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Geologic and Engineering Constraints on the Feasibility of Clandestine Nuclear Testing by Decoupling in Large Underground Cavities

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Contents

Previous Work

For the past 40 years, the U.S. Geological Survey has supported efforts to monitor worldwide nuclear testing and to negotiate and verify nuclear test limitation treaties. This support has included:

- Compilation of atlases of Eurasia supporting nuclear test detection [e.g., *Elias et al, 1966*];
- Geologic assessments of the surface and subsurface environments at foreign nuclear test sites, including remote geologic evaluations of individual test site locations [e.g., *Leith et al., 1990; Matzko, 1992a; 1992b; 1994a, 1994b*];
- Remote geologic evaluations of the sites of so-called Peaceful Nuclear Explosions, worldwide;
- Country-by-country profiles of geologic factors affecting seismic monitoring, including reviews of industrial mining and blasting activities[1] [*Leith and Rachlin, 1992; Leith, 1995*];
- Evaluation of underground environments with potential for clandestine testing, including maps of salt deposits and low-coupling media [e.g., *Fryklund, 1977; Rachlin, 1985*];
- Direct support for, and participation in, the negotiation of nuclear test limitation treaties, including the Threshold and Comprehensive Nuclear Test Ban Treaties;
- Development of digital geologic, terrain and geographic databases supporting nuclear test monitoring [e.g., *Unger and Leith, 1991*].

Of the various ways in which the Earth plays a role in monitoring, verification and the evaluation of underground nuclear testing, the following geologic factors have been considered in detail:

- Levels and characteristics of natural and man-made seismicity (relevant to discrimination between earthquakes and explosions) [*e.g., Leith and others, 1996*];
- Seismic wave attenuation in the crust and upper mantle (relevant to determining the "bias" between various test sites) [e.g., *Leith and Rachlin, 1992*];
- Regional geologic structure (relevant to evaluating the seismic records obtained at local and regional distances) [e.g., *Matzko, 1995*];
- Existence of natural environments for reduced coupling e.g., porous rock in areas where the water table is very deep [e.g., *Matzko 1984a, 1984b, 1984c*];
- Existence of cavities and underground environments suitable for cavity construction (with a focus on large salt domes or thickly-bedded salt and on the potential for construction of large caverns in hard rock) [*Matzko, 1990; Leith and Glover, 1992*];
- Characteristics and frequency of large mining explosions (also relevant to discrimination between earthquakes and explosions) [*Leith et al., 1996a, 1996b, 1996c; Leith and Baumgardt, 1997*];

This support has also included numerous detailed studies of existing or presumed nuclear test sites and, specifically, the evaluation of underground construction activities at individual test boreholes and adits.

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[1] In the early 1990s, following the re-negotiation and ratification of the Threshold Nuclear Test Ban Treaty, the USGS profiled the geologic factors affecting seismic monitoring of that treaty for a number of countries. These included those countries that were actively testing (such as the former Soviet Union, China, etc.) and countries of nuclear proliferation concern (such as North Korea, India, Pakistan, Iran, Algeria, Libya, Iraq, and Syria).

All of these studies relate to an evaluation of the feasibility of a foreign country conducting an underground nuclear test and evading detection by the various monitoring systems, since they apply to most facets of such an undertaking, including site selection, underground construction, decoupling, containment, concealment, seismic detection and nuclear explosion discrimination.

The Cavity Decoupling Scenario

A central issue in assessing the verifiability of the Comprehensive Nuclear Test Ban Treaty (CTBT) is the potential for a determined country to conduct a nuclear test clandestinely —that is, evading detection and identification by the various international and national monitoring systems. Among a number of potential "evasion scenarios" that have been considered [e.g., detonation in outer space, during an earthquake, in low-coupling geologic media, in remote ocean areas, or in the atmosphere under heavy cloud cover, see, e.g., *OTA, 1988*], evading detection by decoupling the seismic signal of the explosion in a large cavity constructed deep underground has received considerable attention. Numerous papers have been published discussing the theoretical and practical aspects of this evasion scenario [*Herbst and Werth, 161; Murphy, 1980; Glenn and Goldstein, 1994; Sykes, 1995; Linger et al., 1995*].

Since the concept of cavity decoupling was first developed by Albert Latter [*1959; Latter et al.,1961*], considerable work has been done to develop a theoretical understanding of the phenomenon, and both the U.S. and the former Soviet Union have conducted nuclear and high-explosive tests in decoupling configurations [*Springer et al, 1968; Adushkin et al., 1992; Murphy et al., 1995, 1997; Reinke, 1995*].

In 1988, the Office of Technology Assessment concluded that nuclear tests with yields over about 10 kilotons (kt) could be monitored with high confidence, and that "no method of evading a seismic network is credible", adding only that it would be desirable to have "treaty restrictions for handling the identification of large chemical explosions in areas where decoupling could take place" [*OTA, 1988*, p.14]. Below 1-2 kt, *OTA* [*op. cit.*] concluded that "it would be possible to decouple illegal explosions not only in salt domes but in media such as granite, alluvium and layered salt deposits," and that "there is no convincing evidence that such events could be confidently identified with current technology."

The yield range of greatest uncertainty lies between 1 and 10 kt, where explosions could be decoupled in cavities in salt and perhaps also in hard rock. While improvements in the monitoring networks and technologies have decreased the event identification threshold in many regions, achievements in underground construction have likewise increased the feasibility of constructing large underground caverns that could conceivably be used for nuclear explosion decoupling (see material presented in this report). Although Russian scientists have cited cavity decoupling as "the general method of evasion" in a paper on CTBT monitoring [*Spivak, 1995*], the feasibility of clandestine testing through cavity decoupling at yields of more than about 1 kt is nevertheless a subject of considerable debate [see, for example *Sykes, 2000*].

The purpose of this paper is to review available information on the geologic and engineering constraints on the feasibility of cavity decoupling[2], for explosions in the yield range from 1-2 to

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[2] This review covers only decoupling in large, unsupported, air-filled cavities. Other *partial-decoupling* methods have been considered as possibilities for evading detection under the CTBT and TTBT. These scenarios rely on the presence of significant air-filled porosity in the rock, which crushes to absorbs the energy of the explosion. This is a well-documented phenomenon for tests in dry alluvium at the Nevada test Site, and can results in a decrease of as much as one unit of seismic magnitude, m_b. However, in USGS reviews of the geologic environments in countries of nuclear proliferation concern [e.g., *Rachlin, 1989*], very few regions have been found outside of the U.S. where adits could be constructed into rocks with porosities greater than 20% (although there are many areas where adits could be constructed into rocks with porosities in the range of 5-20%). Similarly, there are very few areas where a vertical shaft could be constructed above the water table at 200 m depth, and only one area (the Kalahari desert) where rocks at containment depths may have porosities greater than 20%. Examples of more

about 10 kt, considering current practical limits on cavern construction and costs, and the containment of explosion products. The subject of concealment of the cavity construction cannot be fully treated here, but is briefly discussed.

To successfully evade detection of the decoupled event by monitoring systems and identification of it as a nuclear test, the following constraints must be considered:

> --the seismic magnitude of the event must be less than the threshold of the monitoring networks for event detection[3] and identification[4].
>
> --the depth and geologic environment of the test must be sufficient to ensure the containment of the radioactive products of the explosion, to the extent that it is not detected and identified by the radionuclide monitoring system (i.e., above detection minima and distinguishable from other sources such a power plant releases);
>
> --the construction of the cavern must be concealed from detection by satellite monitoring systems and from public knowledge.

Because these constraints may not be completely controllable by the evader, it is necessary to make some assumptions about what might be the minimum requirements for success; or, alternatively, what geologic and engineering factors limit the feasibility of the undertaking. Unfortunately, these constraints are variables, depending on the specific sites available and considered for fielding the test and on the yield of the test [e.g., *JAYCOR, 1996*]. After presenting the relevant information, the discussion will focus specifically on decoupling in the yield range from 1 kt to 10 kt.

Decoupling in Non-spherical Cavities

Following the publication of the OTA report on Seismic Verification [*OTA, op cit.*], *Stevens et al.* [*1991*] conducted a series of non-linear, finite-difference calculations which indicated that effective decoupling could be achieved in ellipsoidal cavities in salt with aspect ratios of 4:1. Construction of *spherical* cavities in hard rock that are large enough for full decoupling[5] of explosions over 1 kt (see **Figure 1**) is expensive and requires technological sophistication not widely available. Therefore, this finding was quite important for the cavity decoupling scenario, because the engineering stability of most underground openings relies on the relative strength of the smallest dimension of the opening. It also means that cavity decoupling in hard rock above 1 kt, which was rejected in the OTA report, has to be reconsidered.

Both the U.S. and the Soviets have conducted high-explosive tests in elongated underground chambers, and analyzed the seismic data in terms of decoupling effectiveness. Analysis by *Murphy et al. [1997]* of Russian high-explosive tests conducted in limestone in Kirghizia in 1960

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exotic applications of this idea are: 1) detonation in room-and-pillar mines; 2) detonation in the rubble-filled chimney of a previous explosion; 3) detonation near a planar air-filled gap. All of these techniques were tested with nuclear explosions by the Soviets, and have been described as methods of evading detection under the CTBT [*Spivak, 1995*], although none have been validated with respect to their effect on seismic monitoring. Also described is the use of Carbon as a heat sink in cavities to enhance decoupling, and replacing the air in cavities with hydrogen or helium has also been proposed to extend the radiation phase of the fireball growth, thus allowing less energy to go into shock motion. Both of these schemes, however, may result in chemical reactions that could negatively affect containment of radioactivity.

[3] It is beyond the scope of this paper to review the subjects of the seismic magnitudes of decoupled nuclear explosions, and the capabilities of the various monitoring networks.

[4] The event *identification* threshold magnitude is typically assumed to be one-half unit above the detection-and-location threshold. Also, to help evade identification, a near-threshold event could be “masked” by the concurrent detonation of a non-nuclear explosion, such as a large mining blast.

[5] i.e., a decoupling factor of about 70; see discussion in *OTA, 1988*, p. 101.

concluded that the low-frequency decoupling effectiveness is approximately independent of cavity shape for cavities with length-to-width ratios of as much a 6:1 to 12:1.

Similar high-explosive decoupling experiments were conducted in limestone at the Magdalena mine in New Mexico in 1994. Small high-explosive charges were detonated in elongate rooms with aspect ratios of 8.5:4:2 meters [*Reinke et al., 1995*]. The analysis concluded that decoupling factors were in reasonable agreement with values calculated for decoupling in spherical cavities (from the COWBOY experiments, see *Herbst et al., 1961*).

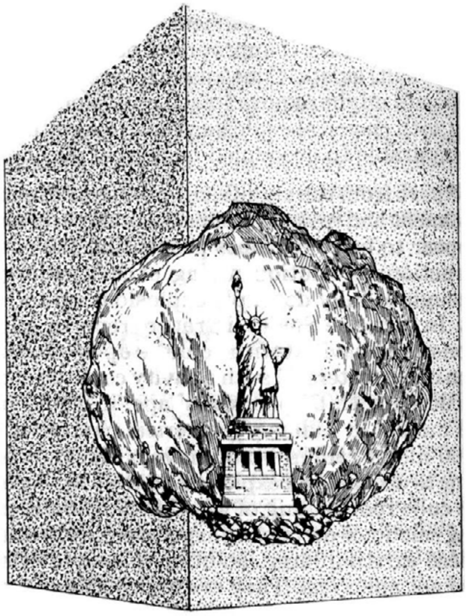

Fig 1. Illustration of the large size of a hypothetical cavity, necessary to fully de-couple a 5 kiloton nuclear test in salt, relative to the height of the Statue of Liberty [*from OTA, 1988*]. The height of the Statue of Liberty, with pedestal (73 m), is 85% of the required diameter (86 m).

While limited, these experimental studies have essentially supported *Stevens et al.* (*op. cit.*) calculations[6]. Subsequent calculations by S-CUBED, of decoupling in cylindrical cavities with aspect ratios of 20:1, showed that even cavities with such a large aspect ratio provided most of the decoupling (at long periods) of a cylindrical cavity of the same volume [*Rimer et al., 1994*]. *Knowles et al.* [*1994*] used these studies in an issue paper on the feasibility of detecting decoupling-cavity construction, for yields from 1 to 10 kt, and *JAYCOR* [*1996*] used these results to justify its consideration of 20:1 and 10:1 cylindrical cavities in its study of specific CTBT evasion scenarios.

Based on the above theoretical and experimental work, the analysis and conclusions in this paper assume that, in air-filled caverns in which the ratio between the longest and shortest dimension is small (equal to or less than 8:1), full decoupling can be achieved for cavity volumes close to that of the spherical case. Note that, if the later S-CUBED 20:1 cylindrical calculations are correct, this may actually be a somewhat conservative assumption. However, there is still some debate over the long period decoupling effectiveness of larger aspect ratio cavities, on the generation of S-waves by highly elongate cavities, and on high-frequency decoupling ratios. If future research shows that larger aspect ratios are equally effective in cavity decoupling of nuclear explosions, this presentation and conclusions would have to be modified accordingly. Note that this assumption affects primarily the conclusions related to cavity decoupling *in hard rock*, where construction of large spherical cavities is limited by current mining technology.

Decoupling Factors in Salt and Granite

Also assumed in this paper are the decoupling factors for nuclear explosions in spherical cavities in salt and granite that were published in the 1988 OTA report ¾i.e., 25-meter (m) radius for 1 kt in salt; 20 m in granite (these radii are for explosions at 828 m depth and are depth-dependant, scaling at depth$^{-1/3}$; in order to simplify the presentation in this report, this depth is implied in all estimations of cavity radii or volume). If future research shows that these radii are incorrect (and *Sykes* [*1995*] has asserted that the radius for granite is poorly determined), this presentation and conclusions would have to be modified accordingly. However, unless these

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[6] Note that the S-CUBED work has been reviewed by Chinese scientists [*Jin et al., 1997*], who focussed on modelling the S-waves generated by explosions in ellipsoidal cavities. This suggests that there may be broad international interest in the concept of decoupling in non-spherical cavities.

are significantly increased, a change would have only minor affect in the conclusions made herein.

Environments for Underground Cavity Construction

The seismic decoupling of underground nuclear explosions requires the construction of large, unsupported cavities. In considering the potential for conducting a nuclear test underground without being detected by the various monitoring systems, a number of geologic and geotechnical issues must be considered:

- Identification of geologic environments at moderate depths[7] that are conducive to large-volume cavity development, either by conventional or solution mining;
- Knowledge of and experience using existing mining techniques at a given site (i.e., “constructability”);
- Stability of the mined cavity (including pre-test support requirements and long-term stability);
- Decoupling effectiveness of the mined cavity (for spherical, non-spherical and over-driven cavities);
- Containment characteristics of the geologic medium and the engineered access to the cavity (borehole or adit);
- Concealment of the mining operation from remote observation and public knowledge;
- Cost.

These factors must also be considered when building a monitoring plan for the verification of nuclear test limitation treaties and agreements, and should also be considered when developing a program of experimental testing to evaluate the feasibility of evasive nuclear testing and the capabilities of current and future monitoring systems.

Cavern Construction in Salt

Thick salt deposits at moderate depths (100-1500 m) probably provide an ideal environment for both cavity construction and containment. This is because of the unique rheology of salt, which is strong under short-duration loading, yet plastic, impermeable and self sealing over long periods of time. There is also little doubt about the feasibility of decoupling nuclear explosions in salt --both the U.S. and Soviet Union have detonated contained, decoupled nuclear explosions in air-filled cavities in salt, with yields up to about 10 kt [e.g., *Murphy et al., 1994; Sykes, 1995*][8]. In a review of constraints on clandestine nuclear testing in South Asia, *Davis and Sykes* [*1999*] concluded that cavity decoupling in salt is “the most plausible means by which a nation could conduct clandestine testing of militarily significant weapons” (p. 11090).

The petroleum and energy industries have constructed thousands of caverns in salt deposits for the storage of hydrocarbons, such as crude oil, natural gasoline and gas, propane, butane,

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[7] The *minimum* depths that might be required for containment of tamped nuclear explosions with yields of 1-10 kt range from 100-400 meters (i.e., *scaled depths* of 100-200 meters --see section on Containment). At shallower depths, containment is considered unpredictable; at great depths, rock may become unstable due to either overburden pressures or tectonic stresses.

[8] The yield of the Soviet decoupled test is somewhat uncertain, but probably lies in the range of 8-10 kt. The explosion was therefore only partially decoupled. While this was not known at the time the OTA [1988] report on Seismic Verification was published, it seems feasible that a slightly larger cavity could have been used without engineering difficulty, with similar containment success, and with greater decoupling.

ethylene, as well as compressed air. The former Soviet Union also constructed numerous storage caverns in salt using nuclear explosions [*Kedrovskiy, 1974*].

Salt Deposits

Salt is an evaporite, precipitated from confined saline water and concentrated by evaporation. It has a unique rheology, with a compressive strength comparable to concrete, yet at depth it deforms plastically over time to seal fractures and voids and is generally impervious to liquids and gases. It can also easily be mined by dissolution in water (including seawater). While salt deposits are found throughout the world, the distribution of salt deposits that are of adequate thickness and depth for the construction of large cavities is limited; in fact, such deposits are not present in some countries of nuclear proliferation concern [see *Leith and Rachlin, 1992,* and below].

Salt is commonly interbedded with limestone ($CaC0_3$), gypsum ($Ca_50_4*2H_20$), anhydride (Ca_50_4), sylvite (KCl), complex salts of various composition, and clastic sediments such as sandstone or shale. The bulk of the material is halite (NaCl). Bedded salt deposits can have thicknesses of less than a meter to many thousands of meters. Salts domes, or plugs, are formed when the less dense salt is forced upward by the weight of overlying denser sediments (e.g., see *Wu and Phillips* [*1964*] for the example of the Gulf Coast, U.S., region). These are relatively narrow stems of salt, generally one to two kilometers in diameter, which have intruded into the enclosing sediments from an underlying salt bed that may be hundreds or thousands of meters deep. During the growth of the salt dome, much of the interbedded impurities are left behind, so that the dome becomes enriched in halite.

Some salt domes outcrop on the surface; others may be unexposed, lying several hundred meters below the surface. Because the salt is less dense than the surrounding rocks, these unexposed domes are often mapped by gravity surveys. Most domes have nearly vertical walls, but some may overhang. The enclosing sediments are commonly turned up and complexly faulted against the dome. The more permeable beds sometimes contain oil and gas that may be trapped by the folds and faults, by impermeable beds, or by the salt dome itself. It is common that oil and gas reservoirs are found in adjacent to salt domes [*DeGolyer, et al., 1926*].

At depth, where the salt is subjected to increased pressure from the overlying sediments as well as higher temperatures, salt behaves similar to a fluid plastic (the physical properties of rock salt and other evaporite minerals can be found in *Robertson* [*1962*] and *Bell* [*1981*]). In a large dome, the rheology of the salt therefore gradually changes from a fluid condition at its base to a more plastic one at its top. When the overburden pressure is relieved, the salt becomes quite brittle. Some salt domes consist of almost pure halite. Most, however, contain varying amounts of anhydrite, which may comprise 5 to 10 percent of the mass. Salt domes commonly have a cap rock up to a few hundred meters thick, consisting of anhydrite, gypsum, calcite, and perhaps free sulfur. These minerals are probably the product of anhydrite alteration caused by the leaching of the salt face as the dome was being formed. Most cap rocks are highly fractured and contain many voids or “vugs”, or even rather large caverns.

The hard / plastic nature of salt at depth makes it an excellent medium in which to construct large caverns or cavities. The salt’s ability to yield and divert stress away from the cavern walls minimizes the stress conditions that can cause rocks to spall or cave. Storage caverns are designed and built to take advantage of these conditions.

Solution Mining

While salt can be mined by conventional methods, the most cost-effective method of constructing large cavities in salt domes is by solution mining. Solution mining is relatively inexpensive (see below), the technologically is simple, and cavern construction is quick in comparison to conventional mining. Solution mining for brine production has been around since the latter part of the 19th century. Since the 1950s, many caverns that were created for brine production have been utilized for the storage of hydrocarbon liquids and gases and compressed air. Storage caverns are now designed and built to take advantage of the in-situ stress conditions and the material properties of the salt [*API, 1994; CSA, 1993; IOGCC, 1995*].

In order for solution mining to be used for cavern construction, three conditions must be met:

- A sufficient thickness of structurally competent salt at a proper depth;
- An adequate supply of fresh or low-salinity water (including seawater);
- A means for disposal of the saturated brine.

The technology of solution mining is widely known, worldwide (see *API, 1994*, and Appendix I). The basic technique is to drill a hole into the salt dome and to pump water into the hole to dissolve the salt (**Figures 2, 3**). The pressure differential between the point of entry and the point of exit from the cavern, and the fact that the injected water is lighter than brine, causes convection, which is responsible for the major portion of the dissolution.

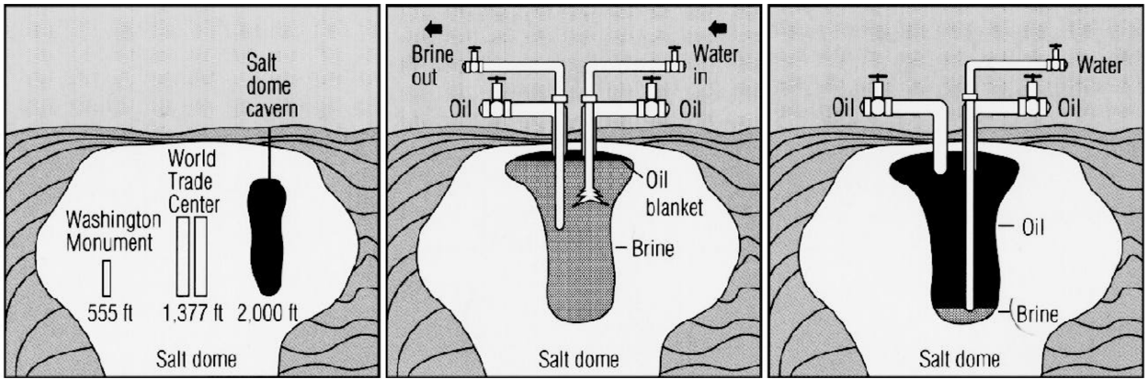

Fig 2. Cartoon illustrating the process of solution mining in a large salt dome. The diagram in the center shows the configuration during solution mining; on the right, during storage of a petroleum product. On the left, the relative sizes of a typical solution-mined cavern of the Strategic Petroleum Reserve, in comparison to the World Trade Center Buildings and the Washington Monument (Source: DOE).

Fig 3. Aerial photograph of the surface features at Bryan Mound, Louisiana, a site of the Strategic Petroleum Reserve. Note the large tanks and ponds that are typical of a storage site.

Fig 4. Photograph of a wellhead "Christmas tree" above a solution mined storage cavern, at natural gas storage well No. 2, Boling, Texas. At an operating storage cavern like Boling (which has two caverns, each 2.5 Mbbl), this may be the only visible evidence for the mining operation.

Solution mining starts with the drilling of a hole into the salt dome, using a drill rig. Various sizes of holes, casings, and pipe strings are used, depending on local conditions, regulations and other factors. In the United States, the pipe string usually is 8 $^5/_8$-inches or $10^3/_4$-inches in diameter and may extend several thousand feet. Sometimes, to decrease the cavern construction time, two or more wells are drilled and worked simultaneously. Distances between wells are tens of meters.

After the hole has been drilled and the casing cemented, a casing head is attached to the conductor casing. Additional injection wells may also be drilled if needed. The drill rig is then removed and a valve assemblage or "Christmas tree" is attached to the casing head (**Figure 4**). Pipes for raw water injection, brine removal, and blanket injection are the attached to the Christmas tree (the "blanket" is a light oil used to isolate portions of the cavern to control dissolution and, therefore, cavern shape.) For caverns to be used for storage of liquid products, a brine pond is excavated to store brine for the displacement of liquid products during cavern operation.

Either surface water or subsurface water (groundwater) can be used, or both. The water can be fresh *or saline*, but not saturated, and seawater has frequently been used. The use of subsurface water, however, requires the drilling of high-volume water wells. Leaching rates vary with the amount and salinity of the water injected. A rule of thumb in the industry is that for every seven cubic meters of fresh water injected, a volume of one m^3 is leached. Normally expressed as the amount of water or brine circulated, leaching rates can reach 1600 m^3 per day. In the U.S., leaching rates of 320,000 m^3 to 400,000 m^3 per year are common[9].

An example of the construction time for a solution-mined cavity comes from the Huntorf caverns in Germany, which were the first compressed air energy storage (CAES) caverns built for production use [*Crotogino and Quast, 1981*]. At Huntorf, two 150,000 m^3 caverns were excavated in 14 months between 1975 and 1977--an average of about 360 m^3 of salt per day, at a maximum circulation of 600 m^3 per hour. Also of interest is that it took 5 months to remove the brine from each of the Huntorf caverns, so that they could be used for compressed air storage.

Brine displaced from a leached cavern is normally first pumped into a tank so that any insoluble residues may settle out, and then disposed of by injection into subsurface saline reservoir adjacent to the salt dome. Brine is sometimes disposed of by injection into the vugs found in the cap rock at relatively shallow depths. Brine also has been disposed of in sea water, such as the Gulf of Mexico.

Large, solution-mined caverns can also be constructed in bedded salt, even if the individual salt beds are not of sufficient thickness to accommodate the entire cavern. **Figure 5** shows examples of two solution-mined caverns constructed in the Salina formation (U.S.) in bedded salt, with volumes of 116,000 m^3 and 335,000 m^3. In these cases, the insoluble (i.e., non-salt)

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[9] To obtain the same leaching capacity when using water which is 6 % saline (sea water is about 3.5% saline) another 30 % must be added to the amount of water injected (in other words, it would take 91,000 BBl of 6% saline water to get the same leaching effect as 70,000 barrels of fresh water).

residues fill a larger proportion of the base of the cavern. Cavern stability appears not to be compromised.

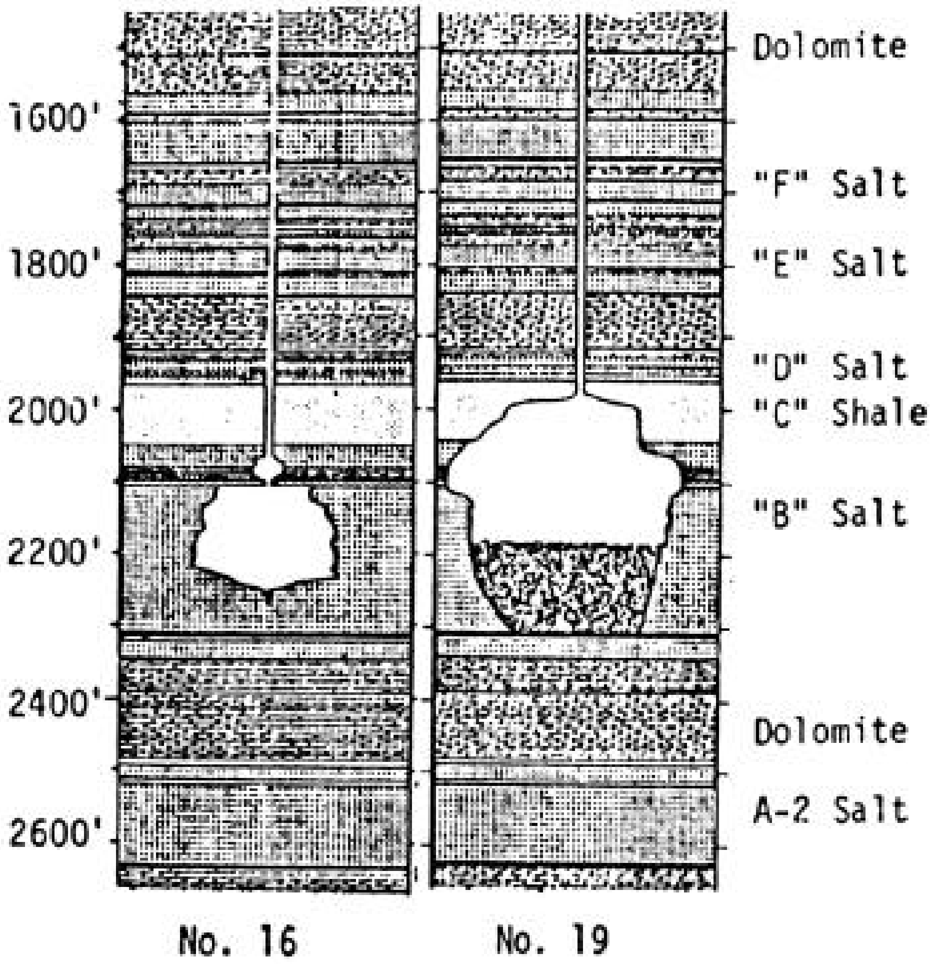

Fig 5. Stratigraphic sections of the bedded salt of the Salina Formation (U.S.), for two solution-mined caverns with volumes of 116,000 m^3 (well no. 16) and 335,000 m^3 (well no. 19).

Cavern Sizes and Shapes

More than 50 solution-mined caverns have been built for the U.S. Strategic Petroleum Reserve (SPR) in Texas and Louisiana [see *http://www.fe.doe.gov-/spr/spr.html*]. A typical SPR storage cavern holds 10 million barrels (about 2 million cubic meters) of crude oil, has a diameter of 200 ft (61 m) and a height of 2000 ft (610 m) --large enough to hold New York's World Trade Centers. The roofs of these caverns are mostly below 2000 ft (610 m).

Private entities in the U.S. have constructed cavities with capacities many times larger than those of the SPR. For example, **Figure 6** shows a schematic diagram of a Gulf Coast salt dome operated by private interests. This salt dome contains 15 caverns of various sizes. The two largest have capacities of over 17,000,000 m^3, with heights of 670 meters and diameters of 180 meters. *Permyakov* [*1986*] indicates the caverns have been solution mined with diameters of 100-150 meters and depths to 200 ft in the former USSR, Germany, and the former East Germany.

One cavern in the Macintosh salt dome of Alabama has a capacity of 315,000m^3 (19 million ft^3) and is filled with compressed air for a Compressed Air Energy Storage project in the United States [EPRI, 1994]. The cavern is about 70 meters in diameter and 275 m high; its top lies at 457 meters below the surface. It was constructed by a single leaching well over a period of 629 days. Because of its use for energy generation, it is subjected to continual cycles of pressurization-depressurization (similarly, caverns filled with natural gas are also subjected to pressure variations).

Cavern shape is controlled by varying the positions of the pipe and casings, by changing the direction of convection, the blanket placement, and by the operator's skill. To store liquid or gaseous hydrocarbons, storage caverns are frequently mined with cylindrical or tear-drop shapes.

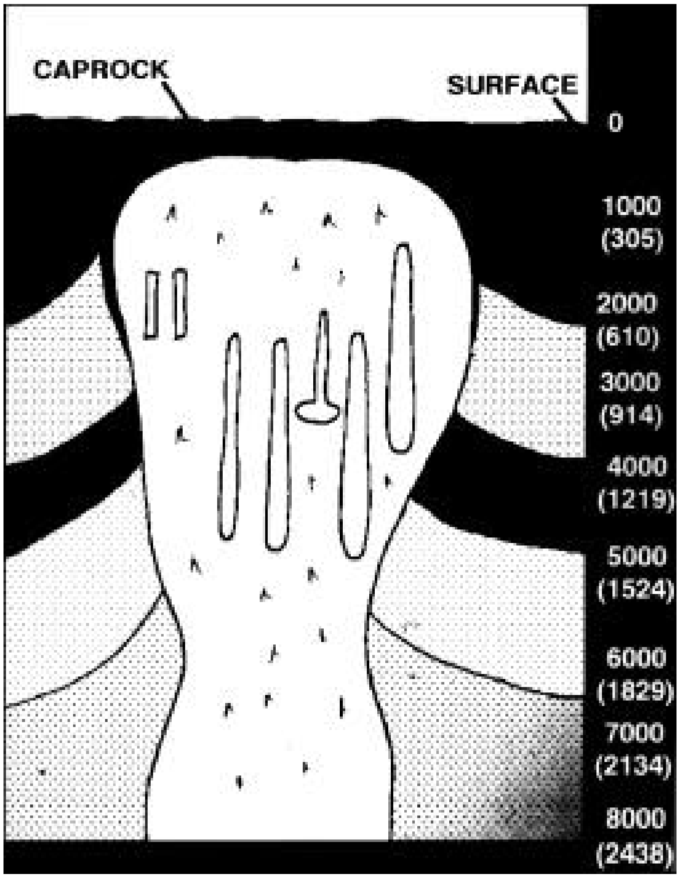

Fig 6. Diagram of a salt dome in Texas that is mined by a private company, illustrating the approximate locations and shapes of a number of huge solution-mined caverns [from D. Glover, pers. comm., 1994]. The two largest of these caverns have volumes of 17 milliom m^3.

Salt Cavern Stability

In the context of cavity decoupling, the term stability applies to periods of time measured in weeks or months —during which a cavern could be emptied and a nuclear test conducted in it— and refers primarily to a rapid reduction in cavity volume through flow of the salt at depth (also termed *creep*), and also to the possibility of cavern or roof collapse upon depressurization.

The principal factors affecting salt cavity stability are [after *Berest and Minh, 1981*]:

--cavern depth and overburden characteristics (i.e., pressure and temperature);

--internal cavity pressure (and its variations);

--cavern shape;

--salt properties (and their variability).

Cavities in salt are generally stable between a few hundred meters and about 2000 meters depth, depending on local stress and thermal conditions (**Figure 7**). Depending on the composition of the salt, the geothermal gradient and the overburden pressure, there is an elastic-plastic transition zone that occurs between ~1000 and ~2000 m deep. Cavities built below this zone may be relatively unstable and show large volume decreases through rock creep. For example, in the case of the Eminence cavern (U.S.), built at depths from 1700-2000 m, closure was 40 percent of the initial volume in just two years [*Baar, 1977*]. Cavities built above or within the transition zone can be extremely stable and may lose only a few percent volume a year, if properly located, designed and operated.

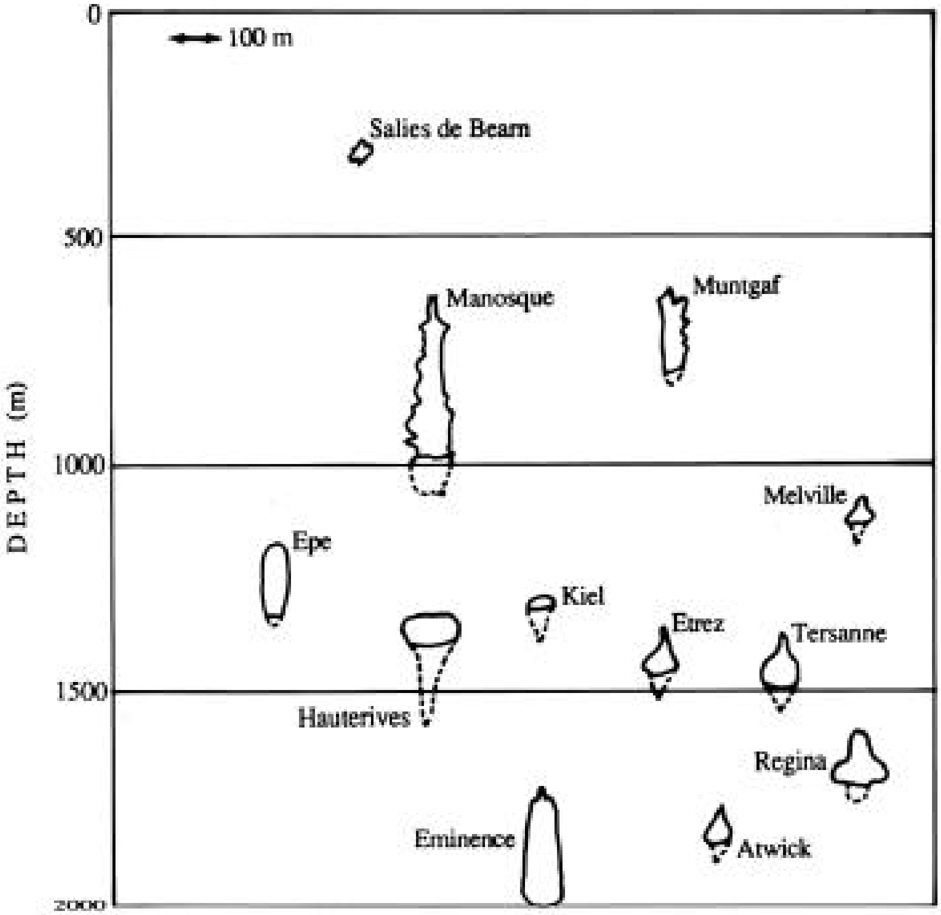

Fig 7. Illustration of the sizes and depths of large solution-mined storage caverns in salt [after *Berest and Minh, 1981*]. The dashed lines indicate the original dimensions of the caverns, after mining; the solid lines, the caverns after some period of time (which varies). Note the typical range of depths, between about 500 and 2000 meters.

Man-made cavities in salt are usually filled with a liquid or pressurized gas[10]. However, they do not, in general, fail catastrophically or close rapidly when depressurized for short periods of time. Most cavities are held at hydrostatic pressure; some may have “empty” periods (i.e., at atmospheric pressures). Few cases of catastrophic failure (collapses) are known, even upon the rapid depressurization or abandonment of a cavern. As a rare example, the roof of a cavern at Kiel, Germany, collapsed upon the pumping out of the cavity to atmospheric pressure; the volume loss was 7500 m^3, or 11% of the 68,000 m^3 cavern [*Berest and Minh, 1981*].

At moderate depths, closure rates are generally slow (e.g., mm to cm per year in Kansas and Texas salt mines, at depths to ~600 m; see *Fryklund, 1977*). This makes it conceivable to empty a cavity for a relatively long period of time (weeks to months), detonate an explosion, and re-pressurize the cavity (see estimates of required time and accompanying cavern closure in **Figure 8**).

In some cases, depressurized cavities have remained stable for decades. For example, in the 1950s, a lenticular cavern with a roof span 366 meters (**Figure 9**) was excavated by solution mining in the Bryan Mound salt dome in Texas, a site of the later Strategic Petroleum Reserve. It was constructed at an average depth of 550 meters, and a height of 55 meters. After excavation, it was filled with LPG (Liquefied Petroleum Gas) but subsequently lost wellhead pressure and was abandoned (empty). Thirty years later, measurements indicated that the cavern was remarkably stable, having lost only about 4 percent of it total volume. According to a study by *Serata* [*1984*], the stress envelope surrounding the cavern was unaffected by the loss of wellhead pressure.

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[10] Fryklund [1977] noted that “these cavities are filled with fluid for the convenience of the operator, not because of stability considerations.”

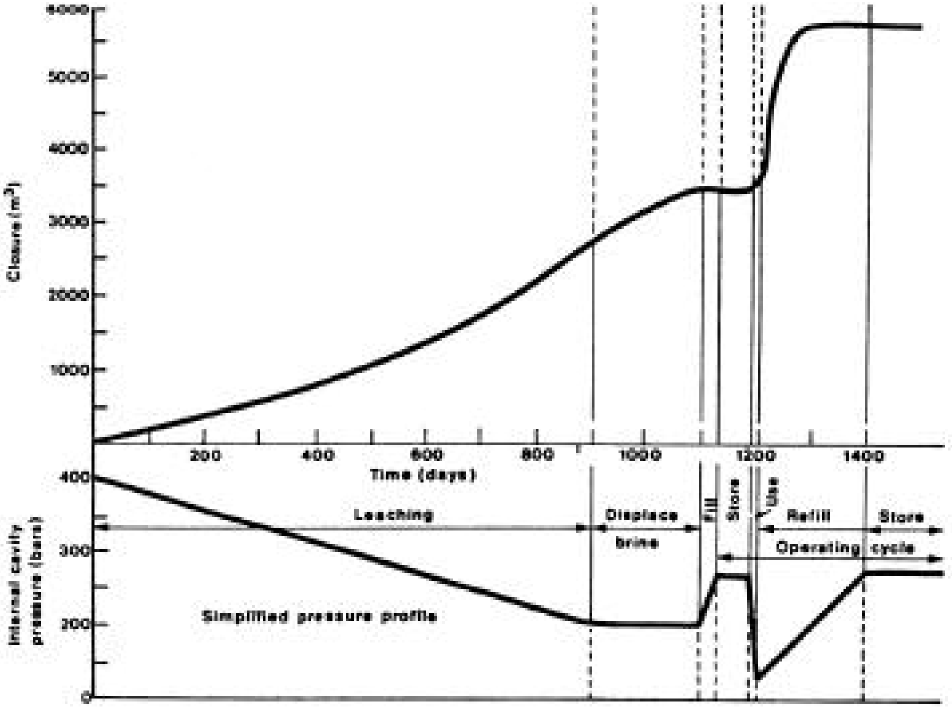

Fig 8. Graph shows the predicted closure for a 200,000 m^3 gas-storage cavity during construction and the first operating cycle. Several features are of interest: a leaching time of about 900 days; brine displacement requiring 200 days; and an overall closure of about 1% as the cavity pressure is reduced to less than 100 bars in the first operating cycle.

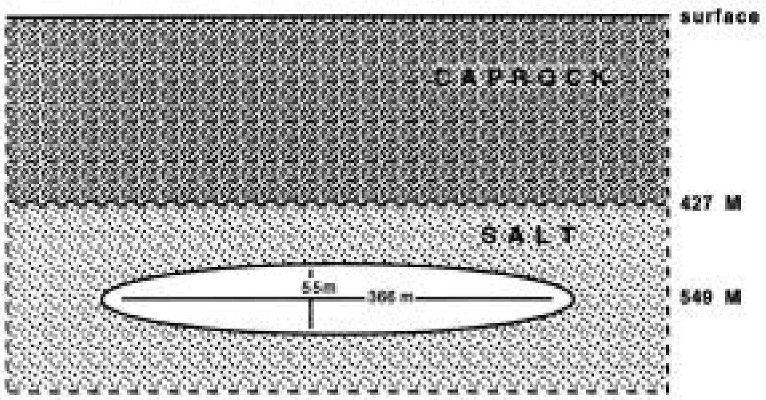

Fig 9. Size and shape of the first solution mined cavern at Bryan Mound, Louisiana. The lenticular cavern, with a roof span 366 m, at an average depth of 550 m, was excavated by solution mining in the 1950s. After excavation, it was filled with Liquified Petroleum Gas but subsequently lost wellhead pressure and was abandoned. Thirty years later, measurements indicated that the cavern was remarkably stable, having lost only about 4 percent of it total volume.

Other examples of salt-cavern stability are the CAES storage caverns at Macintosh, Alabama and Huntorf, Germany, described above. At Macintosh, during the replacement of the main operating pipe, the cavern was depressurized for more than six months. There were no roof falls, and from subsequent observations it was estimated that the volume of the cavern was unchanged [*L. Davis, Plant Manager, pers. comm., Dec. 2000*]. At Huntorf, the two cavities were held at atmospheric pressures during brine displacement and before pressurization, a process that took 5 months [*Crotogino and Quast, op. cit.*].

Also note that there was no perceptible closure of the Salmon cavity (at 825 m depth) in the 2 years between the Salmon and Sterling nuclear tests, or between the Sterling explosion and later chemical explosions (3 years) [*Fryklund, 1977*].

As far as the maximum depth at which salt caverns could be stable, *Fryklund (op cit.)* noted the following:

depth	observation
915 m	salt is being mined by conventional methods to below this depth in Canada
1280 m	stable cavity in bedded salt at Landis, Saskatchewan, Canada, *at atmospheric pressure,*
1980 m	Eminence cavern showed significant closure when internal pressure was reduced below hydrostatic
3050 m	brine cavity at Bryan Mound is open to at least this depth, but the creep rate is not known
3650 m	during drilling, salt closes in behind a drill bit
4420 m	depth of the deepest hole drilled in salt

Based on these observations, *Fryklund (op cit.)* concluded that somewhat below 6000 ft (about 2000 m) is the maximum depth for a dry and unpressurized cavity, depending on the *in situ* temperatures.

Geographic Distribution of Thick Salt Deposits

Table 1 summarizes, for the nuclear nations and states of nuclear proliferation concern, the extent and type of opportunity for large cavity construction by solution mining in salt. This information can be used both to gauge the significance of the threat of treaty evasion by seismic decoupling in salt, and to develop a monitoring strategy for the areas of greatest concern. For each country, the distribution of salt deposits suitable for solution mining is qualitatively stated, and accompanied by a brief description of the salt deposits and their extent. This work is based on previous USGS studies of geologic factors affecting seismic monitoring in the nuclear states and other countries of nuclear proliferation concern[11].

Except for North Korea, where no salt deposits have been identified, salt is present to in all countries of nuclear proliferation concern, although in a few cases (e.g., Libya, Israel, India) the identified salt deposits are very limited (and note that offshore areas have not been completely studied). Additional information on the distribution of world salt deposits can be found in *Lefond* [*1969*], *Zharkov* [*1974*], and *Vysotskii, et al.* [*1988*].

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[11] The selection of countries of interest is based on *Jones et al* [*1998*], and has no official U.S. Government status. The countries are the nuclear weapons states (CH, FR, RS, UK, US), the non-NPT nuclear weapons states (IN, IS, PK), and the “high-risk” states (IR, IQ, LI, KN), as defined in *Jones et al*., p. 11.

Table 1. Geographic distribution of salt deposits suitable for solution mining in nuclear states and some countries of nuclear proliferation concern (see footnote 10). Offshore deposits are not fully studied in most cases.

Country	Distribution	Description
China	widespread	
France	widespread	
India	very limited	rare salt occurrences along faults in the Kumaun Himalaya are of unknown extent and thickness
Iran	widespread	
Iraq	widespread	domes and bedded salt occur in a belt extending across the foothills region between Iran and Syria
Israel	very limited	limited to the Dead Sea region; thickness and depth not known
Libya	very limited	salt outcrops in northwestern Libya, near the border with Tunisia are of unknown thickness and depth
North Korea	none described	
Pakistan	limited	deposits known from the Salt Range and Sargodha
Russia	widespread	
U. K.	limited	
USA	widespread	

Construction Feasibility

Table 2 summarizes the constructability of large volume caverns in salt, in terms of the fully-decoupled yield of nuclear explosions in the range of 1 to 50 kt. In the table, the full decoupling radius (from *OTA, 1988*) is used to calculate a spherical cavity volume. From that, the dimensions of an equal-volume cylinder are calculated, with a length to diameter ratio of 4:1 (to approximate the ellipsoidal cavity dimensions in the decoupling calculations of *Stevens et al., 1992)*. The judgement of construction feasibility is based on the previous discussion and information on the sizes and shapes of existing solution-mined caverns.

Note that cavities in salt domes with volumes in excess of 2,000,000 m^3 are rare, but cavities of 17,000,000 m^3 have been constructed. Note also that *Fryklund* (*op cit*., p. 51) likewise concluded that, "*cavities large enough to decouple nuclear explosions with yields up to, and possibly exceeding, 50 kt could be excavated at a large number of sites in several regions of the USSR*" (although even a decoupled 10 kt explosion would be identified by current seismic monitoring systems in some areas; see below).

Table 2. Feasibility of large cavern construction in salt, based on known cavities of equal volume and/or diameter and expressed as a comparable-size, 4:1 scale cylinder. Note that at aspect ratios of ~8:1, all volumes are feasible (common).

yield	full decoupl. radius	spherical cavity volume	diameter x height dimensions of a 4:1, equal-volume cylinder	construction feasibility
1 kt	25 m	65,500	28 x 110 meters	feasible
5 kt	43 m	333,000	47 x 189	feasible
10 kt	54 m	659,600	60 x 238	feasible (common)
20 kt	68 m	1,317,000	75 x 300	feasible
50 kt	92 m	3,261,800	101 x 404	feasible (rare)

Cost

Solution mining permits large-scale cavern excavation at a relatively low cost. This is evidenced by the fact that there are literally hundreds of commercially-developed, solution mined cavities in salt, that are used primarily for hydrocarbon storage. Estimates from the early 1990s were \$0.11-0.14 per cubic meter of salt leached (i.e., \$110,000 - \$140,000 for a 1,000,000 m^3 cavern). A cost of only \$0.084 to \$0.113 per cubic meter (\$3 to \$4 per thousand cubic feet) is quoted by *ICF Resources* [*1989*], for installing wells, compressors, pipes and other hardware, and leaching caverns for gas storage.

In 1992, for the construction of "Big Hill", a 14.3 million cubic meter, solution-mined cavity of the U.S. Petroleum Reserve, the leaching cost was estimated at \$1.80 per cubic meter of salt excavated, and the total cost of the project (including land acquisition, design, site development, pipeline development, drilling, hydrocarbon interfaces, etc) was \$21.80 per cubic meter. This is consistent with total costs for oil storage in salt domes estimated by *Bergman* [*1984*] at less than \$25 per cubic meter (in 1981 dollars), for caverns of $1Mm^3$.

At \$1.80 per cubic meter leached, the following costs would be incurred for various decoupled yields (with decoupling volumes, and therefore costs, dependent on depth):

yield	volume (m^3)	leaching cost
1 kt	65,500	\$118,000
5 kt	333,000	\$600,000
10 kt	659,600	\$1,187,000
20 kt	1,317,000	\$2,371,000

These costs are considered to be quite small in comparison with the overall cost of a nuclear weapons development and testing program, and about an order of magnitude less than the estimated costs of similar construction in hard rock.

Cavern Construction in Hard Rock

Hard, high-strength, low-porosity rocks are of widespread occurrence, making up the bulk of the Earth's crust, and this geologic environment is present in every country of nuclear proliferation concern [*Leith and Rachlin, 1992*]. Typical rocks in this category include most of the plutonic igneous rocks (e.g., granites) and most metamorphic rocks (e.g., schist, gneiss). For the purposes of this discussion, a hard rock geologic environment is any high-strength, low-porosity rock in which the rock mass has a quality of "good" or higher (i.e., with a Rock Mass Rating, $RMR > 60$, or Rock Quality, $Q > 10$; see *Bienawski, 1984, Fig. 6.6*).

Even in the mid-19th century, large underground caverns were constructed with spans of more than 10 meters and volumes over 20,000 m^3. For example, **Figure 10** shows a recent interior view of the "Box Cathedral," an unusual quarry in Wiltshire, England, that was worked by hand from a vertical shaft, beginning in 1830. This room has an unsupported span of 40ft (13m), length of 200ft (61m), and height of 90ft (27m).

Fig 10. Recent photograph of the interior of the "Box Cathedral," a large cavern in Wiltshire, England, that was worked by hand from a vertical shaft, beginning in 1830. This room has an unsupported span of 40 ft (13 m), a length of 200 ft (61 m), and a height of 90 ft (27 m).

Large Unsupported Spans

By 1980, numerous large caverns in hard rock had been built with unsupported spans[12] over 30 meters and volumes over 200,000 m^3. Compilations of data on large cavern construction were published in *Hoek* [*1980, 1989*]. *Willett and Curtis* [1981] compiled data for 30 man-made caverns with spans up to 33.5 m and depths to 2130 m. Data on large caverns in France have been published by *Duffaut et al.* [1987], including unsupported spans up to 35 meters.

Table 3 lists fourteen underground cav-erns with volumes over 200,000 cubic meters, and Appendix II lists 80 underground caverns with unsupported spans greater than 23 m (75 ft). These include the Norwegian "rock record" --an underground Olympic sports hall that was constructed in the early 1990's with a 61-meter unsupported span (**Figure 11**). The largest known, unsupported, man-made underground opening is a *stope (*see footnote 12) at the Joma copper mine, in Norway, that has a span of 70 meters. Also included are the Tytyri limestone mine (60 meter stope), and the Vihanti mine (40 meter stope).

According to *Johansson et al.* [*1980*]:

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[12] In the context of this discussion, "unsupported" implies the absence of pillars left during mining to support the roof of the underground opening. In practice, few underground openings that are slated for personnel access are left truly unsupported; generally, these are "engineered openings" in which the roof is supported by rock bolts or cable bolts. In contrast, the use of the term *stope* does imply a complete lack of roof support. Stopes are generally not intended for personnel access.

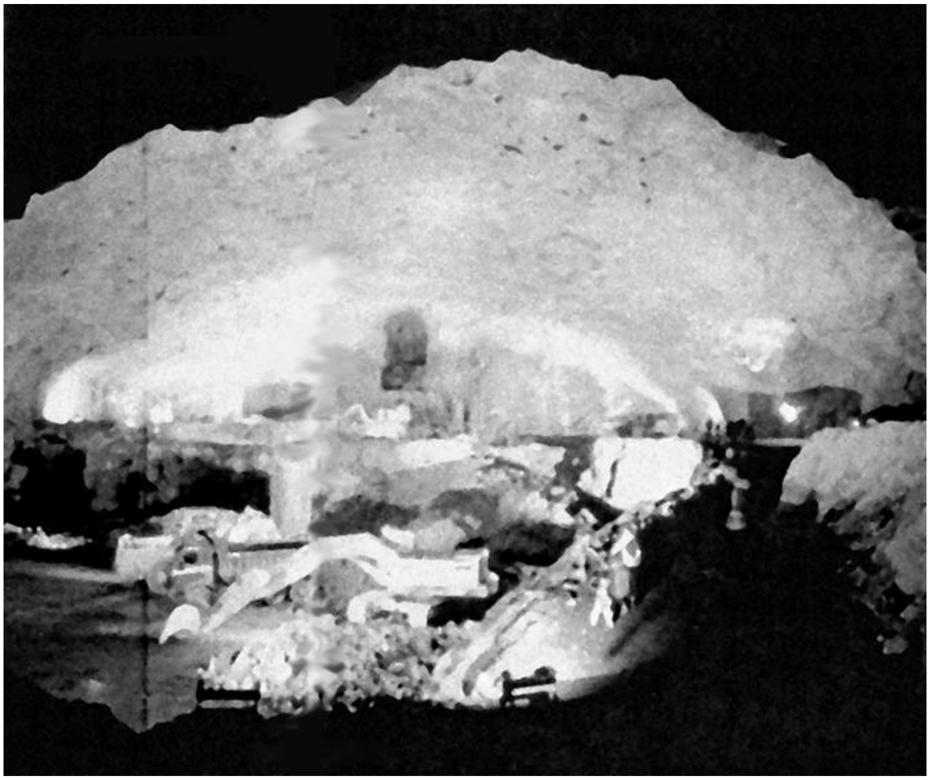

Fig 11. Photograph of the interior of the Olympic sports hall at Gjovick, Norway, during construction in 1991 [from *Wheeler, 1992*]. The main hall has an unsupported span of 61 meters, among the largest constructed in hard rock, a length of 90 m, and a height of 25m, at a depth of 25-50 m.

Table 3. Examples of cavities in hard rock with volumes over 200,000 cubic meters, unsupported spans of 24 meters or more, and depths of 100 meters or more (from *Hoek and Brown, 1980; Hoek, 1989*, and Appendix II).

Country	Cavern Name/Use	Rock Type	Est.Vol.m^3	Dimensions (LWH), depth
Nepal	Chisipani (proposed)	Sedimentary	900,000	700 x 28 x 50 at depth??
Gr. Britian	Bulk Storage Facility	unknown	788,000	900 x 25 x 35 at depth??
Canada	La Grande Pwr. Sta.	Gneiss	600,000	483 x 27 x 47 at 100 m
China	Ertan Hydro Power	Syenite, Basalt	421,000	240 x 27 x 65 at 250 m
Tadjikistan	Rogun Turbine Rm.	Sandstone	381,000	200 x 28 x 68 at 351 m
Canada	Kimano Power Sta.	Granitic	360,000	347 x 25 x 42 at 300 m
Finland	Vihanti mine	Dolomite	350,000	150 x 40 x 160 at 200 m
Canada	Churchill Mach. Hall	Gneiss	348,000	296 x 25 x 47 at 294 m
Indonesia	Cirata Hydro. Pwr.	Breccia, Andesite	320,000	253 x 35 x 49.4 at 109 m
Mozambiq.	CaboraBassa PwrSta	Gneiss	300,000	220 x 27 x 57 at 160 m
Canada	Mica Dam Power Sta.	Gneiss	250,000	237 x 24 x 44 at 200 m
Japan	Shintakasegawa Pwr.	Granite	240,000	163 x 27 x 55 at 250 m
Gr. Britian	Dinorwic Power Sta.	Slate	225,000	180 x 24 x 52 at 300 m
Japan	Imaichi Power Sta.	Sandstone, breccia	220,000	160 x 33 x 51 at 400 m

> "*No limitations are imposed on the size of a rock cavern by the rock itself. In suitable rock conditions, spans of hundreds of metres are possible.*"[13]

This statement is supported in a number of publications by observations of numerous natural caves with spans of over 50 meters (see **Figure 12**). The largest known cave, in Indonesia, has a span of over 400 meters. In France, a rock cave with a span of 230 m has a total volume of 11 million_m^3.

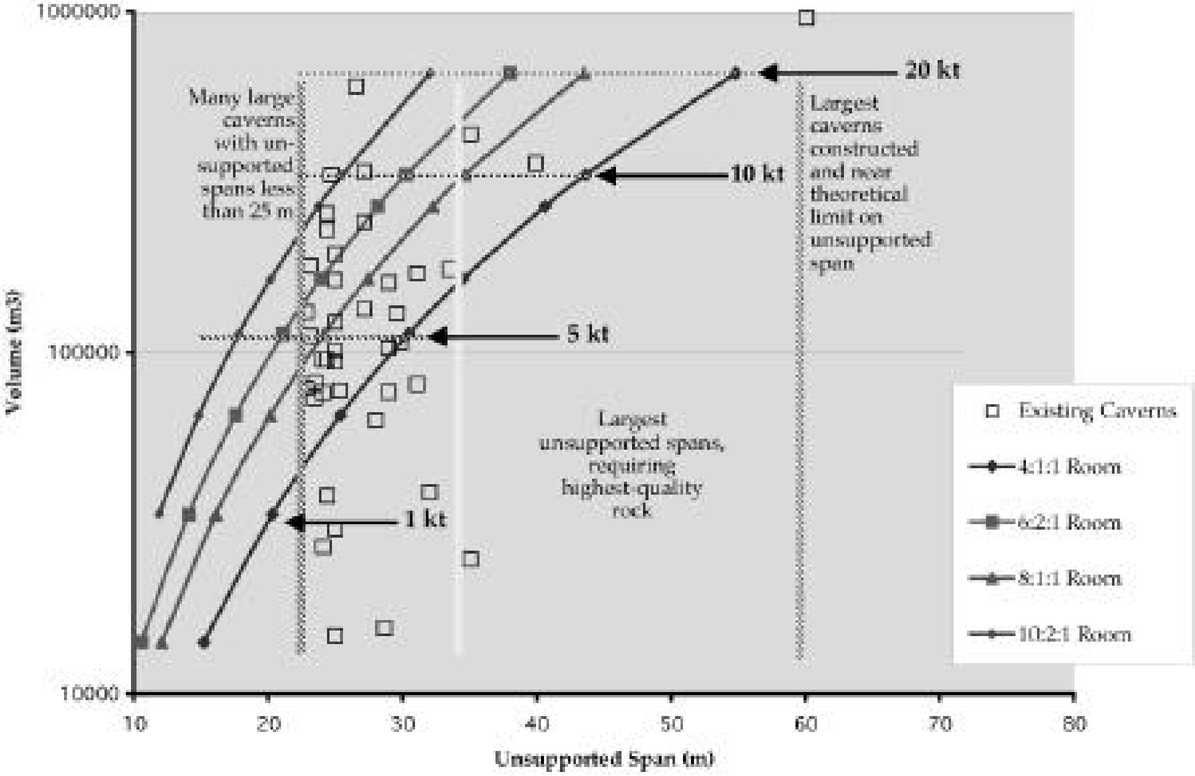

Fig 12. Plot of unsupported span versus cavity volume for 43 of the facilities with spans over 25 meters listed in Appendix II. The curves are span vs. volume for rooms of various aspect ratios (see legend box); the arrows indicate the volumes necessary for full decoupling in hard rock at various yields. Note that unsupported spans over 35 meters and/or volumes over about 350,000 m^3 (at 10 kt) are rare (see Table 4).

Of the caverns listed in Appendix II, the 45 with volumes that can be calculated from the available dimensions are plotted on **Figure 12**. Depths range from 20 meters to over 1400 meters: 36 facilities have depths over 100 meters; 26 over 200 meters, and 7 over 400 meters. Of the 43 facilities that have both span and volume information; only four have spans of 35 meters or greater and volumes over 300,000 m^3.

Many underground caverns have been constructed with spans of 30-40 meters. For example, the Chinese have built an aircraft hall with a span of 42 meters [*Wu et al., 1982*], and an underground power hall with a span of 31 meters [*Zongliang and Bingjin, 1980*]. In both Japan and Indonesia, hydropower turbine halls with spans of 35 meters have been built in poor-quality rock [*Kamemura et al., 1987*]. Two underground ice hockey halls have been constructed in Finland, with spans of 32 meters [*Roinisto, ed., 1986*].

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[13] A similar statement was made by N. Barton, in a telephone conversation with Dennis Lachel in Aug. 2000 (D. Lachel, pers. comm., 21 Aug. 2000). Barton said that "he did not believe that there was any limit on the maximum potential span width in competent rock."

A correlation between rock quality and maximum unsupported spans for underground opening in hard rock published by *Barton and others* [*1980*] is shown in **Figure 13**. This figure is consistent with the data in Appendix II, and indicates that the largest unsupported spans require exceptional rock quality. However, this trend appears to be contradicted by the construction of the Olympic Sports Hall at Gjovick (61-meter span, plotted and labeled on the figure), which was constructed in rock in only "good" quality (average Q = ~30). Over all, the available data indicate that numerous facilities have been built with unsupported spans up to about 35 meters, suggesting that such construction is not "heroic."

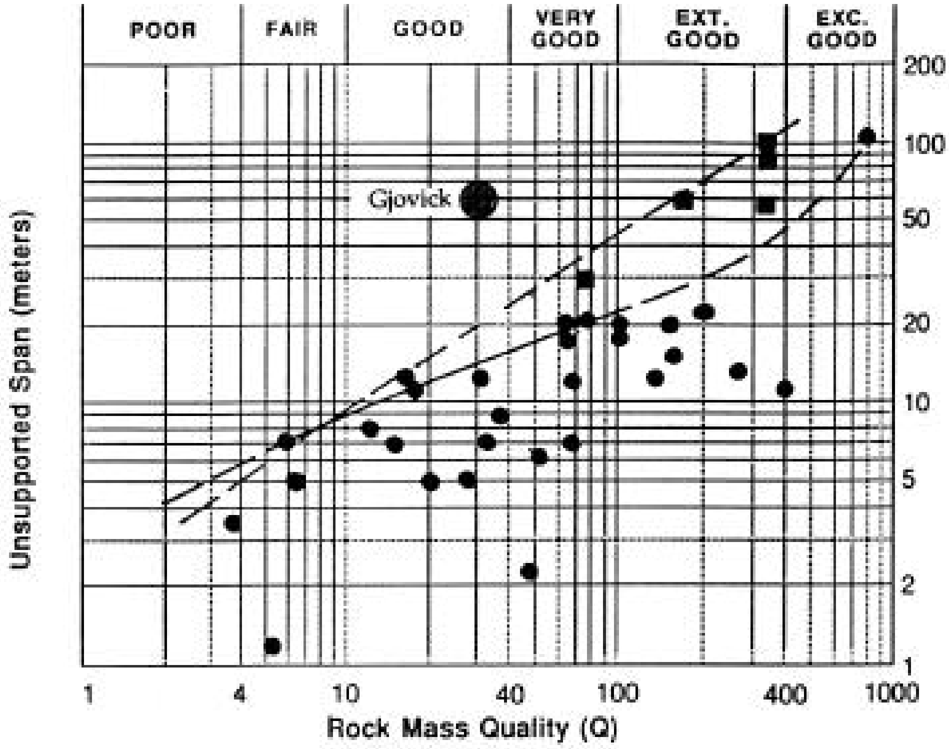

Fig 13. Plot of rock mass quality (Q) versus unsupported excavation span. Circles are man-made caverns; squares are natural caverns. The curved envelope is an estimate of the maximum design span for permanently-supported man-made openings [from *Bienawski, 1984,* after *Barton et al., 1980*]. Note that the single man-made opening with a span over 100 meters cannot be confirmed. Also plotted is the Olympic sports hall at Gjovick, Norway, a 61 meter span in rock with an average rock mass quality of 30 [*Barton et al., 1991*].

Maximum Depths

The construction of large openings at great depth is limited by the increased stresses in the rock (which may approach the strength of the rock mass) and by cost. For civil construction (powerhouses, pump houses, etc.), requirements for deep construction (e.g., over 1000 meters) are rare, but a number of examples exist. For example, a potash mine in Saskatchewan, Canada, has caverns with multiple adjacent roof spans of 20.4 meters at a depth of over 1200 m) [*Serata, 1984*]. By the late 1970s, Swedish workers had constructed a number of large chambers at depths from 500-900 meters at the iron ore mines at Kiruna and Malmberget [*Hansagi and Hedberg, 1978*].

Among the deepest man-made caverns in hard rock is the Sudbury Neutrino Observatory, in Ontario, Canada. There, at a depth of over 2 kilometers, a large (22 m diameter by 10-stories tall) cylindrical cavern has been constructed at the base of a deep nickel mine (see Appendix V). The cavern was constructed uniform rock in a low-stress portion of the mine, over a period io 30 months between 1990 and 1992.

As noted above, *Willett and Curtis* [1981], in a study of the feasibility of constructing large, deep caverns (up to 6.1 million cubic meters at depths up to 1500 meters), compiled data for 30 man-made, civil and military caverns with depths to 2130 m. Below 1000 meters, cavity dimensions and volumes are typically smaller, and spans reached only 18 meters (with cross-sectional areas of 280 m^2). Four cases were noted wherein the underground stresses approached the strength of the host rock mass (note that such large depths are not required for containment, see below). In contrast, at moderate depths (150-750 meters), spans up to 35 meters and cross-sectional areas up 1000 m^2 were found.

For military construction, where there may be requirements for depth, there is generally not a requirement for large openings (or there is no knowledge of the underground configuration). However, there are anecdotal examples of deep underground construction (e.g., jet fighter storage caverns) that indicate that large openings have been built. An example is the underground nuclear power station of the Krasnoyarsk (Russia) Mining Chemical Combine. This facility, constructed in the 1950s at a depth of 250 meters in hard rock, consists of a number of chambers with spans up to 20 meters, heights to 60 meters, and lengths to 300 meters [*Zverev et al., 1995*].

It is also important to note that high natural rock stresses may, in some places, be present at very shallow depths --less than 100 meters. Planning a deep underground excavation therefore requires detailed site investigations, in-situ testing and, for a new location, exploratory drilling.

Construction Feasibility

It is rare that large underground caverns are constructed in a spherical geometry. Linear, arched-roof rooms are common, and a number of hemispherical caverns have been built (see Appendix II). Because of the technological challenges of building large, unsupported spherical openings, as well as the large costs involved (see below), it is assumed here that for decoupling an underground nuclear test of 1 kt or more, it is both necessary and sufficient to rely on non-spherical cavities; i.e., underground rooms, either arched-roof “boxes” or caverns with cylindrical shapes.

The available information on cavern construction is summarized in terms of decoupling volumes and decoupled nuclear yields in **Table 4** and **Figure 12**. Underground cavities --built as rooms with aspect ratios from 4:1:1 to 8:1:1-- of sufficient volume, span and depth to fully decouple 1 kt in granite are not uncommon. Underground caverns with larger unsupported spans (up to 30 meters) and volumes (over 160,000 m^3) are sufficiently numerous that it appears feasible to construct a decoupling cavern for explosions of 5 kt or more.

For yields up to 10 kt, unsupported spans and cavern volumes are sufficiently large that such construction is rare, and larger aspect ratio rooms would be required (8:1:1 or larger). But note that cavities with volumes over 500,000 m^3 are known, and the largest cavity spans (intermediate dimension) that have been constructed are 61 m for drift-type construction and 70 meters for stope-type construction.

While the construction of large-span openings requires considerable expertise, the methods, equipment and design technology used “are extensions of those used in most underground construction activities found throughout the civilian sector, worldwide” [*Knowles et al., 1994, p. 7*]. However, for many “third world” countries of nuclear proliferation concern, some of the necessary technologies would have to be imported (**Figure 14**). It may be feasible to monitor international markets for sales sophisticated construction equipment and technological expertise.

Fig 14. Photograph of a drilling "jumbo," an example of the type of specialized equipment necessary to construct large caverns in hard rock.

Table 4. Feasibility of large cavern construction in hard rock, based on known cavities of equivalent volume and/or span and expressed as a comparable-volume, 8:1:1 or 4:1:1 scale room. Decoupling radii are for "granite."

yield	full decoupl. radius	spherical cavity volume	unsupported span of a 4:1:1 equal-vol. room	same, for 8:1:1	construction feasibility
1 kt	20 m	33,500	20.3 meters	16.1 m	feasible (common)
5 kt	34 m	164,500	34.5 m	27.4 m	feasible
10 kt	43 m	333,000	43.6 m	34.6 m	feasible (rare; Note 1)
20 kt	54 m	659,600	54.8 m	43.5 m	not feasible (Note 2)

Notes:

1. While cavities over 500,000 m^3 are known, the largest unsupported cavity spans that have been constructed are 61 m for drift-type construction and ~70 meters for stope-type construction. Barton (1980) suggests that such openings are constructed only in "exceptionally good" rock.
2. Few cavities of this unsupported span are known in hard rock, and none of this combined span and volume. However, note that *Laneus* [*1987*] has proposed cost effective methods for huge cavities (1,000,000 cubic meters), at depths of 1000 meters or more (see **Figure 15**). It is not known that any such cavern has actually been built.

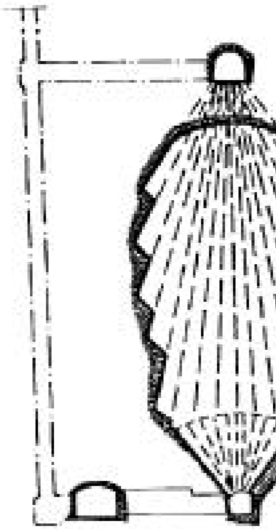

Fig 15. Design of a 1-million m^3 cavern to be constructed in hard rock by the longhole stoping method [from *Laneus, 1986*].

Cost

Costs for construction of large underground decoupling cavities were estimated by Lachel and Associates, Inc., for the Defense Special Weapons Agency in 1994 [see *Linger et al., 1995*]. **Table 5** presents these estimates, which include a breakdown for the excavation and support costs (but not access tunnel construction, see notes to the table). Comparison to yield is given on the left; these are taken from *OTA* [*1989*]. The same values are presented in **Figure 16**, which shows graphically the rapid increase with increasing cavity size. Note that these costs are more than an order of magnitude larger than those for solution-mining a similar-size cavern in salt. Note that the Lachel and Associates' estimated costs are consistent with those estimated by *Bergman* [*1984*] for cavern construction for oil storage; the latter ranged from $30-60 per cubic meter for caverns in the range of 100,000 m^3 to 1,000,000 m^3 (in 1981 dollars).

Table 5. Cost estimates for construction of cavities in hard rock (in 1994 dollars), as a function of decoupled yield, for spherical, rectangular and cylindrical caverns (from *Linger et al., 1995; JAYCOR, 1996)*. *The abbreviation NF means that this project was deemed "not feasible." Costs estimated in the JAYCOR study for a cylinder with an aspect ratio of 20:1 were the same as for a 10:1 cylinder of the same volume.*

decoupled yield, in kilotons	spherical volume in cubic meters	spherical cavity cost, in 1994 $USD	4:1:1 equal-volume chamber cost, $USD	10:1 or 20:1 cylinder equal-vol. chamber
1	33,500	2.4 M	2.2 M	2.4 M
5	168,000	13.1 M	11.9M	14 M
10	335,000	30.2 M	24.9 M	25 M
20	670,000	NF	53.8 M	55 M

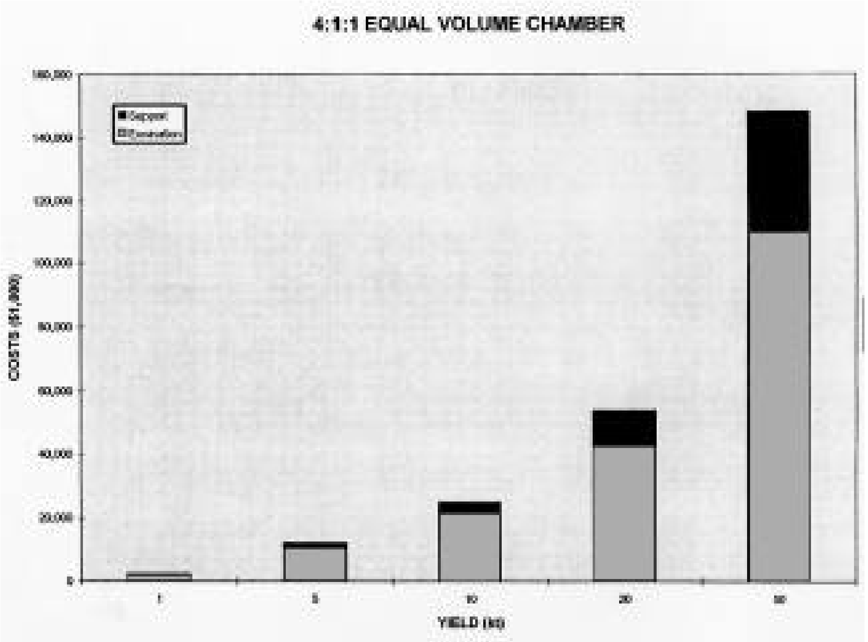

Fig 16. Construction costs (excavation and support) for a 4:1:1 chamber in hard rock, as a function of fully decoupled yield [from *Linger et. al.*, 1995; costs estimated by R. Linamen, Lachel and Assoc., Denver].

Note that it was judged to be not feasible to construct *spherical* cavities in hard rock for fully decoupling explosions larger that 10 kt (an older example of cost estimates for *hemispherical* cavities can be found in *EDAC* [*1978*]). On the other hand, costs for non-spherical cavities were estimated for rooms up to 50kt. While at the larger yields these costs are large, they are not overwhelming when compared to the overall cost of a nuclear testing program [*JAYCOR, 1995*].

As noted in *Knowles et al.* [*1994*], costs vary considerably depending on the rock environment and depth, but are not prohibitively expensive ($100-$300 per cubic meter excavated, based on U.S. labor costs and safety requirements). In the case of cavities created by ore extraction, the excavation costs are partially offset by the value of the extracted ore.

These estimates also do not include the cost that would be incurred to conceal this construction from detection (see Discussion, below). But keep in mind that, if the construction is within or adjacent to an existing mine (surface, underground or both), some of the expense of the cavern construction would be taken up by the existing infrastructure. This would also greatly improve the prospects for avoiding detection during the construction phase.

Containment of Explosion Products

Definitions of Containment

The Limited Test Ban Treaty of 1963 defined an international requirement for adequate containment of the radioactive products of underground nuclear explosions. Article 1.1(b) of this treaty prohibits and explosion that "*...causes radioactive debris to be present outside of the territorial limits of the State under whose jurisdiction or control such explosion is conducted.*" Using this simple criterion, one might judge that the majority of U.S., Soviet, Chinese and French underground nuclear tests, which were detonated in hard rock, were "contained," at least in terms of LTBT compliance[14]. However, both the U.S., the Soviets/Russians and the French have developed more sophisticated definitions of containment, as follows.

The U.S. defines successful containment as "*such that a test results in no radioactivity detectable off-site as measured by normal monitoring equipment, and no unanticipated release of radioactivity on site within a 24-hour period following execution*"[15]. The U.S. further characterizes prompt (seconds to hours), high-release containment failures as "venting", and late-time, small, slow radiation releases as "seeps" (see *OTA*, *1989*). Also defined are "controlled tunnel purgings," which are mostly small, intentional releases of gasses trapped in sealed tunnels, and "operational releases," which are also small releases upon post-test sampling (tunnel reentry or drill-back). Early ventings (e.g., DesMoines, 1962, and Baneberry, 1970) account for the major radioactivity release from U.S. underground tests (more than 25 million curies). Since Baneberry, there have been only two ventings that released more than 1000 curies (Diagonal Line, 1971 and Riola, 1980), and only one seep releasing more than 100 curies (Tierra, 1984). Note that only one post-Baneberry test (Cannikin) was conducted in either salt or hard rock, and none were fully decoupled[16].

In contrast to the U.S., both the Soviets and the French conducted all of their underground military nuclear tests in salt or hard rock[17]. These countries have recently described their under-

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[14] Note that the U.S. and the Soviet Union differed in their interpretation of the LTBT definition of radioactive debris.

[15] Charter of the Containment Evaluation Panel, Article VIII, subpara. F.

[16] Some DNA tests were partially decoupled.

[17] The term "hard rock" is here liberally extended to include the basalts at the French Pacific underground nuclear test site, which vary greatly in their physical properties [*Int. Geomech. Comm, 1999*]. Rock Mass Ratings range from good to very good (60 < RMR <100); strengths range from 20-200 MPa but are mostly in the range of 75-100 MPa; porosities average 25%.

ground nuclear test containment records in terms similar to (or derived from) the U.S. definitions of containment failures described above. The next three sections of this paper review this information.

While the above definitions of containment are relevant and can be used to review the available information on the containment of underground nuclear tests, under the CTBT, the new *de facto* criterion for "containment" will be non-detection by the radionuclide monitoring system of the International Monitoring system (IMS). While there is no specific capability established for this monitoring system, it was apparently evaluated with respect to its ability to detect the venting of 10% of the radioactive gasses from a 1 kt underground nuclear explosion within 12 hours of the explosion (specifically, about 10^{14} Bq of ^{133}Xe; see the Working Papers of the Conference on Disarmament *CD/NTB-/WP.224* and *CD/NTB/WP.283,* 1995).

How this relates to the previous definitions of containment cannot be quantitatively stated, however, the 10%/12hr criterion appears to describe a *prompt vent*. Therefore, the following assumptions are made in this paper:

- a *prompt vent* may be rapidly detected and characterized (*i.e.*, 10% of the radioactive gasses from a 1 kt underground nuclear explosion, within 12 hours) ;
- a *seep* may not be detected and characterized (*i.e.*, less than 10% of the gasses of a 1 kt underground test, *or* up to 10% of the gasses but over a period of time longer than 24 hours).

U.S. Experience in Salt and Hard Rock

U.S. conducted only 12 nuclear tests in salt or hard rock (**Table 6**), of a total of 815 underground nuclear explosions [*NRDC, 1996*]. All but one of these tests were conducted before Baneberry (1970), and therefore without the benefit of the increased scrutiny given to containment designs following that test and the formation of the Containment Evaluation Panel. Only the Sterling test, conducted in 1966 in salt, was decoupled.

Table 6. U.S. Nuclear Explosions in Salt and Hard Rock (after *Boardman, 1970,* and unpublished USGS technical reports)

Name	Date	Geology	Yield	Depth	Scaled Depth (m/kt$^{1/3}$)
Gnome	611210	salt	3.4	360	240
Hard Hat	620215	granite	4.9	285	170
Shoal	631026	granite	12-13	368	~160
Salmon	641022	salt	5.3	830	475
Handcar	641105	dolomite	12	402	175
Long Shot	651029	andesite	80-85	2300	~160
Sterling	661203	salt cavity	0.38	830	1145
Pile Driver	660203	granite	61	464	120
Gasbuggy	671210	shale	26	1292	435
Rulison	690910	sandstone	40	2542	745
Milrow	691002	lava & breccia	~1030	1218	~120
Cannikin	711106	basalt	~4300	1958	~120

Except for the first of these tests, Gnome[18], none had prompt venting, although more research is needed to determine whether any seeped or had significant operational releases. The containment records of these tests were not presented in the 1989 OTA report, which only provided detailed histories for the few uncontained tests conducted on the Nevada Test Site (NTS) since Baneberry. In that report it is noted that the pre-1970 record is incomplete. The subsequent (1995) review of containment published by the Department of Energy and Defense Nuclear Agency [*Carouthers, 1995*] contains only anecdotal information on the containment of a few of these tests.

Because of this lack of information, one must rely for containment study on the more complete information that has been published in recent years by the Russians and the French (see below).

Of particular interest are the containment records of the U.S. tests in salt, Salmon (1964) and Sterling (1966). Analysis of ^{85}Kr and ^{131}Xe isotopes from gas samples taken from the Salmon cavity 4.5 months after the test indicated that very little if any radioactive gasses escaped from the cavity [*Rawson et al., 1968*]. In fact, pressures inside the cavity were less than atmospheric (air was sucked into the cavity when penetrated during drillback) and the cavity was dry. Note that a similar environment was encountered by the Soviets during drillback into the Azgir A-III salt cavity, three months after the explosion (see below).

The containment of the decoupled explosion, Sterling, was also excellent. According to the Project Manager's Report [*REECO, 1967*], no positive radiation measurements were reported by the ground and aerial instruments surrounding the ground-zero and to distances of several kilometers, and levels remained at background following the test. At 2 hours 35 minutes after the blast, a positive radiation measurement was recorded on a downhole gamma detector probe. Apparently, radioactive gas had migrated along the firing cable. At the surface, this cable was then cut and embedded in a sealant. Monitoring equipment indicated only nominal exposure rates, of 0.3 mR/hr. On-site air sampling indicated only natural background radioactivity. There was no indication of any geologic or stemming containment failure, and recent interviews with several of the key participants in the fielding and evaluation of that test indicate that the test probably did not even seep (G. Higgins, D. Springer, W. Woodruff, pers. comm., Jan. 2001).

Soviet Experience[19]

Based on the early underground nuclear tests, the Soviets had, by the early 1970s, developed the following criteria for minimum depth of burial, at each of their principal underground test sites:

Degelen: $W_m = 70\ q^{1/3.4}$

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[18] According to Higgins (in *Carothers et al, 1995,* p.551), containment of the Gnome event was lost by venting past the gas seal through a clay seam just above the tunnel: "There was no evidence of anything except steam in the fracture or shaft. Leakage must have come from the cavity after it formed, through that [clay] seam, bypassing all the engineered features."

[19] This summary is draws from discussions with Dr. Vitaliy Adushkin, Director of the Institute of Dynamics of Geospheres of the Russian Academy of Sciences (RAS), that were held between 13-17 October, 2000, reported by *Leith and Knowles* [*2000*]. Dr. Adushkin has 40 year of experience working in the fielding of atmos-pheric and underground nuclear tests, and his institute had responsibility for making specific recommendations for minimum depth-of-burial and containment plans for many Soviet under-ground nuclear tests. His institute was formerly known as the "Spetzsektor" (Special Section) of the Inst. of Chemical Physics of the RAS, and has supported both the Soviet Ministries of Atomic Energy and Defense in their nuclear testing programs. He was also at times either a member or Chair of the Soviet-equivalent of the U.S. containment evaluation panel.

Balapan: $W_m = 110\ q^{1/3.4}\ [\ (1 + 0.36\eta)\ /\ 3.16\ ]$

NZ: $W_m = 95\ q^{1/3.4}$ (for rocks with a low gas coefficient).

where W_m is the minimum *slant depth* in meters, and q is yield in kilotons, and η is the gas coefficient of the rock (determined by heating the rock and calculating the percentage of non-condensable gasses released). The Soviet depth-of-burial criterion was related to the minimum distance between the charge and the surface (referred to in the U.S. as the slant depth, and in the FSU as the "line of minimum resistance"). Typical gas coefficients for the rocks at the NZ test site range from 7% for schists and shales to over 40% for carbonate rocks. For a "standard" underground nuclear test at Degelen, the *maximum* scaled depth was 100 $\mathrm{m/kt^{1/3.4}}$ [20].

The key factor used in evaluating adequate containment was a minimum time for the appearance of radioactive explosion products at the Earth's surface. This was apparently related to an over-arching goal of keeping any products released into the atmosphere within Soviet territory for a minimum of five (5) days[21]. For underground tests of any yield, containment plans were designed so that explosion products would not be detectable at the Earth's surface for at least 20 minutes, and this time was increased for larger yields. The primary concerns were, therefore, the production of gas by the vaporization of the rock, and the existence of natural pathways for gas migration to the surface (i.e., geologic faults and fractures). Studies were undertaken to understand the relationship between the pressure in the explosion cavity and the time to appearance of radioactive gasses at the surface (i.e., studies of rock mass permeability, which the Russians refer to as "filtration characteristics").

Based on experience, the IDG RAS developed sets of curves to predict the times at which explosion products would be detected at the Earth's surface. These depend on both depth and yield, and on rock type. For example, for tests at the Novaya Zemlya site, specific formulae were developed for each of the major rock types, based primarily on the gas coefficient of the rocks. Beginning in about 1978, minimum scaled depths ranged from 85 $\mathrm{m/kt^{1/3.4}}$ for the quartzites (with low gas coefficients) to 95 $\mathrm{m/kt^{1/3.4}}$ for the limestones, using the basic formula:

$$W_m = A(\eta)\ q^{1/b} \qquad \text{(where } b = 3.4 \text{ or } 3.6\text{)}$$

Containment Record

The Soviet record of containment varied greatly between the principal military test sites at Semipalatinsk, Azgir and Novaya Zemlya. Data published in the 1990s by several authors is summarized as follows:

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[20] Note that the Russian minimum scaled depths (70, 95 or 100 $\mathrm{m/kt^{1/3.4}}$) are significantly lower than the 120 $\mathrm{m/kt^{1/3}}$ used by the U.S. for tests at NTS [*OTA, 1989*]. This is not surprising, since the rocks in which the tests were conducted are much denser than those in which the U.S. tested at NTS, and therefore the overburden pressures are greater at the same depths (this also means that all of the U.S. tests that were conducted in hard rock or granite , which all had scaled depths of 120 $\mathrm{m/kt^{1/3}}$ or greater, were "over-buried" in comparison to a minimally-buried test in tuff or alluvium). The Soviet minimum of 70 $\mathrm{m/kt^{1/3.4}}$ is, in fact consistent with the model developed by *McKeown* [*1972*] to help understand the *Baneberry* venting. McKeown's model, which accounted for hydrofracturing on joints or faults intersecting the cavity, proposed that a depth of at least 7 cavity radii was required for containment. Using cavity radii data for Degelen tests from *Adushkin et al* [*1999*] , averaging about 9 $\mathrm{m/kt^{1/3}}$, McKeown's formula indicates the minimum scaled depths for containment at Degelen would be 63 $\mathrm{m/kt^{1/3}}$.

[21] Atmospheric conditions were closely monitored, and tests were scheduled for detonation only in periods of stable weather systems. It was noted that some tests at Novaya Zemlya were delayed for periods of 2-4 weeks, waiting for favorable weather patterns.

At the Semipalatinsk test site, where 345 fully-buried, underground nuclear tests were conducted in granitic and metamorphic rocks between 1961 and 1989, 50% were completely contained, with no seepage of radioactive gasses, 49% seeped radioactive gasses, and less than 4% vented [*Gorin et al., 1993*]. Most of the ventings occurred in the early years (like tests in the U.S.), with only one case since 1976. Note that the great majority of these tests were tamped in hard-low-porosity rock; this creates high pressures that force gasses into the rock. Also note that the Soviets were not highly concerned with gas seepage (see below).

At Azgir, where 8 nuclear tests were conducted in salt domes, containment was apparently especially good [*Adushkin, pers. comm., 2000*], although few specific data are available . For the A-III nuclear test at Azgir, detonated on December 22, 1971, no radioactivity was detected until drillback, three months after the test. Like the environment in the U.S. Salmon cavity, the Soviets encountered gas pressures less than atmospheric (0.1 atm; *Spivak, pers. comm.* [*2000*] [22]), and the cavity was dry.

In general, containment was better (fewer failures, more predictable) at Degelen than at Balapan or Novaya Zemlya (see below). This has been attributed to the low gas coefficient of the rocks. At Degelen, scaled depths ranged from $59\ \mathrm{m/kt}^{1/3.4}$ to $690\ \mathrm{m/kt}^{1/3.4}$. For underground nuclear tests in boreholes, Adushkin provided the following summary (**Table 7**) of containment between 1965 and 1989 (for 138 tests conducted at Semipalatinsk (Balapan and Murzhik fields) and sites of Peaceful Nuclear Explosions):

Table 7. Groupings of those Soviet underground nuclear explosions that were conducted in boreholes, according to the time of appearance of radioactive explosion products at the surface.

Category Number	Time of Appearance of Explosion Products at the Earth's Surface	Range of Scaled Depths	Number of Tests
I	10 sec. - 50 min.	79-960	30
		51-72	3 (subset)
II	40 min. - 50 min.	88-236	40
	1 hour - 5 hours	“	30
	5 hours - 25 hours	“	10
III	no venting	96-225	23

Andrianov and Bazhenov [*1992*] provided data on the containment of radioactive products from underground nuclear tests at the former Soviet nuclear test sites on Novaya Zemlya (NZ). More than 4 million curies of radioactivity were released by underground nuclear tests at NZ; this compares with only about 54,000 for the U.S. Nevada test site. Of the 42 underground nuclear test conducted on the Novaya Zemlya Islands, 28 (67%) have leaked radioactive gasses into the atmosphere, and there were three significant ventings, two of which occurred at the northern test site (Matochkin Shar). The major containment failure at the Matochkin Shar test site in 1969 (likened to Baneberry), apparently resulted in a change in containment practices.

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[22] According to *Spivak* [*pers. comm.* Nov. 2000], upon reentry into the cavity of A-III, air flowed very strongly *into the cavity*. Later, in March, 1972, the borehole was re-opened and the gas pressure in the cavity was about 4-5 atm, so that radioactive gas flowed out from the cavity. This change in pressure had resulted from a geological process: groundwater had entered the cavity with the air that flowed into the cavity upon reentry and over the intervening three months. Because the temperature in the cavity was high, the pressure increased.

The statistics on containment for underground nuclear tests at NZ are summarized in **Table 8**; more detailed information is included in Appendix III.

Table 8. Summary of Containment Record for Underground Nuclear tests on Novaya Zemlya

	total tests	"gas seeps"	"significant vents"
Matochkin Shar	36	26	2
since the TTBT	20	12	1
Krasino	6	at least 2	1

Partially-Decoupled Underground Nuclear Tests

Apart from the single nuclear explosion that was decoupled in an air filled cavity at Azgir in March, 1976, Adushkin stated that the Soviets did not undertake any fully decoupled nuclear tests. A number of tests were conducted in rooms (e.g., a 3x3x3m opening for a 1 kt explosion), or in elongate tunnel sections in which the closest stemming plus to the explosion might be 50 meters down the tunnel for a 3 kt explosion. In some cases, these open spaces were used to eliminate gas seepage to the surface by partial decoupling (how this was done is not clear[23]); in other cases, for radiochemistry diagnostics. The particle velocity in the rock for these partially decoupled tests was reduced by 30-50% (this is probably based on near-field, high-frequency recordings). The smallest yield-to-cavity volume ratio was 2 tons/m^3 (i.e., one kiloton in a 500 cubic meter volume). Note that this is consistent with calculations of decoupling in various media by *King and others* [1989], who predicted partial decoupling of 35-40% in spherical cavities with radii of only 3.42 $\text{m}/\text{kt}^{1/3}$.

In a brief discussion of the containment of fully decoupled nuclear explosions in hard rock, using the example of explosions in the yield range of 1-10 kt, Adushkin stated that he thought that full containment of a decoupled explosion in hard rock was feasible, based on his experience with containment of gases in the partially decoupled explosions. These remarks were of course speculative, since the Soviets did not conduct any fully decoupled nuclear explosion in hard rock, and tunnel or borehole stemming or closure schemes were not discussed[24].

It is worth emphasizing that, in most cases, containment "success" meant preventing the *prompt venting* of radioactive debris and gasses. Longer-term seepage of radioactive gasses was apparently expected and tolerated, so long as the goals mentioned above were met. Their overriding concern were about the gas produced by the vaporization and heating of the rock, and natural fracture pathways for this gas to get to the surface.

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[23] In the several Soviet underground nuclear tests at Degelen, the partially-decoupled charge was not the main charge, but a small charge near the tunnel portal. The goal was to cause this section of the tunnel to close, to contain the larger test (see above remarks on tunnel closures). Many of the small charges of the multiple-device tests at Degelen were nuclear blasts for tunnel closure for containment purposes. Several configurations were tested –some failed miserably.

[24] There is a big contrast with the U.S., in terms of tunnel closure mechanisms. The Soviets did a number of tests using small nuclear charges to seal off the tunnel, while the U.S. generally used mechanical and/or high explosive closures. For both sides, the goal was often to get a radiation beam down the tunnel to detectors or test-objects, and then to seal the tunnel to the gas and debris. It is not clear that in a device-performance test, that sort of closure complexity is actually needed. Without it, simpler and more robust tunnel or borehole closures could be engineered, that would give higher confidence to the containment assessment.

French Experience

At the French Pacific test site, where underground nuclear explosions were conducted in basalt rocks overlain by karstic, carbonate reef deposits, recent studies concluded that "it is very probable" that there was no *venting* at any of the 147 tests conducted there (Int. Geomech. Comm., 1999; see Appendix IV). According to data provided by *DIRCEN/CEA* (*1998*, Document 6, see **Figure 17**), the scaled depths of underground nuclear tests on Mururoa and Fangataufa were considerably greater than those of either the U.S. or the Soviet Union. For 137 of the 147 tests conducted, scaled depths (depth / yield$^{1/3}$) ranged from 170 to 800 m / kt$^{1/3}$; for the remaining 10 tests, depths were in excess of 800 m / kt$^{1/3}$ (see **Figure 17**). Because the maximum depth for tests on the atolls was 1000 meters, tests at the lower scaled depths were probably the higher yield explosions.

Of the 140 tests at the French Pacific test site that had nuclear yields, 121 (86%) have showed no evidence of containment failure (either venting or seeps), even with on-site and underground monitoring. Twelve relatively shallow tests (8.5%), in which the chimney that formed (as a result of collapse of the nuclear explosion cavity) reached the karstic carbonates, *may have* contributed to releases of tritium, strontium and cesium into the groundwater in the carbonates. Of these 12 tests, there are apparently four "leaky holes" (<3%), although the areas of tritium concentration may encompass more than one hole [*Int. Geomech. Comm.*, *op.cit.*, p. 300]. For an additional four tests (<3%), tritium has been detected in the karst, even though the volcanic cover should have been enough to ensure containment. It has been speculated that these tests were in rock that was sufficiently weak that the drilling of the 1.5-meter borehole damaged the surrounding rock, allowing early release of tritium from the chimney.

The French record suggests that the consistent use of large scaled depths of burial have a strong effect in ensuring the containment of underground nuclear tests, even for small nuclear yields (in which the closure of the borehole is not assured). Of the 140 nuclear tests, only the four tests that should have been sufficiently buried but leaked to the carbonates represent unpredicted releases. Further, it is not clear that any of the French Pacific underground tests produced seeps that would be detected by the IMS radionuclide monitoring network, since the seeps were essentially buffered to the atmosphere by the overlying carbonate rocks and seawater.

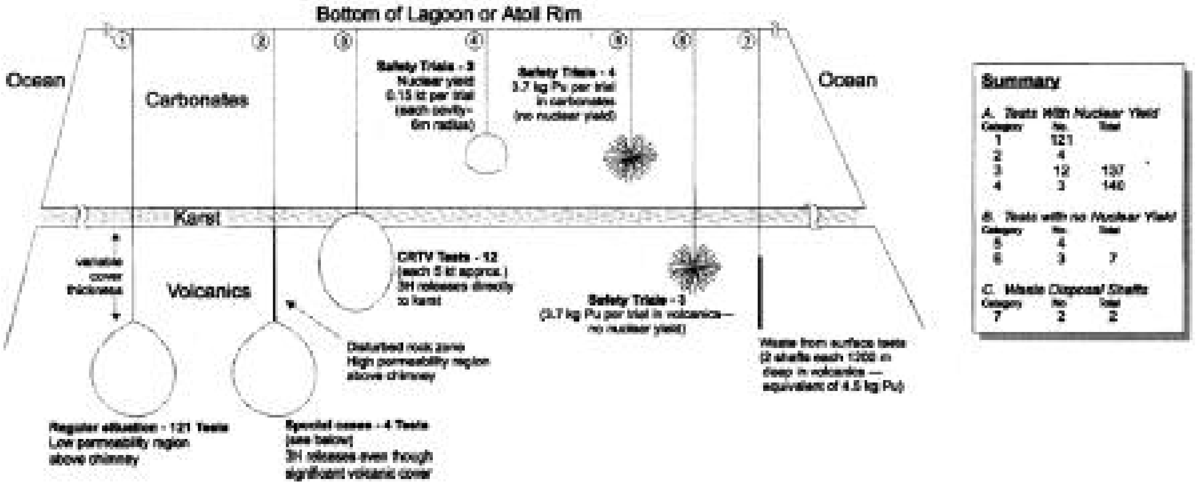

Fig 17. **Sources of potential release of radionuclides from underground nuclear tests at the French Pacific test site [from *Int. Geomech. Comm., 1999*].**

Discussion

Full decoupling of underground nuclear explosions requires the construction of large, unsupported cavities, the concealment of that construction from detection, and the containment of radioactive explosion products. For the purpose of discussion, consider the three yield ranges that were specifically addressed in the *OTA* [*1988*] report: less than about 1 kt, 1-10 kt, and over 10 kt.

Yields Over 10 kt

For nuclear explosions with yields in excess of about 10 kilotons, a full-decoupling volume of at least 333,000 cubic meters is required (660,000 m^3 in salt, and depending on depth). For cavities of this size or larger, it appears that the only feasible method of cavern construction is by solution mining in a buried salt deposit or dome. While caverns with volumes larger than this have been constructed in hard rock, no caverns of the necessary combined volume and unsupported span have been constructed that do not also have large aspect ratios (over 10:1), and few have been constructed at containment depths. Caverns in hard rock with unsupported spans over about 35 meters require high-quality rock and complex engineered support systems and, therefore, considerable technical expertise. They are expensive, and, because of the technological sophistication required and the volume of material excavated, may be difficult to construct clandestinely. While it is conceivable that a 10 kt decoupling cavity could be built clandestinely in hard rock at containment depths, it would be a landmark achievement.

Further, fully- or partially-decoupled nuclear explosions with yields of over 10 kt, would have seismic magnitudes greater than about 3.5 m_b, (depending on tectonic environment; this is an average of estimates of *Murphy* [*1980*] and *Sykes* [*1993*] for stable tectonic areas). Based on IMS seismic monitoring capability studies [*Claassen, 1996; Bache et al, 2000*], for explosions occurring in broad areas of Eurasia[25], an event of that magnitude could be detected by the various seismic international and national monitoring systems. Even if masked by, for example, a large mining explosion, a decoupled event with a seismic magnitude over 3.5 m_b might still be identified using sophisticated seismic data processing techniques.

Thus, even though cavities large enough to fully decouple a nuclear yield larger than 10 kt can certainly be constructed by solution mining in suitably thick salt deposits (and conceivably in hard rock), would be stable when air-filled, and would probably contain the radioactive products of the decoupled nuclear explosion, the resulting test would probably be detected by the IMS and/or national seismic monitoring systems (in most of Eurasia, assuming these systems are fully implemented, performing reliably and have the detection capabilities that have been estimated).

Because salt deposits suitable for the solution mining of very large cavities are relatively rare, this limits geographically the areas of opportunity for clandestine underground nuclear testing at these larger yields. Because these salt-bearing regions can generally be identified, it may be feasible to develop a monitoring plan that could strongly reduce this threat. On the other hand, many countries of nuclear proliferation concern have salt deposits in areas that are seismically active (e.g., Iran, Iraq, Syria, northern Algeria) and have petroleum resource development in the salt-bearing regions. These present difficult problems for monitoring, both technical (event discrimination) and political (plausible denial). A further complication is that active salt dome tectonics can produce earthquakes with magnitudes in the range of interest (over seismic magnitude m_b=3; e.g., see, e.g., *Leith and Simpson* [*1986*]).

Yields Less Than 1 kt

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[25] In the land areas of the southern hemisphere, this might be 20 kt or more, with seismic magnitudes over 3.8 m_b [e.g., see *Claassen, 1996*]

To fully decouple an explosion of 1 kt in hard rock, the size of the full-decoupling volume required is at least 33,500 m^3 (65,000 m^3 in salt, and depending on depth). Numerous caverns of this volume have been built, worldwide, at small aspect ratios, and their construction poses only modest technical challenge and is not expensive in comparison to the cost of a nuclear weapons development program. If salt is available at containment depths and at sufficient thickness, a solution-mined cavern could be constructed with few surface "observables." In terms of containment, it appears likely, based on the U.S. "Salmon" and "Sterling", and the Soviet "A-III" tests in salt, that the cavern would not seep radioactivity, much less vent.

In hard rock, if care is taken in selecting the construction site, depth and geologic environment, a decoupled test could be contained with high confidence in an elongated cavern at scaled depths over 120 $m / kt^{1/3}$. The cavern could also be tested for stability and gas permeability by detonation of small chemical (e.g., TNT) explosions prior to the nuclear detonation with high-explosive charges (which would also serve to locally calibrate the seismic efficiency and decoupling effectiveness of the cavity) and tracer gasses (which have been used by the U.S. at the Nevada Test Site). The decoupling site could be located (in most countries of nuclear proliferation concern) so as to minimize the possibility detection by regional seismic stations. While a small nuclear test in hard rock may seep radioactivity in the long term, if it is adequately buried, sealed and stemmed it is unlikely that sufficient radioactivity would be released to be detected and identified by the IMS radionuclide monitoring system above back-ground levels.

Fully-decoupled nuclear explosions with yields of 1 kt or less would have seismic magnitudes less than about 2.6 m_b. For most of the northern hemisphere and all countries of nuclear proliferation concern (except perhaps North Korea and parts of northwestern Russia), an event of this magnitude would not be detected and located by the CTBT International Seismic Monitoring System [*Claassen, 1996.*].

Yields from 1-10 kt

Construction Issues

The summaries of construction feasibility for salt and hard rock given in Tables 2 and 4 indicated that cavities of sufficient dimensions to decouple a nuclear explosion up to 10 kt can be readily built, given the required geologic conditions. Following the discussion, above, for explosions above 10 kt, it is certainly feasible that cavities could be constructed in salt that would fully decouple 10 kt. Salt cavities would be stable when filled with air for periods sufficiently long to conduct the test, and would provide a high probability of containment.

However, for cavities in hard rock of moderate aspect ratio (e.g., 4:1:1), unsupported volumes over 100,000 m^3 are rare and require sophisticated mining techniques and cavern support systems. But for larger aspect ratios (e.g., 8:1 or more), such cavity construction is *not strongly limited by widely-available engineering technology*. Numerous large, unsupported cavities with volumes in excess of 200,000 cubic meters and spans reaching 60 to 70 meters have been built in hard rock.

Assuming that: 1) the decoupling factors for granite published in the 1988 OTA report are correct and can be extended to most granitic rock types; and 2) the non-spherical decoupling calculations of *Stevens et al.* [1991] for salt are correct and can be extended to granitic rock, this makes it possible, in principle, to construct cavities capable of fully decoupling over 5 kilotons nuclear yield (and over 10 kt in more elongated cavities) almost anywhere that hard rock is found within a depth range that is appropriate for containment. Further, it also seems likely, based on *Stevens et al.* [1991] results for over-driven cavities, that significant partial decoupling (factor of 45) might be achieved for explosions in the yield range 5-15 kilotons, in large non-spherical cavities constructed in hard rock.

As noted for decoupling cavities for explosions less than 1 kt, cavern stability and permeability can be tested by detonating small chemical explosions. These would also serve to locally calibrate the seismic efficiency and decoupling effectiveness of the cavity.

Containment Issues

Containment of radioactive explosion products is essential, and a prompt venting of a significant amount of radioactive particulate materials would, over broad areas of the globe, result in a detection by the radionuclide monitoring network [*Hourdin and Issartel*, 2000]. To minimize the possibility of detection, the determined evader must limit test releases to seeps: small late-time releases of noble gasses.

While prediction of containment of decoupled nuclear explosions in hard rock is uncertain, post-1970 Soviet/Russian, and French experience indicates that prompt venting can be avoided with some predictability. The French data indicate that a great deal of protection is afforded by increasing the burial depth. As with constructability, the issue of containment is *not limited by current underground engineering technology*. If a country truly wants to cheat on the test ban by decoupling an explosion underground, one can argue that they need only devote resources to building the decoupling cavity at a more-than-minimal depth. In most hard-rock geologic environments, this improves both cavern stability and containment. The increased pressure at depth closes joints, improving both cavern stability and containment.

In addition, like cavern stability, rock permeability can be tested by small chemical (e.g., TNT, ANFO) explosions and using trace gasses. In this way, the constructed cavern can be "calibrated" for potential gas release. Gas production from a chemical explosion is far greater than from a nuclear explosion. Successful containment of the chemical explosion is therefore a potentially reliable indicator of the probability of the containment of the nuclear explosion. While this will not, of course, insure containment, it could give the evader confidence in the probability of success.

Concealment, Deception and Denial

Preparations for a test to be conducted in a solution-mined cavity can be both concealed from remote monitoring and, if identified, denied with plausible justifications. In salt dome environments, drill rigs, piping, sump pits and related equipment necessary for solution mining are common because of the oil and gas deposits that are frequently associated with the salt dome structure. These identifiable areas therefore need special monitoring. Of particular concern would be existing gas or air storage caverns, since these can be rapidly emptied without any visible evidence. In liquid-filled caverns, because the displacement liquid is usually stored in tanks, it would also be difficult to identify the emptying of a cavern. After a decoupled test, the relatively small seismic signal that might be detected from the vicinity of the salt dome could be ascribed to shooting for geophysical exploration, hydrofracturing of oil-or gas bearing formations, or to natural seismicity [see *Leith and Simpson, 1986*].

Similarly, a low-yield, decoupled explosion could be conducted in hard rock in a mine or mining region, and be misidentified as blasting operations or rock bursts. Most countries of nuclear proliferation concern that have been reviewed by the USGS routinely use explosives in mining (except Pakistan); although there is little information on the rate and sizes of industrial explosions for many Third World countries.

Mining blasts as large as 1 kiloton are rare, so that mining or other industrial seismicity is not expected to be a major discrimination problem for seismic events at larger magnitudes. However, in limited areas of some countries, rockbursts in deep mines can be greater than magnitude 5 and occur in areas of underground construction; these could be confused with explosions of 10 kt or more. There is also evidence that the size and time of rockbursts can in many cases be controlled by mining practice. It could therefore be challenging to identify a small decoupled nuclear explosion (m_b=3) detonated at the same time as a triggered rockburst of m_b=4. Other types of artificially-induced earthquakes are more rare, but also can have magnitudes greater than m_b=5 (e.g., reservoir-induced seismicity).

In terms of radioactive seepage from the decoupled test, the evader may time the test so as to coincide with a favorable weather pattern, and/or with an intentional release from a nuclear power plant. These scenarios were considered in the *JAYCOR* study [*1996*].

Seismic magnitude, detection and identification

It has been estimated that fully decoupled explosions in salt and granite in the yield range from 1-10 kt will have seismic magnitudes ranging from about $m_b=2.0$ to $m_b=3.5$, depending on yield, depth and tectonic environment. In this magnitude range, seismic events in the continental areas of the northern hemisphere may or may not be detected and located by the IMS, depending on both the magnitude and the exact location of the event with respect to the seismic stations of the network (in the southern hemisphere, this magnitude range extends to over 4.0 m_b see *Claassen*, [*1996*] ¾i.e., over 20 kt). It is also typically assumed that there is about a 0.5 magnitude unit difference between the detection capability of a global seismic network and the explosion identification capability. Further, even if detected, located and identified as an explosion, the size of the error ellipse of a small event may be large, making difficult the problem of evaluating the source region of the event with other resources or by on-site inspection.

Further, the event may not be easily identified as an explosion. There are many example of small explosion events that, under event discrimination techniques, fall in "earthquake" or "undiscriminated" populations" [e.g., *Bennett et al., 1989; Baumgardt et al., 1992*]. A recent example is the July 27, 2000 seismic calibration explosion, Omega-3, a 100-ton single-source explosion of magnitude $m_b=4.0$, that was discriminated as an earthquake [*CMR, 2000*].

Potential Monitoring Improvements

Monitoring Network Enhancements

Of course, improvements to the monitoring networks that increase the detectability of small events will likewise limit the feasibility of successful evasion by cavity decoupling. For the seismic network, an example is the "upgraded IMS" of *Bache et al.* [*2000*], in which a number of 3-component seismic stations are upgraded to arrays. Adding stations in areas where major salt deposits are present would increase the local detection capabilities in these regions. For the radionuclide monitoring network, adding Xe detectors at all stations could greatly increase the likelihood of detecting a significant seep from a clandestine underground nuclear test.

Database Development and Monitoring of Construction Technologies

Because of the great variability known to be present in most of the countries we have examined, geologic factors must be considered in designing a monitoring plan that addresses the possibility of cavity decoupling. A detailed data base needs to be developed for each of target country, identifying potential regions for large-scale underground construction, and identifying and accurately mapping regions of thick buried salt. In particular, it will be necessary to identify and characterize the locations of salt deposits suitable for large cavity construction. This could also include a database of known solution mining sites and companies. There may be a need to monitor solution-mining technologies and large-scale underground construction technologies, and to develop and implement a monitoring strategy for potential underground mining and construction sites. The database development could initially focus on seismic areas within nuclear states and countries of nuclear proliferation concern, since these areas will receive most of the attention during the evaluation of routine seismic events. Information collection strategies could be developed for mining and ore extraction areas within seismically active areas of these countries, with special focus on areas identified as having potential for solution mining.

The Need for Experimental Testing

Sykes [*2000*] has stated, "Resolution of the feasibility of decoupling at militarily significant yields in hard rock is of prime importance...." Because hard rock is a geologic environment available at containment depths in every country of nuclear proliferation concern, cavity decoupling in hard rock must be considered as a potential evasion scenario for explosions less than about 10 kt. This is especially true for countries that have no salt deposits suitable for solution mining of a large cavity at containment depths.

However, as emphasized by *Sykes* [*1995, 2000*] there are a number of uncertainties associated with this important cavity-decoupling scenario:

- no country is known to have attempted full-decoupling of a nuclear explosion in hard rock;
- the decoupling factor for nuclear explosions in *spherical* cavities in hard rock may be poorly determined;
- the decoupling effectiveness at various cavity aspect ratios is based primarily on theoretical calculations, with experimental data available only for small yields of high-explosives, and only in one rock type (limestone);
- the probability of containing explosions in hard rock is less than salt, and may depend greatly on the state of stress and fracture system in the rock;
- the short- and long-term stability of a decoupling cavity following explosive loading has not been studied.

These uncertainties could be lessened by undertaking one or more actual field tests using conventional explosives[26]. A series of small chemical explosions, detonated in a cavity in hard rock of moderate-aspect ratio could address all of the issues listed above. Such tests would also serve to locally calibrate the seismic efficiency, and to study high-frequency and shear waves emanating from the decoupled explosion. Tests in several cavities of varying dimensions and depths would add to confidence in the results.

Other Issues

Theoretical and experimental studies are needed to document and explain the phenomenon of negative cavity pressures, that apparently result from nuclear explosions in salt. On-site inspection techniques for detecting hidden underground excavations could be tested (e.g., see K*icker et al* [*1991*]. Finally, to lessen concerns of the potential use of existing large caverns and areas of deep mining, such areas could be voluntarily declared under the CTBT as a confidence-building measure.

Conclusions

- In thick salt deposits and domes, it is feasible to construct cavities of sufficient volume and dimensions for full decoupling of an underground nuclear explosion larger than 10 kt. Salt probably provides an ideal environment for both cavity construction and containment, and it is possible (or even likely) that the cavity would not leak radioactivity for years. However, several factors limit the feasibility of this scenario for evading detection by the monitoring systems:

  -- Above 10 kt, the resulting seismic event would have a magnitude over 3.0-3.5 *mb*, and in the broad areas of Eurasia, might be detected, and located by the fully-functioning CTBT International Monitoring System (the southern hemisphere, this threshold will be higher);

  -- Salt deposits of suitable thickness and depth for such large-scale cavern construction are relatively rare and are not present in many countries of nuclear proliferation concern. The regions of the Earth that host suitable salt deposits can, in most cases, be identified by following the geological literature

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[26] For example, DTRA conducted a 100-ton high explosive test in granite at Degelen mountain in 1998, which produced approximately one billion times more gas than an equivalent-size nuclear charge. After this explosion, the gas pressure was contained in the tunnel with a single, well-placed concrete plug, which maintained the pressure inside the tunnel without apparent leakage, until it was released several days later. Obviously, this granite was extremely impermeable to gas migration, despite the shallow depth of the test (about 100 meters).

and developments in the field, and these areas could conceivably be monitored.

• In hard rock, construction of cavities of sufficient size and dimension for full decoupling of an underground nuclear explosion is feasible to at most about 10 kt, principally because of the difficulty in constructing a cavern of sufficient size at the depths required for containment, and the possibility of detection of the excavation. Avoiding detection of a decoupled test in the 1-10 kt range would require:

--careful site selection (considering distance from monitoring stations); a source of plausible denial (such as a co-located underground mining operation); adequate depth; high-quality rock; rock with low gas content and distant from faults, and other geology-specific criteria;

--concealment of the mining operation from public knowledge and from remote monitoring systems;

--considerable attention to containment issues, both in terms of the geologic environment and in terms of the engineered openings to the cavity (boreholes and/or adits) and cabling;

--favorable weather conditions, given the possibility that radioactive products from the test might eventually seep radioactivity to the surface through atmospheric pumping and migration along fractures;

--a substantial commitment of expertise and resources.

As the desired decoupled yield approaches 10 kt, more and more elongate cavities (up to 10:1) may be required to relieve the technological difficulties of constructing large unsupported spans in hard rock. However, calculations and small-yield experiments with conventional explosions have suggested that cavities with aspect rations up to 20:1 may provide adequate long-period seismic decoupling.

• At yields less than about 1 kt, any country desiring to decrease the seismic signal from an small underground nuclear explosion can do so by detonation in a deep, moderate-size, elongated cavity mined in high-strength, low porosity rock (e.g., granite) or, if available, in salt. The construction of such a cavity is not limited by the available mining technology, based on numerous examples of underground construction at depth, worldwide. With careful attention to the selection of the geologic environment and to ensuring adequate depth and stemming of the tunnel complex, the determined evader could have confidence that the event would be sufficiently contained as to preclude detection by the radionuclide monitoring network. In most countries, sufficiently high relief is generally present to allow such a cavity to be built by horizontally tunneling into unsaturated or low-permeability rocks where water flow would be easily controllable. With careful site selection, the decoupled event would not be large enough to be detected seismically, for broad areas of most countries.

• In designing a monitoring plan that addresses the possibility of cavity decoupling, geologic factors must be considered on a country-by-country and region-by-region basis. Because of the great variability known to be present in most of the countries we have examined, a detailed data base needs to be developed for each of country to be monitored, of an appropriate level of detail to resolve seismic events to the desired kiloton level.

• Because no country is known to have attempted full-decoupling of a nuclear explosion in hard rock, there is relatively large uncertainty associated with this particular cavity decoupling scenario (e.g., the decoupling effectiveness at various cavity aspect ratios, the detectability of seeps of radioactive explosion gasses, the generation of shear waves from non-spherical cavities, and so on). These technical issues could and should be addressed by undertaking one or more field tests of cavity decoupled explosions in hard rock, using conventional explosives.

- Because of the apparent lack of suitable salt deposits, full decoupling of explosions larger than 10 kt is probably not feasible in land areas of North Korea, NW Russia and India, and is feasible only in limited regions of, for example, Libya and Israel. In contrast, because extensive, suitably thick salt deposits are present in many naturally-seismic regions that are also areas of nuclear proliferation concern (e.g., Iran, Iraq, Syria, China, Russia), these areas would require special monitoring to ensure adequate verification of a comprehensive test ban treaty.

- The potential for evading detection and identification of an underground nuclear test through cavity decoupling is not limited so much by geologic environments and engineering technology (i.e., the difficulties of cavern construction or of ensuring containment) as it is by the capabilities of global seismic and radionuclide monitoring networks and other remote monitoring systems.

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Appendix I: List of countries known to have used solution mining technology for underground cavern construction

(in alphabetical order), based on the published literature and correspondence with the Solution Mining Research Institute, Encinitas, Calif.

Belgium
Brazil
Bulgaria
Canada
China
Denmark
France
Germany
Italy
Kazakhstan
Mexico
Morocco
Netherlands
Poland
Portugal
Romania
Russia
Slovakia
Spain
Switzerland
Tajikistan
Thailand
Turkey
United Kingdom
United States

Appendix II: Man-made Underground Openings with Spans Greater Than 75 Feet (23 m).

Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
1	Mecheko-Kemano-Kitimet British Columbia, Canada	Owner: Aluminum Co. of Canada Contractor: British Columbia International Co., Ltd.	Hydroelectric power-plant	1952	Span: 82 Height: 120 Length: 700 Depth: 1500	Granodiorite w / dike intrusions and faults. UCS=16-25 ksi; Density=171 pcf	Pattern rock bolting	Parabolic arch roof mined with rise 37 ft and span of 103 feet; vertical walls	A
2	NORAD Cheyenne Mountain Complex, Colorado Springs, CO Chamber B	Owner: North American Air Defense Command Designer: PBQ&D Contractor: Utah Mining & Construction Co.	Military Defense Installation	1964	Span: 72 Height: 72 Length: 58 Depth: -	Granite w / dike intrusions. UCS= 19-29 ksi; Density= 174 pcf	Pattern rock bolting		A
3	NORAD Cheyenne Mountain Complex, Colorado Springs, CO Intersection	Owner: North American Air Defense Command Designer: PBQ&D Contractor: Utah Mining & Construction Co.	Military Defense Installation	1964	Span: 104 Height: 84 Length: - Depth: -	Granite w / dike intrusions. UCS= 19-29 ksi; Density= 174 pcf	Pattern rock bolting	Spherical shaped opening	A
4	Snowy Tumut Development Snow Mountains, Australia	Designer / Owner: Snowy Mountain HydroElectric Authority Contractor: CITRA Enterprises	Hydroelectric Power	1957	Span: 77 Height: 110 Length: 306 Depth: 1100	Biotite granite, granite gneiss. UCS=20 ksi	Rock bolting	Curved roof with vertical sidwalls	A
5	Boundary Dam, Metaline Falls, WA	Owner: City of Seattle Designer: Bechtel Contractor: Mannix Contractors	Hydroelectric Power	1965	Span: 76 Height: 175 Length: 477 Depth: 500	Dolomitic limestone UCS=10 ksi	Pattern rock bolting	Arched roof with vertical side walls	A
6	Ranier Mesa, Nevada Test Site, NV Test Cavity I and II	Owner: Atomic Energy Comission Designer: Fenix & Scisson, Inc. Contractor: Reynolds Electrical Engineering	Nuclear Testing	1965	Span: 80 Height: 140 Length: 120 Depth: 1300	Porous Tuff UCS=1.5 ksi Density= 125 pcf	Rock bolting	Approximately sperical segment with plane surface inclined 68 degrees from horizontal; because of cavity geometry, span is taken as 100 ft	A
7	El Toro Power Station, Chile		Hydroelectric Power		Span: 80 Height: 126 Length: 335	Granodiorite	Cable bolts and rock bolting		A
8	Churchill Falls, Labrador, Canada	Owner: Churchill Falls Labrador Corp Designer: Acres / Bechtel	Hydroelectric Power	1971	Span: 81 Height: 145 Length: 1000 Depth: 984	Gneiss UCS=16 ksi Density = 170 pcf	Rock Bolting	Circular shaped arch with vertical walls	A
9	Tytyri Limestone Mine Lohja, Finland		Sublevel Stope Mine Opening		Span: 197 Height: 525 Length: 328	Limestone			B, K

Appendix II: Man-made Underground Openings with Spans Greater Than 75 Feet (23 m).

Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
10	Vihanti Mine, Finland		Mine Opening		Span: 131 Height: 197 Length: 492 Cover: 656	Dolomite			B, F
11	Joma Copper Mine, Norway		Mine Stope		Span: 230 Height: 66			Unreinforced flat roof	B
12	Underground Aircraft Hall, China		Aircraft hangar		Span: 138	Dolomite			B
13	Ferrera		Hydroelectric Power	1962	Span: 95 Height: 82 Length: 469	Gneiss		Semi-circular cross-section	C
14	Huinco		Hydroelectric Power	1965	Span: 102 Height: 79 Length: 354	Gneiss		Semi-circular cross-section	C
15	Porabka Zur		Pumped Storage	1976	Span: 89 Height: 131 Length: 407	Siltstone / mudstone thinly bedded		Egg-shaped cross-section	C
16	El Cajon		Hydroelectric Power	1985	Span: 97 Height: 139 Length: 341	Karst Limestone		Vaulted crown with vertical sidewalls	C
17	PSS Middle East		Pumped Storage	1986	Span: 75 Height: 135 Length: 274	Limestone / marl with high ground water		Vaulted crown with slightly curved upper sidewalls and rectangular lower cavern part	C
18	Hervanta Underground Ice Rink		Underground Recreation	1982	Span: 105 Height: 30 Length: 436	Porphyre Granite	Grouted rock dowels at 1.5 c/c		D, M
19	Kauniainen Indoor Sports Center Kauniainen, Finland		Underground Recreation	1987	Span: 94 Height: 40 Length: 146	Gneiss			D, I
20	Afonso IV Powerhouse Cavern Brazil		Hydroelectric Power	1979	Span: 82 Height: 74 Length: 177 Cover: 184	Migmatite containing granite, biotite gneiss, amphibolite, and biotite schist	Rock bolts and tendons		E, P
21	Liujiaxia Powerhouse, Liujiaxia, China		Hydroelectric Power	Early '60's	Span: 102 Height: 210 Length: 282				G
22	Baishan Powerhoues, Baishan, China		Hydroelectric Power		Span: 82 Height: 178				G
23	Cirata Hydroelectric Power Project,		Hydroelectric		Span: 115				H

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Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
	Weatern Java (Indonesia)		Power		Height: 162 Length 830				
24	Itakeskus Swimming Hall, Helsinki, Finland		Underground Recreation	1989	Span: 79 Height: 49 Length 246	Granodiorite			I
25	Holmlia Sportshall and Pool, Holmlia, Norway		Underground Recreation		Span: 82 Height: 43 Length 148 Cover: 66	Gneiss			J
26	Tai Koo Cavern, Hong Kong, China		Transit Station		Span: 79 Height: 52 Length: 823	Granite			L
27	Turku Underground Ice Rink		Underground Recreation		Span: 102 Length: 262			Two caverns of these dimensions	M
28	Salto Sheque Hydropower Cavern, Peru		Hydroelectric Power	1976	Span: 98 Height: 125				C
29	Anjou Slate Mine, France		Slate Mine		Span: 98 Height: 230 Cover: 1150	Slate		Mined in chambers	N
30	Le Sautet Power Station, France		Hydroelectric Power	1933	Span: 115 Height: 66 Length 115 Cover: 328	Limestone		Half circle arched roof	N
31	La Bathie Power Station, France		Hydroelectric Power	1959	Span: 82 Height: 107 Length 407	Gneiss		Parabolic arch opening	N
32	Montezic Pumped Storage Facility, France		Pumped Storage	1978	Span: 82 Height: 138 Cover: 984	Granite		Half circle arched roof	N
33	Tersanne, Etrez Storage Facility, France		Hydrocarbon Storage		Span: 262 Height: 492 Cover: 4600	Rock Salt		Solutioned out storage faciltity; opening is never discharged of fluid	N
34	Manosque Storage Facility, France		Hydrocarbon Storage		Span: 262 Height: 1150 Cover: 1970	Rock Salt		Solutioned out storage faciltity; opening is never discharged of fluid	N
36	Hauterives Storage Facility, France		Hydrocarbon Storage		Span: 394 Height: 820 Cover: 4265	Rock Salt		Solutioned out storage faciltity; opening is never discharged of fluid	N
37	Kariba Powerplant, Rhodesia		Hydroelectric		Span: 75	Biotite Gneiss			O

Appendix II: Man-made Underground Openings with Spans Greater Than 75 Feet (23 m).

Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
			Power		Height: 132 Length: 468 Cover: 200				
38	Kisenyama, Japan			1968	Span: 83 Height: 165 Length: 200 Cover: 810	Chert, Sandy Slate			O
39	La Grande LG-2 power station, British Columbia, Canada		Hydroelectric Power	1979	Span: 87 Height: 155 Length: 1586 Cover: 328	Granitic Gneiss	Rock Bolts		P
40	Mica Dam Power Station, British Columbia		Hydroelectric Power	1976	Span: 80 Height: 145 Length: 778 Cover: 722	Quartzitic Gneiss UCS=150 Mpa	Rock Bolts		P
41	Bremm Trial Cavern for Power Station, West Germany		Hydroelectric Power	1970	Span: 79 Height: 30 Length: 98 Cover: 656	Clay Slate with sandstone	Rock Bolts and Shotcrete		P
42	Sackingen Power Station, West Germany		Hydroelectric Power	1966	Span: 76 Height: 98 Length: 531 Cover: 1312	Granite and Gneiss	Rock bolts; ribs in one section		P
43	Waldeck II Power Station, West Germany		Hydroelectric Power	1973	Span: 110 Height: 164 Length: 344 Cover: 1148	Interbedded shale and Greywacke	Shotcrete and rock bolts		P
44	San Massenza Power Station, Italy		Hydroelectric Power	1953	Span: 95 Height: 92 Length: 650	Limestone			P
45	Okutataragi Power Station, Japan		Hydroelectric Power	1973	Span: 82 Height: 161 Length: 436 Cover: 656	Quartz Porphyry, Diabase, and Rhyolite			P
46	Shintakasegawa Power Station, Japan		Hydroelectric Power	1978	Span: 89 Height: 179 Length: 535 Cover: 820	Granite			P
47	Cabora Bassa Power Station, Mozambique		Hydroelectric Power	1975	Span: 89 Height: 187 Length: 722 Cover: 525	Granitic Gneiss			P

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Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
48	Vanderkloof Power Station		Hydroelectric Power	1976	Span: 82 Height: 161 Length: 328 Cover: 98	Dolerite of high strength	Rock bolts		P
49	Cavergno Power Station, Switzerland		Hydroelectric Power	1955	Span: 92 Height: 72 Length: 338	Mica Schist			P
50	Grimsel II East Power Station, Switzerland		Hydroelectric Power	1978	Span: 95 Height: 62 Length: 459 Cover: 328	Granodiorite			P
51	Hongrin Power Station, Switzerland		Hydroelectric Power	1970	Span: 98 Height: 86 Length: 449 Cover: 492	Limestone and Limestone-schist			P
52	Cruachan Power Station, Scotland		Hydroelectric Power	1965	Span: 77.1 Height: 125 Length: 300 Cover: 1050	Diorite	Rock Bolts		P
53	Dinorwic Power Station, North Wales, England		Hydroelectric Power	1980	Span: 80 Height: 171 Length: 592 Cover: 984	Slate	Rock anchors, bolts, and shotcrete		P
54	Bear Swamp Power Station, Massachusetts		Hydroelectric Power	1973	Span: 79 Height: 151 Length: 226	Chlorite Mica Schist	rock bolts and shotcrete		P
55	WMATA Rosslyn Station, Washington D.C.		Transit Station	1973	Span: 82 Height: 56 Length: 722 Cover: 69	Gneiss	Ribs, spiles, and shotcrete		P
56	Norwegian Olympic Hockey Cavern		Underground Recreation		Span: 197 Length: 295 Cover: 164				
57	Rio Grande No.1 Project, Cordoba, Argentina	Owner: Agua y Energia Electrica	Hydroelectric Power		Span: 125 Height: 203 Cover: 348	Massive Gneiss	Rock bolts and shotcrete	Cylindrical opening with spherical cap to serve as surge tank	Q
58	Imaichi, Japan			1982	Span: 110 Height: 167 Length: 525	Sandstone, breccia			R
59	Tenzan, Japan			1982	Span: 79	Granodiorite			R

Appendix II: Man-made Underground Openings with Spans Greater Than 75 Feet (23 m).

Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
					Height: 157 Length: 292				
60	Matano, Japan			1981	Span: 77 Height: 152 Length: 510	Granite, porphyrite			R
61	Honkawa, Japan			1980	Span: 86 Height: 156 Length: 322	Black Schist			R
63	Tanbara, Japan			1979	Span: 87 Height: 162 Length: 382	Conglomerate			R
64	Numazawa No.2, Japan			1979	Span: 85 Height: 156 Length: 317	Rhyolite			R
65	Shintakase, Japna			1975	Span: 89 Height: 179 Length: 541	Granodiorite, diorite			R
66	Nabara, Japan			1974	Span: 82 Height: 156 Length: 281	Granite			R
67	RMR Case No. 264		Chamber		Span: 108 Depth: 1148	Gneiss			S
68	RMR Case No. 76		Chamber		Span: 144 Depth: 656	Salt			S
69	RMR Case No.248		Chamber		Span: 82 Depth: 98	Dolomite			S
70	RMR Case No.265		Chamber		Span: 95 Depth: 561	Gneiss			S
71	RMR Case No. 263		Chamber		Span: 110 Depth: 984	Greywacke			S
72	RMR Case No.17		Chamber		Span: 81 Depth: 981	Gneiss			S
73	RMR Case No.79		Chamber		Span: 98 Depth: 331	Sandstone			S
74	RMR Case No.44		Chamber		Span: 100 Depth: 1316	Tuff			S
75	RMR Case No. 33		Chamber		Span: 81	Gneiss			S

Appendix II: Man-made Underground Openings with Spans Greater Than 75 Feet (23 m).

Compiled in 2000 by Lachel and Associates, Golden, CO.

List No.	Project Name and Location	Responsible Party	Purpose	Completion Date	Excavation Dimensions (ft.)	Geology	Initial Support	Remarks	Source
					Depth: 984				
76	RMR Case No.80		Chamber		Span: 98 Depth: 328	Siltstone			S
77	RMR Case No.64		Chamber		Span: 100	Limestone & schist			S
78	RMR Case No.53		Chamber		Span: 100 Depth: 1312	Tuff			S
79	RMR Case No.110		Chamber		Span: 305 Depth: 69	Quartz-mica schist			S
80	RMR Case No.81		Chamber		Span: 98 Depth: 308	Siltstone			S

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Appendix III: Summary of information on the containment of underground nuclear tests at the Novaya Zemlya underground nuclear test sites [from *Andrianov and Bazhenov, 1992*]

Gas seeps.

The seepage of radioactive gasses has generally occurred within minutes to an hour after the event. These include inert gasses such as krypton and xenon, but also cesium, strontium, and iodine. Total releases from "gas seeps" have ranged from 10^{11} to 10^{18} Bq., but are generally in the range 10^{11} - 10^{13} Bq. The accompanying table lists the amount of radioactivity released (total or single-element maximum), the local dose rate (at the test site or adit), test numbers and dates. Note that even since tests were limited to 150 kt, many events released radioactive gasses in excess of 100 Curies (Ci) and exposed the test site to doses of 10-1000 Rem per hour (R/h).

Significant vents.

All of the significant ventings are associated with tectonic faults. These containment failures (described as "Baneberry-like") resulted in "abnormal radiation conditions" and the evacuation of personnel. One of these vents occurred at the southern NZ test site in 1973; the other two at the northern NZ test site in 1968 and 1987. Further information on the three ventings follows [dates and scaled depths taken from *Andrianov and Bazhenov*, 1992, based on years and locations given by *Adushkin* [1993]. Yield estimates from Sykes and Ruggi, 1989, in Nuclear Weapons Databook [*NRDC, 1989*]. Note that both ventings at Matochkin Shar were along faults intersecting the tunnel between the device emplacement point and the hermetic seal near the adit.

> Nuclear test at borehole site "Yu-4" (southern testing area), 27 Sep. 1973. Yield estimated at 100 kt; SDOB about 190 m/kt$^{1/3}$:
>
> > Test was of an unexpectedly small device at great depth (the inference is that the device yield was smaller than expected). Apparently the venting occurred as a result of tectonic motion on an undetected fault, which opened a passageway for the gasses to reach the surface (from Adushkin's remarks in a presentation of this material on 24 June, 1993, it can be inferred that the test was conducted in carbonate rocks (limestones) with significant amounts of pyrite). Fault displacement was about 1 meter. The area contaminated was about 1.5 x 7 km; radiation readings made in 1990 were 25 microren/hr of Cs-137 and Sr-90; fallout was 0.1 Ci/km^2 (The two sources (see Note 1) differ in their description of the fallout from the 27 September 1973 test. The information from Adushkin and others is presented here; Andrianov and Bazhenov reported only a "low intensity seepage" from this event, with a total release of 3.7 x 1010 Bq (1Ci)).
>
> Nuclear test at tunnel site A-9 (part of a double event at the northern testing area), 14 Oct. 1969. Yield estimate of both events is 140 kt; SDOB of A-9 was about 100 m/kt$^{1/3}$.
>
> > Venting occurred by explosive escape of gasses along a fault (apparently, without fault motion) that cut the tunnel between the two main stemming blocks and the blast door (see accompanying diagram). Mechanism apparently involved a moisture lens in the permafrost layer. About 10% of the radioactive gas escaped and personnel were evacuated. Containment practices were apparently changed because of this event.
>
> Nuclear test at tunnel site A-37A (northern testing area), 2 Aug. 1987. Yield estimated at 70 kt; SDOB about 95 m/kt$^{1/3}$:

Like the 1969 test, venting occurred by escape of gasses along a fault (apparently, without fault motion) that cut the tunnel between the two main stemming blocks and the blast door. About 10% of the radioactive gas escaped. The extensive description of the radiological conditions caused by this event given by Andrianov and Bazhenov (1992) are included on the next page.

Appendix IV: Summary of information on the containment of underground nuclear tests at the French Pacific nuclear test site [after *Int. Geomech. Comm., 1999*]

Category 1 --the majority of the nuclear tests (121 of the 137) — i.e. where a significant thickness of essentially undamaged volcanic cover exists above the test chimney (see Note 1 below)

Category 2 --4 tests where tritium releases to the karst have been detected even though the minimal depth of (low-permeability) volcanic cover should be high enough (140 m in the case of the Lycos tests at Fangataufa) to prevent this. French Liaison Office suggests that, in these cases, the original volcanic cover was relatively weak, such that drilling of the 1.5-m borehole (for installation of the nuclear device at depth) created an annulus of damaged rock around the hole. This annulus acts as a high-permeability conduit from the chimney to the base of the carbonates, allowing early release of tritium from the chimney.

Category 3 --12 relatively shallow CRTV (Chimney Reaching Top of the Volcanism) tests in which the chimney came into immediate contact with the base of the carbonates (karst). All CRTV tests are on Mururoa [7 tests carried out (1976–81) in test area 1° 4 in test area 2 (1976–80)° 1 in test area 3 (1976–80)]. Together with Category 2 tests, the CRTV tests would produce a total of 16 tritium (and strontium, cesium) release locations on the atolls. Measurements reported in *DIRCEN/CEA* [*1998*] Document No. 10 (Figs. 1-4°8) suggest at least 4 “leaky” holes at Mururoa, and 1 (Lycos) at Fangataufa. (Some of the concentration contours shown in these diagrams — especially for Mururoa — could encircle more than one leaky hole (i.e. the releases could be produced from several such holes relatively close to each other).

Category 4 --3 safety trials conducted (1976–81) in test area 2 (Mururoa rim) at a depth greater than 280 m in the carbonates, in which a (small) nuclear explosion (average yield 0.15 kt) resulted from each trial. Assuming that the resultant cavity radius (Rc) scales according to the same cube-root law as the cavities in the volcanic rock (i.e. Rc =12Y 1=3 m, where Y is the nuclear yield in kt), we obtain, for Y = 0.15 kt, a cavity radius of approximately 7 m. It is probably sufficient to assume that the radionuclide inventory in each of these three trials will be similar in composition to those in the larger tests, but directly proportional, in quantity, to the yield of the explosive. (See Notes 2 and 3 below.)

Category 5 --4 safety trials conducted in test area 1 (Mururoa rim), at a depth greater than 280 m in the carbonates, where there was no nuclear yield. In these cases, the plutonium contained in the device that was tested (estimated to be 3.7 kg plutonium oxide per trial) remains at depth. There are essentially no craters associated with these safety trials, but radial fracturing will occur around the seat of the chemical explosion (see (IAEA 1998c), App. 1, pp. 81–82, for names and dates of trials also see Notes 2 and 3 below)

Category 6 --3 safety trials conducted at depth in the volcanics (Mururoa rim). None of these trials resulted in a nuclear explosion. There are essentially no craters. Approximately 3.7 kg of plutonium (per trial) remains at depth from these trials. (see (IAEA 1998c) and Notes 2 and 3 below)

Category 7 --Radioactive waste produced by surface safety trials has been deposited in two shafts on the Mururoa rim, just west of test area 1 in the volcanic rock, at a depth of about 1200 m. The total quality of alpha activity was 10 TBq, equivalent to the plutonium from one trial. Because most of the plutonium was incorporated into cement and buried at depth in the volcanic zone, this waste represents a much lower safety hazard than the safety trials (Categories 4 and 5) carried out in the carbonate zone.

Note 1. The 134 underground tests listed in the Appendix to Bouchez and Lecomte (1996) include the 3 Category-4 safety trials, but do not include the 6 tests (4 at Mururoa, 2 at Fangataufa) carried out in 1995–96 (see also the table in Barrillot (1996), p. 178).

Note 2. It is probable that explosions in the carbonates will produce compaction and pore collapse, leading to a lower permeability in the zone around the seat of the explosion—so it would be conservative to assume no permeability change due to the explosion

Note 3. The safety trials were all conducted in the general vicinity of Dora / Denise (at the westerly end of test area 1) on Mururoa—i.e. slightly east of the most northerly portion of the Mururoa rim.

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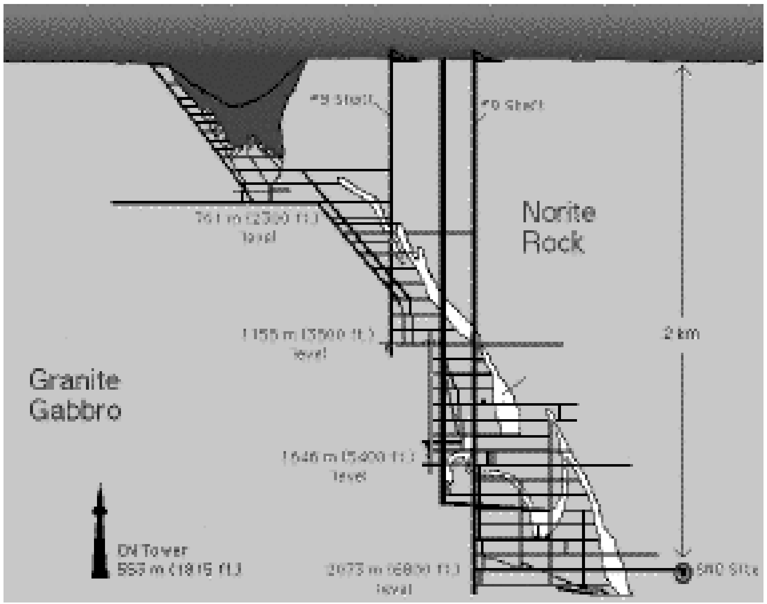
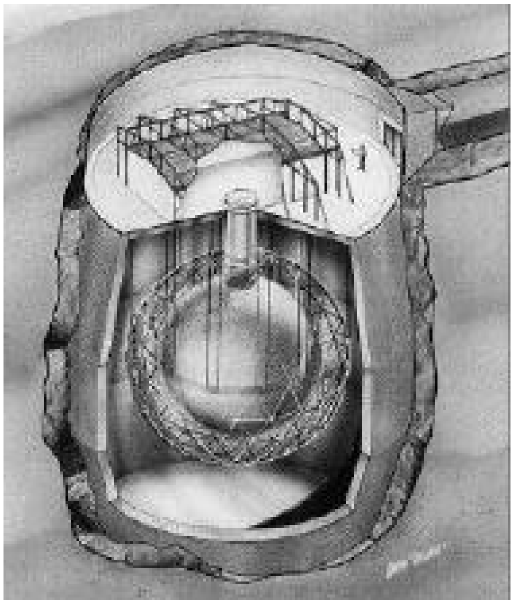
Appendix V: Construction of the Sudbury Neutrino Observatory

More than two kilometers below the earth's surface, deep in the rock of the Canadian Shield near Sudbury, Ontario, a 60 member team of scientists from Canada, the United States and Britain is completing the world's most powerful observatory to study the energy generation processes inside the sun and distant stars.





The Observatory is housed in a cavern as large as a 10-story (30 m) building in the deepest section of Inco Limited's Creighton Mine. As the western world's largest producer of nickel, Inco is a major participant in the project and applied its advanced mining technology in making the huge excavation required. Within a 22-meter-diameter underground cavity, a 12-metre diameter acrylic sphere contains over 1000 tons of heavy water on loan from Atomic Energy of Canada Ltd.

The $70 million project was funded in January 1990 and construction took place over a seven year period. Excavation of the underground site began in February 1990 and completed in June 1992; the detector was completed in March 1998. Because of environmental regulations, all of the waste rock was brought to the surface for reprocessing. The Sudbury Neutrino Observatory Institute has been formed to build and operate the laboratory. An engineering and project management company, Monenco-Agra Limited, prepared the detailed design and supervised much of the construction of the observatory. Most of the research and development work needed to finalize the design and materials used was carried out at the participating institutions.

For more information, see: *http://www.sno.phy.queensu.ca/*

Footnote 26: Clarification (2/26/01)

The statement in footnote 26, “approximately one billion times more gas than an equivalent-size nuclear charge,” pertains only to the tamped case (and also assumes that rock does not contribute to the non-condensible gas produced by the explosion). For the case of a fully tamped nuclear explosion (NE), where there is no significant amount of air, the nuclear charge does not produce a significant volume of non-condensible gasses. In some rock types, there can also be produced a large volume on non-condensible gases formed from, for example, carbonates in the rock or even reduction of steam to H_2 and O_2, if there is iron in the rock. This phenomenon has been a serious problem for NE containment and caused both the U.S. and the Russians to alter their test siting (and possibly the Chinese as well, based on USGS assessment of their abandoned underground test site); see the section of the report on *Containment/Soviet Experience*, p. 27.

In the case of a TNT explosion, the explosive reaction does not proceed to completion. For a 100-ton granulated-TNT explosion, about 40 tons of unburned carbon (soot) will be formed, which does not contribute a gas pressure. The remaining 60 tons will be gaseous, in the form of H_2O, H_2, CO, CO_2, NH_3, etc. The gross estimate of "approximately one billion" pertains to the comparison of these 60 tons with the relatively insignificant amount of non-condensible, noble gas produced by the tamped 100-ton nuclear explosion itself, without contribution by the rock.

For the decoupled case, a 1-kT decoupled cavity has about 34 metric tons of air in it, so the mass of non-condensible gasses from a NE is inconsequential. The proper comparison with a 1 kt TNT charge is, therefore (approximately), 600 tons versus 34 tons, still assuming that heating of the rock does not contribute (and would not in granite) --a factor of 20. The point is that an HE underground explosion over-simulates the pressures of a nuclear test, and therefore provides a “worst-case” environment for testing gas containment.