Micro-Thermonuclear Plasma Tunneling by Rock Melting

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Abstract

Standard drilling has limits as at some depth the pressures and temperatures force the drilled opening tight when the drill is lifted.This paper proposes a reliable and rapid method of penetration of rock masses by melting all or part of the rock face and penetrate therein, cool the resulting glassy tube to be a stabilized liner. The methods proposed to heat the tip of the melting element include heat generated by a micro-thermonuclear reaction. High rates of advance are sustainable because only heat and cooling water must be advanced to the tunnel head. The equipment is simple and without need for unduly high pressure lithofracturing, and the equipment may be regularly removed and switched out to avoid time and personnel-intensive breakdowns in place. This method can achieve depths heretofore unreachable to access deep gas, oil, or to create an airtight and waterproof shaft for geothermic energy.

Key Words: rock melting, tunneling, plasma, thermos-nuclear, subterrene, deep wells

Introduction

Problems with Deep Drilling.

Ryan Carlyle, an engineer at an oil company elucidates the major difficulties in current deep well drilling technologies.[1]

1) **Heat:**The most obvious obstacle to deep drilling is heat. The deeper you go, the hotter things get.
2) **Drill bit wear:**Replacement time goes up with depth: The wear on the drill string increases with depth. This is a big problem compounded with the fact that the deeper the shaft the greater replacement time is as the entire drill string must be tripped to exchange the bit each time one wears out.Moreover, this is further exacerbated by the fact that as depth increases it becomes increasingly difficult for the operating crew to judge when a bit has worn out making a guessing game out of when to pull out and exchange the bit.
3) **Weight**: A major depth-related issue is the hanging weight of the drillpipe. Very deep wells are drilled by lowering a "mud motor" into the well on a long segmented pipe. Drilling mud is pumped down the pipe, pushes through the motor to hydraulically turn the bit against the rock face, and then the mud flows back up the hole outside the drillpipe

to carry away the rock cuttings. This process requires very thick, heavy pipe to withstand the necessary pumping pressures and motor torques. (The weight of pipe used to drill very deep wells might be around 40-50 lb per foot on average.) And as the pipe gets longer, the weight really adds up -- easily over a million pounds (~500 tonnes) for very deep wells. This is a problem for the drilling rig's derrick hoisting equipment which must be able to lift and lower this weight often.But the real issue is that the pipe must be strong enough to support its own hanging weight! To make the pipe stronger, the walls can be madethicker, but that makes it even heavier. In fact, making the walls thicker through the whole length of pipe gains absolutely nothing! The increase in strength is exactly offset by the increase in weight. So ultra-deep wells require elaborate "tapered string" designs with light pipe at the bottom, medium pipe in the middle, and heavy pipe at surface. A lot of engineering goes into this to extend the maximum feasible depths reachable. There is a depth limit where it is no longer practical to construct a tapered pipe in this fashion.

4) **Metal strength:**To reach greater depths stronger materials are required. High-strength steels with yield strengths over 150 ksi, which is 3-4x stronger than typical structural steel are routinely used. Unfortunately, this really pushes the limit of what steel is capable of since the stronger you make the metal, the more brittle it gets. But high strength steel has another problem-**Chemical corrosion:**The stronger the steel, the more susceptible it is to chemical attacks. The deep, hot subterranean environment is often highly corrosive. The most worrisome chemical found underground is deadly-toxic hydrogen sulfide gas. But it's extremely hard on high-strength metals, too. There is a phenomenon called "hydrogen embrittlement" where the H2S gas releases one of its hydrogen atoms at the metal surface, leaving acidic HS- on the metal face and allowing a highly-reactive H+ ion to *enter the metal*. The free hydrogen actually diffuses around inside the steel until it runs into a carbon atom used in the alloy. Hydrogen + carbon = hydrocarbon, so this process literally creates methane molecules *inside the metal walls of the drillpipe*. Methane is a very big molecule compared to elemental carbon and elemental hydrogen, so these new gas molecules effectively create high-pressure nano-bubbles and substantial stresses within the grain structure of the steel alloy. **The net result is extreme embrittlement**. But these high-strength steels are already quite brittle -- so hydrogen sulfide attack renders most advanced steel alloys useless. They pit and crack and fail. So softer metals that are less brittle to start with, generally 80 ksi yield strength or lower are generally used. That way hydrogen embrittlement is not catastrophic. However, Dropping from 150 ksi yield strength pipe to 80 ksi almost cuts in half the depth you can drill to. In recent years 110 ksi materials that can handle H2S have been developed, and 125 ksi sour-service steel is under testing today.
5) **Cost of special metal:**To avoid the chemical breakdown advanced nickel-based alloys such as Inconel were developed that resist hydrogen attack at much higher strengths. But the cost to make drillpipe out of such alloys is prohibitively expensive.
6) **Friction:**Another problem is friction loss. The weight of the drill string and the effect of borehole friction become larger and larger multiples of the force desired on the drill bit causing increasing difficulty controlling bit force as the depth increases.
7) **Casing design:**Another major impediment, possibly the biggest technical challenge to ultra-deep wells, is **casing design**. As wells are drilled, they encounter various high-pressure aquifers and occasionally non-economical hydrocarbon zones on the way to the target depth. The deeper you go, the higher pressure these fluid-bearing zones get. (The

weight of rock above pushes down on the fluids, among other things.) A major function of drilling mud is to provide sufficient hydrostatic pressure to "overbalance" the formation pressure and prevent all these pressurized fluids from flowing to surface. When the mud hydrostatic fails to contain pressure for whatever reason, you get a dangerous "kick" and possibly a blow-out. That's game-over. Generally speaking, near-surface hole sections are drilled with mud densities a little heavier than seawater, maybe 9 pounds per gallon (SG=1.1). Then as the well gets deeper, the mud is "weighted up" to 10, 11, 12 pounds per gallon. Extremely deep wells may get up over twice as dense as fresh water, around 17-18 pounds per gallon. That's getting up around the limit of how dense we can reliably and economically make fluids with the right properties for drilling. But a bigger issue is how that density affects previously-drilled rocks. Raising the fluid density to go deeper increases the hydrostatic pressure throughout the well, not just at the bottom. If you need a 12 ppg mud to contain bottomhole pressure and "drill ahead," but the exposed rock higher in the well can only withstand the pressure exerted by 11 ppg mud without fracturing, you have to stop. Fracturing the rock means mud losses, so you can't lift rock cuttings to surface, and you can't maintain a full column of fluid to exert sufficient pressure on the bottom of the well. Then you take a kick, and probably have an underground blowout that may destroy the well. This is a serious challenge when drilling deep wells: the pressure trapped within deep rocks is sufficient to literally break open the shallow rocks above. By making a big conduit between these differently-pressured rock formations, a big potential problemis created. The solution is to cement a thick steel casing pipe against the wellbore wall to isolate the weaker rocks. The steel withstands the pressure and cement seals off the rock face. Casing the well is necessary to drill deeper than a few *hundred*feet, let alone tens of thousands. It prevents wellbore collapse, isolates aquifers from hydrocarbons, and prevents deep pressures from destroying shallow rock formations. So the basic process of oil well drilling is to make a hole as deep as you can without breaking anything, then case it off. Then weight up to denser mud, switch to a smaller bit, and drill *through* the casing as deep as you can without breaking anything. Then case off that new hole section. Repeat until you reach the depth target. The downside to this process is that the hole keeps getting smaller as you go deeper. We might start at surface with a thousand feet of 22" diameter casing. Then we drill out the bottom and go a few thousand feet deeper until the bottomhole pressure gets close to the fracture pressure at the 22" casing shoe, and set 18" casing to isolate that weaker rock. Then we drill out the bottom for another few thousand feet, and set 16" casing. Each casing point shrinks the hole because you have to fit the drillbit and next casing through the previous casing. This process continues with 13-3/4", then 10-3/4", then 7-5/8", then 5-1/2", and now you're out of sizes that drillpipe will fit through and you can't go any deeper. This problem of casing design -- getting to bottom before your hole gets too small -- is the single biggest challenge with ultra-deep drilling. It's even a major challenge with regular-depth drilling in unusual geology, such as through salt formations. If a drilling rig hits unexpected pressure and has to set a particular size of casing too high in the well that may make it impossible to get to depth. Casing design is a major engineering challenge to ensure the target depth can be safely reached, hopefully with enough margin to have a contingency casing size to deal with uncertainty about deep rock pressures. There are some tricks to extend the limits, such as starting with bigger casing at surface (eg 36") but that rapidly gets too large to be feasible.

8) **Danger:**Pushing the limits of well depth by conventional means is an engineering nightmare. And it's dangerous, too -- the deeper you drill, the harder it is to know what sort of rocks and pressures you'll encounter. An unexpected over-pressured sour gas pocket that exceeds your equipment pressure limits may kill everyone at the drill site, and *then* blow up the rig, and *then* uncontrollably erode away the well casing for months until a relief well can be drilled. You may end up with a giant crater filled with toxic hellfire, and not even break the depth record. And there really isn't much reason to drill that deep. The hotter the rock formations get, the less likely it is that they contain oil. Crude oil pyrolitically decomposes into natural gas when it gets too hot and deep. And natural gas is too dangerous to produce from ultra-deep formations -- the low density of gas carries the deep subterranean pressures all the way to surface, which is exceptionally dangerous. The surface safety and processing equipment in use today can't handle the heat and pressure from traditional gas reservoirs deeper than about 30,000 ft. The limit right now for surface equipment is around 25,000 psi at 350F, and that's seriously pushing the limits of engineering design and metallurgy too. Any higher pressure and the well can't be safely flowed to surface. So there's no economic reason to drill anything that deep. With high costs and no profit potential on the table, plus extreme safety and environmental risks, no one is crazy enough to try to beat the world drilling depth record. But technology is improving all the time.
9) **Overall cost of deep well:**All in all deep well drilling by conventional means is a very expensive enterprise. Over 500 tons of special metal is required and special casing not to mention the labor costs of the engineers and the drill operating team over the extended period of time it takes to make a deep well.

This paper proposes a technology that obviates the above obstacles using the Thermonuclear Plasma Tunneler (TPT).

1. The TPT can operate under great heat
2. Since TPT does not have a drill head all complications involving drill heads are avoided. The tungsten head can operate for the entire shaft creation and doesn’t require replacement mid drill.
3. In TPT there is no mud pipe driver and therefore doesn’t have the weight issue.
4. TPT uses a tungsten head that is not large in quantity and is affordable and resistant to corrosion.
5. TPT is not a drill and therefore has no loss from friction.
6. TPT creates a super strong compressed crystalline rock interface that can withstand enormous pressure and heat. Casing is therefore not necessary and danger from blow out is minimized.
7. Cost of TPT is much cheaper and can reach heretofore unreachable depths.

Rock Melting Technology

A series of investigations in the 1960s and the 1970s established the possibility of a melting drill or tunneler with a free wandering ability called a 'subterrene' in work done in the national laboratory of Los Alamos in New Mexico. [2]Their configuration was nuclear powered, thermally penetrating rock and then forcing the melt outward to harden in a splash-profiled glass tunnel, removing the need for hauling muck or indeed for supplying the tunneler with most consumables. The tunneler or subterrene may proceed on a given path and then return to base, leaving a sealed intact tunnel behind it. This work never matured to the stage of a real-world full scale trial though many melt tests were done with electrical heaters, but the principle was proved practical; sufficient heat will melt rock in its path.

To appreciate the scale of energy required to melt rock, the power density on the surface of the earth is about .1 watt per square centimeter in the sunlight. Since there are 10,000 square centimeters in a meter this is about a kilowatt a square meter. (In space the solar constant is 1.37 kw/square meter but here we are concerned with the surface of the earth and what men consider normal.) On the Sun's surface, on the other extreme, densities about 60,000 times this occur, or over 6 kilowatts a square centimeter.For comparison the thermal output of the firestorm at Hiroshima was about 10 cal/cm^2 or about 41 watts per square centimeter.[2] Clearly these are large figures.

The rock melter envisaged in the Los Alamos Scientific Laboratory publication LA-4547 [3]would put out about 500 watts per square centimeter. These heats, though impressive, are manifestly survivable by at least part of the mechanism. The artifact built by the hand of man with the greatest resistance to heat was the Galileo heat shield used for the entry probe into the atmosphere of Jupiter in 1995; that was subject to a peak heating of 42 kilowatts per square centimeter, or 7 times the heat level at the surface of the sun, corresponding to the shock front temperature of 16000 degrees K or 28,000 degrees F. About 2/3 of the 152 kg heat shield was consumed protecting the entry probe. And the entry probe worked undamaged after the heat shield was jettisoned, for its full design life.

Los Alamos National Laboratory Study LA-4547 determined that it took about 4300 joules (watt-seconds) per cubic centimeter to melt rock: "Common igneous rocks melt at about 1200”C and, in being heated from 20”C to just above their melting ranges; they absorb about 4300 joules of energy per cubic centimeter. In comparison, the corresponding figures for metallic aluminum are about 660”C and 2720 J/cm3, and for steel they are about 1500”C and 8000 J/cm3. The energy requirement for rotary drilling in most igneous rocks is about 2000 to 3000 J/cm3."

The same study determined that heat loss to rock on the sides of the tunnel will be only on the order of 4% of the minimum 50 watts per square centimeter required to actively melt through rock. Therefore side heat losses will be minor; heat percolating forward may be useful in preheating the upcoming rock; and obviously internal insulation barriers are part of the skills "known to the art" of designing a thermal penetrator to protect non refractory components following the penetrator head.The 50 watts per square centimeter may be compared with about 41 watts per square centimeter developed during the firestorm at Hiroshima, the 500 watts per square centimeter developed at the nose of a Los Alamos designed penetrator, the 6000-6200 watts on the surface of the photosphere of the Sun.

A typical rock melt at lava temperatures will contain about 1.15 gigajoules per ton of melt which is about 1/19th the energy content of a given weight of coal; adding the weight of a coal and oxidizer mix brings the energy content of lava up to 1/6 the energy of a mixture of coal and oxygen combined.[4]"An average value for the thermal energy of coal is approximately 6150 kilowatt-hour (kWh)/ton." A ton of coal by this measure yields 22.14 GJ, the equivalent of 19.252 tons of lava melted per ton of coal.A eutectic or eutectic mixture of two or more rock types will have a lower melting point than pure compounds, which are relatively rare in nature. Therefore, in many cases less power will be needed to melt a stratum than a rough estimate would suggest.

Feasibility of Rock Melt Tunelling

The innovation relies on the known fact that creating a void in rock is not only heat melting but pressure alone can condense rock creating a void. This second process, compressing rock by pressure is a straightforward principle: With sufficient pressure and heat rocks metamorphize into denser versions of their previous selves. A variant of this method is described in an expired patent [5] and active patent [6]. This phenomenon may be seen in nature when a "Contact aureole" is formed by a body of hotter, pressurized rock forcing its way through a body of cooler, less pressured rock. The outer rock becomes a denser form, a contact aureole; a ring of increased density in a less dense rock mass.In the study entitled "Zoned contact aureole developed around an igneous body", the aureole extends from the igneous contact, where the metamorphic effects are the greatest, out into the country rocks to where the temperature or heat energy is insufficient to effect any changes. This temperature lies between 400 and 750°F (200 and 400°C), and actual widths of contact aureoles range from several inches to miles.

Contact metamorphism can occur over a wide range of temperatures, pressures, or chemical gradients in rocks of any composition. Thus any mineral assemblage or facies of metamorphic rocks can be found. However, the nature of contact aureoles results in minerals characteristic of low to moderate pressures and moderate to high temperatures usually in common rock types: shale, basalt, limestone, and sandstone. Characteristic minerals developed in shale are andalusite, sillimanite, cordierite, biotite, orthopyroxene, and garnet. At the highest temperatures, tridymite, sanidine, mullite, and pigeonite form; whereas in limestone unusual calcium silicates form, including tilleyite, spurrite, rankinite, larnite, merwinite, akermanite, monticellite, and melilite.

Compositional changes in a contact aureole range from none to great, but as a rule, contact metamorphism entails relatively little change in bulk rock composition. Some wall rock compositions, such as limestone, can be greatly changed and form rocks termed skarn. Because metamorphic changes are largely brought about by heat, contact aureoles are often termed thermal aureoles. However, there is a tendency for volatiles (water, carbon dioxide, oxygen) and alkalies (sodium, potassium) to be lost from rocks in the aureole. Stable isotope compositions (oxygen, sulfur) change in response to the thermal gradient and flow of fluids through the rocks. In some cases, volatiles (boron, fluorine, and chlorine) and other elements from the crystallizing magma are gained. The magma can incorporate material from the wall rocks by assimilation or mixing with any partial melts formed mixing results in elemental and isotopic contamination of the magma, crystallization of different minerals from the melt, and hybrid rock types at the margin of the igneous body.[7]

Cooling rates necessary for proper annealing of the tunnel wall

Los Alamos Report LA-4547 [1] establishes that in order to cool rock melt from the liquidus to 200 degrees centigrade. According to Los Alamos calculations detailed in Report LA-4547, for example, a 7 meter tunnel progressing at a rate of 100 m/day, would encounter a "Total Rock Mass Flow" of ~10,000 tons/day of which it was assumed 25 percent would be melted. There, the "Rock-Cooling Water Flow Required to Cool Rock Mass to ~ 200°C" was given as 7 kg/second --604.8 tons of water a day." To cool down the entire 10,000 tons of melt and not 2500 tons would therefore take about 2,420 tons of water a day. Given that no more than about 4% of the heat remains in the walls surrounding the removed material, of the 10000 tons in the Los Alamos example only about 250 tons equivalent of melt would need to be cooled down-- a potential 90% savings in cooling water, down to about 60 tons a day for that size tunnel at that rate of advance.

In our own example of a 10" or about .25 meter pilot tunnel or shaft, we see that compared to a 7 meter tunnel the relative areas are in the ratio 49:0.0625 or 784 times less for the smaller tunnel. Since we are melting the entire cross section we see the true power demand to be only 1/196 of the Los Alamos scenario of 50mw per 100 meters per day advance. If we demand a rate of penetration of 5 kilometers a day, for example, power demand may go to about 12.5 megawatts. Considering the cooling water demand for a 10" (.25 meter) pilot tunnel or well, we see that the total rock flow per 100 meters progress would be about 12.75 tons of melt, and the 4% retained in the tunnel walls could require less than an ounce a second of direct water delivery and several tens of tons should be ample reserve for a progress of up to five kilometers a day--exclusive of tunnels or shafts driven through high geothermal gradients.

The current limit of human cooling technology involves forced liquid convection through micro-channels along lines first proposed by David Bazeley Tuckerman in his February 1984University of California doctoral thesis[8]. Such cooling is capable of reducing heat at the rate of 1 kilowatt per square centimeter, or one sixth that power density at the surface of the sun.'

Regarding the needs of annealment for proper tunnel liner strength

According to "LMF Paving Robot Subsystem" [9]if cooling is virtually immediate - minutes or tens of minutes - the liquid basalt is quickly quenched and becomes a polymeric glassy substance. The material is very strong but also moderately brittle, permitting cracks to propagate rather easily. Using this option, it is necessary to divide the platform into small square-meter-size slabs to help isolate fracture failures and to permit relatively easy maintenance and repair. If the liquid basalt is permitted to cool more slowly - allowing perhaps several hours for the melt to pass from full liquidity at 1570 K to hard solid below about 1370 K - the material anneals into a crystalline form."It will help that the shaft profile is often round because that will help resist cracks better than the rectangular slabs in the above example. In addition, an additional reheating/annealing stage may follow the tunneler in one embodiment, slowly conditioning and crack proofing the lining. An inflatable collar can also mold against the tunnel wall a semi liquid hardenable substance to seal it in, along the lines of a grout or epoxy. This may be pumped down to the penetrator by line or be shuttled in the capsules going back and forth.

Burn time to depths of interest:

It will be noted that such a penetration speed will make it theoretically possible to reach the lower depths of 'the oil window' (about 5 kilometers down) within days or a few weeks of operations. Penetration to record depths is much easier-- to one approximation-- with a thermal penetration system, since the limiting factor that stopped, for example, the Kola Super deep Borehole is actually an aid to thermal operations, as the rocks are preheated. Annealing may be more difficult, however. Another facet of thermal penetration technology which will need adjustment as deep strata heat up progressively downward is the increasing softness of the new tunnel walls. Liners, particularly those that harden at the target heat, may be necessary to add.

As to the near-term practical depth limits accessible with the preferred embodiment of this innovation, it seems immediately practical at many locations up to 20 kilometers depth, and at selected spots up to 25; as experience is gained those operation limits may be increased, though only at places and times where the extraordinary pressures and flow rates of deep gas make this economically feasible. Despite the extraordinary expenses and financial risks of very deep gas wells, a rapid-penetrating means of penetrating beyond current record depths rapidly and cheaply by comparison would open up the potential prospects of great gains. Besides the simple fact of tapping virgin territory in the 'methane' window below the oil window opening a geometrically very large area underneath proven strata to exploitation, There is the simple fact that increasing pressure can lead to increasing rewards from the same sized hole.

Advantages of Melt and Pressure over Drilling

The advantages are currently mostly theoretical but there are many practical problems to be solved before a reliable cheap, rapidly penetrating method is to be recognized as such by the tunneling community, and any method that desires to achieve market penetration must first assure rock penetration without the problems that have stopped other patented methods from achieving such success. Some of these problems are:

- Lack of means of dealing with the melt/muck
- logistical difficulties in the hole
- excessive/exotic demands of power source (i.e. super high power or nuclear engineering required)
- excessive logistical demands in the field
- Poor penetration of many rock types

Advantages of Thermal Penetration

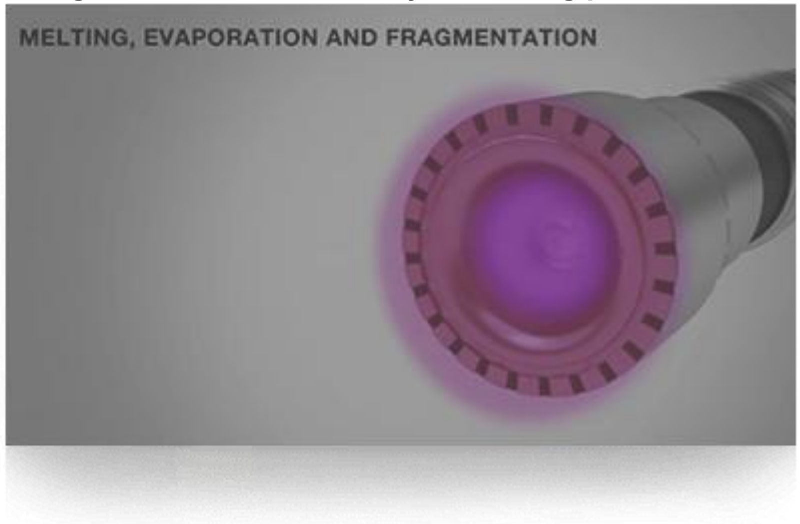
The main advantage of thermal penetration is the minimal tool wear as long as a refractory ceramic coating remains over the refractory probe nose. Another very great advantage of using a melting penetrator is the possibility of automating the muck handling to a degree impossible while handling substantial solid fragments. Rendering the matrix to be penetrated into a liquid capable of intake into a holding reservoir is far easier to manage on an automated basis than trying to channel solid chunks of material with variable geometric shapes.

Conventional Tunnel Boring Machines (TBM) (such as patents 6431653 [10], 6595724) [11]) simply breaks up rock which requires less energy, however the broken rocks needs to be continuously carted back to the borehole entrance. The greater expense in energy is made up for by the savings in cuttings management because it is easier to open a valve and pump a liquid than to accommodate by automatic machinery fine judgments on sizes and no uniform geometries of incoming solids.

Comparable Technology

GA Drilling designed PLASMABIT™ [12] system which they claim is able to efficiently reach deep underground sources using a robust plasma generator. In contrast to the classical drilling methods, this one uses non-contact drilling process based on an approach modified for extreme thermal, physical and pressure conditions. Unlike the method and device described in this paper, it is not a method based on physical contact between the rock and the drilling platform, but rather exploits electric plasma arc.

Figure 1. PLASMABIT™ system using plasma



Rock disintegration: Their claim is PLASMABIT uses a thermal heat flow generator optimized for thermal rock processing. The system ensures destructive spatial plasma disc impact, full drilling diameter impact, enhanced disintegration force, computer control over impact and speed of disintegration, and enhanced electrode guarding principle

Figure 2. ContiCase attached to PlasmaBit to ensure well stability

They further claim that ContiCase ensures efficient well stability enhancement and prevents its collapse while drilling. Consequently it allows access to currently inaccessible reservoirs through unstable rock and sand layers.

Movement and anchoring: They further claim that a subsystem is necessary for synchronization of the drilling process with surface material supply channels. This anchoring system holds whole weight of the PLASMABIT system with no load on the cabling system. Movement system secures movement of the PLASMABIT rock disintegration system with the drilling process. It is computer controlled and synchronized with all drilling activities. Movement and anchoring system secures no load and twist on inner cabling of the PLASMABIT system. They further claim that their RTDA utilizes interaction of electric arc with rock for optical emission spectroscopy which can be used as rock type detection by comparison of measured signal with sampled data of known and previously measured pattern of rock composition (fingerprinting) and recognition of selected chemical elements, precious metals or hydrocarbons.

They claim that their device can operate in harsh and high pressure environments inside borehole in deep positions. Moreover they claim that their system can perform systematic search for precious or radioactive elements by providing intensity directions (gradients) of their occurrence.

Their empirical data has not been published and it is unknown its efficacy in the field. Los Alamos Report LA 4547 established that "(Common igneous rocks melt at about 1200°C and, in being heated from 20°C to just above their melting ranges; they absorb about 4300 joules of energy per cubic centimeter. In comparison, the corresponding figures for metallic aluminum are about 660°C and 2720 J/cms, and for steel they are about 1500°C and 8000 J/cms. The energy requirement for rotary drilling in most igneous rocks is about 2000 to 3000 J/cms.)" By using the waste heat or direct plasma produced by hotter thermonuclear reactions should result is a far more efficacious rock melting mechanism.

Bolonkin's Micro thermonuclear Device

Bolonkin has designed mini and micro thermonuclear reactors for the production of electricity generation and for space craft propulsion as well as detailing spin off technology from this approach. [13][14][15][16][17][18][19][20]. Bolonkin's books in which he detailed facets of is innovation include [21][22][23][24] and book sections include [25]. These innovations are based on Bolonkin's early patents [26][27][28][29][30][31][32][33][34][35][36][37][38][39]; classified report [40]; and papers presented in The World Space Congress [41][42][43] and International Astronautical Congress [44], and American Institute of Aeronautics and Astronautics Conference and Journal [45][46]. The components of the devices proposed in this paper have been detailed in Bolonkin's previous papers. The rock melt and void making and destroying are applications of what in his papers have been called AB-reactors or mini or micro thermonuclear device.

Brief Description of Bolonkin'sMicro thermonuclear Device

Existing thermonuclear reactors are very complex, expensive, large, and heavy. They cannot achieve the Lawson criterion which is the temperature and pressure required for any particular fuel to fuse. More specifically, Lawson criterion (L) relates to plasma production temperature, plasma density and time. The thermonuclear reaction is realized when L is more than a certain magnitude.

In order to create the required conditions, the fuel must be heated to tens of millions of degrees, and/or compressed to immense pressures. This number has not yet been achieved in any reactor. Fusion reactions require a very large amount of energy to initiate in order to overcome the so-called *Coulomb barrier* or *fusion barrier energy*. The key to practical fusion power is to select a fuel that requires the minimum amount of energy to start, that is, the lowest barrier energy. The best fuel from this standpoint is a one-to-one mix of deuterium and tritium; both are heavy isotopes of hydrogen. The D-T (Deuterium & Tritium) mix has a low barrier.

The innovation proposed by Bolonkin in numerous papers is a micro-thermonuclear Reactor, a new revolutionary type of reactor with very small fuel pellet that uses plasma confinement generated by multi-reflection of laser beam or its own magnetic field. The Lawson criterion increases by hundreds of times. Bolonkin's innovations dramatically decrease the size, weight and cost of thermonuclear reactor, installation, propulsion system and electric generator.

Derived from the Equation for thermonuclear reaction it is apparent that it is necessary to rapidly and greatly increase the target-enveloping temperature, the density of target proper and to shorten the time of the operation in order to keep the fuel in these precisely induced conditions. In ICF the density of plasma is very high (10^{28} m^{-3}, it increases in 20-30 times in target), the temperature reaches tens of millions ^{o}K, but time is measured in nanoseconds. As a result, the Lawson criterion is tens to hundreds of times lower than is required. In a tokomak, the time is mere parts of second and the ambient temperature is tens of millions of degrees, but density of plasma is very small (10^{20} m^{-3}). The Lawson criterion is also tens to hundreds of times lower than needed. Two types of the micro-thermonuclear reactors are proposed: multi-reflection reactor (MRR) and self-magnetic reactor (SMR).

Multi-reflect reactor (MRR). Conventional ICF has conventional inside surface of the combustion chamber. This surface absorbs part of the heat radiation emanating from the pellet and plasma, the rest of the radiation reflects in all directions and is also absorbed by walls of combustion chamber. As result the target loses energy expensively delivered by lasers. This loss is so huge that very powerful lasers are needed and the target cannot be efficiently heated to reach ignition temperature (Lawson's criterion). In all current ICF installations this loss is tens of times more than is acceptable. In the Multi-reflect reactor, the ICF has, on the inside surface of combustion chamber, a covering of small Prism Reflectors (PR) or multi-layer reflector which reflects the laser beam. The system of prism reflectors has great advantages in comparison with conventional mirror and especially with conventional combustion chamber. In particular, this innovation may be used in already built current reactors for their improvement.

Self-Magnetic reactor (SMR) The magnetic pressure is proportional to the inverse value of electric conductor diameter. (The conventional magnetic reactor has a diameter of plasma flex some meters). The high temperature plasma has excellent conductivity which does not depend from plasma density. If the diameter is decreased to 0.1 mm and electric currency is high, the magnetic pressure is increased by hundreds or thousand times and that can keep the high-density plasma. Thus, the plasma is confined by self-generated magnetic field (and by pinch-effect) and it does not need in powerful outer magnetic field created very complex, high cost super-conductivity system! This innovation in MCF is dramatically decreasing the size of reaction zone and using of gaseous compression fuel pellet (micro-capsule) in magnetic confinement reactor.

The other innovation in SMR is uses the electric current (electric impulse) for initial heating of microcapsule targets. That means we don't need a large, very complex and expensive laser (or ion beam) system for inertial confinement reactor or induce system in magnetic confinement reactor. That is possible in special design of the fuel microcapsule. The energy for heating of the microcapsule to thermonuclear temperature is small and conventional condensers may be used for it.

These innovations decrease the size, weight and the monetary cost of thermonuclear reactors by thousands of times and allow the widespread future construction of thermonuclear electric stations, engines, and space propulsions. The computations below show the power of the micro-thermonuclear reactor can reach some thousands of kW.

The offered self-magnetic reactor is different from present magnetic confinement reactor. That is smaller because this self-magnetic reactor works a small fuel capsule. In present-day reactor, the rare fuel gas (D+T) fills all volume of large chamber. In Micro-thermonuclear the fuel is located into small capsule under high pressure.

List of Main Equations

In Bolonkin's previous papers he detailed equations to describe parameters of the microthermonuclear device. In this application, these equations are relevant to delineate the energy needed for the reaction, and the temperatures expected from the reactions which heat the element that heats the rock and therefore these equations are reproduced in this paper.Below are the main equations for estimation of benefits from the offered innovations.

1. Energy, E, is needed for Thermonuclear Reaction

$$F = k\frac{Q_1 Q_2}{r^2}, \quad E = \int_{r_0}^{\infty} F\,dr, \quad E = \frac{kZ_1 Z_2 e^2}{r_0}, \quad 1J = 0.625\cdot 10^{19} eV \qquad (1)$$

$$r_i = (1.2 \div 1.5)\cdot 10^{-15}\sqrt[3]{A}, \quad A = Z + N, \;\; r_0 = r_1 + r_2$$

where$k$ = 9×10^{9} constant; Z_1, Z_2 are charge state of 1 and 2 particles respectively; e = 1,6×10^{-19} C is charge of electron; $r_o = r_1 + r_2$ is sum of radius of nuclear force, m; A is number of element; F is force, N; E is energy, J; Q is charge of particles.

For example, for reaction H+H (hydrogen, $Z_1 = Z_2 = 1$, $r_o \approx 2\times10^{-15}$ m) this energy is ≈ 0.7 MeV or 0.35 MeV for every particle. This energy nuclear has in temperature $T_k = 1.16\cdot10^4 T_e = 4\cdot10^8$K.The real energy is about 30 times less because part of the particles has more average speed and there is a tunnel effect.

2. Energy Needed for Ignition. Figure 3 shows a magnitude $n\tau$ (analog of Lawson criterion) required for ignition.

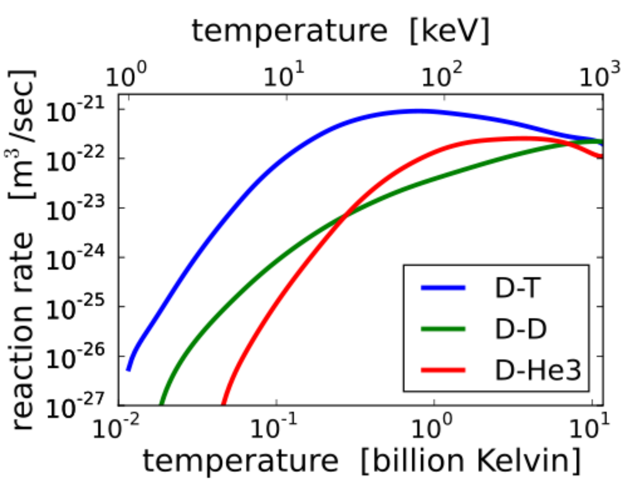


Figure 3. **Ration rate versus temperature in K.**

3. Radiation energy from hot solid black body is (Stefan-Boltzmann Law):

$$E = \sigma T^4 . \qquad (2)$$

Where E is emitted energy, W/m^2; $\sigma = 5.67\times10^{-8}$ - Stefan-Boltzmann constant, W/m^2 ^{o}K^4; T is temperature in ^{o}K.

4. Wavelength corresponded of maximum energy density (Wien's Law) is

$$\lambda_0 = \frac{b}{T}, \quad \omega = \frac{2\pi}{\lambda_0}, \tag{3}$$

Where $b = 2.8978\times10^{-3}$ is constant, m ^oK; T is temperature, ^oK; ω is angle frequency of wave, rad/s.

5. Pressure of light for Single Full Reflection is

$$F = 2E/c, \tag{4}$$

where F - pressure, N/m^2; $c = 3\times10^8$ is light speed, m/s, E is radiation power, W/m^2. If plasma does not reflect radiation the pressure equals

$$F = E/c. \tag{5}$$

6. Pressure for Plasma Multi-Reflection [23-25] is

$$F = \frac{2E}{c}\left(\frac{2}{1-q}\right), \tag{6}$$

Where q is plasma reflection coefficient. For example, if $q = 0.98$ the radiation pressure increases by 100 times.

We neglect losses of prism reflection.

7. The Bremsstrahlung (Brake) Loss energy of plasmaby radiation is ($T > 10^{6o}$K)

$$P_{Br} = 5.34\cdot10^{-37} n_e^2 T^{0.5} Z_{eff}, \quad \text{where} \quad Z_{eff} = \sum(Z^2 n_z)/n_e \tag{7}$$

Where P_{Br} is power of Bremsstrahlung radiation, W/m^3; n_e is number of particles in m^3; T is a plasma temperature, KeV; Z is charge state; Z_{eff} is cross-section coefficient for multi-charges ions. For reactions H+D, D+T the Z_{eff} equals 1.

That loss may be very much. For some reaction they are more than useful nuclear energy and fusion nuclear reaction may be stopped. The Bremsstrahlung emission has continuous spectra.

8. Electron Frequency in Plasma is

$$\omega_{pe} = \left(\frac{4\pi n_e e^2}{m_e}\right)^{1/2}, \quad \text{or} \quad \omega_{pe} = 5.64\times10^4 (n_e)^{1/2} \tag{8}$$

$$\text{in "cgs" units, or} \quad \omega_{pe} = 56.4(n)^{1/2} \quad \text{in CI units}$$

Where ω_{pe} is electron frequency, rad/s; n_e is electron density, [1/cm^3]; n is electron density, [1/m^3]; $m_e = 9.11\times10^{-28}$ is mass of electron, g; $e = 1.6\times10^{-19}$ is electron charge, C.

The plasma is reflected an electromagnet radiation if frequency of electromagnet radiation is less than electron frequency in plasma, $\omega < \omega_{pe}$. That reflectivity is high. For $T > 15\times10^6$ ^oK it is more than silver and increases with plasma temperature as $T^{3/2}$. The frequency of laser beam and Bremsstrahlung emission are less than electron frequency in plasma.

9. The Deep of Penetration of outer radiation into plasma is

$$d_p = \frac{c}{\omega_{pe}} = 5.31 \cdot 10^5 n_e^{-1/2} \text{ . [cm]} \tag{9}$$

For plasma density $n_e = 10^{22}$ 1/cm^3 $d_p = 5.31\times10^{-6}$ cm.

10. The Gas (Plasma) Dynamic Pressure, p_k, is

$$p_k = nk(T_e + T_i) \quad \text{if} \quad T_e = T_k \quad \text{then} \quad p_k = 2nkT \tag{10}$$

Where $k = 1.38\times10^{-23}$ is Boltzmann constant; T_e is temperature of electrons, ^oK; T_i is temperature of ions, ^oK.

These temperatures may be different; n is ion density, 1/m^3; p_k is plasma pressure, N/m^2.

11. The gas pressure, p, is

$$p = \frac{2}{3} nkT. \tag{11}$$

Here n is gas density in 1/m^3.

12. The magnetic p_m and electrostatic pressure, p_s, are

$$p_m = \frac{B^2}{2\mu_0}, \quad p_s = \frac{1}{2}\varepsilon_0 E_S^2 \tag{12}$$

Where B is electromagnetic induction, Tesla; $\mu_0 = 4\pi\times10^{-7}$ electromagnetic constant; $\varepsilon_0 = 8.85\times10^{-12}$, F/m, is electrostatic constant; E_S is electrostatic intensity, V/m.

13. Ion thermal velocity is

$$v_{Ti} = \left(\frac{kT_i}{m_i}\right)^{1/2} = 9.79\times10^5 \mu^{-1/2} T_i^{1/2} \quad \text{cm/s} \ , \tag{13}$$

Where $\mu = m_i/m_p$, m_i is mass of ion, kg; $m_p = 1.67\times10^{-27}$ is mass of proton, kg.

14. Transverse Spitzer plasma resistivity

$$\eta_\perp = 1.03\times10^{-2} Z \ln \Lambda T^{-3/2}, \quad \Omega \text{ cm} \quad \text{or} \quad \rho \approx \frac{0.1\text{Z}}{\text{T}^{3/2}} \quad \Omega \text{ cm} \quad , \tag{14}$$

where $\ln \Lambda = 5 \div 15 \approx 10$ is Coulomb logarithm, Z is charge state.

15. Reaction rates $<\sigma v>$ (in cm^3 s^{-1}) averaged over Mexwellian distributions for low energy (T< 25 keV) may be represent by

$$(\overline{\sigma v})_{DD} = 2.33\times10^{-14} T^{-2/3} \exp(-18.76\, T^{-1/3}) \quad \text{cm}^3\text{s}^{-1},$$
$$(\overline{\sigma v})_{DT} = 3.68\times10^{-12} T^{-2/3} \exp(-19.94\, T^{-1/3}) \quad \text{cm}^3\text{s}^{-1}, \tag{15}$$

where T is measured in keV.

16. The power density released in the form of charged particles is

$$P_{DD} = 3.3\times10^{-13} n_D^2 (\overline{\sigma v})_{DD}\ , \quad \text{W cm}^{-3} \tag{16}$$
$$P_{DT} = 5.6\times10^{-13} n_D n_T (\overline{\sigma v})_{DT}\ , \quad \text{W cm}^{-3}$$
$$P_{DHe^3} = 2.9\times10^{-12} n_D n_{He^3} (\overline{\sigma v})_{DHe^3}\ , \quad \text{W cm}^{-3}$$

Here in P_{DD} equation it is included D + T reaction.

As this this is a means of generating heat sufficient to melt rock, either by direct plasma or indirect by transmitting the heat using insulated thermal conductors that maintain a heat at the head which has contact with the rock to melt it and a secondary cooling device to press the melt against the walls of the void so that it hardens upon cooling not in a volcanic rock but dense glassy formations that render the void capable of withstanding great deal of pressure and high temperatures so that the void does not collapse by pressure or heat.

RELATIVE UTILITY OF INNOVATION

The innovation relates to a process for the making tunnels, shafts, wells, and boreholes, of all kinds, by melting rock by means of a direct or remotely shuttled heat source and wherein the resulting molten rock muck is retained in the tunneler's insulated muck melt chamber, whereupon being shuttled to the logistical base at the beginning point of the excavation, is switched with an empty muck melt chamber or entire fresh tunneler unit and reinserted. With progressively longer drives the option exists to lessen the 'shuttling time' by bringing streams of fresh muck chambers to the tunneler front which is disposed of in underground caverns or where intense pressure condenses it to a hard rock wall.

The utility of the innovation is not necessarily replace standard drilling but to supplant it where drilling reached its limitation. At certain depths, for example, the intense heat and pressure closes a drilled hole as soon as the drill bit is retracted. Numerous applications of melt and pressure devices have been advanced, but the application of direct mini or micro thermonuclear reactions for tunneling has not been advanced.

Conclusion

The innovation simulates two processes found in nature: (1) Every substance, however hard, has a melting point and (2) Pressure condenses rock to harder, compressed rock. Volcanic lava flows are a dramatic illustration of the first process while converting coal to diamonds by pressure illustrates the second process. This proposed innovation is a reliable and rapid method of penetration of rock masses by melting all or part of the rock face and penetrate therein, cool the resulting glassy tube to be a stabilized liner and remove the muck from the tunnel face rearward to a surface disposal site. The methods proposed to heat the tip of the melting element include heating by waste heat generated by a micro-thermonuclear reaction. High rates of advance are sustainable because only heat and cooling water must be advanced to the tunnel head.

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