Advanced Drilling and Its Impact on Heat Mining

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ABSTRACT

Given today's energy prices and optimistic projections of abundant oil, gas, and coal supplies, a significant improvement in the reservoir development costs for heat mining in hot dry rock systems is needed before mid- to low-grade resources can be exploited for electric power production. Higher fluid productivity and/or lower well drilling costs are needed. This paper focuses on drilling technology requirements and possible new developments that could achieve substantial reductions in drilling costs. Such revolutionary change could shift the drilling cost versus depth relationship from its current exponential dependence to a more linear dependence. Improvements discussed include: systems integration with advanced "look-ahead geophysical characterization of the rock coupled to on-line control of key drilling parameters, and advanced penetration concepts involving thermal spallation, erosion, and cavitation with and without coupling to rotary methods. A new national initiative on advanced drilling and excavation technology is reviewed as an example of what would catalyze the development of such improvements.

1. ECONOMIC TRADEOFFS FOR HEAT MINING

If geothermal energy use is to increase to the point where it represents a substantial portion of the world's primary energy supply, some fundamental changes are needed. For example, if one projected geothermal energy growth to say 20% of the current world's electric generating capacity of ~ 3,000,000 MW_e, which is two orders of magnitude larger than the 6000 MW_e provided by geothermal systems today, then hot dry rock (HDR) and lower grade hydrothermal resources will need to be exploited using heat mining concepts.

Conventional wisdom in formulating strategies for the development of alternative energy systems frequently assumes that two things will happen to shift the balance away from our current stock of fuels. First, there will be enormous increases in the prices of oil, gas, coal, and nuclear fuels because of short supplies, political or social uncertainties and/or other non-technical factors -- an unlikely set of events according to many energy economists (e.g., see Adelman, 1994). Second, the "real" prices of fossil and nuclear supplied electricity will increase markedly due to the internalization of environmental externalities or because of perceived health risks -- however, the magnitudes of these "damages" are difficult to estimate. Further, many governmental policies provide substantial barriers to this type of internalization in a worldwide free market system.

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Perhaps a more realistic view is to assume that geothermal energy itself must be made more attractive and competitive by lowering development costs and risks. For example, to achieve universal heat mining with low- to mid-grade hot dry rock resources utilized on a large scale, substantially lower drilling costs or higher reservoir productivities per well will be needed. This paper focuses on how drilling costs may be reduced by new technologies to enhance or replace conventional rotary drilling methods that are used today.

Economic tradeoffs exist for heat mining systems that are characteristically different than for more conventional hydrothermal resources. Because heat mining from hot dry rock does not utilize indigenous reservoir fluids of a specific composition, temperature, and pressure at a specific depth, choices can be made to optimize performance and costs. These include specifying depth, wellbore arrangement, and ultimately reservoir size to provide a sustainable fluid temperature-production time history that is economically compatible with the "grade" or "quality" of the HDR resource. Resource grade is globally determined by two variables: average geothermal gradient and a set of *in situ* rock properties that control the capacity of the rock formation depth to be stimulated by hydraulic pressurization or other means (Tester *et al.*, 1989; Armstead and Tester, 1987).

In effect, the interdependence of these optimization parameters with variables that control performance and costs leads to a simple tradeoff for heat mining. For a specific gradient and fixed power plant output, shallower completions involve lower costs for individual wells, but require more production flow to maintain power output because fluid temperatures and subsequent conversion efficiencies are lower. On the other hand, drilling deeper increases produced fluid temperatures thereby reducing required flow rates, but individual well costs are higher because they are deeper. If production rates per well or per well pair are relatively constant, the tradeoff becomes one between fewer, more expensive versus more, less costly wells. In addition, multiple well arrangements (e.g., triplets with a central injector and two producers or five-spot patterns) or multiple downhole completions could enhance reservoir productivity and reduce the need for drilling additional wells or for drilling deeper to increase fluid temperatures. Recently, downhole completions using multiple sidetracked sections in production zones have been employed for geothermal and oil and gas production (Henneberger, *et al.*, 1993; Steffen, 1993). These ideas are discussed further for heat mining applications by Armstead and Tester (1987), Tester and Herzog (1991), and finally by Herzog *et al.* (1995) in a paper presented at this World Geothermal Congress.

In all proposed heat mining concepts, low-grade resources are characterized by low average gradients (<40°C/km) and rock properties that limit reservoir heat production rates. Thus by lowering individual well drilling costs, the economic picture brightens for these low-grade systems as less stress is placed on maximizing reservoir production output which may be difficult to achieve in certain situations because of unfavorable *in situ* conditions. Consequently, it is appropriate to focus on improvements to drilling itself as a means of making heat mining more competitive.

Two central questions can be used to frame the discussion that follows:

1. How much lower do drilling costs need to *go* to achieve universal heat mining even in low-grade areas?

2. What technologies show promise to achieve these required cost reductions?

2. LINEAR VERSUS EXPONENTIAL DRILLING

Because selected drilling depths and well completion geometries (e.g. single versus multiple bottomhole assemblies) are inherently linked to drilling costs, projected costs for HDR reservoir systems can be based on interpolation and extrapolation of existing costs for oil, gas, and hydrothermal geothermal wells drilled using conventional rotary methods. Figure 1 illustrates the approach we have used as reported in earlier reports and papers (Tester and Herzog, 1990, 1991; Tester, 1992; Herzog *et al.* 1994). In Figure 1 a-b, actual and projected costs for completed wells in geothermal and oil and gas reservoirs, respectively, are shown. One clearly sees the strong dependence of cost on depth -- represented approximately as an exponential function in Figure 1c. Note the straight line correlation for average oil and gas wells based on U.S. continental (on-shore) drilling experience as reported by the Joint Association Survey (1978-1992).

The causes of this exponential dependence of cost on depth are numerous and mostly centered on problems of lower penetration rates in harder rock located at greater depths, the accelerated wear of drilling apparatus, and the round trip times required to remove and replace the drilling assembly. Although one might be able to mitigate the cost increases associated with deep drilling, there still remains the basic problem of bit wear given the inherent nature of the crushing and grinding comminution mechanisms employed in conventional rotary drilling practice. With these inherent limitations, a different approach to drilling is needed to change the exponential relationship between cost and depth.

We believe that new approaches to drilling could result in a more ideal, linear dependence of cost on depth by coupling a fundamentally different approach to comminution that achieves high penetration rates with minimal wear of the drilling apparatus. Figure 1c illustrates the idea of linear cost vs. depth drilling by using the average oil and gas cost value at 4 km (−13000 ft) as the common intersection point between linear and exponential dependence. As discussed by Tester (1992) and Herzog *et al.* (1995), such a shift in costs would open up the low-grade HDR resource to producing electric power in today's markets. It is interesting to note that the significant scatter in the ultra-deep Joint Association Survey (JAS) cost data suggest that reaching the linear drilling line may not require major breakthroughs in technology.

In order to achieve such marked cost reductions, different rock penetration methods will be needed and will require integration with other advanced control features. For example, "look-forward" downhole geophysical analysis of rock properties to adjust drilling parameters to optimize performance while drilling and self-contained directional guidance systems. These features could then be integrated into new designs that either replace or substantially enhance conventional rotary methods of penetration. Although many of these penetrator concepts have been evaluated earlier by Maurer (1980), new developments suggest that thermal spallation, water jet erosion, and cavitation methods might now meet the criteria needed for a linear drilling system. These are discussed in more detail in the two sections that follow.

3. ADVANCED SPALLATION SYSTEMS

As mentioned earlier, in stable rock formations, drilling deep (3.2 to 4.6 km or 10,000 to 15,000 ft) and ultra-deep holes (to 10 km or 33,000 ft or more) using conventional rotary methods is ultimately limited in a practical sense by the forces of friction and material wear. The mechanics of rotary drilling causes the borehole to deviate from the vertical with consequent increasing frictional forces while the direct contact of the drill bit with hard abrasive materials (along with induced heating) results in irreversible equipment and tool wear. In fact, one can conclude that it is the direct mechanical contact at the drilling face that leads to non-vertical holes and along with friction-induced bit wear leads ultimately to the premature failure of the drilling process itself.

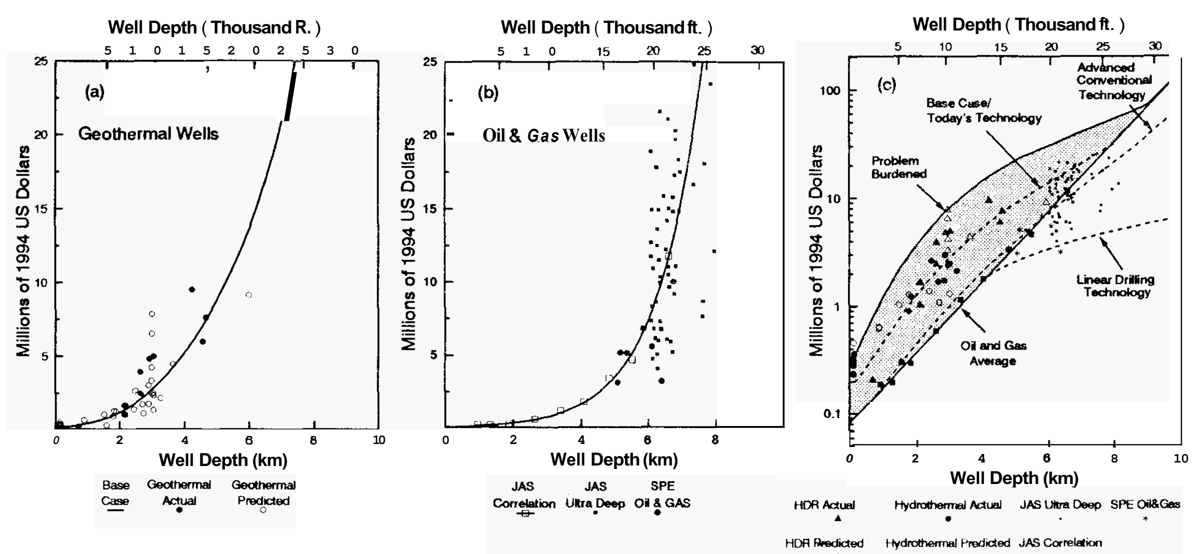

Figure 1. Actual and estimated completed well costs: a) geothermal wells b) oil and gas wells c) all wells. Note that JAS oil and gas correlation extrapolated beyond 7 km.

Methods employed to lessen these problems include the use of downhole motors to rotate the drill bit and percussion or hammer bits which virtually eliminate rotational torque. These methods have greatly reduced the non-verticality problem but still leave the immense problem of mechanical bit wear. Improved materials such as the polycrystalline diamond compact (PDC) and hydraulic aids such as cavitating nozzles have greatly increased bit life, but they still leave unsolved the persisting quasi-exponential drilling costs encountered in drilling very deep holes. Almost all present day large drilling rigs have the capacity to drill linearly if only the actual drilling mechanism has a working lifetime equal to the task of creating the desired wellbore depth itself.

Such an idealized drilling mechanism would have the rock magically "dissolve" ahead of the drilling rock face with little or no mechanical contact. This would eliminate wear and enable the drill string to land vertically like a plumb bob. If this ideal mechanism could also enlarge the borehole diameter beyond the diameter of the drilling tool or bit (a process known in the drilling industry as "under-reaming"), then much larger diameter vertical boreholes, a desirable feature for geothermal applications, could be produced than are now practical using mechanical drilling methods. To further add to its desirability, this mechanism should employ to the greatest extent possible, the capabilities of present day surface rigs and their associated drill strings.

Modified low-density, flame-jet spallation. To a significant degree, rapid thermal spallation of rock can provide such an idealized process. In earlier manifestations of this concept, a combustion flame jet impinges on a rock surface thereby inducing stresses high enough to cause the rock to spall (Browning, **1957**, Browning et *al.*, **1965;** Calaman and Rolseth, **1961).** The mechanical action of the jet combustion gases removes the spall and the process repeats itself. Field experience has shown that thermal spallation drilling intrinsically results in "under-reaming" in a controlled fashion (Rauenzahn and Tester **1985** and **1989;** Williams et *al.*, **1988).** The inherent versatility of this process permits the use of existing oil and gas field drilling equipment such as a dual-string system. This enables gas lift removal of the cooled combustion products and rock spalls in a separate pipe or annulus. Normal passage of spalls in the annulus of a large, deep borehole would be impossible without the injection of additional air to create the necessary lift velocity. Larger diameter wellbores also reduce the local gas velocity near the drilling assembly. This results in such insignificant erosional wear that ultra-deep wellbores can be drilled with minimal need to remove the drilling assembly and its pipe for servicing. True verticality of the drill string would subject it to only pure tension thereby reducing the risk of its failure to a very low level.

Although flame-jet spallation methods have been used for shallow blast hole drilling and quarry-block slotting for over **35** years, the proposed application to vertical hole drilling to greater depths is more recent (Williams et *al.*, **1988).** However, much remains to be done to develop practical techniques and equipment for achieving capability for deep drilling using spallation.

In order to be compatible with conventional drilling rigs and their drilling pipe, we propose the following features:

1. Three-component, three-phase transport of compressed air, liquid fuel and cooling water in the drill pipe
2. Downhole, two-stage centrifugal separation to separate air from the liquid phases followed by fuel water separation
3. Downhole fuel storage to accommodate periodic injection of fuel (**5** to 10% of the time) so as to permit easier separation of fuel and water. Typically, only a capacity of 200 liters (~50 gallons) will be required.
4. Communication linkage between the surface and the drilling assembly via armored cable magnetically attached to the non-rotating drill pipe
5. Instrumentation for control, including:
   - fuel/air rates
   - standoff distance
   - penetration rate
   - spall lifting capacity of air/water mixture
6. Instrumentation for diagnostic measurements, including:
   - flame temperature
   - combustion chamber pressure
   - spallation zone pressure
   - cooled gas temperature and velocity, caliper, hole orientation and inclination

These features permit continuous insertion of drill pipe using a pressure chamber designed to contain pressure when connecting a new stand of drill pipe. There would be no loss in overall drilling velocity or fluid returns using this concept. Alternatively, coiled tubing could be employed. High strength, light weight titanium tubing might permit drilling to depths greater than **10 km.** Depending on OD tubing size, lengths of 1-6 km (3000-20000 ft) are available on reels with nested coiling tubing, e.g., several small diameter tubes along with an electrical conduit cable contained in a larger tube. Such an approach would eliminate the need for a downhole fuel storage system.

The above system employs the capabilities of the modem drill rig. Using demonstrated elements of thermal spallation technology, reasonable engineering progress should allow significant progress towards the goal of linear drilling. However, one major requirement for technical success is inherent in this proposed concept. It requires that the formation being penetrated does not deliver formation water or pore fluids in quantities greater than the lift capabilities of the exiting gas stream.

In the above discussion, we assumed that an empty (dry) wellbore, that is (one occupied by low density gases such as compressed air and/or combustion products) is stable to these depths. It is estimated that an approximately **6 km (20,000** ft) deep dry hole would require an intrinsic rock strength of **> 43,000** psi to be stable. Increasing the density of the fluid in the "empty" borehole will increase the depth below which instability occurs. Clearly, the need to drill to great depths will require a higher density fluid possibly approaching or exceeding that of liquid water. The question then arises: Is there a process which will cause the rock interface to spall in a manner similar to that occurring with traditional combustion flame-jet technology?

Several studies indicate that the heat flux into the rock surface just prior to spallation is the main determining factor in the process (Rauenzahn and Tester, **1991 a,** b; Wilkinson and Tester, **1993 a,** b). The heat flux determines the penetration rate and onset temperature of spallation. One could then suppose a heat transfer process in which a very hot dense supercritical fluid flowing past the rock surface to be spalled might perform the same function as a flame does in "conventional" jet spallation.

Hydro-combustion high-density spallation. The low-density flame jet spallation system uses the conventional drill string to transport the three required fluid components (air, fuel and cooling water) to the drilling face. Calculations show that a pressurized flow of water through a drill pipe can transport the required amounts of air and fuel as a multiphase mixture to support a combustion process theoretically capable of thermal spalling rock at a useful rate.

Compressed air and fuel would be injected into the flow of water (or drilling mud) from the rig pumps and transported as bubbles in the water phase. The pressure of the two transported phases would be approximately equal to the local hydrostatic condition. Even at great depths (10 km or more) the solubility of nitrogen and oxygen in the water phase will be quite low (less than **5%** by weight). Furthermore, the density of these gases relative to liquid water will be a factor of 0.1 to **0.5** lower allowing easy separation by centrifugal means. The use of a low-density hydrocarbon fuel such as kerosene will again allow a second stage separation from the water phase. Again, as in the low density system, downhole storage capacity for the fuel phase will allow transport of the fuel at much higher concentration.

Recombination of the separated compressed air and concentrated fuel will permit oxidation whose exothermic heat of combustion will produce a mixture of hot supercritical water, nitrogen, and carbon dioxide to be expanded as a subsonic jet. This jet flow at turbulent Reynolds numbers of 3 to **4** million can produce stagnation heat fluxes of 10 to 20 MW/m^2 (see for example, Anderson and Stresino, 1963; Pamadi and Belev, 1980; Popeil et *al.*, 1980). The remaining water flow exiting through the annulus carries sufficient kinetic energy to overcome pressure losses and will provide the required lifting force to remove the spalls. Hydraulic pressure adjustment is also possible to intensify the pressure drop across the nozzle to a level beyond the critical ratio (approximately 2.0), thereby producing a potential supersonic flame-jet flow.

These heat fluxes are so high that post-combustion injection of water will allow lower temperature flame jets, which will facilitate wellbore diameter control and may allow spallation of rock types with low brittle to ductile transformation temperatures (e.g., limestone, phyllites, etc.). The very large mass ratio of water to combustion products ensures low temperature increases in the mixed upward annulus flow.

This high density modification would employ all of the control and diagnostic instrumentation described earlier. **A** further gain provided by the high density fluid phase is the ability to communicate down hole using current Measurement While Drilling (MWD) techniques. The high density even in the high temperature region results in much lower fluid velocities which will virtually eliminate any surface erosion problems. Remote acoustic monitoring arrays could also be used for ultra high temperature drilling environments where direct measurement at the cutting surface is not permitted.

Estimated heat transfer coefficients that result from these "submerged flame jets show a very strong depth dependence (Fig. 2). Potential drilling velocities may reach hundreds of meters per hour. Coupling of the trend of increased ease of spallation due to faster heat transfer with increasing stresses in the wellbore from overburden loading may result in the only significant limit to rate of penetration being the handling of the drill string at the rig. Even with the complexities of the separation systems this concept has the potential of being very close to an ideal linear drilling process.

4. ADVANCED WATER EROSION AND CAVITATION SYSTEMS

The rotary drilling process can be greatly enhanced by using high velocity water jets or cavitating bubbles to impart additional energy at the rock-fluid interface assisting the comminution process. The erosive intensity of a high velocity liquid water jet increases penetration rate in two fundamental ways: first by increasing the rate of fracture assisted partly by chemical-stress induced effects and secondly by improving the removal efficiency of rock chips from the cutting face of the bit. Cavitation processes enhance drilling by creating a rapid fluctuation in the local stress at the cutting interface. Until recently, the major problem associated with either method was in having a simple,

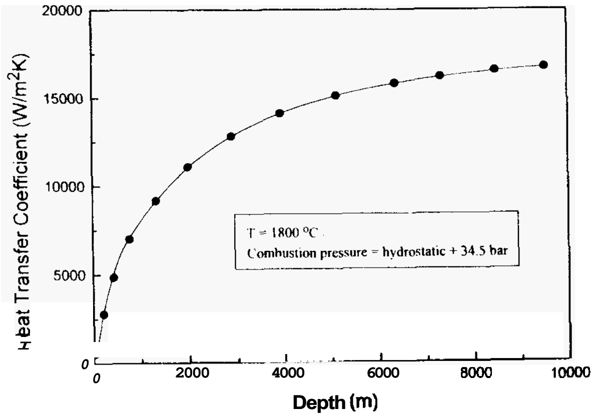

Figure 2. Estimated heat transfer coefficients for submerged flame jets in a pressurized water environment (full scale of depths).

robust mechanical design for inducing either erosion or cavitation locally at the rock/fluid interface in a deep borehole. Furthermore, it is important to avoid secondary cavitation or splash back of drilling fluids which could lead to standoff erosional wear of downhole equipment and tubular goods. These effects are intensified when abrasive drilling muds are used. Prodrill, Worldrill, and other company designs employ such advanced methods and recently introduced prototypes are undergoing testing for the suitability of drilling deep geothermal holes in hard crystalline rock.

Another advanced concept being considered jointly by MIT and Worldrill is a hybrid design that couples high velocity liquid water erosion to spallation with a combustion flame jet. In this concept, the erosive action of a hot, supercritical water jet is superimposed onto the heat flux induced spallation action of the same jet. The required temperatures for producing the supercritical water jet are provided using the technology described in the previous section. Further, there is an opportunity to re-inject a portion of the compressed air back into the water vortex swirl to enhance the erosive action of the supercritical water jet. Another possible advantage of such an approach would be the ability to induce acoustic coupling to transfer energy to the rock in an oscillatory mode that could further enhance rock failure and increase drilling rates.

5. CONCLUSIONS AND RECOMMENDATIONS

The ideas presented in this paper represent a sample of technologies that may lead to dramatic reductions in drilling costs, The linear cost versus depth relationship discussed provides a performance target for new technologies that would open up low-grade hot dry rock resources to commercial development.

In order to realize these goals, more R&D effort needs to focus on such revolutionary drilling methods. The U.S. has started a National program to promote Advanced Drilling and Excavation Technologies (NADET) which has as its main objective to develop technologies within the next seven years capable of substantial cost reductions for drilling, excavation, and mining applications (NADET, 1994). Hopefully such initiatives will lead to more international cooperative efforts to develop enabling technologies for geothermal energy applications.

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