Preface

The following résumé summarizes almost 15 years of activities for the International Association of Engineering Geology (IAEG) Commission No. 14. The importance and range of engineering geology, both today and in the future, can only be roughly outlined with regard to developing methodologies and guidelines for safe underground disposal of waste.

It is my great pleasure to thank all the commission members for their persistent and devoted participation in this work. The satisfaction of participing in a project of such importance for coming generations is the reward for all the work.

I also wish to heartily thank the manager of The Swedish Nuclear Fuel and Waste Management Co. (SKB), Dr. Sten Bjurström and his staff, and my colleagues Professor Dr. Michael Langer and Civ. Eng. and Geologist M. Sc. Leif Eriksson for their stimulating and most valuable co-operation when creating this publication.

Finally, special thanks to the Swedish Council for Building Research. Without their generous support it would not have been possible to realize this report.

Stockholm, February 1989.

Carl-Olof Morfeldt
Dr. Techn. - Chairman Commission No. 14

1. Introduction

During recent years, the problems associated with waste products in industrialized countries have become more and more noticeable.

Several main groups of waste can be delineated as follows :

- household waste;
- industrial waste (excluding mine waste);
- mine waste;
- radioactive waste products;
- other hazardous non-destructible wastes.

Waste products within the five main groups differ considerably from one another and therefore the economic solutions for storage facilities also differ.

The problems are further complicated by the fact that deposited waste can undergo change, e.g. through chemical reaction, resulting in other dangerous substances being developed. Adequate knowledge of reaction processes within the deposits is therefore essential.

Free water can cause the leakage of substances in dangerous and unacceptable concentrations and storage facilities should therefore be regarded as "process piling".

Over a long period of time these products have been placed underground and with time they have decayed and have long since been forgotten, but they can still be dangerous to man and his environment. Poisonous and radioactive waste products require special treatment when it comes to long-term storage underground.

Amongst other things, they require deep level deposition so that they are well away from human contact, and dangerous substances cannot leak out and be spread by the ground water.

Finding such tight rock masses is possible in most countries. If storage can be achieved in dry conditions, the problems can be simplified considerably. Even if the bedrock itself is water Fight, water can flow in cracks and fracture zones. The risk for the spreading of dangerous products by flowing ground water up to the biosphere is therefore the greatest problem. Thanks to the intensive research that is being carried out around the world today, to isolate radioactive waste products in a safe way for hundreds of thousands of years, these problems have been sufficiently analysed and methods for tightening rock masses and isolating dangerous products from ground water have been developed.

Over the last few decades, nuclear power has become one of mankind's most important energy sources. Today it is used in more than 25 countries, with a worldwide production figure of 1,300 bn KWh of electrical power in 1984. Nuclear power is still being developed in most industrial countries, and it is projected that worldwide nuclear power production will exceed 2000 bn KWh by 1990.

Thus, the question of safe storage of nuclear waste is international. In recent years, most countries with a sizeable nuclear power production have drawn up plans for safe disposal of resultant, highly toxic radioactive waste materials.

In addition to the awareness of the nuclear energy and medical research, private industry, private and governmental authorities and the general public, have become aware of the need to protect the environment and mankind from the potentially damaging effects of all man-made toxic and hazardous substances now being produced.

International environmental protection organizations are deeply concerned and involved in resolving the issue of how dangerous materials can be rendered harmless or stored to protect mankind and the environment for coming generations. The issue goes beyond the safe storage of radioactive waste and includes all toxic or hazardous materials. The optimal long-term solution for the isolation and safe storage of radioactive waste, as well as all types of substances dangerous to mankind and the environment, is in the use of low-permeability rock masses deep in the earth's crust. This storage concept is generally recognized and acceptable as safe. Thus, the ongoing research and development of safe radioactive waste storage techniques to isolate the waste and prevent contamination of the biosphere, is also applicable to all types of underground storage and other toxic and hazardous waste.

In 1975, the International Association of Engineering Geology, IAEG, showed great foresight in its timely decision to address the issue of safe storage of waste, by forming a commission to examine developments in engineering geology within this extremely important research field.

2. Progress Report

2.1. Background information

In September 1975, a working group of the IAEG met in Krefeld, West Germany, under the leadership of Professor Matula (Czechoslovakia) and formed the IAEG Commission no. 14, to address the issue of "Underground Disposal of Wastes" under the direction of Dr. Jean Sarcia (France). A subsequent meeting was held in 1976 in Sydney, Australia, under the leadership of Dr. G. Souliez (France), where reports by Dr. Sarcia during an earlier meeting in Orleans on 10 August, 1976, were presented :

A summary of the text contained in these documents follows below :

"Problems of the underground disposal of waste include two different fields : (1) underground storage where the waste remains accessible and (2) injection in deep geological layers.

The first field is not essentially different, geologically, from superficial storage and, therefore, does not seem to be the main part of the work of the commission.

Conversely, the second field presents the geologist with special problems regarding techniques and ethics. The duty of geologists is to make studies allowing the authorization of injection of dangerous products; if safety is not sufficiently ensured, the human environment and man himself may be affected for many generations.

If the wastes concerned have the same characteristics as natural materials existing in the ground or are products of which the degradation processes are well known, it is likely that the geologist can, with his own techniques, give advice with sufficient safety coefficients.

Conversely, if the wastes concerned are atomic, chemical or biological products, the question remains as to what extent should the geologist persist with his investigations in order to give absolute advice (i.e., without a safety coefficient).

At this level we have the true problem of the responsibility of the engineering geologist; the feasibility of a project and its cost depend on him alone. In an effort to ensure responsibility (or refuse it), an engineering geologist may be too conservative in his investigations and thus necessitate the use of other means for the elimination of dangerous waste. Alternatively, his investigations could be too superficial.

The following schedule and working plan were outlined by Commission No. 14.

Schedule

- A meeting would be held in Sydney to determinate the by-laws, objectives and scope of work for the new commission.
- In 1976 and the first quarter of 1977, discussions would be held within national or continental groups about investigation techniques and ethical problems.
- In the middle of 1977, a plenary commission meeting would be held to compare results and establish the basis of a report.
- A meeting in connection with the 3rd International Congress of Engineering Geology, for written documentation and presentation of the final report to the International authority UNESCO :

Working Plan :

Investigate the following :

1. Experiences in each country.
2. Developed techniques for surface disposal and for disposal in undergrounds pits.
3. Developed techniques for deep injection
    - ground : stratigraphy, tectonics, petrography, hydrogeology, seismicity...
    - wastes : (solid-gas-liquid) nature, degradability, stability, concentration...
    - compatibility : adsorption-lixiviation-thermodynamism...
4. Ethical problems of deep injections.
5. Existing legislation.
6. Proposals.

The initial debates consisted essentially of discussions of the preliminary text presented in Sydney. It appeared that the ethical aspect of storage problems had not been addressed with the same level of detail by the different groups and commission members, even though all agreed that the ethical aspect was an essential concern.

It was also agreed that the role of engineering geology goes betond the technical and scientific aspects. It is from engineering geological characteristics that security (safety) rules for short, medium, long and very long term storages may be proposed. These security rules, in turn, should serve as the basis for administrative and legal rules for the preservation of the environment and the safety of mankind.

In 1976 the IAEG working group decided that an investigation of the reutilization of wastes was not an appropriate task for Commission No. 14. The working group concluded that this obviously important issue could be more efficiently pursued by the creation of another specialized commission.

2.2. Meetings

The activities of the IAEG Commission No. 14 can best be summarized by the accounts of participation and activities at national and international conferences as follows :

Stockholm, September 1977

In September 1977, a conference "Rockstore 77", was held in Stockholm on the subject of underground construction. The IEAG was one of the sponsors of this broadly defined conference. The conference attracted over 1,000 participants from many different countries. Dr. Morfeldt, who also was the initiator and chairman of Rockstore 77, had earlier been entrusted with the leadership of the IAEG Commission No. 14, subsequent to Dr. Sarcia's retirement. Therefore, Rockstore 77 provided many opportunities for the members of the Commission No. 14 to discuss "The Basis of the Report".

Madrid, September 1978

During the IAEG's third international conference in Madrid, between 4 and 8 September, the special section on "Disposal of Urban Industrial and Radioactive Refuse" attracted great interest.

Specialists from many countries contributed presentations and discussions as summarized below :

1. Introduction by the Commission Chairman,
   Dr. C.-O. Morfeldt (Sweden).
2. Hydrogeological aspects, general summary by
   Dr. Gianni Bonati (Italy).
3. Industrial waste in fractured rocks of the Caucasusregion, by Prof. Joseph M. Buachidze (USSR).
4. Provisional methods of evaluating the transfer of pollutants in aquifers
   J.C. Payrus, C. Madoz-Escande and A. Doury (France).
5. Alternatives for storing atomic residues in areas of low geological activity
   A.J.S. Björnberg and R.A. Abrahao (Brazil).
6. Field investigation at Stripa, Sweden, on some engineering geology problems in underground radioactive waste storage.
   Prof. P.A. Witherspoon and J.E. Gale (USA).
7. Swedish experiences of underground radioactive waste storage.
   Dr. Ulf Lindblom (Sweden).
8. Geological research project dealing with underground disposal of radioactive waste in Finland.
   Dr. Heikki Niini (Finland).

9. The problematics of solid waste in Spain : Current attitudes.
   Dr. Rafael Fernandez-Aller (Spain).
10. Disposal of waste in rock salt formations in Germany — some engineering-geological aspects.
    Prof. Dr. M. Langer (Germany).
11. Research into landfill waste disposal, including hydrological aspects and ground water pollution.
    Dr. M.J. Knight (Australia).
12. Geological phenomena and the storage of fission products.
    Prof. P. CH Leveque (France).

In Newsletter Number 6, page 5, Niini and Morfeldt presented a résumé of special session number 11, which is reproduced below :

> "Special Session 11 was devoted to the engineering geological problems of the underground disposal of urban, industrial and radioactive wastes. Research work conducted in both western and eastern countries indicates that engineering geological investigations, carried out in close connection with technical and economic studies can permit safe disposal of dangerous wastes, both solid and liquid, into certain geological formations, mainly into salt formations, homogeneous granitoid massifs, and deep-seated porous layers lying underneath thick impermeable formations. These investigations have to consider — on local, regional and international levels — the changes in geological phenomena and human attitudes over exceptionally long periods of time (some 100,000 years)".

The members of the Madrid commission conference were actively involved in the task set forth by the Commission No. 14. The participation of the commission members listed below contributed to the completion of this progress report.

Dr. Carl-Olof Morfeldt (Chairman)
President, Hagconsult AB, Sweden.

Prof. J.M. Buachidze
Department of Engineering Geology and Hydrology
Tiblisi, USSR.

Prof. K.G. Eriksson
University of Chalmers, Sweden.

Dr. R. Fernandez-Aller
Spain.

Dr. M.J. Knight
University of New South Wales, Australia.

Prof. Dr. M. Langer
Bundesanstalt f. Geowissenschaften und Rohstoffe
FR Germany.

Dr. J.D. Mather
Institute of Geological Sciences, England.

Prof. Dr. Heikki Niini
The Eng. Geological Society of Filand, Finland.

Mr. Jean Sarcia
Chef du Service Geotechnique du CEA, France.

Prof. Paul Witherspoon
Lawrence Berkeley Laboratory, USA.

Dr. Owen L. White
Ontario Geological Survey, Canada.

Helsinki, July 1979

In preparation for the IAEG-Nuclear Energy Agency (NEA) symposium to be held in July 1979 in Helsinki, the following questions were presented to the commission's participants for consideration and discussion :

1. Which authorities deal with these questions in your country ?
2. Which regulations — if any — are already in effect ?
3. Are there any investigations with the object of making further regulations ?
4. Are there any ongoing research and/or developing projects in the form of full-scale tests ?
5. How are refuse problems handled today ?
   Are central destruction facilities being built ?
6. Which norms are applied for industrial waste and pollution injection into air and water ?
7. How is radioactive refuse dealt with ?
8. In your country, do they grout at great depths in sedimentary formations ?
9. What regulations are applied in order to control and protect ground water ?
10. What research institutions are dealing with these problems ?
11. Have attempts been made to map and classify various geological areas in this context ?

The increasing attention to and world-wide interest in underground storage of wastes was evidenced by the international IAEA-OEDC/NEA symposium on "The Underground Disposal of Radioactive Wastes" held in Helsinki 1979. This symposium attracted more than 400 delegates from 40 countries. Many of the Commission No. 14 members participated.

In connection with the Helsinki conference, the commission's members visited the Stripa mine in Sweden, where full-scale thermomechanical, hydrogeological, geomechanical and engineered barrier tests have been conducted. At Stripa, American and Swedish scientists have been conducting tests for more than one year at about a 400-m mine level. Professor paul Witherspoon from the University of California, USA, and Professor Ulf Lindblom, Chalmers-Hagconsult, Sweden, acted as guides during the demonstration period.

Because the research at the Stripa mine is being performed on a cooperative basis with other nations, this work has been of epoch-making importance and is dealt with in detail, later on in this résumé.

Tbilisi, September 1979

At the invitation of Prof. Buachidze, Prof. Leopold Müller discussed the possibilities of deep underground storage of primarily radioactive waste (especially by means of deep boreholes in sedimentary layers) in various European countries with Commission members.

Paris, 7-17 July, 1980 — International Geological Congress

During the 1980 International Geological Congress in Paris, a special session dealing with the geological precautions needed to store waste in rock was discussed. Dr. A. Garcia Yague, general secretary of the Madrid conference, was present at this Congress.

New Delhi, October 1982 - IAEG 4th International Congress

A large number of commission members had the opportunity to meet and exchange experiences concerning recent developments, relevant primarily to radioactive waste storage. The lecture given by Dr. Morfeldt generated great interest and a special interview was televised.

Aachen, May 1982 — Symposium on Rock Mechanics related to Caverns etc.

A Special session was held on Underground Waste Disposal and included a presentation by Dr. C-O Morfeldt.

Berlin and Freiberg, January 1983

This conference focused on experiences from the injection of waste in deep boreholes in sedimentary rocks, and of waste in salt formations.

Tbilisi, May 1983

This conference provided excellent opportunities for in-depth discussions on hydrogeological problems at depth in rock masses. Because of the great interest generated by the discussion on radioactive waste storage, a televised interview was given. (Prof. Joseph Buachidze and Dr. C-O Morfeldt).

Lisbon, 12-15 September, 1983 — Engineering Geology and Underground Construction

At the conclusion of this conference, a meeting was arranged for a small group to discuss the questions raised previously at the Helsinki meeting. Unfortunately, Prof. Buachidze was unable to participate in these discussions.

Amman, September 1983 — Underground Construction Conference

The presentations by Professor Langer and others on the storage of waste in salt formations attracted great interest.

Moscow, 1984 — International Geological Congress

Many of the commission's members took part in this congress. Dr. Morfeldt could not participate and was replaced by Geol. Eng. M. Sc. M. Finkel. Mr. Finkel was successful in arranging for some of the members of the commission to become acquainted with the research and testing being carried out in connection with "Super Deep Drill holes" in both granitic rock masses and sedimentary formations.

Hannover, 16-18 October 1985

The commission's work was discussed in Hannover in conjunction with "The 4th International Symposium on Mineral Resources — arranged by The Federal Institute for Geosciences and Natural Resources".

Winston Salem (USA), October 1985

On the occasion of the AEG-IAEG Symposium "Management of hazardous chemical waste sites", many engineering geologists presented their view-points on the problems related to the disposal of hazardous chemical wastes above and underground. Updated versions of some papers presented at that symposium were published in IAEG-Bulletin No. 37, Paris 1988.

IAEG Council Meeting Washington, October 1985

The chairman of the Commission No. 14 was asked to publish an activity report of the Commission's work as soon as possible.

At the October 1985 Council meeting of the IAEG, held in Washington, DC, USA it was decided that a new Sub-Commission of the Commission No. 14 should be formed to address the rising interest and involvement of many engineering geologists within the investigation of land contamination by hazardous waste from past or present industrial practice or other activity.

Large numbers of such sites have been identified in the USA, UK, Europe, Australasia and Asia, and others remain to be discovered. Considerable health hazards can be avoided and appropriate land-use strategies could be developed if correct principles and practices are established. A Sub-Commission of the IAEG that focuses on this issue can perform a valuable service function.

The Sub-Commission title reflects these aims; "Evaluation and Management of Historical Hazardous Waste Sites".

Dr. Michael J. Knight, Australia was nominated as chairman of this Sub-Commission.

At this stage, four aims are apparent :

- enable the sharing of information between countries,
- encourage the preparation of "State-of-the-Art" papers for publication in IAEG Bulletins,
- report national trends in the field, and
- develop an inventory of IAEG people with waste site evaluation and management skills.

Argentina 1986 — 5th International Congress of Engineering Geology

On the occasion of the 5th International Congress of Engineering Geology (Buenos Aires, October 1986) a special colloquium on "Engineering Geology related to nuclear waste disposal projects" was held. A selection of papers given at this Symposium was published in IAEG-Bulletin No. 34, 1986. This selection briefly summarizes the activities of engineering geologists of various countries in the field of radioactive waste disposal underground.

In the opening address, the Chairman of this colloquium, Prof. Michael Langer said :

"Widespread awareness of the environmental implications of human activities has been apparent all over the world during the last two decades, but only recently has more attention been devoted to the relationship bet-

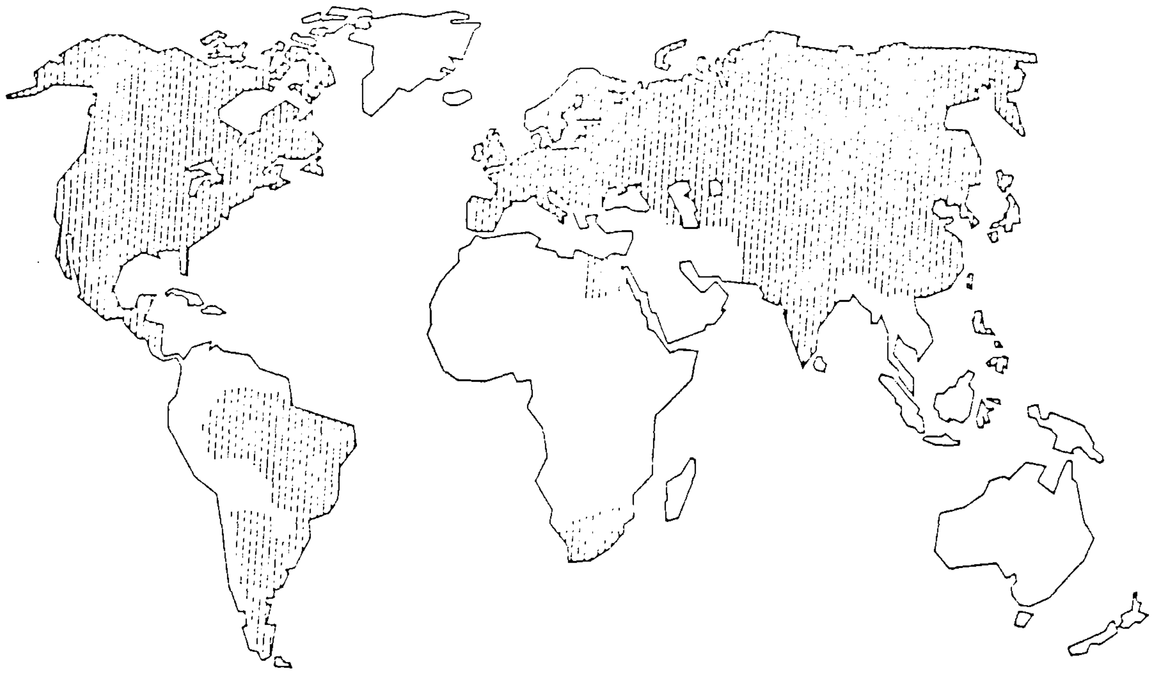

Fig. 1 : Countries with nuclear power plants.

ween the different systems of the total geo-environment. One of the major causes contributing to the degradation of the geo-environment is the disposal of wastes from industry, agriculture, municipal services and mining, radioactive waste being a big part of them. While studying the geological situation and processes of the upper portion of the lithosphere in relation to construction, mining, industrial and agricultural development, Engineering Geology makes an essential contribution to the solution of today's environmental problems. The numerous contributions of papers to Colloquium B "Engineering Geology related to nuclear waste disposal projects" are again a proof of this fact. (IAEG-Bull. No. 34, p. 3-4, Paris 1986).

3. Geological waste disposal : state-of-the-art

3.1. Principles

Geo-environmental change is induced by anthropogenic pressure and this produces multiform effects on the total environment. One of the major causes contributing to the degradation of the geo-environment is the disposal of waste. This as led to unpredictable and variable behaviour of the geo-environment which hampers the planning and management of geo-resources.

These considerations led Unesco to initiate an interdisciplinary meeting on "Geo-environment and Waste Disposal". This meeting of experts was held at IAEA headquarters in Vienna from 21-23 March, 1983 (Cidlinsky, K. : Geo-environment and waste disposal. Proc. Interdisciplinary Expert Meeting by UNESCO/IAEA, Vienna, 1983). A technical document (IAEA-TecDoc 292) summarizes the conclusions that were drawn. Regarding the disposal of toxic wastes, this document makes the following recommendations for improving the understanding of the problems and processes involved, and for a better assessment of the mutual influences of waste and the environment :

A) To collect data and experience from existing, well-controlled waste disposal facilities.

B) To encourage research aimed at better understanding of the nature, behaviour and characteristics of different types of waste in order to improve classification methods.

C) To encourage scientific investigations on the long-term behaviour of natural barriers to waste movement, including sealing materials such as clay layers.

D) To establish and promulgate recommendations and guidelines for :
   1. safety concepts in waste disposal,
   2. site selection criteria,
   3. disposal performance criteria, and
   4. the needs of earth-science data for site selection.

Most industrial and other activities produce waste materials for which there is no further use. Waste comes from many sources: domestic, urban, industrial, (especially radioactive) and from mines. They vary widely in form and amount. Most are relatively harmless. There are some, however, that can cause health and environmental problems if they are not properly managed, and most people are probably aware of instances in the past where inadequate management methods were used. As a result, there is an understandable public concern that adequate controls are maintained to protect the quality of life.

The wastes that probably receive most attention from the scientific community, from governments and from the general public are radioactive wastes. Extensive guidelines for their management have been established at local, regional and international level, and countries with commitments to nuclear power have programs to demonstrate and implement technology for the safe management of the wastes that are produced.

The management of the final storage of toxic chemical wastes is not yet developed to the same extent as the repository of radioactive wastes. Waste products differ considerably from one another and therefore the ecomomic solutions for storage facilities also differ.

The problems are further complicated by the fact that deposited wastes can undergo change, e. g. through chemical reaction, resulting in other dangerous substances being developed. Adequate knowledge of reaction processes within the deposits is therefore essential.

It is generally accepted that repositories in geological media can provide a most certain safe containment, even of toxic chemical wastes; one technical solution being the construction of a waste mine or the use of an old abandoned mine. The most important reasons favouring this form of disposal are that in a carefully sited repository, the geological barriers are expected to be able to contain the wastes for very long periods of time. Some corroborative evidence for this is provided by the existence of many natural deposits of minerals that would be expected to behave like many of the waste components. In conjunction with this is the fact that disposal in a deep underground location decreases the likelihood of deliberate intrusion and essentially rules out the possibility of accidental intrusion. The system is also entirely passive because, once sealed, it does not depend on human involvement.

Wastes from a deep repository could be exposed to the biosphere either by some geological processes such as tectonism, diapirism, or erosion that directly expose the waste, or by some processes that transport the wastes to the biosphere. Transport by ground-water is acknowledged to be the most probable mechanism for moving the toxic particles from the repository to the biosphere. Therefore, deep underground disposal would best be done in a geological environment with little or no ground-water circulation. Present considerations are that such repositories should be at least a few hundred metres below the surface. Deeper repositories would further reduce the likelihood of the release of toxic material, but increasing the depth would increase the cost and possibly the risks of mining. Some wastes may not require as high a degree of containment as is provided by deep disposal. For such wastes, disposal in pre-existing cavities or excavations at intermediate depths may prove to be adequately safe.

It is possible to complement the natural geological system with a variety of engineered barriers such as the waste form, the waste container, buffer materials, and the backfill. The long-term effectiveness of these multiple barriers in a deep geological setting cannot be verified experimentally. Their performance must be estimated from safety analyses which take into account, in addition to the engineered barriers, site specific features such as the geological properties of the host material, seismic activity, and hydrogeological conditions.

There are established techniques, investigations and controls for construction in rock at a moderate depth (some 100 metres) that ensure the safety of the facility (see Table 1). In the summary, the outer crust of the Earth is quite well understood and can be dealt with effectively. The tectonic analyses, seismic investigations, borehole investigations and sampling, controlled blasting, monitoring during construction, control and test pumping of the ground water system, and sealing and injection techniques, are all well proven routines.

Table 1 : The main subsurface disposal methods; their relative depths and common waste forms.

Disposal Method	Relative Depth *	Common Wastes Disposed
Borehole injection and container placement	Very deep: 200 m to kilometres	Usually liquid industrial wastes, but also slurries that later solidify. Radioactive waste in containers and as slurries.
Mine-filling and container placement	Deep: 200 m - 1,000 m (shaft tunnel and open cut type mines)	Domestic and industrial solid waste; toxic industrial liquid wastes freely deposited or in containers. Radioactive wastes in containers.
Landfill and container placement	Shallow surface excavations down to about 100 m	Domestic solid wastes; industrial liquid wastes (free and contained). Radioactive wastes in containers.

* Depths are relative and not intended to be construed as absolute.

However, there is less experience in deep storage in hard rock or sedimentary rock masses 1,000 m or more below the surface. The experiences gained from mine workings are of a very special nature and cannot be directly related to underground civil structures. In conventional mining operations, the objective is to collect existing minerals in the rock mass that generally occur in localized veins. If an investigation of the rock is carried out for the purpose of deep storage of a hazardous substance (e.g. radioactive waste), it can be concluded that it is a simple project because of the general possibility to chose a suitable rock mass. Tectonic studies, fissure investigations, seismic measurements, etc., can be used to screen potentially good rock masses. However, it is extremely difficult to prove that there exists a sound, fissure-free rock mass at 1,000 m or more with little or no water movement because of the great time-scale inherent in such a project. The integrity of a high-level radioactive repository must be ensured for hundreds of thousands of years, periods which are usually regarded as belonging to geological time-scales rather than an engineering system. A great deal can happen during such a time period. For example, several ice ages are expected, subsidence and uplift can occur, even in seismically stable areas such as the Scandinavian shield and several other shield masses on the earth's crust, and erosion can be considerable. Therefore, the repositories must be placed at such depths that changes in the geological and climatical conditions do not allow the waste to escape to the surface. Additionally, the effects of earthquakes on deep lying storage must also be addressed.

In summary, the principal question is, of course, how great is the risk that dangerous toxic material could travel to the biosphere via circulating ground water, or stated more simply, how "tight" does the rock need to be ?

In order to address these questions, intensive studies have been carried out in many countries to investigate long-term geological and crustal behavior. For example, the interpretation of plate tectonics has been improved by using satellite photographs to describe tectonic processes, by computer-aided measurement and interpretation. In combination with laboratory experiments, these developments in plate tectonics theory and interpretation are beginning to enable scientists to better characterize precise locations and precise depths.

Completely watertight (impermeable) rock masses are unlikely to exist. Many rock types may be classified as practically watertight; however, rock masses are generally considered more or less water bearing because of their inherent porosity fractures and other discontinuities. Very watertight rock masses can be found in large igneous rock massifs (magmatic rocks), substantial deposited layers (sedimentary formations), metamorphosed rocks and rock salt.

It is in intact portions of such rock masses that caverns and tunnels and shafts could be constructed, for long-term storage of dangerous substances that cannot be altered or rendered safe through incineration or chemical processing.

The level of the water tightness necessary in the geological formation depends on which waste product it is intended to isolate and the life cycle of the toxic product(s). Specific and stringent requirements apply in particular to long-lived radioactive elements. For these elements, the need for water tightness around a rock repository is critical to prevent ground water transport of radionuclides through the rock mass to the surface (see figure 1, Annexe 1).

Dr. R.W. Corkey (Geological Society of New South Wales) and Dr. M.J. Knight (School of Applied Geology, University of New South Wales; Member of the IAEG Commission No. 14 on Underground Waste Disposal), have illustrated different types of geological waste storages and their function in relation to regional geohydrological balance in Figure 2.

In the following chapters the main objectives of mines for waste disposal purposes and the measures and methods to achieve the objectives are treated. This treatment is qualitative throughout, although the quantitative treatment of many of the topics is underway in many countries.

The text of these chapters is based on a contribution by Prof. Dr. M. Langer to the Commission and has been orally presented to the UNESCO - Workshop "Impact of Mining on the Geo-environment", Tallin (UDSSR), June 1986.

3.2. Objectives

Final disposal is considered to be maintenance-free, unlimited duration and safe storage of particularly harmful (toxic) materials. The final disposal of wastes in a geological medium should guarantee the protection of man and environment from harm caused by the toxicity of the waste during the operation of the repository. After the completion of the operational phase the total repository must be closed off securely

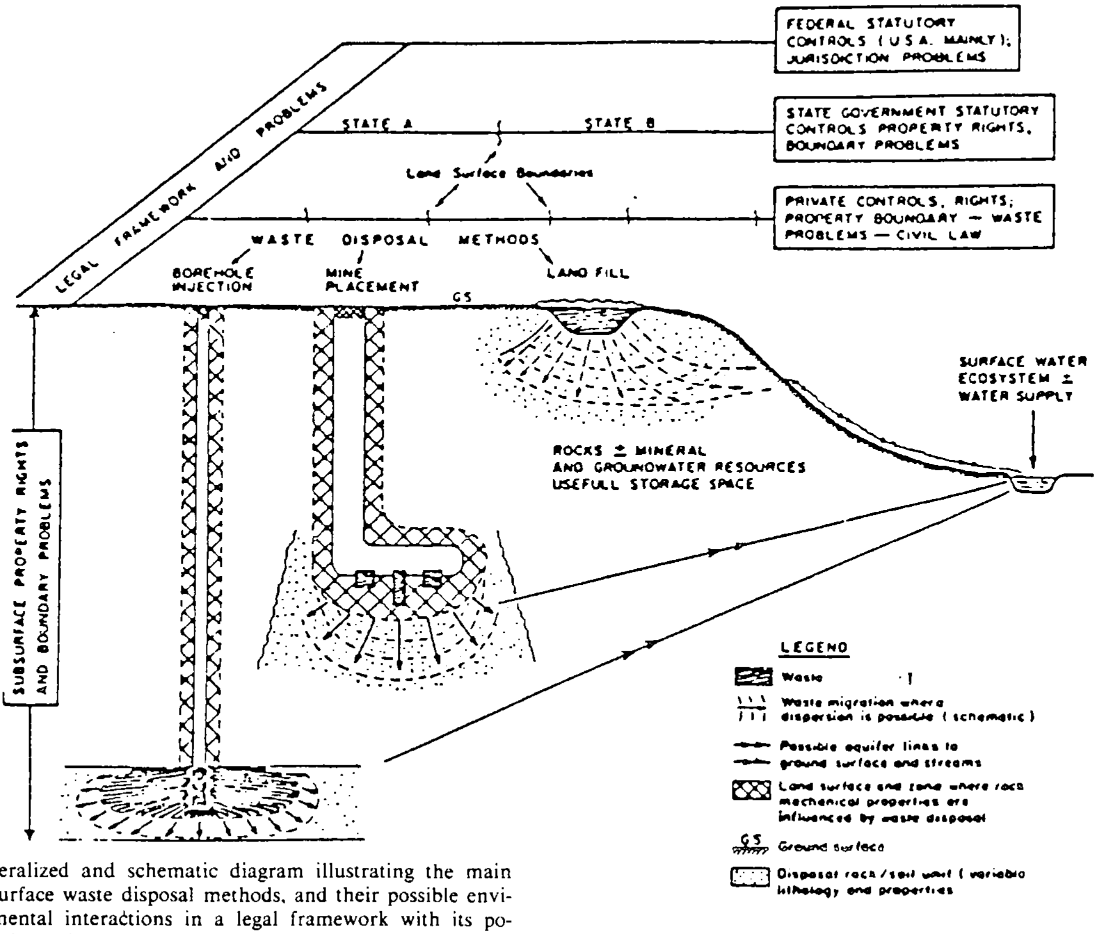

Fig. 2 : Generalized and schematic diagram illustrating the main subsurface waste disposal methods, and their possible environmental interactions in a legal framework with its potential problems.

from the biosphere. Even after decommissioning, toxic material which might escape from the closed repository and into the biosphere as a result of not completely excludable transport processes, may not lead to an amount which exceeds the values given in protection regulations.

For the selection and exploration of a site as well as for the planning and construction of a repository mine, no generally valid quantitative safety criteria which guarantee the objectives can be established, because the engineering concept for the repository mine and the requirements for the disposal products (wastes) are formed from the actual, non-standard, total geological situation. The necessary safety of a repository mine in a geological formation consequently must be demonstrated by a site-specific safety analysis. This analysis has to assess the impact of the waste product, engineered features of the repository, and geological conditions taking into account coupled processes.

Speaking in most general terms :

The objective of waste disposal is to ensure that wastes are dealt with in a manner which protects human health and the environment, and minimizes any burdens placed on future generations.

Because of the complexity of the problems, attitudes towards the environment vary among different individuals, groups, and countries. The environment is regarded by some as a resource, by others as an amenity, but there is a widespread feeling that the environment should not be abused and that the quality of the environment is an important factor in determining the quality of human life. Although it is difficult to define the quality of the environment, standards are being developed by regulatory authorities in many countries to try and quantify the acceptable environmental impacts of human activities.

Considering the welfare of future generations, the general principle is commonly accepted : it is wrong to knowingly commit preventable harm and it is right to make every effort to prevent harm from occurring. Looking at the risks associated with the disposal of toxic waste, we have to accept the principle that the present generation should pay attention to minimize this risk for future generations.

Since it is never possible to ensure absolute safety at any time, it is generally accepted that this society should attempt to leave conditions for future generations no worse than it would accept for itself.

3.3. Measures to achieve the objectives

To achieve the objectives, methods of procedure and technical measures should be adjusted to one another and be based on geological realities. Having in mind that the protective aims of waste disposal can only be reached if the interaction between the subsystems 'waste product, disposal facility, geo-environment' is considered, the objectives are achieved by the following procedural methods :

A) site selection,
B) multi-barrier principle,
C) safety concept, and
D) state-of-the-art technology.

A) The choice of the site is significant not so much for the construction and operation of the repository mine, but rather primarily for long-term safety. The host rock in connection with the total geological subsystem is decisive. Site selection involves :

- identification of sites that meet broad criteria for tectonic stability, slow ground water movement, and long flow paths to the surface,
- intensive subsurface exploration of such sites to determine the hydrological and geological conditions in and around the potential repository,
- predictions of repository behaviour, based on the initial conditions and on various assumptions about the future, and
- evaluation of the risk associated with these predictions.

This implies a comprehensive site-specific investigation and exploration program (see Chapter 6).

B) In principle, all final disposal concepts should be safeguarded by a system of parallel or interlocking natural and technical barriers (multi-barrier principle), although the effectiveness of such technical and natural barriers may receive different weighting in different disposal concepts.

Technical barriers are the packing (enclosure) of the waste products (if any), and any artificial sealing materials. The task of such barriers is to reduce the leaching rate to a minimum, and to hinder chemical reactions between the waste materials and the soil or rock which could lead to a disintegration of either or both of them.

Natural barriers consist of the soil or rock formations surrounding the waste. Above all, the geological setting should ensure that the inflow of water, capable of leaching, and/or outflow of contaminated water from the final deposit facility into the biosphere, is either fundamentally impossible, or at least can be kept within acceptable limits as a result of the natural hydraulic conditions.

Therefore, two important components of the geological barrier have to be considered : the host rock itself and the geological surroundings. Proper rock structures provide physical and chemical properties that contribute to repository strength. Sufficient repository depth and the lateral extent of the rock mass contribute to the isolation capability of the repository. Tectonic stability and a non-communicating hydrological regime are to be combined with rock properties to maintain repository strength and isolation integrity.

The multi-barrier principle has proved itself in technology.

C) The proof of safety for a final disposal facility takes a central position among all other considerations. Since in the case of waste disposal in geological formations, the load-bearing capacity of the soil or rock, the protective effects of the surrounding rock formations over extended periods of time, and the geological stability of the area around the facility are all important factors, such a demonstration of safety cannot be undertaken solely from the viewpoint of constructional engineering, but must also consider geological factors. Safety factors as applied to normal engineered structures are not sufficient in this case.

D) The state-of-the-art technology is to be applied during construction, operating, and decommissioning of a repository mine. The continued development of science and technology should be given adequate latitude. The sum of the experience of miners, engineers and geologists has to be taken into account.

3.4. Safety concept

A safety concept, in consideration of the above requirements and which is based on the principle of multiple barriers (i. e. systems to hinder the release of harmful materials) has been developed for radioactive waste (Langer, M. u.a. : Engineering geological methods for proving the barrier efficiency and stability of the host rock of a radioactive waste repository. Proc. IAEA Symposium, IAEA-SM-289/23, Hannover 1986) and chemical waste (Langer, M. : Safety criteria required for waste disposal. — Proc. Int. Exp. Meeting of Geo-environment and Waste Disposal, Vienna, 1983, Publ. UNESCO/UNEP, 203-215) The main features of this concept are (see Fig. 3) :

A) Separate analysis of the effectiveness of the individual barriers from the technical point of view (type of waste, sealing), rock-mechanical systems (borehole, mines, dumps) and geological systems (hydrogeology, tectonics) using methods appropriate to each case, e. g. :

- statistical risk analysis in the case of the technical systems,
- proof of stability in the case of the rock-mechanics systems, and
- prediction of future geochemical, hydrogeological and tectonic processes in the case of the geological systems.

B) Analysis of the physical and geochemical processes which may result from the mutual interaction of the barriers of the various systems, with evaluation of their significance for the undesired transport of harmful materials, both in the direct vicinity of the final storage facility and over extended distances, e. g. :

- investigation of the corrosion of packing and sealing materials in a natural environment, and its significance for the leaching rates,
- evaluation of the geochemical long-term processes in soil and rock,
- thermo-mechanical calculation of the stresses and deformations in relation to the heat potential of the stored waste, and the characteristics of the formations in the vicinity of the disposal site.

C) Comprehensive analysis of the safety of the final disposal facility, by identifying and evaluating the mutual interaction of all barriers for the case of particular, theoretically possible events (accidents, failures) which could lead to a risk of the release of toxic materials, e. g. judgement of the possible paths of release, and the thereby ensuing damage (failure analysis), e. g. :

- failure of the sealing,
- collapse of the mine or dump for rock-mechanics reasons, and

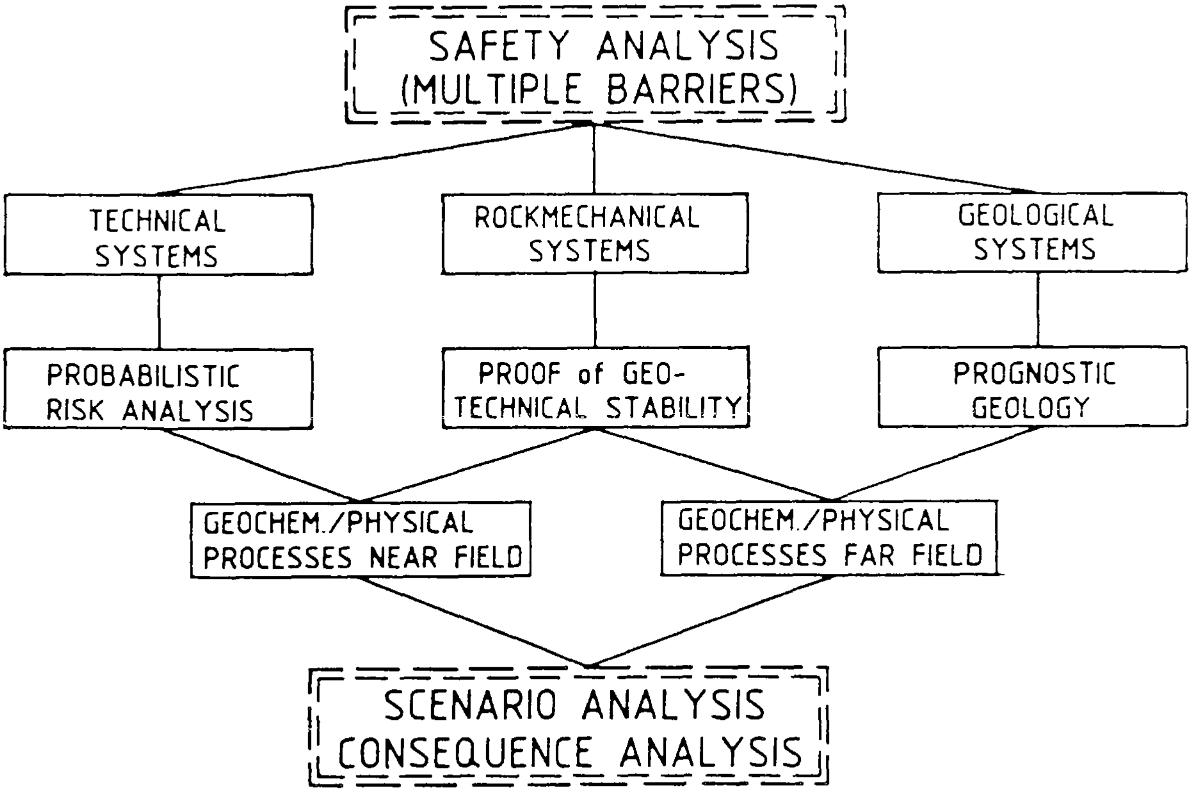

Fig. 3 : Safety concept for waste disposal.

- geological or tectonic catastrophes.

For more details see chapter 5 (safety analysis).

4. Evaluation of barrier efficiency

Safety considerations regarding underground waste disposal in mined repositories are first of all based on the efficiency of the natural geological barrier. This barrier is expected to be able to isolate the wastes for very long periods of time. Therefore, a quantitative evaluation of the efficiency of the geological barrier is necessary.

4.1. Modelling

Due to the multi-barrier principle, the geological setting must be able to contribute significantly to the isolation over long periods of time. Although qualitative understanding, descriptive, models and expert judgement are important factors for a reasonable assurance that the integrity of the geological barrier -- within the system 'waste product, disposal facility, geological situation' will be valid, the assessment of the integrity of the geological barrier should be performed by calculations with validated geomechanical and hydrogeological models. The proper idealization of the host rock and the surrounding geological formations into a computational model is the basis of a realistic calculation. The natural system has to be considered with given properties, such as permeability, thermomechanical behaviour, tectonic fractures (in-situ stress). Initial conditions given by the operation of the repository also have to be taken into account, whereby the repository as a geotechnical system can be optimized to the existing geological situation. This optimization must regard inherent system conditions, e. g. geological and geochemical long term processes, limiting values for temperature, rock failure modes. The adequacy of the computation model with respect to predicting the barrier efficiency has to be proved by a validation procedure.

It is obvious that modelling can only reach a certain level of accuracy, since the actual behaviour of a complex geological structure will always remain unknown to a certain extent.

The geo-scientific approach to overcome this general difficulty is continuous improvement of the model, appropriate to improved knowledge of the input data. The main features of this approach are the establishment of a consistent constitutive relationship for the mechanical and hydrological behaviour, validation of this model, and quantification of site-relevant input data.

Herein, model validation has to follow a strict scientific procedure.

- prior to validation, the numerical program used for computation has to be verified. This means, it has to be proved that the program gives mathematically correct answers,
- model validation is achieved through successful predictions for laboratory tests or in situ tests, taking into account a consistent constitutive model, proper boundary conditions, and initial conditions. Model validation in this sense is not curve fitting by back-analysis but a demonstration of to what extent a particular consistent model is able to describe the response of the host rock, although the constitutive model perhaps does not take into account the entire mechanical and hydrological behaviour, and
- a validated constitutive relationship for the rock mass is then the proper basis for modelling the site-specific geological situation. However, site-specific units of equal behaviour and related parameters have to be determined and are to be confirmed by field tests.

The numerical models used in the assessment of the efficiency of the geological barriers have to represent the physical system of the geological medium. The degree of representation (simulation) is significant because the misapplication of mathematical models may produce erroneous results. Anyway, the use of mathematical models must be justified by the site data. Even if this data were based on a comprehensive site investigation, there is always a certain amount of uncertainties in modelling a geological system. Therefore, boundary approaches must be used in a conservative manner. The extent to which boundary approaches can be justified and demonstrated as being conservative will affect the reliance of the estimation of the barrier efficiency.

Nevertheless, numerical calculations based on models are of particular significance in the case of the final storage of wastes, since licensing procedures require a prior reliable and convincing demonstration of safety.

4.2. Geomechanical models and calculations

The main aim of geomechanical modelling is directed to stability calculations in order to demonstrate that stress redistribution, due to mining operations and possible thermally induced stresses, does not endanger the failure-free state of equilibrium in the rock, and does not cause any inadmissable convergence or support damage during the operative period, and maintains the long-term integrity of the rock formations. It is necessary to calculate the distribution of stress and deformation in the formations surrounding the mine, considering the temperature-dependent rheological properties of the rock and to compare them with the limiting load-bearing capacity of the rock mass. Above all, this requires the formulation of a geomechanical model and associated calculation models, the study of parameters, and the definition of failure criteria (Fig. 4).

To build up a model for calculation, certain idealizations are unavoidable. In the terms of this model one can distinguish between :

- rock-mechanics models and
- static models.

The rock-mechanics model encompasses :

- the geological structure of the rock mass,
- material laws to describe the time, temperature- and stress-dependent deformation and strength behaviour of the rock mass, and

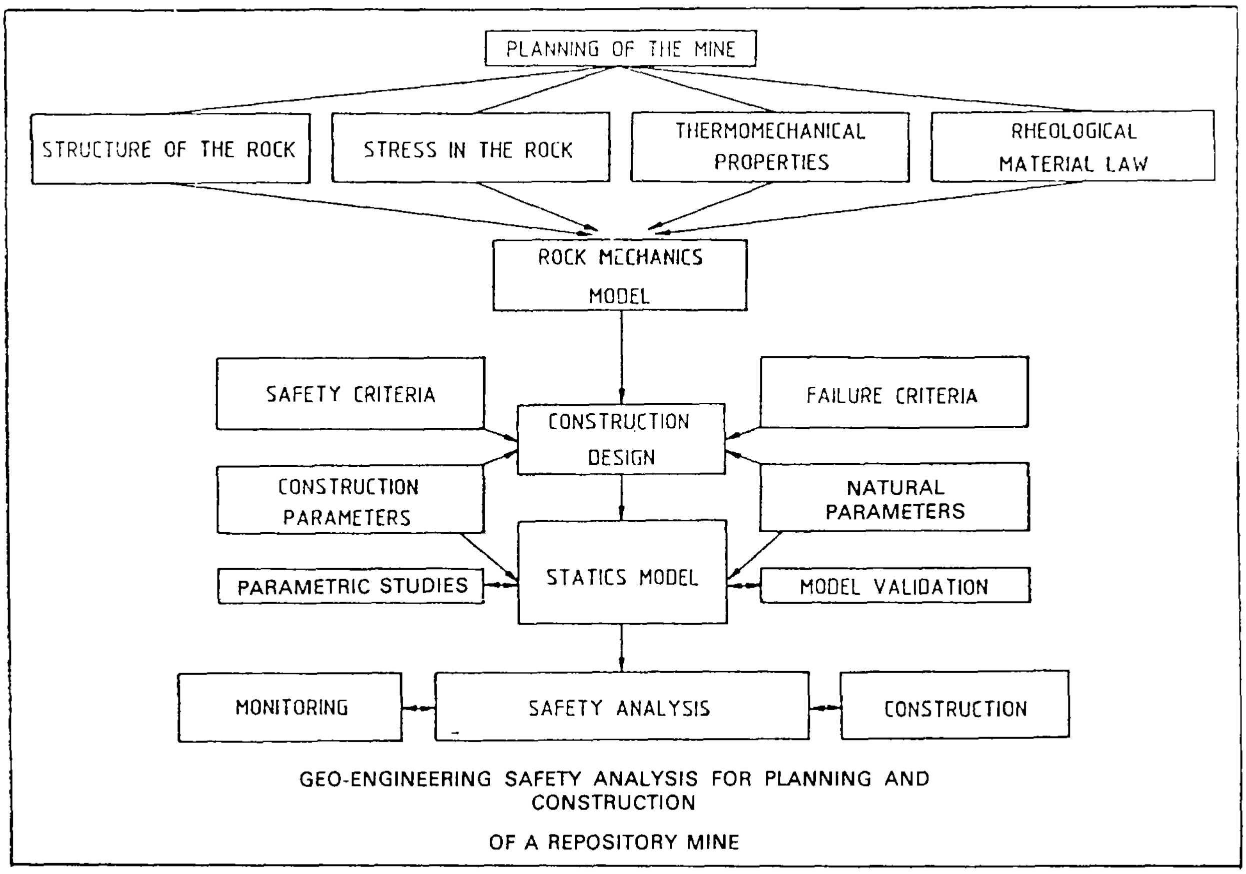

Fig. 4 : Geomechanical modelling.

- the primary state of the rock mass (stresses, temperature).

In the static model the following conditions have to be determined :

- geometry (establishing the load-bearing capacity of the rock mass by spatial, planar or rotation-symmetric substitute systems), and
- stress states and their changes over time :
  - a) thermal effects (e. g. storage and heat-generating wastes, ventilation), and
  - b) mechanical effects (e. g. leaching, backfilling, static loads, etc.).

A calculating method which is particularly suitable for the solution of such geomechanical problems is the method of finite elements (FEM). This numerical calculation method, which is specifically tailored to the requirements of automatic data processing, even allows consideration of many important factors, e. g. tectonic features, operating conditions, mine geometry, construction methods, etc. (Fig. 5) to an accuracy closely approaching the real situation. The FEM method is also suitable for the calculation of non-linear limiting values. For the specific purpose of the analysis of waste disposal facilities, the Federal Institute of Geosciences and Natural Resources (BGR), F.R.G., has developed the ANSALT computer program (analysis of non-linear thermo-mechanical analysis of rock salt).

Another capable computer code used for rock-mechanical purposes is the ADINA code.

Geomechanical computations on the rock behaviour of a waste mine have the following objectives :

- analysing thermo-mechanical processes by calculations shall lead to a proper assessment of consequences,
- experience-based conclusions can be extended by computations,
- rock-mechanical criteria for a stable mine design can be developed from computational parametric studies,
- such criteria are necessary to adapt a preliminary mine design to the real geological situation, and
- the long-term assessment of the integrity of a geological barrier cannot be evaluated from experiments alone but is only possible by computations.

4.3. Hydrogeological models and calculations

The main aim of hydrogeological modelling is directed towards calculation in order to :

- better understand the processes by which toxic materials can be transported by ground water,
- demonstrate that no harmful concentrations of toxic materials is transported to the biosphere, and
- proof that long-term isolation of the waste is guaranteed.

Hydrogeological modelling must therefore especially take into account factors that affect transport by ground water. These include :

- convective transport by the flow,
- dispersive and diffusive transport,

SAFETY CRITERIA	NATURAL INFLUENCES	TECHNICAL INFLUENCES	MEASURES
Deformations	Geological conditions	Cavity geometry	Geological exploration
Stresses	Tectonics	Building processes	Geotechnical investigation
Failure mode	Primary stress	Method of utilization	Static design
Bearing capacity	Mechanical rock characteristics	Conditions of operation	Control test
Brine incursion	Gas and brine deposits	Temperature	Mining measures

Fig. 5. : Criteria and factors of geotechnical stability.

- chemical interactions with the rocks along the flow path, and
- rates at which the waste transforms into solution.

The concept of hydrogeological modelling must be based on the main types and areas of recharge, where water is added to the system and points of discharge, where ground water leaves the system, including the qualitative amounts of water. It also has to consider the general flow paths of the water passing through the system, quantitative data of water transport velocity and chemical and physical characteristics of the ground water in various parts of the whole system.

Adsorption and chemical reactions, including adsorption, ion exchange, and precipitation, retard or restrain the movement of some contaminants. Adsorption and ion exchange are strongly dependent on the chemical form of the contaminants, including their oxidation state and extent of complexing. The sorptive properties of various chemical substances vary through many orders of magnitude and have yet to be determined for many of the elements for various endorsing media and under repository conditions. However, the basic principles of these reactions are well known.

In order to construct a complete model of contaminant flow, the availability of the waste to percolating ground water must be known. This availability will depend on the form of the wastes.

In the simplest, one-dimensional case in which ground water flows through a porous medium (soils), the velocity of flow is given by Darcy's Law.

Regarding the modelling of a barrier of crystalline host rock, the consideration of water conductivity and water permeability along discontinuities (fissures, joints, faults) is necessary, because the inflow of water capable of leaching and/ or the outflow of contaminated water from the final deposit facility into the biosphere is a critical feature. In fissured or jointed rock, the discontinuities are the major factors influencing the permeability of the rock mass, whereas the pore volume of the intact rock is of secondary, or even negligible importance. The hydraulic conductivity depends for the most part on the discontinuity surfaces, their width and filling material, as well as on their origins and intersections.

In this case, hydrogeological modelling and calculation (as well as the testing of the rock) serve to quantify the direction-dependent permeability of the rock with respect to rock pressure and water pressure. They also strengthen the understanding of the applicability of equivalent porous media conceptualizations of ground water flow in fractured rock. The controlling factors and the appropriate scale of application of Darcy's Law — if any — can be determined.

Computer codes for hydrogeological modelling on the basis of Darcy's Law are available world wide (e. g. computer program SWIFT, PHOENICS). Unfortunately, regarding the modelling of water flow in fissured media, several large gaps exist in knowledge of the details of transport systems. Indeed — in spite of recent big international research efforts in this area, the physical basis (that is the mechanics) is missing which would allow reliable and validated calculations of water flow and transport mechanism in fractured media.

A promising approach to fracture flow may come from statistical analysis of fracture patterns. Statistical information is already used in discrete fracture modelling in an attempt to reproduce statistically the hydraulic characteristics of a field site by numerical modelling. This approach is only possible in cases where a lack of information on fracture patterns within the body of the rock mass is stated. It is considered in this approach that the range of results obtained from numerical calculations will approximate the range of results that would be obtained from random sample volumes in the field.

The finite element program ADINAT or the newly developed FE program DURST (BGR, Hannover) can be used to simulate flow processes in fissured rock. The fissures are represented three-dimensionally, the finite elements can be one-, two-, or three-dimensional in these codes.

4.4. Rock testing

The proper idealization of the repository mine in the geological formation into a computation model is the basis for a realistic evaluation of barrier efficiency. The geological environment has to be considered with complex properties, such as internal structure, thermo-mechanical behaviour, hydrogeological features, and initial conditions. Thereby, the correct description of the behaviour of rock within a constitutive model is of fundamental importance, the calculation result can only be as good as the input data. Therefore, rock testing is an indispensable part of any modelling.

The rock properties of principal interest for waste disposal are those related to strength, deformation, and hydrological characteristics. These properties and characteristics are discussed and presented in tabular form in Tables 2 and 3.

Substantial strength is necessary for engineering design of subsurface repository facilities, especially in maintaining the integrity of underground openings. Strength properties provide the durability or resistence of material to processes such as erosion and weathering.

In general, the greater the strength, the greater the ability to resist weathering. Parameters representative of strength include cohesion or friction angle, uniaxial compressive strength, tensile strength and yield limit.

Table 3 : Hydrogeological characteristic values and measuring methods.

Hydrogeology	
Data	Method
Potentiometric Head of Aquifer	Hydrologic drill stem testing; piezometer in deep well
Porosity of Aquifers	Down-hole geophysical logging methods; laboratory testing of core samples
Permeability of Aquifers	Hydrogeologic drill stem testing; field tracer tests
Water Table Elevation	Test well; piezometers; surface electrical resistivity survey
Ground water Temperature	Temperature logging
Ground water Viscosity and Density	Laboratory testing
Transmitty, Storage coefficient, specific capacity	Pump tests in well
Ground water recharge and discharge points	Piezometers; aerial photos; well logs

Stress-strain properties indicate the deformation characteristics that a material will exhibit under stress. Parameters that describe the nature of the deformation of a disposal medium include elastic parameters (Young's modulus, Poisson's ratio, bulk modulus, and shear modulus) and rheological parameters (creep parameters, plasticity). They are significant in the analysis of the properties of earth materials for mineability and isolation. The ability of an earth material to deform and seal discontinuities to fluid flow is desirable. Conversely, a rigid earth material is important to the stability of the repository tunnel opening.

Hydrological properties are essential for assessing the potential for fluid flow. They are evaluated by the parameters of permeability, hydraulic gradient, and porosity. Restriction to transport of radionuclides requires a permeability as low as possible.

Table 2. : Rock mechanic characteristic values and measuring methods.

State of Stess		Deformation characteristics		Strength characteristics	
Characteristic values	Measuring methods	Characteristic values	Measuring methods	Characteristic values	Measuring methods
primary state of stress (internal) stresses, tectonic residual stresses)	stress release measurements a. in the borehole b. in the slit	Elasticity (E-modulus, G-modulus, lateral compression ratio	a. mono-axial hydraulic press, tri-axial laboratory dynamic measurements b. in-situ rock dynamic measurements	compressive strength	mono-axial hydraulic press
secondary state of stress (pressure on the lining (support)	a. borehole extensometer b. stress gauges (anchor)			tensile strength	Brazilian test
tertiary state of stress (stress-redistribution in time)	adit deformation measurements	rheology (V-modulus, plasticity, post-elasticity)	a. laboratory fatigues press, realtri-axial hydraulic press b. in-situ plate bearing test pressiometer (borehole dilatometer bearing test)	shear strength (cohesion, angle of friction).	a. laboratory direct shear test b. in-situ expansion test, shear test

5. Safety analysis

5.1. Methodology

The principles of a safety concept for a waste disposal mine have been explained in Chapter 3.4. To undertake a safety analysis successfully, methods and data are required which enable the evaluation of potential harm from released toxic substances to man and the environment, and which allow a comparison between this harm and acceptability criteria defined in national regulations.

The main steps and methods to complete a safety assessment are given in Fig. 3.

Safety assessments should be carried out for all major stages in the development of a disposal system. At the conceptual stage, safety considerations answer typical questions regarding site selection and disposal system components like the host rock or sealing methods. At the design stage, safety analysis comprises conventional safety assessments associated with normal mining operations, and the demonstration that the complete system proposed should enable relevant acceptability criteria to be met, so that construction and operation can proceed. The final safety assessments performed should check that these criteria will continue to be met, taking into account more detailed data which may have arisen during planning and construction of the repository. In this final stage of safety assessment, not only predictions of potential consequences but also the estimation of the associated probabilities and uncertainties are required. Figure 6 gives an overview of safety assessment tasks and related regulatory work throughout the project development.

The methods involved are always basically the same, although at earlier stages simplifications may be appropriate for efficiency and sensitivity analyses.

Referring to the safety concept as illustrated in Fig. 3, it is obvious that the proof of geotechnical stability, geological predictions (scenario analysis), and the consequence analysis, are the main parts of an overall safety analysis for an underground waste disposal mine. Therefore, some more detailed explanations are given in this chapter.

5.2. Proof of geotechnical stability

An undergound opening (tunnel, cavern, mine) is considered to be stable when the load-bearing capacity and/or the usability of the underground construction (system cavity, support, surrounding rock') has been demonstrated. The load-bearing capacity of an underground construction or part thereof is defined as the ability to bear or accommodate additional loads (e. g. due to mining operations) to an extent that the transition from one equilibrium condition to another (e. g. due to stress redistribution) does not lead to the occurrence of fractures or inadmissably large deformations. For a final disposal facility this means that no failure or convergence may occur which could impair the function of the planned safety pillars, either during the mining operations (primary / secondary stress condition) or during long-term thermal loading cycles (secondary tertiary stress condition). Furthermore, the barrier function of the surrounding rock must be good enough to ensure that any impairment of the integrity of the rock, due to decomposition of minerals containing water, or by cracks due to possible thermal loads, does not exceed the levels defined in the failure analysis.

From this general definition of stability, and the particular protection aims of radioactive waste disposal, it follows that a disposal mine can be considered stable when the following separate proofs can be demonstrated.

For the construction and operation phase (open/partly filled mine) :

- the load-bearing capability of the rock will not be impaired as the result of stress changes (including thermal stresses) to such an extent that the load-bearing capacity of the system is exceeded, either suddenly (rock burst) or slowly (creep failure),
- during or after the mining operations no inadmissable deformation and/or creep rates occur, neither in the underground openings (convergence, creep failure) nor on the surface (subsidence) which may critically influence the usability of the mine and/or the safety of above-ground constructions,
- the extent of decomposition of minerals (e. g. dehydration) due to thermal loads must not lead to endangerment of the integrity of the host rock, and
- uncontrolled leaks of water, brine and/or gas leaks can be avoided.

For the post-operative phase (completely filled mine) :

- the integrity of the surrounding rock will not be inadmissably impaired even over extended periods

	Conceptual phase	Design phase	Construction and operation phase
Type of safety analysis	Simple modelling for scoping purposes and sensitivity analysis of concepts	Proof of geotechnical stability Advanced modelling for final safety analysis	Confirmatory analysis of release from the system (consequence analysis)
Geoscientific and geotechnical activity	Acquisition of general geo-environmental data Preliminary engineering-geological design	Site investigation Engineering-geological complete design of mining facilities	Evaluation of data from monitoring construction and operation Geotechnical assessment and optimation of detailed design
Regulatory activity	Formulation of acceptability criteria	Review of safety analysis report Construction licence	Issue of final repository licence Control and injection

Fig. 6 : Principal stages of safety assessment of waste disposal activities.

of time as a result of stress changes (possible crack formation), the decomposition of minerals and/or corrosion, and
- thermally induced brine migration and ground-water movement must not initiate any inadmissible release of harmful toxic substances.

From these criteria it can be seen that repository design and evaluation of long-term effectiveness of the host rock barrier, must consider the following additional factors :

A) Natural factors :

- geological conditions (e. g. sequences, petrographic composition of the rock, tectonic features, joint texture),
- hydrogeological conditions (e. g. pore water, joint water, permeability, ground water movement),
- in situ stress condition,
- effect of earthquakes,
- occurrences of gas and brine,
- temperature- and time-dependent deformation characteristics of the rock and/or rock mass (e. g. elasticity, creep behaviour, plasticity), and
- temperature- and time-dependent failure behaviour of the rock and/or rock mass (e. g. compression, shear and tensile strength, creep failure parameters, maximum load-bearing capacity).

B) Technical factors :

- properties of the radioactive waste (e. g. heat generation, radioactivity, half-life of the radionuclides, long-term physical/chemical effects),
- mining techniques (e. g. blasting or excavation by cutting machines),
- geometry of the underground openings (e. g. shape and size of galleries and pillars, construction of dams), and
- operational data (e. g. arrangement of the boreholes for final storage, maximum admissable temperature in accessible galleries, safety measures).

C) Factors relating to the system :

- failure modes of the rock/support,
- limiting values for temperature increase in the ground water (overburden),
- limiting values for temperature increase in minerals,
- change of rock properties due to radioactive irradiation,
- absorption properties of the rock (e. g. adsorption of radionuclides in clay minerals),
- long-term geochemical processes, and
- long-term geological processes (e. g. tectonic processes).

The practical demonstration of stability of a final disposal facility can only be done by a combination of various investigations and calculations. Engineering-geological and geotechnical investigations, rock-mechanic measurements, static calculations, the monitoring of technical parameters, and mining experience must all be taken into receive consideration.

The required extent and accuracy of the investigations and measurements, and the definition of safety factors in the case of static calculations for the individual demonstrations, should depend on the seriousness of the effects of possible failures as indicated by the consequence analysis (see next chapter 5.3). Investigations, measurements, and theoretical calculations should be considered as a unit together with their mutual interaction (e. g. mechanical model of the rock, parametric analysis, check of static calculations). Since the final exploration of the rock and thus the definite determination of rock parameters relevant to stability can only take place after the mine has been excavated, stability calculations carried out during the planning phase are only of the nature of a prediction.

5.3. Scenario and consequence analysis

The main objectives of the scenario analysis are :

- identification of the phenomena which lead to a release of toxic substances and influence the rates of release, or of transport from source to man, and
- estimation of the probabilities of occurrence of these phenomena and quantification of their effects on the disposal system, thus providing the necessary initial and boundary conditions for the subsequent consequence analysis.

Consequence analysis involves modelling the subsequent transport of toxic substances and estimating the resulting effects. The tasks in the consequence analysis include the estimation of :

- the behaviour of the waste (in particular with respect to leaching,
- the behaviour of engineered barriers, such as lining and backfilling within the repository, and the interactions with the near-field host rock as well as the transport of substances through these barriers,
- the transport of substances through the geo-environment,
- the transport of substances to the biosphere and exposure to mankind, and
- the evaluation of potential consequences of possible exposure.

The methods and techniques employed in the either scenario or consequence analysis can be divided into the following broad categories :

A) Probabilistic methods :

One example is the linking through a fault tree of individual events to which probabilities are attached in order to determine possible outcomes in a total system. Another example is the representation of model input parameters by a probability distribution in order to produce statistical estimates of output results.

B) Deterministic methods :

Here processes are taken to be sufficiently well understood, so that the basic laws of science and engineering can be quantitatively applied, although data can be uncertain.

C) Sensitivity and uncertainty analytic methods :

The interdependence of parameters and their relative importance in the determination of system behaviour can be deduced by studying the influence of individual parameter variations on the overall results.

These different types of methods complement one another and can be applied in all the main components of the safety analysis. However, application of these methods requires that their limitations are clearly understood. Models of the future development of natural systems that have come into use in recent years all suffer from lacking the possibilities to determine the future rates of many events and processes, such as tectonism (faulting, folding, earthquakes, volcanism) and geomorphology (weathering, erosion, landslides, subsidence), and from the current lack of adequate data needed to allow the model to function from start to finish — for example the data needed to characterize ground water flow systems.

Past geological events such as faulting, seismicity, or climate change probably have not been random, but deterministic explanations for their frequency, place of occurrence, magnitude, and rate of change are difficult to establish. Regardless of whether deterministic or probabilistic models are favoured to explain particular past geological events, a use of the geological record to predict future events seems to be impossible at present.

Of particular concern in assessing the uncertainty of geological prediction is the effect of complex interactions among events and processes whose individual effects may be simple.

Therefore, long-term prediction in earth sciences is unreliable and impossible to perform with high confidence limits, because of the great complexity of possible interactions among processes, both identified and unidentified.

The degree of confidence which a probabilistic safety analysis deserves depends primarily on the quality of the statistical data fed into the analysis. Failure events having significant consequences are rare. Their frequencies can therefore not be predicted as such by statistical techniques. To cause those events, a complex technical system has to fail. Failures of a complex technical system, however, are caused by failures of less complex sub-systems and again by even simpler subsystems. If empirical data on the performance of a sufficiently great number of these components are available, an expectation value for the frequency of their failure can be derived with a fairly high degree of confidence. Combination of those predicted failure frequencies by means of suitable logic, such as a fault tree, leads to expectation values for the failure frequency of the complex system which also have a fair degree of confidence.

This technique of descending from a complex system to very simple and conventional system components, whose performance is well-known, is usually not applicable for geological systems. It is, of course, possible to estimate failure frequencies of those complex systems either based on relatively few events or on plausibility considerations. Those estimates will, however, have a poor degree of confidence and it is questionable if they are of much benefit for a safety analysis in the waste disposal field.

Therefore, it seems advisable to use the deterministic method for this part of the safety analysis, rather than a probabilistic approach. This means that failure scenarios are to be identified by means of the release tree technique and that their consequence in term of toxicity release into circulating ground water is to be calculated.

6. Site-specific, engineering-geological investigation program

Engineering-geological/geotechnical data are required for the siting, design, construction, and safety analysis of a final repository for toxic wastes, which can only be obtained by the execution of a comprehensive site-specific geomechanical exploration and investigation program. The type and scope of such a program is outlined directly by the methods described in Chapter 4 for the safety proof, in particular from the criteria and the influential factors requiring inclusion. The following may be regarded as check lists of that data required from a geomechanical point of view or of investigations which have to be initiated. They cover technical, rock-mechanics, and geological barriers.

6.1. Investigation of technical systems

A) Form of waste, waste package :

- amount, type of conditioning, geometric dimensions, weight,
- chemical constituents, heat content,
- corrosion and leaching data, and
- transportation to site, handling at final location, type of final storage.

Information to be gathered from industry and responsible authorities.

B) Backfill material, e. g. crushed material :

- mineralogical/chemical composition, heat behaviour, long-term chemical behaviour,
- thermo-mechanical properties (compaction, expansion, rheological material data, long-term strength), and
- pore volume, permeability as a function of pressure, time and temperature.

Mineralogical/chemical and geotechnical laboratory investigations should be carried out by suitably equipped special laboratories.

C) Sealing material, e. g. bitumins, elastic-plastic materials :

- mineralogical/chemical composition, heat behaviour, long-term chemical behaviour,
- thermo-mechanical properties (compaction, expansion, rheological material data, long-term strength), and
- pore volume, permeability as a function of pressure, time and temperature.

Mineralogical/chemical and geotechnical laboratory investigations should be carried out by suitably equipped special laboratories.

6.2. Investigation of rock-mechanic systems

A) Host rock in near-field :

- lateral expansion in near-field, density and depth of the storage horizon,
- engineering-geological/petrographical characterisation of the rock and in situ composition, outlining of homogeneous zones, jointing structure, permeability,
- temperature- and time-dependent deformation behaviour (elasticity, creep behaviour, plasticity),
- temperature- and time-dependent failure behaviour (shear strength, tensile strength, creep failure conditions, load-bearing capacity limits), and
- in situ stress state.

Depth seismics, coring, undamaged core recovery, and geophysical borehole measurements (including temperature measurements) are to be initiated; undertake determination of in situ stress state; have engineering-geological expertise prepared; undertake preparation of rock-mechanics expertise by a geomechanical special laboratory.

B) Interaction of host rock and cavities in construction phase :

- geometry of cavities (form and size), lay-out of pillar (form and size),
- excavation method (e. g. wet or dry drilling, cutting), construction conditions, supporting measures, and
- possible failure types (critical states) of cavities and dimensioning criteria.

Present design of final storage by suitable engineering consultants or construction company, request rock-mechanics safety expertise by experienced specialist (in so doing develop rock mechanical and mathematical model of final storage area).

C) Interaction of waste/backfill material/host rock during operation phase :

- geochemical processes (migration),
- backfill method (material, transportation method, compaction measures),
- time-, pressure-, and temperature-dependent compaction and load-bearing effect on backfill material and sealing material, and
- integrity of overall rock-mechanics system, safety criteria, safety stipulations of the authorities.

Investigate current level of know-how with respect to the effect of interaction waste/rock and also for migration, design a detailed rock-mechanics model of overall system and execute optimisation work with respect to storage technology and geometries, determine safety concept, criteria, and official stipulations.

6.3. Exploration of the geological system

A) Host rock in far field :

- general geological, hydrogeological and tectonic relationships (stratification details, petrography, folding, faulting, gas and brine occurrences),
- geological long-term processes (salt dome movement, earthquake stresses, neotectonics), and
- geochemical long-term processes (leaching, dynamothermal metamorphism, absorption properties).

The proposals for the preceding investigations are based on purely engineering-geological and rock-mechanic considerations. They therefore do not claim to be comprehensive.

7. Recommendations

In conclusion, the following recommendations are given. These should serve for a better understanding of the problems and processes involved in the underground disposal of toxic wastes in mines, and for a better assessment of the mutual influence waste, geo-environment and the impact on the environment :

1. collect data and experiences from existing, well-controlled waste disposal facilities (as an example see the report from Sweden, Annex 1),
2. collect information about various national procedures in the management of underground waste disposals (as an example see the report from USA, Annex 2),
3. encourage scientific investigations on the long-term behaviour of natural barriers, including sealing materials like clay layers (as an example see the report from the Federal Republic of Germany, Annex 3),
4. encourage scientific investigation on ground water system behaviour (especially ground water flow patterns, hydraulic characteristics of fissured rock, and quality of ground water), and
5. set up recommendations (guidelines) for waste disposal in mines regarding
   A) safety concept,
   B) site selection criteria,
   C) disposal performance criteria, and
   D) need of earth science data for site characterisation.

The community involved in resolving the safe storage of radioactive waste must strive for "Worldwide public confidence and acceptance". The challenge is to ensure the proper disposal of substances that must be prevented from returning to the biosphere in even minute quantities, during time periods of almost geological time-scale. This means that for national considerations general guidelines should exist at the international level according to an internationally accepted "Code of Practice". The IAEG Commission No. 14 has worked and will continue to work to reach this important goal, through international participation and technical exchange among commission members and the international community concerned with the issue of radioactive waste disposal.