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Dear John:

Attached is a copy of a paper we prepared two years ago concerning "Site Exploration, Design and Construction Principles for Radioactive Waste Repositories." This is the paper Dr. Fairhurst discussed with you at the 25th U. S. Symposium on Rock Mechanics. We believe it may be appropriate to re-emphasize the concerns stated in this paper at this time, in light of the questions concerning "reasonable assurance" which were raised during the panel discussion at the symposium.

I think this paper may be useful to you and help stimulate further thought about issues associated with repository engineering strategies. Dr. Fairhurst and I would be happy to discuss this with you at length at your convenience.

Yours sincerely,

Roger

Roger D. Hart
Project Engineer

Encl.

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SITE EXPLORATION, DESIGN AND CONSTRUCTION PRINCIPLES FOR RADIOACTIVE WASTE REPOSITORIES

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Abstract

This submission is concerned with basic issues arising from the limited amount of site exploration possible in the host rock mass for a radioactive waste repository. It is shown that the design problem is similar in principle to that arising in the layout and design of an underground mine. In both repository engineering and mine engineering, the majority of site characterization data is collected following access to the site for underground activity. This allows direct observation of conditions in the rock mass by their expression in the walls of development openings. Pre-development site data is sparse in both cases. Other similarities between repository and mine engineering include the physical scale of the rock structures to be developed, the repetitive development of similar types of excavations to generate the structure, and the inability to construct a comprehensive conceptual model of the complete rock structure.

It is suggested that repository engineering should invoke the philosophy and methodology of mining engineering. This implies that detailed design of a repository should evolve in response to observed in-situ conditions, and that the general features of the design, such as overall repository shape and disposition, be compatible with the dominant geomechanics characteristics of the rock mass. It also requires that adverse geomechanics characteristics of a rock mass, which could affect the long-term performance of a repository, be stated prior to development of access and that specific engineering responses to potential problems rising from such characteristics be formulated. Such an approach would (1) ensure that observation of any adverse feature in a rock mass, after commencement of development, would not disqualify it as a site for a geomechanically- and generally-acceptable repository and (2) increase public credibility.

1. Introduction

Emplacement of spent fuel elements and other waste products of the nuclear industry in mined subsurface excavations is currently the preferred scheme for terminal or permanent storage of this highly radioactive material. In concept, this scheme involves the development of galleries in rock formations that are at sufficient depth and that have geomechanical and hydrogeological

properties suitable for waste containment. The site properties and operating depth are to be chosen to eliminate the possibility of radionuclide release into the biosphere from waste packages located in the repository galleries.

The subsurface storage of nuclear wastes is complicated by the long periods required for decay of their radioactivity. Decay is accompanied by heat liberation. Therefore, the emplacement of the waste in a rock mass leads to the generation of thermal stresses, with the attendant possibility of induced fracturing in the medium. In the usual case where a subsurface rock mass is saturated with water the heat generation will cause convective flow of groundwater in any natural and induced fissures in the formation.

Credible mechanisms for the migration of radionuclides from a subsurface repository to the biosphere involve their transport by solution in the thermally induced groundwater flow. Groundwater flow is governed by fissure aperture and temperature gradients, and these are related to thermomechanical stresses and rock mass properties. Thus, development of effective containment strategies requires comprehensive understanding of the thermo-hydro-mechanical response of a rock mass to emplaced heat sources. The options presented in the notional performance specifications of a waste repository, given a particular set of site conditions and for an imposed thermal load in the rock medium, include:

(a) transport of radionuclides to the biosphere can occur so slowly that these materials constitute no biological hazard, i.e. only harmless decay products could conceivably appear at the ground surface after an indefinite elapsed time;

(b) the repository and its near-field elements are designed such that migration of groundwater from the repository to the far-field and biosphere is effectively prevented.

Either of these two principles, or a combination of them, may be employed in the formulation of the primary operating mode for a waste containment system. The obvious requirement is that the selected operating mode and repository design be compatible with the hydro-mechanical properties of the repository host rock mass, or that a site be chosen specifically to implement a selected operating mode. In examining any candidate rock formation, the operative containment option should be kept open as long as possible.

2. Current Concepts for Repository Design

The current technical consensus, in the various government agencies and related professional groups, appears to favor a room and pillar layout for a waste repository. A typical conceptual design is shown in Figure 1. It resembles a mining layout and associated access and service facilities for the partial extraction of a flat-lying stratiform orebody. The waste packages are emplaced in suitable receptor holes drilled in the floors of the repository galleries.

Two distinctly different geologic media are currently discussed as host sites for waste repositories. These are:

- evaporite mineral deposits, such as halite (rock salt);
- other sedimentary and igneous crystalline lithologies, such as tuffs, shales, granites and basalts.

It appears that the prime operating mode for a repository in salt would be principle (a) above. Evaporite deposits are taken to be water free, and the ductile and viscoplastic properties of halite are implicitly assumed to produce a near-field containment system that is self-sealing. Any fractures which are induced by excavation of galleries or by the subsequent thermomechanical load are to be healed by deformation and flow of the host medium. Groundwater flow

is, therefore, absent initially and precluded in the long term. Various engineered barriers, discussed below, may augment this waste isolation scheme.

The mode of operation of repositories in media other than evaporites is presumed to be based on principle (b) above. In this case, it is assumed that groundwater infusion will occur into the repository near-field. Waste containment then relies on:

- the waste package -- the container for the radioactive materials;
- various engineered barriers, such as the packing material around the waste package in the receptor hole, and backfilling material emplaced in the repository gallery;
- slow rate of release (e.g. by leaching), and slow transport of any released material by the induced groundwater flow.

Features common to both types of repositories, in the current thinking, are the extensive areal extent of the repository horizon and the limited scale of any engineered barrier. In the latter case, the gallery backfill will represent the greatest dimensional extent of any artificial element designed to impede groundwater flow. There is thus no repository-scale engineered barrier to groundwater flow. This function is assumed to be fulfilled by the rock mass in its natural and post waste emplacement state enclosing the repository.

Reliance on the natural state of a rock mass to provide a barrier to groundwater flow from a repository poses significant problems for repository siting and design. In particular, it assumes that a rock mass of considerable size can be explored in sufficient detail to identify any and every structural geological feature which could function as a hydraulic conduit to the biosphere. This presents an obvious and acute dilemma in site investigation for repository design. A comprehensive core drilling program for adequate definition of site

conditions destroys the hydraulic integrity of the candidate rock mass. *In the absence of penetrative, non-destructive methods for detailed determination of rock structural conditions in the subsurface, a repository must be sited, if not designed in detail, without adequate engineering characterization of the host medium.*

Various procedures may be proposed to provide estimates of conditions at a candidate site for a repository. For example, exploration holes may be drilled around the boundary of a domain enclosing a candidate site. Geological conditions at the site might then be inferred from the remote field data, by interpolation, using a suitable methodology such as regionalized variable theory. Some confirmation of the inferred site data could then be obtained by exploration holes drilled down the proposed axes of service and ventilation shafts. However, the data generated in this way would be sparse and provide no basis for detailed design of the repository layout or the desing of individual galleries. The major part of the site exploration would, in fact, occur as service openings were developed at the selected repository horizon.

3. Civil, Mining and Repository Engineering Design

In assessing the scale and nature of the geotechnical problem presented by repository design requirements, it is instructive to consider issues which arise in the design of mining and civil subsurface structures in rock. The intention is to identify any points of similarity between repository design and the other main areas of rock engineering activity. Mining engineering is assumed to include both coal and metalliferous mining. The arguments advanced here take account of some of the conclusions, stated above, related to restrictions on site investigation for repository design.

Size of the Structure

In modern mining practice, the size of the rock structure generated by extraction activity frequently exceeds kilometers in various coordinate directions. Stratiform orebodies, of either metallic or non-metallic minerals, almost without exception result in mined openings distributed over areas of many square kilometers. For massive metalliferous orebodies, mining operations may extend over a plan area of many square kilometers, and also through a vertical height of many hundreds of meters. In these cases, geometrically complicated rock structures, related to the orebody shape and the needs of the mining method, are generated by the extraction activity.

Civil engineering activity never generates underground rock structures which are comparably large and extensive in two or three dimensions. A tunnel is the only extensive civil excavation, and these excavations are, of course, basic elements of a mine structure.

It has already been noted that current notions of repository design involve a two-dimensionally extensive layout of repository galleries. Alternative designs for repositories might reasonably involve three-dimensional configurations of waste package emplacement galleries. *In either case, a repository structure will be of a scale and geometric configuration resembling those created by mining activity.*

Site Characterization

Because many civil engineering ventures are concentrated in a relatively small domain, detailed engineering data are usually obtained in the course of determining the technical and economic feasibility of a project. These data may be obtained by a variety of means, including mapping surface exposures of rock adjacent to the site, core drilling and hole logging, mapping and testing in exploration shafts and adits, and test enlargements of instrumented trial

excavations. The execution of such a site investigation program can be expected to produce a coherent description of the dominant engineering features on the subject rock mass, and their mechanical properties.

Comprehensive pre-mining characterization of the mechanical properties and state of an orebody and its enclosing rock is rarely practical, with the current methods of site investigation. In general, attempts are made to recover site data from mineral exploration holes and cores, but these are rarely of a level of quality suitable for engineering description of the rock mass. Accumulation of an accurate description of virtually all geological and engineering data is deferred until significant development occurs in and around the orebody. This situation is completely analagous to that presented in repository engineering, with the exception that in the latter case, even low quality exploratory drilling is precluded in the candidate domain.

It is clear that a common factor in repository engineering and mining engineering is that *limited site characterization data is available prior to excavation activity* and that this is in distinct contrast with established civil engineering practice.

Repetition of Unit Design

Most ore extraction activity proceeds by the repetition in space of a unit mining entity. For example, cut-and-fill stoping in a metalliferous orebody frequently involves a series of lifts, or segments of vertical advance, at successively increasing depths below ground surface. In massive, fractured orebodies, block caving proceeds by undercutting and drawing ore from a series of geometrically similar blocks or panels. In the simplest case of room-and-pillar mining in a flat-lying, stratiform orebody, excavations are mined to create the support elements which are distributed fairly regularly throughout the orebody. In each of these cases, the essence of the mining procedure is

repetitive generation of the mining unit, taking due account of local variations in geomechanical conditions.

The current conceptual design for a waste repository and alternatives which may be readily conceived, involve a similar spatial repetition of geometrically similar storage galleries throughout the host rock medium. There is thus a direct analogy between the designs and physical realizations of a mining layout and a subsurface waste containment system. In contrast, a typical civil engineering exercise involves the design and construction of a limited number of geomechanically and conformationally unique elements, such as a machine hall, a valve gallery, a transformer hall, and so on.

The preceding considerations suggest that the design and development of a waste repository involves principles and constraints which are cognitively equivalent to those posed in underground mine design and distinctly different from those involved in underground civil engineering. The differences which exist between waste isolation and mining are related to the divergent performances required of the host rock masses. In underground mining (using supported methods of extraction) the geomechanical objective is to predict and control rock displacements in the developing mine structure and near-field rock. The repository design problem is to control the rock mass permeability and to assure the long-term hydromechanical integrity of the repository and its near-field rock. The conclusion is that, taking due account of these differences in performance requirements, the principles and methodology of underground mine engineering should be adopted and applied in repository design and development.

4. The Philosophy of Underground Mine Engineering

It has been observed that the main characteristic of mine excavation design is uncertainty, prior to mining, about geomechanical conditions in

and around the orebody. This led historically to a high degree of observational empiricism in mine design. This has been modified significantly in recent times, with more general recognition of the role of geomechanics principles and application of a rational observational method in designing elements of the mine structure. In particular, *the current judicious mine design methodology recognizes implicitly the inherent uncertainties of the mine geomechanical environment. In its implementation, (i) it invokes evolutionary design concepts to meet observed mine geomechanical conditions; (ii) it provides intrinsic flexibility of mining action in a variable rock mass.* Such an approach implies that specific mining problems can be anticipated and effective remedial measures be designed to assure that the basic mining objective is attained. It is instructive to consider some typical geomechanical problems associated with different mining methods and the measures which are implemented when they are encountered.

Cut-and-Fill Mining

This method involves up-dip advance of mining in an orebody, with operating personnel working directly beneath the rock surface generated repetitively by extraction activity. The main mining problem is prevention of episodic falls from the stope crown. In general, the shape of the crown is mined to conform with the dominant structural features, as suggested by Figure 2(a). The preferred method of operation is by uphole benching, as shown in Fibure 2(b), because this is a mechanized and highly productive procedure. If this method of working leads to unacceptable conditions in the stope crown, the method can be changed readily to flatback stripping, as shown in Figure 2(c). This mining technique allows better observation of rock conditions in the stope crown during mining and more accurate blasthole drilling to produce a more uniform and regular crown surface for the stope. Thus, the natural mining response

to deteriorating peripheral rock performance is to improve the quality of excavation practice and to reduce local rock disturbance.

In spite of the ground control achieved by flatback mining, adverse rock structural conditions can arise which will jeopardize the safe operation of the stope. For example, the steeply dipping fault shown in Figure 2(d) will release a large wedge or rock from the stope crown when it is transgressed by mining activity. The usual mining response to this type of problem is to install reinforcing tendons in the rock mass above the advancing stope crown, as shown in Figure 2(e). These may consist of untensioned prestressing tendons up to 20 m. long, grouted into boreholes drilled parallel to the direction of stope advance. The up-dip advance of mining then occurs into a pre-reinforced mass. Correct design of the reinforcing system assures the stable performance of the stope crown in the presence of the adversely oriented structural features.

Large Open-Stoping Operations

Open stoping is a mining method which employs pillars, or unmined remnants in the orebody, to control displacements in the orebody peripheral rock. The success of the method requires that sufficient pillar support be provided to assure stable performance of the orebody and country rock. However, provision of excessive pillar support reduces the total recovery from the orebody. Therefore, the tendency in metalliferous mining practice is to limit the dimensions of pillars and to attempt to recover ore contained in pillars in the final stages of mining.

The observed inadequacies of mine site exploration and basic deficiencies in estimating the in-situ strength of rock both lead to uncertainties in the design of pillar support schemes and extraction strategies. Thus, established mining practice recognizes that a stoping or pillar recovery program

would be compromised by the large-scale, adverse performance of rock in and around faulted and fractured pillars. Successful mine operation under these conditions is based on provision of extensive ground control measures, particularly a capacity for selective placement of sizable quantities of backfill. The stoping and pillar recovery operation can then evolve in response to the observed state of the rock mass exposed by mining and the observed performance of the rock mass under the mining-induced loading.

A useful example of the evolution of a mining strategy in a large base metal mine is provided by the extraction of lead and copper orebodies at the Mount Isa Mine, Australia (Alexander and Fabjanczyk, 1981; Goddard, 1981). In both cases, high and efficient recovery of reserves was achieved by provision of backfill manufacture and placement systems, creating a capacity to respond to observed rock mass conditions and performance during mining.

Mining in Cavernous Rock

Some mining environments are characterized by the occurrence of water-filled caverns, or vugs, distributed irregularly through the rock mass. Penetration of these entities by drill holes or mine development can lead to rapid release of water and local or extensive flooding of the mine. Although the existence of cavernous ground may be recognized by exploratory drilling, neither the location of caverns nor the magnitude of the potential problem can be predicted.

The mining engineering reaction to this type of problem is to formulate various local groundwater exploration and control measures. For example, slightly inclined, core-drilled probe holes may be drilled from recesses cut into the sides of a development excavation. Local "water cover" holes may be drilled ahead of each development end. Response to groundwater inflow may take the form of immediate cavern drainage, closure of flood barriers, a grouting

campaign, or extensive drift sealing, depending on the nature of the perceived threat to the mine.

An interesting example of the way in which a designed response is implemented following a groundwater inflow is given by the West Dreifontein inrush of 1970 (Tress, 1971). In this case, mining-induced fractures provided hydraulic connections to undrained, cavernous ground above the active mining zone. The potentially catastrophic inflow was controlled by pumping in the endangered mine and in an adjacent mine, and emplacement of large, grouted concrete structures in openings adjacent to the inflow. The existence at the time of the inrush of both a sufficient installed pump capacity at the mine and a design principle for the water retaining structure, were the result of the recognition in advance of a real, but undefined potential for significant water inflow from the overlying strata and development of procedures to prepare for that contingency. It is perhaps worth noting that considerable attention to such "emergency scenarios" is given for other engineering situations in which the consequences of unplanned events can be very adverse (e.g., the manned space exploration program).

5. Appropriate Principles for Repository Design and Construction

It has been shown previously that the design and construction of a radioactive waste repository bear close conceptual resemblance to the problems posed in mine design and development. This conclusion was based on comparison of the sizes of the respective rock structures, similar problems in site characterization, and similarity in the geometric replication of elements of the structure.

A significant consequence of the similarity between mine and repository engineering is the site specificity of any underground excavation layouts and

designs. Mining layouts are generated to match the dominant structural and geomechanical properties of the orebody rock and host rock mass for mining. A repository design should also be developed to be compatible with the dominant structural, geomechanical and geohydrological properties of the host medium. Thus, the prevalent conceptualization of a nuclear waste repository as a simple layout of rooms and pillars independent of the local geological environment is not supportable in conventional geomechanics practice. As an example, some simple geostatistical arguments demonstrate that an extensive planar repository in a fractured rock mass presents a much greater probability of intersecting a hydraulic connection with the surface, compared to a quasi-spherical repository of the same storage capacity. The point here is that the most effective repository design for any candidate host medium requires proper consideration of all geomechanical and associated properties of the rock mass.

The second consequence of the common basis of mining and repository engineering is the need to identify all conceivable and credible adverse site characteristics prior to repository development and to formulate effective engineering responses to these problems. Failure to approach repository design and development in this way can have only the most serious results in loss of public credibility of the technical design and long-term performance of a repository. In particular, it is not inconceivable that public awareness of the existence of some types of geological features in a repository host rock mass could immediately invalidate its use as a waste isolation medium. *The way to deal with this problem is to invoke the mine design and development philosophy comprehensively, i.e., identify possible geotechnical deficiencies in the host rock mass and establish, prior to repository development, the measures which will be undertaken to remedy each deficiency.*

6. Conclusions - An Effective Engineering Response

The three brief mining case studies provided above demonstrated the principle that in a large rock structure such as a mine, adverse rock mass conditions may be exposed during its development. It was shown that uncertainties about the geomechanical condition of a rock mass can be accommodated in practice by recognition of the potential for adverse conditions, and the formulation of measures and procedures to deal with them in advance of excavation. It is now suggested that similar or greater uncertainties will exist about site conditions in the host rock medium for a nuclear waste repository, and that a design and construction philosophy, similar to that discussed, should by applied in this case.

A previously unobserved, extensive and penetrative fracture system is one example of an adverse site characteristic requiring an effective engineering response. If the fracture system is water-bearing, the problem is compounded. This situation not only presents an adverse mining condition but also may provide pathways for excessive groundwater movement rates away from the heat-generating waste after repository de-commissioning.

One possible response measure to this problem is to construct an impermeable engineered barrier partially or completely surrounding the repository. The barrier would act to provide both a destressed and dry region for repository construction and a confinement medium of known physical properties to prevent radionuclide transport away from the repository.

Other adverse conditions may be anticipated. A few that come to mind are water-bearing cavities, rocks and minerals subject to weathering, particularly upon heating, and steeply dipping faulted zones. In each case, measures extrapolated from mine design practice can be applied to establish a remedial plan of action which then can become an integral part of the repository construction plan.

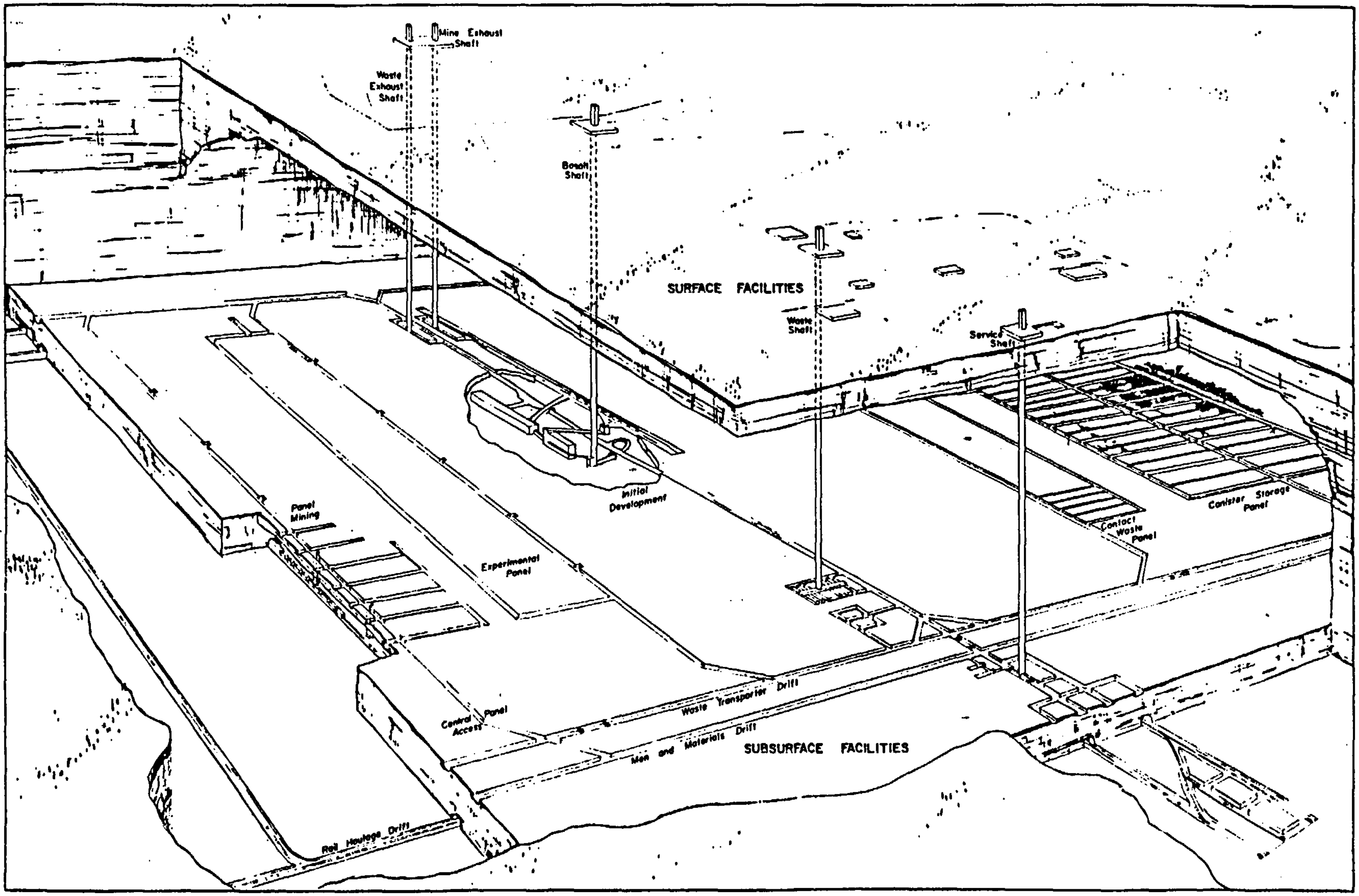

Figure 1. Preconceptual Layout of a Nuclear Waste Repository (from Rockwell BWIP Annual Report, 1979)

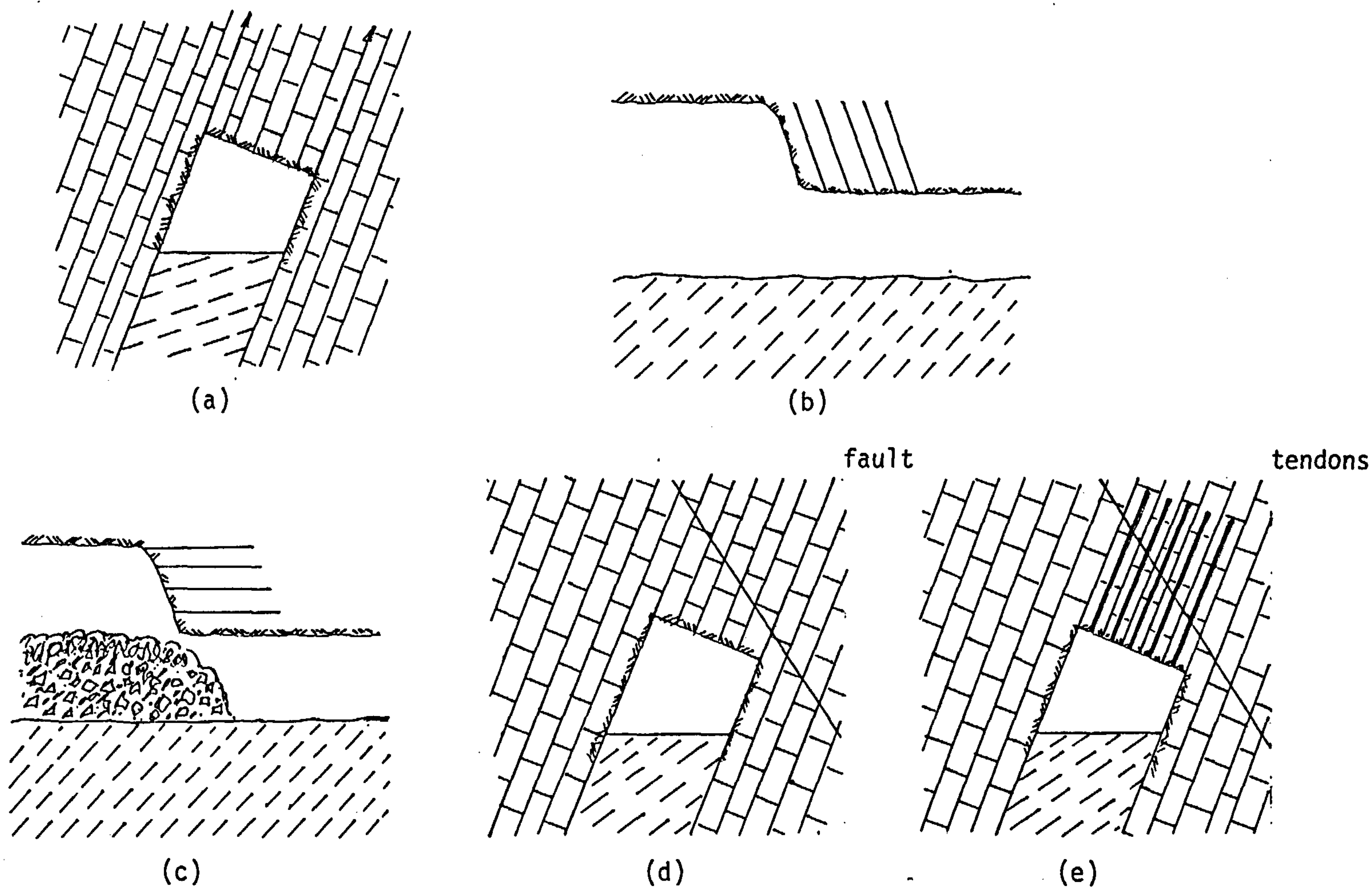

Figure 2: Geomechanical Responses in Cut-and-Fill Mining, Taking Account of In-Situ Conditions Including: (a) Dominant Structural Features; (b), (c) Deterioration of Conditions in Stope Crown; (d), (e) Tendon Installation for General Reinforcement of Stope Crown.

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