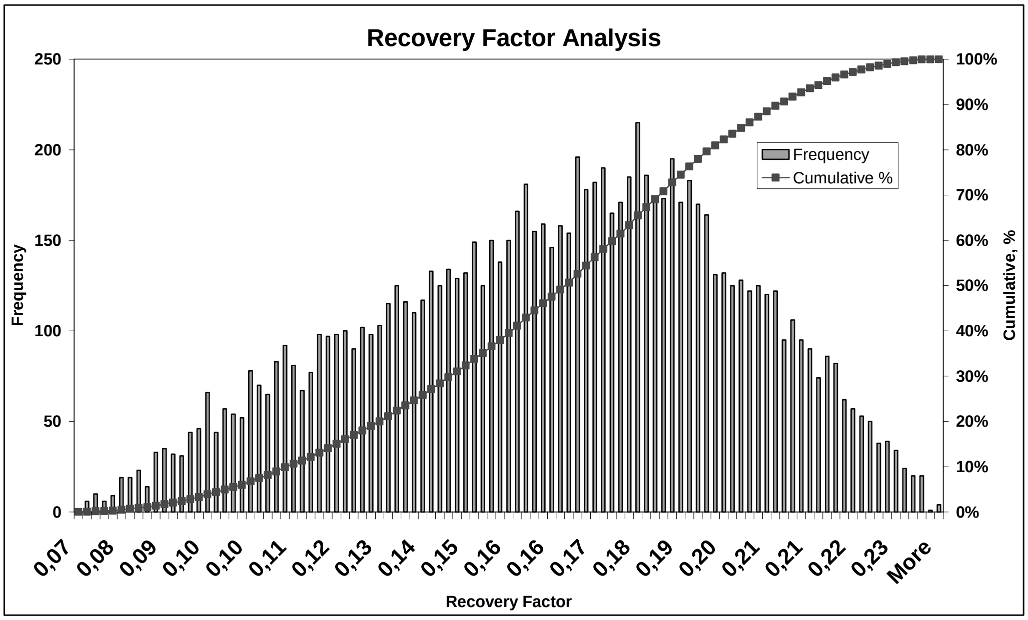


Figure 6.16 Histogram and Cumulative Graphs for Recovery Factor

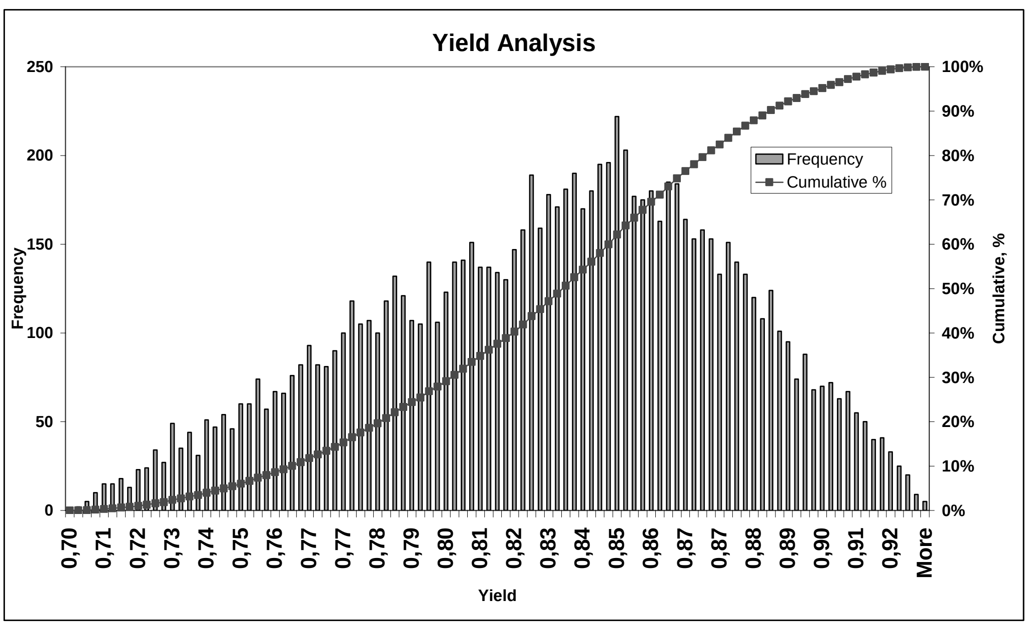


Figure 6.17 Histogram and Cumulative Graphs for Yield

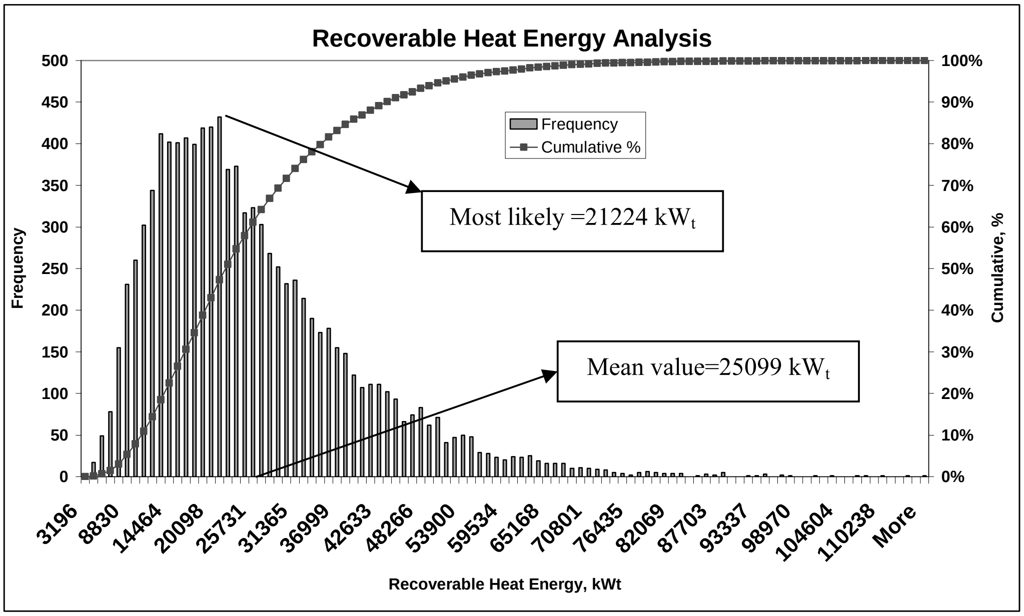


Figure 6.18 Histogram and Cumulative Graphs for Recoverable Heat Energy

Analysis of the results of @RISK shows that Balçova-Narlıdere geothermal field has recoverable heat energy of 43.6 MW_t at the optimistic approach (90% probability), 10.8 MW_t at the pessimistic approach (10% probability). Mean value was found to be 25.1 MW_t (Figure 6.19).

These values can also be reported as the number of dwellings that can be heated with the available heat energy. According to ORME Geothermal Company Inc. (Satman et al., 2001), a house with an area of 100 m^2 in Balçova needs 0.004 MWt in order to raise its temperature to 22 °C when the outside temperature is 8.6 °C. The number of dwellings are found to be 2700, 6275 and 10900 for pessimistic, mean and optimistic values of heat energy, respectively.

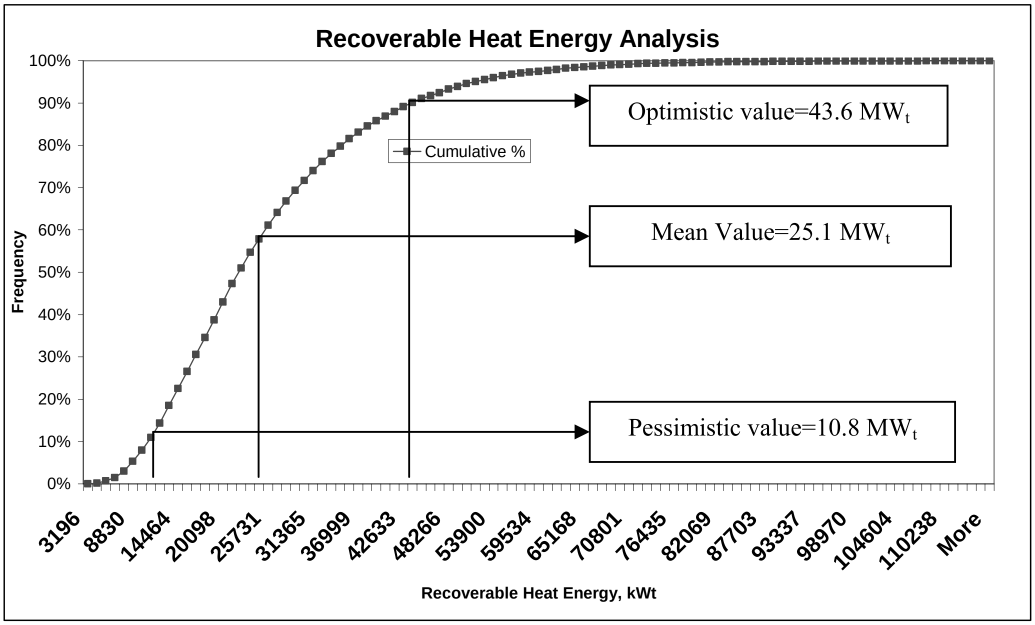


Figure 6.19 Cumulative Analysis of Recoverable Heat Energy

6.4 COMPARISON OF DISTRIBUTION TYPES

The type of distribution was selected as triangular so far. In this section the effect of distribution type is studied by assigning uniform distributions to the variables in Equations 4.1 and 4.2. Table 6.6 and 6.7 list the limits of the variables for uniform type distribution. The results of @RISK simulation with uniform distribution are tabulated in Table 6.8 and Table 6.9.

Analysis of the results of @RISK with uniform distribution shows that Balçova-Narlıdere geothermal field has recoverable heat energy of 54.3 MW$_t$ at the optimistic approach (90% probability), 8.24 MW$_t$ at the pessimistic approach (10% probability). Mean value was found to be 27.6 MW$_t$ (Figure 6.20), and the number of dwellings that can be heated are found to be 2060, 6900 and 13575 for pessimistic, mean and optimistic values of heat energy, respectively.

Table 6.6 Values for the variables in Equation 4.1 with Uniform Distribution

İzmir Balçova-Narlıdere Geothermal Region			
Accessible Resource Base			
Parameters	**Type of Distribution**	**Minimum**	**Maximum**
Porosity, ϕ (fraction)	Lognormal	0.002	0.07
Specific Heat of Rock, c_R (kJ/kg-^oC)	Uniform	0.80	1.09
Density of Rock, ρ_R (kg/m^3)	Uniform	2600	2850
Area, A (m^2)	Uniform	5.00 E+05	2.00 E+06
Thickness, h (m)	Uniform	250	1000
Temperature of Rock, T_R (^oC)	Uniform	100	145
Density of Fluid, ρ_F (kg/m^3)	Uniform	921.7	958.1
Utilized Temperature, T_U (^oC)	Constant	80	80
Specific Heat of Fluid, c_F (kj/kg-^oC)	Constant	4.18	4.18

Table 6.7 Values for the variables in Equation 4.2 with Uniform Distribution

İzmir Balçova-Narlıdere Geothermal Region			
Recoverable Heat Energy			
Parameters	**Type of Distribution**	**Minimum**	**Maximum**
Accessible Resource Base, (kJ)	Lognormal	1.26E+13	2.50E+14
Recovery Factor, (fraction)	Uniform	0.07	0.24
Yield, (fraction)	Uniform	0.7	0.93
Total Life, (sec)	Constant	7.88 E+8	7.88 E+8
Yearly Production, (fraction)	Constant	0.50	0.50

Table 6.8 Simulation Summaries for Accessible Resource Base with Uniform Distribution

Number of Iterations					10000		
Number of Inputs					7		
Number of Outputs					1		
Sampling Type					Monte Carlo		
Input	***Statistics***						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Porosity, ϕ (fraction)	0.0020	0.0238	0.0699	0.0073	10%	0.0472	90%
Specific Heat Rock, c_R (kJ/kg-°C)	0.80	0.94	1.09	0.83	10%	1.06	90%
Density of Rock, ρ_R (kg/m^3)	2600	2725	2850	2624	10%	2824	90%
Area, A (m^2)	5.00E+05	1.25E+06	2.00E+06	6.58E+05	10%	1.85E+06	90%
Thickness, h (m)	250	624	1000	325	10%	924	90%
Temperature of Rock, T_R (^{o}C)	100	122	145	105	10%	140	90%
Density of Fluid, ρ_F (kg/m^3)	921.7	940.0	958.1	925.3	10%	954.6	90%
Output	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Accessible resource base (kJ)	7.01E+12	8.63E+13	3.47E+14	3.01E+13	10%	1.62E+14	90%

Table 6.9 Simulation Summaries for Recoverable Heat Energy with Uniform Distribution

Number of Iterations					10000		
Number of Inputs					3		
Number of Outputs					1		
Sampling Type					Monte Carlo		
Input	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Accessible Resource Base, (kJ)	7.01 E+12	8.63 E+13	3.47 E+14	3.01 E+13	10%	1.62 E+14	90%
Recovery Factor, fraction	0.07	0.15	0.24	0.09	10%	0.22	90%
Yield, fraction	0.70	0.81	0.93	0.72	10%	0.91	90%
Output	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Recoverable heat energy (kWt)	1.03 E+03	2.76 E+04	1.59 E+05	8.24 E+03	10%	5.43 E+04	90%

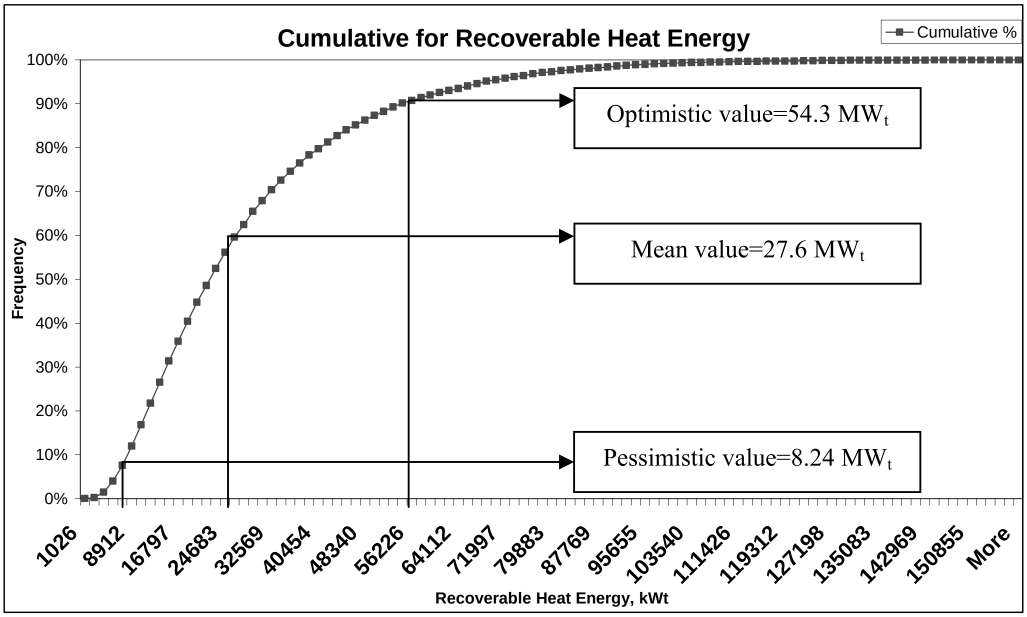


Figure 6.20 Cumulative Analysis of Recoverable Heat Energy with Uniform Distribution

It is also possible to make the uniform distribution analysis in EXCEL by the help of random number generator (without @RISK). The analysis of the results obtained by the use of with and without @RISK showed that the results of these two methods do not differ from each other significantly (Figure 6.21 and 6.22).

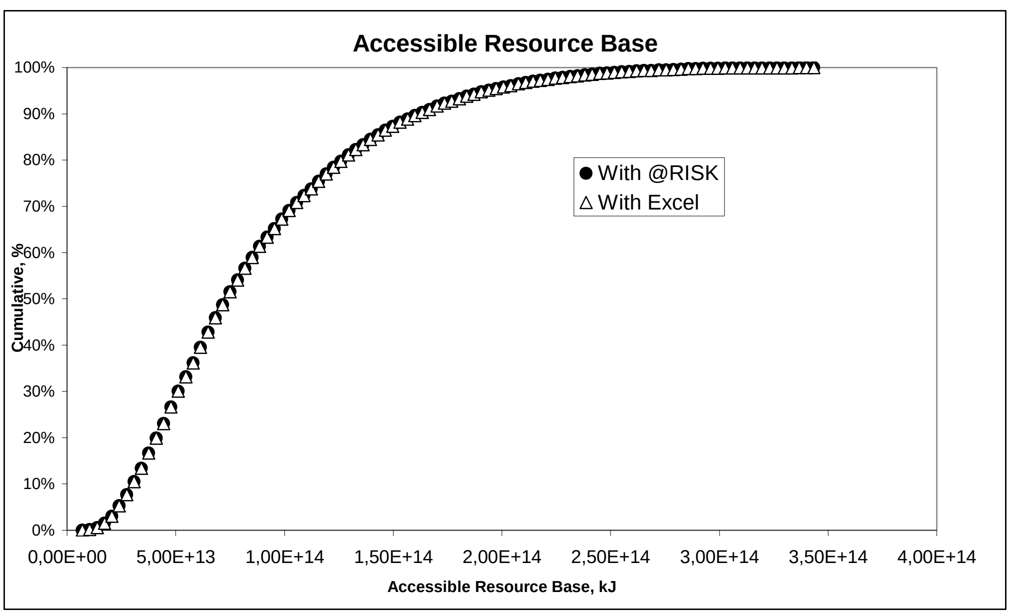


Figure 6.21 Comparison of Uniform Distribution Results of Accessible Resource Base with @RISK and with EXCEL

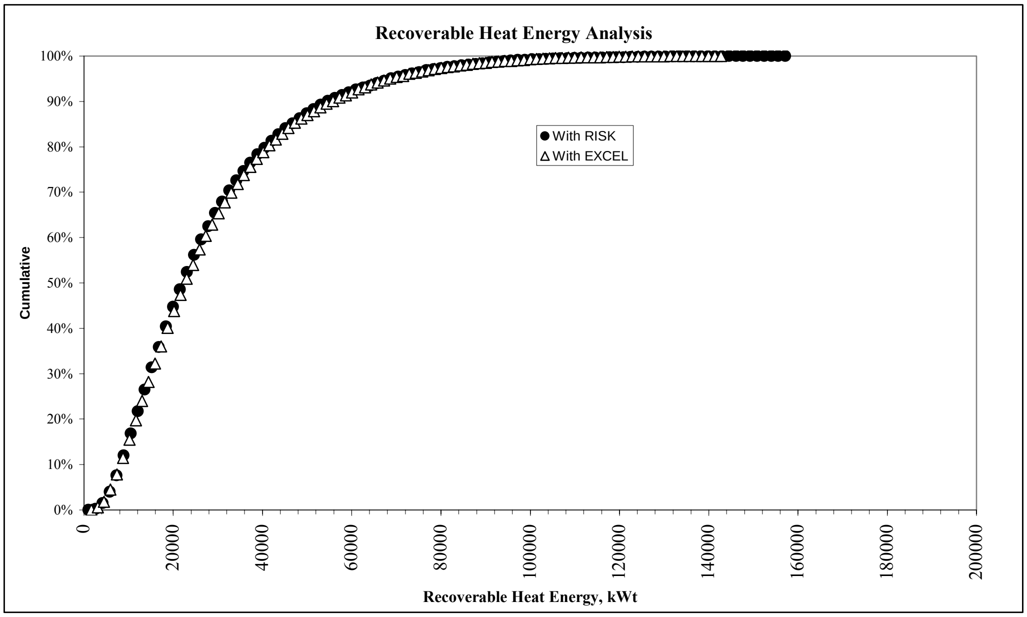


Figure 6.22 Comparison of Uniform Distribution Results of Recoverable Heat Energy with @RISK and with EXCEL

Recoverable Heat Energies obtained from triangular distribution and uniform distribution with and without @RISK are tabulated in Table 6.10.

Table 6.10 Comparison of the Recoverable Heat Energy values with different distribution types in @RISK and Microsoft EXCEL.

Balçova-Narlıdere	Triangular Distribution with @RISK		Uniform Distribution with @RISK		Uniform Distribution without @RISK	
Cumulative Approaches	Recoverable Heat Energy, MW_t	# of Dwellings	Recoverable Heat Energy, MW_t	# of Dwellings	Recoverable Heat Energy, MW_t	# of Dwellings
Pessimistic value (10%)	10.8	2700	8.24	2060	8.1	2025
Mean Value	25.1	6275	27.6	6900	27.8	6950
Optimistic value (90%)	43.6	10900	54.3	13575	54.4	13600

6.5 ITERATION ANALYSIS

The effect of the number of iterations on the results of simulation, 100, 500, 1000, 5000 and 10000 are separately applied to the variables in simulation. The results of the Recoverable Heat Energy with different iteration numbers are plotted in Figure 6.23. It is clear from Figure 6.23 that 500 and higher number of iterations give very close results.

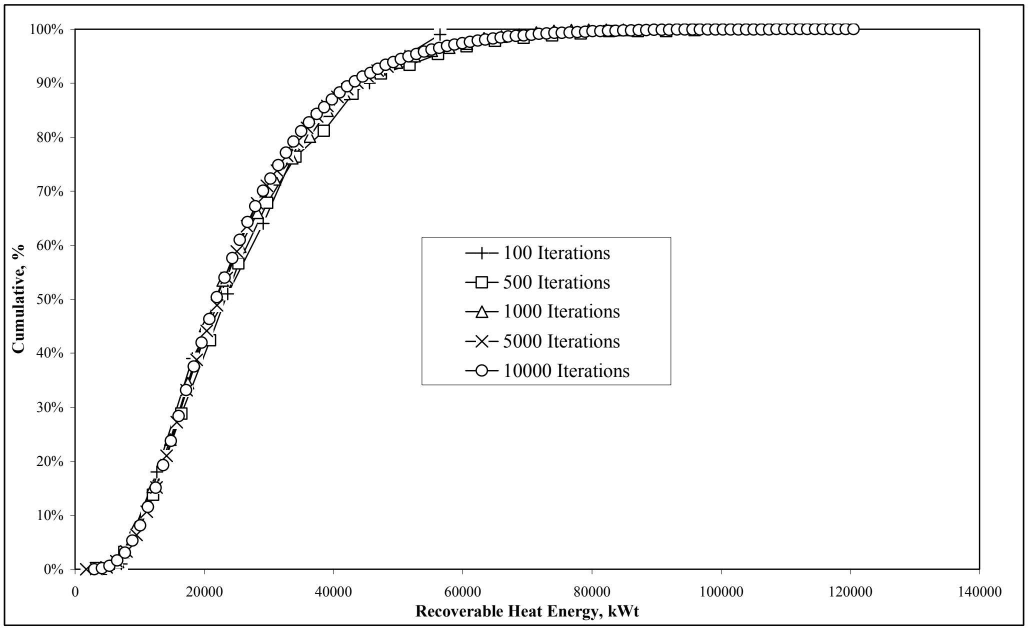


Figure 6.23 Different Numbers of Iterations for Recoverable Heat Energy

6.6 SENSITIVITY ANALYSIS

The Sensitivity analysis performed on the output variables and their associated inputs uses either a multivariate stepwise regression analysis or a rank order correlation analysis.

In the regression analysis, the coefficients calculated for each input variable measure the sensitivity of the output to that particular input distribution. The overall fit of the regression analysis is measured by the reported fit or R-squared of the model. The lower the fit the less stable the reported sensitivity statistics. If the fit is too low, a similar simulation with the same model could give a different ordering of input sensitivities.

The sensitivity analysis using rank correlations is based on the calculation of a correlation coefficient between the selected output variable and the samples for each of the input distributions. The higher the correlation between the input and the output, the more significant the input is in determining the output's value.

The sensitivity analysis for accessible resource base and recoverable heat energy are given in Tables 6.11 and 6.12.

The most important factors for the calculation of accessible resource base are the thickness and the area, thus in other words the volume of rock. The temperature of the rock is also effective while porosity and density of rock do not have significant effects.

Recovery factor is in third rank for recoverable heat energy, following thickness and area of the reservoir.

Table 6.11 Sensitivity Analysis for Accessible Resource base Parameters

Rank	Name	Regression	Correlation
#1	Thickness, h (m)	0.642	0.654
#2	Area, A (m^2)	0.572	0.571
#3	Temperature of Rock, T_R (°C)	0.418	0.431
#4	Specific Heat of Rock, c_R (kJ/kg-°C)	0.120	0.115
#5	Density of Rock, ρ_R (kg/m^3)	0.038	0.019
#6	Porosity, ϕ fraction	0.021	0.015

Table 6.12 Sensitivity Analysis for Recoverable Heat Energy Parameters

Rank	Name	Regression	Correlation
#1	Thickness, h (m)	0.570	0.582
#2	Area, A (m^2)	0.510	0.513
#3	Recovery Factor, fraction	0.394	0.404
#4	Temperature of Rock, T_R (°C)	0.372	0.390
#5	Specific Heat of Rock, c_R (kJ/kg-°C)	0.109	0.100
#6	Yield, fraction	0.108	0.110
#7	Density of Rock, ρ_R (kg/m^3)	0.037	0.013
#8	Porosity, ϕ fraction	0.016	0.023

CHAPTER 7

CONCLUSIONS

The following conclusions can be drawn from the results of the current study,

1. Balçova-Narlıdere geothermal field has recoverable heat energy content of 58.6 MW_t as an optimistic value (90% probability) and 33.5 MW_t as mean value when triangular type distribution is used for the input variables.
2. The change in type of distribution from triangular to uniform resulted with a change in the recoverable heat energy content. The changes in the current study are in the direction of increase in the mean and optimistic values when uniform distribution is applied.
3. No significant difference is observed in the output of @RISK when 500 and higher number of iterations is applied.
4. Sensitivity analysis showed that the most important input parameters are thickness and area of the reservoir rock for both accessible resource base and recoverable heat energy calculations.
5. Recovery factor has also a significant importance for the calculation of recoverable heat energy, based on sensitivity analysis.

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APPENDIX A

PROBABILITY DENSITY FUNCTION& CUMULATIVE DISTRIBUTION FUNCTION

A.1 PROBABILITY DENSITY FUNCTION (PDF)

The significance of the pdf f (x) is that f (x) dx is the probability that the random variables, x^1 is in the interval (x, x + dx), written as:

$$prob\left(x \le x^l \le x + dx\right) \equiv P(x \le x^l \le x + dx) = f(x)dx$$

This is an operational definition of f (x). Since f (x) dx is unitless (it is a probability), and then f (x) has units of inverse random variables units, e.g., 1/cm or 1/s or $1/cm^2$, depending on the units of x. Figure A.1 shows a typical pdf f (x) and illustrates the interpretation of the probability of finding the random variables in (x, x + dx) with the area under the curve f (x) from x to x + dx.

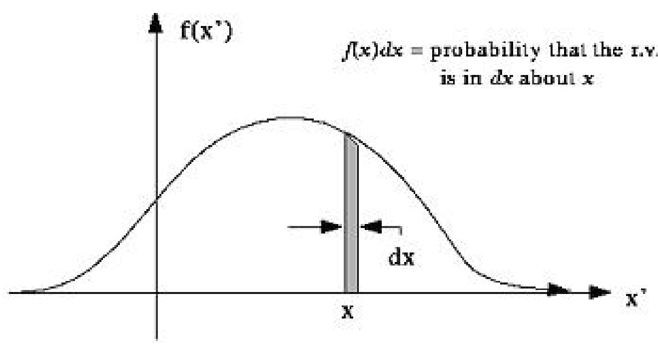


Figure A.1 Typical probability distribution function (pdf)

We can also determine the probability of finding the random variables somewhere in the finite interval [a, b]:

$$prob\ (a \le x \le b) \equiv P(a \le x \le b) = \int_b^a f(x^l)dx^l$$

A.1

which, of course, is the area under the curve f (x) from x = a to x = b.

Note that these restrictions are not very stringent, and in fact allow one to apply Monte Carlo methods to solve problems that have no apparent stochasticity or randomness. By posing a particular application in terms of functions that obey these relatively mild conditions, one can treat them as pdf's and perhaps employ the powerful techniques of Monte Carlo simulation to solve the original application. While applying these density functions, some statistical terms such as mean, variance, etc. are utilized. The brief definitions of these terms are given below.

A.1.1 Mean, Mode and Median

The *mean*, *mode* and *median* are often misunderstood concepts, which may all be grasped in terms of histograms. For symmetric histograms these three numbers are the same. But for asymmetric ones they will be different as shown in the Figure A.2.

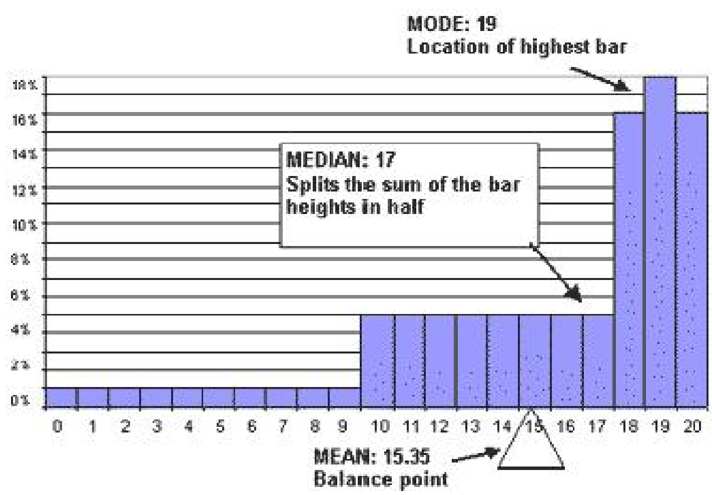


Figure A.2 Mean, Mode and Median (RISK Manual)

The Mean, Average or Expected Value

If the histogram were made of a solid material, this is the point at which it would balance. It is calculated by the sum of the height of each bar multiplied by its location on the x-axis.

The Median

This is the point at which half the sum of the entire bar heights are to the left, and half to the right. The median is also known as the 50^{th} percentile.

The Mode

This is the location of the highest bar. If more than one bar is higher than both its neighbors, the distribution is said to be multi-modal.

A.1.2 Variance

The *variance* is one of several indices of variability that statisticians use to characterize the dispersion among the measures in a given population. To calculate the variance of a given population, it is necessary to first calculate the mean of the scores, then measure the amount that each score deviates from the mean and then square that deviation (by multiplying it by itself). Numerically, the variance equals the average of the several squared deviations from the mean.

We now define an important quantity, intimately related to the pdf, which is known as the *cumulative distribution function*, or *cdf*.

A.2 CUMULATIVE DISTRIBUTION FUNCTION (CDF)

The *cumulative distribution function* gives the probability that the random variables x^l is less than or equal to x:

$$\begin{aligned} CDF &\equiv prob\left(x^l \le x\right) \equiv F(x) \\ &= \int_{-\infty}^{x} f\left(x^l\right) dx^l \end{aligned} \qquad \text{A.2}$$

Note that since $f(x) \geq 0$ and the integral of f(x) is normalized to unity, F (x) obeys the following conditions:

- F (x) is monotone increasing
- $F(-\infty) = 0$
- $F(+\infty) = 1$

Figure A.3 illustrates a representative cdf. Note the dependence of F (x) as $x \rightarrow \pm \infty$. Since F (x) is the indefinite integral of f (x), $f(x) = F^{l}(x)$.

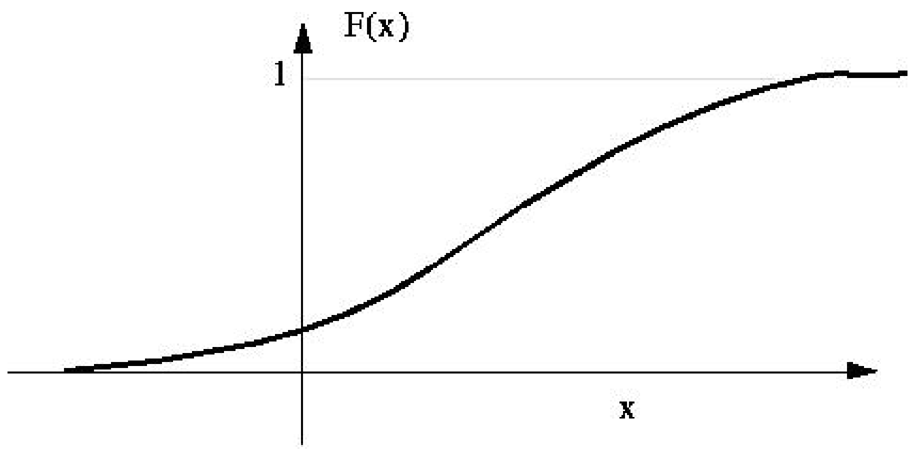


Figure A.3 Representative cumulative distribution function (cdf) (RISK Manual)

APPENDIX B

DISTRIBUTION TYPES

B.1 NORMAL DISTRIBUTION

Normal

RISKNormal(μ, σ)

Parameters:

$\boldsymbol{\mu}$	continuous location parameter	
$\boldsymbol{\sigma}$	continuous scale parameter	$\sigma > 0$

Domain:

$-\infty \leq x \leq +\infty$ continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}$$

$$F(x) = \Phi\left(\frac{x-\mu}{\sigma}\right)$$

where Φ is the *Error Function*.

Mean:

μ

Variance:

σ^2

Skewness:

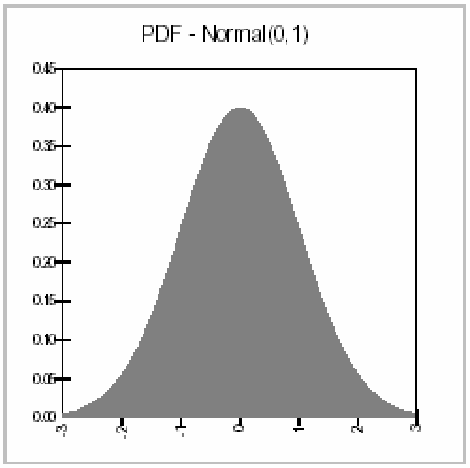
0

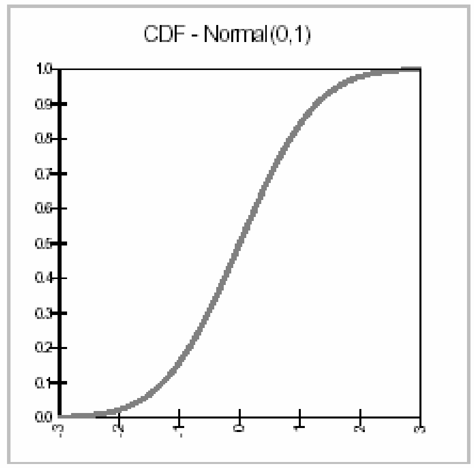
Kurtosis:

3

Mode:

μ





B.2 TRIANGULAR DISTRIBUTION

Triangular

RISKTriang(min, m.likely, max)

Parameters:

min	continuous boundary parameter	min < max
m.likely	continuous mode parameter	min ≤ m.likely ≤ max
max	continuous boundary parameter	

Domain:

min ≤ x ≤ max	continuous

Density and Cumulative Functions:

$$f(x) = \frac{2(x - \min)}{(\text{m.likely} - \min)(\max - \min)} \qquad \min \le x \le \text{m.likely}$$

$$f(x) = \frac{2(\max - x)}{(\max - \text{m.likely})(\max - \min)} \qquad \text{m.likely} \le x \le \max$$

$$F(x) = \frac{(x - \min)^2}{(\text{m.likely} - \min)(\max - \min)} \qquad \min \le x \le \text{m.likely}$$

$$F(x) = 1 - \frac{(\max - x)^2}{(\max - \text{m.likely})(\max - \min)} \qquad \text{m.likely} \le x \le \max$$

Mean:

$$\frac{\max + \text{m.likely} + \max}{3}$$

Variance:

$$\frac{\max^2 + \text{m.likely}^2 + \max^2 - (\max)(\text{m.likely}) - (\text{m.likely})(\min) - (\max)(\min)}{18}$$

Skewness:

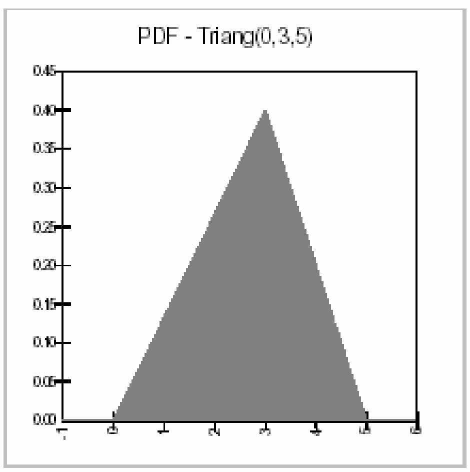
$$\frac{2\sqrt{2}}{5}\frac{f\left(f^2-9\right)}{\left(f^2+3\right)^{3/2}} \qquad \text{where } f \equiv \frac{2(\text{m.likely}-\min)}{\max-\min}-1$$

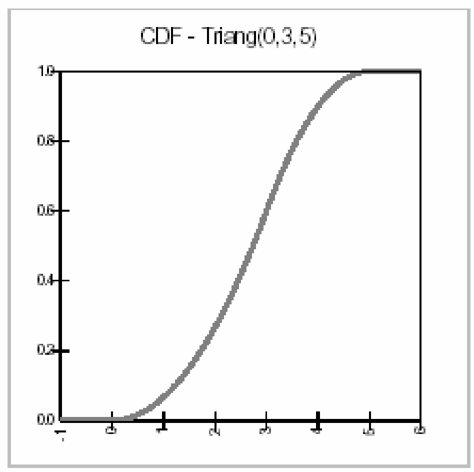
Kurtosis:

2.4

Mode:

m.likely





B.3 UNIFORM DISTRIBUTION

Uniform

RISKUniform(min, max)

<u>Parameters</u>:

min	continuous boundary parameter	min < max
max	continuous boundary parameter	

<u>Domain</u>:

$\min \le x \le \max$	continuous

<u>Density and Cumulative Functions</u>:

$$f(x) = \frac{1}{\max - \min}$$

$$F(x) = \frac{x - \min}{\max - \min}$$

<u>Mean</u>:

$$\frac{\max - \min}{2}$$

<u>Variance</u>:

$$\frac{(\max - \min)^2}{12}$$

Skewness:

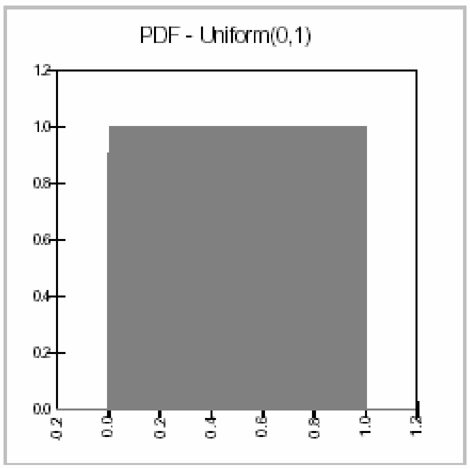
0

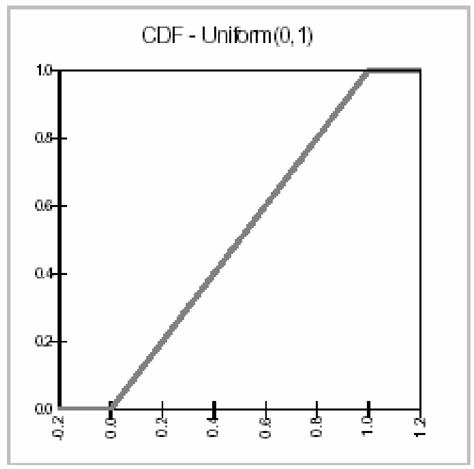
Kurtosis:

1.8

Mode:

Not uniquely defined





B.4 LOGNORMAL DISTRIBUTION

B.4.1 Lognormal Distribution Format 1

Lognormal (Format 1)

RISKLognorm(μ, σ)

Parameters:

μ	continuous parameter	$\mu > 0$
σ	continous parameter	$\sigma > 0$

Domain:

$0 \le x \le +\infty$ continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{x\sqrt{2\pi}\sigma'} e^{-\frac{1}{2}\left[\frac{\ln x - \mu'}{\sigma'}\right]^2}$$

$$F(x) = \Phi\left(\frac{\ln x - \mu'}{\sigma'}\right)$$

with $\mu' \equiv \ln\left[\frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}}\right]$ and $\sigma' \equiv \sqrt{\ln\left[1 + \left(\frac{\sigma}{\mu}\right)^2\right]}$

where Φ is the *Error Function*.

Mean:

μ

Variance:

σ^2

Skewness:

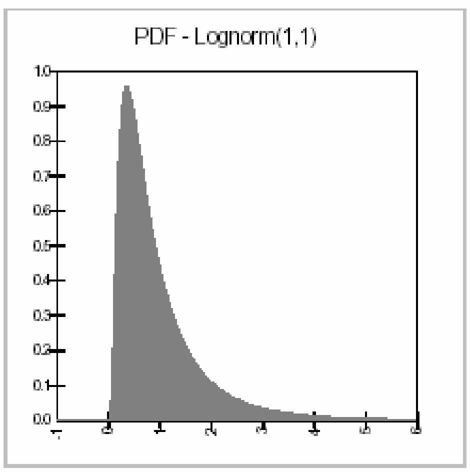
$$\left(\frac{\sigma}{\mu}\right)^3 + 3\left(\frac{\sigma}{\mu}\right)$$

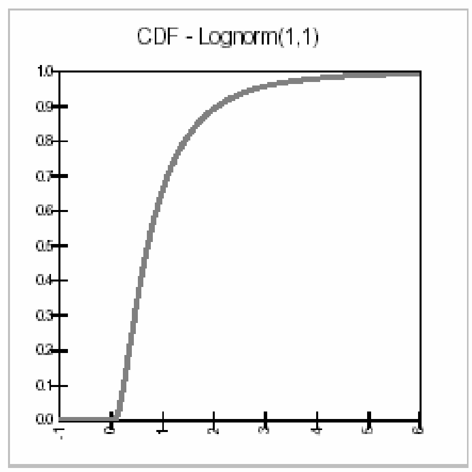
Kurtosis:

$$\omega^4 + 2\omega^3 + 3\omega^2 - 3 \qquad \text{with } \omega \equiv 1 + \left(\frac{\sigma}{\mu}\right)$$

Mode:

$$\frac{\mu^4}{\left(\sigma^2 + \mu^2\right)^{3/2}}$$





B.4.2 Lognormal Distribution Format 2

Lognormal (Format 2)

RISKLognorm2(μ, σ)

Parameters:

μ	continuous parameter	
σ	continous parameter	$\sigma > 0$

Domain:

$0 \leq x \leq +\infty$ continuous

Density and Cumulative Functions:

$$f(x) = \frac{1}{x\sqrt{2\pi}\sigma} e^{-\frac{1}{2}\left[\frac{\ln x - \mu}{\sigma}\right]^2}$$

$$F(x) = \Phi\left(\frac{\ln x - \mu}{\sigma}\right)$$

where Φ is the *Error Function*.

Mean:

$$e^{\mu + \frac{\sigma^2}{2}}$$

Variance:

$$e^{2\mu}\omega(\omega - 1)$$ with $\omega \equiv e^{\sigma^2}$

Skewness:

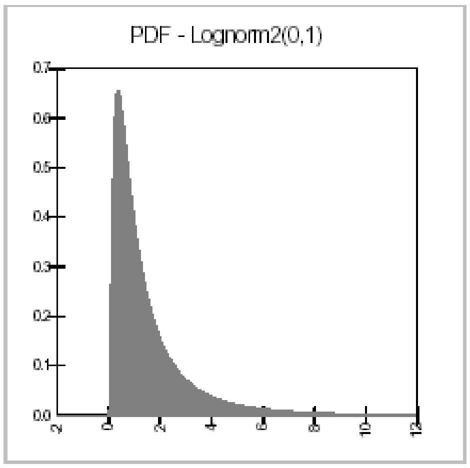
$$(\omega+2)\sqrt{\omega-1} \qquad \text{with } \omega \equiv e^{\sigma^2}$$

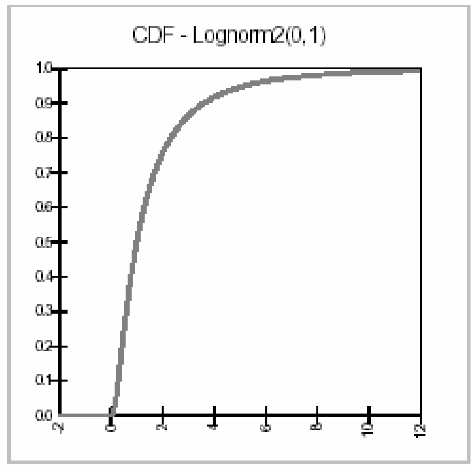
Kurtosis:

$$\omega^4 + 2\omega^3 + 3\omega^2 - 3 \qquad \text{with } \omega \equiv e^{\sigma^2}$$

Mode:

$$e^{\mu-\sigma^2}$$





APPENDIX C

@ RISK SOFTWARE PROGRAM

@RISK is an add-in to Microsoft Excel. As an add-in, @RISK becomes seamlessly integrated with your spreadsheet, adding risk analysis to your existing models. Working with @RISK is as easy as working in your existing spreadsheets. @RISK uses a technique known as *Monte Carlo simulation* to show you all possible outcomes. Running an analysis with @RISK involves three simple steps:

C.1 DEFINE UNCERTAINITY FOR INPUT VARIABLES

The first step of running an analysis with @RISK is to define all the variables that are uncertain in the model. The nature of the uncertainty of a given variable is described with probability distributions, which give both the range of values that the variable could take (minimum to maximum), and the likelihood of occurrence of each value within the range. In @RISK, uncertain variables and cell values are entered as probability distribution functions for example: RiskNormal (10;100), RiskUniform (20;30), or RiskTriangular(100;135; 145). The numbers in normal and uniform type distributions in brackets indicate the minimum and maximum values of the variable that it could take while the numbers in triangular type distribution indicate minimum, most likely and maximum values of the variable, respectively.

Table C.1 lists the values of the variables with triangular and uniform distribution types.

Table C.1 Inputs

Accessible Resource Base				
Triangular Distribution				
Parameters	**Most Likely**	**Type of Distribution**	**Minimum**	**Maximum**
Porosity, ϕ (fraction)	-	Lognormal	0.002	0.07
Specific Heat of Rock, ρ_R (kg/m^3)	0.92	Triangular	0.80	1.09
Density of Rock, ρ_R (kg/m^3)	2750	Triangular	2600	2850
Area, A (m^2)	9.00 E+05	Triangular	5.00 E+05	2.00 E+06
Thickness, h (m)	350	Triangular	250	1000
Temperature of Rock, T_R (^{o}C)	135	Triangular	100	145
Density of Fluid, ρ_F (kg/m^3)	930.6	Triangular	921.7	958.1
Uniform Distribution				
Parameters	**Type of Distribution**		**Minimum**	**Maximum**
Porosity, ϕ (fraction)	Uniform		0.02	0.7
Specific Heat of Rock, ρ_R (kg/m^3)	Uniform		0.80	1.09
Density of Rock, ρ_R (kg/m^3)	Uniform		2600	2850
Area, A (m^2)	Uniform		5.00 E+05	2.00 E+06
Thickness, h (m)	Uniform		250	1000
Temperature of Rock, T_R (^{o}C)	Uniform		100	145
Density of Fluid, ρ_F (kg/m^3)	Uniform		921.7	958.1
Recoverable Heat Energy				
Triangular Distribution				
Parameters	**Most likely**	**Type of Distribution**	**Minimum**	**Maximum**
Accessible Resource Base, (kJ)	5.53E+13	Lognormal	1.26E+13	2.50E+14
Recovery Factor, (fraction)	0.18	Triangular	0.07	0.24
Yield, (fraction)	0.85	Triangular	0.7	0.93
Uniform Distribution				
Parameters	**Type of Distribution**		**Minimum**	**Maximum**
Accessible Resource Base, (kJ)	Lognormal		1.26E+13	2.50E+14
Recovery Factor, (fraction)	Uniform		0.07	0.24
Yield, (fraction)	Uniform		0.7	0.93

C.2 DEFINE OUTPUT VARIABLES

Next, output cells in which the values of the variables that are interested in will be recorded are defined. For the current study, these variables are accessible resource base and recoverable heat energy (Table C.2).

Table C.2 Outputs

Triangular Distribution							
Output	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Accessible resource base, (kJ)	1.26E+13	7.33E+13	2.50E+14	3.47E+13	10%	1.22E+14	90%
Recoverable heat energy (kWt)	3.20E+03	2.51E+04	1.16E+05	1.08E+04	10%	4.36E+04	90%
Uniform Distribution							
Output	**Statistics**						
Name	**Min.**	**Mean**	**Max.**	**x1**	**p1**	**x2**	**p2**
Accessible resource base, (kJ)	7.01E+12	8.63E+13	3.47E+14	3.01E+13	10%	1.62E+14	90%
Recoverable heat energy (kWt)	1,03E+03	2,76E+04	1,59E+05	8,24E+03	10%	5,43E+04	90%

C.3 SIMULATE

Simulate is the option of @RISK which recalculates the spreadsheet model hundreds or thousands of times. The number of different scenarios that can be looked at is limited by 10000 iterations. @RISK samples random values for each iteration from the @RISK functions that were entered and records the resulting outcome. The overall result is a look at a whole range of possible outcomes, including the probabilities that will occur.

C.4 RESULTS

C.4.1 @RISK Graphs for Accessible Resource Base

Inputs

,

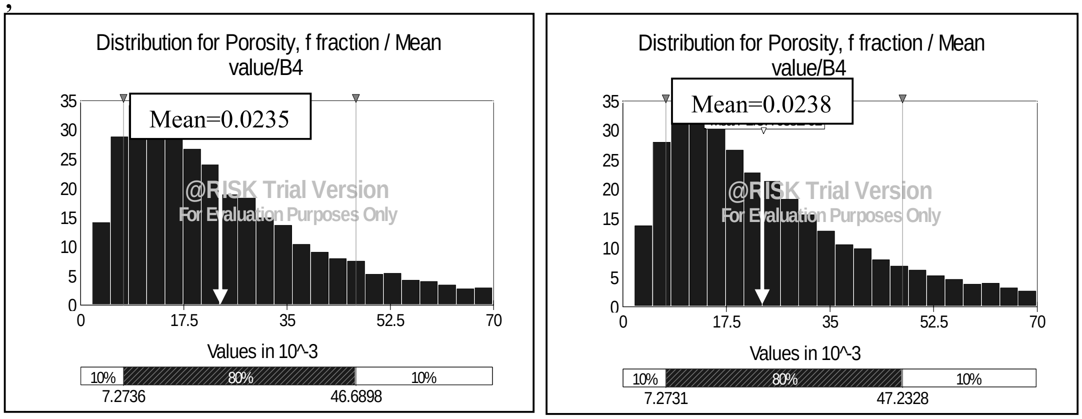


Figure C.1 Triangular and Uniform Distributions for Porosity

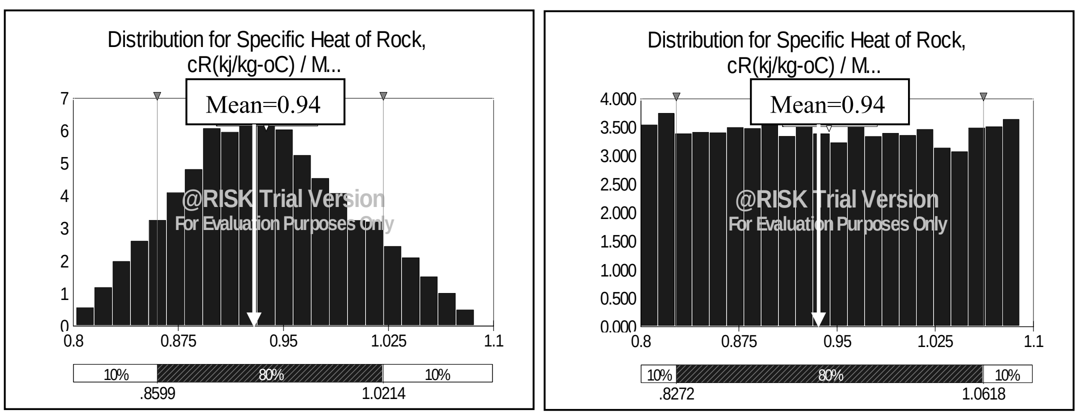


Figure C.2 Triangular and Uniform Distributions for Specific Heat of Rock

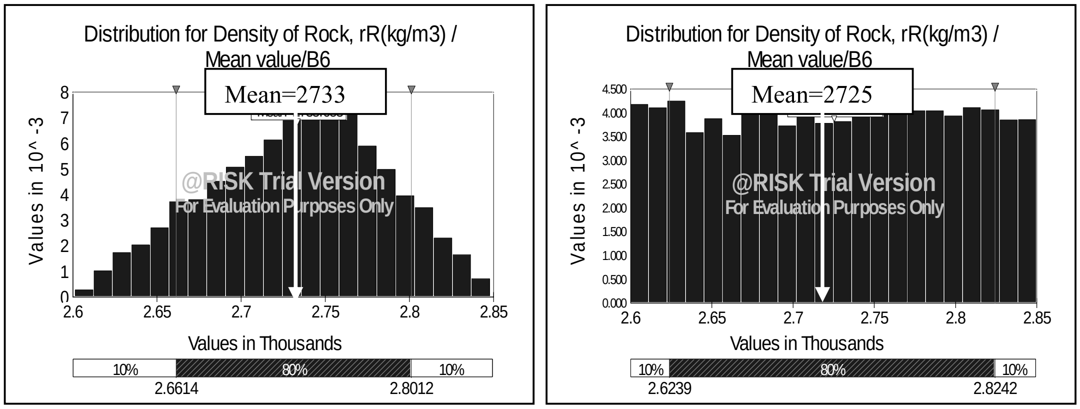


Figure C.3 Triangular and Uniform Distributions for Density of Rock

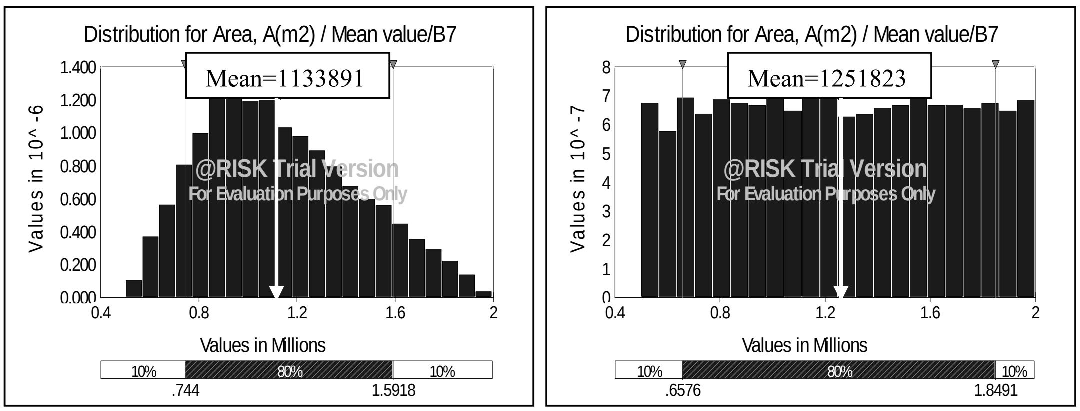


Figure C.4 Triangular and Uniform Distributions for Area

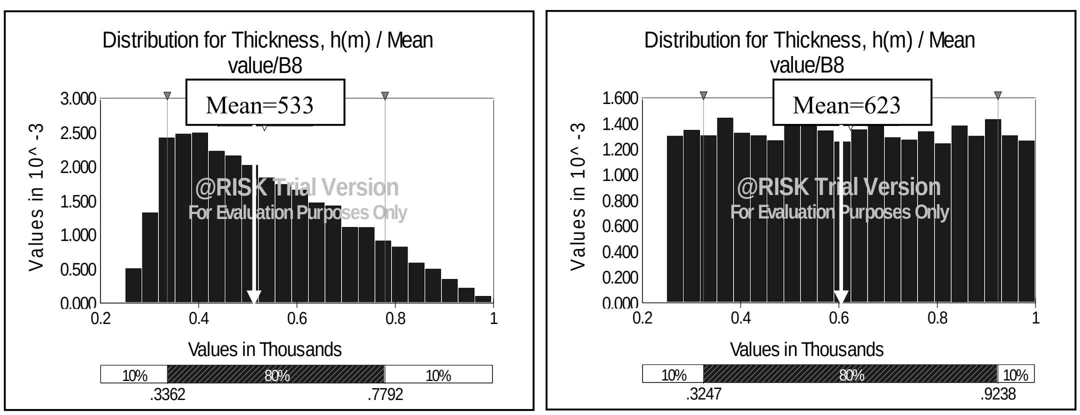


Figure C.5 Triangular and Uniform Distributions for Thickness

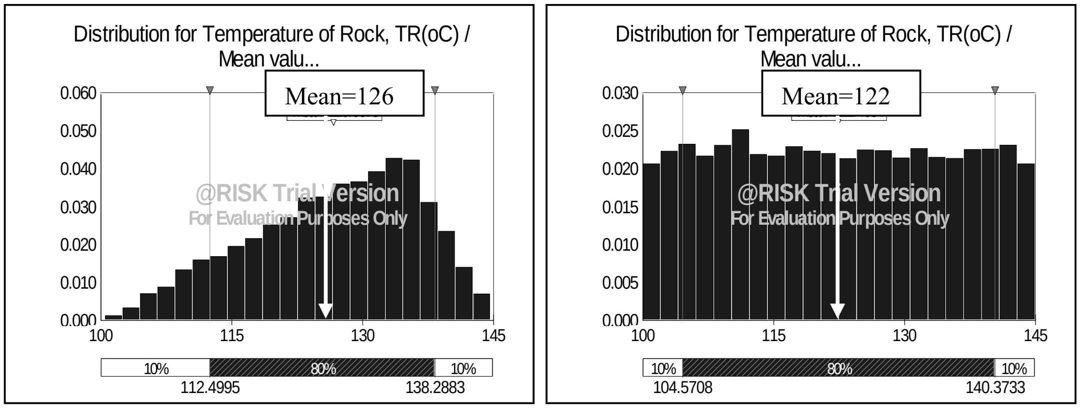


Figure C.6 Triangular and Uniform Distributions for Temperature of Rock

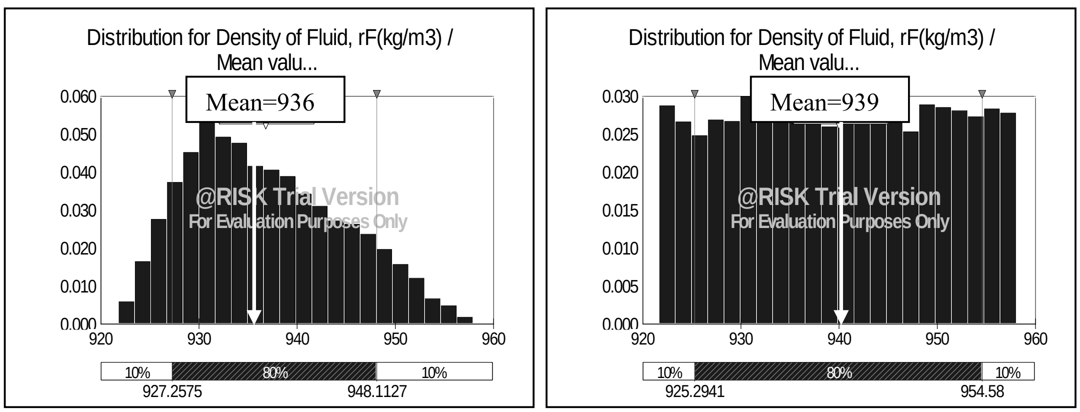


Figure C.7 Triangular and Uniform Distributions for Density of Fluid

Outputs

Table C.3 Summary Information for Accessible Resource Base

Summary Information		
Workbook Name	Balcova-triangular.xls	**Balcova-Uniform.xls**
Number of Simulations	1	1
Number of Iterations	10000	10000
Number of Inputs	7	7
Number of Outputs	1	1
Sampling Type	Monte Carlo	Monte Carlo

Table C.4 Summary Statistics for Accessible Resource Base

Summary Statistics							
Triangular Distribution				Uniform Distribution			
Statistic	**Value**	**%tile**	**Value**	**Statistic**	**Value**	**%tile**	**Value**
Minimum	1.26E+13	5%	2.90E+13	Minimum	7.01E+12	5%	2.37E+13
Maximum	2.50E+14	10%	3.47E+13	Maximum	3.47E+14	10%	3.01E+13
Mean	7.33E+13	15%	3.95E+13	Mean	8.63E+13	15%	3.59E+13
Std Dev	3.56E+13	20%	4.35E+13	Std Dev	5.33E+13	20%	4.11E+13
Variance	1.2667E+27	25%	4.72E+13	Variance	2.8398E+27	25%	4.63E+13
Skewness	1.106175361	30%	5.08E+13	Skewness	1.15857856	30%	5.11E+13
Kurtosis	4.446729247	35%	5.44E+13	Kurtosis	4.27141060	35%	5.66E+13
Median	6.60E+13	40%	5.81E+13	Median	7.33E+13	40%	6.20E+13
Mode	5.10E+13	45%	6.21E+13	Mode	5.07E+13	45%	6.72E+13
Left X	3.47E+13	50%	6.60E+13	Left X	3.01E+13	50%	7.33E+13
Left P	10%	55%	7.03E+13	Left P	10%	55%	7.95E+13
Right X	1.22E+14	60%	7.51E+13	Right X	1.62E+14	60%	8.66E+13
Right P	90%	65%	7.98E+13	Right P	90%	65%	9.50E+13
		70%	8.54E+13			70%	1.04E+14
		75%	9.23E+13			75%	1.15E+14
		80%	1.00E+14			80%	1.27E+14
		85%	1.09E+14			85%	1.41E+14
		90%	1.22E+14			90%	1.62E+14
		95%	1.43E+14			95%	1.92E+14

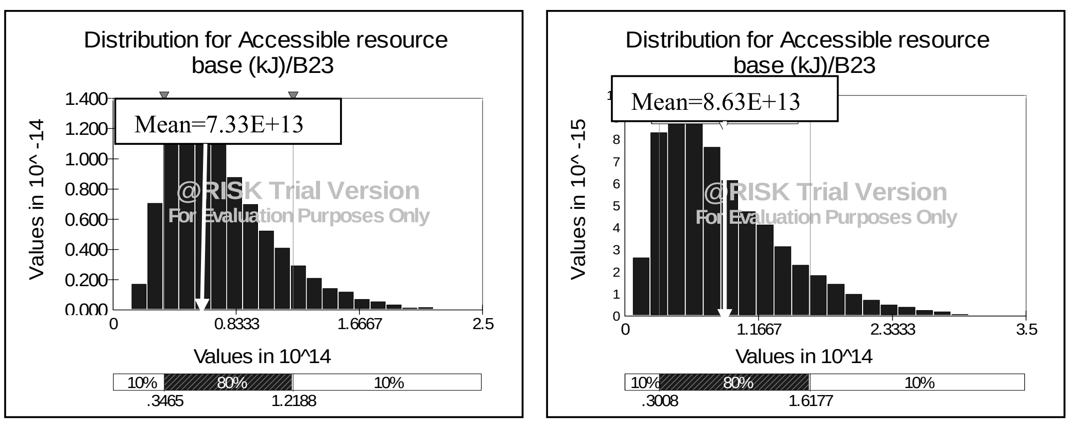


Figure C.8 Histogram for Accessible Resource Base

C.4.2 @RISK Graphs for Recoverable Heat Energy

Inputs

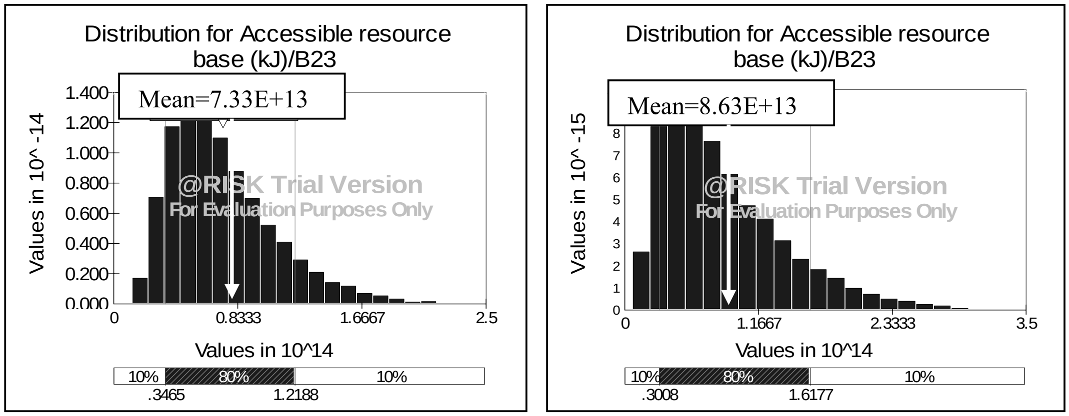


Figure C.9 Distributions for Accessible Resource Base

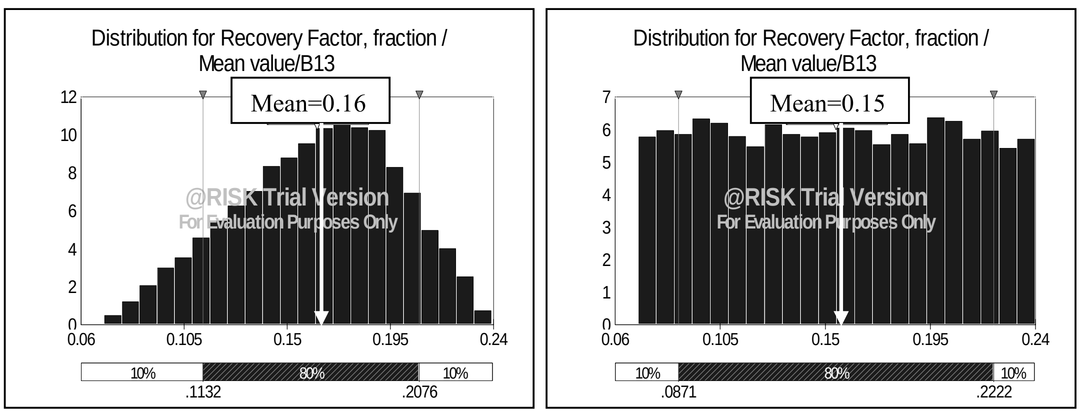


Figure C.10 Triangular and Uniform Distributions for Recovery Factor

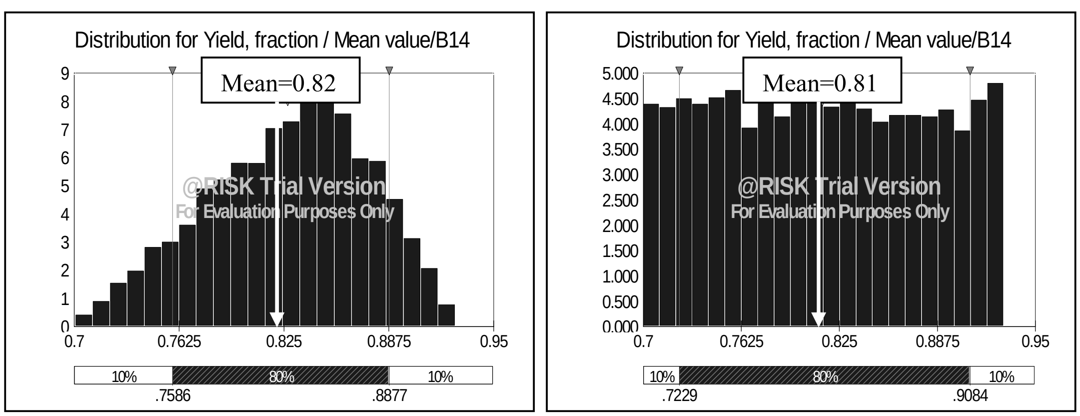


Figure C.11 Triangular and Uniform Distributions for Yield

Outputs

Table C.5 Summary Information for Recoverable Heat Energy

Summary Information		
Workbook Name	Balcova-triangular.xls	**Balcova-Uniform.xls**
Number of Simulations	1	1
Number of Iterations	10000	10000
Number of Inputs	3	3
Number of Outputs	1	1
Sampling Type	Monte Carlo	Monte Carlo

Table C.6 Summary Statistics for Recoverable Heat Energy

Triangular Distribution				**Uniform Distribution**			
Statistic	**Value**	**%tile**	**Value**	**Statistic**	**Value**	**%tile**	**Value**
Minimum	3.20E+03	5%	8.67E+03	Minimum	1.03E+03	5%	6.26E+03
Maximum	1.16E+05	10%	1.08E+04	Maximum	1.59E+05	10%	8.24E+03
Mean	2.51E+04	15%	1.24E+04	Mean	2.76E+04	15%	9.85E+03
Std Dev	1.37E+04	20%	1.37E+04	Std Dev	2.01E+04	20%	1.15E+04
Variance	187521636.9	25%	1.52E+04	Variance	405272877.9	25%	1.31E+04
Skewness	1.336070224	30%	1.66E+04	Skewness	1.622117388	30%	1.48E+04
Kurtosis	5.655568352	35%	1.80E+04	Kurtosis	6.414656723	35%	1.65E+04
Median	2.20E+04	40%	1.93E+04	Median	2.21E+04	40%	1.82E+04
Mode	1.90E+04	45%	2.06E+04	Mode	8.94E+03	45%	2.00E+04
Left X	1.08E+04	50%	2.20E+04	Left X	8.24E+03	50%	2.21E+04
Left P	10%	55%	2.35E+04	Left P	10%	55%	2.42E+04
Right X	4.36E+04	60%	2.54E+04	Right X	5.43E+04	60%	2.64E+04
Right P	90%	65%	2.72E+04	Right P	90%	65%	2.92E+04
		70%	2.94E+04			70%	3.23E+04
		75%	3.19E+04			75%	3.61E+04
		80%	3.49E+04			80%	4.06E+04
		85%	3.84E+04			85%	4.65E+04
		90%	4.36E+04			90%	5.43E+04
		95%	5.15E+04			95%	6.83E+04

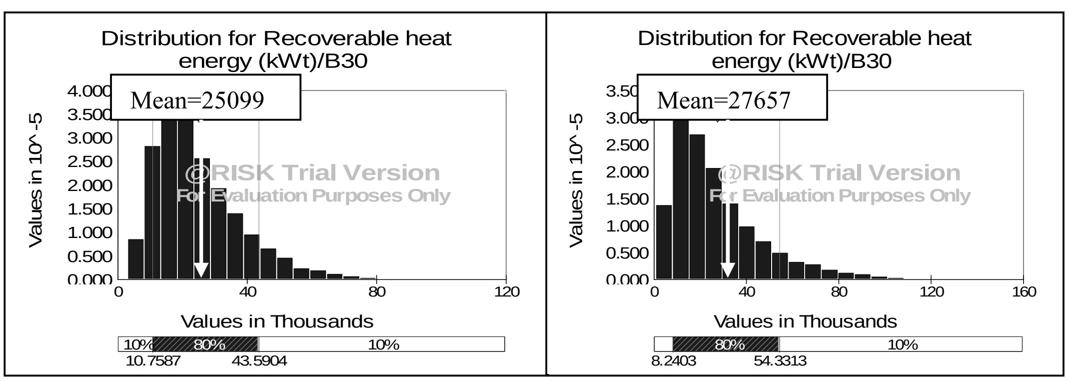


Figure C.12 Histogram for Recoverable Heat Energy

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