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Issues for Detecting Undeclared Post-Closure Excavation at Geologic Repositories

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Following closure, safeguards monitoring will be required for geologic repositories storing spent fuel and other waste forms not qualifying for international safeguards termination. Monitoring for acoustic emission from tunneling machinery, periodic satellite surveillance and site visits are the primary methods proposed for detecting undeclared excavation. Of these, only acoustic monitoring can detect subsurface activity, allowing a fixed monitoring perimeter to be established around a repository. If acoustic monitoring can be defeated, and other subsurface detection methods are unavailable, then surface monitoring must be performed for a larger, more ambiguous radius around the repository. This paper presents a fundamental classification scheme for identifying excavation technologies. The classification allows definition of a spectrum of small-diameter tunnel excavation scenarios. Analysis suggests that even for hard rock, national groups may be able to field compact, modular hydraulic or thermal excavation machinery with acoustic emission below background noise levels. This provides motivation for additional studies of subsurface monitoring methods and diversion scenarios, and suggests that the selection of repository geological media may have important implications for detecting undeclared tunnel excavation.

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INTRODUCTION

After spent fuel and other waste forms containing recoverable fissile material age a few hundred years, the radioactive barrier that makes the theft and the chemical separation of plutonium difficult disappears, and spent fuel becomes roughly equivalent to fresh MOX fuel in its proliferation attractiveness. Strategies for the direct geologic disposal of such materials call for the substitution of a geological barrier to replace, in the long term, the radioactive barrier to theft and diversion.[1]

Because the geologic barrier is imperfect and can be bypassed by tunneling, geologic repositories containing these materials will require monitoring and safeguards to detect any attempt to divert or steal fissile material by undeclared excavation.[2] Compared to above ground spent-fuel storage, the repository safeguards task is complicated because accounting becomes impossible following closure.

The clandestine recovery of two pressurized-water-reactor (PWR) spent-fuel assemblies per day would permit plutonium production at rates exceeding the maximum production achieved by the United States during the Cold War,[3] so the successful clandestine construction of a small-diameter tunnel into a spent-fuel repository could have significant strategic implications. Thus far, international efforts to identify geophysical techniques for postclosure subsurface monitoring have focused on detecting heavy excavation or drilling equipment, rather than smaller-scale equipment that might be applied to excavate small-diameter tunnels.[4] However, because the signatures generated by excavation depend on the volumetric rate of excavation, nations attempting undeclared excavation will choose the smallest possible tunnel diameter consistent with removing individual fuel assemblies. Here a reference two-meter diameter tunnel is studied, although yet smaller tunnel cross sections are credible.

The primary methods which have been proposed for detecting an overt or clandestine undeclared excavation attempt have been microseismic monitoring for acoustic emission from tunneling machinery and periodic satellite observation of surface activities.[5] Of these, only acoustic monitoring allows detection of subsurface activity and the establishment of a fixed subsurface monitoring perimeter around a repository. If subsurface monitoring can be defeated, a potentially much larger radius around the repository must be monitored for surface activity, a radius set by the maximum credible tunneling penetration rates nations could achieve and the maximum time period over which nations might attempt diversion.

Besides heavy excavation or drilling equipment, alternative rock excavation technologies currently exist that could involve smaller, modular equipment with smaller acoustic emission, requiring monitoring for more subtle acoustic emission and surface activities. Other human activities may generate similar surface signatures, and thus must be prohibited, or only permitted to occur with appropriate on-site monitoring. Future changes in tunneling technology may require changes in the types of human activities requiring prohibition or on-site monitoring, as well as changes in the radius around repositories where activities are controlled.

Following the classification method of Cook and Harvey,[6] the methods available for excavating a clandestine tunnel can be divided into three fundamental categories: mechanical, hydraulic, and thermal. All of these excavation methods can be described by two parameters: a specific energy for rock disaggregation, and a specific power delivered to the tunnel working face.

The efficiency of any excavation technique is determined by the *specific energy,* the energy required to convert a unit volume of solid rock into a broken, melted or vaporized form that can be removed from the working face. Table 1 summarizes typical specific energies for different excavation methods. The specific energy depends primarily on the properties of the geologic medium and on the size of the rock particles that the excavation method generates. In some softer geologic media, manual hand picking can remove material using very low specific energy. Among the other mechanical methods, drill and blast generates large pieces of rock and has a low specific energy, while diamond cutting generates a fine rock dust and has a large specific energy.

For hydraulic excavation with high-pressure water jets, the specific energy also depends on the characteristic grain size of the media, so that fine-grained rock like welded tuff can have a high specific energy, while granite with courser grain structure has lower specific energy. Relatively weak materials like clay shales and unwelded tuff have low specific energies for water-jet cutting, while salt presents a more interesting case because it is soluble in water. Thermal methods that involve melting or vaporization rather than thermal spall typically have large specific energies and consequently have seen only prototype development for rock excavation due to poor economics, but could still be of interest for a clandestine tunneling attempt due to the potential for very low acoustic emission.

For a given specific energy, the maximum rate at which rock can be removed is determined by the maximum *specific power* of the excavation technique, which is the maximum rate at which energy can be delivered to a unit area of the tunnel working face. The maximum *instantaneous rate of penetration* of the excavation technique is given by the ratio of maximum specific power to specific energy. Increases in penetration rates for mechanical excavation techniques in the last three decades have come primarily from increases in specific power.

This paper presents a comprehensive list of excavation methods and discusses potential penetration rates and acoustic emission, based on information available in the technical literature. The properties of the geologic media currently under consideration for repositories—welded tuff, crystalline rock (granite), clay and salt—are then considered, showing that the difficulty of excavation and the acoustic emission from tunneling activity are much lower in soft rock like clay shale and salt. A reference diversion scenario is then constructed. The scenario uses commercially available, modular hydraulic equipment, with a design selected to minimize acoustic emission while achieving reasonable penetration rates in granite (and rapid penetration in clay shale and salt). All equipment items are sufficiently compact to allow delivery to the tunnel mouth in a pickup truck or passenger vehicle.

The high-pressure water-jet technology selected for the reference scenario is now used commercially for granite and clay-shale excavation in quarries, but has only been applied commercially in sandstone for tunnel excavation due to its relatively low penetration rates compared to mechanical methods. The force imparted to the working face by water jets, however, is at least an order of magnitude lower than that achieved by mechanical tools, and the pumping and nozzle equipment is compact and more easily concealed. Combined with the commercial availability of water-jet equipment, and the relative simplicity of the technology compared to that required to construct and operate reactor or enrichment facilities, these features make the water-jet method a useful reference technology for judging the suitability of proposed postclosure safeguard methods for geologic repositories. Thermal methods also deserve additional study.

COMPREHENSIVE ASSESSMENT OF EXCAVATION METHODS

The excavation methods that could potentially be used for tunnel construction can be subdivided into the three fundamental categories summarized in Table 1: mechanical, hydraulic, and thermal techniques. The utility of each method depends on the material being excavated. For geologic repositories, the geologic media currently under active study are welded tuff (United States), crystalline rock (Canada, Finland, Sweden, France), salt (Germany), and clay shale (Belgium, France).

Mechanical Excavation

Drill-and-blast excavation methods have among the lowest specific-energy requirements, but are limited in their penetration rates by the average specific power that can be delivered to the working face, typically around 1.3 kW/m^2. [7] The average specific power is limited primarily by the time required to drill holes in the rock face for explosives. The instantaneous specific power is much higher when the explosives detonate, generating pressures of $2x10^9$ Pa to $50x10^9$ Pa. The force imparted to the rock face is correspondingly high, generating a strong acoustic signal.

Machine excavation (drag and roller bits) involves specific energies an order of magnitude greater than drill-and-blast methods, due to the much smaller rock particle size generated. Machine excavation, however, allows much larger specific power to be applied to the rock face, and thus allows penetration rates over an order of magnitude greater than drill-and-blast methods. Thus, machine excavation has replaced drill-and-blast methods for most tunneling operations in soft and medium-to-hard rock. Currently the fastest tunneling advance rates are achieved with full-face tunnel boring machines (TBM), which drive numerous disk-shaped roller bits mounted on a rotating cutterhead against the tunnel face. The most recent record for TBM advance rates was set in Nevada in 1996 with an advance of 150 m in one day in a 6.4-km long, 4.3-m diameter, $20 million tunneling project. [8] Considerably longer tunnels have been constructed from a single point of surface access, which must be considered in setting the radius for surface monitoring if failures in subsurface monitoring prevent a relatively short repository monitoring perimeter from being established.

In general, the amplitude of the acoustic emission from mechanical excavation will depend on the force with which the cutting tools contact the rock. Typical tunnel boring machines have large hydraulic thrust cylinders which press a large number of cutting tools against the tunnel face, with a total force per unit of working face area (specific force) around $3x10^5$ Pa (i.e. for a typical modern 5.6-m-diameter TBM with 40 disk-type cutters, a total force of $8x10^6$ N ($1.8x10^6$ lb_f), giving advance rates around 3 m/hr in medium-to-hard rock.)[9]

Hydraulic Excavation

Hydraulic cutting with high-pressure water jets has been used extensively for commercial excavation operations, including cutting rock, concrete, metal and composites and excavating soil, clay shales, and sandstone,[10] as well as being studied for creating vertical bore holes for granite geologic repositories.[11]

Water jets have also proven to be economically competitive for tunneling in soft rock. For example, tunnels in the sandstone rock underlying Minneapolis, MN have been mined with water pressures of approximately 1.7 to 3 MPa using nozzles measuring between 0.9 and 1.8 cm in diameter.[12] Specially designed carts are used to carry the equipment to pressurize the water and feed it though nozzles to the working face of the tunnel. The water jets erode the sandstone, generating a slurry which is pumped out of the tunnel. Advances of 4.5 m have been achieved in an eight-hour shift.

Water jets with higher pressures, tens to hundreds of megapascals, are capable of cutting granite and are now used commercially for that purpose to cut slots in granite in quarries. The relatively high specific energy required to excavate hard rock with water jets limits the possible penetration rate at reasonable specific power. The low penetration rate increases operating costs, making hydraulic excavation economically uncompetitive with TBMs for tunneling in hard rock. The acoustic characteristics of water-jet cutting differ greatly from mechanical methods. For the reference granite water-jet cutting system discussed later, a 0.4 m/hr advance rate (compared to 3.0 m/hr for a TBM) would generate a specific force of 3.2×10^3 Pa, considerably lower than the TBM specific force of around 3×10^5 Pa.

Thermal Excavation

A wide variety of thermal methods exist for the excavation of materials. Flame jets cause thermal spall, a mechanical effect, using fuels like kerosene with oxygen. Flame jets have been used extensively for granite quarrying and have been studied for cutting reinforced concrete structures.[13] Because thermal spall is induced by thermal stresses and results in the removal of solid material in relatively large pieces, the specific energy required for flame jet excavation is typically much smaller than other thermal methods involving melting or vaporization (Table 1). Flame jet systems can have high noise levels, and the combustion products and heat would create a difficult environment for workers in a tunnel, placing difficult constraints on tunnel ventilation or requiring remote operation.

Rock melting using a heated, refractory metal penetrator or "subterrene," has been studied extensively for drilling small-diameter bore holes for geothermal-energy wells.[14] Technical issues related to penetrators for dense rock, debris handling, electrical heater configuration, and establishing penetrator life have been addressed, although the subterrene has not succeeded as an economically competitive excavation method, due to its relatively high specific-energy requirement. Laboratory experiments with dense basalt rock have demonstrated advance rates of 1.0 m/hr, with specific powers (heat fluxes) of 5 MW/m^2, for the basalt specific energy of 18,000 MJ/m^3.[15] The penetrators work by pressing a heated refractory-metal surface against the tunnel working face. The pressure gradient established in the thin molten rock film between the metal surface and the solid rock causes the molten rock to flow to extrusion ports, where the rock-melt is removed in the form of chilled glass pellets, glass rods, or rock wool. Alternatively, in porous materials like welded tuff, melting can cause density consolidation at the tunnel wall which reduces or eliminates the need to remove debris. With laminar flow in the thin molten rock film and constant pressure applied to the penetrator, a subterrene would be expected to generate a negligible amount of acoustic emission due to vibrations or fluctuating forces applied to the working face. Acoustic emission from the subterrene tunneling process would be expected to come primarily from the gas flow used to entrain and remove debris, and from microseismic response to cracking caused by thermal stresses in the rock. Information about the acoustic emission from subterrenes is not available, and would need to be generated prior to designing an acoustic monitoring system for a specific repository site.

Laser melting and ablation are used extensively in industrial machining applications for material removal, and are the subject of intense ongoing research and development. Applied to the excavation of rock, laser cutting would be expected to have a negligible acoustic signature, with the sub-millimeter-diameter ablation plume from the pulsed laser imparting a very small force to the working face, and thermal stress effects limited to very small depths away from laser-cut surfaces. To completely melt and/or vaporize the entire mass of rock to be excavated would result in very large specific energies, which with the high cost of laser power (around $70/watt for CO_2 lasers[16]) would be prohibitive. Tunnelers would be likely to take advantage of the ability of lasers to cut slots with very small kerfs (widths). By cutting closely spaced slots in the tunnel working face, the rock could be removed as centimeter or larger sized pieces. The efficiency of laser slotting depends on the balance between absorbed beam power, power for melting/vaporizing material, power for heating material, and conduction heat losses. For example, a 1.2 kW CO_2 laser can cut a 2-cm deep slot at a rate of 0.05 cm/sec in aluminum oxide.[17] If used to excavate rock material in pieces with a specific area of 3 cm^2/cm^3, the specific energy of the system would be 36,000 MJ/m^3.[18] For this specific energy, a 1.5-m diameter tunnel, advancing at 1 m/day, would require a 74-kW laser system, with a laser-system cost exceeding 5-million dollars. Advances in industrial laser technology will bring laser costs down and create more rugged systems in the future; thus laser cutting may become attractive to groups attempting to evade acoustic monitoring.

BASIS FOR SELECTING REFERENCE DIVERSION SCENARIOS

The design basis for postclosure repository safeguards systems must consider a spectrum of diversion scenarios. Selecting diversion scenarios presents some difficult questions. The physical processes that could potentially be used for excavation can be determined (Table 1). However, one can only speculate about the effects technological change may have on the acoustic emission, penetration rates, cost and other characteristics of potential excavation technologies, or indeed on the monitoring technologies that could be used to detect tunneling operations. Furthermore, insufficient information exists in the technical literature to assess the acoustic emission of all of the potential excavation methods, so assessing the full spectrum of methods will require new experimental programs.

A repository safeguards system should be designed to detect the full spectrum of credible undeclared excavation methods. On one end of this spectrum the safeguards system should detect crude and inexpensive tunneling methods like drill-and-blast excavation, and for media where it is possible (i.e. some clay shales and salt) manual hand picking. On the other end of the spectrum, the safeguards system should detect the efforts of more sophisticated national and subnational groups with larger economic resources, who would have the motivation to research and develop more sophisticated methods to elude detection.

For waste forms like commercial spent fuel containing concentrated fissile material, clandestine divertors would choose a small-diameter tunnel. A typical PWR spent fuel assembly, with a 17x17 array of 0.92-cm diameter, 3.85-m long fuel pins, contains 4.2 kg of plutonium. For direct disposal in a repository, several fuel assemblies would be placed inside a hermetically sealed canister, and disposed with an overpack in either a horizontal or vertical orientation, potentially with a low permeability back fill material. After 300 years, assembly radiation levels drop sufficiently to allow considerable direct-contact handling, allowing canisters to be cut open insitu and individual assemblies removed manually. Typical spent-fuel repositories will contain a few to many thousand fuel assemblies (approximately 2,000 fuel assemblies per plant lifetime).

Contrasted to plutonium recovery from repositories, a typical large (3,000 MW_t) plutonium production reactor would produce 750 kg/year of plutonium with a capital cost of several billion dollars. [19] To equal the production rate of four large production reactors, and to approach the maximum plutonium production rate ever achieved by the United States during the Cold War, a clandestine tunneling group would need to cut open canisters and recover two PWR spent fuel assemblies per day. Because such low rates of spent fuel removal would allow very high rates of plutonium production, particularly for old fuel where handling and chemical separation become easy, all clandestine tunneling groups would have little or no motivation to build a tunnel with anything except the *smallest* possible diameter consistent with available tunneling equipment. This clandestine tunneling equipment would certainly be smaller than the equipment used during construction of the repository, and the acoustic and visual signatures generated by the equipment would also be smaller. Acoustic data gathered by monitoring tunneling equipment during repository construction will have little value unless suitably scaled to the smaller, different equipment that would be selected for an undeclared excavation attempt.

Additional considerations would also motivate the selection of a small-diameter tunnel, at least for spent fuel and other concentrated waste forms. Most of the signatures that would be monitored by safeguards—acoustic emission, removal of excavated debris, surface activity, heat emission—depend on the volumetric rate of rock excavation. The smallest feasible tunnel diameter would provide the maximum possible clandestine penetration rate for a given volumetric excavation rate.

Consistent with a clandestine group's likely desire to minimize its tunnel cross-sectional area, in the Appendix a 2-m diameter tunnel is selected as the reference tunnel, although smaller tunnels and non-circular cross sections are certainly credible.[20] The group would also select an excavation method that would minimize acoustic emission. A national group might devote resources to develop rock melting or ablation methods (i.e. a subterrene penetrator or laser cutting equipment) to minimize acoustic emission. Insufficient information is available to assess how successful such a development effort might be, making the analysis of potential thermal excavation scenarios difficult. Therefore water-jet excavation is considered here, as a commercially available technology that is amenable to analysis using data available in the literature. Acoustic emission from water-jet excavation would be at least an order of magnitude lower than that from mechanical excavation with a typical tunnel boring machine, although still greater than the acoustic emission likely achievable with thermal excavation methods. Initially a diversion scenario using hydraulic excavation of granite is considered, and then the extension to welded tuff, unwelded tuff, clay, and salt is discussed.

A Hydraulic Excavation Reference Scenario

The Appendix provides a detailed technical analysis of a reference water-jet tunneling system capable of advancing a 2-m-diameter tunnel 10 m/day in granite with a power input of 4.1 MW and water consumption of 230 m^3/hr. Figure 1 illustrates schematically the equipment arrangement the water-jet tunneling operation would potentially employ. The reference design was selected based on the limited acoustic and specific energy data available in the literature. A divertor group would likely work to optimize the system design further by testing water-jet equipment at a clandestine site away from the target geologic repository to optimize acoustic emission characteristics, minimize specific energy consumption, and maximize the tunneling advance rate.

The reference water-jet tunneling system would generate acoustic emission by four primary mechanisms: direct water-jet impact against the rock surface; coupling of water jet and equipment noise through the tunnel air space to the rock mass; pump and motor vibration transmission through support structures to the tunnel floor; and excavation-induced and thermally-induced rock stress changes. Here it is assumed that the positive-displacement pump and motor noise transmission to the rock mass can be mitigated through appropriate mounting and sound damping techniques, similar to those applied in modern submarines, and that rock stress changes can be minimized by cutting a smooth tunnel contour to minimize stress concentration and by appropriate orientation of the tunnel relative to the insitu stress distribution in the rock.[21] Because the high-pressure region created by the water jets is only a few millimeters in diameter, and elsewhere the maximum pressure is the hydrostatic pressure associated with the pooling of water, it is reasonable to assume that essentially none of the water will penetrate deeply into fractures to induce microseismic activity.

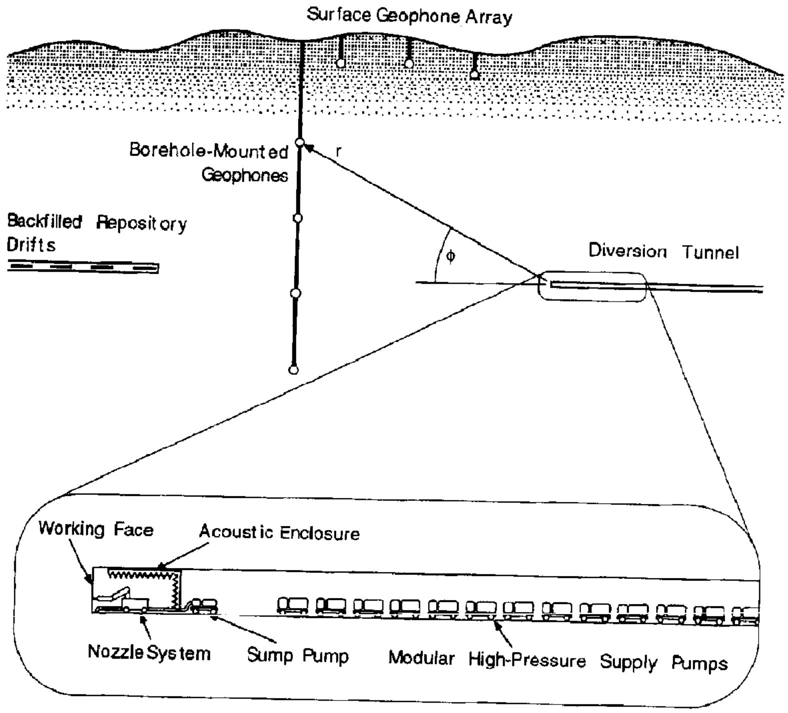

Figure 1: Schematic illustration of a hydraulic tunneling operation.

For mechanical and hydraulic excavation techniques, the unavoidable mechanism for transmitting acoustic energy to the rock mass is the contact of the cutting media with the rock working face. In the case of water jets, each jet generates an oscillating point force on the rock surface. The Appendix presents analysis for the amplitude of the displacements these forces would generate at geophones located 30 and 100 m away from the tunnel face for the reference scenario, as a function of frequency.

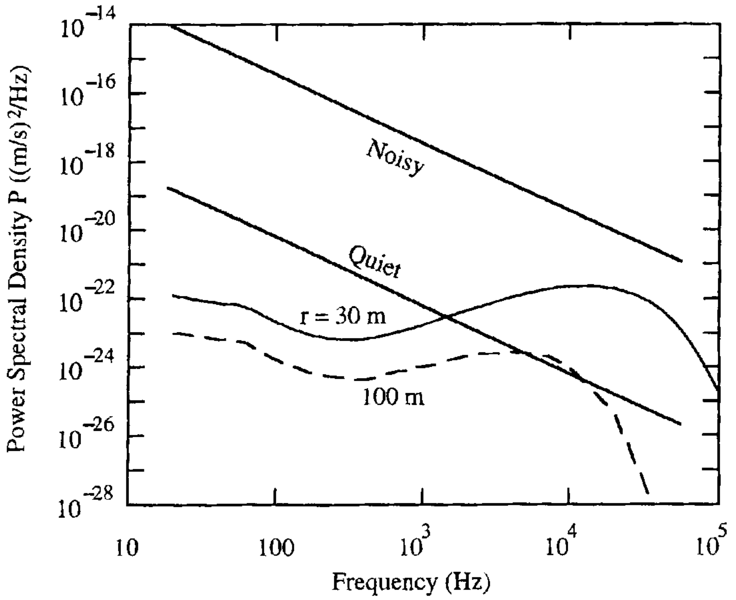

Figure 2: Power spectral density in low-attenuation granite due to reference water jet impact with a force totaling 10,000 N and power spectrum given by Figure A3, at radii of 30 m and 100 m. Shown for comparison are typical power spectra of ambient seismic noise for hard basement rock.

Figure 2 shows the results of this analysis for granite with relatively low attenuation characteristics, expressing the amplitude of the fluctuations in terms of the power spectra density.

The water jets and pumping equipment also generate noise in the tunnel air space, which creates a fluctuating air pressure at exposed surfaces of the tunnel wall. Experiments indicate that the pump system noise can be substantially lower than the jet noise over a broad range of frequencies (100 Hz - 20 kHz). The sound pressure level in a reverberant enclosure builds up until

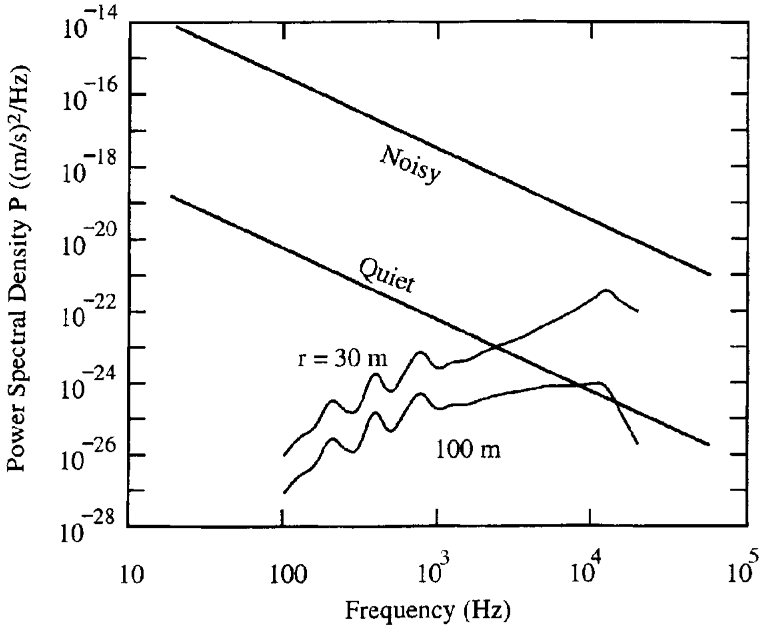

Figure 3: Power spectral density transmitted by air pressure fluctuations to the reference 2-m diameter tunnel working face due to water jet sound power spectrum given by Figure A4, in low attenuation granite at radii of 30 m and 100 m. Shown for comparison are typical power spectra of ambient seismic noise for hard basement rock.

the total sound power absorbed by surfaces in the room is equal to the sound power generated by the source.

To minimize the acoustic signature from water-jet noise, the tunneling group would likely cover all of the tunnel surfaces except the working face, or portions of the working face, with an acoustic lining system consisting of plastic films and glass-fiber board or other porous materials, to attenuate the sound intensity reaching the rock surface. By providing additional acoustically-absorbing material surface area in the form of free-standing panels, sound energy reflected from the tunnel working face could be absorbed even more effectively. Energy transmission to the rock would then occur primarily by direct transmission from the water jets through the air to the unprotected portion of the working-face surface. Figure 3 summarizes the results of calculations presented in the Appendix for power spectral density generated by noise from the reference water jet system, in granite at distances of 30 and 100 m from the tunnel working face. While this acoustic engineering would require some degree of sophistication, the technology is still relatively simple compared to that required for uranium isotope separation or production-reactor operation.

The detection of water jet tunneling activities will depend on the number, location, and sensitivity of the detectors employed and the ambient noise level. The tunneling acoustic emission of primary interest will occur at frequencies above 1 Hz, where ambient seismic noise for a typical station in hard basement rock remote from cultural (human) activities can be characterized by a relatively simple relationship given as Equation (9) in the Appendix. These ambient seismic noise levels fall below the detection threshold of most commercially available instruments, however, specialized seismometers do exist which can detect signals in this low range.[22] Figures 2 and 3 show the typical range of ambient seismic noise levels based on Equation (9) in the Appendix, and allow comparison with the predicted noise levels from the reference water-jet tunneling scenario. The ambient noise curves are approximate, as are the rock specific energy, sound speed and attenuation coefficient used in the calculations, so that site-specific experiments will ultimately be required to assess the actual capability to detect hydraulic (or thermal) excavation.

Wind and human activities can increase noise levels near the surface. These surface effects attenuate with depth, typically dropping to around 10% of the noise level at the surface at a depth of 100 m.[23]

In excavating granite, a tunneling group could consider using the capability of water jets to cut narrow slots to reduce the specific energy requirements and thus the acoustic emission for a given advance rate. This technique would require drilling holes in the working face with the water jets, attaching a rigid strong-back to support the block being cut, to prevent acoustic emission caused by the block cracking free, and then cutting slots to free the block. For example, by cutting blocks roughly $1.0 \times 0.7 \times 0.7$ m, with 2-cm wide slots, the volume of granite cut by the water jets could be reduced by a factor of 10, reducing the effective specific energy and acoustic emission by a factor of 10.

At distances of several tens of meters the reference water-jet system is capable of maintaining acoustic emission near or below ambient noise levels.

The tunneling group would be likely to monitor its own acoustic emission by mounting accelerometers inside short, small boreholes in the tunnel wall at several distances along the tunnel away from the working face. The group would use either analytical techniques or data obtained from a clandestine tunneling-system development program, at a location with similar geologic media, to analyze the accelerometer measurements and assess the magnitude of the microseismicity generated by their tunneling activities at the closest safeguards monitoring geophones. Because the power spectral density increases with the square of the water jet impact force, which in turn depends linearly on the number of nozzles operating, the group could then control its acoustic emission by changing the number and diameter of cutting nozzles, reducing as necessary its advance rate below the reference value of 10 m/day, to attempt to remain undetected when passing near safeguards monitoring geophones. Again the technical sophistication required for such self monitoring would be relatively low compared to that required for uranium isotope separation or dedicated reactor construction and operation.

Hydraulic Excavation in Other Media

The power spectra shown in Figures 2 and 3 for a 2-m diameter, 10-m/day advance rate tunnel in granite can be scaled to the other geologic media that are under consideration for geologic repositories. From Equation (3) in the Appendix, for a fixed nozzle pressure P_{wj} the amplitude of the impact force $\bar{F}_i$ applied to the working face scales linearly with hydraulic power $\dot{q}$. For a fixed advance rate and tunnel diameter, the amplitude of the force then scales linearly with the specific energy for excavation E. From Equation (5), the amplitude of displacements u_{rms} generated by these forces varies linearly with the force, inversely with the density ρ_r, and inversely with the square of the compressional velocity V_p. The power spectral density P(f), Equation (8), varies with the square of the displacement. Therefore the power spectral density is proportional to $E^2/\rho^2_r V^4_r$. Table 2 summarizes typical values of these parameters for granite and the other media, allowing comparison.

Clay shales. Large-scale water jets are commonly used for open-pit mining of clay shales, where high excavation rates can be achieved. Relatively low nozzle pressures of 0.5 to 5 MPa are used, with specific energy requirements around 20 to 40 MJ/m^3, much lower than the specific energies for hydraulic excavation of granite.[24] The relatively low pressures and specific energies required for disaggregation of clay shales suggest that acoustic emission from water jet excavation in clay shales would be three orders of magnitude lower than that for granite (Table 2), making the acoustic signature of hydraulic excavation activity in clay shale much smaller than background noise levels even at close distances. Energy requirements for clay shales are also substantially lower, reducing the number of pumps required, the power consumption, and any thermal signature from the excavation activity.

Salt. Salt is soluble in water. Data for the specific energy requirements for hydraulic excavation of salt are not available, but the specific energies will be low like clay shales. The relatively high compression wave velocity in salt makes its acoustic signature even smaller than clay shales, leading to the conclusion that for salt the acoustic emission from hydraulic excavation could easily be kept below background noise levels.

Welded tuff. Due to its very fine grain size, welded tuff can be significantly more resistant to water jet cutting than granite. In tests with a 98.1 MPa, 2.4 m^3/hr, 1.6-mm-diameter water jet cutting system, Matsuki et al. found specific energy requirements for water-saturated Shirakawa welded tuff varying between 50,000 and 200,000 MJ/m^3 depending on pump pressure and nozzle standoff distance, roughly an order of magnitude greater than the specific energy required to excavate granite.[25] This results in a much larger acoustic signature than for granite (Table 2), and substantially larger energy consumption. Any attempt to use water jets to excavate welded tuff of this type would likely require the use of abrasive particles to reduce the specific energy of excavation. Data for water-jet cutting of Yucca Mountain welded tuff is not available. Although the repository horizon of the proposed repository at Yucca Mountain lies in welded tuff, nearby bedded layers of unwelded tuff could be excavated at significantly lower specific energies, although the dry desert environment could make the signatures associated with any hydraulic excavation more obvious. (For granite sites overlain by softer sediments, a group could also consider tunneling through the softer material to increase its advance rate and the distance from the tunnel entrance to the repository).

In general, the acoustic signatures generated by hydraulic excavation in granite and welded tuff are much larger than those for clay shale and salt. Similar conclusions apply for mechanical excavation methods. Power requirements are also substantially lower for clay shale and salt, decreasing the size of equipment and thermal signatures from excavation. Hard-rock repositories provide much larger physical barriers to clandestine tunnel excavation than clay shale and salt sites.

Economics for Hydraulic Excavation

The cost of the simplest overt, 2-km long, 2-m diameter TBM-excavated tunnel has been estimated at $2.5 to $3.0 million (1992$).[26] The cost of a covert, hydraulically-excavated tunnel in hard rock would be substantially higher. Water-jet pumping equipment costs are around $500 to $775 per kW hydraulic (1992$),[27] or $0.9 to $1.6 million for the reference 2-MW pumping system. Appropriate nozzles for the reference system (70 MPa, 52 kW) have average lifetimes of 400 hr and cost $40 to $300 each (1992$).[28] For a 2-km long tunnel with a 10-m/day advance rate, a total of 530 nozzles would be used with a cost between $21,000 and $160,000. Allotting $1.5 million for four six-axis industrial robots and other support equipment, the total capital cost for the reference hydraulic excavation system would be $2.5 to $3.3 million, comparable to the $1.9 million capital cost (1992$) of a new 2-m diameter TBM.[29]

Energy costs will be a relatively small fraction of operating costs.[30] Assuming similar crew sizes for TBM and hydraulic excavation systems, operating costs for hydraulic excavation will be roughly eight times higher than for TBMs, due primarily to the smaller average penetration rate of the reference hydraulic system (0.4 m/hr vs. 3.0 m/hr). The additional research and development and other costs required to keep the tunneling effort covert could potentially increase the tunneling cost by another factor of ten. Thus a crude estimate of the cost of a covert, hydraulically excavated tunnel would be 80 times the cost of a simple, overt tunnel excavated with a TBM, or $200 to $240 million for a covert tunnel (1992$). This total cost would be prohibitively high for subnational groups, but would be within the resources available to many national groups. At 10-m/day, the 2-km-long tunnel would require 200 days to construct, not including research and development and surface set-up time.

In contrast to hard-rock (granite and welded tuff) repositories, soft-rock (clay shale and salt) repositories would provide a much lower economic barrier to hydraulic tunneling, since the excavation cost scales roughly proportionally to the specific energy, reducing excavation costs by more than two orders of magnitude compared to granite. This raises concerns that, with inadequate surface monitoring, even subnational groups could succeed in constructing a clandestine tunnel into a soft-rock repository.

For comparison to recovery from repositories, the capital cost for an overt, 400-MWt reactor, capable of producing 100 kg of plutonium per year, including mining, milling, conversion and fabrication costs, would range from $1.0 to $2.2 billion (1992$) and require 50 to 75 engineers and roughly 150 to 200 technicians working for 5 to 7 years.[31] The clandestine construction and operation of such a reactor system would be difficult and much more expensive.

The capital cost of a dedicated enrichment facility is difficult to estimate, because the choices of technology and procurement routes are more uncertain, and because most openly available information is associated with very large commercial plants, where costs per unit enrichment can be relatively low. Nevertheless, an approximate estimate of costs can be generated by considering smaller commercial facilities. The cost for constructing an overt centrifuge facility capable of producing 300 kg of HEU per year could run from $100 to $500 million (1992$). Including a 85 tonne/year uranium mining, milling, and conversion capability, and research, development, testing, engineering, and startup costs would increase the capital costs to $160 to $750 million (1992$). The costs of building such enrichment facilities in secret, at a clandestine location, could increase these enrichment facility capital costs "substantially."[32]

Compared to enrichment or dedicated production reactors, a clandestine tunnel allowing the recovery of two old PWR spent fuel assemblies per day would allow clandestine plutonium production at 3,400 kg/yr,[33] a rate which would be strategically significant if arms-control agreements can reduce weapons-states' stockpile sizes to a few hundred nuclear weapons as envisioned by some arms-control analysts.[34] The DOE Office of Arms Control and Nonproliferation has noted that "proliferating states using designs of intermediate sophistication could produce weapons [using diverted reactor-grade plutonium] with assured yields substantially higher than the kiloton-range possible with a simple, first-generation nuclear device." An advanced nuclear weapon state, "using modern designs, could produce weapons from reactor-grade plutonium having reliable explosive yields, weight, and other characteristics generally comparable to those of weapons made from weapons-grade plutonium."[35] For old repositories, the much lower radioactivity and heat generation of old, repository-grade plutonium would make repository-grade plutonium effectively equally as attractive as weapons-grade plutonium to a national group or advanced nuclear weapons state.

With the potential for very high plutonium production rates at relatively modest cost, and the high utility of repository-grade plutonium for nuclear explosives, a national group contemplating a strategically-significant, covert nuclear-weapons production effort could be expected to commit significant economic resources (tens to hundreds of millions of dollars) to developing covert tunneling technology, if it had access to an old repository, and if surface-monitoring did not clearly prevent the clandestine surface activities required for a small-diameter tunnel.

Non-Acoustic Diversion Signatures

This section discusses the surface signatures that various clandestine tunneling activities could generate in the area of the tunnel entrance, and the human activities and natural features that could potentially conceal these signatures. Here it assumed that a clandestine diversion attempt would use compact, modular equipment to excavate a small-diameter tunnel, rather than the large-scale, heavy tunneling equipment that would be used in initial construction of a repository.

The use of compact, modular excavation equipment would allow equipment to be delivered to the tunnel entrance in relatively small vehicles, potentially even passenger vehicles. The tunnel mouth could be small, concealed by a small building or by vegetation at forested sites. The initial excavation could be accomplished by hand, to provide space underground for equipment storage to minimize the size of the structure required to cover the tunnel entrance.

Hard-rock excavation equipment requires substantial power input, at a minimum tens of kilowatts and likely hundreds of kilowatts to a few megawatts for more rapid advance rates. Hydraulic methods would also require substantial water flows. These energy and water requirements would be unremarkable for an area permitting light industry, and could potentially even be concealed in an area permitting scattered residences or farm and ranch buildings.

A variety of methods are available for transporting and disposing of tunneling debris. For a low-technology group excavating soft rock by hand picking over a period of several or many years, debris generation rates could be as small as a few hundred liters per day.[36] More sophisticated and rapid excavation methods would generate debris at substantially larger rates, for example around 30 m^3/day for the reference 2-m diameter, 10-m/day tunnel. The vehicular traffic required to remove debris at this rate would be unremarkable for a light-industrial area, and could potentially even be concealed for a residential area. Pneumatic or hydraulic transport of fine-grain debris in suspension could permit excavated material to be transported away from the tunnel surface entrance in buried pipes. At coastal sites or near lakes and rivers, these bodies of water could be used as clandestine dumping areas.

For hard rock, large specific energies are required for excavation methods with low acoustic emission, although hydraulic rock slotting and block removal may reduce these energy requirements significantly. For reasonable advance rates, surface rejection of the resulting heat will create a substantial thermal signature. A variety of legitimate human industrial and commercial activities also generate waste heat at these rates. Buried pipelines may allow heated water to be transported significant distances. Likewise an injection well, or nearby large body of water, could be used to reject heated water. For soft rock (clay shales and salt) specific energies are low and thermal emission would be correspondingly small.

CONCLUSIONS

The analysis presented in this paper supports the following observations:

- A group attempting undeclared excavation into a spent-fuel repository would select a small tunnel size, likely under 2-m high, much different from the tunnels excavated for the original repository construction.
- A clandestine tunneling group would select compact, modular excavation machinery. The tunnel entrance could be hidden by a small, unremarkable structure.
- Based on the limited data available in the literature, a scenario for hydraulic excavation of granite with water jets can be constructed which keeps acoustic emission at background seismic noise levels at distances of tens of meters, for a 10 m/day advance rate. With additional development, a national group could potentially field thermal or hydraulic excavation machinery that would be undetectable by passive acoustic methods at a few tens of meters or less.
- A variety of human surface activities, such as light industry and construction of residences and farm and ranch structures, could conceal surface observation of a clandestine tunneling attempt using compact, modular equipment, unless subjected to sufficiently rigorous on-site monitoring.
- The resistance of soft rock (clay shale and salt) to clandestine tunneling will be much lower than the resistance of hard rock. Penetration rates can be substantially higher in soft rock, and acoustic and thermal emission orders of magnitude lower. Theft by subnational groups is much more readily conceivable for soft rock repositories.

If subsurface monitoring by acoustic or other geophysical methods proves to be unreliable, this has a significant negative implication for the viability of repository safeguards because the area that must be covered by surface monitoring grows substantially. This suggests that additional engineering design and experiments are warranted to study the feasibility of detecting hydraulic and thermal excavation methods. These studies should focus on the detection of small-diameter tunnels, rather than the larger diameters that would be used originally to emplace waste.

Based on the analysis presented here, future repository monitoring and safeguards burdens could be reduced in four ways:

(1)

1) Select hard-rock sites (granite or welded tuff) with minimal vegetation and no nearby bodies of water to maximize the technical difficulty of undeclared tunneling.

2) Select sites where future surface activities would have low economic potential (i.e. desolate sites), and consider requirements that the host nation agree to permanently prohibit human activities involving the construction of any surface or subsurface structures, except structures directly required for repository construction and operation, for a suitable radius around the site (i.e. perhaps 15 km). Make provisions for unrestricted onsite inspections to a significantly larger radius (i.e. perhaps 40 km), to deter long-term, long-distance attempts to construct tunnels.

3) Minimize the number of repository sites by forming multinational high-level waste compacts. Although most nations could conceivably identify repository sites inside their borders that would protect future human health and safety, many do not have areas which meet the safeguards criteria 1 and 2. Forming international compacts for waste disposal would also help minimize the number of repositories future generations would be required to monitor. Waste trading could allow the disposal of waste of lower attractiveness at repository sites with weaker proliferation resistance. Potential choices for repository host nations for attractive waste forms would be the United States, Russia, and China.[37]

4) Study and develop waste treatment processes that would reduce substantially the concentrations of weapons-usable isotopes in repository waste forms, to increase the mass of material that must be recovered to obtain a given quantity of fissile material, as well as the magnitude and duration of the radiation barrier protecting the material.

These siting criteria have the potential reduce the long-term burden that repository safeguards will place on future generations. The prohibition of all surface and subsurface structures that could conceal even a small tunnel entrance would make the construction of any structures, which could be readily detected by periodic satellite observation, a clear violation of the host nation's safeguards agreement. Reducing the concentrations of weapons-usable isotopes in waste-forms, even if just for a subset of the world's repositories, could reduce the attractiveness of undeclared excavation and help deter such efforts. Alternative disposal methods, such as sea-bed or ocean-island disposal, can also be reconsidered as providing greater barriers to undeclared recovery.

Of repository sites currently under consideration in various nations, the Yucca Mountain site in the United States most readily meets the safeguards criteria of hard rock (welded tuff) and low economic potential. The sparsely vegetated, sparsely populated site is located on Federal land managed overlapping the Nevada Test Site, Nellis Air Force, and Bureau of Land Management (BLM) lands. The closest farm lands are 25 km away, in the Amargosa Desert and Oasis Valley. Grazing occurs on leased BLM land 10 km away. Highway 95 from Las Vegas passes within 20 km of the proposed repository, while the closest towns are Amargosa Valley (22 km) and Beatty (30 km). Active surface and underground mining occurs at Bare Valley (20 km), and mining has occurred previously at other locations, the closest being Amargosa Desert (18 km) and Lee (22 km). The Desert National Wildlife Range occupies a large area to the east of the site.[38]

Although the Yucca Mountain site provides hard rock in a Federally owned area of low economic potential, legislative action would be required to increase the current limits on the maximum mass of spent fuel that can be stored of at this site, just to accept the spent fuel that existing US plants will generate over their current operating licenses. Recommendations to also accept commercial spent fuel from other countries to achieve long-term nonproliferation goals would likely encounter strong domestic opposition.

ACKNOWLEDGEMENTS

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APPENDIX: ANALYSIS OF HYDRAULIC EXCAVATION IN GRANITE

In water jet cutting of rock, high-pressure (tens to hundreds of megapascals) water is focused through a nozzle to create a high-velocity water stream. When the water jet is moved across the rock surface, it penetrates into existing cracks, weakness planes and grain and crystal boundaries, pressurizing the crack and dislodging material. When a particularly large, resistant grain is encountered, water jets can penetrate around the grain and remove it, making the jets particularly efficient in excavating concrete containing highly resistant aggregate. Rotating water jets have been found to be effective for cutting granites in quarries, and are used commercially for cutting long, deep slots of roughly 5-cm width in granite blocks. The addition of abrasives can increase the cutting rate of water jets by factors of two to ten.[39]

Depending on the water supply pressure, flow rate, nozzle diameter, standoff distance, traverse rate, and rock properties, the specific energy required for granite excavation can range from 1,000 to 50,000 MJ/m^3, much higher than the energy consumed by tunnel boring machines (i.e. 10 - 50 MJ/m^3). The typical specific energies reported for granite center around 5,000 MJ/m^3; this value is used here.

In studies of water jet tunneling in hard rock, commercial six-axis industrial robots have been used to move the water jet over the rock surface, allowing cutting in a similar manner to that achieved with roadheaders. Flexible high-pressure hoses carry the water from high-pressure supply pumps to the nozzle assemblies.[40] Experiments for plain water jet cutting have shown that more efficient cutting is obtained by using smaller numbers of jets for the same total flow rate, due to the increase in the diameter of the jets.[41] Here, however, relatively small nozzle diameters are considered, because acoustic and specific energy data are only available for these smaller nozzles.

As a reference case, this Appendix considers an water jet tunneling system using 44 nozzles of 1.53-mm diameter, supplied with water at a pressure $P_{wj} = 69MPa$ by pumps with a total water-jet hydraulic power of $\dot{q} = 2MW$. These parameters were selected to match conditions for which experimental data are available for granite excavation. [42]

The 44 reference nozzles would be ganged in sets of eleven at the end of the four six-axis robot arms. Neglecting high-pressure pumping losses, the pump work $\dot{q}$ is related to the volumetric flow $\dot{Q}$ in each of the n nozzles by

$$\dot{q} = n\dot{Q}P_{wj} \qquad (1)$$

For the reference supply pressure P_{wj}, from Equation (1) the water flow to each of the n nozzles would then be $\dot{Q}$ = 2.4 m^3/hr (10.6 gpm), for a total water flow rate of 105 m^3/hr (466 gpm). Based on the performance prediction of Bortolussi et al.[43], these nozzles would excavate granite with a specific energy requirement of 5,000 MJ/m^3 without the addition of abrasives. For the 2 MW of power provided and a 2-m tunnel diameter, this power input would permit an advance rate of 10 m/day in granite assuming a 90% utilization factor. Substantially better specific energies have been reported for granite, some below 1,000 MJ/m^3, [44] indicating that a water jet tunneling system optimized for the local conditions could potentially have an advance rate as much as five times higher. The use of abrasives could also reduce specific energy by a factor of 2 to 10. Studies of water jet excavation of large-diameter bore holes at the Canadian Underground Research Laboratory showed that insitu stresses and confinement can increase specific energy by factors of 2 to 5.[45] In the reference scenario this problem is mitigated by cutting a narrow slot around the periphery of the tunnel at higher specific energy to relieve compressive stress on the core, which is then excavated at lower specific energy.

In addition to the 2-MW pumping power supplied at the nozzles, an additional 0.4 MW would be required for high-pressure pumping losses, 0.4 MW for auxiliary system power (air cooling fans, sump pumps), and 1.2 MW for jet and cooling water pumping (based on a 5-km-long tunnel to a depth of 500 m, 230 m^3/hr (1000 gpm) total flow rate, 0.20-m-diameter supply line, 0.15-m-diameter return line), for a total power consumption of 4.0 MW. Upon reaching the heated repository region, which in a water-saturated granite would have a temperature below 100°C, additional heat removal of approximately 0.1 MW would be required to maintain acceptable working temperatures in the tunnel.[46] The 230 m^3/hr water flow would provide heat rejection, removing the 4.1 MW with a temperature rise of 16°C.

The 4.1 MW would be rejected to the environment outside the tunnel by one of several possible methods. The tunnelers might use a river or the ocean as a heat sink, or a cooling tower. A buried pipeline could allow the tunnelers to locate the point of heat rejection relatively far from the tunnel entrance. Due to the relatively large heat load carried by the underground lines, the buried pipes could be detected by infrared observation unless concealed under a roadway or other long structure with a different albedo and temperature than the surroundings, or concealed by relatively heavy vegetation. Monitoring for thermal emission at the location used for heat rejection to the air or a body of water could allow detection of the tunneling activity, unless the heat rejection was disguised as a permitted surface activity. The relatively small return-line diameter would be selected to achieve relatively high water velocities (i.e. 3-4 m/s) to allow excavated rock particles to be carried to the surface by the water flow and removed at the surface by filtration for ultimate clandestine disposal.

ACOUSTIC EMISSION FROM THE REFERENCE GRANITE SCENARIO

The average magnitude of the point forces created by several water jets comes from the momentum change of the *n* jets, which is given by the product of the jet mass flow rate and the change in jet velocity upon impact ΔV,

$$\bar{F}_i = n\dot{m}\Delta V = n\dot{Q}\sqrt{2\rho_w P_{wj}} \tag{2}$$

When no jet rebound is assumed, the velocity change of the water can be expressed in terms of the nozzle supply pressure P_{wj}, and water density ρ_w, as $\Delta V = \sqrt{(2P_{wj})/\rho_w}$, giving the final form of Equation (2). Using Equation (1), Equation (2) can be rewritten

$$\bar{F}_i = \dot{q}\sqrt{\frac{2\rho_w}{P_{wj}}} \tag{3}$$

emphasizing the advantage of using a high water supply pressure P_w to minimize the impact force $\bar{F}_i$ for a given power $\dot{q}$ delivered to the working face. For the reference water-jet system each of the 44 nozzles generates a point force of 250 N (56 $\mathrm{lb_f}$), for a total thrust of 10,000 N (2,500 $\mathrm{lb_f}$).

Water jets impart seismic energy directly to the rock by fluctuations in the point force generated by the jets and by the traversal of the jet across the rock face. Matsuki et al.[47] used a high-pressure (49.0 MPa) water jet directed against a pressure transducer to study pressure fluctuations for a stationary jet. Figure A1 shows the typical pressure histories recorded for a d = 1.6-mm diameter jet, showing the effect of the distance L between the nozzle and transducer face. At lower frequencies (10 Hz - 100 Hz) the primary source of force fluctuation is the fluctuation in supply pressure from the positive-displacement pumps used to pressurize the water. For shorter standoff distances ($L/d < 50$) the 23-Hz pump pressure fluctuations in Figure A1 have a root-mean-square (rms) amplitude around 5% of the total jet impact pressure. A tunneling group might use hydraulic damping equipment to reduce this low-frequency pump pressure fluctuation.

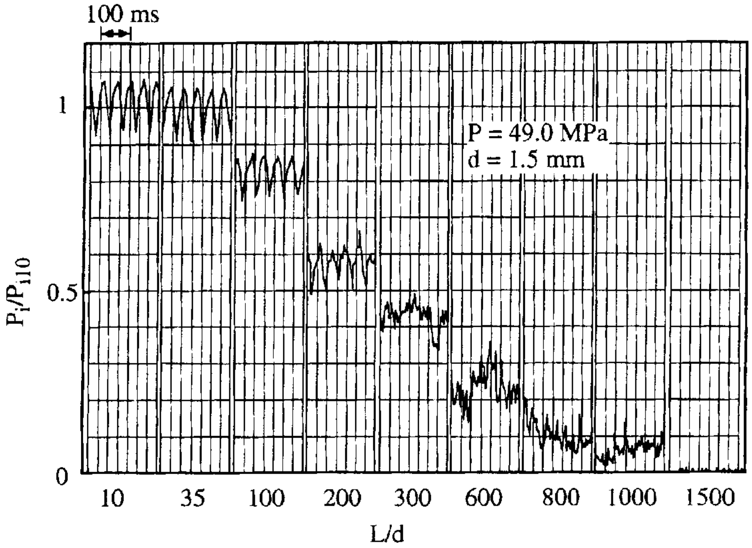

Figure A1: Time history of a typical water jet impact pressure, with impact pressure normalized to the value measured for a L = 10cm standoff distance.[58]

For a jet traversing over a rock surface, additional fluctuations in the jet force will occur due to changes in the momentum transfer by the jets as they are deflected in different directions by the rock surface topology, changing ΔV. For typical surface feature sizes around one millimeter and jet traversal rates of a few centimeters per second, the frequency of these fluctuations will be below 100 Hz, like the pump fluctuations. The analysis below suggests that these lower-frequency components of the acoustic signature will be relatively unimportant compared to the high-frequency components.

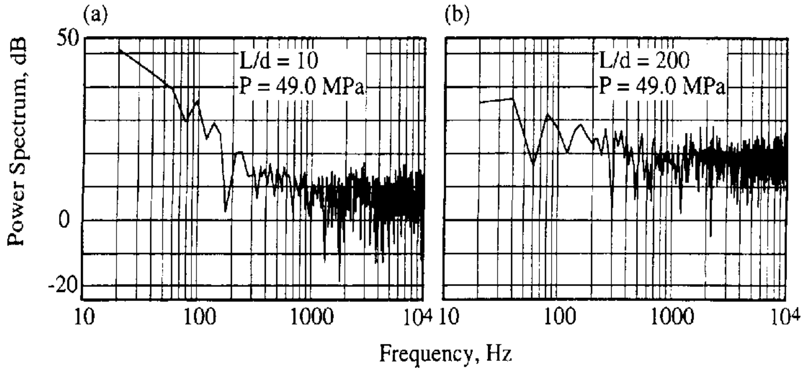

Figure A2: Power spectra for impact pressure of typical water jet at various standoff distances.[59]

At higher frequencies, water-jet force fluctuations occur primarily due to hydrodynamic instability, waviness and break up of the water jet, a chaotic process that generates a continuous-spectrum signal. At larger standoff distances (*L/d* > 80) the aerodynamic interaction of the jet with air begins to break up the water jet, increasing the amplitude of the higher-frequency force fluctuations significantly. Figure A2 shows water jet power spectrum data for different standoff distances, corresponding to the impact pressure time histories given in Figure A1.

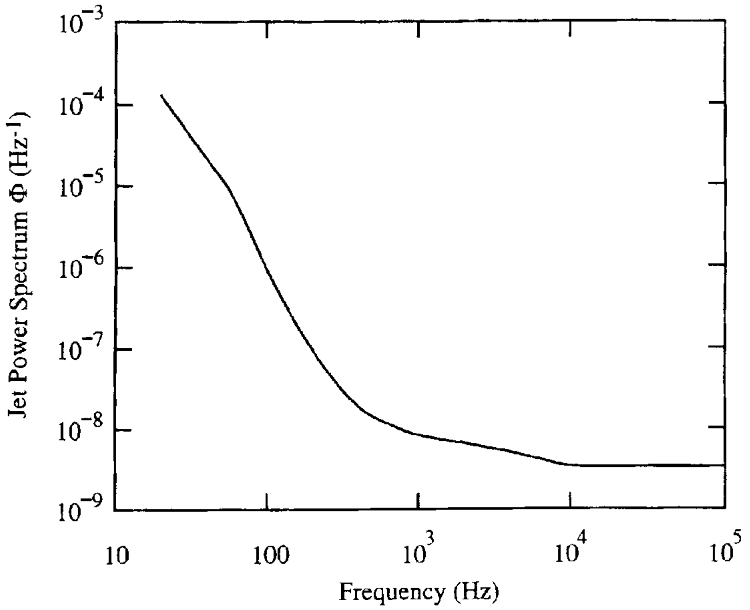

Figure A3: Power spectrum for impact pressure of typical water jet at various standoff distances.[60]

Increasing the standoff distance for the jet increases the amplitude of the pressure fluctuations at higher frequencies (> 100 Hz), primarily due to the increased hydrodynamic breakup of the jet and the resulting impingement of droplets on the transducer surface.

A tunneling group would likely optimize its water jets to keep the standoff distance *L/d* below 80 to achieve a power spectrum similar or lower than that reported in Figure A2 (a) for *L/d* = 10. Figure A3 shows the impact-pressure power-spectra function that results from a curve fit to Figure A2 (a)[48], plotting

$$\Phi(f) = \frac{(F_{rms}/\bar{F}_i)^2}{f} = \frac{(p_{rms}/\bar{p}_i)^2}{f} \qquad (4)$$

where $\overline{Pi}$ is the average impact pressure (i.e. 49 MPa in Figure A1), p_{rms} the rms amplitude of the pressure fluctuation at the frequency *f*, and F_{rms} the corresponding rms amplitude of the force fluctuation at frequency *f*. Figure A3 can be interpreted as follows. For example, at $f = 10^4$ Hz, we find F = 3 x 10^{-9} Hz^{-1}. Considering a bandwidth equal to half the frequency, the rms amplitude of pressure fluctuations at 10^4 Hz is ((3 x 10^{-9} Hz^{-1})(5 x 10^3 Hz))$^{1/2}$ = 0.004, that is, the rms amplitude of the pressure fluctuations at 10^4 Hz is around 0.4 % of the average impact pressure.

The displacement that would be measured by a geophone due to water jets impacting against a tunnel working face can be estimated by considering a fluctuating point force applied in an infinite, elastic, homogeneous medium. The compressional displacement a distance *r* away is given by[49]

$$u_r = \frac{\cos(\varphi)}{4\pi\rho_r V_p^2 r} F\left(t - \frac{r}{V_p}\right) \qquad (5)$$

where V_p is the velocity of compressional waves in the rock and φ the angle from away from the force vector. The maximum compressional displacements then occur along the axis of the force vector, φ= 0°. The point force also generates shear displacements of similar magnitude to the compressional displacements with maximum magnitude at φ= 90°, however, since the maximum displacements are similar, compressional displacements are considered here.

At frequency *f*, the water-jet forcing function in a narrow frequency band width Δf is:

$$F\left(t - \frac{r}{V_p}\right) = \bar{F}_i \sqrt{2\Delta f \Phi(f)} \sin\left(\frac{f}{2\pi}\left(t - \frac{r}{V_p}\right) + \theta\right) \qquad (6)$$

where θ is a phase delay.

Compressional waves will be attenuated exponentially with distance as $\exp-(-a_p r)$, where the attenuation coefficient is given by $a_p = (\pi f)/(Q_p V_p)$ and Q_p is the rock mechanical quality factor. The rms velocity induced at a neighboring geophone by the impact of the water jets can be found by substituting Equation (6) into Equation (5), differentiating to obtain velocity, multiplying the velocity by the exponential attenuation at frequency *f*, and averaging for the rms value. The rms velocity along φ = 0° is then

$$\dot{u}_{rms}(f) = \frac{\bar{F}_i f \sqrt{\Delta f \Phi(f)}}{8\pi^2 \rho_r V_p^2 r} \exp(-a_p r) \tag{7}$$

The power spectral density P of the noise induced by water-jet tunneling activities is then

$$P(f) = \frac{(\dot{u}_{rms}(f))^2}{\Delta f} \tag{8}$$

and has units of $(\text{m/s})^2/\text{Hz}$.

Figure 2 shows the power spectral density predicted by Equation (8) at distances of 30 and 100 m from the reference water jet system, with $\bar{F}_i$ = 10,000 N, for granite with ρ_r = 2600 kg/m^3, V_p = 5880 m/s, and a relatively high quality factor (low attenuation) of Q_p = 250.[50]

The ambient seismic noise for a typical station in hard basement rock remote from cultural (human) activities can be characterized by the equation[51]

$$P_n(f) = \frac{C}{f^2} \tag{9}$$

where C can range from a low of 6 x 10^{-17} $(\text{m/s})^2$ Hz to high of 3 x 10^{-12} $(\text{m/s})^2$ Hz. Figure 2 shows the typical range of ambient seismic noise levels based on Equation (9).

The water jets and pumping equipment also create noise in the tunnel air space, which causes a fluctuating air pressure at exposed surfaces of the tunnel wall. Limited information is available on the noise characteristics of water-jet cutting systems. Merchant and Chalupnik[52] measured sound pressure levels of 97.1 dBA (adjusted to 100.5 dB for a free field) with the sound power spectra peaking at 10 kHz, for an industrial abrasive water-jet system for cutting 1.3-cm thick aluminum plate. The dominant contribution to the noise came from the water jet itself, with the pump system noise being 20 to 40 dB lower than the jet noise over the range of frequencies studied (100 Hz - 20 kHz). Figure A4 shows the sound power spectra L_w measured during these experiments over one-third octave bands, for plate cutting with the jet exiting into a bed of steel balls. These noise levels are consistent with those reported for a 112 kW water-jet-assisted roadheader for cutting harder rock which used 24 0.43-mm-diameter water jets, where noise levels ranging from 85 to 107 dBA were measured.[53]

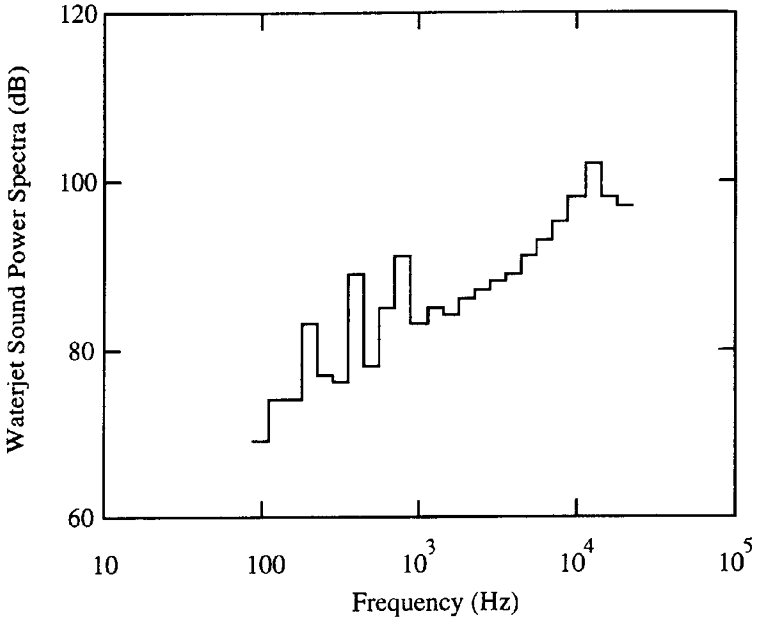

Figure A4: Sound power spectra L_w measured for a single water jet cutting 1.5-cm thick aluminum plate, with the jet discharging into either a water tank or a steel ball catcher.

Here the energy transmission to the rock is assumed to occur primarily by direct transmission from the water jets through the air to the unprotected working-face surface. Because the water-jet noise source is very close to the working surface, the sound pressure level L_p at the wording face depends on the radial distance R from the jet impact point. For a flat, rigid surface the sound pressure in decibels at radius R can be estimated in mks units as[54]

$$L_P \mathrm{re} 2\mathrm{x}10^{-5} Pa = (L_w re 10^{-12} watt) - 10\log(R^2) - 8 \qquad (10)$$

where L_w is the sound power level in decibels.

The force fluctuation applied to the working face inside a one-third octave bandwidth Δf centered on frequency f can then be estimated by integrating the pressure over area out to the maximum radius R_m,

$$F(t) = \sqrt{2}\sin\left(\frac{ft}{2\pi} + \theta\right)\int_0^{R_m} 2\pi R\sqrt{n}\,p_{rms}\,dR \qquad (11)$$

$$= \sqrt{8n}\,\pi\rho_{ref}\sin\left(\frac{ft}{2\pi} + \theta\right)\int_0^{R_m} R\,\mathrm{antilog}\left(\frac{L_w - 10\log(R^2) - 8}{20}\right)dR$$

$$= \sqrt{8n}\,\pi R_m (2x10^{-5} Pa\ \ m)\,\mathrm{antilog}\left(\frac{L_w - 8}{20}\right)\sin\left(\frac{ft}{2\pi} + \theta\right)$$

Here the total force imparted by the noise from n water jets is found by summing the squares of the rms pressure contributions of each individual jet. If the noise from the water jets, acting over the entire working face, is assumed to act as a point forcing function in a much larger isotropic medium, then the displacement induced at a geophone a distance r away can be estimated by substituting Equation (11) into Equation (5), differentiating, multiplying by the exponential attenuation at frequency f, giving along $\varphi = 0°$

$$\dot{u}_{rms}(f) = \frac{f R_m \sqrt{n}(2x10^{-5} Pa\ \ m)\,\mathrm{antilog}\left(\frac{nL_w - 8}{20}\right)}{4\pi\rho_r V_p^2 r}\exp(-a_p r) \qquad (12)$$

Using Equation (12) with Equation (8), the power spectral density induced by n water jets at a geophone a distance r from the tunnel working face can be calculated. Figure 2 shows the result of this calculation for the reference n = 44 water jet system in granite, based on the power spectrum for a single water jet given in Fig A3, using R_m equal to the working face radius of 1 m. As with the power spectra generated by the direct impact of the water jets (Figure 2), acoustic emission with frequencies above several kilohertz is the most likely to be detected. The tunneling group would likely work to minimize this source of acoustic emission by using baffling reduce the effective value of R_m and the sound pressure fluctuations at the tunnel working face.

Table 1: Efficiency of various excavation methods.[55]

Excavation Method	Specific Energy E (MJm^3)	
Rock Compresive Strength (MN/m3)	Soft (0-50)	Hard (100-200)
Mechanical		
Hand picking	<6	-
Drill and blast	6	6
Impact driven wedge		
Drag bit cutting	20	80
Roller bit boring (TBM)	20	210
Percussive drilling	-	180
Diamond cutting	-	1120
Hydraulic		
Soft material (clay/salt/unwelded tuff)	20	-
Coarse grained rock (granite)	-	5,000
Fine-graiined rock (welded tuff)	-	50,000
Thermal		
Thermal spall (flame jet)	-	3,000
Melt (heated penetrators)[56]	-	18,000
Vaporization (lasers, plasma torches)	-	30,000

Table 2: Comparison of approximate acoustic parameters for hydraulic excavation of different geologic media.[57]

Geologic Media	Specific Energy E (MJm^3)	Velocity V_p (m/sec)	Density ρ_r (kg/m^3)	$\frac{(E^2/\rho_r^2 V_r^4)}{(E^2/\rho_r^2 V_r^4)_{granite}}$
Granite	5,000	5,880	2,600	1.0
Slotted Granite	500	5,880	2,600	1.0×10^{-2}
Welded Tuff	500,000*	3,200	2,200	1.6×10^{3}
Clay Shale	30	2,700	2,300	1.0×10^{-3}
Salt	30**	6,000	2,200	4.6×10^{-5}

* Specific energies for unwelded tuff would be much lower.

** Data for the specific energy for salt are not available, so the average value for clay shale is used here.

NOTES AND REFERENCES

1. National Academy of Sciences, *Management and Disposition of Excess Weapons Plutonium* (Washington, D.C.: National Academy Press, 1994), p. 148.

2. The International Atomic Energy Agency (IAEA) position on repository safeguards is outlined by A. Fattah and N. Khlebnikov, "A Proposal for Technical Criteria for Termination of Safeguards for Materials Characterized as Measured Discards," *Journal of Nuclear Materials Management*, XIX (2), (1991), pp. 29-34.

3. Peterson, P.F. , "Long-Term Safeguards for Plutonium in Geologic Repositories." *Science & Global Security*, Vol. 6, (1996), pp. 1-29.

4. The IAEA has sponsored a cooperative effort of several member states (called SAGOR) to study safeguards issues for repository waste disposal, including the evaluation of geophysical techniques like micro-seismic monitoring, as discussed in Canadian Safeguards Support Program, *Application of Geophysical Techniques for Geological Repository Safeguards (SAGOR Activities 5b and c)*, CSSP Report No. 94, Atomic Energy Control Board, (1997), pp. 87-96.

5. For instance, the NRC report on excess weapons plutonium disposition notes, "Feasible technical approaches for low-cost monitoring of such sites are available, such as the use of remotely operated seismic stations to detect drilling operations in the vicinity of the repository." NAS, *op. cit.*, pg. 59. See also J. Myatt, "Design Information Verification for Conditioning Plant and Geologic Repositories," *Transactions of the American Nuclear Society*, Vol.75 (1996) p. 92-93; G.A. Ekenstam, S.-E. Larsson, and H. Forsström, "Spent Fuel in Geologic Repositories: Swedish Aspects of Safeguards," *Transactions of the American Nuclear Society*,Vol. 75 (1996), pp. 96-97; and B. Richter, "Recent Development in Final Disposal Concepts for Spent Fuel and Related IAEA Safeguards Issues," *Transactions of the American Nuclear Society*,Vol. 75 (1996), p. 97.

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13. Shimida, S., "The Cutting of Reinforced Concrete Structures by Flame Jet," *Jet*

Cutting Technology - Proceedings of the 10th International Conference, (Elsevier, 1991), pp. 293-304.

14. Hanold, R.J., *et al.*, *Rapid Excavation by Rock Melting - LASL Subterrene Program*, LA-5979-SR, Los Alamos National Laboratory, (1977).

15. Hanold, *op. cit.*, (1977), Fig. II-10, p. 9.

16. Chryssolouris, *Laser Machining: Theory and Practice*, (New York: Springer-Verlag, 1991), p. 87.

17. Chryssolouris, *op. cit.*, (1991), p. 240.

18. $(1.2\ \text{kW})(3\ \text{cm}^2/\text{cm}^3)(10^{-3}\ \text{MJ/kJ})/(2\ \text{cm})(0.05\ \text{cm/s})(10^{-6}\ \text{cm}^3/\text{m}^3) = 36{,}000\ \text{MJ/m}^3$.

19. Peterson, *op. cit.*, (1996), p. 17.

20. For methods like hydraulic excavation a circular cross section is not required. Work remains possible in tunnels even under 1-m in height. Such small tunnels were common in earlier mines, due to the difficulty of excavation, motivating the use of children for the labor.

21. Young and Martin discuss the acoustic emission and microseismicity that can occur due to tunnel excavation, Young, R.P. and C.D. Martin, “Potential Role of Acoustic Emission/Microseismicity Investigations in the Site Characterization and Performance Monitoring of Nuclear Waste Repositories,” *Int. J. Rock Mech. Min. Sci. & Geomech. Abst, Vol.* 30 (1993), pp. 797-803.

22. For example seismometers based on laser interferometry. A.Araya, et al., “Highly Sensitive Wideband Seismometer Using a Laser Interferometer.” Rev. Sci Instrum., Vol. 64, (1993), pp. 1337-1341.

23. Aki, K. and P.G. Richards, *Quantitative Seismology: Theory and Methods*, (New York: W.H. Freeman and Co. 1980), p. 498.

24. Jackson M.K., and T.W. Davies, “Optimization of Nozzle Flow/Head Requirements for China Clay Mining,” *Seventh International Symposium on Jet Cutting Technology*, (Ottawa, Canada, 1984), pp. 293-314.

25. Matsuki, K., K. Okumura, and H. Nakadate, “Some Aspects of Slot Cutting of Rocks With High Speed Water Jets Both In Air and In Water,” *9th International Symposium on Jet Cutting Technology, (*Sendai, Japan, October 4-6, 1988), pp. 495-511.

26. Peterson, *op. cit.*, (1996).

27. Summers, *op. cit.*, (1995), p. 51.

28. Summers, *op. cit.*, (1995), p. 73.

29. Extrapolation of (1987 $) TBM capital costs in U.S. *Bureau of Mines, Bureau of Mines Cost Estimating System Handbook: 1. Surface and Underground Mining,* IC-9142, United States Department of the Interior (1987), pp. 368-369.

30. For the reference scenario energy costs $220,000 at 0.10 $/kWh for a 5-km long tunnel (4.1 MW total, 2.0 MW hydraulic, 2-m diameter, 5,000 MJ/m^3 specific energy).

31. Peterson, *op. cit.* (1996); Office of Technology Assessment (OTA), *Technologies Underlying Weapons of Mass Destruction*, OTA-BP-ISC-115, U.S. Government Printing Office, (1993), p. 156.

32. OTA, *op. cit.*, (1993), p. 158.

33. For old (a few hundred years) spent fuel, reprocessing can be accomplished with modest shielding requirements in unremarkable, nondescript buildings; emission of radioactive noble gas (i.e. 10.76-yr half-life ^{85}Kr) would be negligible, Peterson, *op. cit.*, (1996).

34. The most recent NAS-CISAC study recommends a progression of nuclear force reductions to the levels of a few hundred warheads for both Russia and the United States, with the caveat that verification methods be in place to detect, with high reliability, the covert retention or acquisition of illegal nuclear warheads. National Academy of Sciences, *The Future of U.S. Nuclear Weapons Policy*, (National Academy Press, 1997), p. 79.

35. DOE Office of Arms Control and Nonproliferation, "Final Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Plutonium Disposition Alternatives," DOE/NN-0007, (1997), p. 41.

36. A low-technology, 2-km long tunnel with a cross sectional area of 1 m^2, excavated over a 40-year period with an average advance rate of 14 cm/day, would create 140 liter/day of debris.

37. Because the U.S. nuclear industry is so large, increasing the capacity of the United States' planned spent fuel repository by 100% would allow one repository to accommodate all the spent fuel that will be generated by all existing plants in countries which do not currently plan to reprocess spent fuel.

38. U.S. Department of Energy, *Environmental Assessment: Yucca Mountain Site*, DOE/RW-0073, Office of Civilian Radioactive Waste Management, (1986), pp. 3-7, 3-23, 3-34, 3-35.

39. Bortolussi, A., S. Yazicci, and D.A. Summers, "The Use of Waterjets in Cutting Granite," *9th International Symposium on Jet Cutting Technology*, (Sendai, Japan, October 4-6,1988), pp. 239-254; Summers, op. cit., (1995), pp. 433-436.

40. Vasek, J., and J. Foldyna, "Abrasive Waterjet Cutting of Hard Rocks," *Jet Cutting Technology-Proceedings of the 10th International Conference*, (Elsevier Science, 1991), pp. 413-424.

41. Summers, *op. cit.*, (1995), p. 453.

42. Bortolussi, *op. cit.*, (1988).

43. Bortolussi, *op. cit.*, (1988).

44. Bortolussi, *op. cit.*, (1988) Table 2.

45. Puchala, *op. cit.*, (1988).

46. Peterson, *op. cit.*, (1988), p. 10.

47. Matsuki, *op. cit.*, (1988).

48. Matsuki, *op. cit.*, normalize their pressure data and do not report absolute values, or the reference pressure used in generating the power spectrum. Figure 4 is derived using a smooth curve fit from L_p = 52 dB at 23 Hz to 6 dB at 10^4 Hz. For the 20-Hz bandwidth intervals shown in Fig. 3, $p_{rms}/\bar{p}_i = 0.05$ at 23 Hz gives Φ (23 Hz) = $(0.05)^2/20$ Hz = 1.25 x 10^{-4} Hz^{-1}. Values of Φ at other frequencies follow from $\Phi(f_1)/\Phi(f_2) = \text{antilog}((L_P(f_1) - L_P(f_2))/10)$.

49. White, J.E., *Seismic Waves: Radiation, Transmission, and Attenuation*, (McGraw-Hill, 1965), p. 214.

50. For the 4-8 kHz band. These properties are characteristic of the granite at the Atomic Energy of Canada Limited's Underground Research Laboratory (Young, *op. cit.*, p. 799). Attenuation coefficients in granites are commonly an order of magnitude higher (White, op. cit., 1965), p. 89.

51. Aki, *op. cit.*, p. 497. Araya, *op. cit.*, recommends $C = (10^{-7}/2\pi)^2 =$
2.5×10^{-16} $(\text{m/s})^2$ Hz for quiet sites for gravity wave detection.

52. Merchant H.C., and J.D. Chalupnik, “Sound Power Measurement of an Abrasive Water Jet Cutting System,” *International Conference on Noise Control Engineering* (Cambridge, Mass., 1986), pp. 241-244.

53. Sato, K., et al., “Development of Roadheader for Harder Rock,” *9th International Symposium on Jet Cutting Technology*,” (Sendai, Japan 1988), pp. 341-356, Table 12.

54. Beranek L.L., and I.L. Vér, *Noise and Vibration Control Engineering*, (New York: John Wiley and Sons, 1992), pp. 165-166, 222-228.

55. Abstracted from Cook, *op. cit*, (1974).

56. Hanold, *op. cit.*, (1977), Fig. II-10, p. 9.

57. Granite: Young, op. cit., p. 799; clay shale/salt: W.M. Telford, R.E. Sheriff, D.A. Keys, *Applied Geophysics*, (Cambridge: Cambridge University Press, 1976) pp. 25, 27, 257; tuff: R.S. Carmichael, *Practical Handbook of Physical Properties of Rocks and Minerals*, (Boca Raton, Florida: CRC Press, 1989), p. 474.

58. Matsuki, *op. cit*, (1988).

59. Matsuki, *op. cit*, (1988).

60. Matsuki, *op. cit*, (1988).