National Technical University of Athens
M.Sc. Design and Construction of Underground Works

MASTER’S THESIS

# Risk Assessment of an Underground Nuclear Power Plant. The Case Study of Halden’s Research Nuclear Reactor, Norway.

**Ioannis Kampouris**

Dipl. Rural and Surveying Engineering, National Technical University of Athens

**Supervisor: Andreas Benardos, Professor, NTUA**

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ΜΕΤΑΠΤΥΧΙΑΚΗ ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

# Αξιολόγηση Κινδύνου σε Υπόγειο Πυρηνικό Σταθμό. Η Περίπτωση του Ερευνητικού Πυρηνικού Αντιδραστήρα στο Halden της Νορβηγίας.

**Ιωάννης Καμπούρης**

Διπλωματούχος Αγρονόμος και Τοπογράφος Μηχανικός, Ε.Μ.Π.

**Επιβλέπων: Ανδρέας Μπενάρδος, Καθηγητής, ΕΜΠ**

ΑΘΗΝΑ, ΟΚΤΩΒΡΙΟΣ 2022

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**Ioannis Kampouris**
M.Sc. in Design and Construction of Underground Works

# Acknowledgements

The completion of my thesis marks the end of my studies in the postgraduate program “Design and Construction of Underground Works” at National Technical University of Athens.

Firstly, I would like to express my sincere gratitude to Dr. Andreas Benardos, Professor at National Technical University of Athens, for giving me the opportunity to study not only the interesting subject of the development of the underground spaces but also the subject of risk analysis and risk assessment for underground spaces.

Secondly, I would like to express my sincere gratitude to my family. Without their support I would not have achieved my goals.

Finally, I would like to dedicate this master’s thesis to my grandmother Eftychia.

Ioannis A. Kampouris,

Athens, October 2022

# Abstract

The aim of the thesis is to assess the risk of siting nuclear reactors in caverns and to search the literature for cases in which nuclear reactors have been constructed below the surface of the earth.

In the first part of the thesis, a literature review of cases of nuclear reactors that have been built, partially or entirely, underground is carried out. More specific, the characteristics of three well-known underground nuclear power plants, located in Europe and that they were built in the decades of 1950 and 1960 are presented. The three cases are in Agesta in Sweden, in Chooz in France and in Lucens in Switzerland.

In the second part of the thesis, an attempt is made to carry out a simplified risk assessment of the operation of a nuclear power plant in an underground environment. The system under study is the underground research nuclear reactor located in Halden, Norway.

Firstly, a literature review is carried out regarding the subject of risk assessment and the methods used in risk assessment and risk analysis of various systems, such as the Nuclear Power Plants (NPP).

Then, a detailed description of the underground nuclear reactor at Halden is given. Afterwards, using the Fault Tree Analysis method, the Fault Tree is constructed, with the main event being a radioactive pollution, which is then analyzed.

Finally, the results and the conclusions that emerged from this thesis are presented, as well as suggestions on what the next research steps should be, on such a contemporary and interesting subject as the use of underground works for locating nuclear reactors.

# Περίληψη

Στόχος της διπλωματικής είναι η διερεύνηση της επικινδυνότητας χωροθέτησης πυρηνικών αντιδραστήρων σε μεγάλους υπόγειους θαλάμους καθώς και η αναζήτηση στη βιβλιογραφία περιπτώσεων κατά τις οποίες πυρηνικοί αντιδραστήρες φιλοξενούνται σε υπόγειους θαλάμους.

Στο πρώτο μέρος της διπλωματικής, πραγματοποιείται μια βιβλιογραφική επισκόπηση των περιπτώσεων κατασκευής και τοποθέτησης, μερικώς ή εξ ολοκλήρου, πυρηνικών αντιδραστήρων κάτω από την επιφάνεια της Γης. Πιο συγκεκριμένα, παρουσιάζονται τα χαρακτηριστικά τριών γνωστών υπόγειων πυρηνικών σταθμών που κατασκευάστηκαν στην Ευρώπη τις δεκαετίες του 1950 και του 1960, οι οποίοι βρίσκονται στην Agesta της Σουηδίας, στο Chooz της Γαλλίας και στην πόλη Lucens της Ελβετίας.

Στο δεύτερο μέρος της παρούσας διπλωματικής, γίνεται μια προσπάθεια να πραγματοποιηθεί μια απλοποιημένη αξιολόγηση κινδύνου λειτουργίας ενός πυρηνικού αντιδραστήρα σε υπόγειο περιβάλλον. Το υπό μελέτη σύστημα είναι ο ερευνητικός υπόγειος πυρηνικός αντιδραστήρας ο οποίος βρίσκεται στο Halden της Νορβηγίας.

Αρχικά, πραγματοποιείται μια βιβλιογραφική έρευνα που αφορά το αντικείμενο της αξιολόγησης κινδύνου καθώς και των μεθόδων που χρησιμοποιούνται κατά την αξιολόγηση και ανάλυση της επικινδυνότητας διαφόρων συστημάτων όπως είναι τα εργοστάσια πυρηνικής ενέργειας.

Στη συνέχεια, γίνεται η αναλυτική περιγραφή του υπόγειου πυρηνικού αντιδραστήρα στο Halden, έπειτα από τη βιβλιογραφική ανασκόπηση. Έπειτα, εφαρμόζοντας τη μέθοδο των Δέντρων Σφαλμάτων (Fault Tree Analysis) κατασκευάζεται το Δέντρο Σφαλμάτων, με κύριο γεγονός τη μόλυνση από ραδιενέργεια, το οποίο στη συνέχεια αναλύεται.

Τέλος παρατίθενται τα αποτελέσματα καθώς και τα συμπεράσματα τα οποία προέκυψαν από την εκπόνηση της συγκεκριμένης διπλωματικής, καθώς και προτάσεις για το ποιά θα πρέπει να είναι τα επόμενα ερευνητικά βήματα, πάνω σε ένα τόσο επίκαιρο αλλά και ενδιαφέρον αντικείμενο όπως η χρήση των υπογείων έργων για τη φιλοξενία πυρηνικών αντιδραστήρων.

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# Chapter 1

# 1. Introduction

The first chapter is the introduction of the thesis. In this chapter, the motivation behind and the concept of the thesis are introduced, while in the end of the chapter the framework and the outline of the thesis are presented.

## 1.1. Motivation

Nowadays, there is a tendency of designing, constructing, and re-using underground spaces. The main purpose behind this tendency is that underground spaces could facilitate uses that are unnecessary, unwanted, or even undesirable to be at ground level, for example to storage toxic or radioactive wastes, or usages that even perform better when located in an underground environment, such as Data Centers.

In addition, the oversaturation of structures in the ground level, the vast, rapid and in many cases without proper design, expansion of urban areas and the increase of the number of the megacities worldwide, create problems and one of the proper and obvious solution is the utilization of the underground space.

Furthermore, another main reason for using the underground space is for locating sensitive facilities, such as nuclear reactors for power plants. The idea of locating nuclear power plants underground is not new. In the late fifties and the early sixties, four small nuclear plants have been built in Europe in rock cavities and more specific in Halden (Norway), in Agesta (Sweden), in Chooz (France), and in Lucens (Switzerland).

In general, safety has been the main motivation for locating nuclear reactors underground. The feeling of insecurity and the disastrous consequences of previous nuclear accidents led to build the first underground sitting plants and to design many others, to enhance the level of safety [5].

Moreover, the production of clean energy, generated by non-fossil fuels and by renewable energies is at most priority. One of the proposed methods for energy production is the usage of nuclear power. However, the production of energy using nuclear power is a controversial issue, mostly because of the disastrous consequences in case of an accident, even though nuclear power plants are among the safest modes of electricity generation. Consequently, in the resent years, governments and organizations are strongly against this type of energy production.

However, nuclear power is the most stable among the renewable energies. In contrast to solar or wind power, nuclear power can generate electricity in a constant way and the only time that the power plant must shut down is through the process of refueling. Therefore, the necessity for safe energy production using nuclear power is more demanding than ever. Providing safe nuclear power plants is one of the most promising solutions to the climate change and to the energy crisis that we may have to face in the near future.

### 1.2. Concept

In recent years, the construction of underground nuclear power plants has become a subject of research in many European and North American countries such as Norway, Sweden, Germany, Switzerland, USA, and Canada. The reason for such studies is to determine the safety offered by the underground, as well as to compare the construction time and cost between the underground nuclear plants and above the surface nuclear power plants.

This master thesis consists of two parts. The first part is literature research for case studies of underground nuclear power plants. More specific, three case studies are presented.

The second part is dealing with the risk assessment of a research nuclear reactor, which is located underground, in Halden in Norway. More specific, through a preliminary fault tree analysis the risk level of a radioactive pollution accident to happen is calculated.

The goal of this thesis is to investigate the level of safety in an already existing nuclear reactor that is sitting underground and to demonstrate that the underground nuclear power plants is a feasible solution.

### 1.3. Master's Thesis Outline

Regarding the outline and the structure, the master's thesis consists in total of 6 chapters, as follows:

- **Chapter 1- Introduction**: The first chapter is dedicated to the introduction of the topic, the motivation behind the research and the presentation of the framework of the thesis.

- **Chapter 2- Underground Spaces**: The second chapter is focusing on the development of underground spaces. This chapter was split into two parts. More specific, at the first part, a review on the different usages of underground spaces is presented, while the second part is focusing on the different uses of caverns.

- **Chapter 3- Underground Nuclear Power Plants**: The third chapter is the literature review regarding underground sitting of nuclear power plants. In this chapter, a general review of how underground spaces were already used to facilitate nuclear power plants in Europe is presented.

- **Chapter 4- Risk Analysis and Risk Assessment**: This chapter is dedicated to the methodology that was used in the second part of this master's thesis. More specific, the risk analysis and risk assessment processes are described and the method of the fault tree analysis that was used in this thesis is explained.

- **Chapter 5- Case Study:** The fifth chapter is dedicated to the case study of this thesis. More specific, the system that is going to be analyzed is described and then the fault tree analysis is presented.

- **Chapter 6- Result and Conclusion:** The sixth chapter is the last chapter. In this chapter, the results and conclusions of this analysis are presented.

# Chapter 2

# 2. Underground Spaces

This chapter is dedicated to the literature review regarding underground spaces and the most common ways of using underground space. The literature review was split into two parts. The first part is a general introduction to underground spaces and more specific an insight to the different types of underground spaces according to the usage of each space. In the second part, we are focusing on the different usage of the caverns. Moreover, in this part, the extensive use of rock caverns is described, focusing not only to the main reasons why to construct a cavern but also to the main principles of constructing caverns.

## 2.1. Underground Spaces

### 2.1.1. Introduction

With the word underground spaces, we describe every space that is under the surface of the earth. These spaces could be constructed in various depths and sizes, according not only to the given geotechnical and geological factors, but also to the purpose of usage of each case [1]. Additionally, different construction methods could be applied, depending on the nature and the characteristics of each project.

The most common way of distinction between underground spaces is according to their main use. There are two main categories. The first one is spaces that were created for mining purposes and the main usage of these spaces is to extract metal-ore and transport it to the surface, such as coal mines. The second category involves spaces that they were created for non-mining purposes, for example underground repositories for hazardous toxic wastes [1].

These subsurface spaces could be constructed by one of the three main methods which are [2]:

- Open Stopes method
- Filling Stope method
- Caving Stopes method

The selection of the proper method of depends on various factors such as [2]:

- The location of the metal-ore and its geometric attributes (size, shape, inclination).
- The natural and mechanical attributes of the metal-ore and of the surrounding formations.
- The quality and the value of the metal-ore.
- The desirable production rates.
- The cost of the product.
- The protection of the environment.

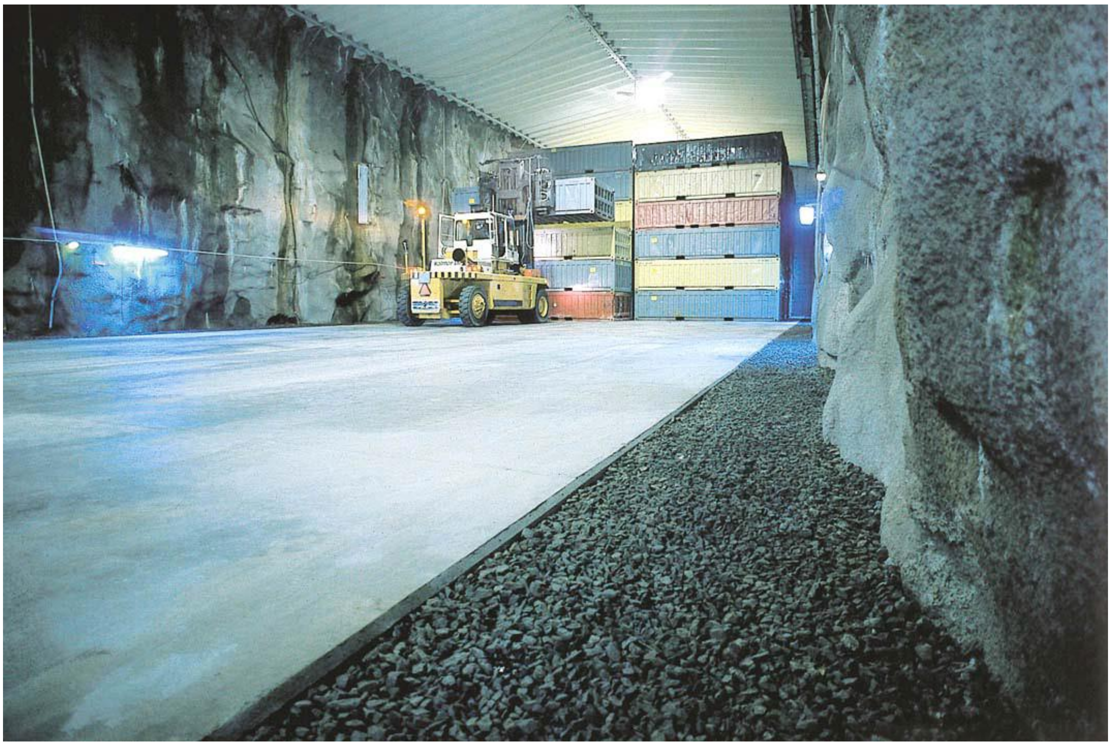


*Figure 1 Underground Hazardous Waste Repository in Sweden (Source: Kaliampakos, 2009).*

*Figure 2 Underground Coal Mine (Source: www.miningforschools.co.za).*

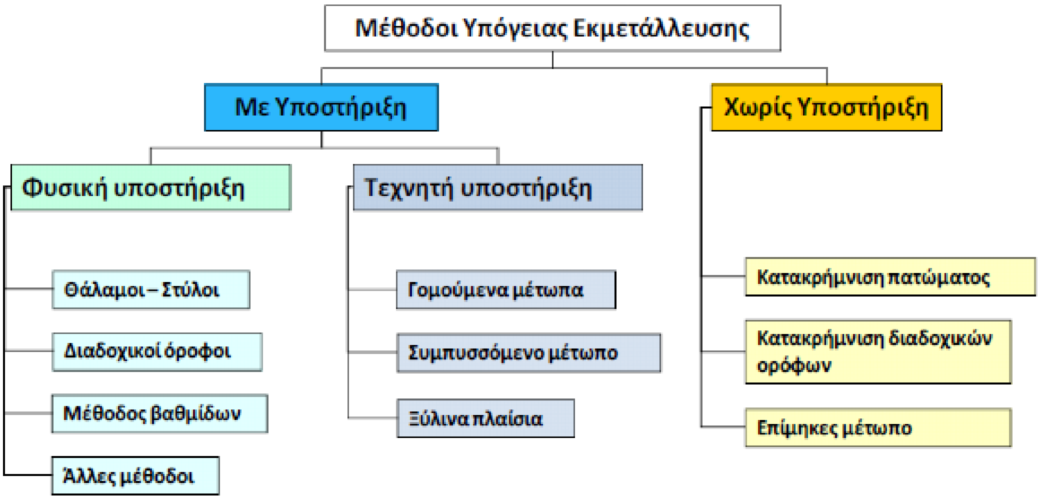


*Figure 3 Underground Extraction Methods (Source: Benardos, 2014).*

Regarding the shape and size of the underground spaces, there are three main categories. Tunnels, caverns, and shafts [1].

Tunnels are long horizontal underground passageways, produced by the excavation of the soil or rock. Their diameter varies from 1m up to 15m and usually the inclination is the minimum required. There are various reasons for constructing a tunnel, however the main reasons are for transportation purposes, such as road tunnels, railway tunnels and subway tunnels, and for transportation of water, such as hydraulic tunnels [1].

The main methods for constructing a tunnel are:

- New Austrian Tunneling Method (NATM)
- Drill and Blast
- Cut and Cover
- Using of Tunnel Boring Machine (TBM)
- Using machines such as Road Headers and excavators.

The selection of the applied method may vary according to the given geological and geotechnical factors.

*Figure 4 Tunnel of Eupalinos (Eupalinian Aqueduct) in Samos, Greece (Source: Wikipedia.org).*

Caverns are openings with big dimensions. Their width may excess the 35m and usually their length is no longer than 200-250m. Caverns are used for a variety of storage purposes such as storing a food, drinking water oil and other liquid hydrocarbons, pressurized gas and air and industrial waste. Caverns are also used for industrial and municipal installations such as hydropower caverns and water and sewage treatment plants. Last, but not least, caverns could also be used as civil defense shelters in war time [1].

Finally, Shafts are long vertical openings. Their diameter usually is between 3m to 8m, while their length maybe reaches the 500m [1]. Mine shafts are used for a variety of purposes such as:

- A mean of escape in the event of an emergency
- A mean of transportation for people and material
- For ventilation

*Figure 5 The Underground Cavern of the Hydroelectric Power Plant in Thisavros, Greece (Source: Kaliampakos, 2009).*

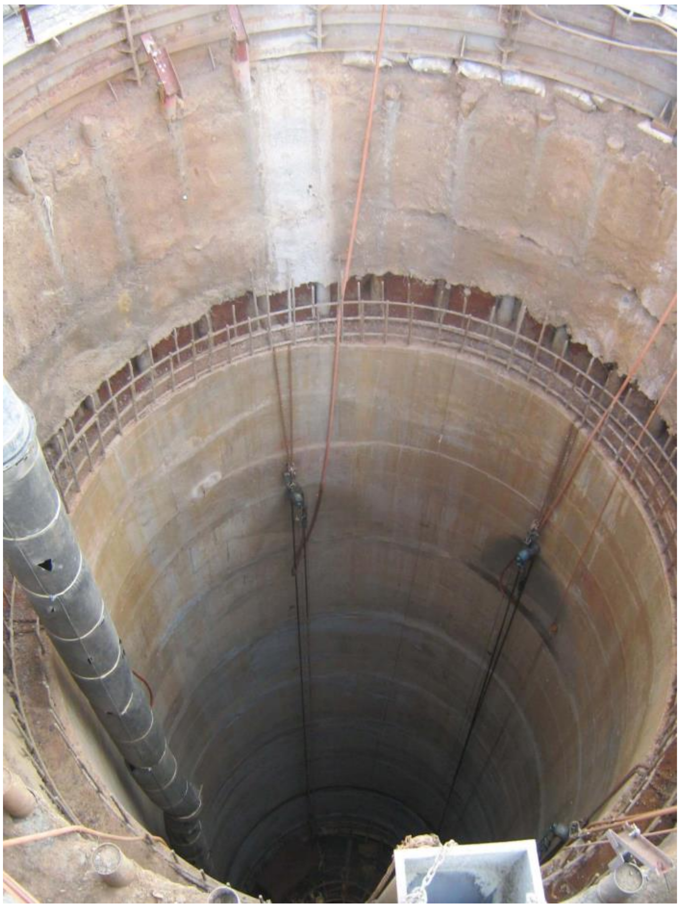


*Figure 6 Mining Shaft (Source: https://www.srk.com/en/publications/geotechnical-design-considerations-for-mine-shafts)*

The following table shows briefly, that according to their characteristics, each type of underground space could be used for different applications:

| Usages | Tunnels | Shafts | Cavers |
|---|---|---|---|
| **Transportation Infrastructure** | 1. Underground Pedestrian's Passageways<br>2. Road Tunnels<br>3. Rail Tunnels<br>4. Subway | 1. Transportation of humans<br>2. Transportation of materials<br>3. Transportation of equipment | 1. Metro Stations<br>2. Parking |
| **Logistics** | 1. Water supply/ irrigation<br>2. Drains<br>3. Flood Defenses | 1. Water supply/ irrigation<br>2. Drains<br>3. Flood Defenses | - |
| **Utilities** | - | 1. Access | - |
| **Storage** | 1. Various Liquids<br>2. Fuels<br>3. Wastes | 1. Various Liquids<br>2. Fuels | 1. Various Liquids<br>2. Fuels<br>3. Wastes<br>4. Food |
| **Recreation** | - | - | 1. Swimming Pools<br>2. Sport Facilities<br>3. Underground theaters |
| **Defense** | 1. Shelters<br>2. Military Facilities | 1. Military Facilities | 1. Shelters<br>2. Military Facilities<br>3. Storage of military equipment |
| **Exploitation of Deposits** | 1. Ventilation<br>2. Transportation<br>3. Mining | 1. Ventilation<br>2. Transportation | 1. Mining |
| **Exploitation of underground water and drainage** | 1. Drainage | 1. Drainage | - |

*Table 1 Types of different Underground Spaces (Source: Kaliampakos, 2009).*

### 2.1.2. Advantages

As already mentioned, the necessity for modern cities to develop efficient infrastructure continues to bring forth the options for a systematic utilization of the subsurface space. The use of underground spaces has various advantages such as [1]:

- Limitation in surface spaces and facilities
  The use of the underground does not require the existence of above ground facilities.

- High availability
  The construction of a subsurface space could be held almost in every location that the geological and geotechnical factors are favorable. Therefore, the high availability of the underground spaces means that even when the topography of the locations is not favorable or there is limitation in the free space above ground, such as in case of an urban environment, the underground space is still going to be constructed, regardless of these factors.

- Low environmental impact
  The development of the subsurface space is a decisive contribution to addressing several environmental impacts. Firstly, underground structures have no impact on the natural environment neither in the construction phase nor in the operational phase. Moreover, the preservation of the geomorphological landscape and of the ecosystem suggests that underground works proves the environmentally friendly footprint of the underground works.
  In addition, the construction of major underground work such as the subway, help to reduce the traffic and as a result lead to a reduction of air pollution and of the greenhouse gases.

- Isolation/ Hide
  Isolation and the ability to hide comes with the nature of the underground space. Thanks to the natural impermeability barrier imposed by the geology, significant advantages are offered in terms of protection of the underground spaces from surface activities and extreme weather conditions. Additionally, several types of uses and activities, which may be not accepted in a above surface location, such as waste-water treatment or the storage of toxic or radioactive wastes, can be located underground.

- Seismic protection compared to surface structure
  It is well established that the underground structures are not affected so severe, as the surface structures, in case of a seismic event.

- Protection from acts of war
  The rock and the geology between the surface and the underground spaces are used are a protective shield in case of acts of wars or terrorist attacks.

- Usage of the mining material for economic benefit
  In many cases, not only the underground space provides to the owner profit, but also the excavated material is also used for economic benefit.

### 2.1.3. Disadvantages

However, the very nature of the subsurface space comes with various disadvantages, such as the following [1]:

- High initial and investment costs
  The construction of an underground work requires a high amount of initial funding and usually long duration time of construction.

- Uncertainty
  The uncertainty of the geological and geotechnical conditions of the location of the underground work plays a major role to the design and the construction of the underground project and may lead to a confrontation between the parties involved.

- Human Psychology/ User behavior
  Psychological factors, people's fears, and doubts about operating in an underground, enclosed space, it may often act as a decisive factor for the construction of an underground project, as it threatens its economic viability.

### 2.1.4. Prospects-Future Steps

It is commonly accepted that the development of the underground is one of the key factors in order to improve living conditions. The main issue that has to be addressed is the high cost of construction, compared to the cost of the development above the surface.

According to Edelenbos et al. (1988), the demand for the utilization of the underground is expected to be increased if the following conditions are met:

- Increased interest in quality of life, related to the protection of the environment, the safety, and the increase of living conditions.
- Increased pressures for the preservation of the remaining above surface space, which an example is the situation in Hong-Kong.
- The deterioration of the environmental conditions, which will lead to social pressures to address them and the adoption of new techniques for to achieve this objective.
- High economic growth, which will allow for more dynamic investment programs, but also leading to increase the demands from the citizens' side towards the improvement of living conditions.
- Technological progress, which will create new construction opportunities, while allowing for more cost-effective construction of projects.

- Active policy on the part of government agencies and implementation of strict environmental and land-use regulations, which in turn will lead to greater and more active use of underground space.

This master's thesis is focusing on the usage of caverns for siting underground nuclear power plants. In addition, this thesis is an attempt to prove that in general, the construction of the nuclear power plant inside caverns enhances the safety and minimize the probability of a catastrophic event, such as a radio-active pollution, to happen. Therefore, the following sections are dedicated to design and construction methods for underground works such as caverns.

## 2.2. Caverns

### 2.2.1. Introduction

During the last decades, there has been a rapid growth of our cities and an increasing awareness of the need to preserve the quality of our environment. In addition, there has been a rapid development in excavation techniques and methods for rock masses. As a result, the use of the underground has been exponential increased.

Utilization of the underground, besides transportation purposes, such as road tunnels, railway tunnels, subway tunnels etc., is not well known and therefore this chapter is an effort to demonstrate how caverns excavated in rock may be used in urbanized areas for a variety of purposes.

Caverns can be used to facilitate and to locate various activities. However, the most common types of uses of underground spaces are:

- Underground Storage Facilities (Food, Drinking Water, Oil and Liquid Hydrocarbons, etc.)
- Underground Parking Facilities
- Underground Power Plants (Hydro-Power Plants, Nuclear Power Plants)
- Underground Military Facilities
- Underground Hazardous Wastes Repositories (Industrial Wastes, Radioactive Wastes, etc.)
- Underground Entertainment and Recreational Facilities

The width of a cavern is usually larger than 15m, while height-wise, caverns are higher than 20m, depending on the purpose of use. According to bibliography, the maximum width of a constructed cavern is 60 m (Gjovic Mountain Hill, Norway), while in abandoned underground mines there are underground spaces with width exceeding 60 m (Kaliampakos, Lecture Notes, 2009).

### 2.2.2. Case Studies

In the following section, briefly, case studies of unique and interesting usages of subsurface spaces are presented.

#### 2.2.2.1. Underground Car Parking Facility

One of the major problems of urban areas is the lack of sufficient number of parking spaces. To address this problem, urban planners, and designers, firstly tried to create dedicated spaces for parking in urban areas and to construct high-rise buildings for car parking. However, these solutions prove to be inadequate in many cases due to the lack of sufficient space and to the rise of the number of the cars. Therefore, the solution is instead of going up, to go underground. Nevertheless, this approach comes with many advantages and disadvantages.

The main advantages of underground car parking facilities are:

- Addressing the problem of vehicle parking and possible congestion relief is surrounding area.
- Saving valuable surface. This advantage becomes particularly important when it comes to areas with increased tourist or commercial activities
- Zero visual pollution (except for the entrance and the exist galleries
- High protection of vehicles against weather conditions
- Alternative use of the underground space as a shelter in case of an event of war.
- Reduction of the noise from vehicle. However, this advantage is offset by the noise that is generated by the operation of the fans to remove the exhaust gases.

The main disadvantages of underground car parking facilities are:

- High construction costs compare to car parking facilities in the surface
- Necessity of ventilation of the underground space. When the vehicles are moving inside the underground space, they emit gases, such as CO, $CO_2$ and $NO_x$. These gases are hazardous for the health and therefore they should be removed in a short time
- Increased lighting costs due to the need that the space should be lighted continuously

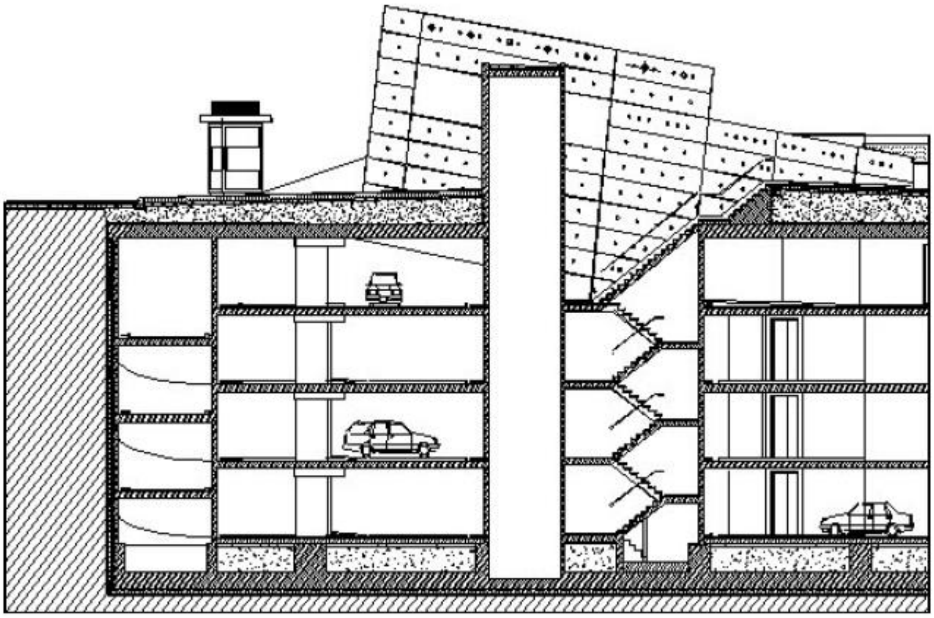


Figure 7 Underground Parking Facility, Marousi Greece (Source: Kaliampakos, 2009).

#### 2.2.2.2. Underground Power Plant (Hydro-Power Plant)

The underground Hydropower Plants consists of a complex system of tunnels, shafts, and caverns in which the huge mechanical equipment of the power station is located. For that reason, the dimensions of the caverns should be particularly big. Thus, the excavation and the support of these caverns are of particular interest.

The construction of these caverns should be done with various methods. The cross-sections of the caverns are typically semi-circular, oval, or arch-shaped with straight side walls.

The support of the construction used to be by concrete lining but nowadays is common to use rock bolts and shotcrete, with a density and thickness according to the geotechnical characteristics of each case.

There are various reasons to construct an underground hydropower plant. Some of them are the followings:

- The cost for the construction of a subsurface hydropower plant is lower than the cost of constructing a plant above the ground
- The nature of underground provides safety
- The cost of maintenance is low
- The protection of the environment

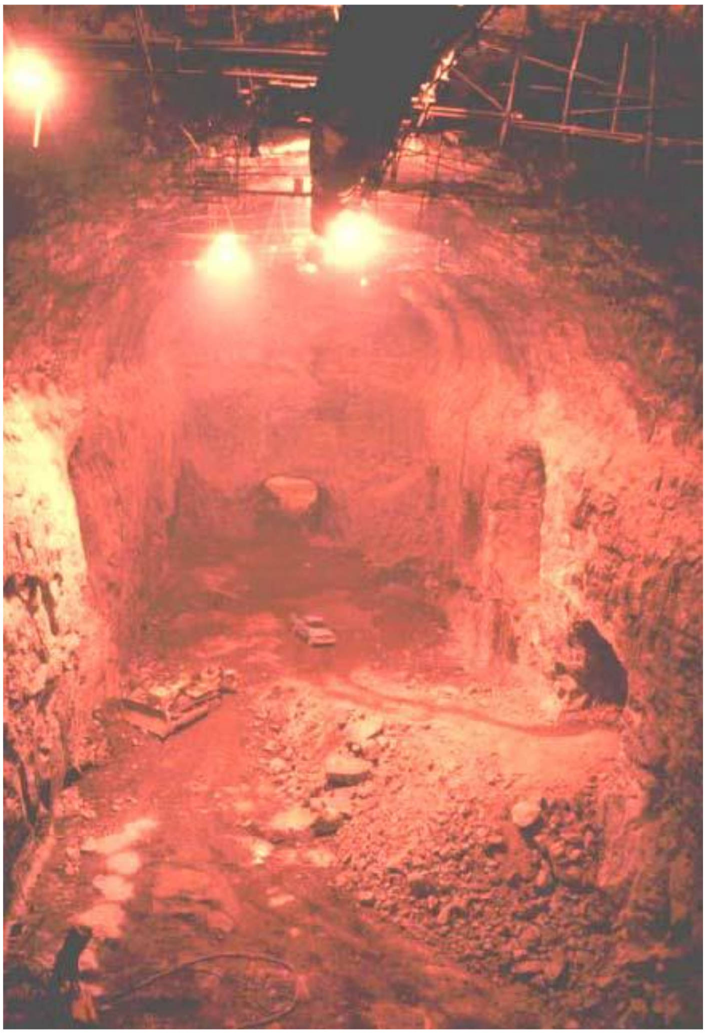


*Figure 8 The Under Construction Cavern of the Underground Hydropower Plant in Rio Grande (Source: Kaliampakos, 2009).*

#### 2.2.2.3. Underground Hazardous Waste Repositories

The use of underground spaces for storage and locating hazardous waste is a viable candidate to supplement existing and developing technologies and it has been already successfully demonstrated [18].

Furthermore, the usage of underground repositories for the storage of hazardous wastes presents various advantages over above ground landfill sites [17]. Considering the strict environmental legislation and the continuing growth of hazardous waste volumes, the development of underground spaces is a vital and a sustainable solution.

The main advantages of underground spaces for locating hazardous waste derive from the nature and the characteristics of underground spaces. The natural visual screen and barrier offered by the geological medium prohibits the diffusion of the internal processes to the above ground environment and as a consequence, protects the biosphere from the disturbances and risks inherent in certain types of activities [17]. In addition, underground repository complexes are located in deep impermeable geologic formations ensuring the waste’s isolation from the biosphere, as well as attenuation of any pollutants leaking from the contaminant source. However, favorable geologic conditions are not always available and thus the development of repositories in hard rock should also be considered [17].

Existing or new mines are considered to be a feasible method for long-term storage capability for large volumes of contaminated materials or for permanent storage of the toxic end products of hazardous waste treatment, technically wised and economically wised [18].

According to Stone R. (1986), the advantages of using mined spaces as repositories for hazardous waste are [18]:

- Mined space can be created economically in large volumes
- In shallow mined space the waste would be contained above the ground water table
- In deep mined space the waste would be contained below the aquifer
- Isolation from the public and the surface ecology
- If required, waste can be isolated from the hydrological environment by encapsulation or containerization
- Security can be readily maintained
- In a sealed mine, no continuing maintenance will be required
- If retrievability is desired, the mine could be used as a long-term underground warehouse

The waste to be stored in such repositories may be nuclear or non-nuclear, non-toxic or toxic, delivered in special containers or in bulk masses, conditioned or deposited in its original state of production [19].

Included in the category of non-nuclear waste are [19]:

- Industrial waste
- Residues of burned waste
- Low-hazard bulk materials, such as gypsum from sulphur cleansing or coal plant smoke
- Hazardous waste that cannot be recycled.

Nuclear wastes are highly radioactive wastes that are produced by Nuclear Power Plants, and they must be disposed of safely [20]. According to Rempe (2007), solid radioactive waste first entered a deep geologic repository in 1959, liquid radioactive waste has been injected into confined underground reservoirs since 1963 while solid wastes containing chemically toxic constituents with infinite half-lives have been isolated underground since 1972 [21].

Excavations in low-permeability crystalline basement rocks, such as gneiss and granite, are currently being used to dispose of some categories of radioactive waste, while in addition former limestone and uranium mines are serving the same purpose [21].

Furthermore, another acceptable confinement medium suitable for permanent waste isolation is the old rock salt [21]. Salt is impermeable and easy and safe to mine, while deep excavations in salt close gradually by creep, encapsulating and isolating anything located inside [21]. Proof of the success of salt mines is the fact that mined spaces is rock salt and potash have hosted chemotoxic and radiotoxic wastes for several decades [21].

*Figure 9 Underground Radioactive Waste Disposal in Morsleben (Germany) in rock salt (Source: Benardos, Lecture Notes).*

According to Kaliampakos (2009), the basic rules for the disposal of radioactive material are [1]:

- The disposal of the radioactive waste in underground spaces is favorable in terms of safety in contrast with any other method of disposal.
- Passive Systems that are not accessible by human activities after their confinement are favorable.
- Geologic phenomena such as erosion, existence of faults etc., lead to radiation release and therefore must be avoided.
- The quality of the surrounding rock formations must be at the same level as the quality of the rock that the radioactive wastes are located in.
- The depth of the cavern should be high enough in order not to be affected by human activities.
- The region of disposal should be isolated by the underground water table.
- Wastes with high level of radiation and radioisotopes with high half-life must be disposed with special methods and the region of disposal must be a remote area and not near urban areas.

The most famous underground radioactive waste disposal caverns are located in the Yucca Mountain in Nevada (U.S.A.), the SFR and CLAB in Sweden, and in Morsleben and Gorleben in Germany. In addition, a lot of risk analysis studies have been performed regarding the level of safety if Waste Isolation Pilot Plant (WIPP) in New Mexico (U.S.A.).

### 2.2.3. Design Aspects of Caverns

Main factors for the selection of the optimal location to build a cavern are [1]:

- The type of the rock and geotechnical properties of the rock
- The quality of the rock mass and the rock mass characteristics.
- The level of rock deterioration
- The characteristics of joints family (orientation, distance between joints, filled material)
- The permeability of the geological formations and the hydrogeological conditions of the area.
- Rock overburden.

According to the literature [1] and from experience gained in various projects, rocks such as granite, gneiss, shale, limestone, quartzite, and sandstone are able to support the construction of big caverns.

In contrast, rocks such as soapstone, serpentinite, and peridotite have severe stability problems, especially when they have been subjected to tectonism. Furthermore, the construction of big caverns should be avoided in rock formations such as andesites, liparites, and clay [1].

In the following Figure are presenting schematically the construction areas of underground works, according to the rock mass classification system Q and the economics of the project (Barton et al., 1981)

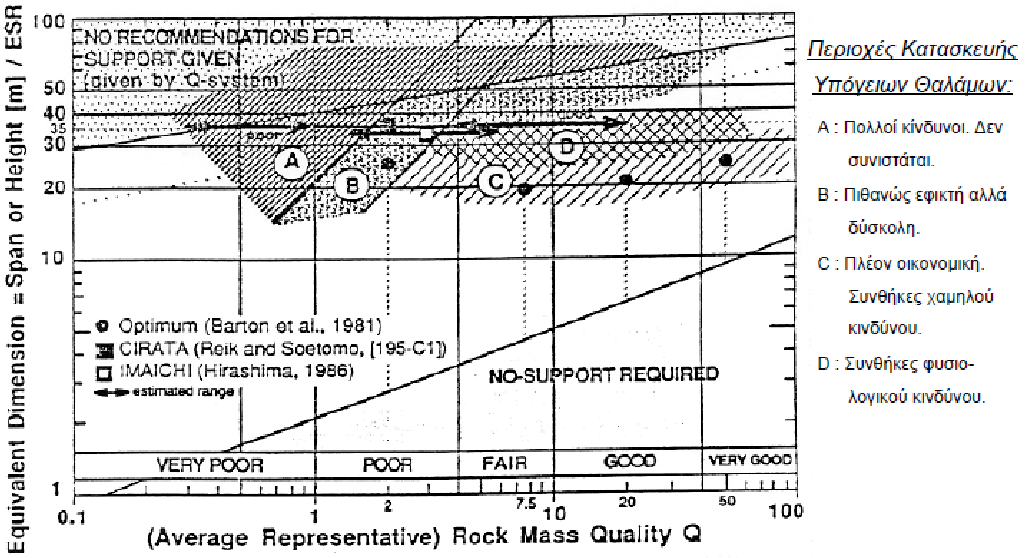


*Figure 10 Possibilities of construction of an underground cavern, in relation to the quality of the rock mass (Barton et al., 1981).*

In addition, major factors that should be taken into consideration in the design and construction of big caverns are the depth from the surface (overburden), the orientation of the cavern and the dimension and the cross-section of the cavern.

- Location of Excavation

The location of the cavern is the first thing that must be determined at the design phase. Usually, caverns are built in low depths from the surface, if the geological and geotechnical conditions are favorable, in order to be easily accessible. Nonetheless, the usage of the cavern may suggest that the cavern should be constructed in a high depth. Such a usage is for generating power in a hydroelectric power plant.

The advantages of selecting a low depth, expect for the easy access is the fact that, the main (vertical) stresses from the overburden are not too high. However, the radial stresses might be a problem.

- Orientation of the Excavation

The orientation of the axis of the excavation shall be such as to minimize stability and over-excavation problems. These problems are generated not only by the stress field but also from the discontinuities in the rock.

A general rule for orienting the axis of excavation is that, when there are not high stress values, the excavation axis should be parallel to the direction of the axis of the angle bisection, which is formed by the directions of two main families of discontinuities. In any case, the alignment of the axis of excavation with secondary families of discontinuities, it should be avoided too.

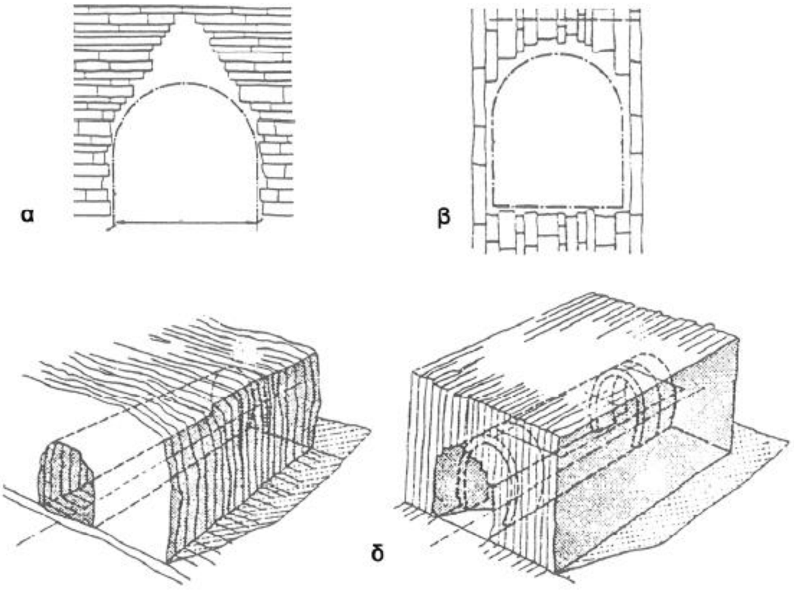
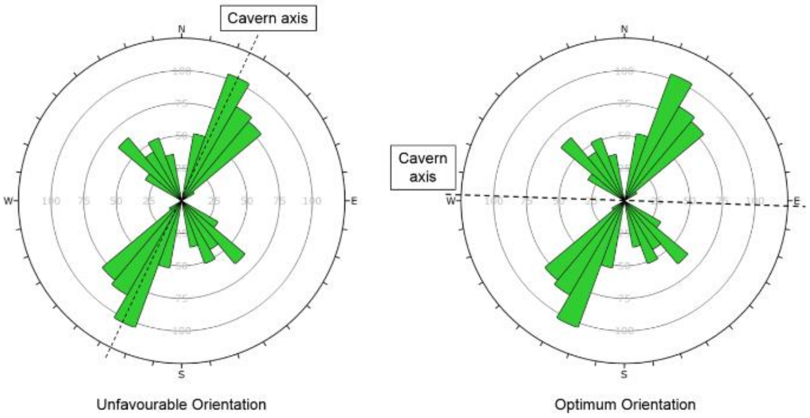


*Figure 11 Orientation of the excavation axis in relation to the orientation of discontinuities in the rock (Source: Kaliampakos, 2009).*

When the stress values are high, these values should be taken into consideration in the choice of the orientation of the excavation axis. The optimum orientation of the excavation axis, in relation to the stress field, is achieved when the axis forms an angle of 15°-30° with the horizontal projection of the main stress. In the case on high stress field, the inappropriate orientation of the axis may lead to over-excavation and therefore, to increased costs. Thus, the orientation of the axis of excavation is a crucial matter.



Unfavourable Orientation

Optimum Orientation

*Figure 12 Orientation of the axis of the excavation according to the orientation of the main discontinuities (Source: Kaliampakos, 2009).*

- <u>Dimension- Cross-section</u>

Except for the orientation of the excavation axis, the dimensions and the cross-section of the cavern is at utmost importance in order the load and stress distribution to be achieved successfully.

In shallow underground openings the design of the roof of the cavern depends on the number and the characteristics of discontinuities.

The cross-sections should not have any corners, because stresses have the tendency to concentrate into corners and that will lead into failures. Therefore, the shape of the cross-section should be round, oval or arc.

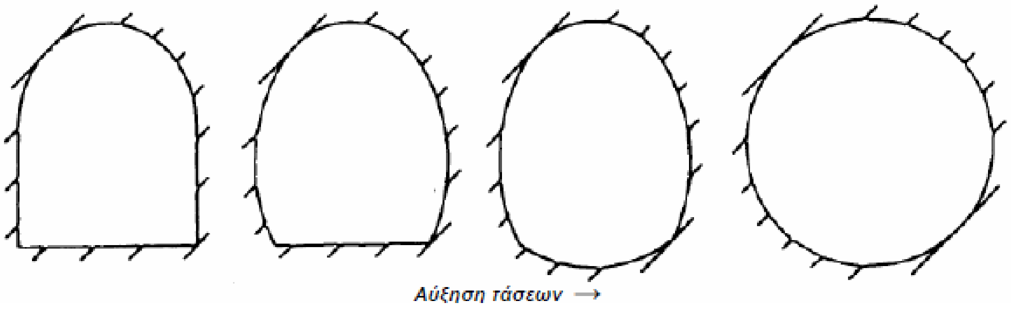


*Figure 13 Different Cross-section sketches (Source: Kaliampakos, 2009).*

### 2.2.4. Excavation Methods- Support Methods

Due to their big dimensions, when constructing underground caverns, the cross-section is not able to be excavated in one phase. Therefore, the excavation is conducted in phases, using explosives (blast and drill method) or special machines, the Roadheaders [1].

In the most common excavation method, firstly, the top part is excavated (Top Heading) and then the rest of the cavern is excavated with the method of benching, as shown in the following figure.

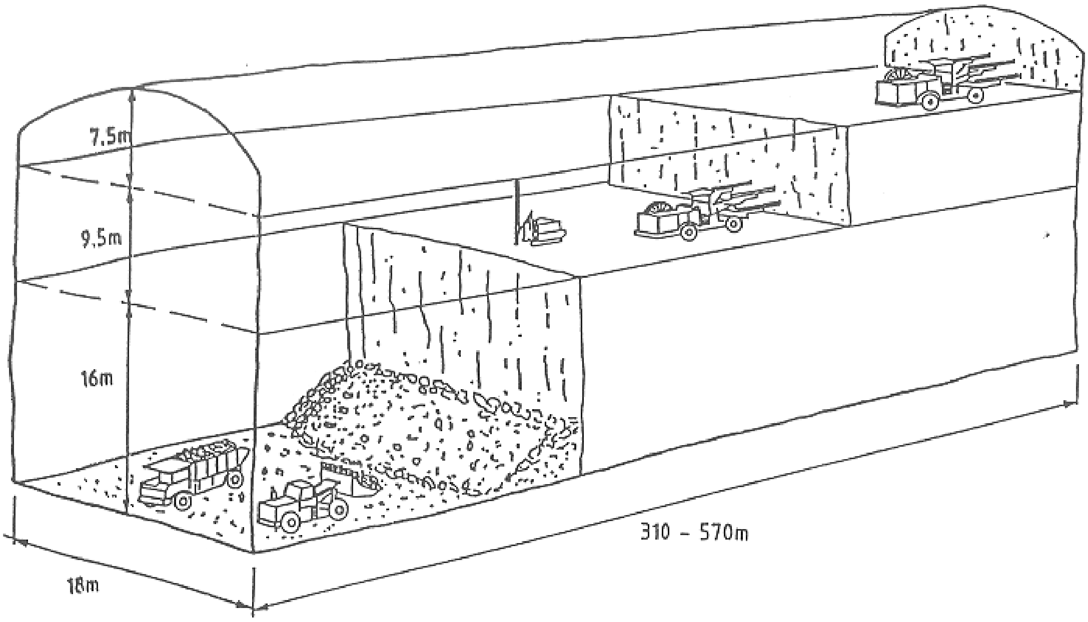


*Figure 14 Excavation of a Cavern with the Drill and Blast Method (Source: Kaliampakos, 2009).*

In order to avoid over-excavation and to minimize the deterioration of the rock-mass, special techniques are possible to be applied, such as smooth blasting, presplitting, and line drilling.

The design of the support of the excavation is done firstly with empirical methods, such as with the Q- classification (Barton et al., 1974, 1994). With this method, the appropriate support of the roof, the side walls, the plan of the installation of the rock bolts and the thickness of the shotcrete are estimated, from the diagram that is shown is the following figure:

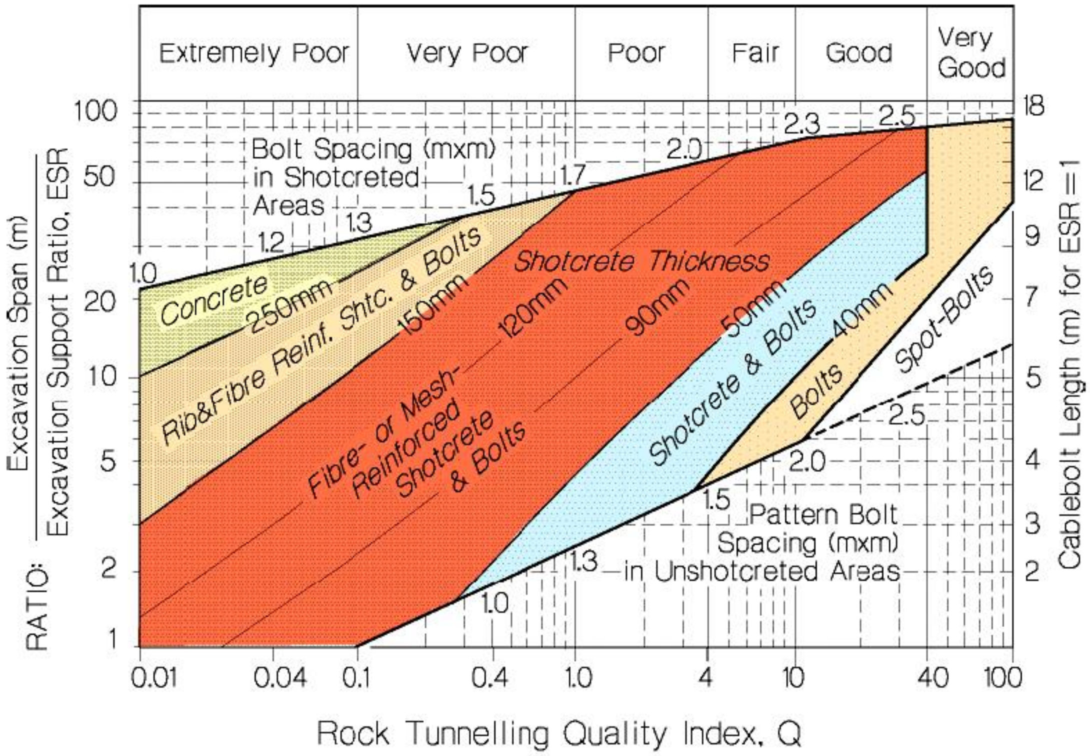


*Figure 15 Choice of Support Measures (Barton et. al, 1994).*

The support is installed in stages. On the first stage, rock bolts or cables of various kind are installed. The rock bolts may be simple or pre-tensioned, and they may be installed in the whole surface of the cavern if this is necessary, or they may be installed in specific spots that require attention (spot bolting) [1].

On the second stage of support, shotcrete is applied. The shotcrete may be simple or may have as admixtures steel fibre. In this case, the shotcrete is called steel fibre shotcrete. In addition, final lining from concrete, usually without reinforcement may be installed [1].

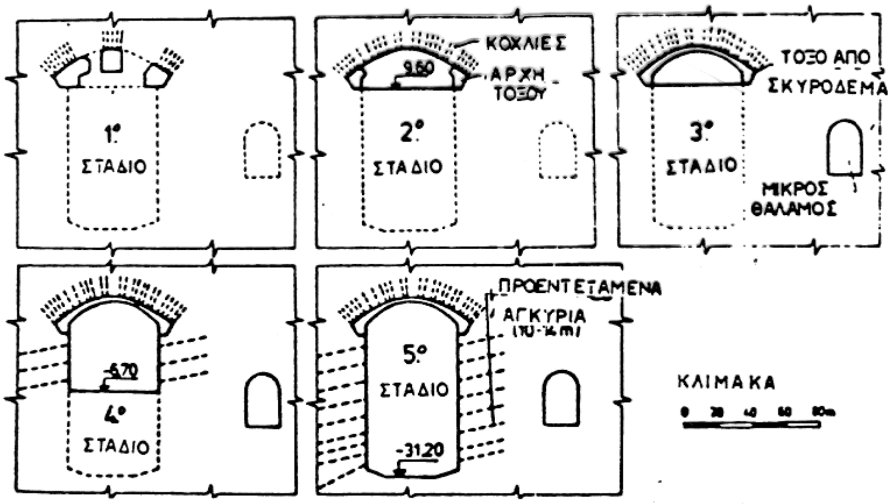


*Figure 16 Stages of Excavation and Placement of the Support of the Excavation.*

# Chapter 3

## 3. Underground Siting of Nuclear Power Plants

This chapter is dedicated to the literature review regarding underground siting of Nuclear Power Plants. In this chapter, four different case studies of nuclear power plants located underground in different countries in Europe and USA are presented.

### 3.1. Introduction

The idea of locating Nuclear Power Plants or Nuclear Reactor underground or partially underground is not new. In fact, since the late 1950s and the early 1960s, there are various case studies of construction and operation of underground nuclear power plants, especially in Europe. In this section, a description of the major case studies is presented [5].

The main reason behind the idea of underground siting Nuclear Power Plants was safety. The feeling of insecurity and inadequacy of the knowledge of the nuclear phenomena that, at that time, was common in the nuclear field led to build these four plants and to design many others, underground to achieve a safety level higher than that considered possible for a surface plant [5].

However, studies have shown that the consequences of accidents in surface nuclear power plants could be kept within acceptable limits. As a result, the interest in underground siting has been decreased [5].

Nevertheless, factor such as the increasing power transmission costs, decreasing number of suitable sites above ground or the difficulties in obtaining site approval, the protests of the societies for nuclear power and the increasing concern for extreme nuclear accidents, together with the possibility of utilizing the waste heat and the urban siting concept have renewed the interest for the underground siting as an alternative to surface siting [5].

Thus, many studies aimed at assessing the feasibility of the underground siting and at evaluating advantages, disadvantages and costs of the concept have been undertaken in various European countries, mostly in the North- Centre Europe, and in USA [5].

According to a study perfomed by Pinto (1979), the main alternatives of the underground siting concept, usually considered in studies on the subject, are the following [5]:

- Surface Mounded

In this alternative the plant is constructed above grade and the outside surfaces of vital structures, like the nuclear reactor, are backfilled with soil and/or special material.

*Figure 17 Sketch of a Surface Mounded Concept (Source: Pinto S., 1979).*

- Pit Siting

In this alternative, also known as cut and cover or cut and fill, the plant is constructed below grade in an open cut excavation and then covered with soil and/or special material.

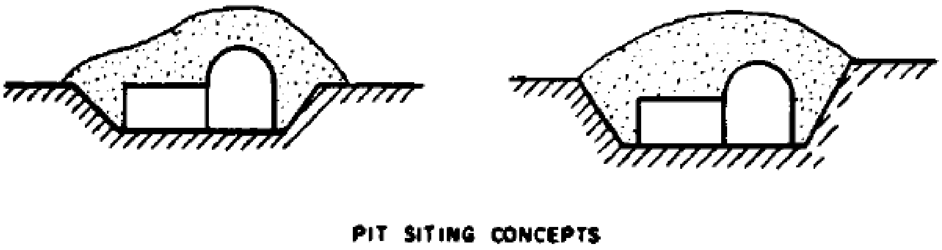


*Figure 18 Sketch of Pit Siting Concept (Source: Pinto S., 1979).*

- Deep in Rock

In this concept variation, usually referred to as rock cavity alternative, the plant is constructed in caverns excavated at depth in a rock mass,

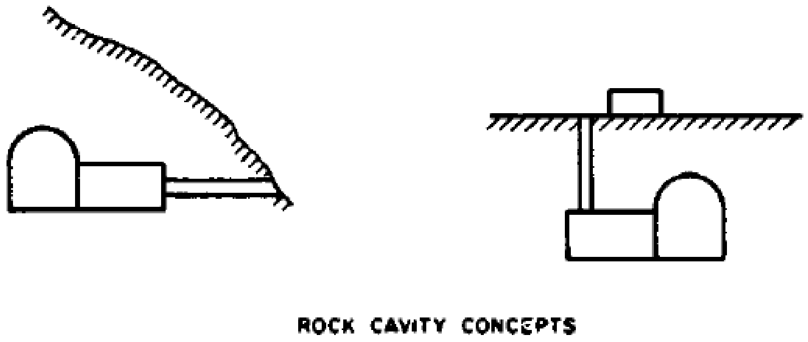


*Figure 19 Sketch of Rock Cavity Concepts (Source: Pinto S., 1979).*

Within these three main alternatives, several variations are possible. The plant may be totally or partially underground, the buildings may have all the same elevation as in surface plants or a different elevation, the rock cavities may be excavated in the side of a hill or deep below the surface, the excavations for the pit siting may be in soil or in rock, access to the plant may be through tunnels or vertical shafts etc [5].

Each variation is expected to influence both the technical and economic feasibility of the plant. However, the optimum combination of possibilities is strictly dependent on local conditions and on the aims to be achieved.

The main reason for building these plants underground was to mitigate the consequences of extreme accidents. However, the safety aspect was not the only motivation. Protection against acts of war and the possibility of locating the plants in populated areas have also been major considerations in the choice of this type of siting together with economical motivations as savings on costs of the structures and in the elimination of the conventional containment building [5].

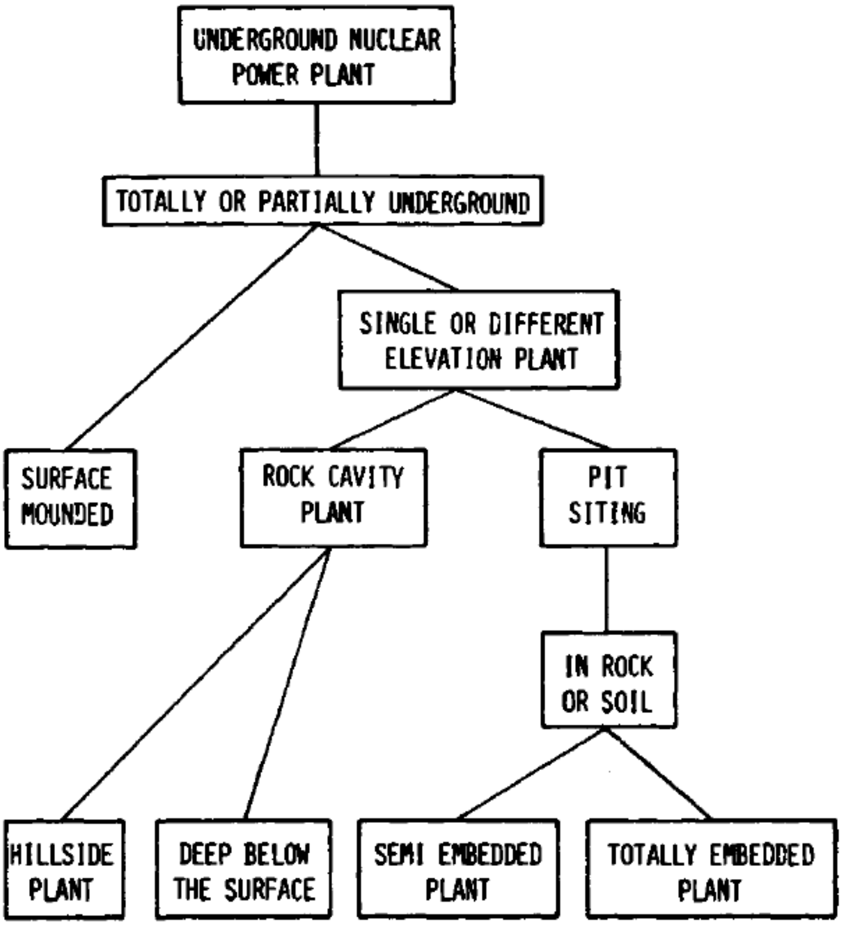


*Figure 20 Alternative Siting Concepts for Underground Nuclear Power Plant (Source: Pinto S., 1979).*

## 3.2. Underground Nuclear Powerplants

In the following paragraph, three case studies of underground siting nuclear power plants are presented. All the cases are located in Europe.

### 3.2.1. Agesta Nuclear Power Plant

Agesta was a pressurized heavy water cooled and moderated reactor, fueled with natural uranium in oxide form, rated at 80 MWth [5]. This experimental installation meant to provide experience for future reactors, and it has been developed in 1958 from the combination of two older projects, Adam and R3 [5]. Adam was a pressure-vessel reactor intended for the production of heat, while R3 was a pressure-vessel reactor intended for the combine production of heat and electricity. However, neither of these two projects could be alone economically competitive and therefore, they were combined in one plant called Agesta or R3/Adam.

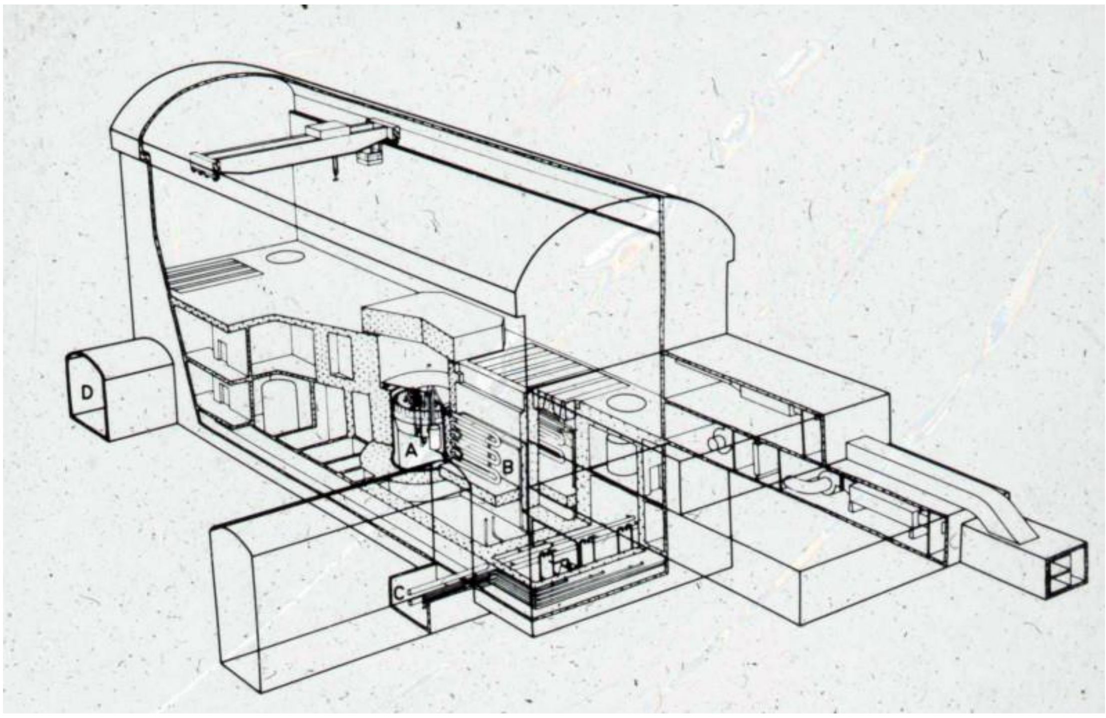


*Figure 21 Adam Atom Plant, Reactor Hall (Source: https://history.vattenfall.com/stories/agesta-power-plant).*

The reactor was in Agesta, about 14 km south of Stockholm, while the site was 3 km from a populated area. The plant, which reached criticality in July 1963 and went into operation in March 1694, was producing 20 MW of electricity and providing 60 MW to the district heating system of the Stockholm suburb of Farsta [5]. However, it has been decommissioned in 1974 for economic reasons.

The reactor, the control room and the reactor auxiliary systems were in rock in a hillside whereas the turbine was in a conventional turbine building above the surface [5]. The dimensions of the cavern containing the reactor building were 16.5 m width, 53.5 m length and 40 m height [5]. Regarding the minimum rock overburden above the reactor hall, that was about 15 m.

The reactor was situated in the northern part of the reactor building together with the main steam generators which were distributed around the reactor, outside the iron-ore concrete radiation shield [5]. The fuel storage facilities, ion-exchange equipment and other auxiliary systems were located in the middle of the hall, while the southern area was occupied by service facilities for the refueling machine. In the eastern wall, an off shot of the main containment contained the expansion tanks of the pressure control systems [5].

The connection between the plant and the top of the hill was achieved through three vertical shafts. One of the shafts was at the northern end of the cavern and it was connected with the cooling towers, while the other two were located at the southern end, and they were used for the reactor cavern ventilation. Furthermore, in the reactor hall, there was a 120-ton overhead crane.

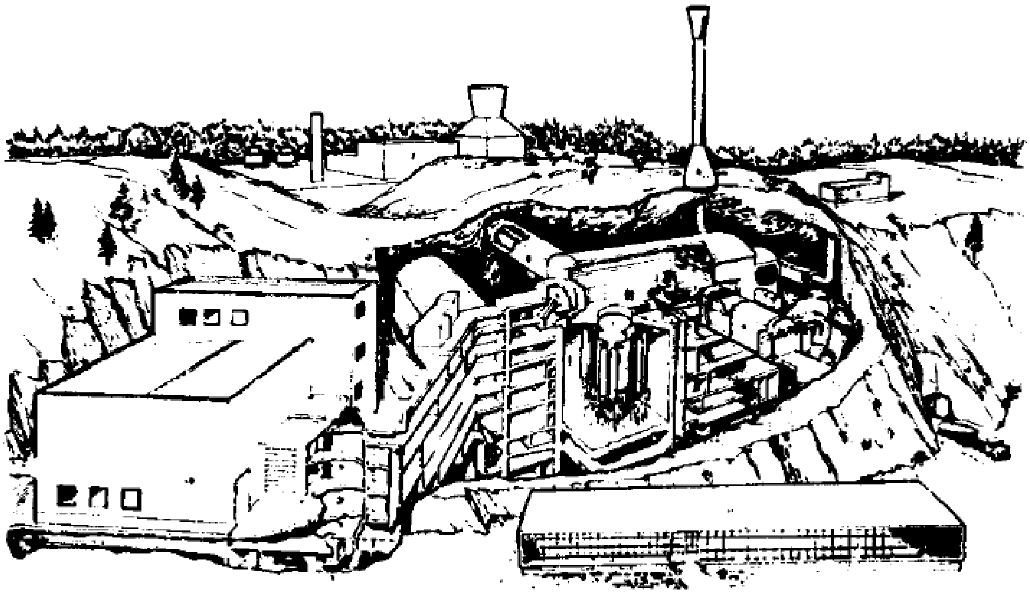


*Figure 22 Outline Drawing of the Agesta Plant (Source: Pinto S., 1979).*

Regarding the lining of the reactor's cavern, it was lined with concrete and welded steel plates 4mm thick for the walls and the ceiling and 8 mm for the floor to provide a completely gas-tight containment since the plant was very close to Stockholm [5].

In case of accidents, it was possible to isolate the containment with fast-acting valves of 1 $m^2$ section, in the ventilation ducts, closing within 7/10 of a second [5].

Access to the plant was by means of three airlock tunnels, the largest permitting road transports to enter the fuel handling area in the reactor hall for removal of spent fuel flask. In this tunnel shock-wave pockets with a capacity of 10 persons each. The one near the control room was utilized as the normal entrance whole the other one, near the transport tunnel, was used only as an emergency exit.

The underground excavations, which also include the control room, for total of about $60000\, m^3$ were in gneiss and granite. It must be noted that the rock quality was such as to limit the width of the reactor hall. The site, however, was chosen because it was the only one of sufficient size within acceptable distance of Farsta.

The plant construction took five years from the first opening of the work site until final start-up and two and a half years for preconstruction planning and design. The excavation of the cavities, which started in November 1957, was completed in January 1960.

*Figure 23 The control room in Agesta (Source: https://history.vattenfall.com/stories/agesta-power-plant).*

### 3.2.2. “Centrale Nucleaire des Ardennes”

The “Centrale Nucleaire des Ardennes” owned by SENA is a RWR rated 266 Mwe and is one of the largest existing underground nuclear plants. This plant, built for power production, reached criticality in October 1966 and full power operation in April 1967 [5].

The plant is located in Chooz, France, near the Belgian border, 8 km south of Givet, on the river Meuse, where the cooling water is taken from.

Figure 24 Location of “Centrale Nucleaire des Ardennes”. (Source: Google)

This plant is partially located in rock, in a hillside. The underground portion of the plant consists of three caverns and connecting galleries. The caverns house respectively the reactor with four primary loops, the auxiliary systems and the fuel storage and handling facilities, and the electrical equipment while the turbogenerator group, the control room, the water depuration systems etc. are above ground [5]. Because of this layout, the steam pipes connecting the steam generators to the turbine are, on the average, 200 m long causing then a pressure drop of about 2.4 $^{kg}/_{cm^2}$ [5].

The reactor cavern, which is connected to the outside through a gallery of 40 $m^2$ section and 120 m long, is 18.5 m wide, 41 m long and 42.8 m high and is lined with 3mm thick steel plates to provide a gastight containment [5]. This cavern, designed to withstand the maximum temperatures and pressures of a loss-of-coolant accident, has been tested for leak-tightness at a maximum pressure of 0.7 $^{kg}/_{cm^2}$ [5].

The reactor cavern is not accessible during plant operation. The cavern housing the auxiliary systems and the fuel storage and handling system is 49 m long, 15 m wide and 42 m high and has been built like a hydroelectric plant cavern, without any special leak tightness requirements. [5] The distance that separates this cavern from the reactor cavern is about 26 m. This distance is the result of a compromise between the interest to have short connections between the two caverns and the necessity to have a suitable rock separation to avoid a collapse of the cavities [5].

Partially between these two caverns, there is the electrical equipment cavern. This cavern is quite small as compared to the others, the dimensions being 2 m length, 5.10 m width, 12.5 m height. The location of this cavern has been chosen in order to keep the cables length as short as possible [5].

Galleries containing the fuel transfer system, ventilation ducts, electrical cables, piping etc., connect the various caverns.

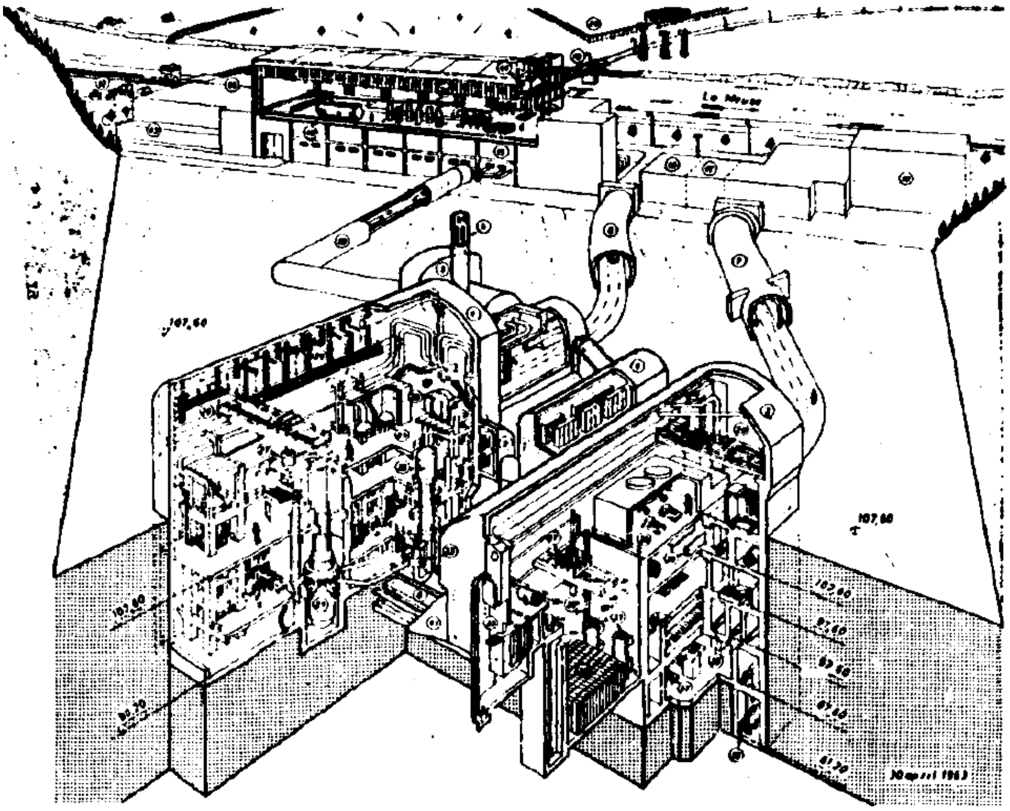


*Figure 25 The Centrale Nucleaire des Ardennes (SENA) Sketch (Source: Pinto S., 1979).*

The connection to the above ground is through two main tunnels leading respectively to the reactor cavern and to the auxiliary systems cavern [5]. The dimensions of these tunnels are such as to allow the transport of large components. The steam pipes run through a separate tunnel, about 170 m long, to the turbine building above ground [5].

The underground excavations, reaching a total of about $85000m^3$ are in chalk and shale [5]. It should be noted that the dimensions of the caverns have been fixed by the equipment to be installed and by the required accessibility for serving and repair and bot by the rock quality [5]. However, the rock instability in a certain area, caused a delay in the execution of civil engineering work. The total plant construction took four years including the design. The civil engineering work three years [5].

The Chooz nuclear power plant has two very particular characteristics, the safety injection system, and the spent fuel transfer system [5].

Two reservoirs containing in total about 1300 $m^3$ of borated water are installed on the hill housing the plant, about 200 m above the reactor level. These two reservoirs ensure by gravity water injection in the reactor core and water spraying in the cavern in case of an accident [5].

Because of the distance of about 30 m between the reactor and the spent fuel pool in the auxiliary systems cavern, a new fuel transfer system has been developed. This system consists of a tube of 40 cm diameter, a small wagon to vary the fuel elements and two pistons: the motion of this wagon inside the tube is obtained by the differential pressure of the water on the two pistons [5].

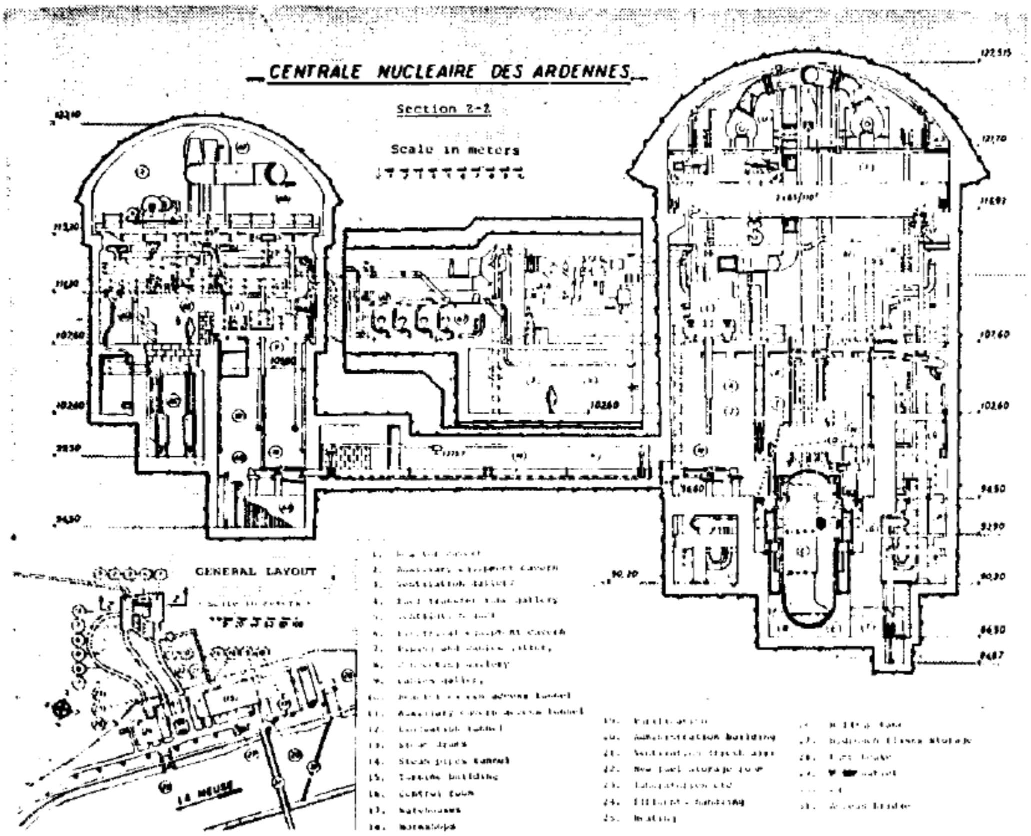


*Figure 26 SENA plant. Caverns transverse section sketch (Source: Pinto S., 1979).*

### 3.2.3. Lucens Experimental Nuclear Power Station

The Lucens plant was a heavy water moderated, $CO_2$ cooled, pressure tube reactor fueled with slightly enriched uranium.

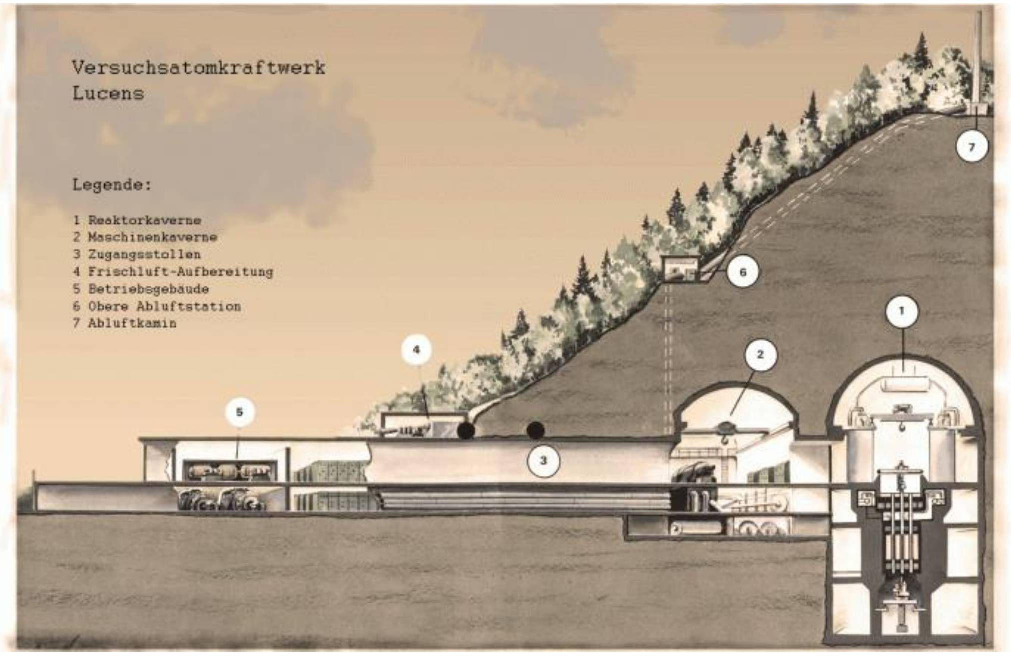


*Figure 27 Transverse section of the Lucens plant (Source: https://www.ensi.ch/en/topic/versuchsatomkraftwerk-lucens/).*

The plant, purely experimental, meant as a prototype for a new line of reactors, was located in Lucens, Switzerland, about 25 km north of Lausanne, on the left bank of the river Broye. In the area of the reactor 175 persons per $km^2$ lived within a 2 km radius from the site at that period of time [5].

*Figure 28 Location of Lucens' Nuclear Power Plant (Source: https://en.wikipedia.org/wiki/Lucens_reactor).*

The construction of the plant was started in August 1962 and the first reactor criticality was achieved on the 29th of December 1966 [5]. Regular operation was started, however, in May 1968. After a short period, the reactor was shut down for research and testing before being started up again on the 14th of August. The plant was operated successfully until the 24th of October, when it was shut down again for some corrective work. On the 21st of January 196, during start-up, a serious accident with coolant and moderator losses and fuel element took place. As a consequence of this event, the plant has been decommissioned. The power rating of this experimental plant was 30 MWth and 8.5 Mwe [5].

The underground portion of the plant, in a hillside, consists of three caverns housing respectively the reactor, the turbine and the fuel elements storage pool. The reactor, the primary loop, two steam generators, the charge and discharge machine and various reactor auxiliary systems were housed in the reactor cavern. This cavern, cylindrical with a doomed roof, with a diameter of 17 m and a maximum height of 30 m, was lined with porous concrete (utilized also for the drainage of the groundwater), alternate layers of bitumen and aluminium foils and reinforced concrete to achieve the required leak-tightness [5].

The leak-tightness specification for the airlocks, the penetrations and ducts were such as to allow, also in case of major accidents, the direct ventilation of the machine cavern and of the access gallery. The access to the reactor cavern was sealed by a large steel wall comprising two airlocks, the equipment hatch and penetrations for piping and cables [5].

A short tunnel with an airlock connected the reactor hall with the machine cavern. In the machine cavern the turbogroup and auxiliaries were housed in the southwest part of the cavern together with some ventilation equipment [5]. Electrical equipment was located in the middle of the cavern, while the monitoring and decontamination facilities for operators and equipment, the purification system for the fuel pool etc. were located in the north-east part of the cavern. The dimensions of this cavern were 51 m maximum length, 10 m width and about 18 m height [5].

A ventilation shaft was driven through the rock from the machine cavern up to the surface. It was followed by a duct on the slope of the hill reaching the bottom of the stack on the ridge of the hill. The stack height was about 50 m [5].

The fuel storage cavern, located perpendicularly to the machine cavern was 37.5 m long, 5.5 m wide and about 15 m high. A special passage was provided for transfer of fuel elements from the reactor hall to the fuel pool The irradiated fuel elements, after removal from the storage pool, were taken through the end of the machine hall. Access to this cavern was through the lower floor of the machine cavern [5].

A two-level gallery, approximately 100 m long, connected the underground cavities with the service building in the outside where the control room, the diesel generator sets, workshops and the offices where located [5].

The cooling tower, the switchyard and the waste disposal station were located close to the service building, on the hill besides the ventilation stack, there were the ventilation building and a tank containing about 500 $m^3$ of water constituting the plant water reserve [5].

All the underground excavations were in sedimentary molasse. The average rock overburden was of 30 m with a maximum of about 54 m above the reactor cavern. The groundwater seepage rate in the reactor hall was about 5 $m^3$ a day [5].

This plant had a very particular safety feature. In fact, in the case of an accident associated with a pressure build-up in the reactor cavern, the pressure could be relieved to the porous concrete surrounding the cavern, through valves penetrating the containment walls [5].

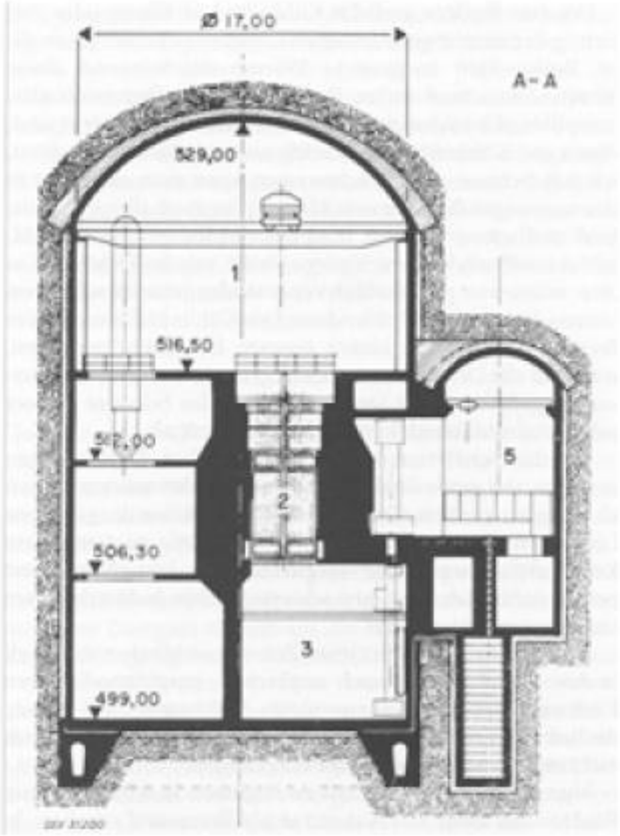


*Figure 29 Lucernes' Cross section (Source: Duffaut P., 2007).*

| Plant | Year of Operation | Plant Purpose | Plant Configuration | Containment Type and Dimensions | Rock Type |
|---|---|---|---|---|---|
| Agesta | 1964 | Experimental, heating and power production | Hillside plant in rock cavities, partially underground, turbine above ground | Rock excavation lined with painted concrete (53.5x16.5x40 m) | Gneiss/ Granite |
| Chooz | 1967 | Power production | Hillside plant in rock cavities, partially underground, turbine above ground | Rock excavation lined with steel plates (41x18.5x42.8 m) | Chalk and Shale |
| Lucens | 1968 | Experimental, power | Hillside plant in rock cavities, partially underground, turbine in cavern | Cylindrical rock excavation lined with a sandwich construction: concrete, aluminium foils in bitumen, concrete | Sedimentary Molasse |

*Table 2 Main Characteristics of Existing Underground Nuclear Power Plants (Source: Pinto S., 1979).*

| Plant | Total Excavation Volume $(m^3)$ | Reactor Cavern Volume $(m^3)$ | Reactor Cavern Span $(m)$ | Civil Engineering Work Costs (% Total Costs) |
|---|---|---|---|---|
| Agesta | 60000 | 30000 | 16.5 | 20 |
| Chooz | 85000 | 36000 | 18.5 | 17.5 |
| Lucens | - | 6300 | 17.0 | - |

*Table 3 Excavation Characteristics of Existing Underground Nuclear Power Plants (Source: Pinto S., 1979).*

### 3.3. Summarize

To conclude the literature review regarding underground siting of nuclear power plants, all the above-mentioned nuclear power plants are located in hillside rock cavities and only partially underground.

In summary, the main reasons that have led to the underground siting of these nuclear reactors are:

- Greater safety in case of major accidents because of an additional level of containment
- Protection against acts of war
- Possibility of siting the plants in urban areas

Moreover, these three underground nuclear plants have some common characteristics, such as:

- They are all rock cavity plants
- They are all single elevation plants
- They are all small experimental or prototype plants
- They have small cavern spans
- In all plants there is no conventional containment but just some sort of lining for the reactor cavern
- They have all been located in urban areas

Finally, According to Pinto S., the operating experience of these underground nuclear power plants has been satisfactory. Besides the accident at the Lucens and a long outage at Chooz, no significant incidents have been reported. It is worth mentioning that the accident at the Lucens and any other malfunction were not caused or related to the underground siting.

# Chapter 4

## 4. Methodological Framework

In this chapter, the proposed methodology that was used is described. Firstly, a general introduction to the concepts of risk analysis, risk managements and risk assessment is carried out, while afterwards, the Fault Tree Analysis method, which is the method that was used to perform the risk analysis of the case study of this thesis is described.

Main goal of was not only to identify the potential risks and what sequences of events may lead to a disastrous event, but also to calculate the probabilities of specific events to happen. Therefore, in order to reach the objectives of the thesis, specific tools and methodologies were used.

More specific, the probabilities of each intermediate event to happened were calculated with the Fault Tree Analysis, while the probabilities of each basic event of the Fault Trees were estimated from the bibliography.

### 4.1. Risk Analysis and Risk Assessment

It is well known that tunnelling and underground construction works impose risk on all parties involved, as well as on those not directly involved in the project [13]. Risk analysis is a tool which was initially developed to investigate safety of potentially dangerous industrial processes or potentially dangerous industrial plants [26]. The application of risk analysis should help to establish a proactive safety strategy by systematically investigating potential risks.

In general, risk analysis is dealing with potential negative consequences of a system in the future. As nobody can predict future events, the only option in such a situation is to develop, as realistic as possible, a model of the risks associated to the system in question.

Risk evaluation methods are aimed at evaluating and managing the risk associated with a specific system in relation to the consequences on the potentially exposed population. But firstly, we should give the definition of basic terms.

According to the ISO/Guide 73,2009, hazard is the source of potential harm, while Risk Source is the element which alone or in combination has the intrinsic potential to give rise to risk. With the term risk we define the effect of uncertainty on objectives. Furthermore, risk is defined as the combination of the consequence or severity of a hazard and its likelihood.

Risk evaluation is a process that leads to the identification of the possible dangers or safety issues which can derive from an accidental event. This also includes the estimation of the uncertainties related to the risk evaluation process.

Risk management is a decision-making process, subsequent to risk evaluation, that involves the realization of safety measures and/or procedures which the activity is realized. According to the code of practice for risk management of tunnel works that was prepared by the International Tunnelling Insurance Group [25], risk management is the systematic process of:

- Identifying hazards and associated risks, through risk assessments, that impact on a project´s outcome in terms of costs and program, including those to third parties
- Quantifying risks including their program and cost implications
- Identifying pro-active actions planned to eliminate or mitigate the risks
- Allocating risks to the carious parties to the contract

Risk analysis is the methodology that contributes to the determination of measures that have to be applied, in order to control and assess the hazards in a specific system or activity.
In general, risk analysis methodology is following the following steps, as shown in the Figure 30.

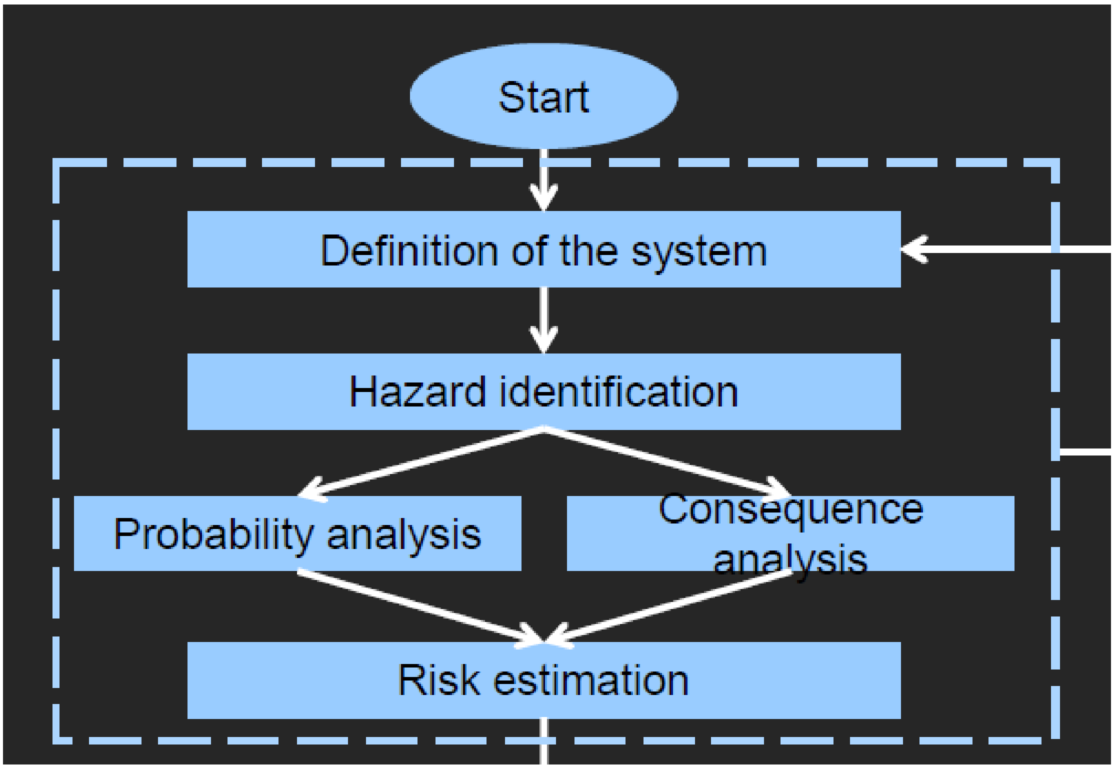


*Figure 30 Risk Analysis Steps (Source: Benardos, Lecture Notes).*

The first step of this process is the definition of the system. In this step, the system or the activity should be well defined. Every aspect and every characteristic should be identified and well determined.

The second step is the Hazard Identification. In this step, every source of potential harm should be identified and then every negative or undesirable possible consequence should be taken into consideration.

The final step is the Risk Estimation. However, in order to achieve the risk estimation, two different analyses should be performed. One of the analyses is the probability analysis and the other one is the consequence analysis.

In probability analysis, the probability of a hazardous event to happen is estimated or calculated, while in the consequence analysis, the possible consequences that are affecting the system, in case of the appearance of the hazardous event are estimated.

When the process of risk analysis is completed, the results should be evaluated. This process is the risk evaluation. In risk evaluation, the outcome of the process of risk estimation is compared to specific limits and criteria that are pre-defined in respect to the system that is under evaluation.

If the results of the risk estimation meet the risk criteria, then we can accept the risk. Otherwise, we have to introduce additional safety measures in the system in order to mitigate the risk into acceptable levels.

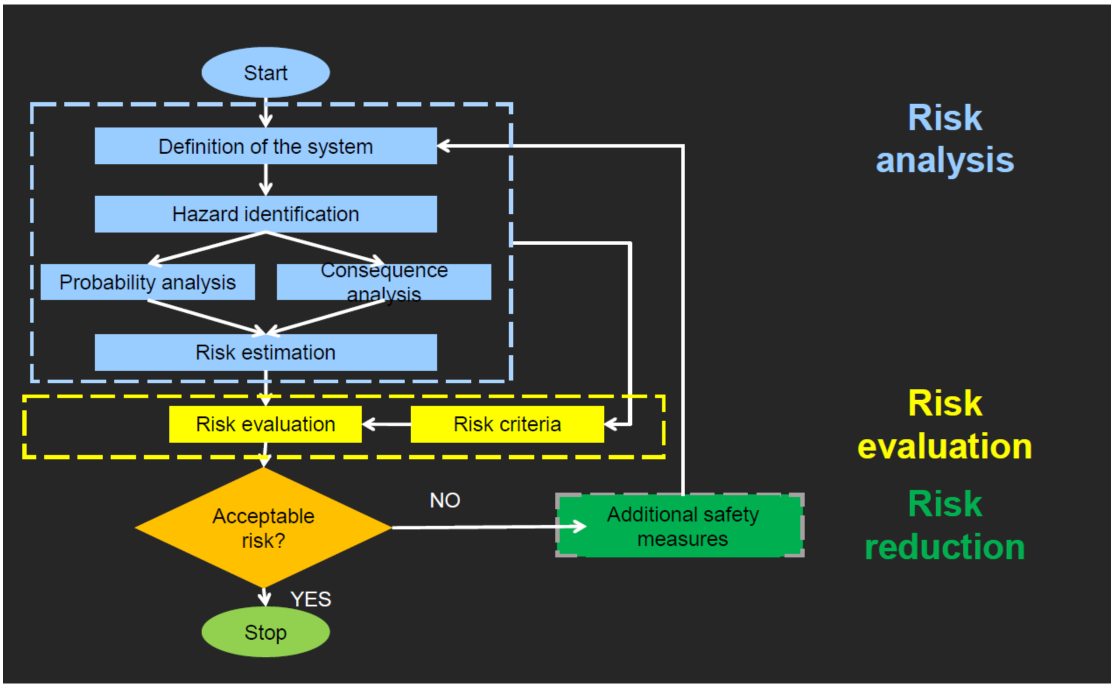


*Figure 31 Risk Assessment Analysis (Source: Benardos, Lecture Notes).*

## 4.2. Risk Assessment Methodologies

The risk assessment could be done either with a qualitative approach or with a quantitative approach. The first method is called qualitative risk assessment and the second one is called quantitative assessment.

### 4.2.1. Qualitative risk assessment

Qualitative method is used for a preliminary risk assessment. In this method, qualitative data are used, and the outcome is a qualitative conclusion. This method has a discrete point scale for assessing the severity of a consequence and another discrete point scale for characterizing the likelihood of an undesired event to happen [3].

The scale for assessing the severity of a consequence of the event is divided in the categories. The first category is high severity, when the consequence is permanent, the second one is medium severity, when the consequence are major and temporary and the third one is low severity, when the consequence are minor and temporary [3].

Regarding the scale for characterizing the likelihood of an undesired event to happen, there are three categories. The first is high likelihood, for undesired events that are happening often, the second one is medium likelihood, for undesired events that are happening rarely and lastly, the third category is low likelihood, for undesired events that are happening nearly never [3].

Eventually, the level of risk is characterized as High (H), Medium (M) or Low (L) according to the combination of the level of severity of the consequence and the level of likelihood of the undesired event to happen, as it is shown in the following table:

| Consequence | Likelihood | Risk |
|---|---|---|
| High | High | High |
| High | Medium | High |
| High | Low | Medium |
| Medium | High | High |
| Medium | Medium | Medium |
| Medium | Low | Medium |
| Low | High | Medium |
| Low | Medium | Medium |
| Low | Low | Low |

*Table 4 Level of Risk according to the level of Consequence and the Level of Likelihood of an Undesired Event.*

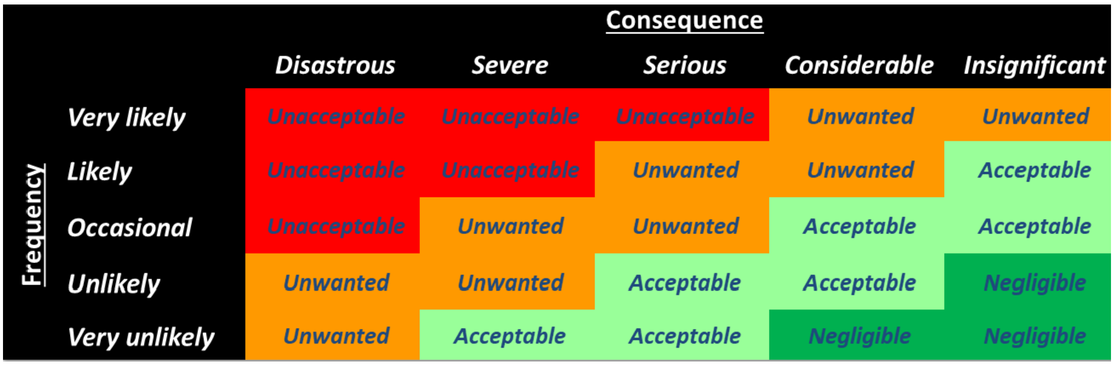
Advantages of the qualitative risk assessment method are [3]:

- Qualitative risk assessment method is easy to be applied and it could be applied without former analysis or the collection of previous data
- It could be used to assess High risks that require immediate

However, a disadvantage of qualitative risk assessment is the fact that, because of its simplicity, this method may lead to fault conclusions and results.

### 4.2.2. Semi- Qualitative risk assessment

Except for the qualitative risk analysis method, there is a semi-qualitative risk analysis method. In this method, risk analysis matrixes are used in order the level of risk to be estimated, depending on the level of the consequence and the probability of the undesired event to happen [3], as shown in the following Figure:



| | | | | Consequence | | |
|---|---|---|---|---|---|---|
| | | Disastrous | Severe | Serious | Considerable | Insignificant |
| Frequency | Very likely | Unacceptable | Unacceptable | Unacceptable | Unwanted | Unwanted |
| | Likely | Unacceptable | Unacceptable | Unwanted | Unwanted | Acceptable |
| | Occasional | Unacceptable | Unwanted | Unwanted | Acceptable | Acceptable |
| | Unlikely | Unwanted | Unwanted | Acceptable | Acceptable | Negligible |
| | Very unlikely | Unwanted | Acceptable | Acceptable | Negligible | Negligible |

*Figure 32 Semi-Qualitative Risk Assessment (Source: Benardos, Lecture Notes).*

### 4.2.3. Quantitative risk assessment

Quantitative risk assessment methods are used for making yes or no decisions regarding the acceptance or not of the risk’s levels and for comparing two or more alternative solutions to improve a system [3].

Using statistical data and the probabilistic theory, the value of the risk of each activity is calculated and then compared with a value that is considered as the acceptance limit value. Two of the most famous quantitative risk assessment methods are event tree analysis and fault tree analysis [3].

Advantage of this risk analysis method is the fact that with quantitative risk assessment the level of risk is calculated with mathematical precision. However, in order to use this method is a necessity to have plenty of data and information for statistical processing.

- Event Tree Analysis

Event Tree Analysis is an inductive procedure and is used for analyzing of the consequences of an accident, failure or in general of an undesired event. This method provides a quantitative description of every possible consequence, starting from the accident and gives the probabilities of certain consequences to happen. For that reason, safety measures could be introduced to the system accordingly in order to mitigate the consequence and to control the system [3].

Eventually, the probability of a consequence to happen is calculated as the probability of an event to happen multiplied by the probability of the success or failure of the safety measures that are introduced in order to mitigate the effect of the consequence [3].

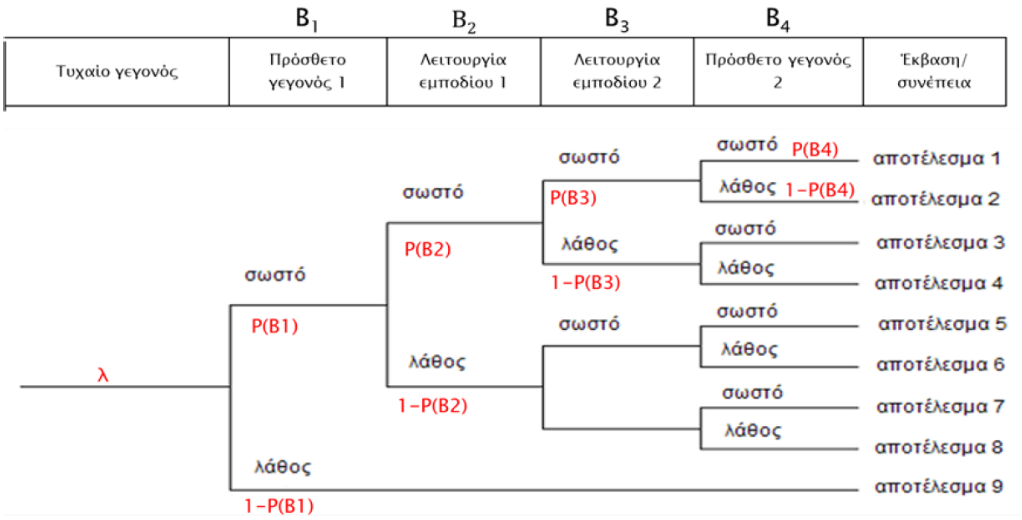


*Figure 33 Event Tree Analysis (Source: Benardos, Lecture Notes).*

- <u>Fault Tree Analysis</u>

Fault Tree Analysis is a method that is used for the graphical representation of all combinations of logical events that they lead to an undesired event [4]. The structure of a Fault Tree is relied on connection between different events through logical gates such as “AND” and “OR” [3].

Major advantages of this method are [4]:

- With this method, the identification of the risk is easier for complicated systems.
- It offers a graphical representation of the sequences that may lead to unwanted and undesired consequences.
- Provides quantitative result of the probability of a failure to lead to a system’s failure and thus to an undesired event.

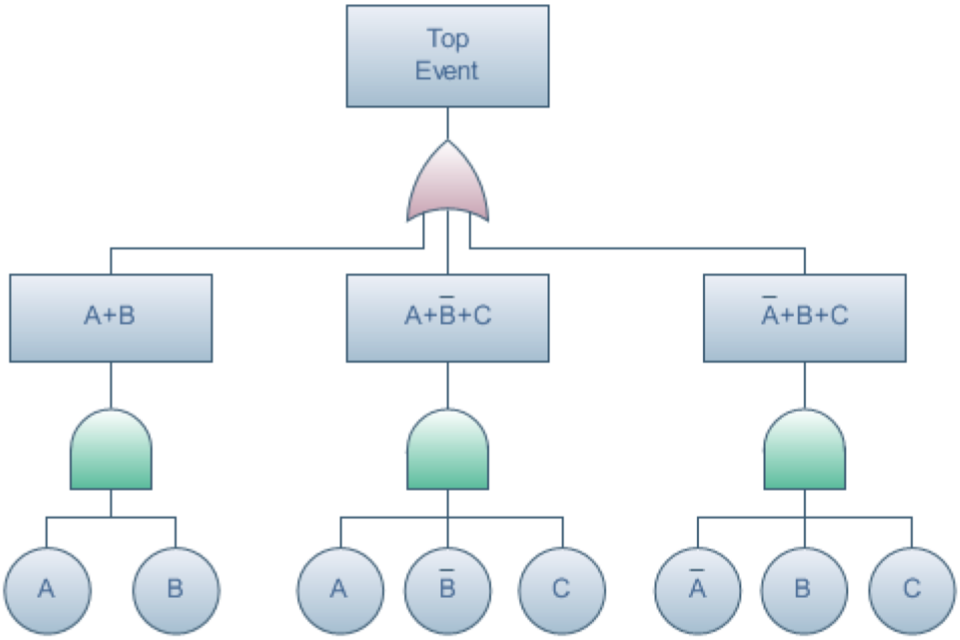


*Figure 34 Typical Fault Tree Analysis (Benardos, Lecture Notes).*

In this master’s thesis, the method that was used for the risk assessment of the underground research nuclear reactor in Halden, Norway was the Fault Tree Analysis. Therefore, the following sector is focusing only to this quantitative method for risk analysis.

## 4.3. Fault Tree Analysis

In this part of the chapter, the proposed methodology that was used is described. As already mentioned, the main goal was not only to identify the potential risks and what sequences of events may lead to a disastrous event, but also to calculate the probabilities of specific events to happen. Therefore, in order to reach the objectives of the thesis, the Fault Tree Analysis was used.

Fault Tree Analysis (FTA) is a well-established technique, widely used for dependability evaluation of a wide range systems. In FTA, the logical connections between faults and their causes are represented graphically [10].

FTA was invented in 1961 in Bell Laboratories by H.A. Watson, with the support of M. Mearns [10]. The intention behind this invention was to help in the design of US Air Force's missile system. Later, this technique was improved by Boeing, and it is widely used after the Three Mile Island nuclear accident (1979).

In general, the analysis starts with a top event, the system failure, and works backwards from the top of the tree towards the "leaves" of the tree to determine the root causes of the top event. The results of the analysis show how different components failures or certain environmental conditions can be combined and the outcome is the system failure.

A Fault Tree consists of [4]:

- Top Event:
  The Top Event represents the undesired event or the failure of the system

- Basic Event:
  The Basic Event represents the parts of the system that contribute to the occurrence of the top event. Furthermore, may express the type, the intensity, and the duration of the effects of the system's environment on the environment when the top event occurs. The Basic Events that make up a Fault Tree present the causes of the error or failure expressed by the top event.

- Intermediate Event:
  Intermediate Events express the state of the system (other than the top event) when two or more Basic Events are combined through the logical gates

- Logical Gates:
  The Logical Gates indicate how the extracted event (Intermediate or Top) can arise with the previous imported events (Basic or Intermediate). The most important logical gates are the "AND" and "OR" gates. The "AND" gate gives output if all inputs to it are satisfied simultaneously. The "OR" gate gives an output if at least one of the inputs to it is satisfied.

Regarding the symbology, a Fault Tree consists of three types of nodes: events, gates, and transfer symbols [10], as shown in the following Figure.

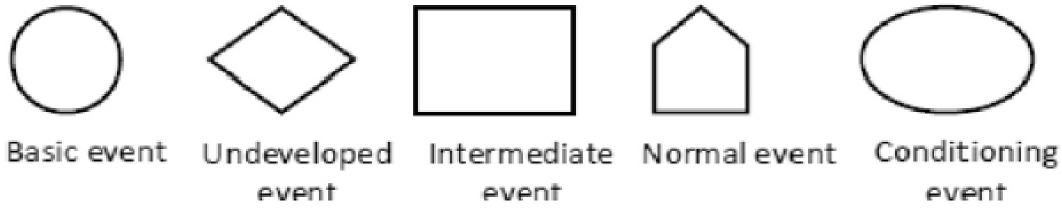


*Figure 35 Symbols for Events n Fault Tree Analysis (Source: Kabir S., 2017).*

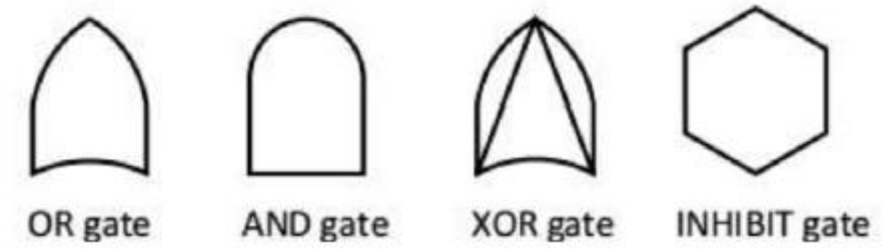


*Figure 36 Symbols for Gates in Fault Tree Analysis (Source: Kabir S., 2017).*

### 4.3.1. Construction of a Fault Tree

The process of constructing a Fault Tree diagram requires the following steps [4]:

1. Determination of the Top Event
   First and foremost, the top event should be determined, according to the undesired event that is under analysis. The top event might be the consequence of the appearance of an undesired event, an accident in the system, a type of a failure or the undesired event itself.

2. Determination of all undesired events
   This step is coming after the determination of the undesired event. All the detected undesired events of the system should be clustered according to similar characteristics. Regarding the complexity of the system and the undesired events, the construction of more than one fault trees may be necessary.

3. Information about the system under analysis
   All the available data and information regarding the system and its environment should be already collected, prior to the initiation of the analysis.

4. Construction of the Fault Tree

In this step, all the main and secondary events that lead to undesired events must be written down and connected to each other. The connection between the events is done almost inclusive by using the logical gates or operations “AND” and “OR”.

The result should be simple, understandable, continuous and with logical flow. In addition, the titles of the events should be as simple and clear as possible in order to avoid confusion.

Furthermore, the logical gates should not be connected to each other. The same rule applies to the basic events too.

Additionally, the basic events should be statistically independent, except for specific situations. However, in this thesis, the events are considered statistically independent.

5. Assessment/ Analysis of the Fault Tree

   After the construction of the Fault Tree, the diagram should be checked thoroughly for improvements. In this step, part of the system that may be improved are detected in order to mitigate the risk or the consequences of the undesired event.

6. Alternative events

   In the previous step, alternative solutions may be detected. Therefore, the alternative solutions have to be assessed and investigated in more depth.

7. Examine of alternative events and recommendations

   This is the final step. In this step, recommendations and proposals are raised to improve the system and mitigate the risk.

   A typical example of a Fault Tree diagram with the Failure of fire protection system as a Top Event is presented in the following figure:

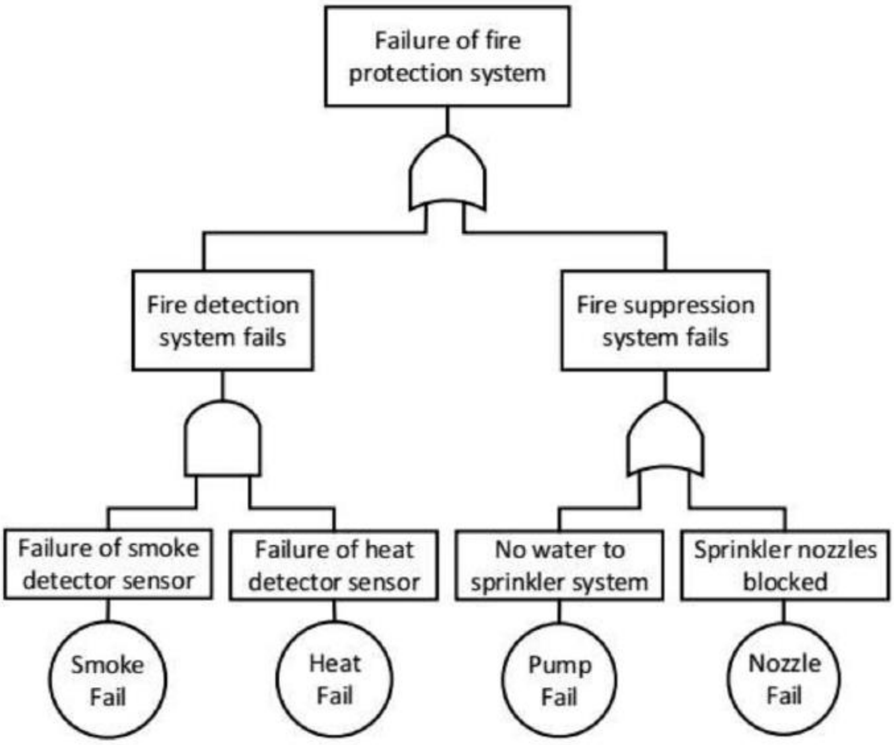


*Figure 37 Typical Fault Tree Diagram (Source: Kabir, 2017).*

### 4.3.2. Analysis of a Fault Tree

After the construction of the fault tree, the analysis may be carried out in two levels, the qualitative level or the quantitative level [10]. In the case study of Halden's research nuclear reactor, a quantitative analysis was performed.

Quantitative Analysis of a Fault Tree can estimate the top event occurrence probability from the given failure rates or the probabilities of basic failure events of the system [10]. In the quantification process, the basic events are usually assumed to be statistically independent, even though there are methodologies that can quantify fault trees with statistically dependent events [10].

A procedure that helps to analyze the results and better understand the failure mechanism of a system is to identify all the failure paths (cut sets) and construct a list of all possible event sequences [4]. In this list, it is easy to identify the events that occur in more combinations, which play a more important role than the others and are therefore more critical in their contribution to the failure. Limiting these events or eliminating them completely is an effective approach to risk control. Furthermore, it is necessary to identify the smallest critical paths with the fewest events (minimal cut sets), which are the first to be addressed by the analyst, since they contribute significantly to the occurrence of failure. Eventually, the possibility of a top event to happen is calculated using the rules of Boolean Algebra [4].

### 4.3.3. Boolean Algebra

Boolean algebra was developed in 1847 by the mathematician George Boole. The main operations of Boolean algebra are the conjunction “AND”, denoted as ∧, the disjunction “OR” denoted as ∨, and the negation “NOT” denoted as ¬ [8]. Furthermore, the Complement of a Set “a” is denoted as “a`”. The Boolean algebra is binary, which means that a variable can take only two values: 1 or true and 0 or false.

The probability of a Top Event to happen is calculated by the rules of Boolean algebra. According to Boolean algebra, if the Basic Events are connected with the operation “AND”, the probability of the Top Event is the multiplication of the probabilities of the basic events. Furthermore, if the basic events are connected with the operation “OR”, the probability of the Top Event is the addition of the probabilities of the basic events.

Therefore, according to Set Theory:

- <u>For Operation “AND”:</u>

  In Set Theory, AND represent the intersection of two Sets A and B.
  Therefore, the probability is calculated as follows:

  $$P(TOP\ EVENT) = P(A) \cap P(B) = P(A) * P(B)$$

- <u>For Operation “OR”:</u>

  In Set Theory, “OR” represent the union of two Sets A and B.
  Therefore, the probability is calculated as follows:

  $$\begin{aligned} P(TOP\ EVENT) &= P(A) \cup P(B) = P(A) + P(B) - P(A) \cap P(B) \\ &= P(A) \cup P(B) = P(A) + P(B) - P(A) * P(B) \end{aligned}$$

In general, the events are considered statistically independent. Therefore, the intersection of sets is systematically ignored in “OR” operation. Thus, for operation “OR” the probability of the Top Event is calculated as:

$$P(TOP\ EVENT) = P(A) \cup P(B) = P(A) + P(B)$$

| Boolean Algebra | | Set Theory | | Propositional Logic | |
|---|---|---|---|---|---|
| Addition | + | Union | ∪ | AND | ∧ |
| Multiplication | · | Intersection | ∩ | OR | ∨ |
| Zero | 0 | Empty Set | ∅ | False | F |
| One | 1 | Complex Number Set | ℂ | True | T |
| Elements | α, β | Sets | A, B | Propositions | p, q |
| Complement of α | α` | Complement of A | $A^C$ | Denial of p | $\neg p$ |

*Table 5 Symbols in Boolean Algebra, Set Theory and Propositional Logic (Source: Benardos, Lecture Notes).*

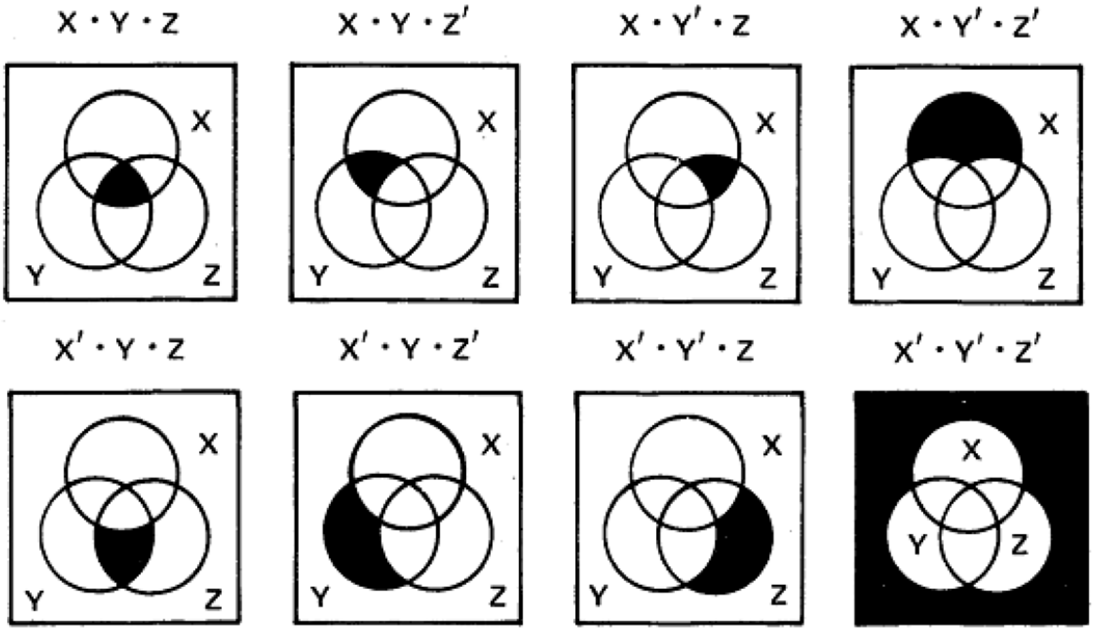


*Figure 38 Venn Diagrams and Boolean Algebra (Source: Benardos, Lecture Notes).*

## 4.4. Acceptable Risk Levels

The classification of the risk as acceptable or not, depends on the perception of risk and the sources of risk. Apart from the quantify estimation of risk, which is an objective and mathematical estimation, the perception of tolerance in risk acceptance is a subjective matter.

The most common method to evaluate the level of risk and to decide if it is acceptable or not is the ALARP (As Low As Reasonable Possible) method. According to the Health and Safety Executive (HSE) of the United Kingdom, risk criteria are not determined by one specific number, but from a range of values.

Risk level is split into three categories: High, Tolerable if ALARP and Acceptable. When a risk level is in the Broadly Acceptable Region, the risk is considered as acceptable, while when the risk level is in the Generally Intolerable Region, the risk is considered High and, thus unacceptable and therefore measures to mitigate the risk should be applied or the event must stop.

In addition, there is a third region, the so called ALARP or Tolerable Region. When the risk level is in the ALARP Region, the risk level may be considered as acceptable if the benefit gained from the activity or the event is high.

Regarding the range of every region, the Health and Safety Executive of the UK proposed that events that with appearance from 0 time per year up to $10^{-6}$ per year belong to the Broadly Acceptable Region. The events that have a frequency of appearance from $10^{-6}$ per year up to $10^{-3}$ per year are coming under the ALARP Region and lastly, events with frequency of appearance higher than $10^{-3}$ per year are considered as High-risk level events.

More specific, according to the following Figure, we can conclude that:

- The unacceptable risks are the risks in the top of the diagram near the base of the upside-down triangle. Those risks could be acceptable in very rare and only under special circumstances.
- The acceptable risks are the risks that they are coming under the lower part of the diagram, near the top point of the upside- down triangle.
- The Tolerable risks are the risks that they are coming under the region between the High-Risk Region and the Acceptable Region. These risks are considered as acceptable when the mitigation measures are extremely costly in comparison to the gain from the event or activity.

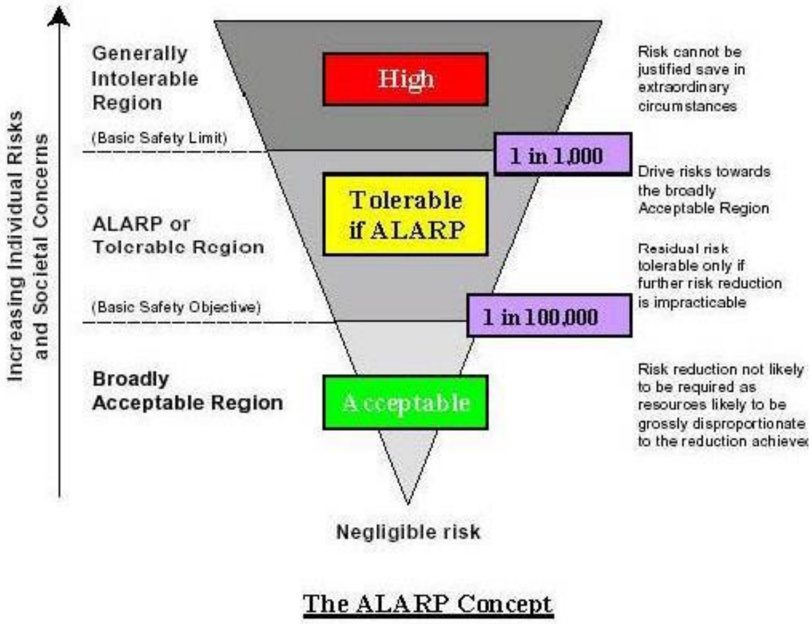


*Figure 39 ALARP Method Diagram (Source: Benardos, Lecture Notes).*

### 4.5. Risk Analysis in Nuclear Reactors

Probabilistic safety assessment has been extensively implemented to assess the performance of nuclear power plants. One well-known modelling approach in nuclear power plant probabilistic safety assessment is the Fault Tree Analysis [15].

In the case of Nuclear Reactors, the Fault Tree Analysis is used to determine the probability of undesired events such as the probability of excessive leakage of containment atmosphere following a loss-of-coolant accident [15] or the probability of a nuclear reactor’s nuclear melt down [14].

The main goals of Nuclear Powerplants safety systems are not only to guarantee the normal operation of the plants without risk exposure to operators, public and environment but also to prevent accidents when unexpected event happen and to mitigate the consequences of accidents when they actually occur [15]. Fault Tree Analysis is a comprehensive approach to evaluate significant plant vulnerabilities, to construct accident scenarios, to predict the safety level of the plant and to numerically estimate potential risks [15].

In general, applying fault tree analysis to such a large and complex system as a nuclear reactor’s systems requires a systematic and well-organized procedure [14]. Therefore, a solid and comprehensive approach should be applied, including the following steps:

- Assemble and organize information of the description of the system under analysis
- Define the system failure and determine the initial conditions
- Construction of the detailed Fault Tree, taking into consideration all contributing fault paths
- Determine the minimal cuts. This action will lead to the reduction of the fault tree to only important fault paths
- After the determination of the events, the components failure and human error data such be assigned appropriately
- Evaluate the fault tree to determine information such as major contributors to system failure and probability of occurrence of system failure

However, the Fault Tree Analysis is not only used in nuclear power industry to estimate the probability of an undesired event to happen. Another application of the Fault Trees is to analyze undesired events that have been already occurred and to investigate what sequence of events led to the appearance of the undesired event.

### 4.5.1. The Case Study of Three Mile Island Accident

The first major accident in Commercial Nuclear Power Plant was the accident that occurred in the Three Mile Island Nuclear Power Plant. The accident occurred on March 28, 1978, when one of the two nuclear reactors experienced a partial meltdown.

A stuck-open pilot operated relief valve (PORV) in the primary section of the reactor and blocked valves in a back-up safety system led to this accident. The blocked valves prevented the flow of feedwater to the steam generators while the stuck-open valve allowed a large amount of nuclear reactor coolant to escape [16]. Consequently, the loss of coolant in the primary system and lack of feedwater in the steam of generators led to an incredible rise of the temperature of the primary section and thus, the core was severe damaged [16].

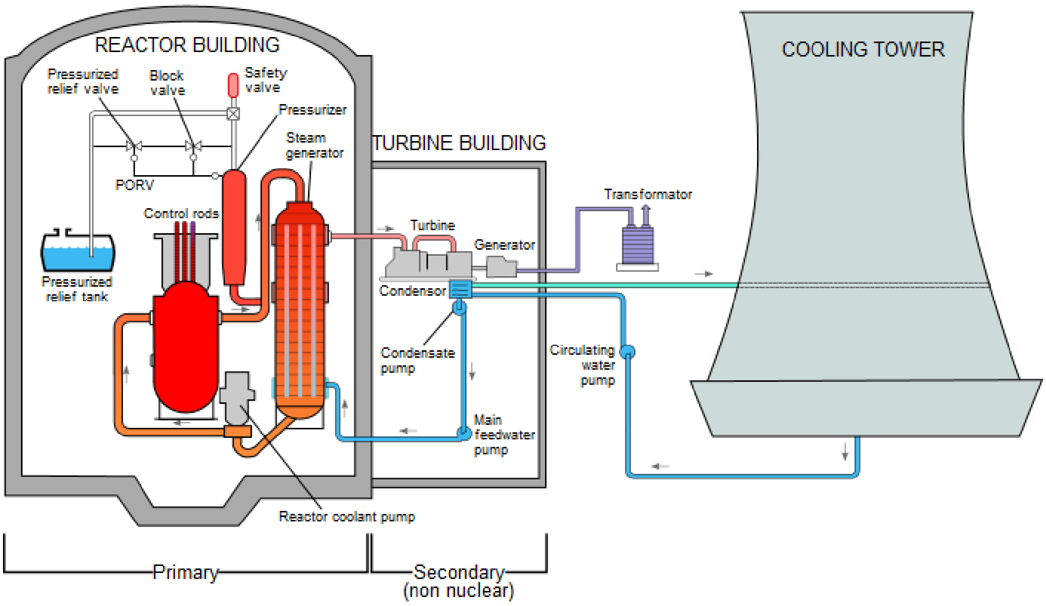


*Figure 40 Schematics of the Three Mile Island (TMI-2) Nuclear Power Station Reactor (source: Clement C., 2014).*

Clement C. [16], using the result of the investigation that took place by the U.S. National Reactor Commission (U.S.NRC), determined the basic events that led to this disastrous event and then he created the Fault Tree Analysis that shows the accident was a result of the combination of many technical and human factors.

After the construction of the Fault Tree Analysis, each basic event was provided by its probability, usually determined by the literature and then using the gate-by-gate approach, the probabilities of the Intermediate Events were calculated and then, the probability of the Top Event was estimated.

# Chapter 5

## 5. Case Study

This chapter is the main chapter of the master's thesis. Firstly, the system of the Halden's Research Nuclear Reactor is presented and

### 5.1. Introduction

Halden is a coastal city in south-east Norway, approximately 120 km from Oslo and near to the Swedish border, while the plant is located on the north bank of the river Tista [5]. The population of Halden, according to the latest available data is 31387 people and is the 18th largest city in Norway.

*Figure 41 Halden, Norway (Source: https://www.freecountrymaps.com/map/towns/norway/27537743/).*

Halden's reactor is a Boiling Water Reactor (BWR) rated at 25Mwth [6]. This reactor was built for experimental purposes and to provide steam to a paper factory after completion of the experimental work. The reactor reached criticality in June 1959 and full power operation with the second fuel charge, in October 1962. Excavations and blasting on site were started in November 1955 and all civil engineering work was completed in October 1957 [5].

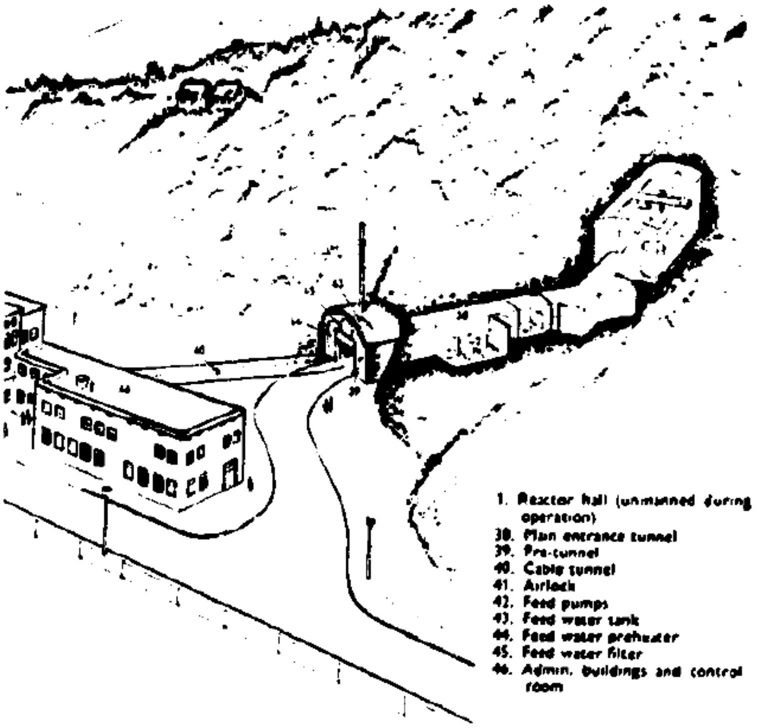


*Figure 42 Outline Drawing of Halden´s Plant (Source: Pinto S., 1979).*

The reactor was built by the Institutt for Atomenergi . Since 1958 it has been operated as a test station under the auspices of ENEA. The entire installation expect for the control room and the emergency diesel engine, is contained in rock in a hillside. The reactor is located in a cavern, rectangular in shape with an arched roof, 30 m long, 10.5 m wide and 25 m high at the center of the roof span, with minimum rock overburden of 30 m and a maximum of 60 m [5][6].

The rock in which the reactor hall is located, consists of gneiss. Fissures formed by dislocations are distributed through the rock. The fissures are filled with stone powder and cloritic materials formed by the leaching of the gneiss. Furthermore, the 5-10% of the total material in the cracks is montmorillonite clay. The total volume of the excavations is about 8900 [5].

The cavern is lined with painted concrete 15-30 cm thick. Concrete is also used for the flooring and foundations for the reactor. The height from the floor level to the roof is 12.5 m and from the floor level to the lowest sump is about 15.5

m. The rock quality has been the limiting factor for the maximum width of the reactor cavern, while the height has been fixed by lifting requirements [5].

The foundations contain three large pits, one for the reactor, one for the auxiliary equipment and one for the storage of large, contaminated components. A smaller pit is also provided for the fuel elements storage [5].

In the reactor hall there is a 50-ton crane utilized during the erection period and for servicing and refueling. It is worth mentioning that the reactor hall is not accessible during plant operation.

Connection to the outside is through a 59.5 m long tunnel fitted with two pressure-tight doors, 7 m apart, to provide an airlock between the reactor hall and the entrance of the tunnel [5].

The tunnel is built with an angle in the horizontal plane, before the reactor cavern, to provide a shockwave pocket. All cables and piping to the reactor, including the ventilation system, go through this tunnel [5]. The feedwater tank, filters and preheaters are in the concrete pre-tunnel section, triplicating in that way the piping required, since water from the feedwater tank flows to the reactor hall and, there, through the low- temperature coolers, then returns to the pre-tunnel section to the preheater and then back to the reactor hall through the feedwater pumps which are located very close to the concrete section of the tunnel [5].

The reactor area is entirely underlain with bedrock which permits very little subsurface drainage. However, some drainage occurs through the cracks and fissures in the gneiss [5]. Groundwater flows slowly but continuously through the rock into the reactor hall and is collected in a sink in the lowest part of the excavation, 1.2 m above sea level, at a rate of about 1 $^{m^3}/_{h}$. This inleakage has been found to be independent if the weather conditions [6].

In the case of accidents, fast-acting automatic valves are provided for to block the ventilation ducts and a water spray system is installed to flush the cavern walls and ceiling to minimize the contamination of concrete surface and to quench the steam pressure [5]. An emergency purification system is available for taking care of the spray water and the continuous inleakage of water through the rock, in case of an accident with radiation released to the reactor hall [5].

This thesis is focusing primary on the usage of the cavern as a siting location for a nuclear reactor. Therefore, technical characteristics regarding the operation of a nuclear reactor, the procedures that should be applied in order to mitigate the risk of a meltdown of the core and the steps that should be followed to deal with a meltdown event are simplified.

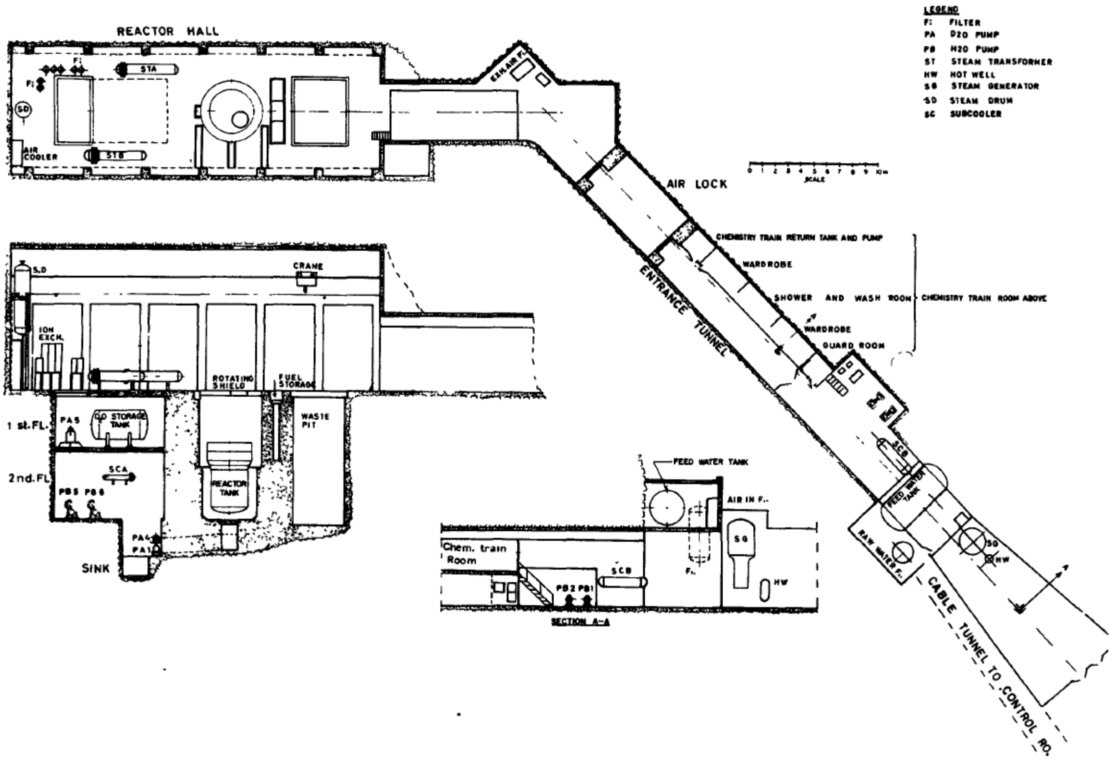


*Figure 43 Halden's Reactor Layout (Source: Pinto S., 1979).*

| Plant | Year of Operation | Plant Purpose | Plant Configuration | Containment Type and Dimensions | Rock Type |
|---|---|---|---|---|---|
| Halden | 1962 | Experimental, steam production | Hillside plant in rock cavities, partially underground, no turbine | Rock excavation lined with painted concrete (30x10.5x26 m) | Gneiss |

*Table 6 Main Characteristics of Halden's Underground Experimental Nuclear Reactor (Source: Pinto S., 1979).*

| Plant | Total Excavation Volume $(m^3)$ | Reactor Cavern Volume $(m^3)$ | Reactor Cavern Span $(m)$ | Excavation Time (months) | Civil Engineering Work Costs (% Total Costs) |
|---|---|---|---|---|---|
| Halden | 8900 | 5600 | 10.5 | ≈23 | 10.5 |

*Table 7 Excavation Characteristics of Halden’s Underground Experimental Nuclear Reactor (Source: Pinto S., 1979)*

## 5.2. Description of the system

In this part, a preliminary approach regarding the probability of an event of radioactive pollution after a nuclear accident in Halden is presented.

### 5.2.1. Hazard Identification

The existing hazards, the possible accidents and the corresponding effects are determined by the special characteristics of each system under evaluation. In the case of the Halden’s underground nuclear reactor, the system is characterized by the following critical elements:

- An active BWR nuclear reactor (risk of a core melt down).
- The system is inside gneiss.
- Groundwater flows into the reactor hall.
- Paint Concrete Lining.
- The nuclear reactor is inside a hillside.
- The probability of an event of an earthquake (seismic event) was not taken into consideration, because underground structures behave well under a seismic event.

With regard to these characteristics, the main threat of the facility derives from the potential leakage of radiation through the cavern to the aquifer or to the atmosphere, in case of a nuclear accident, such as a core melt down, which can result in serious ecological and environmental damage with catastrophic consequences. This analysis is starting from the top event (Radioactive Pollution) and tries to investigate which sequence is needed in order the top event to happen.

### 5.3. Fault Tree

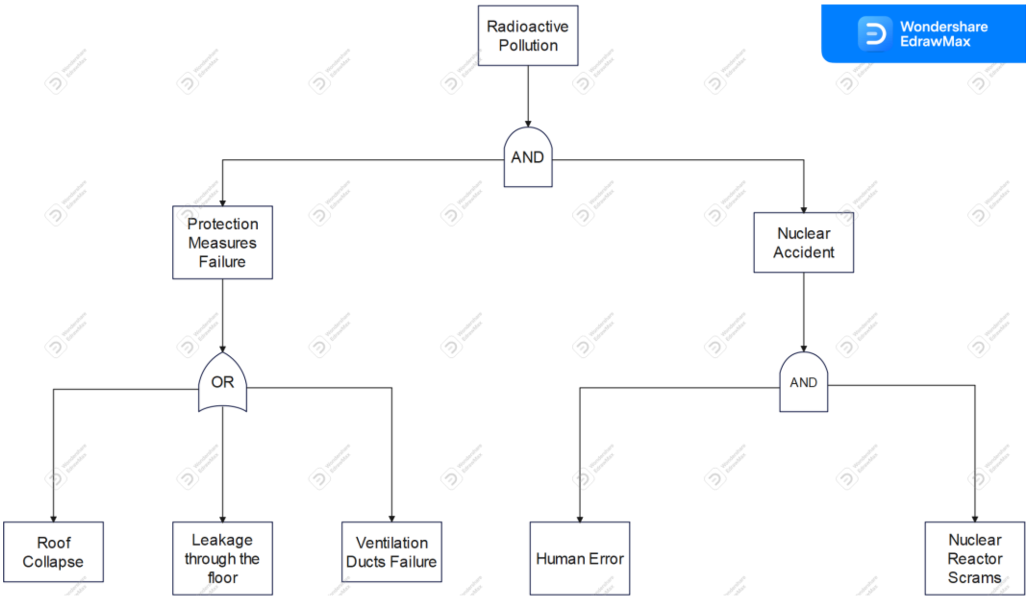
The Top Event was the event of radioactive pollution. In order this event to occur, two intermediate events should happen at the same time. Firstly, a nuclear accident should happen in order radiation to be released and at the same time, the already established safety measures should fail. Therefore, the logical gate that connects the two intermediate events is the logical gate "AND". Each intermediate event is connected with the appropriate logical gate with the basic events.

The fault tree is divided into two main intermediate events that the intersection ("AND") of these events may lead to radioactive pollution. The first main intermediate event is the failure of the protection measures while the second main intermediate event is the nuclear accident and more specific the nuclear core meltdown.

The protection measures are the measures provided by designing and locating the system inside a rock cavity. More specific, protection measures are the systems and the characteristics that provide protection in case of an accident, such as the cavern itself, which is practically the shield of the nuclear reactor and the systems that should ensure that radiation should not be released, such as ventilation ducts.

The nuclear core melt down is the result of many intermediate events that combined may result to disastrous consequences. As aforementioned, fault trees have been already used to analyze nuclear accidents that have been occurred [16]. Therefore, a similar analysis will be used in this thesis.

The first, simple Fault Tree that was created, using the trail version of the software Wondershare Edrawmax, is the following:



. *Figure 44 Simple Fault Tree of the System.*

However, this analysis is a simplistic one and therefore the system should be analyzed in more depth. For that reason, the events that may lead to a nuclear accident (nuclear core meltdown) should be further investigated and analyzed, using case studies from the literature [16].

As already mentioned in chapter 4, one of the first and most catastrophic accidents in a nuclear power plant was the partial nuclear core meltdown in Three Mile Island nuclear reactor number 2 (TMI-2). An extend fault tree analysis to explain this undesired event is already existing in the literature [16].

Based on this fault tree analysis [16], the following Fault Tree was developed:

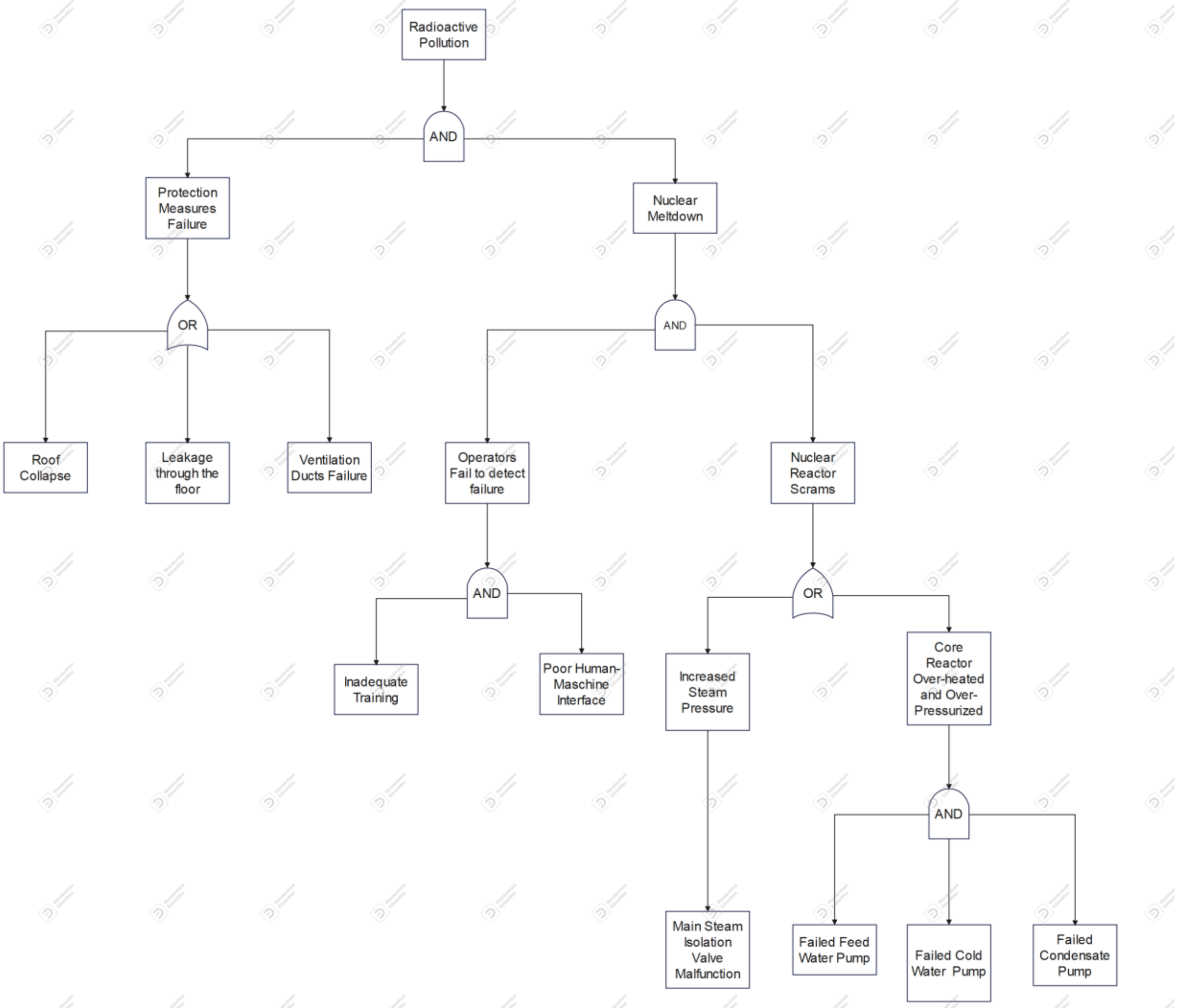


*Figure 45 Extensive Fault Tree Analysis.*

The table below shows a breakdown of the Basic Events that may lead to the undesired event of radioactive pollution:

| Number | Basic Event | Description |
|---|---|---|
| 1 | Roof Collapse | The collapse of the roof will lead to a release of radiation in the atmosphere in case of an accident |
| 2 | Leakage of Contaminated Water | The leakage of contaminated water through the floor to the aquifer or to any source of water may lead to a radioactive pollution in case of an accident |
| 3 | Ventilation Ducts Failure | In case of ventilation ducts stuck open the radiation may be released in the atmosphere in case of an accident |
| 4 | Inadequate Personnel Training | If the personnel are not well trained, may not be able to detect or to address failures of the system |
| 5 | Poor Human Machine Interface | If the Human Machine Interface design is not sufficient, then the personnel will not be able to detect or to address any possible failure of the system |
| 6 | Main Steam Isolation Valve (MSIV) Malfunction | If the Main Steam Isolation Valve is not working sufficiently, the pressure inside the reactor is increased and that may lead to a reactor trip. |
| 7 | Failed Feed Water Pump | If the Feed Water Pump fails, the heat will be rise and thus the reactor will suddenly shut down |
| 8 | Failed Cold Water Pump | If the Cold-Water Pump fails, the heat will be rise and thus the reactor will suddenly shut down |
| 9 | Failed Condensate Pump | If the Condensate Pump fails, the heat will be rise and thus the reactor will suddenly shut down |

*Table 8 Basic Event and their descriptions.*

The table below shows a breakdown of the Intermediate Events that may lead to the undesired event of radioactive pollution

| Number | Intermediate Event | Description |
|---|---|---|
| 1 | Protective Measures Failure | Roof Collapse or Leakage of Contaminated Water or Ventilation Ducts Failure |
| 2 | Increase Steam Pressure | Caused by Main Steam Isolation Valve (MSIV) Malfunction |
| 3 | Core Reactor Overheated and Over pressured | In order the Core Reactor Overheated and Over pressured, the Feed Water Pump, the Cold Water and the Condensate Pump to fail at the same time. |
| 5 | Nuclear Reactor Scrams | If the turbine is tripped and the pressure is increased, then the nuclear reactor scrams |
| 6 | Operator Fails to Detect Failure | If the operator has inadequate training and also the Human Machine Interface is poor designed, then the personnel will not be in a position to detect and address the failure |
| 7 | Nuclear Core Melt-Down | The result of the shutting down of the reactor in combination with the fact that the personnel will not detect and address the failure, will lead to a nuclear core melt-down |

*Table 9 Description of the Fault Trees Intermediate Events.*

Using data from the literature and making conservative assumptions:

| Symbol | Basic Event | Probability | Source |
|---|---|---|---|
| P(1) | Roof Collapse | $4.7 * 10^{-7}$ | Karachaliou T., Benardos A., Kaliampakos D, [12] |
| P(2) | Leakage of Contaminated Water | $10^{-4}$ | Conservative assumption, |
| P(3) | Ventilation Ducts Failure | $10^{-4}$ | Conservative assumption, |
| P(4) | Inadequate Personnel Training | $3 * 10^{-3}$ | Clement C., [16] |
| P(5) | Poor Human Machine Interface | $3 * 10^{-3}$ | Clement C., [16] |
| P(6) | Main Steam Isolation Valve (MSIV) Malfunction | $2.51 * 10^{-7}$ | Changxian Gan et al 2021, [24] |
| P(7) | Failed Feed Water Pump | $5 * 10^{-6}$ | Clement C., [16] |
| P(8) | Failed Condensate Booster Pump | $5 * 10^{-6}$ | Clement C., [16] |
| P(9) | Failed Condensate Pump | $5 * 10^{-6}$ | Clement C., [16] |

Table 10 Symbol of the Events and Probability Data used for the Fault Tree Analysis.

| Symbol | Intermediate Event |
|---|---|
| P(A) | Protective Measures Failure |
| P(B) | Increase Steam Pressure |
| P(C) | Core Reactor Overheated and Over pressured |
| P(D) | Nuclear Reactor Scrams |
| P(E) | Operator Fails to Detect Failure |
| P(F) | Nuclear Core Melt-Down |

Table 11 Symbol of the Probabilities of the Intermediate Events.

The next step of the analysis is to calculate the probabilities from the bottom (Basic Events) up to Intermediate Events and the to the top (Top Event)

According to the Boolean algebra and the Fault Tree, the P(A), which is the probability the Protective Measure to fail is calculated by the equation:

$$P(A) = P(P(1) \cup P(2) \cup P(3))$$

$$P(A) = P(1) + (P(2) + P(3)$$

$$P(A) = 4.7 * 10^{-7} + 10^{-4} + 10^{-4}$$

$$P(A) = 2 * 10^{-4}$$

The probability for the Steam Pressure <u>NOT</u> to be increased is equal to the probability of Main Steam Isolation Valve (MSIV) <u>NOT</u> to be malfunction. Therefore:

$$P(\bar{B}) = P(\bar{6}) = 1 - P(6)$$

$$P(\bar{B}) = 1 - 2.51 * 10^{-7}$$

$$P(\bar{B}) = 0.999999$$

The probability for the Core Reactor <u>NOT</u> to be over-heated and NOT over-pressured is calculated by the equation:

$$P(\bar{C}) = P(P(\bar{7}) \cap P(\bar{8}) \cap P(\bar{9}))$$

$$P(\bar{C}) = P(\bar{7}) * P(\bar{8}) * P(\bar{9})$$

$$P(\bar{C}) = (1 - P(7)) * (1 - P(8)) * (1 - P(9))$$

$$P(\bar{C}) = (1 - 5 * 10^{-6}) * (1 - 5 * 10^{-6}) * (1 - 5 * 10^{-6})$$

$$P(\bar{C}) = 0.999985$$

The probability for the Nuclear Reactor to be scrammed is:

$$P(D) = P\big(P(B) \cup P(C)\big)$$

$$P(D) = P(B) + \ P(C)$$

$$P(D) = \big(1 - P(\bar{B})\big) + (1 - P(\bar{C}))$$

$$P(D) = (1 - 0.999999) + (1 - 0.999985)$$

$$P(D) = 1.6 * 10^{-5}$$

The Probability for the Operator NOT to fail to detect the Failure is calculated as:

$$P(\bar{E}) = P(P(\bar{5}) \cap P(\bar{6}))$$

$$P(\bar{E}) = P(\bar{5}) * P(\bar{6})$$

$$P(\bar{E}) = \left(1 - P(5)\right) * (1 - P(6))$$

$$P(\bar{E}) = (1 - 3 * 10^{-3}) * (1 - 3 * 10^{-3})$$

$$P(\bar{E}) = 0.994009$$

Therefore, the Probability of a nuclear core melt-down of a BHW Reactor NOT to take place is:

$$P(\bar{F}) = P(P(\bar{D}) \cap P(\bar{E}))$$

$$P(\bar{F}) = P(\bar{D}) * P(\bar{E})$$

$$P(\bar{F}) = \left(1 - P(D)\right) * P(\bar{E})$$

$$P(\bar{F}) = (1 - 1.6 * 10^{-5}) * 0.994009$$

$$P(\bar{F}) = (0.999984) * (0.994009)$$

$$P(\bar{F}) = 0.993993$$

Therefore, the Probability of a nuclear core melt-down of the BWR Reactor to take place is:

$$P(F) = 1 - P(\bar{F})$$

$$P(F) = 6 * 10^{-3}$$

Eventually, the probability of the Top Event is denoted as P(Radioactive Pollution).

The probability of the Top Event P(Radioactive Pollution) is calculated by the equation:

$$P(\text{Radioactive Pollution}) = P(P(A) \cap P(F))$$

$$P(\text{Radioactive Pollution}) = P(A) * P(F)$$

$$P(\text{Radioactive Pollution}) = 2 * 10^{-4} * 6 * 10^{-3}$$

$$P(\text{Radioactive Pollution}) = 1.2 * 10^{-6}$$

Therefore, according to a simple approach, an estimation regarding the probability of an event of radioactive pollution to happen in the underground experimental nuclear reactor in Halden is:

$$P(Radioactive\ Pollution) = 1.2 * 10^{-6}$$

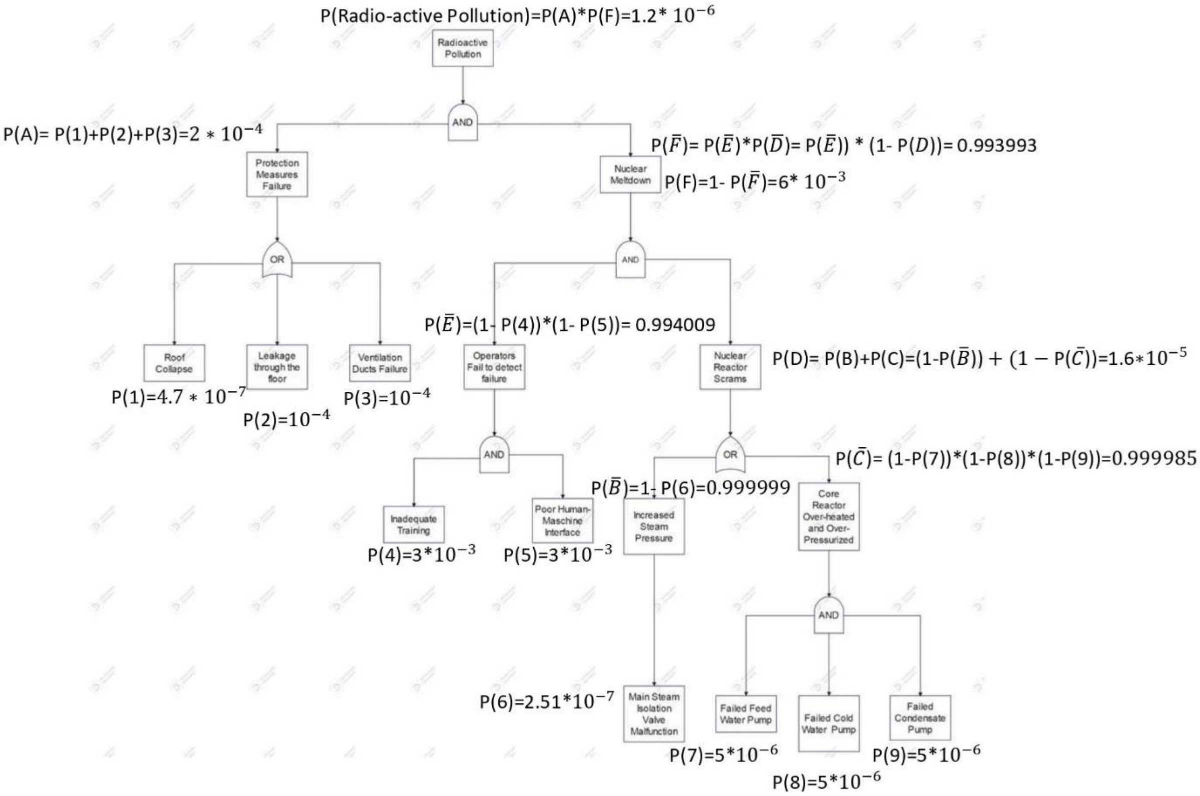


Figure 46 Fault Tree Analysis with Probabilities.

# Chapter 6

# 6. Results and Conclusions

## 6.1. Results

In chapter 5, the Fault Tree Analysis that was carried out and the probability of an event of radioactive pollution caused by the melt down of Halden´s experimental underground nuclear reactor was estimated as:

$$P(Top\ Event) = 1.2 * 10^{-6}$$

Furthermore, according to the ALARP Method Diagram, this event is coming under the lowest part of the upside-down diagram. Therefore, the risk of this event to happen is considered to be inside the Broadly Acceptable Region of the diagram and thus, the risk of this event to happen is considered as Acceptable.

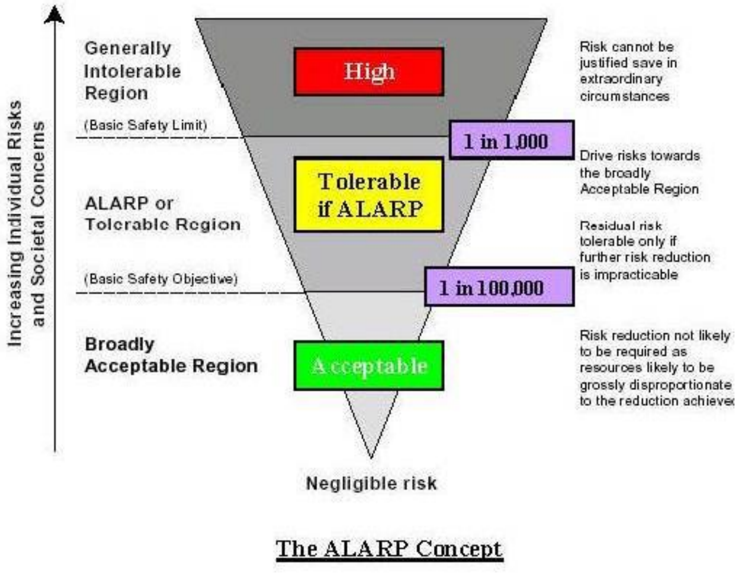


*Figure 47 ALARP Method Diagram (Source: Benardos, Lecture Notes).*

## 6.2. Conclusions

With this simple and preliminary approach, it is shown that the risk of locating a fully operational nuclear reactor inside a cavern is considered as acceptable, even though advantages of the underground spaces that were mentioned in chapter 2, such as the protection of acts of war, are not taken into consideration. Furthermore, in this analysis, the possibility of an earthquake was not taken into consideration, because underground works response to an earthquake event is better than the response of above surface structures.

In addition, the fact that until now there is no known nuclear accident in an underground nuclear reactor supports the argument that caverns could be a feasible option for nuclear reactors to be located in.

Nevertheless, through the Fault Tree Analysis we can easily observe and determine which events are crucial and need attention and what recommendations should be provided in order the system to be improved. The proposed recommendations are:

I. It is clear that the Human Factor is crucial to this system. Therefore, the nuclear plant operators and personnel must be well trained and fitness-for-duty schemes should be established in order the personnel to be prepared to address emergencies and to detect undesired events and failures.
II. Furthermore, regarding the Human Factor, the Human Machine Interface should be user friendly and designed in a way that there is no communication barrier between the plant operators and the machine.
III. Nuclear Reactors and in general Nuclear Power Plants and equipment design and specifications should be upgraded and testes up to the detail.

Last but not least, it is worth mentioning the fact that according to Clement C. [16], the probability of the partial melt down of the Three Mile Island Nuclear Reactor 2 (TMI-2) was estimated as $P(Top\ Event) = 6.78 * 10^{-3}$, while in this analysis, the probability of the event of the partial melt down in the BWR was calculated as $P(F) = 6 * 10^{-3}$, and by locating the reactor in a cavern, the probability of a radio-active pollution is $P(Top\ Event) = 1.2 * 10^{-6}$.Therefore, it is proven that locating a nuclear reactor underground decreases the probability of a catastrophic event to take place.

Finally, I would like to point out that the subject of risk analysis and risk assessment of an underground nuclear reactor was quite challenging. First and foremost, I was not familiar with the way a nuclear reactor works and therefore, the system regarding the nuclear reactor's core meltdown is quite simplistic. Furthermore, it was not easy to collect data and reliable information regarding such an old system (Data from 1979) and such a sensitive system as a fully operational nuclear reactor.

## 6.3. Future Research

However, this study does not take into consideration any costs of design and construction of these caverns. Therefore, the future research should be focused on a cost- benefit analysis between underground nuclear reactors and nuclear reactors that are built above the surface.

Furthermore, more complicated scenarios should be developed and assessed not only with the Fault Tree analysis, but also using other methods of assessment, such as Event Tree Analysis and Monte-Carlo Analysis.

It goes without saying that the future of the mankind is related to the development of the underground and to the advance of nuclear technology. Thus, we should utilize the subsurface environment for not only our economic benefit, but also for our social prospect.

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