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ON EARTHQUAKES INDUCED BY UNDERGROUND FLUID INJECTION

W. C. McClain

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ABSTRACT

In 1966, an unusual series of earthquakes near Denver, Colorado, were correlated with deep well waste disposal operations at the Rocky Mountain Arsenal. Since that time, additional investigations have confirmed the postulated cause-and-effect relationship and have established the mechanisms responsible. Because of this experience, various questions have been raised about the possibility of a similar occurrence related to ORNL's hydraulic fracturing waste disposal practices.

In this report, the mechanisms of the Denver earthquake sequence are examined in detail and the conditions necessary for such a phenomena determined. These conditions are so stringent that only in very rare occasions are they approached in normal industrial or oil field deep well disposal operations. By applying these necessary conditions to the situation existing at the Oak Ridge site, it can be unequivocally demonstrated that hydraulic fracturing operations cannot result in earthquakes by the mechanism responsible at Denver.

1. INTRODUCTION

It is now widely (but not universally) accepted that the series of earthquakes in the Denver area, which began in 1962 and is still continuing, was triggered by the injection of large volumes of chemical waste water generated at the Rocky Mountain Arsenal into the crystalline basement rocks underlying the site. This unique situation has frequently prompted questions and expressions of concern that the ORNL technique of disposal of radioactive waste solutions by hydraulic fracturing might lead to a similar series of events. The various research activities and other experiences related to the Denver seismic phenomena have been followed with considerable interest because of the superficial similarity of the two operations. This report summarizes many of the results of the investigations carried out in the region around the Arsenal injection well and reviews the current understanding of the mechanics of the earthquake triggering action. This review places special emphasis on the geologic conditions required for the generation of earthquakes. These necessary conditions are then compared with the situation existing at the Oak Ridge hydraulic fracturing site.

2. THE DENVER EARTHQUAKES

2.1 History

The disposal of highly toxic chemical-manufacturing fluid wastes at the Rocky Mountain Arsenal northeast of Denver, Colorado, had presented particularly difficult problems, for which underground injection appeared to be an ideal solution. Consequently, a 12,045-ft well was drilled at the Arsenal site through the nearly flat-lying sedimentary rock in the Denver basin and about 100 ft into the Precambrian crystalline rocks. This well was much deeper than is usual for deep well disposal operations and is indicative of the magnitude of the waste disposal problem. Routine injection of fluids was begun on March 8, 1962, and continued through September 30, 1963, at an average rate of 5.5×10^6 gal/month. No fluid was injected from October 1963 to August 1964. From August 1964 to April 1965, fluid was injected under gravity flow at an average rate of 2×10^6 gal/month. Commencing on April 6, 1965, pressure injection was resumed at an average rate of 4.5×10^6 gal/month.

In April and May 1962, seismological observatories operated by the Colorado School of Mines (at Bergen Park, Colorado) and Regis College (Denver) began recording a series of small earthquakes originating in the Denver area which previously had been considered to be a zone of low seismicity. In June 1962, several earthquakes occurred which were large enough to be felt by residents and caused considerable concern. By November 1965, over 700 shocks had been recorded and, although 75 of these had been felt, no damage was reported since the strongest to that time had a Richter magnitude of only 4.3.

In November 1965, David M. Evans,[1] a consulting geologist, published a paper showing a correlation between the number of earthquakes and the volumes of fluid injected into the well (Fig. 1) and suggested that a direct relationship existed. The U. S. Geological Survey, in cooperation with the U. S. Army Corps of Engineers, Colorado School of Mines, Regis College, and the University of Colorado, immediately began intensive investigation of the phenomena and a reexamination of the evidence used by Evans to support his supposition.

On February 20, 1966, all fluid injection at the Arsenal well was stopped, and in March a USGS report[2] was released which concluded that the evidence, including some new data, "tend to support the hypothesis that there is a relationship between the injection of water in the Rocky Mountain Arsenal well and the occurrence of earthquakes in the Denver area." The principal points supporting this conclusion were:

1. Seismic activity in the Denver area prior to the beginning of injections at the Arsenal was essentially nil.

2. The correlation between earthquake frequency and rate of waste injection given by Evans (Fig. 1) was confirmed to be an accurate statement of the available information.

3. The clustering of hypocenters about the injection well, based on locations computed from less than four seismograph stations, was confirmed and actually improved by use of data gathered from an augmented network of seismographs installed by the USGS.

4. Analysis of the direction of first motions recorded on the seismographs suggested that all of the earthquakes were generically related and were not isolated random events.

5. Drill stem tests and core samples from the well indicate that the disposal fluids are accepted into a set of preexisting, high-angle fractures in the Precambrian gneiss basement rocks which are otherwise impervious. These fractures, which are apparently capable of opening and closing, contained fluid at a preinjection pressure of 900 psi less than hydrostatic.

Following cessation of injection at the well in February 1966, the earthquake series continued more-or-less unchanged (perhaps slightly declining) for over a year. This pattern consisted of many hundreds

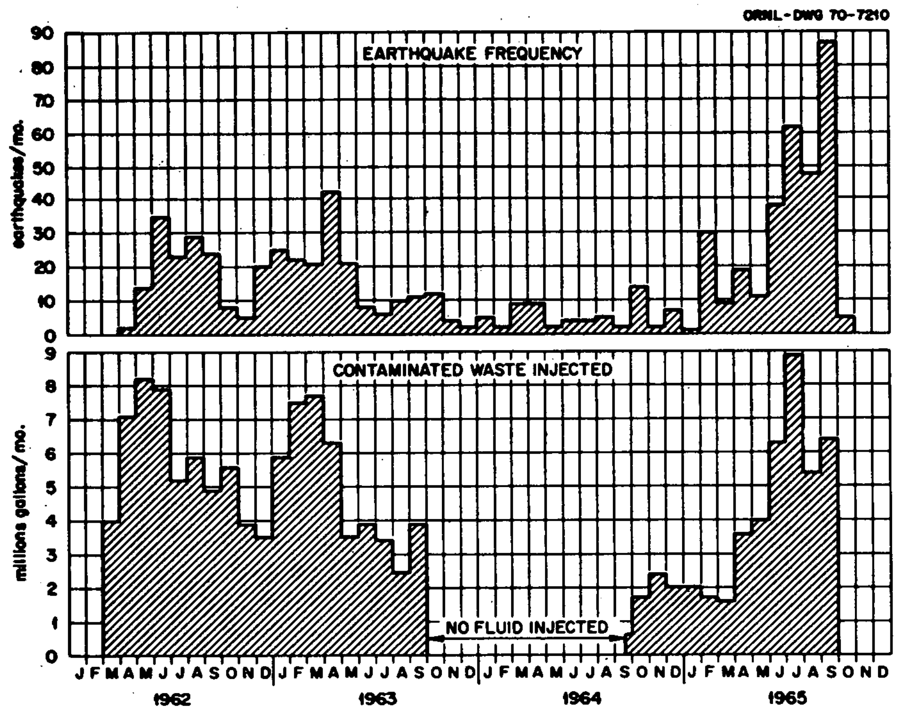

Fig. 1. Histograms Showing Relation Between Earthquake Frequency and Volume of Waste Injected into the Rocky Mountain Arsenal Well (after Evans, 1966).

of very small earthquakes detected on the USGS seismograph network in the epicentral zone and 4 to 71 events per month detected at the Bergen Park station 34 miles distant. None of these earthquakes had a magnitude exceeding 4.0. On April 10, 1967, some 14 months after injections stopped, the largest earthquake in the series to that time occurred. The magnitude of this shock was estimated as 5.0, and minor damage resulted in portions of Denver, Commerce City, and Derby. This large (for the series) earthquake was not inconsistent with the statistics of the frequency and magnitude for the entire series up to that time. However, on August 9, 1967, there was a second large earthquake of magnitude between 5 1/4 and 5 1/2 and on November 26, 1967, a third, of magnitude 5.1. The seismic energy released by these three events and their foreshocks and aftershocks was several times the sum of the energy released in all of the previous smaller earthquakes. Obviously, these three events represented a drastic change in the pattern of seismic activity associated with the injection well.

After the November 26, 1967, earthquake, the activity of the area has slowly declined but is still continuing, as illustrated by a magnitude 3.5 earthquake on May 23, 1970. From time to time there have been various programs proposed which had as their objective the amelioration of the conditions responsible for the earthquakes. These include drilling a new well at the center of the epicentral zone (northwest of the present injection well) and withdrawal of significant volumes of fluid from the reservoir, or removal of fluid through the existing injection well after suitable treatment to improve the transmissibility of the fracture system in the basement rocks. With the exception of a few pumping tests at the existing well, none of these proposed programs has been actively pursued. The prevailing philosophy seems to have been to leave matters alone to return to stable conditions naturally rather than tempting fate by trying to undo an unstable and very sensitive situation. The costs and engineering difficulties of any extensive fluid removal program may also have contributed to this general philosophy.

2.2 Mechanism of the Earthquakes

The mechanism by which the injection of fluids at the Arsenal well can cause the earthquakes has been worked out in considerable and convincing detail.[3] This mechanism is based on evidence indicating that the shocks are the result of right lateral slippage on the system of preexisting nearly vertical fractures striking at about N 60° W, thereby releasing accumulated tectonic strain elastically stored in the basement rocks. The presence of the existing fracture system has been confirmed by examination of the cores recovered during the drilling of the injection well and by hydrologic tests carried out early in the injection program. These tests indicated that the well would accept a flow rate of over 30 gpm at a bottom hole pressure of 5340 psi, but less than 0.02 gpm if the bottom hole pressure was reduced to 5250 psi. The differences in these values are almost conclusive evidence of a system of fractures capable of being opened under pressure. The orientation of the fracture system (N 60° W) was determined from the strong trend in the pattern of epicenter locations and the studies of the seismic radiation pattern. The evidence pointing to a tectonic origin for the elastic strain release derives firstly from an examination of frequency-magnitude relationship for the early earthquakes which was similar to that for tectonically active areas such as southern California. Secondly, the analysis of the seismic radiation from the shocks showed a consistent pattern of right lateral strike slip movement along planes oriented generally northwest. Finally, the total seismic energy released, especially from the three largest events, was so large that only elastically stored tectonic strain energy could have supplied it.

The effect of fluid pressure in the pore spaces of a rock has been established theoretically by Hubbert and Rubey[4] and experimentally confirmed by several workers. In this situation, the effective stress in causing deformations or failure of the rock (σ) is the total stress (S) reduced by the pore pressure (p), or

$$\sigma = S - p \qquad (1)$$

The strength of rock in shear on a specified plane (τ) is given by the empirical relation

$$\tau = \tau_o + \sigma_n \tan \phi \qquad (2)$$

where

τ_o = cohesive strength,

$\tan \phi$ = coefficient of friction (ϕ is about 30° for many rocks),

σ_n = effective stress normal to the fracture plane determined from Eq. (1).

Therefore, an increase in the pore pressure, such as would occur during waste fluid injection, serves to reduce the normal stress [Eq. (1)] and thereby reduces the effective shear strength of the rock [Eq. (2)]. Notice that the increased fluid pressure does not "lubricate the fault surface;" that is, the coefficient of friction has not been affected, but that there has been a reduction in the effective strength of the rocks. At Denver, the injection of wastes caused the original pore pressure of 3900 psi to be increased to 5640 psi.[3] This resulted in a decrease in the strength of the rock by approximately 1000 psi which apparently rendered it no longer capable of resisting the existing stresses in the rock and a failure or slippage on the existing fractures occurred.

The larger magnitude earthquakes which occurred after the cessation of injections at the well are not inconsistent with this mechanism. These can be interpreted as the result of the continued advance of the pressure front to greater distances from the well in spite of the rapid reduction in the maximum pore pressure near the well. If it is assumed that a particular fracture had extended itself beyond the advancing pressure front as a result of an earthquake during the injection period, then this longer fracture, especially in its weakened condition due to the previous slippages, could have been reactivated by the pore pressure front. Based on surface faulting data, the longer fault ruptures are related to larger magnitude earthquakes. Therefore, this interpretation would predict fewer earthquakes, especially near the injection well after the injections had ceased, but a predominance of larger magnitude earthquakes. This is in exact agreement with the actual experience.

2.3 Conditions Necessary for Inducing Earthquakes

Based upon this interpretation of the mechanism of the earthquake triggering action of the fluid injections, which is supported by a number of types of available observational evidence, it is now possible to specify at least some of the conditions which are required if the phenomena are to occur:

1. By far the most important condition is the presence of a regional tectonic stress state which is near to the breaking strength of the rocks before the injection is initiated. This requirement implies that the injection well is located in an area of at least moderate tectonic activity and that the reservoir formation must be at considerable depth, certainly several thousand feet.

2. The reservoir formation should accept the waste fluids into its porosity, but its permeability apparently needs to be low enough so that pore pressure buildup is possible. The type of reservoir formation which best meets this requirement is one where the porosity results from an existing fracture system in crystalline rocks which are otherwise nonporous and impermeable. Presumably, a formation exhibiting a porosity resulting from intergranular spaces, such as in most sandstones, could also meet this requirement.

3. The injection of fluids into the formation must be at such rates and pressures that (in conjunction with item 2 above) the formation pore pressures are significantly increased over a wide area. Based on the Denver situation, apparently flow rates of millions of gallons per month at pressures approaching 1000 psi greater than the original pore pressures are required.

3. INDUSTRIAL DEEP-WELL DISPOSAL OPERATIONS

The selection of the underground injection technique for the solution of the waste-disposal problem at the Rocky Mountain Arsenal was based on a large amount of experience with what was then considered to be the preferred and most economical method for the disposal of large volumes of toxic or noxious waste fluids. The practice originated some 60 years ago[5] when the petroleum industry began returning brines produced along with crude oil through abandoned wells. This practice is now a widespread and common practice in oil fields, especially in Texas, Kansas, California, and Illinois. Although the number of these injection wells is not precisely known, an impression of the magnitude of these operations can be obtained from the 1956 estimates of 250 billion gallons of brine pumped underground through possibly as many as 10,000 wells.[5]

In all of this experience, prior to the Denver situation, there had never been a documented instance or even a suggestion of any earthquakes being related to the brine injection operations. In all probability, at least two of the necessary conditions were not present in these cases: First, most oil production in these areas is from fairly shallow depths, in general, from 2000 to 5000 ft. At these depths, only a moderate tectonic stress can exist; only rarely can this stress approach the strength of the rock. Furthermore, the tectonic stresses in sedimentary basins typical of oil fields are usually low. Second, although large volumes are injected, the high permeability of the reservoir rocks prevents an appreciable buildup of pore pressure. In fact, that pore pressure usually has been appreciably reduced from its original value due to the petroleum production and the return of the associated brines serves only to partially restore the original pore pressure.

Since the association of seismic activity with the deep-well injections at Denver, an interesting apparently similar situation has been discovered at the Rangely oil field in western Colorado.[6] In this case, secondary recovery operations by water flooding were in progress using water injection at high pressure through periphery wells to drive oil towards central extraction wells. A few fairly small earthquakes in the area have been detected, and the presence of microseismic activity has been confirmed by special on-site instrumentation. The level of activity was much less than at Denver, and the mechanism, although not worked out in detail, is presumed to be the same. In this case, a higher than usual tectonic stress could be suspected from the regional geology and specific efforts were made to produce a localized high pore pressure zone, thereby creating the necessary conditions for earthquake triggering. The differences in the level of seismic activity at Rangely and Denver are probably a reflection of both the tectonic stress differences (as implied by the much shallower depths at Rangely) and the different behavior to be expected from sedimentary and fractured crystalline rocks.

The disposal of industrial wastes by deep-well injection is not nearly so widespread as the injection of oil-field brines; only some 110 such wells were in operation at the end of 1967.[7] Although these installations bear a closer resemblance to the Arsenal well than the oil-field brine injection operations, none of these has ever been suspected of triggering earthquakes. Most of these industrial disposal wells are completed at fairly shallow depths into porous sedimentary rocks, and most are located in the highly industrial regions around the Gulf Coast and the Michigan basin. A recent survey[8] of 43 operating industrial injection wells can be assumed to be a typical sampling. Of these 43 wells, only three were reported to be over 7000 ft deep, while the majority (76%) were less than 5000 ft deep. Furthermore, ordinarily both the injection rates and injection pressures were quite low. Over 50% of the wells were utilized at rates less than 200 gpm, and over 60% required wellhead pressures less than 300 psi. From these indications, it would appear that the combination of only moderate volumes injected into highly permeable formations at low fluid pressures and fairly shallow depths has precluded the possibility of triggering earthquakes, especially by the mechanism postulated for the Denver area.

4. THE HYDRAULIC FRACTURING METHOD OF WASTE DISPOSAL

4.1 Description

Development work on a waste-disposal method based on the oil well stimulation technique of hydraulic fracturing began at the Oak Ridge

National Laboratory in 1961.[9] These efforts reached fruition in December 1966, when the experimental plant was first used on an operational basis for the disposal of intermediate-level radioactive wastes generated at the Laboratory. Since that time, a total of about 650,000 gal of these waste solutions containing approximately 320,000 curies of activity have been injected on a routine basis. Ordinarily, batches of 80,000 to 120,000 gal are injected at approximately 6-month intervals.

In this technique, the injection well was completed at about 1000-ft depth in a thick, nearly horizontal, and essentially impermeable shale formation (Conasauga). The steel well casing is first slotted all around at the desired injection point and the well pressurized with water. This "breaks down" the formation by initiating a conformable, nearly horizontal fracture in the shale. This fracture is then extended slightly by the injection of a few hundred (less than a thousand) gallons of water. The waste solutions are then mixed with a preblended combination of dry ingredients containing Portland cement, fly ash, various clays, and slurry conditioning chemicals. The resulting slurry is then pumped down the well and out into the fracture, considerably extending it. The slurry is usually injected at a flow rate of about 250 gpm and wellhead pressures of 1700 to 2500 psi.

When all of the available waste solution has been injected and the equipment cleaned up (Most of the cleanup fluids are also injected.), the well is "shut-in" and the cement-based slurry allowed to harden under pressure. The dry ingredients and their controlled proportioning with the aqueous wastes are specifically designed to absorb essentially all of the available fluids and to chemically bind the radionuclides in a nearly unleachable matrix.[9]

Several of these injections are usually carried out through a single slot in the well casing. Then a new slot is cut about 10 ft above and the entire process repeated. This creates a stack of thin planar grout sheets along the bedding planes of the shale far below any circulating groundwater. (A pictorial view of the equipment used at the ORNL hydraulic fracturing plant and the resulting underground grout sheets is shown in Fig. 2.) Core drilling from the surface and intersecting both the preliminary series of experimental grout sheets and

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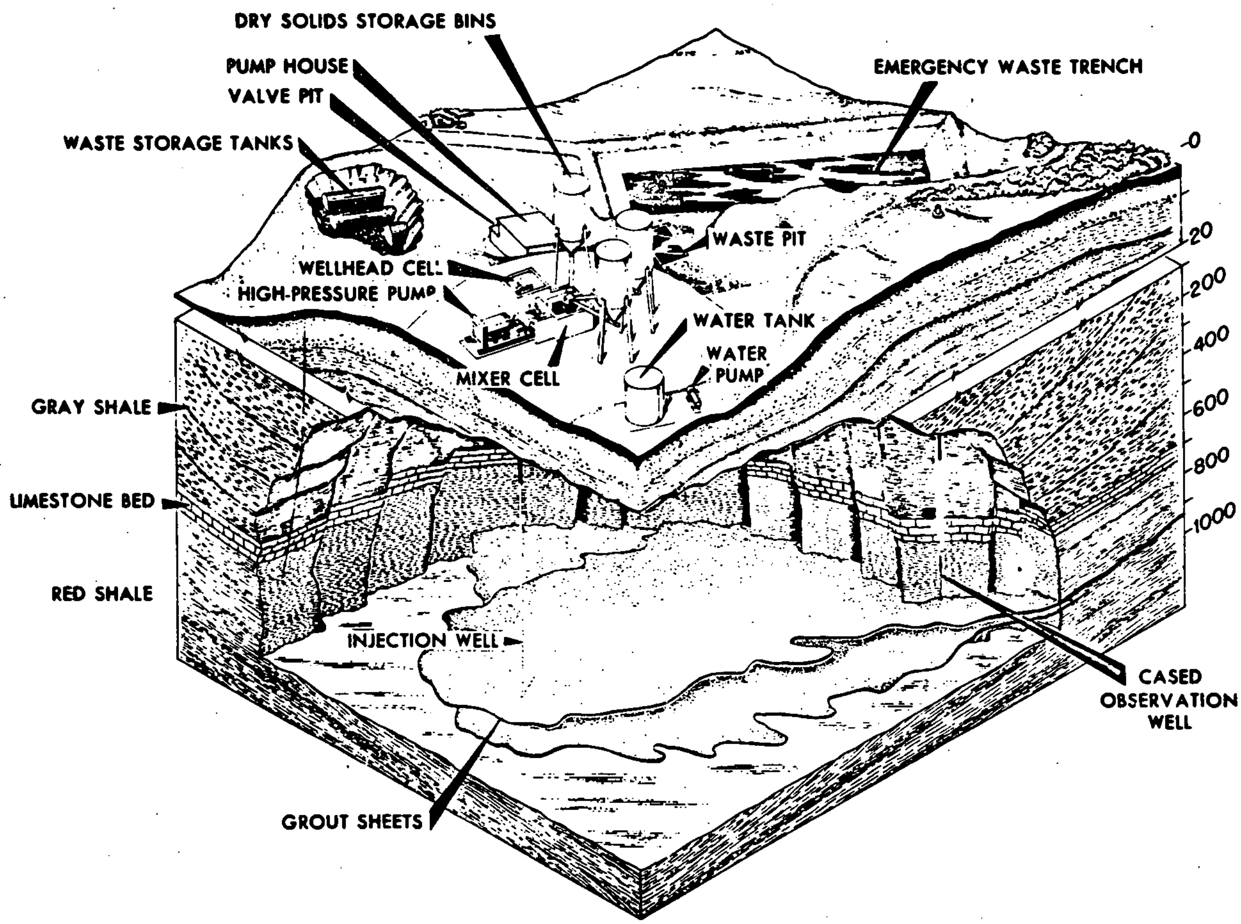

Fig. 2. Pictorial Representation of the ORNL Hydraulic Fracturing Plant and Injected Grout Sheets.

and those resulting from subsequent operational injections have confirmed that all of the sheets are conformable in the nearly horizontal shale formation. This drilling also indicates that the grout sheet resulting from a single injection may extend several hundred feet radially from the well and has an average thickness of approximately 0.1 in.

5. COMPARISON OF HYDRAULIC FRACTURING WITH THE DENVER INJECTION WELL

Based on this description of the hydraulic fracturing waste disposal method as practiced at Oak Ridge, it is obvious that this system is totally different and completely unrelated to "deep well" injection waste-disposal operations. In fact, the only point of similarity is that waste is pumped down a well. In hydraulic fracturing, space for the solidified grout is created in the impermeable shale in the form of a thin fracture along bedding planes. In deep-well disposal, fluids are injected into a preexisting porosity with a consequent and sometimes appreciable disturbance of the hydrodynamic regime of the reservoir formation. Occasionally, deep-well injection operations are carried out in the "fracing" mode, wherein the injection pressure is increased until the reservoir formation breaks down. This serves to increase the permeability of the formation in the high velocity flow area adjacent to the well, but does not alter in any way the overall characteristics of the method.

In spite of the gross differences between the two techniques, it is possible to evaluate the conditions at the Oak Ridge hydraulic fracturing site against those required for inducing earthquakes by fluid injection:

1. The approximately 1000-ft hydraulic fracturing injection depth and the natural plasticity of the shale rocks over the long period of geologic stability precludes the maintenance of tectonic stresses approaching the breaking strength of the rocks. Furthermore, since the hydraulically induced fractures are known to be horizontal, the direction of the least compressive stress must be vertical. This means that

the preferred faulting (or fracture slippage) direction would be by thrust faulting, rather than strike-slip faulting as at Denver, and the stress requirements would consequently be significantly different.

2. In hydraulic fracturing, fluids are not injected into the existing porosity. Therefore, there is no resulting disturbance of the original pore pressure relationships. In fact, the whole concept of pore pressures and hydrodynamic properties is completely meaningless in a formation as impermeable as the Conasauga shale. The only place where pore pressure concepts even remotely apply is at the surfaces of the fracture which are wetted by the advancing slurry. The total volume of material involved in this case is minute, especially in view of the fact that the average injection rates for the hydraulic fracturing operations at Oak Ridge are of the order of 100,000 to 200,000 gal/year (compared with several million gal/month at the Rocky Mountain Arsenal well).

3. Based on instrumental location of earthquake foci at Denver, a volume of rock, 15 miles long, 5 miles wide, and 4 miles deep, appears to be involved. The total volume of rock subjected to any disturbance, however slight, in the hydraulic fracturing operation is quite small: certainly no more than a 1/2 mile from the injection well in all directions and 1/2 mile deep. Even if other conditions were favorable, which of course they are not, the elastic strain energy stored in this volume of rock would be insufficient to produce any significant seismic activity.

Based on this comparison, it can be unequivocally concluded that the possibility of generating or triggering earthquakes at the ORNL hydraulic fracturing facility, by the mechanism postulated for earthquakes associated with the waste injections at the Rocky Mountain Arsenal well, is nonexistent. The two disposal systems are completely different, and there appears to be no way for any of the several necessary conditions for earthquake triggering to be achieved at the Oak Ridge site.

6. CONCLUSIONS

In spite of the fact that the theoretical framework of the mechanism which is now used to explain the earthquake triggering effect of the Arsenal injection well was available before the well was installed, no one suggested the possibility of an earthquake sequence at that time. In fact, the various investigators of the phenomena will readily admit that such an a priori prediction would have been impossible.[10] With this experience in mind, it is not possible to categorically state that hydraulic fracturing operations will not eventually be related to earthquakes or some other natural phenomena by some mechanism as yet unknown. This, of course, does not detract from the conclusion that it would be totally impossible for the ORNL hydraulic fracturing practices to trigger earthquakes by the mechanism of the Denver earthquakes.

The probability that the hydraulic fracturing operations will someday lead to the generation of earthquakes by some as yet unknown mechanism would appear to be very small. As pointed out above, the extent of disturbance introduced into the rocks is limited to distances of about 1/2 mile. Furthermore, the magnitude of the disturbance is extremely small. Analysis of rock stresses (not pore pressures) induced by each injected grout sheet[11] indicates that maximum values of only 5 to 10 psi are achieved in and near the fracture and these decline very rapidly with increasing distance from the grout sheet. The overall rate of injection is so small that these induced stresses would be reduced even further by plastic relaxation of the shale before any appreciable total stress could be accumulated. The very limited nature of the disturbance resulting from the hydraulic fracturing operation would seem to preclude the possibility of eventually leading to an unstable situation by any mechanism and would certainly limit the range of possible effects to minor or even insignificant proportions.

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