PREVENTING HUMAN INTRUSION

INTO A HIGH-LEVEL NUCLEAR WASTE REPOSITORY

A Literature Review with Implications for Standard Setting

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Abstract

This report is a review of studies on human intrusion into a high-level nuclear waste repository and of possible countermeasures. Human intrusion activities include conventional exploration, development and production of minerals and hydrocarbons, non-conventional mining, archeological excavations, and many others. Countermeasures against such activities include institutional controls, markers and barriers. The combination of human activities and counter-measures create scenarios of human intrusion, and in some cases their relative likelihood and consequences.

The human intrusion part of the review covers studies of the potential for natural resources at Yucca Mountain, studies of conventional human intrusion scenarios (e.g., drilling) and studies examining future societies and unconventional intrusion scenarios (e.g., tunneling). The countermeasures part of this review covers studies of markers, general information management, active controls amd and barriers.

Following the literature review, the report provides some reflection on implications of these studies for performance assessment and standard setting for the Yucca Mountain repository. Among the main conclusions are the following:

1. Human intrusion is judged by many experts to be the probably the most important pathway to health effects from disruptions to the repository.

2. The highest concern about human intrusion is with societies that have forgotten about the repository, but have developed a technology comparable to ours or higher.

3. The consequences of many types of many conventional types of human intrusion (drilling and minor excavation) are negligible, as long as credit is taken for natural barriers.

4. The consequences of human intrusion can be significant for unconventional scenarios (e.g., deep strip mining), or for conventional scenarios if no credit is taken for natural barriers (e.g., drilling into a pool of pressurized radioactive brine).

5. Probabilistic risk and performance assessment for human intrusions faces two problems: The impossibility of creating an exhaustive list of intrusion scenarios and the lack of substantive knowledge about future societies and modes of intrusion.

6. Prudent design standards, coupled with prescribing a process for periodically revisiting the intrusion issue, seem for now the best strategy for addressing the risk of human intrusion.

1. Introduction

This report is a summary of studies on human intrusion into a high-level nuclear waste repository and of possible countermeasures. In addition, this paper will provide some reflection on implications of these studies for performance assessment and standard setting for the Yucca Mountain repository.

Four activities were conducted for this review:

1. Obtain references from selected nuclear waste disposal organizations in the US and from the members countries of the Nuclear Energy Agency (NEA) at the Organization for Economic Cooperation and Development (OECD);
2. Collect references, identify primary references and conduct a detailed review of them;
3. Review secondary references as needed;
4. Identify the main issues raised by this review and draft a report, focusing on Yucca Mountain and the problem of setting standards.

The primary references identified in step 2 were:

1. Nuclear Energy Agency. (1993). Assessment of Future Human Actions at Radioactive Disposal Sites. Nuclear Energy Agency, OECD, Paris, 1993;
2. Baker, V. R. et. al. (1992). The Development of Markers to Deter Inadvertent Human Intrusion into the Waste Isolation Pilot Plant (WIPP). B-Team Report to Sandia National Laboratories. Albuquerque, NM: Sandia National Laboratories.
3. Ast D. G. et al. (1992). Marking the Waste Isolation Pilot Plant for 10,000 years. A-Team Report to Sandia National Laboratories. Albuquerque, NM: Sandia National Laboratories.
4. Mattson, S.R. and Matthusen, A.C. (1992). Draft Literature Review for the Human Interference Guideline Section of the Early Site Suitability Evaluation (ESSE). Las Vegas, Nevada: Systems Application International Corporation.
5. Hora, S. C. et al. (1991). Expert Judgment on Inadvertent Human Intrusion into the Waste Isolation Pilot Plant. (SAND90-3063). Albuquerque, New Mexico: Sandia National Laboratories.
6. Nuclear Energy Agency. (1989). Risks Associated with Human Intrusion at Radioactive Disposal Sites: Proceedings of an NEA Workshop. Paris, France: OECD.

7. Human Interference Task Force. (1984). Reducing the Likelihood of Future Human Activities that Could Affect Geologic High-Level Waste Repositories. (ONWI-537). Technical Report prepared for the Office of Nuclear Waste Isolation. Columbus, OH: Battelle Memorial Institute.

These reports include some 600 secondary references of varying degree of relevance for this review. Only those secondary references that appeared to contain materials directly relevant to human intrusion and countermeasures at Yucca Mountain were reviewed in detail, the remaining ones were summarized using the primary sources. The bibliography only lists references that were reviewed in detail.

Several insights emerged from this review:

1. Human intrusion is judged by many experts to be the probably the most important pathway to health effects from disruptions to the repository.

2. The highest concern about human intrusion is with societies that have forgotten about the repository, but have developed a technology comparable to ours or higher.

3. The consequences of many types of many conventional types of human intrusion (drilling and minor excavation) are negligible, as long as credit is taken for natural barriers.

4. The consequences of human intrusion can be significant for unconventional scenarios (e.g., deep strip mining), or for conventional scenarios if no credit is taken for natural barriers (e.g., drilling into a pool of pressurized radioactive brine).

5. Probabilistic risk and performance assessment for human intrusions faces two problems: The impossibility of creating an exhaustive list of intrusion scenarios and the lack of substantive knowledge about future societies and modes of intrusion.

6. Prudent design standards, coupled with prescribing a process for periodically revisiting the intrusion issue, seem for now the best strategy for addressing the risk of human intrusion.

The next section 2 will characterize the problem of human intrusion at Yucca Mountain and other possible repositories and it provides some definitions. Section 3 will review the literature on human intrusion scenarios. Section 4 will summarize the existing studies on countermeasures. Section 5 will draw some conclusions regarding performance assessment and standard setting.

2. Yucca Mountain and the Human Intrusion Problem

The proposed repository site is located at a depth of 200 m under a 2.5 square mile site at Yucca Mountain in Nevada. The rock at this site is consist of tuff and older volcanic materials. Figure 1 from Mattson et al. (1992) shows a cross section through the Yucca Mountain site and the proposed underground location of the repository. The reference scenario for this review is an undisrupted high-level waste repository at Yucca Mountain with about 40 000 metric tons of high level waste coming mainly from commercial nuclear reactors.

This report is concerned with a disruptions of this reference scenario due to human activities. Such activities include conventional exploration, development and production of minerals and hydrocarbons, non-conventional mining, archeological excavations, and many others. This report is also concerned with the identification and assessment of possible countermeasures against such activities, including institutional controls, markers and barriers. The combination of human activities and counter-measures create scenarios of human intrusion, and in some cases their relative likelihood and consequences. Most reports on human intrusion identify the possible pathways for intrusion. Only a few reports assess the consequences of intrusion and even fewer attempt to estimate probabilities of alternative intrusion scenarios. As a result, this report will be primarily concerned with modes of intrusion and countermeasures, and only to a lesser degree with probabilities and consequence estimates.

The Nuclear Energy Agency (1993) draft report defines the area of concern as those human activities that "have the potential to disrupt or impair significantly the ability of the natural or engineered barriers to contain radioactive waste" (p. 9). Furthermore, it confines its attention to those activities "in which either the repository or its barrier system is accidentally penetrated or damaged, because its location is unknown, its purpose forgotten, or the consequences unknown." (p. 16). The time scale of concern was defined in the NEA report as 10,000 years after closure of the repository.

Two distinctions among types of human intrusion are typically made: between inadvertent and intentional intrusion and between direct and indirect intrusion. As in the NEA definition, intrusion is meant to be inadvertent, if the intruder does not know about the repository or its dangers. An example is conventional drilling after the existence of the repository has been forgotten and/or the information and markers indicating its existence are not understood or misinterpreted. In contrast, intrusion is meant to be intentional, if all relevant facts about the repository are known, but an attempt is nevertheless made to obtain access to it. Examples are archeological digs or excavation for the purposes of re-using the waste.

Direct intrusion occurs within the boundaries of the repository, for example, through drilling or excavation in its immediate local environment. Indirect intrusion refers to activities that occur far off-site the repository, yet have impact at the repository . Examples are off-site detonations or large scale water development.

Most studies restrict their attention to inadvertent intrusion, arguing that the intruder is to blame for the risks and consequences of intentional intrusion. However, the distinction between inadvertent and intentional intrusion is easily blurred. For, example, the intrusion may be intentional for the purpose of storing additional radioactive wastes. But if by accident a pocket of highly pressured radioactive brine is hit, radioactivity may be released and unintentional health consequences may occur. Is this a case of intentional or inadvertent intrusion?

In a broader sense, it is useful to use a legal analog for human intrusion. Conviction of an unlawful act usually requires establishment of motivation, opportunity and capability. Similarly, human intrusion requires motivation (e.g., archeological curiosity), opportunity (e.g., access to the site) and capability (e.g., technology for drilling or excavating at depths of 200 m). Countermeasures can be designed to reduce motivation, to create obstacles to intrusion opportunities and to disable an intruder or intruding device.

Tables 1 and 2 provide a summary of the main modes of intrusion and the main types of countermeasures listed in the literature. Almost all the reviewed studies caution that their lists of intrusion modes and countermeasures is not exhaustive. Past emphasis was clearly on conventional modes of intrusion and on long term markers as the main countermeasures. It is clear that much more creativity is needed both to identify modes of human intrusion and to identify countermeasures. In particular, it is important to consider human intrusion modes beyond the capabilities of past and present societies and to expand the study to intentional modes of intrusion with unintentional consequences. It may also be useful to continually revisit the list of countermeasures and to examine their effectiveness in countering motivation, opportunity and capability for intrusion. Therefore, the two lists in Tables 1 and 2 should be thought of as a beginning, inviting creative additions, rather than a final product.

Insert Tables 1 and 2 about here

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3. Studies of human intrusion

Past studies of human intrusion into nuclear waste repositories fall into four categories:

- o Studies of mineral and other natural resources;
- o Studies of point scenarios of conventional modes of human intrusion;
- o Studies of multiple scenarios including consideration of alternative societal developments.

Studies of natural resources are usually very specific to a given site. They simply examine all the resources at the site, including abundant and rare ones, desirable and undesirable ones. The relevance of these studies is primarily for an assessment of the motivation for conventional types of intrusion. A series of studies investigated quite specific scenarios for human intrusion, e.g., drilling a water well into a fractured zone (Reid et al., 1989) or the impacts of large scale solution mining (U.S. Department of Energy, 1981). These studies typically focus on the consequences of intrusion, and very few have examined the likelihood of intrusion by itself. The few that do, typically examined historical drilling activities extrapolated patterns of drilling on or near the site extrapolated over the next generations. Two major studies examined multiple scenarios for human intrusion and also considered alternative social developments: the Human Intrusion Task Force study (1984) and the WIPP study of intrusion and markers (Ast et al., 1992; Baker et al., 1992; Hora et al., 1991).

Studies of the potential for natural resources

A literature review conducted by Science Application International Corporation (SAIC) (Mattson and Matthusen, 1992) lists over 400 references of studies of mineral and other resources related to the Yucca Mountain repository. Clearly, it is beyond the scope of this document to review these studies. Instead, we will briefly review three documents: Brady (1989) provides an in-depth review of mineral and energy resources in the Death Valley region. Two recent articles draw very different conclusions from this and other studies of natural resources in the vicinity of Yucca Mountain. Johnson and Hummel (1991) concludes that there is a high natural resource potential at Yucca Mountain. The second by Mattson et al. (1992), concludes that this is not the case.

Brady (1989), using primarily data on existing mineral exploration activities, identified the resources listed in Table 3 for the Death Valley region. For metal-mineral resources, his data base were 113 metal-mining districts, which produced as many as 25 commodities. Gold and silver were the most valuable of these resources, but there currently is only a very small amount of production left. There also are several non-metallic industrial resources and rocks as listed in Table 3. These resources include some that require drilling at some depths, including the extraction of lithium from brines at depths of around 300 m. In addition to these non-mineral resources, Brady describes some geothermal and hydrocarbon resources. There are two known geothermal resources in the Death Valley region, one in Inyo County, California, east of Yucca Mountain, another one in Esmerald County, Nevada, north-east of Yucca Mountain. According to Brady, there are no know gas or oil resources in the region, and only minor coal finds.

Mattson and Matthusen (1992) expanded Brady's review primarily by adding an analysis of historical and archeological information. These studies report primarily activities concerning gold, silver and copper mining as well as the location of springs and wells. By and large, they do not indicate large scale mining activities. The review by Mattson and Matthusen (1992) also includes a very brief summary of studies providing indirect evidence of minerals in the Yucca Mountain area. These come mainly from analyses of rock formations and fractures and from geo-physical and geo-chemical analyses. While there are numerous studies of this kind, they are at best suggestive of the existence of valuable resources in the area.

It is interesting to note that based on the materials discussed above, two papers can come to two quite opposite conclusions. The paper by Johnson and Hummel (1991) contains a much larger list of potential minerals and other natural resources than the known resources listed in Brady. Most of the additions come from the authors' interpretation of either known finds in other regions of California and Nevada or from extrapolating geophysical data. They conclude that "all this information suggests that the potential for valuable mineral resources in the immediate area surrounding Yucca Mountain must be recognized, along with the potential for resulting human interference and intrusion at the site" (p. 16). The authors also suggest that the potential for oil and gas resources may be larger than the existing record may indicate. Mattson et al. (1992), in a response to this paper, come to the opposite conclusion, stating that "The Yucca Mountain site is currently considered to have a low potential for precious and base metals..." (p. 19). These authors also reject the claim of a higher oil and gas potential as based purely on theory. (It may be worth noting in parenthesis that the first study was published by scientists associated with the Nevada Nuclear Waste Project Office, the second by scientists associated with the Department of Energy).

Leaving this controversy aside for a moment, there is no question that valuable mineral, geothermal and hydrocarbon resources existed and some still exist in the area. To assess human intrusion for the next 10,000 or more years, the critical questions are:

- o What are the resources?
- o How much is available of a given resource?
- o How valuable is the resource today and in the future?
- o How difficult and expensive is it to extract this resource today and in the future?

Answers to these questions are needed to address the underlying question of motivation, namely: "How cost-effective is the extraction of this resource now and in the future?"

It would be desirable to expand the existing literature on natural resources, not by reviewing more detailed accounts of past and existing studies, but by generating a broad list of potential resources at Yucca Mountain including qualitative answers to the questions listed above.

Point scenarios of conventional human intrusion activities

Resource assessments can at best address the issue of motivation for intrusion. To obtain a sense of the possible impacts of human intrusions, one must study specific scenarios. Following the definition of the Nuclear Energy Agency's Working Group on the Identification and Selection of Scenarios for Performance Assessment of Radioactive Waste Disposal (1992), a scenario is "..one possible set of events and processes and provides a broad brush description of their characteristics and sequencing" (p. 11). A human intrusion scenario is often fleshed out as a complete, internally consistent "story" of unfolding events, sometimes with detailed embellishments that provides a sense of realism. Because such scenarios tend to be very specific, they have a very small or zero likelihood of occurrence. In this paper they will be referred to as "point" scenarios.

While point scenarios have a likelihood of near zero, they can nevertheless be helpful to examine the range of consequences of human intrusion. They often take the role of worst case analyses. They begin with a fairly specific intrusion activity (e.g., drilling a water well and piercing a casks) and from then on conduct a performance assessment with these new conditions. The intrusion activity is almost always conventional, i.e. it mimics activities that could be done by today's society with today's technology.

Insert Tables 3 and 4 about here

Table 4, adapted from the Nuclear Energy Agency's review (1993) lists some of the studies of point scenarios conducted in several countries. The studies listed in this table are briefly summarized in the appendix to the NEA studies and this summary is therefore not repeated here. Instead, a few observations about each class of studies is made.

The most common intrusion scenario is conventional drilling, whether to find water, other resources or for undefined reasons. A typical assumption is that a hole of specified diameter is drilled into the ground above the repository and that the drilling activity penetrates the repository and possibly pierces a waste canister, releasing radionuclides through the drilling path into the accessible environment. The performance assessment is conducted from here on to include ground-water, air and surface water pathways and exposure through both direct contact and through the food chain. Risks are estimated, coupled with sensitivity analyses.

A good example of this type of assessment is found in Anderson et al. (1989), who analyze the performance of the Waste Isolation Pilot Plant (WIPP) under a drilling intrusion scenario. In this analysis, human intrusion through exploratory drilling into the repository area was assumed to hit a reservoir of pressurized brine. Chemical processes are assumed to have formed brine in the cavern housing the nuclear waste canisters and it was assumed to contain highly radioactive materials that escaped from the corroding canisters. In this scenario, normal blow out preventers would stop the brine flow from escaping directly into the accessible environment, but radioactive drilling muds and cuttings would be brought to the surface. The main exposure is to the workers who are in contact with these waste products. A reference worker is exposed to eight times the background exposure rate, but assuming that the problem is recognized quickly, the exposure is minor. Off-site exposure under these conditions is very small.

While this study is based on many assumption and a very specific scenario, it concludes that, relative to other forms of releases, "Human intrusion into the WIPP repository after closure has been shown by these analyses and calculations of consequences to be important, perhaps the most important factor in long-term repository performance" (p.82-83). Other studies described in the Nuclear Energy Workshop Proceedings (Nuclear Energy Agency, 1989) have also concluded that the overall contribution of this pathway to risk is low or negligible.

A possible exception is Reid and Chan (1989) who analyzed the contribution of an operating water well that intrudes the fracture zone of a repository, but not the repository area itself. Using models to predict the radionuclide content of water entering this well and assumptions about water consumption and use, the authors conclude that radionuclide (^{129}I) intake from the well for a family or a small group of families can increase background radionuclide intake by a factor of 100 over the base case in which water is used from lake water. The authors make no statements about the incremental health risk, but note that "human intrusion in the form of a domestic well can have a strong effect on the calculated dose to man" (p. 221).

An example of studies concerned with human intrusion by underground mining and excavation is presented in Hirsekorn (1989). In this case the reference repository is placed in an underground salt dome. The mechanism for human intrusion is underground solution mining, either for the purposes of producing salt or for creating a storage cavern. Specifically, the scenario assumed that in 1000 years after closure a 25m x 500 m storage cavern is created by solution mining and that the repository is breached by this activity. Waste canisters will fall into the mined cavern and collect in the brine at its bottom. The storage cavern is filled with the stored materials and the bore hole into the cavern is sealed. From hereon Hirsekorn uses a regular performance assessment model to calculate radionuclide migration and releases using the breached conditions of the storage cavern. The author concludes that the releases to the accessible environment will be slow and negligible in content.

Other studies of underground excavation and solution mining come to similar conclusions. The most cautious one of these is Prij and Glasbergen (1989), who analyzed several scenarios, some of which could lead to direct contact of mining workers with wastes. They conclude that ""extremely high doses could be received by anyone coming in direct contact with high activity waste" but they also note that "if remnants of protection exist around the waste or some degree of dilution occurs before exposure, doses will be low to extremely low" (p. 196).

These point scenarios were primarily concerned with the consequences of a very specific human intrusion activity and they made very restrictive assumptions about the fate of the radionuclides after the intrusion. It is clear that the scenario assumptions practically determine the consequences, as indicated, for example by the difference in results and interpretations between Hiresekorn on one hand and Prij and Glasbergen on the other. It is also clear that as the assumptions about the mode of intrusion and the migration of radionuclides after intrusion become more specific, the probability of the scenarios must decrease. Yet, only a few of the studies reviewed here explicitly addressed the probability of the human intrusion scenario. Those who do will be discussed in the next section.

Multiple scenarios and future human societies

The most ambitious attempts at analyzing human intrusion activities have extended the point scenario studies to multiple scenarios, often involving considerations of alternative human developments. In addition, some of these studies attempted to assess probabilities of societal developments and intrusion modes.

Several of drilling scenarios considered the probability of drilling in the assumed repository area (e.g., Merkhofer and Keeney, 1987; Rickertson and Alexander, 1989; Chapman and Jovett, 1989). The most common method for estimating drilling probabilities is to use historical drilling frequencies in the area of concern, use this data to estimate the parameters of a distribution of drilling frequencies (e.g., a Poisson distribution), and to use this theoretical distribution to estimate the drilling frequency at the repository. The resulting numbers are typically very low. For example, Merkhofer and

Keeney (1987) give estimates of probabilities of about 10^{-3} for ten thousand years for some sites, but judge these probabilities to be less than 10^{-4} for ten thousand years at Yucca Mountain.

Some of the studies cited in the point scenario section investigated multiple scenarios (e.g., Prij and Glasbergen, 1989; Hirsekorn, 1989). However, they basically treated each of the scenarios as a separate entity. In contrast, the Human Interference Task Force study and the WIPP study (Hora et al., 1991) consider multiple scenarios and both saw these scenarios in the context of evolving human societies over several thousands years.

The Human Interference Task Force (1984; see also Gills, 1985) consisted of six DOE contractors' personnel and seven scientific consultants. While the contractors' specialties were primarily in the engineering aspects of the waste management problem, the consultants' experience was mixed, including specialists in materials science, psychology, anthropology, archaeology, climatology, linguistics, and public policy. This Task Force took a very broad view of the human intrusions problem, emphasizing communication as the main mechanism to prevent intrusion. Much of the Task Force's work on communicating the dangers of the repository is described in the section on countermeasures. Here we will briefly discuss some ideas the Task Force raised regarding future societies and alternative intrusion scenarios.

The Task Force's effort was focused primarily on future societies that should have the technology to intrude a repository. They also assumed that languages will significantly change over 10,000 years. Their main concern was with advanced societies that have forgotten about the repository and its dangers, but that had knowledge of physics equivalent to or more advanced than ours. Thus the Task Force's main image of a future society was that of an advanced society with technology to intrude, with a possibly quite different language and culture, and not necessarily possessing any knowledge of the repository. The primary intrusion mode in this societal scenario would be drilling or archeological excavation.

More recently, a study of alternative scenarios of human intrusion into the WIPP repository was conducted by the Department of Energy (Hora et al., 1991). In this study, 16 nationally known experts in diverse scientific disciplines were assembled to structure the problem of human intrusion, to identify pathways for human intrusion and to assess the likelihood of alternative modes of intrusion. The experts were grouped into four "teams" each of which had substantial freedom in deciding on their approach and methodology. For example, one team developed what amounts to an event tree of very general categories of human intrusions (see Figure 2 - Southwest Team). Another team (labeled the "Boston Team" generated very specific point scenarios of human intrusion in addition to generic pathways, see table 5). In addition to the teams' creative activities of structuring the intrusion problem and of identifying alternative societies and modes of intrusion, this study included an exercise in eliciting probabilities for alternative scenarios from individual team members.

Insert Figure 2 and Table 5 here

One of the results of the WIPP study are creative images of human intrusion illustrated by the Boston Team's point scenarios. Another approach is to ask: How could some strange form of intrusion, say from the bottom of the repository, occur. The Southwest team gave a unique answer: Through mole miners, which are self sufficient robot whose only task it is to eat their way through the earth and signal geophysical and geo-chemical data to a receiving station (see Figure 3).

The four teams' ideas about alternative modes of intrusion are captured in Table 1, together with the ideas of other studies. Regarding future societies, all four teams felt that it is unlikely that the US will maintain political control over the site and that substantial societal changes are likely to occur over the next few hundred years. Regarding probabilities of a significant intrusion, all teams thought this to possible if not likely in the next 10,000 years with probabilities ranging from 1% to 10%.

4. Countermeasures Against Human Intrusion

There are four types of countermeasures against human intrusion:

- o Site markers and warning signs
- o General information management
- o Site management and active controls
- o Barriers and other disabling devices.

Site markers and warning signs are designs that are to survive many hundreds and perhaps thousands of years to communicate the danger of the site. General information management includes creation of museums and archives on and off-site that carry the messages of warning and danger. Site management and control usually refer to fencing off the site and patrolling it for the foreseeable future to prevent any undesirable or disruptive human activities. Barriers and disabling devices include physical obstacles to site access (e.g., deep ditches), metal shielding around the site to protect against conventional drilling or gases that are released upon approach to the site.

There have been two major studies of countermeasures: The Human Intrusion Task Force of 1984 and the WIPP study of 1992. Both studies focused mostly on markers and general information management. The lack of attention to active controls can partly be explained by the fact that the Environmental Protection Agency's (EPA) standards for the repository required that active control not be assumed after 100 years (Environmental Protection Agency, 1981). Furthermore, barriers and disabling devices were considered to be potential challenges that intruders would eventually overcome, rather than permanent detractors.

Markers and information strategies: The Human Interference Task Force

The study framework laid out by the Human Interference Task Force (1984; see also Gills, 1985, Kaplan and Adams, 1986) is shown in Figure 4. It is obvious that the main thrust of this effort is to implement effective communication to counter possible motivation against human intrusion. The Task Force placed heavy emphasis on long term markers that would be understandable to many different societies of various degrees of technological development, language comprehension and cultural sophistication. They also emphasized multiple redundant messages that reinforce each other as one goes from the outer perimeter of the repository site to its inner core.

The Task Force proposed a system of messages consisting of

1. Caution messages (first level)
2. Warning messages (second level)
3. Detailed messages (third level)
4. Detailed technical information (fourth level)

Caution messages would be simple and often symbolic, e.g. a sign stating" Warning - Biohazardous Waste Buried Here". Icons and symbols are suggested for this purpose (see Figure 5). The other levels essentially increase the depth of the detail in describing

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Insert Figures 2, 3 and 4 about here

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the nature of the hazard. An example of a third level message is shown in Figure 5.

The Task Force also investigated archeological and historical information to create ideas for long lasting and meaningful architectural markers. Considered were, for example, the pyramids in Egypt and Stonehenge in England. The Task Force proposed several surface structures that provide long lasting markers, including earthworks and monoliths. The main ideas are either a decentralized system of small durable markers with multiple messages or a system of a major central (pyramid-like) marker with different levels of messages. Combinations of these systems with earthworks are discussed in the documents provided by the Task Force. An example is shown in Figure 6.

Insert Figures 5 and 6 about here

In addition, the Task Force explored general educational and information management strategies. They proposed to include maps and offsite archives into a general system of managing information about the US and other repositories in the world.

Surrounding the Human Interference Task Force effort were several papers indicating the interest this topic created at the time. Kaplan and Adams (1986) and Kaplan (1986) examine the message function, role and durability of pyramids, Stonehenge, ancient Grecian structures and the Chinese Great Wall, among others. They conclude that multiple languages are important, natural materials may enhance survivability, and that detectability at the eye level is useful to understand the meaning of the marker. Their recommendations for nuclear waste disposal markers are similar to those of the Human Interference Task Force, of which Kaplan was a member.

Givens (1982) notes that the oldest man made messages are about 300,000 years old, but until about 20,000 years ago, these were primarily signs reporting that "someone was here." Pictographs and more directed messages began about 10,000 years ago, written scripts came much later. Considering these and other observations about the evolution of signs and languages, Givens concludes that it is important to embed the repository marker systems into multiple levels of communication using simple pictorial and symbolic representations as well as detailed verbal and technical descriptions.

In a different context David (1978) describes the effort of providing messages to extra terrestrials as part of the Voyager spacecraft to Jupiter and Saturn. These include a record "Sounds of Earth" and an American flag, as well as pictographs and many written languages, including a message by the Secretary General of the United Nations. Carl Sagan and others were instrumental in this design. Lomberg (1979) comments on it.

Markers and information strategies: The WIPP study

The WIPP markers study involved 14 scientists of various disciplines assembled for the purposes of creating, among other things, ideas about how to counter human intrusion activities that were postulated in the WIPP human intrusion study. The scientists came from diverse backgrounds, including archeology, history, psychology, material science, and linguistics. The scientists were charged with recommending markers for the WIPP disposal site, including physical descriptions and messages. In the process they were to consider each possible intrusion mode identified by the WIPP intrusion panel and estimate the effectiveness of the markers in preventing the intrusion. They were grouped into two teams of 7 scientists, each of which created its own framework and wrote independent reports. Both team focused on the creation of markers and assessment of their durability. In contrast, the reports provide less data on the effectiveness of the markers against the specific intrusion modes suggested by the WIPP intrusion panel. The following summary is based in the reports by the two teams (Ast et al., 1992; Baker et al., 1992).

Team A (Ast et al, 1992) studied markers for three societal and technological scenarios: The first is comparable to iron and metal using societies of some two hundred years ago; the second is much like our present society; the third is a society that went through a period of catastrophe, has forgotten about the WIPP site as a result, but has developed a new high level of technology and science. The team considered the last two scenarios to be the most important ones, since in the first the capability for intrusion would be low. The team rejected a non-marking strategy as dangerous and possibly unethical, and it comes down firmly on a strategy for building a massive marker system. They suggest a systems approach to marking with multiple redundant components, multiple items within each marking component, and cross indexing of different levels of the marking system. Thus, their philosophy was similar to that taken by the Human Interference Task Force.

The team generated several proposals, most focusing around the concept of earthen berms surrounding the site area. In addition, they propose a landscape design on the site surface that is "non-natural, ominous and repulsive" (p. 5). Various buried rooms include messages of warnings, cautions and descriptions of the site and its content. Messages should include archetypes, pictographs, symbols and verbal information. On proceeding to the center of the site, people will find long lasting message kiosks. Messages on several levels of detail are provided in these kiosks that describe the nature of the site and its danger in different languages as well as using pictographs and non verbal symbols. Figures 7-9 provide vivid illustrations of some of the ideas of the Team A.

Insert Figures 7-9 about here

Other useful conclusions of this team are that materials that are used for construction should have little value, other nuclear disposal sites should use similar systems, components of the system should be tested in terms of material properties and cross-cultural understandability, and off-site archives should be established containing replicas of the on-site. In addition they propose a public information effort to spread the concepts and content of the marker systems in today's generation. The team makes few claims regarding the ultimate effectiveness of the proposed marker system under the three societal scenarios, although they clearly consider the third scenario (forgetting and regaining a high level of technology) to be the most worrisome. The team felt that most of their design concepts had a good chance of surviving for 10,000 years or more, at least in terms of material properties, but their report doe not specify the extent to which the information on the markers will be understood or, if understood, deter intrusion.

The B Team (Baker et al., 1992) examined markers and their effectiveness for three different time periods: 0-500 years, 500-2,000 years, and 2,000-10,000 years. They specifically examined the effectiveness of markers in terms of durability and in terms of understandability for the following societal scenarios: Significant change of political control; return to a society similar to that of AD Native American Indians; emergence of vandalism; radical increase of consumption of world resources; and radical discontinuity (catastrophe with an upswing of technology).

As the A team, this team also comes to the conclusion that it is preferable to mark the site than not to mark it. The team also proposes a multi-level, multi-component marker systems consisting of the following features:

- o Earth berms directly above the site;
- o Granite monoliths bearing multiple symbols, pictographs and word messages;
- o A central granite structure for more detailed information;
- o Many small durable markers with warnings spread underground over the site;
- o Buried duplicates of the granite monoliths;
- o Markers that would be recognized by radar;
- o Duplicates of all markers near the site and in off site archives.

Examples of some of the ideas of this team for pictorial and symbolic communication are provided in Figure 10 and 11.

Insert Figures 10-11 about here

The team concludes that the proposed markers are likely to last for 10,000 years. They are less firm about the deterrent effect of the markers on future generations. Just like Team A and the Human Interference Task Force, they are also mainly concerned with the case of radical discontinuity. Additional insights and recommendations are that markers should be standardized throughout the world and that markers and messages should be tested, wherever possible.

In summary, the Human Intrusion task force and the two WIPP marker teams come to very similar conclusions. They suggest to be prepared for many future societies, and they worry most about technologically advanced societies that have forgotten about the repository and its dangers. Even the designs and systems approaches are very similar with all teams including concepts of large structures, multiple levels of information, pictographs and off site information management.

Active controls

The studies described above exclusively focus on markers and information strategies as countermeasures against human intrusion. Thus they primarily propose counter-motivating measures. In contrast, efforts to design systems of active human controls or barriers have been very limited. One of the teams in the WIPP intrusion study (Hora et al., 1991) explicitly assessed the probability that active controls would exist after during the first 1000 years after closure of the WIPP site. Three team members felt that this probability decreases rapidly and is less than .10 after 200 years. This pessimism with respect to the durability of active controls explains perhaps why there was not more emphasis on designing active control measures. One team member was much more optimistic, provided that active controls would become a central focus of the countermeasures effort. He believed that properly designed active control measures could be effective for up to 2000 years. All team members agreed, that if active controls were in effect, they would be the most effective countermeasure against human intrusion.

Barriers and other deterrents

Barriers were not studied by the Human Intrusion Task Force, since they were considered to have relatively marginal effectiveness compared to the existing natural barrier of several hundred meters of earth and rock. In addition, they might become potential attractors and, in any case, would be easy to overcome for a society with a technology that enables them to intrude. The WIPP study teams were not charged with looking at barriers. Thus this review has not uncovered any major efforts to examine alternative barrier designs. Minor efforts, for example to create surface barriers for Hanford tank wastes (Phillips and Hartley, 1986) were not applicable to the repository situation.

Nevertheless, it may it may be desirable to guide future efforts to think more creatively about barriers or other disabling devices. For example, it may not be difficult do design plates that resists or at least substantially delay traditional forms of drilling. Further, it may be possible to create a deterrent system that disables intruders temporarily without causing the type of harm that direct exposure to radioactive materials would create.

5. Implications for Performance Assessment and Standard Setting

The consistent conclusion of the human intrusion studies is that this is an important, perhaps the most important, pathway to health effects. Few intrusion studies attach an explicit probability to a human intrusion scenario. Those that do give varying probabilities ranging from extremely low to very high (e.g., 10^{-4} in Merkhofer and Keeney, 1987 vs. up to .10 for some teams in Hora et al., 1991) The differences are likely due to different assumptions about the mode of intrusion and different methods of determining the probabilities. For the purposes of this review, the important conclusions are that

1. the probabilities of intrusion are considered high by some scientists;
2. the probabilities of intrusion vary by several orders of magnitude.

Even if there is intrusion, most studies conclude that the consequences are small or negligible. However, the studies that come to that conclusion consider mostly conventional modes of intrusion (e.g., drilling) and they take a fair amount of credit for natural barriers functioning reasonably well after intrusion. For the more dramatic types of intrusion (e.g. direct intrusion in the process of creating a storage caverns) or the more exotic ones (e.g., building a tunnel or mole mining) consequences may be large, although no assessment has been conducted yet. Fortunately, the more dramatic or exotic modes of intrusion are also less likely it is to occur.

The main effort on countermeasures has been on markers and information management. The two major efforts in that area came up with admirable ideas and creative designs, but few clear conclusions about their effectiveness in deterring intrusion. Of most concern seem to be a future society that has no knowledge of the repository but is at least as advanced as ours. The modes of intrusion for this type of society is either conventional drilling or exotic intrusions, possibly with modes that are unimaginable to us today. It is unclear from the markers studies how much of a deterrent the proposed systems are for either cases. Thus there is room for a possibly dangerous pathway that needs to be considered explicitly in the performance assessment.

An ideal performance assessment of the human intrusion pathway would match the approach taken for natural events (e.g. earthquakes or magmatic events). One would first determine the probability of different types of intrusion scenarios, possibly conditionalized on alternative societal developments. Next one would assess the likelihood that the markers and signs would be effective in this intrusion scenario and that they thus would deter the potential intruder from proceeding any further. If the markers and other systems of deterrents do not work, intrusion will take place, and the consequence of this intrusion should be assessed first in terms of accelerated migration of radionuclides into the accessible environment and later in terms of health effects.

To be clear, this "ideal" approach requires:

1. An exhaustive set of societal scenarios;
2. An exhaustive set of intrusion modes for each societal scenario;
3. An set (not necessarily exhaustive) of countermeasures;
4. Probability assessments for alternative societal scenarios possibly as a function of time;
5. Probability assessments for alternative intrusion modes conditional on societal scenarios, also as a function of time;
6. Probability assessments of the effectiveness of the system of markers or other deterrents;
7. A quantitative performance assessment conditional on intrusion in spite of markers or deterrents.

As the following comments suggest, this may be an impossible task.

The WIPP intrusion study pushed steps 1,2,4 and 5 about as far as is possible with today's' methods of scenario construction and probability assessment. But even this study concludes, among other things, that "the qualitative findings, including the discussion of governmental control and the identification of possible modes of intrusion, are perhaps the most valuable contributions of the experts" (Hora et al, Executive Summary, p. 11). The WIPP markers study in turn pushed steps 3 and 6 as far as one can today. But both panels were extremely reluctant when asked for probability assessments of the effectiveness of markers under several societal scenarios. One of the teams states that "given that we have explored five designs, a literal interpretation of the charge (to estimate probabilities of the effectiveness of markers) leads to several hundred probability estimates. Using Occam's razor to slice through this forest of logic branches, the A-team interpreted the work of the (Intrusions) panel as the need to be ready for anything..." (Ast et al., 1992; p. 17)

These frustrations reflect a deeper underlying problem with the "ideal" approach to performance assessment in the context of human intrusion. First, except for some fairly trivial cases, it is impossible to create an exhaustive set of future human societies or of future modes of intrusion. Scenarios for future societies can be exhaustive only in trivial categorizations such as "a technologically more advanced society" vs. "a technologically less advanced society". Once one begins to generate more concrete societal scenarios, they soon become as specific as the single point scenarios in Table 5. At this level of embellishment and detail there is an endless number of scenarios and thus no hope of listing them exhaustively. To make matters worse, for many of these scenarios, especially the advanced ones, we cannot possibly imagine all the ways in which humans might intrude.

Probabilities can be assign to scenarios, but they seem meaningful only in fairly trivial cases, e.g. when one assumes extrapolations of existing drilling pattern. In non-trivial cases, for example, when assigning a probability to a scenario of a technologically advanced society, the knowledge base that might bear on the assessment is very uncertain. For example, what existing information would one need to collect to determine whether society in 1000 years is more or less advanced than ours? Are there experts who know more about this issue than others? The uneasiness with answering these questions suggests that there is little substantive knowledge that bears on these issues.

Given these fundamental problems with exhaustiveness and the meaningfulness of probability assignments, it is only logical to question the value of an "ideal" performance assessment for the human intrusion pathway. Clearly, much of this pursuit was motivated by the EPA standard that prescribed this kind of probabilistic analysis and by inference also required its application to human intrusion. When contemplating alternative approaches to setting standards for Yucca Mountain other concepts for assessing human intrusion and countermeasures emerge. In conclusion, I will discuss three alternative approaches to probabilistic, performance assessment based standards for human intrusion:

1. A deterministic approach that would limit consequences in specified point scenarios;
2. An engineering design approach that specifies countermeasures;
3. A process approach that would define both intermediate countermeasures and steps to continually revise and update them.

The deterministic approach seems, on surface, fairly straightforward. First, obtaining a rich and broad set of intrusion modes seems to be in reach. A standard could simply define the most important of those intrusion modes and request some form of assurance that either the countermeasures will definitely deter this intrusion or that its consequences will not exceed a specified level. However, there are two problems with this approach. First, there are no guarantees that the countermeasures will work and there is always the possibility that the consequences of the intrusion will be larger than specified Therefore, the regulation will have to introduce qualifications on the meaning of the effectiveness of deterrence and on the "worst" consequence. Expressed verbally, such qualifications are vague and introduce ambiguity in the tasks of designing for and establishing compliance. The best quantitative qualifications are probabilities, but this approach leads us right back to the problems with the ideal performance assessment approach. Thus, the deterministic approach is also fraught with problems.

The second alternative approach to standard setting involves specifying the engineering design for countermeasures. Clearly the existing literature on intrusion and countermeasures provides plenty of materials and creative thought of the types of systems that one may want to put into place. One possibility is to pick the best approach to countermeasures as we know it today, and make it mandatory. One problem with this approach is that without a formal assessment of the cost-effectiveness of the countermeasures, there will always be requests for more. Assessing the effectiveness of countermeasures brings with it the same problems encountered in the probabilistic and point scenario approaches. Another problem is the rigidity of this approach. While the imagination of the Human Interference Task Force and the WIPP intrusion and markers teams is admirable, I have no doubt that teams in 100 years would come up with more and better ideas for both intrusion and countermeasures. Or, perhaps even more importantly, societal conditions have changed so significantly that countermeasures are no longer needed (e.g., all waste materials are dug up and re-used).

This leads me to the third approach and my recommendation. In it some initial actions and engineering designs and countermeasures would be specified together with a clear vision of institutional controls. In addition, a process for revisiting this initial solution is set up, for example by convening an intrusion panel and a countermeasures panel every ten years. The panels may have antagonistic functions: The intrusion panel tries to think of any possible way to intrude say in the next 100 years and the charge to the countermeasures panel is to define ways to avoid this. After each panel meeting the state of intrusion and countermeasures would be reviewed and new countermeasures would be put in place if deemed reasonable at that time. Furthermore, an assessment and revision of the ability of active controls as a countermeasure is made at this time.

6. References

Anderson, D. R., Hunter, R. L., Bertram-Howery, S. G., & Lappin, A. R. (1989). WIPP performance: Impacts of human intrusion. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 68-84). Paris, France: OECD.

Ast, G., Brill, M., Goodenough, W., Kaplan, M., Newmeyer, F., & Sullivan, W. (1992). Marking the waste isolation pilot plant for 10,000 years. A-Team Report to Sandia National Laboratories. Albuquerque, NM: Sandia National Laboratories.

Baker, V. R., Drake, F. D., Finney, B. R., Givens, D. B., Lomberg, J., Narens, L. E., & Williams, W. S. (1992). The development of markers to deter inadvertent human intrusion into the Waste Isolation Pilot Plant (WIPP). B-Team Report to Sandia National Laboratories. Albuquerque, NM: Sandia National Laboratories.

Brady, B. T. (1989). Mineral and energy resources in studies of Geology and Hydrology in the Basin and Range Province, Southwestern United States, for isolation of high level radioactive waste-characterization of the Death Valley Region, Nevada and California (US Geological Survey Professional Paper 1370 F). Reston, VA: Department of the Interior.

Chapman, N.A. & Jowett, J. (1989) UK Nirex studies of intrusion frequency. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 142-155). Paris, France: OECD.

David, L. (1977-78). SETI: More Than Meets the Ear. AIAA Student Journal, 15, 26-31.

Egan, M.J. (1989). UK Nirex Studies of Intrusion Consequence. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 223-240). Paris, France: OECD.

Eng, T. (1989). The Undersea Location of the Swedish Final Repository for Reactor Waste, SFR - Human Intrusion Aspects. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 100-104). Paris, France: OECD.

Environmental Protection Agency. (1985). Environmental Standards for the Management and Disposal of Spent Nuclear Fuel, High-Level and Transuranic Radioactive Wastes: Final Rule. (EPA 40 CFR Part 191). Washington, DC: EPA.

Gillis, D. (1985). Preventing Human Intrusion Into High-Level Nuclear Waste Repositories. Underground Space, 9, 51-59.

Givens, D. B. (Summer 1982). From Here to Eternity: Communicating with the Distant Future. Et cetera, 159-179.

Hirsekorn, R. P. (1989). Post-operational leakage of a storage cavern constructed by solution mining in a former HLW repository area in a salt dome. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 159-170). Paris, France: OECD.

Hora, S.C., von Winterfeldt, D., & Trauth, K.M. (1991). Expert judgment on inadvertent human intrusion into the Waste Isolation Pilot Plant (SAND90-3063). Albuquerque, NM: Sandia National Laboratories.

Human Interference Task Force. (May 1984). Reducing the Likelihood of Future Human Activities that Could Affect Geologic High-Level Waste Repositories (ONWI-537). Prepared for the Office of Nuclear Waste Isolation. Columbus, OH: Battelle Memorial Institute.

Jacquier, P. & Raimbault, P. (1989). Radiological Consequences Associated with Human Intrusion into Radioactive Waste Repositories in Salt Formations. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 171-185). Paris, France: OCED.

Johnson, C., & Hummel, P. (1991, August). Yucca Mountain, Nevada. Geotimes, pp. 14-16.

Kaplan, M. Mankind's Future: Using the Past to Protect te Future. (1986). Interdisciplinary Science Reviews, 11, pp. 3-10.

Kaplan, M. F., & Adams, M. R. (1986, September/October). Using the Past to Protect the Future: Marking Nuclear Waste Disposal Sites. Archaeology, pp. 51-54.

Lomberg, J. (1978). Pictures of Earth. In Sagan, C., Drake, F.D., Druyan, A., Ferris, T., Lomberg, J., Sagan, L.S., Murmurs of Earth (pp. 71-122). New York, NY: Random House.

Marivoet, J., & Bonne, A. (1988). Performance Assessment of Geological Isolation Systems for Radioactive Waste. Disposal in Clay Formations (EUR 11776 EN). Brussels, Belguim.

Mattson, S.R., & Matthusen, A.C. (1992). Draft Literature Review for the Human Interference Guideline Section of the Early Site Suitability Evaluation (ESSE). Las Vegas, NV: Systems Application International Corporation.

Mattson, S.R., Younker, J.L., Bjerstedt, T.W., & Bergquist, J.R. (January 1992). Assessing Yucca Mountain's Natural Resources. Geotimes, pp. 18-20.

Mejon-Goula, M.J. & Cernes, A. (1989). Assessment of the Radiological Consequences of Human Intrusion into Repositories Located in Granite. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 198-208). Paris, France: OECD.

Merkhofer, M. W, & Keeney, R.L. (1987). A Multiattribute Utility Analysis of Alternative Sites for the Disposal of Nuclear Waste. Risk Analysis, 7(2), 173-194.

Nuclear Energy Agency. (1989). Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop. Paris, France: OECD.

Nuclear Energy Agency. (1992). Systematic Approaches to Scenario Development. Paris, France: OECD.

Nuclear Energy Agency. (June 1993). Assessment of Future Human Actions at Radioactive Waste Disposal Sites: Draft Report of an NEA Working Group. Paris, France: OECD.

Nordman, H. & Vieno, T (1989). Consideration of Human Actions in the Finnish Performance Assessments of Nuclear Waste Disposal. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 94-104). Paris, France: OECD.

Phillips, S.J., & Hartley, J.N. (March 2-6, 1986). Protective Barrier Systems for Final Disposal of Hanford Waste Sites. Proceedings of the 1986 Symposium on Waste Management. (pp. 433-437). Tuscon, Arizona.

Prij, J., & Glasbergen, P. (1989). The role of human intrusion in the Dutch safety study. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 186-196). Paris, France: OECD.

Reid, J. A. K., Melnyk, T. W., & Chan, T. (1989) Effects of a domestic well on assessed performance of a nuclear fuel waste disposal system. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 209-222). Paris, France: OECD.

Rickertsen, L. D., & Alexander, D. H. (1989). Treatment of human interference in US DOE repository system post closure performance assessments. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 59-84). Paris, France: OECD.

Smith, G.M., et al. (1987). Calculations of the Radiological Impact of Disposal of Unit Activity of Selected Radionuclides (NRPB-R205). London, UK: Department of he Environment.

U.S. Department of Energy. (1981). Preliminary Evaluation of Solution-Mining Intrusion into a Salt Dome Repository. (Report No. ONWI-320-1). Washington, DC: Department of Energy.

U.S. Department of Energy. (1985) Performance Assessment Plans for the Salt Repository Project (Report No. BM1/PWW1-545). Washington, DC: Department of Energy

van Dorp, F. & Vigfussen, J.O. (1989). Overview of Swiss Work Concerning Human Effect Scenarios. Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites: Proceedings of an NEA Workshop (pp. 105-111). Paris, France: OECD.

Wuschke, D.M. (1991). Assessment of the Long Term Risks of Human Intrusion into a Proposed Canadian Nuclear Fuel Waste Disposal Vault in Deep Plutonic Rock (AECL-10279). Ottawa, Canada: Atomic Energy Control Board.

Table 1

Modes of and Motivation for Human Intrusion[1]

Direct Intrusion Modes	Motivation
Exploratory drilling	Search for hydrocarbons Search for minerals Search for Water Research
Development drilling	Search for hydrocarbons Search for minerals Search for Water Research
Excavation	Archaeological finds Minerals Construction
Disposal/Storage	Underground injection of liquid wastes Disposal of non-radioactive solid wastes Disposal of additional radioactive wastes
Tunneling	Transportation Pipelines Research (e.g., mole mining)

Indirect Intrusion Modes	Motivation
Explosions	Nuclear testing Other testing and development
Water development	Water impoundment Water injections

Table 2

Countermeasures against Human Intrusion

Reduce Motivation

Reduce value of markers

Use low value of materials
Common rock for markers
Reduce importance of markers

Reduce value of potential resources

Mix components of wastes
Contaminate existing resources
Provide information about abundance of resource elsewhere

Create fear

Use of Special Architectural Design
Pictures (e.g., symbols for radioactivity)
Messages (e.g., models and maps of WIPP)
Off site messages (e.g., off site archives)

Limit Opportunity

Fences
Trenches
Physical barriers
Armed guards

Disable Capability

Disabling physical barriers
Increasing levels of radioactivity
Warning "shock" against intrusion team

Table 3

Mineral and Energy Resources in the Death Valley Region

(from: Brady, 1989)

Metallic Mineral Resources

Gold
Silver
Copper
Molybdenum
Lead
Zinc
Tungsten
plus 17 others

Non-metallic Industrial Minerals and Rocks

Magnesites
Brucite
Fluorspar
Barite
Lithium
Others

Hydrocarbon Resources

Coal
Oil
Gas

Geothermal Resources

Table 4

Analyses of Point Scenarios of Human Intrusion

(Adapted from NEA, 1993; most references are found in the Proceedings of an NEA Workshop on Risks Associated with Human Intrusion at Radioactive Waste Disposal Sites, Paris, June 5-7, OECD/NEA, Paris, 1989)

Conventional drilling

Water well drilling

Marivoet and Bonne, 1989
Reid et al., 1989
Nordman and Vieno, 1989
Eng, 1989
van Dorp and Vigfussen, 1989

Exploratory drilling

Wuschke, 1991
Prij and Glasbergen, 1989
Chapman and Jowett, 1989
Egan, 1989
Smith et al., 1987

Borehole drilling (undefined)

US Department of Energy, 1985
Anderson et al., 1989

Underground construction and mining

Construction of an underground cavern

Mejon-Goula and Cernes, 1989
Hirsekorn, 1989

Mining (incl. solution mining)

Prij and Glasbergen, 1989
Jacquier and Raimbault, 1989
Prij and Glasbergen, 1989
US Department of Energy, 1981

Table 5

Point Scenarios of Possible Future Societies
(Adapted from Hora et al., 1991).

A feminist world, 2091

Women dominate society partially through selection of girl babies. Twentieth century science is discredited as male arrogance. Warnings about repository are dismissed as another example of muddled masculine thinking.

Mysticism and religion, 1091

A religious cult searches emerges rejecting existing scientific consensus and realties. settling in New Mexico, they searched for deeper meaning by digging up the WIPP site.

Buried treasure, 2091

New Mexico secedes from the US and is annexed by Mexico. Knowledge about the WIPP site is lost except for some rumors that somethinp valuable is buried there. Treasure hunters are happy to find "warning signs" and begin to dig.

WIPP as the Nation s nuclear waste site, 2091

WIPP is expanded to receive all kinds of radioactive wastes and other and it is enlarged to many times its planned capacity. Later some of the wastes are recovered for processing or improved storage leading to releases of radionuclides.

A Houston to Los Angeles Tunnel, 2991

A high speed transportation tunnel is dug between Houston and Los Angeles with stops near Carlsbad and Phoenix. The tunnel is 2000 feet underground and passes close by the WIPP site. Construction and vibration disrupt the repository.

Global Illiteracy, 2991

A declining US is replaced by a new State of Eastlandia, which establishes prison mines in New Mexico. Illiterate miners are incapable of reading the messages warning of the danger of the site.

Virus impairs computerized people, 11991

Due to a computer virus. robots disregard commands and begin to dig compulsively in the area of New Mexico, penetrating the WIPP site.

Human warriors return from space, 1191

A battleship returning from a mission lost control upon re-entering the earth environment. Attempting to reduce speed the sip fired lasers into the ground near the WIPP site. The effect of lasers and the crash impact penetrated the site.

Nickey Nuke and WIPP Worlds, 1191

The WIPP museum and WIPP Worlds become major tourist attractions at the WIPP site. Nickey Nuke is a fictional character that survives many generations. As long as he lives the warning s about WIPP survive.

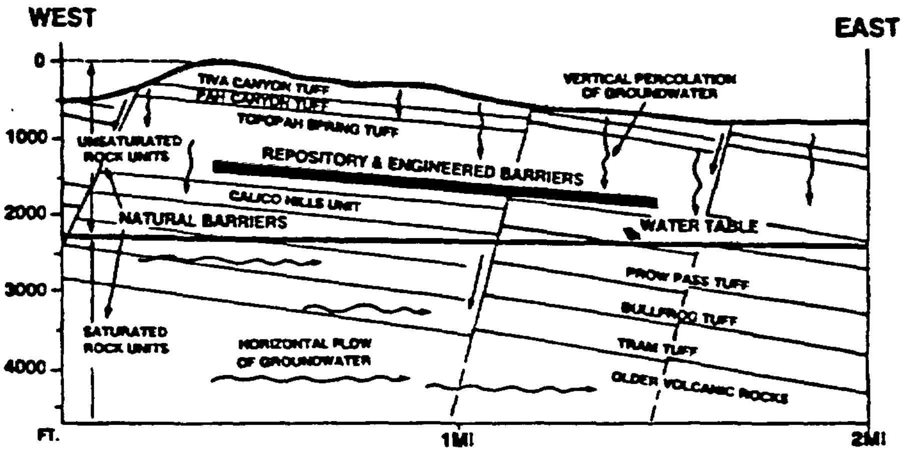

Figure 1

East-West cross section through Yucca Mountain with location of the repository site
(from Mattson et al., 1992)

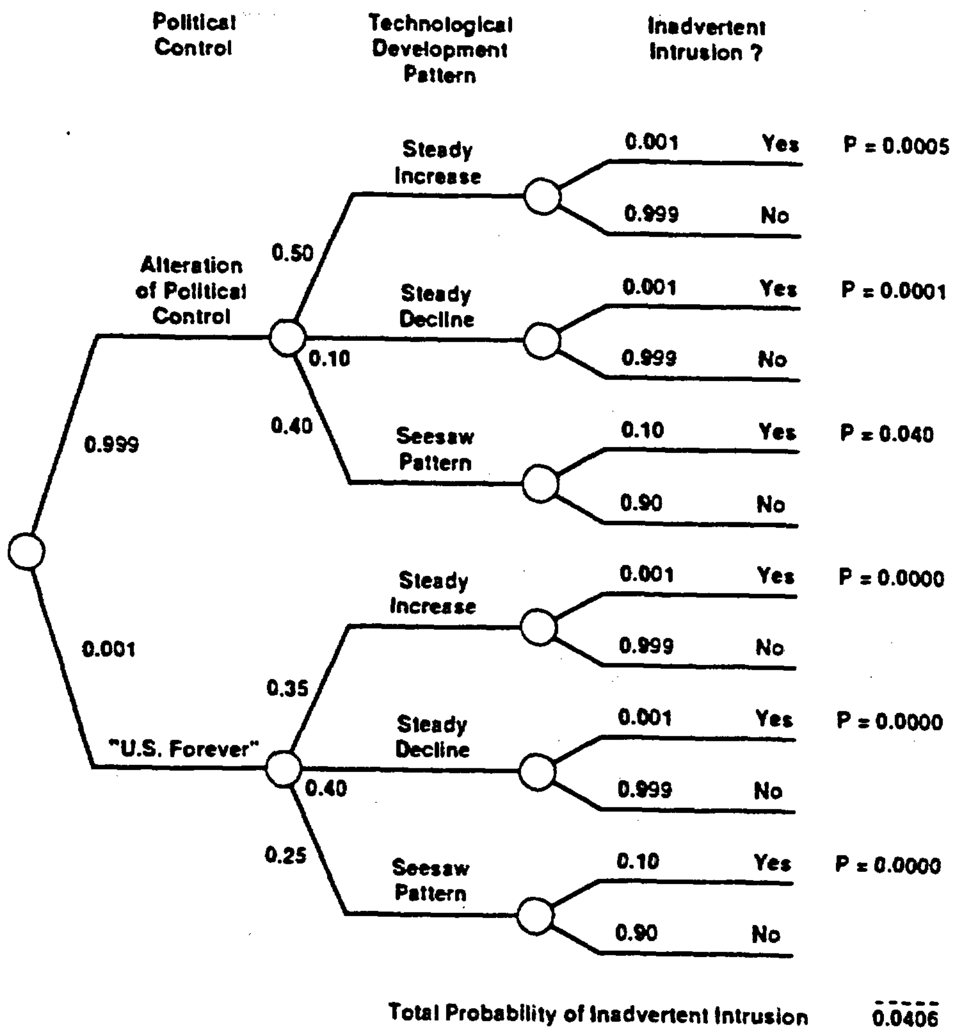

Figure 2

Event tree for societal scenarios for human intrusion (from Hora et al., 1991)

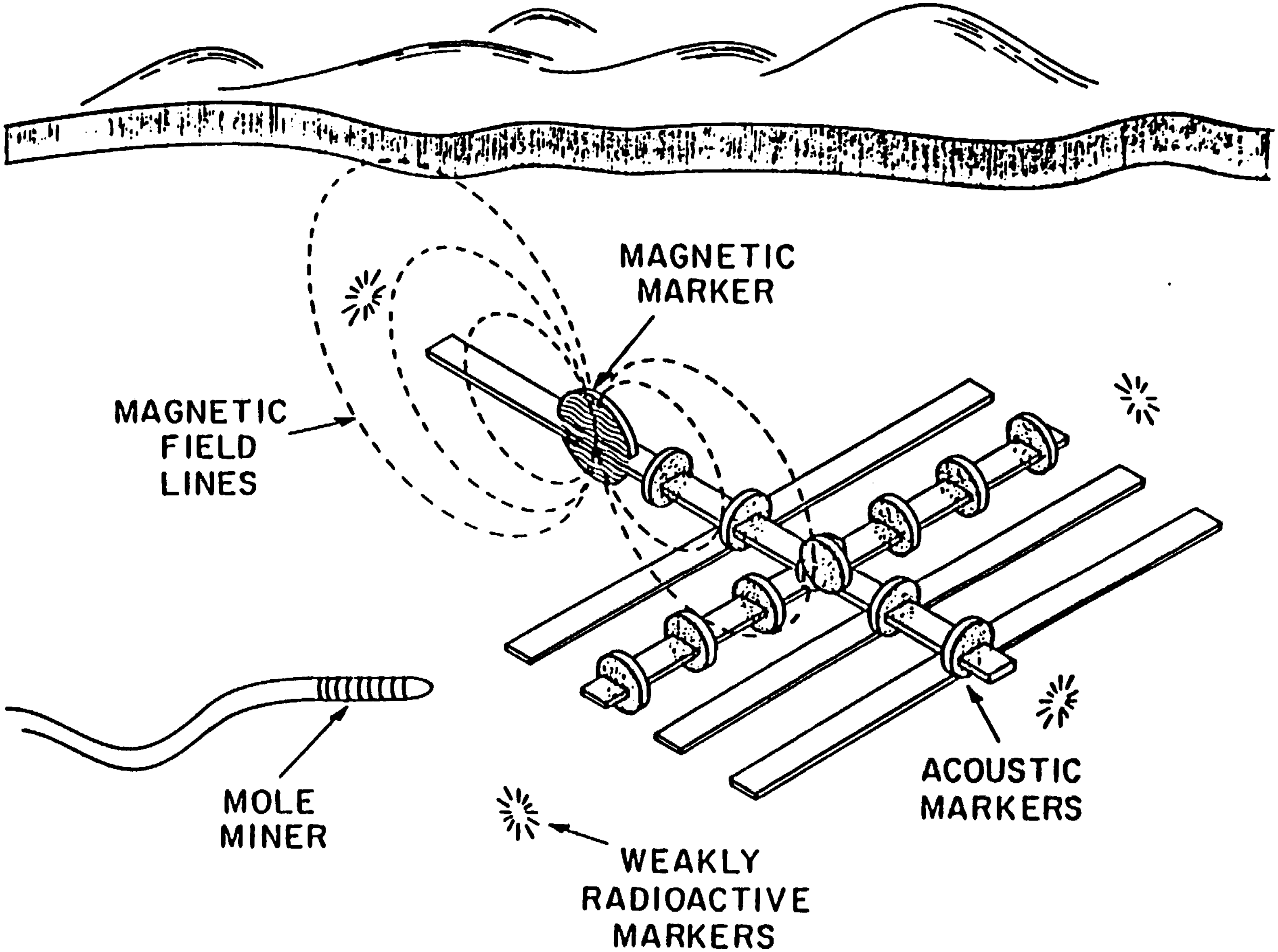

Figure 3

Intrusion by a mole miner
(from Hora et al., 1991)

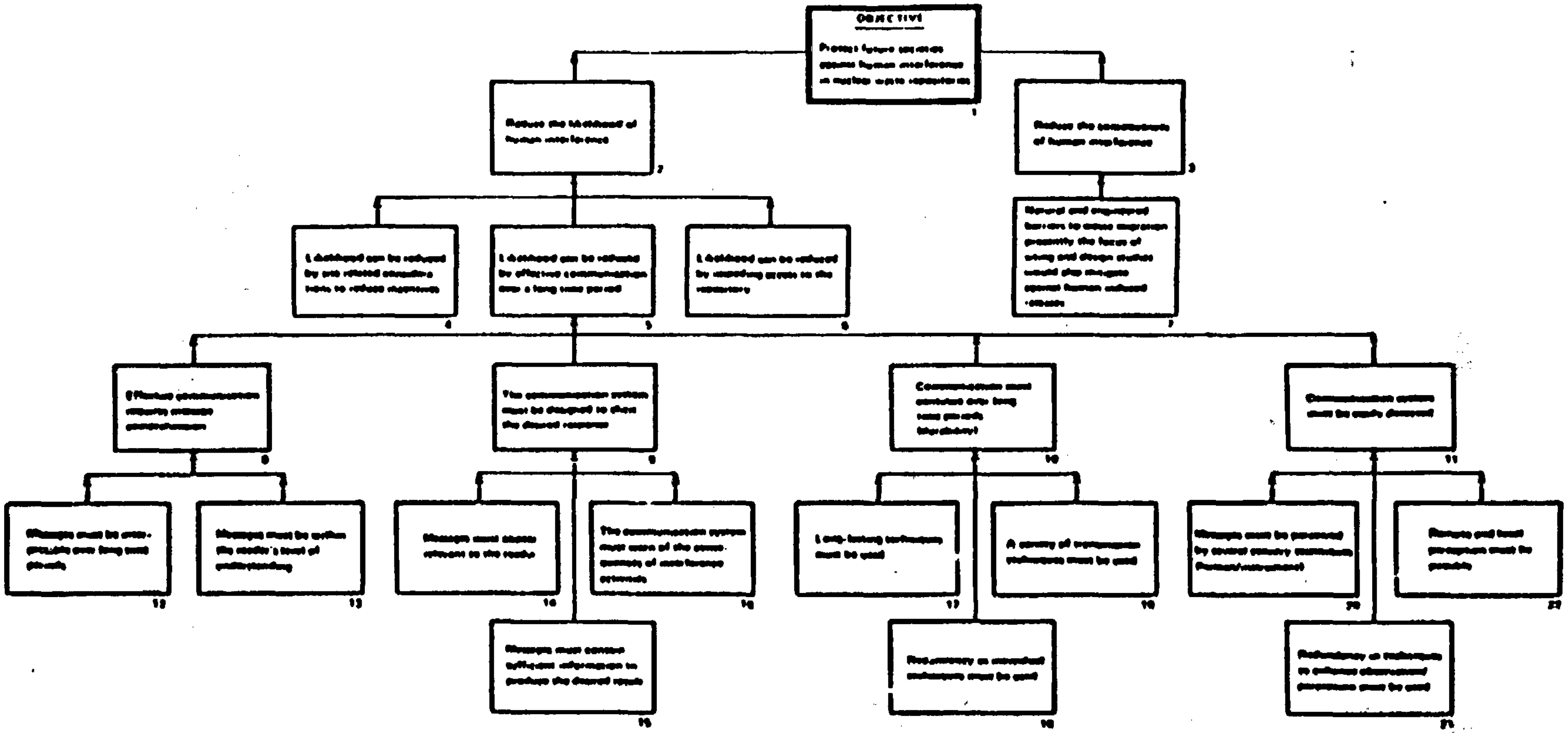

Figure 4

Logic diagram for studying human intrusion
(from Human Interference Task Force, 1984)

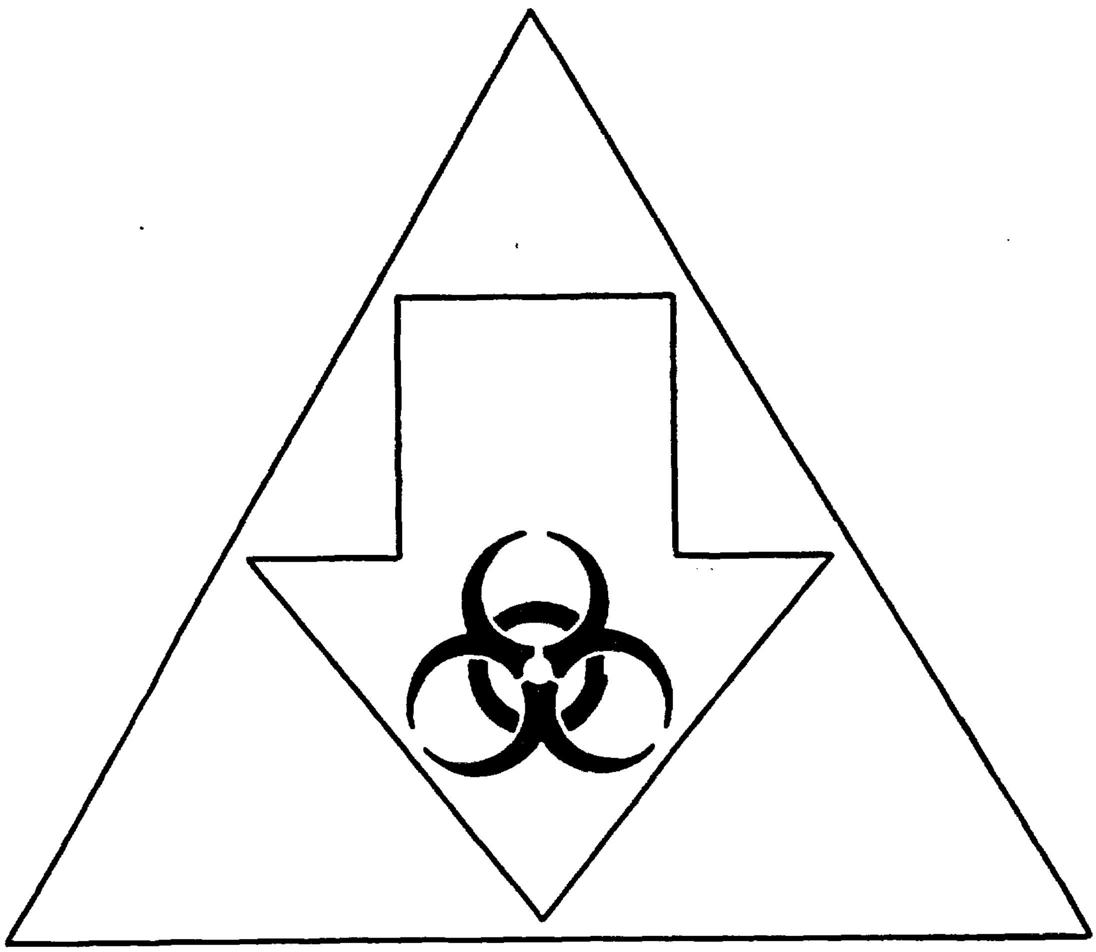

Figure 5

Proposed symbol: "Caution-Biohazardous Waste Buried Here" (from Human Interference Task Force, 1984)

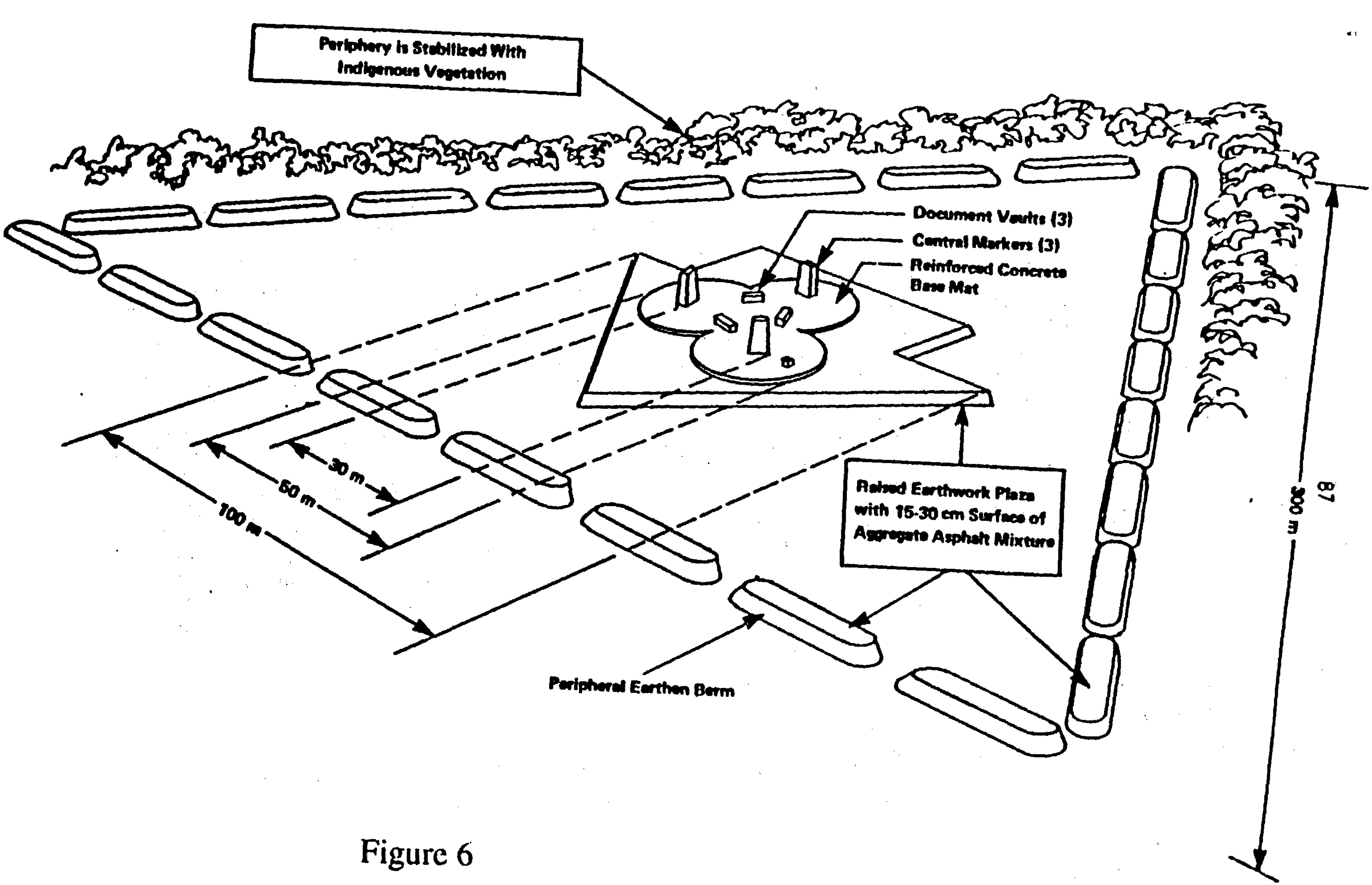

Figure 6

Surface structures to mark repository site
(from Human Interference Task Force, 1984)

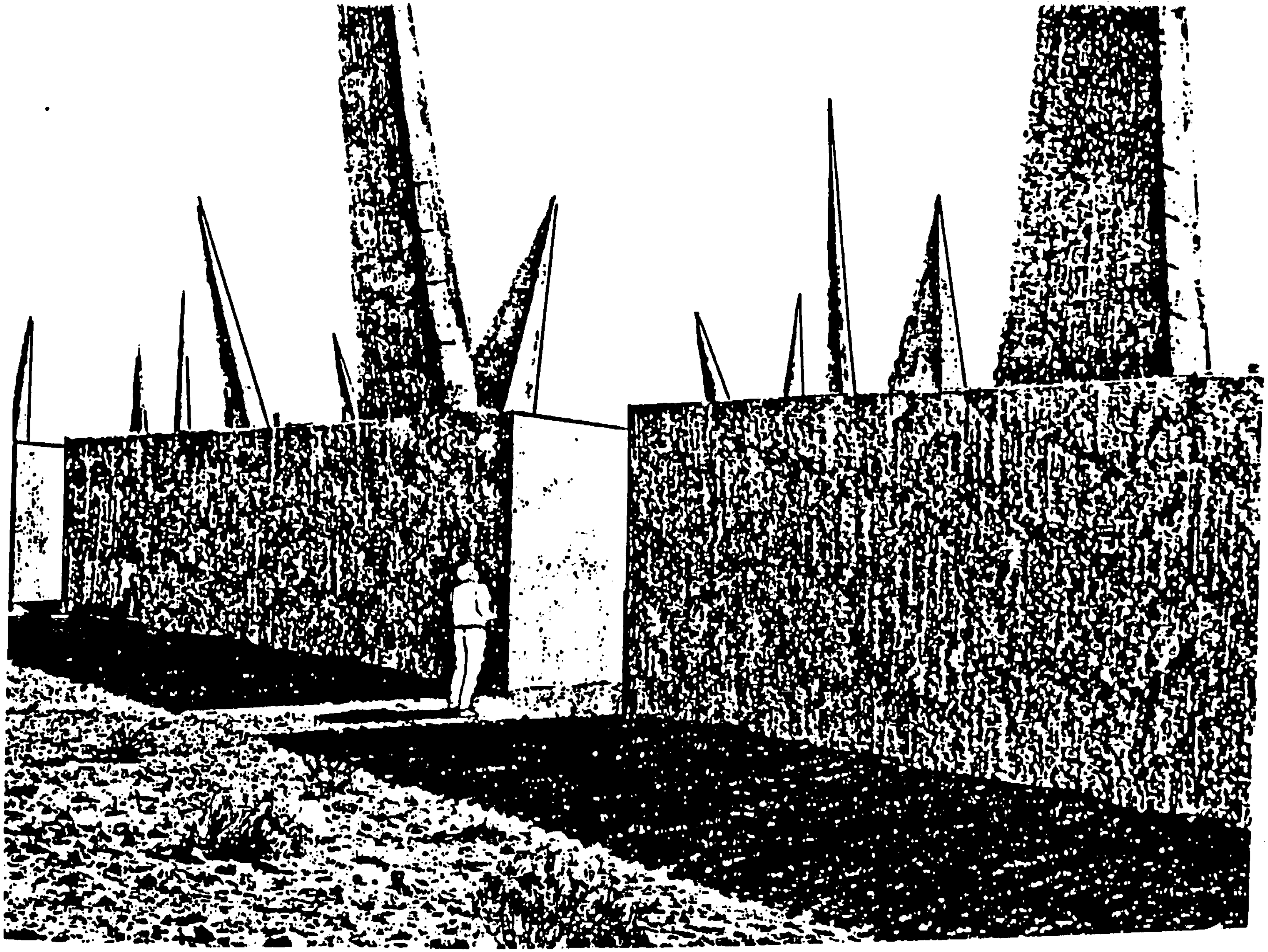

Figure 7

"Spike Field" to mark a repository
(from Ast et al., 1992)

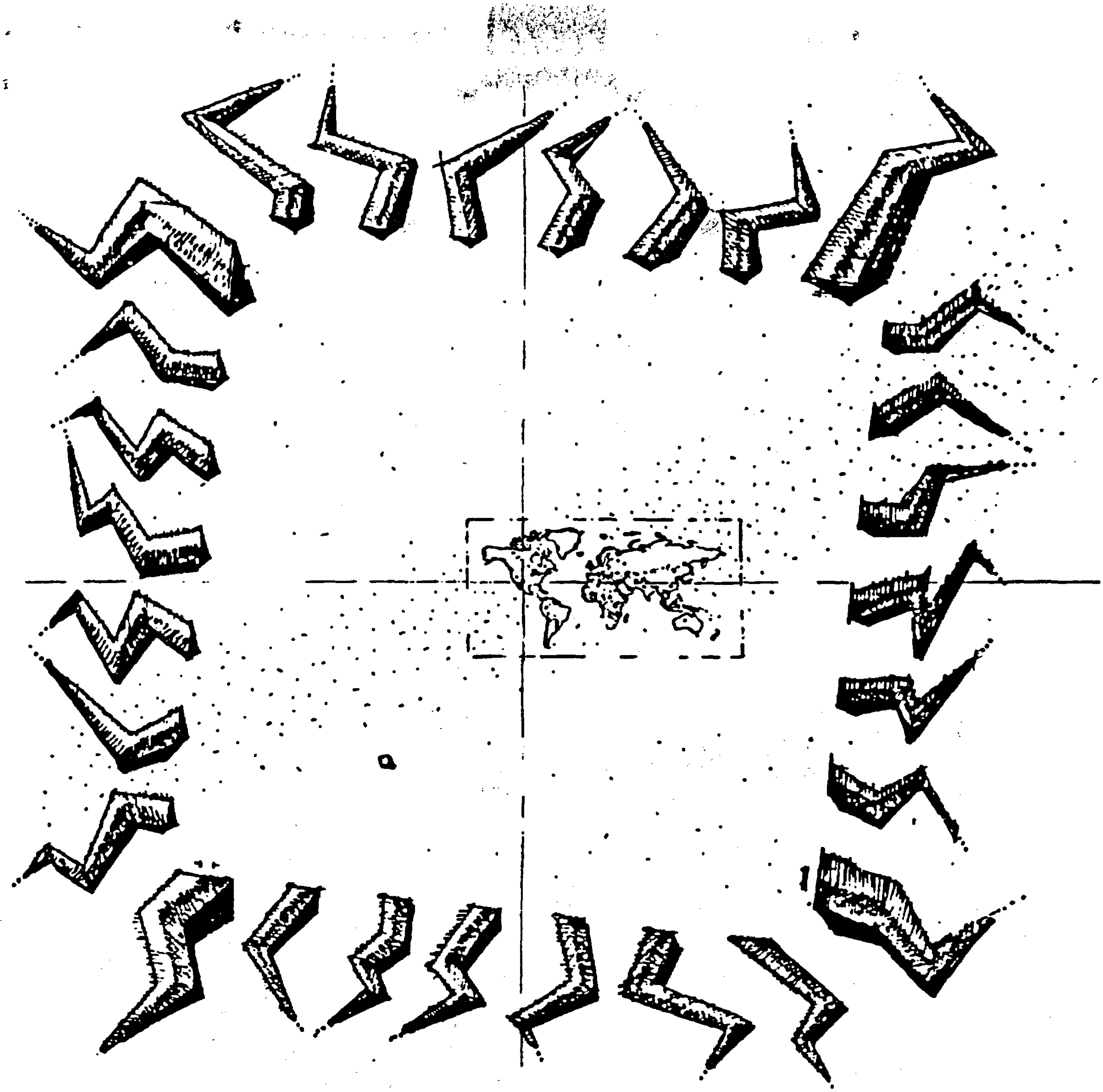

Figure 8

"Menacing Earthworks" to mark a repository
(from Ast et al., 1992)

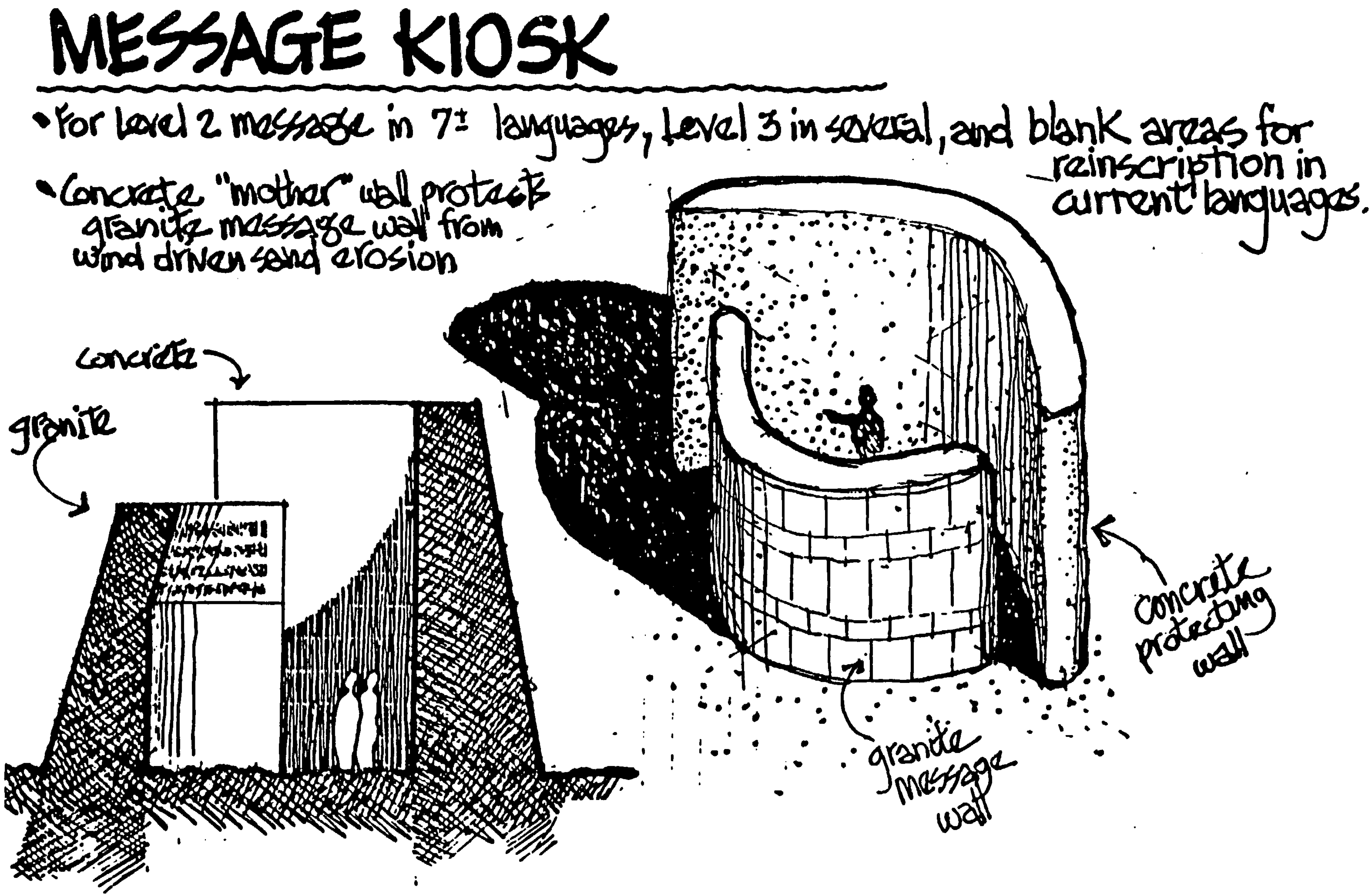

Figure 9

Design ideas for a "Message Kiosk"
(from Ast et al., 1992)

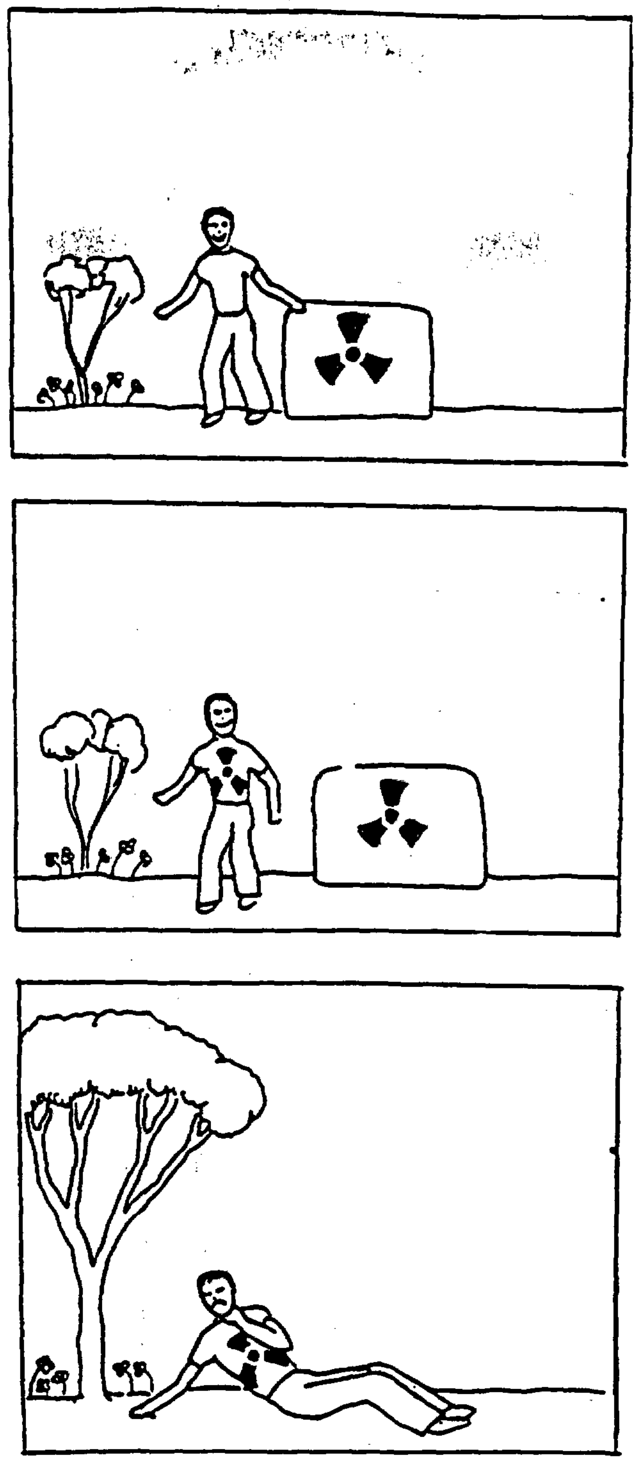

Figure 10

Pictorial indicating danger from radioactive wastes (from Baker et al., 1992)

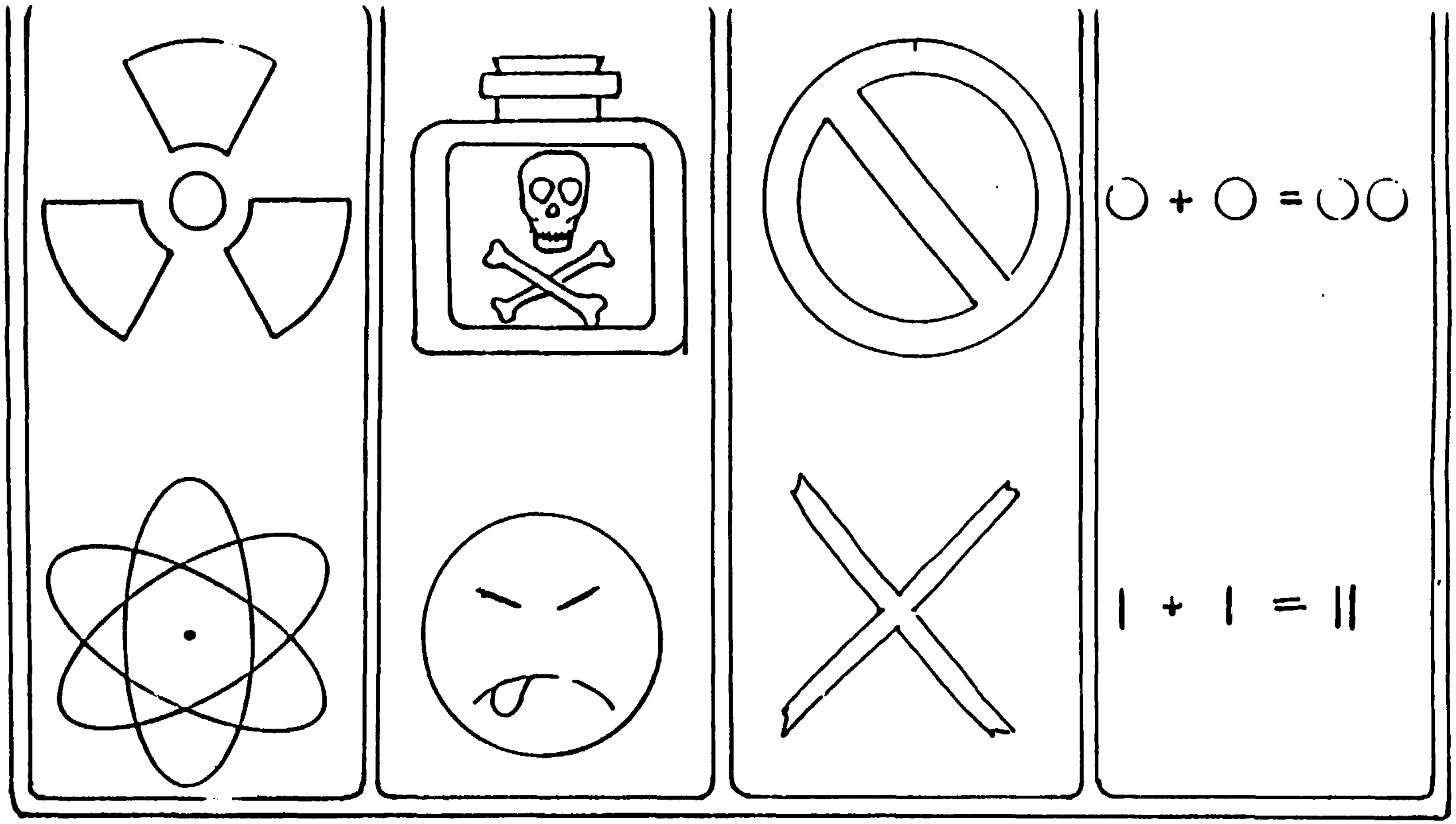

Figure 11

Pictorial indicating that pairs are symbols with the same meaning (from Baker et al., 1992)