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TITLE THE STRENGTHENING AND REPAIR OF UNDERGROUND STRUCTURES: A NEW APPROACH TO THE MANAGEMENT OF NUCLEAR WASTE

AUTHOR(S) Stirling A. Colgate, T-6

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THE STRENGTHENING AND REPAIR OF UNDERGROUND STRUCTURES: A NEW APPROACH TO THE MANAGEMENT OF NUCLEAR WASTE

Stirling A. Colgate
Los Alamos National Laboratory
MS B275,Los Alamos, NM 87545
(505-665-5254)

.bstract: This paper presents three closely related ideas and :chnologies: (1) The secure, repairable, long time confinement of uclear radioactive waste underground by a large surrounding region f compressive overstress; (2) The inherent tectonic weakness and ulnerability of the normal underground environment and its ıodification by overstress; (3) The process of creating overstress by ıe sequential periodic high pressure injection of a finite gel ırength rapid setting grout.

Nuclear Waste: The secure, long-term confinement of ıdioactive nucleotides has traditionally required the assurance of onfinement integrity over many thousands of years. In view of the :ctonic activity of this earth, this seems to me to be unrealistic and ot obtainable. Every location on the continents is visited by the amage of a major earthquake roughly every 10,000 years. Because f the usual, initial, large anisotropy of the tectonically relaxed nderground stress field, an earthquake easily alters this local stress eld in a major fashion so that it is unlikely that any underground tructure can be certified against damage during such an event. lowever, I suggest an approach to this problem that has the dvantage of both periodically augmenting the tectonic security of ıe underground structures and furthermore offers the possibility of ı situ but remote repair. This assures the integrity of underground onfinement of nuclear wastes by a technically competent society ıdefinitely in the future. I am suggesting that it is feasible and :latively inexpensive to engineer a large region of compressive tress surrounding any underground cavity. This curtain of over tress (over and above the local in situ stress due to overburden ressure) can be reestablished at a future time by a future society /henever necessary. The process requires the technology of drilling nd pumping high pressure fluids. A society that has given up these :chnologies indeed would be hampered from such post-repair work, ut it is unlikely that the population density at such a time would ver be threatened by exposure to greatly attenuated and decayed uclear waste.

Results of Overstress: A region of compressive overstress urrounding any underground cavity not only multiplies the ıtegrity against failure by collapse of such a cavity by orders of ıagnitude but also insures that the exchange of fluids either into or ut of a cavity is greatly inhibited by the compressive overstress of ıe medium itself. Therefore the integrity of underground onfinement can not only be greatly improved at the time of its ııtial inception, but more important can be assured in the indefinite ıture. Underground stress engineering is not only feasible but is a :latively inexpensive repair process.

'reating Overstress: The process of creating overstress results ı altering the underground stress distribution. It can be achieved by ıe periodic injection of a settable fluid that has the rheological roperties of finite gel strength and rapid setting to a rock-like ıaterial. Each cycle of injection fractures the medium followed by ıe setting of the injected material to a rock-like, hard solid. This etting processes locks-in the increment of pressure used to fill and pen the fracture in the first place. By successive increments of pressure and successive fractures, the local stress locked into the medium with each cycle can be progressively increased to an arbitrarily high value limited only by the strength of the materials used to inject the special fracture fluid and the compressive strength of rock. The process of underground stress engineering has been partially tested in the field but needs a much larger effort to demonstrate its feasibility for the important role that it can play in the safety of our underground confinement structures.

Introduction: Traditionally we have planned to store our nuclear waste underground as much because of the perceived advantage of massive shielding against the nuclear radiations as well as a perceived sense of safety against the possibility of the radioactive elements reentering our biosphere. Possibly this perception of the optimum strategy should be reaffirmed when one considers how we store our other most precious commodity, namely, money. Be that as it may, one presumably has the consensus to make the underground confinement of nuclear waste as secure as possible within rather vague limits of what possibility means. However, the security of nuclear waste confinement is perhaps somewhat less sensitive to human intrusion as compared to intrusion by the natural environment.

The underground, with the exception of earth quakes, is indeed a relatively benign environment and certainly the studies of the migration of nuclear waste in ground water over billions of years has been investigated in the most extreme case, namely at the natural reactor of the Oklo Mine in the Republic of Gabon, West Africa (Cowan, 1976). In the less extreme case the exploration of a twenty year old nuclear bomb test cavity at the Nevada Test Site by Darlene Hoffman and colleagues, (Hoffman et. al., 1978) demonstrates that water per se is a relatively miner effect on nuclear confinement compared to the possibility of gross structural failure by tectonic motion. In this work a small, 10 kiloton equivalent yield, nuclear test cavity in Frenchmen's Flat at the Nevada Test Site was drilled progressively closer to the bomb cavity itself. Many millions of gallons of water were extracted from the Ash Meadows aquifer with the result that negligible radioactivity, only a few atoms, was found. It was only in the cavity itself that detectable amounts of tritium and cesium were found and then at levels far less than cause a human biological response.

Tectonic failure of an underground structure requires an understanding of underground tectonic forces. By and large we imagine the underground as supporting the material above it, and the weight of the material above it determines the "overburden stress." In this paper 'stress" will be inferred to be compressive stress since rock, in general, supports no tensile forces. In a very few cass of rock bolting will tension forces be mentioned. One might naively suppose that the term "tectonically relaxed' would imply that deep underground the stress would be isotropic as in a fluid and also would have a value equal to the overburden stress. Instead one can think of the ground as being supported by an array of closed packed columns. The space between the columns is frequently filled by fluids. This is a simple analogy to an anisotropic stress distribution with the pore space filled with a fluid pressure that is some fraction of the overburden pressure. Figure 1.

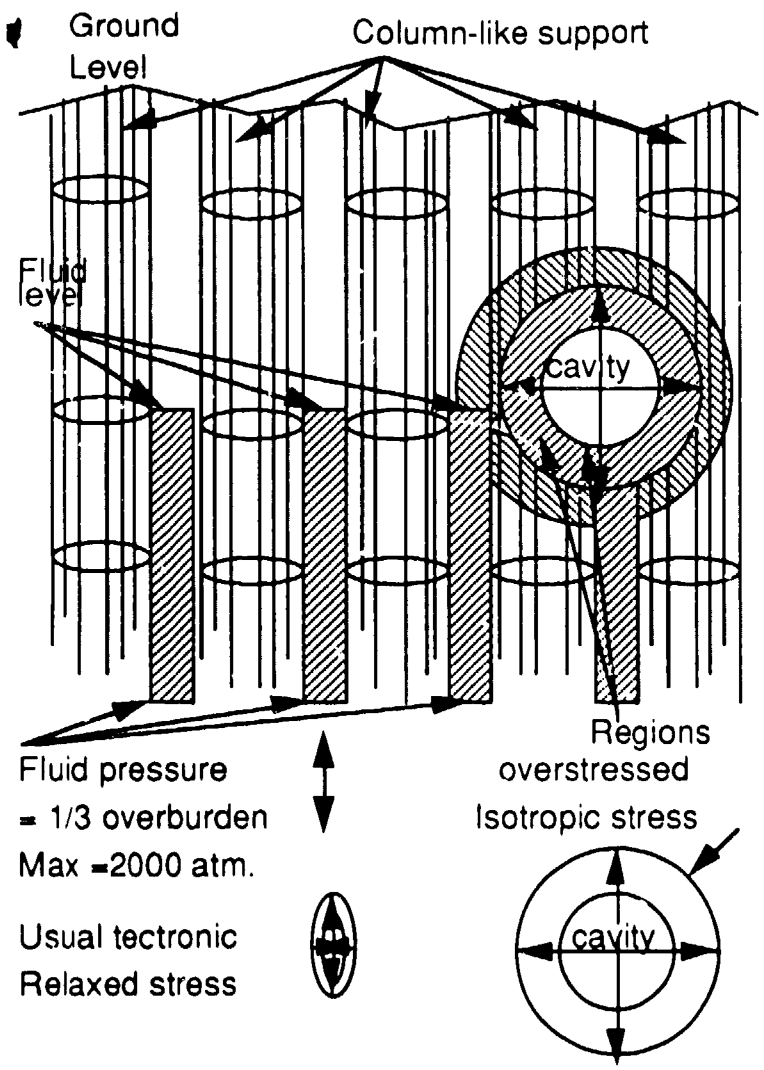
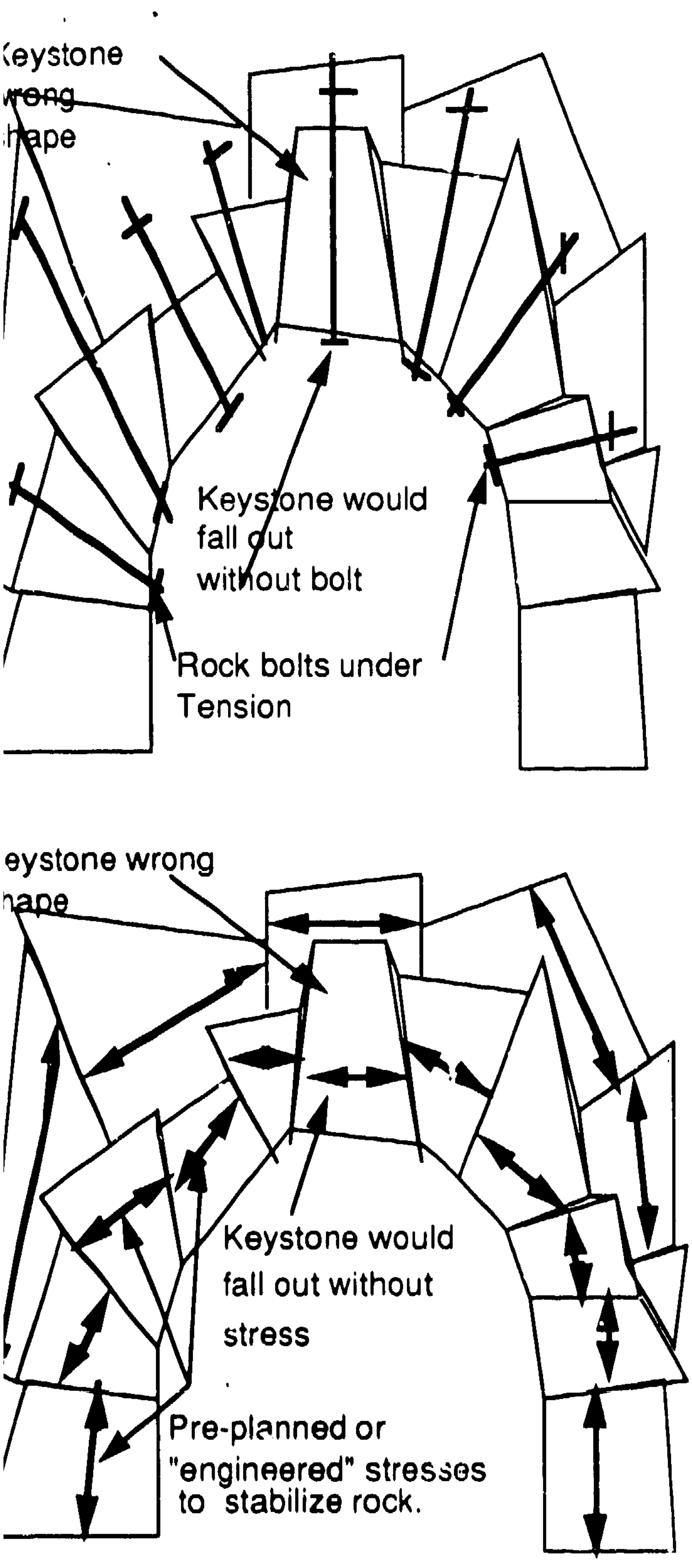


Fig. (1) *shows the underground supported as if by a series of columns. The spaces between the columns are analogous to the pore pressure and in general are filled to various levels with fluids. The pressure of these fluids are typically 1/3 of the overburden pressure. An overstressed region surrounding a cavity tends to make a spherical or isotropic region of stress that excludes fluids.*

It is fortunate indeed that a tectonically relaxed underground stress distribution develops this weird behavior because it permits the flow of lighter fluids such as water, oil, gas, and even bacteria to flow and exist in this extra pore space. On the other hand this stress distribution makes it difficult to create stable tunnels or cavities underground. If one excavates a hole in such an anisotropic medium, then the horizontal pressure, in general, will be significantly less than the vertical overburden pressure. This is because the overburden stress is held up vertically in columns and the pressure between the columns is less. If, at the top of the arch of such a cavity or tunnel, the critical few stones are shaped wrong, they can fall out easily and the roof can cave. This is just like taking the keystone of a Roman arch and reversing the angle of the trapezoid of the stone so that the stone and its neighbors can fall out rather than be held by the horizontal compressive forces. Then when both the stone is misshapen as well as the horizontal forces are weak, the keystone and all its neighbors can start falling out. This is the origin of a cavity collapse underground, and it is why there is so much effort placed in engineering stability in underground cavities.

The usual fashion for engineering stability in underground cavities is to supply tension forces by means of rock bolts in such a way as to hold in place that misshapen keystone rock and its nearest neighbors so that it doesn't fall out of the top of the arch and start the cavity crumbling. Figure 2. Also, of course, one can line the inside of tunnels with reinforced steel and concrete to make the cavity more stable. The concrete and steel primarily hold in place the keystone rock and its nearest neighbors rather than hold up all of the overburden pressure. In general and historically, one does not tamper with the unfavorable in situ stress distribution of the rock, but takes it as it is and just tries to deal with its boundaries. Instead, one should fix the trouble by engineering the underground stress distribution to be favorable for cavity confinement.



g. (2) *shows two rock tunnels, the top one stabilized by rock lts and the lower by stresses created in the fractured rock by the ocess of overstressing.In both cases the keystone or rock at the of of the tunnel is of such a shape that without some support it uld fall out on its own.*

The purpose of underground stress engineering is to alter is unfavorable stress environment underground so that a ntiguous compressive stress curtain can surround the cavity using the compressive forces to being many orders of magnitude greater that existed in the medium originally. It is this far greater stress that can give the cavity such greater strength.

This large overstress can be created on a scale which is very large compared to the cavity itself, up to ten times its dimension, but at a cost that is small compared to the cost of the cavity. Usually cavities are lined with a relatively thin layer of reinforced concrete and steel. If instead we were to surround our cavity as claimed above by a region of compressive stress whose thickness is comparable or larger than the radius of the cavity itself and whose compressive stress is some 10 or even 100 times the overburden stress, then, indeed the cavity would be singularly robust and immune to outside forces. This is the objective of underground stress engineering.

Confinement of underground fluids by Overstress: The secure confinement of radioactive waste depends primarily upon the isolation of the radioactive elements from exchange with the fluids (air or water) of our environment. This exchange can be thought of as either access or egress of fluids to or from the radioactive nucleotides.In general it is much easier for a fluid with a pressure gradient to escape confinement than to enter it.This is because an internal pressure leading to fluid escape tends to open any radial fractures facilitating flow away from the cavity, whereas the converse of a fluid pressure gradient such as to cause a fluid to enter a cavity causes radial fractures to close thus hindering fluid access. Since the breach of nuclear waste confinement requires both fluid access and escape and since escape occurs the easiest, it becomes the critical process that we must ensure against. With this in mind we discuss underground stress engineering from the standpoint of pressure confinement within a cavity. If we can prevent fluid escape, we have reasonable assurance that fluid access to the waste will be even more strongly inhibited.

Techniques of Pressure Confinement: There is a need for stable confinement of high pressure fluids or gases underground. The most familiar case is the design and use of penstocks, lined or unlined tunnels for conducting high pressure water to turbines in hydro-electric projects. Underground cavities have also been considered for the local containment and storage of natural gas for use as a fuel. In addition there may be a need for the reliable containment of small nuclear tests underground. Experience has demonstrated, especially with penstocks, that the containment of such pressurized fluids by just the overburden pressure in the rock is limited to 50% of the overburden stress. For higher pressures the stress is then transferred to a steel or reinforced concrete lining. Since, for penstocks, the water pressure is seldom much greater than half the overburden pressure, the cost of the lining is less than the cost of excavation, and hence, there has not been a major motivation to proceed to alternate technology. For underground pressure vessels with higher pressures there may be a significant cost advantage to transfer the pressure stress to the rock at values much greater than the overburden pressure. The development of the laboratory diamond anvil press has demonstrated repeatedly that one can transfer an external boundary pressure through polyhedral shaped anvils to a confinement volume with a gain in stress by a factor of up to 1000. Underground Stress Engineering is a technology that has demonstrated that one can obtain a significant fraction of this large multiplication factor, up to 100 or greater, underground.

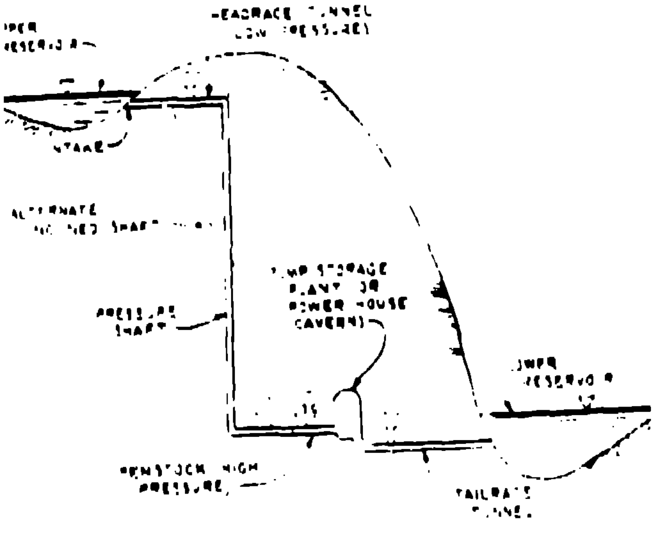
Industrial Practise of Hydroelectric Penstocks: Here large diameter pipes or tunnels, tens of feet in diameter, carry high pressure water from surface reservoirs to deeply buried turbines of hydroelectric power plants. The penstock technology is one of designing and building such high pressure confinement vessels that last, maintenance-free, for many tens of years. In general such vessels must be free of leaks lest the leakage flow, in the coarse of time, undermine or destabilize the overburden. Because of the

:nse cost of the interruption of service and maintenance in ral, a large effort has been made to unc .rstand and review ses. This experience has been brought together by Brekke and y for the Electric Power Research Institute, (1986), and in ire Notes by R. S. Sinha of the US Bureau of Reclamation,)). These two sources of information give a review of cur. ent ice in this industry.

The usual tunneling practice produces an underground void e the surrounding rock is in a compressive state due to the burden pressure, which is large compared to atmospheric ure. (If the Poisson ratio is not favorable and large as is the case (Salt is an exception.), then some rocks in the roof of a el or cavity may find themselves in tension rather than pression. In such cases rock bolting is used to secure small ns that are in tension. In general, however, the region unding underground cavities are in compression.) Penstocks, e other hand, must contain a positive fluid pressure that may me significant fraction of the overburden pressure. The primary tion is what fraction of the overburden pressure may be safely ed for containment? Above that pressure the tensile stress in a or reinforced concrete lining must provide the primary inement mechanism.

Here we review this question first, and then point out how, e laboratory, a diamond anvil press can be used for the extreme pression of very small specimens to pressures that exceed the idary pressures by more than three orders of magnitude (1000), finally how a fraction of this large factor, several hundred fold be achieved in practise underground, thus resulting in less nsive confinement of high pressure fluids.

stocks: Figure (3) from Brekke and Ripley (1986) shows a cal hydroelectric installation with a penstock leading to the er turbines. The over-burden stress surrounding the penstock nds upon the slope angle as well as on local depth. servative design requires a lining of steel or reinforced concrete he tunnel to ensure against leakage.With such a lining the burden pressure may safely contribute up to 50% of the imum principle stress, usually the overburden stress. Unlined ties can safely contain only 50% of the least principle stress ha.1989). Surrounding hydraulic pressure may frequently exceed value and hence water leakage into unlined tunnels.

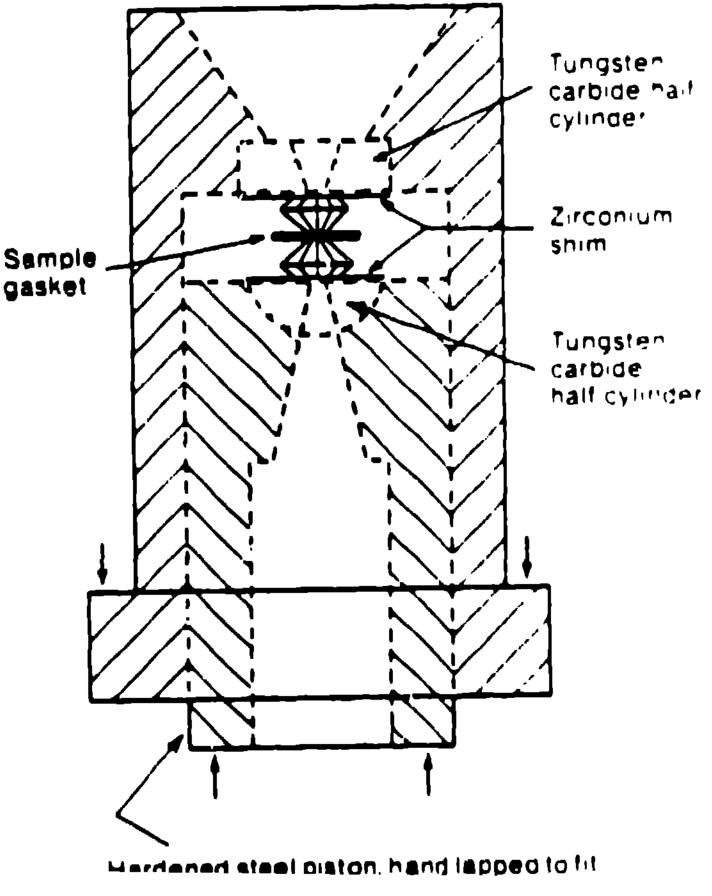


. (3) *A typical penstock installation is shown where an upper ervoir leads to a lower power plant through a penstock. Typically water pressure is less than half the overburden pressure unless a rby slope partially relieves the overburden pressure.*

It is also common practise that the cost of the liner and its installation is less than the cost of excavation of the tunnel in the first place. Thus, in general, if some way can be found to greatly increase the pressure holding capacity of the rock itself, the cost advantage for the penstock construction is not much more than a factor of two. The main advantage of increasing the insitu rock pressure or stress for penstock use is increasing the stability of the overburden. The size of the penstock required is nearly independent of the pressure holding properties of the penstock but instead determined by the required flow capacity.

High pressure Vessels: Natural gas storage vessels and contained underground explosions, on the other hand, require a cavity whose volume is inversely proportional to its pressure holding ability of the essel. Thus if the confinement pressure of the rock can be greatly increased above the typical value by a factor of one hundred, then a significant savings in cost may be achieved. A lining can not be counted on for increased pressure for nuclear waste confinement, because any initial cavity lining will corrode or disintegrate during the necessary time of confinement. On the other hand, an outstanding technical achievement where confinement pressures are routinely produced many orders of magnitude above the boundary pressure is the diamond anvil press. A lining is not used to support this high pressure.

The Diamond Anvil Press: In Fig. (4), which describes a diamond anvil press, the high pressure, created at the sample, is produced because of the increasing compressive strength of the materials and the decreasing area of contact. The steel cylinder concentrates its pressure on the tungsten carbide half cylinders, and these in turn concentrate the pressure on the diamond anvil polyhedral segments. The final concentration of pressure is within these polyhedral segments. The area of central contact is small compared to the area of their outer periphery. Typically up to a thousand atmospheres of pressure may be applied to the steel cylinder. The record pressure achieved at the central sample is currently claimed to be several million atmospheres. There is thus a factor of more than one thousand increase in pressure in this simple, but sophisticated apparatus.



g. (4) *shows a diamond anvil press where the pressure at the ston may be typically 1000 atmospheres, yet the pressure between e diamonds is multiplied by several thousand to several megabars.*

onfinement and compressive hoop stress: Furthermore, should be noted, that if the diamond polyhedral segments, the ngsten carbide half cylinders, and the steel piston and cylinder ere bolted together by radial tension members, and the pressure on c steel piston were made zero, then the confinement pressure ould also be zero; without a finite boundary confining pressure, e polyhedral segments would easily separate and come apart lowing the easy escape of any central pressurized fluid. The ctitious tension members would not produce confinement. Hence, y analogy, rock bolting of an underground cavity primarily events caving of the rock from the roof of the cavity. It does not crease the confinement pressure per se. What increases the onfinement pressure of a central fluid specimen in the diamond vil press is the tangential stresses between polyhedral diamond gments. These segments are not glued together, but are forced gether by a combination of the radial pressure and the wedge shape at together produce a tangential or compressive hoop stress. It is is compressive hoop stress that "seals" the central specimen from uid escape or creates the desired confinement. For secure waste onfinement we wish to produce these compressive hoop stresses urrounding an underground cavity. The ability to confine pressure sing augmented compressive hoop stresses will also prevent roof ving like the stones in a Roman arch. (The diamond polyhedral gments are not likely to fall by gravity into the central specimen hen the system is under such extreme pressure!)

racturing Underground: If a hole is drilled into rock, and a acker or pipe is set in the hole, (either with a hydraulically panded casing or cemented in place), it is well known that the ck can be fractured if a high pressure fluid is forced into the pipe r packer. The fracturing starts at the point of injection, i.e., at the d of the bore hole, when the fluid pressure exceeds the combined onfinement pressure and the yield strength of the rock. (An extreme ample of ultra high injection pressure is the use of an plosive.The fracturing, of course, depends upon the size of the arge, which may be quite small for starting purposes of bsequent hydraulic fractures. The fracture extends as a crack whose ngth depends upon the amount or volume of fluid pumped as well on other factors to be discussed. Figure (5) shows schematically, veral such fractures proceeding in arbitrary directions.

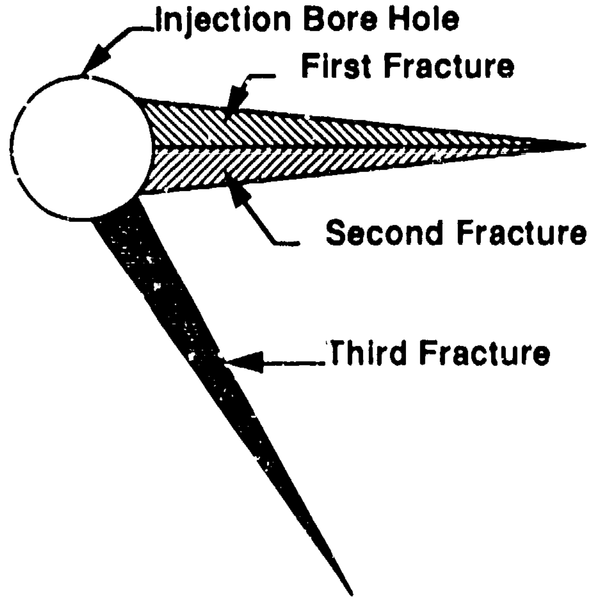


Fig. 5. *shows the process of underground stress engineering. It is illustrated schematically by three sequential fractures formed by injecting a fast setting fluid through a bore hole (into the paper). The direction of the first fracture is normal to the least principle stress. It is depicted unidirectional, but actual formations might result in a tortuous fracture. The first fracture "wedges" open the fracture according to Eq. (4) and solidifies. The second fracture again finds that the least principle stress is in the original direction and so forms directly adjacent to (on top of) the first fracture. It sets and now adds an additional stress normal to the least principle stress. The sum of these two increments of stress from the first two fractures is sufficient so that now, when the third fracture is made, it finds that a different direction corresponds to the least principle stress, and so forms the third fracture, etc.*

The direction of the initial crack is determined by the criterion of whichever direction is easiest. In general, for a medium whose local properties are isotropic, and a medium that fractures or breaks, this easiest direction is usually defined as normal to the least principle stress. This plane, in tectonically relaxed media, is usually vertical because, as we have already pointed out, the underground tends to be supported like a set of vertical columns or blocks with a small but finite space between them. This preference for vertical cracks frequently frustrates the usual attempts at "fracturing" a horizontal lens for releasing trapped oil or gas. If we are to create a region underground of greatly increased overpressure, there most not be an "easy" way out for a high pressure fluid that is to be confined. The question is how to convert the previous "easiest" direction into a new "harder" direction, for fracture propagation, or equivalently how to rotate the plane of the least principle stress?

Rotating the Plane of Least Principle Stress: A fracture is propagated in a hard or fracturable medium like rock, with a very small increment in pressure in excess of that which confines the rock in the direction of the least principle stress. This excess pressure is as small as one to ten atmospheres compared to the rock fracture strengths or overburden pressures of 10 to 1000 times this value. Hence fractures tend to propagate long distances with very little extra pressure above that of the least principle stress. The porosity of the rock, which accepts fluid without fracture, complicates this simple picture as well as many other factors, but for now we consider the simpler problem of fractures in hard rock with a pure fluid.

In Fig. (5) the fractures are depicted as wedge shaped, but in a real case a pure fluid will tend to form a very thin crack. This is because the excess pressure necessary to propagate a fracture in hard rock is so small compared to the bulk modulous of the rock. But let us neglect this "thinness" for the moment, and return later to explain why we must use a "gel" rather than a pure fluid. Also let us assume one more property of the fracturing fluid, namely that after a period of time, it sets to a hard material like the original rock. Then if the first fracture sets to hard rock and we pump or fracture a second time, the fracture will start presumably in the same "easy" direction of normal to the least principle stress and make a second fracture right along side the first one. This is shown schematically in Fig. (5) as the second fracture with opposite cross hatching. Now we have two fractures side by side that are each filled with a finite amount of material that has set to a hard material like the original rock. The plane of the least principle stress is being progressively "jacked" apart by each sequential fracture. But each fracture does add an increment of "locked in" stress equal to the residual increment of pressure when the fluid in the fracture sets. The crack is being "jacked" apart by this small increment of pressure in order to allow the fluid to reach the crack tip.

The process of opening the crack, no matter how small equires an increment of pressure which is "locked-in" when that ame amount of fluid sets to a solid. Although this increment of pressure may be small compared to the anisotropy that defines the east principle stress, nevertheless the process of injection, setting, and re-fracturing can be repeated an arbitrary number of times. Thus t is logically possible to keep increasing the locked-in-stress by means of many sequential fractures and thereby ultimately reach a value of stress for the subsequent fracture that is greater than the stress across a plane in a new direction. In other words a new plane of least principle stress has been defined, or equivalently the plane of least principle stress has been rotated to a new direction. (As a practical matter, as will be discussed later, only a few injections and setting cycles are required to rotate the plane of least principle stress) In the Fig. (5) this process is shown as occuring following wo fractures. (The use of a fluid of finite gel strength, to be discussed later, reduces the necessary number of fractures required to otate the plane of least principle stress by a factor of 10 to 100 fold.) By this process we have added a finite volume of rock-like material to a fracture in the easiest direction, increasing its normal stress, which in turn transforms it into a harder direction. This process inherently converts the easiest fracture direction into a harder one and ultimately this causes fractures to explore stochastically all directions in space.

Creating a Region of Over-pressure: A region of over-pressure is a description of a roughly spherical region underground n which the compressive stress in every direction is significantly greater than the over-burden stress. It is a useful description in that t describes a departure from the usual tectonically relaxed state where the overburden stress in the horizontal plane is just the overburden pressure and where in the average vertical plane, the stress is significantly less than the overburden pressure . A region of over-pressure describes what we wish to accomplish for greater confinement of high pressure fluids underground. A region of over-pressure is just what happens when, in the above process of sequential fracturing and setting to a hard material, the stress normal o the "easiest" or least principle stress is rotated, that is, finds the next easiest direction to be what had previously been the hardest or maximum principle stress. In a presumed tectonically relaxed case, his new direction is just the horizontal direction with exactly overburden stress normal to it. Then the act of rotating the plane of east principle stress is equivalent to the approximate description of creating a region of over-pressure. Of course the fractional increase of the least principle stress above the overburden value would be small in this particular example, but there is nothing in theory and n practise from preventing one from continuing to inject and let set a large sequence of fracturing events. Then the local pressure will increase according to the number of cycles of fracturing, njection, and setting performed.

Injection Volume versus Pressure Increment: The question is how much settable fluid has to be pumped at what pressure to create a given region of over stress? Rock in general is a nonlinear medium in the sense that it does not follow a simple Hooke's law. However, up to pressures of several thousand atmospheres competent, hard rock subject to a pressure, P, results n a change of volume:

$$\Delta(\text{volume}) = (P/E) \times (\text{volume}) \qquad (1$$

Hence for a typical limiting pressure or high pressure grout pumps of 2000 atmospheres and a typical hard rock modulous of E = 40,000 atm., the fractional change in volume would be 5%.Thus if one wanted to overstress the rock surrounding a cavity to a distance double the dimensions of the cavity (or 8 time the cavity volume) and to a pressure of 2000 atmospheres, then a volume of material roughly equal to the volume of the cavity must be added (pumped) into the surrounding the region. This material or special settable fluid can not be pumped continuously, because otherwise a single fracture would extend indefinitely until it intersected a low pressure region, i.e., the surface. This would not add to the local stress around the cavity. Instead, as pointed out before, the settable fluid must be pumped in a sequence of small volumes that are allowed to set after each injection.

Fracture Volume: The question is: what is the volume of fluid that fills a fracture? If a perfect fluid fills a fracture, then as we have already pointed out the increment in pressure above the pressure required to propagate a fracture further is very small, about one atmosphere. This assumes that the increment of pressure extends uniformly from injection point up to the crack tip as it would for a perfect fluid. Thus if our perfect fluid set to a hard solid, the increment of pressure locked into the formation would be not more than an atmosphere. To gain an overpressure of 2000 atmospheres by injecting a sequence of such small increments would be tedious indeed. Instead we resort to a non ideal fluid that can act like a near perfect fluid at high shear stress, and can also return to and retain a finite elastic stress in a static state.This rheological property is called a gel. In the above example we assumed no pressure drop along the length of the fracture for a perfect and static fluid between the injection point and the crack tip. The fluid had to come to a static state in order to solidify to a solid. Hence no shear stress could exist before setting took place. With a gel, on the other hand, a finite shear stress can be locked into the fluid when it sets. This shear stress, that can be locked into the gel at the time of setting, is the equilibrium stress that is required to "break" the gel when it flows or is "forced" to flow along the length of the fracture as the fracture is propagated. This shear stress is called the "gel strength", G. This increment of shear stress with the wall, $2G\,dx$, is balanced by an increment of pressure, dP, such that $dF = W\,dP$, where W is the width of the crack. The integral of this shear stress along the length of the fracture corresponds to a pressure increment, ΔP. Since the width varies along the length the fracture, being a function of pressure and geometry, the mathematical result is complicated, but a rough approximation for the pressure drop is:

$$\Delta P = 2L\,G/W, \qquad (2$$

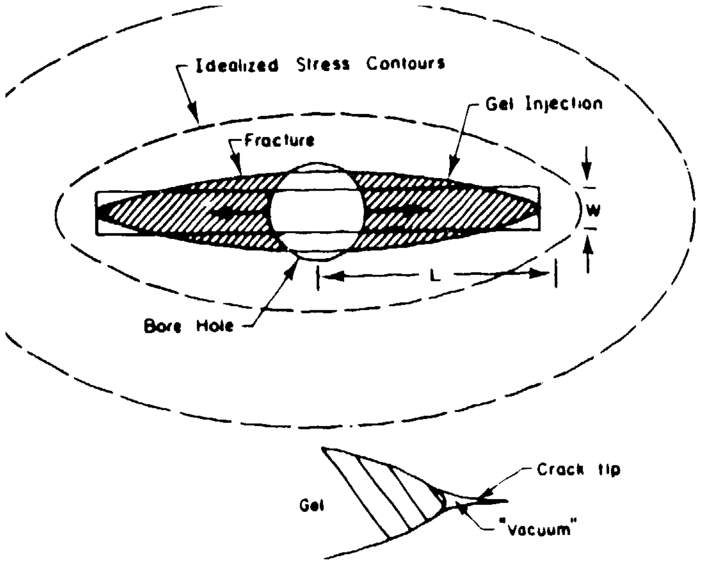
Where L is the length of the fracture and W is a mean width, and G is the gel strength. However, a pressure increment, ΔP, acting on the rock medium over a length L, assuming two dimensional geometry, will open a fracture of width:

$$W = L\,\Delta P/E\,. \qquad (3$$

Thus

$$\Delta P = \sqrt{(2G\,E)}. \qquad (4$$

Since typical gel strengths are one atmosphere, this means that the typical increment of pressure will be several hundred atmospheres. This is entirely satisfactory for repeated injections designed to ultimately reach several thousand atmospheres. Pressure increments of this order have been proven repeatedly in practise, although the the fluid rheological properties were only approximately measured (Colgate et al. 1977) Such a fracture formed by pumping a gel is shown schematically in Fig. (6).



(6) *shows a schematic of a fracture formed by pumping a gel as sed to a perfect fluid. The fracture propagates at a constant ure increment determined only by the gel strength and the ression modulous of the rock. Hence the fracture length is mined only by the volume pumped.*

One notes that the width and length of the fracture are pendent of the pressure increment by Eqs. (2-4), so that the th is determined by the volume of fluid pumped; the width ases accordingly, and the pressure increment is a constant. This ies that the size of an overstressed region composed of multiple sequential fracture and setting cycles can be controled to any ed value simply by determining the volume of settable fluid ped. The increment of pressure desired or overstress similarly be controled simply by terminating the process at the desired pressure. These regions of overpressure then can also be placed ever desired, much as the stones in a Roman arch are placed rding to design.

lding a Contiguous Region of Overstress: By laping smaller regions of overstress, one can design and create r regions such as pre-stressed domes or arches much as one es self-supporting structures with stones and with solely pression stresses. If one wants to surround a cavity with a rical region of overstress, one has a choice of creating one le large region before the cavity is excavated, and then vating the cavity. Instead one can excavate the cavity first, and create overlapping regions of overstress, each the size of the y and covering a sterradian, or 12 in number. These smaller ns would be created by drilling and pumping the settable fluid within the cavity itself, Fig.(8).

ious Experience: There have been experimental tests, tical and numerical modeling of the formation, control, and ication of underground stress engineering. The theoretical sis and numerical modeling of fracture shapes produced by a of finite gel strength were first performed by Colgate, hek, and Shaffer (1973). Here theory and numerical modeling ded the Griffith crack theory (Griffith, 1920, 1924) to the case nite gel strength fluids and confirmed the elementary theory of 2-4).

The first test of stress engineering was done at the Bueno , Jamestown, Colorado in 1975, (Colgate and Bowers, 1976). e tests were performed by injecting under pressure (up to 700 a finite gel strength fast setting grout in volumes of 1 to ral cubic feet. The pressure as a function of volume pumped read visually from a pressure gauge. We repeated these tests chart recording of the pressure signals where 20 fracture tests were performed. All these tests showed the expected sequential increase in fracture pressure associated with adding an increment of volume within the limited volume fractured. Equally important the "backs" or top corners at the roof of the "drift" or tunnel were overstressed, Fig. (9), (3 or 4 sequential fracture and setting cycles) before "pulling" the next "round" (drilling, blasting and mucking). This was performed in unstable ground that caved progressively in time unless it was "shored" or "cribbed" up soon after (several weeks) the drift was complete. The objective and theory of overstressing the backs was to add compressive stress in the roof of the tunnel and expect the tunnel to then hold its position stably without caving. Consequently we painted a white wash stripe around the tunnel at each successive round to see if later the wall and roof surfaces had held stably. We reentered this drift 2.5 years later through the cribbed entrance. Beyond the cribbing and before the start of the overstressed rounds the tunnel roof had progressive failed forcing one to climb caving rubble whose height was equal to or greater than the height of the original drift. A remaining small crawl space allowed one to reenter the region of overstressed rounds. Here no caving had taken place and the original white wash stripes were clearly visible. This was strong evidence that overstressing the backs greatly increased the stability of unstable ground.

The theory and numerical modeling of this enhanced stabilization as well as the stress distribution expected from an ensemble of overlapping overstressed regions was published by Colgate, Petschek, Browning, and Bowers (1977).Here the stabilization of underground voids or cavities expected from overlapping regions of overstress was predicted by finite element calculations just as observed in the experiment.

Finally a sequence of tests, funded by the DOE Oil Shale Program were performed in the Colony Mine of ARCO near Rifle, Colorado. This test overstressed a region roughly 10 meters in diameter to a pressure of roughly 100 atm.It contained some 100 points of triaxial strain measurements computer recorded and later analyzed by Cambell, Colgate, and Wheat, (1980). This test showed the sequential and quasi random increase in stress expected as the fractures following the plain of least principle stress "explored" the accessible space from the injection point. Special cement pumping machinery had to be developed for this test, (DS&M, Ward, CO.), because oil well cement equipment was not satisfactory. The digital recording of 300 strain gauges underground proved satisfactory. The formation chosen, oil shale, made the operation much more difficult than would be expected for nuclear waste storage. This was because the shale was interspersed with random cavities of roughly a cubic meter volume. When a fracture intersected such a volume, it first had to be filled with cement from the flow in the fracture before the fracture could progress to the desired extent. This meant that the volume versus expected length relationship of Eq.(2-4) could not be counted on. despite this difficulty with the rock formation, the planned large volume of rock was successfully overstressed and the necessary increase in stress achieved to demonstrate the stochastic fracture mechanism. It also emphasized the lack of suitability of formations with frequent large voids ("vugs") for the secure burial of waste.

Summary: The need for a single major and secure nuclear waste facility still exists in this country. Because of the large number of buried past nuclear explosion tests at the Nevada Test Site, and the consequential necessity of long term governmental commitment the NTS is still the Nation's logical nuclear waste repository site (Colgate, 1979). The concerns with ground water access and egress over geological time can be greatly ameliorated by the development of the science and technology of modifying the underground stress distribution to a desired distribution rather than attempting to construct barriers against the natural one.

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