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URANIUM IN SITU LEACHING: ITS ADVANTAGES, PRACTICE, PROBLEMS, AND COMPUTER SIMULATION

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INTRODUCTION

In Situ leaching for the recovery of uranium from low grade sandstone deposits is one of the newest technological advances in the mineral industry. It is rapidly developing into a commercially feasible mining system which has economic, environmental, and social advantages over conventional mining systems. Because of the current uranium shortage, development of In Situ leaching into a sophisticated system has gained new impetus. In Situ leaching will become an important mining technique in the future, which will greatly help to supply uranium for our nation's energy needs.

In this paper, I will be giving an overview of the merits of the system, as well as the technology, problems, and research in solution mining of uranium.

Economic Overview[1]

Economically, solution mining is attractive. It requires much lower initial capital investment, considerably shorter lead times, and eliminates the need for the construction of a mill. Very generally, capital costs amount to about $5 per pound of uranium annual capacity of the surface facility. A 100,000 pound per year uranium plant can be constructed for between $250,000 and $750,000, depending upon well and field designs. A leaching cycle can run from about two to twenty years. Additionally, solution mining is not labor intensive in that a 50,000 - 500,000 pound per year uranium oxide (U_3O_8) plant requires only about 12 persons for operation.

The industry generally feels that the cost per pound of U_3O_8 produced is roughly \$15 - \$20.

Presently, with the price of yellowcake set at approximately \$40 per pound, in situ methods look attractive. At this price, the smallest orebody which can be economically mined with in situ leaching is approximately 100,000 pounds. This is dependent on the number of wells which need to be drilled, their depth and design. Although the economics of solution mining do not show it to be the lowest cost method of extracting uranium (conventional stripping and processing of <u>shallow</u> ore bodies is probably the lowest), but it tends to be more economic with (1) the deeper orebodies, (2) those far from the mill, and (3) those with severe environmental problems.

<u>Environmental Overview</u>[2,3,4,5,6]

From the environmental standpoint, solution mining of uranium shows a negligible effect on such factors as surface disturbance, interference with natural groundwater quality and distribution, and aerial discharge of radionuclides. In the surface disturbance category, only one to two pounds of tailings per pound of uranium result in acid leaching and virtually none in the carbonate leaching system, which compares very favorably to the half ton of waste produced per pound of uranium produced from conventional systems. Additionally, the only other surface disturbance is that of clearing the area of brush and trees and grading roads to the area.

Because of the nature of the mining system, the ore body must be in an aquifer which lies under the water table. This raises some very serious environmental questions. Escaping leaching solution from the leach area can contaminate the periphery around the mining zone with leached-out elements. However, by design of the system, solution migration can be controlled and escaping solution can be minimized to an almost inconsequential extent. However, the groundwater is not suitable for human or animal use because of the Radium-226, and frequently high dissolved solids levels in uraniferous aquifers. Accordingly, if something unexpected occurs, i.e. some leach solution escapes, there would be no harm to man and animals, and it would be sufficiently diluted by the surrounding groundwater, and essentially no effects should result.

In in situ mining, the personnel exposure to both alpha and beta radiation is virtually eliminated. The selectivity of the leaching process leaves the radon daughter products untouched in the ground, which would otherwise produce most of the radiation hazards to humans or animals. Additionally, because crushing and grinding are not part of the solution mining system, dust is also virtually eliminated. The solutions have very low levels of radiation which result mainly from Radium-226 carried with the calcium. A build-up of Radium-226 in a circulating load of the leaching solutions can be prevented by controlling the calcium solubility. In discussing radiation protection, the solution mining of uranium has outstanding merit.

The in situ mining system shows some inherent advantages; however, there may be some long term environmental disadvantages. One of these is the long term effects of the clays after the leaching operations stop and the ore zone reverts back to its original equilibrium with the groundwater. Questions such as, are there ions the clays will release which were earlier absorbed during the leaching cycle? And, what kinds of problems will these present? This is one of the things presently being investigated which may reduce the many pluses of solution mining.

Again, on the plus side, in situ leaching shows many environmental advantages over conventional mining systems, which contribute to the overall favorability of its usage. A thorough examination of the environmental problem is not treated here as it is a large field and is beyond the scope of this paper.

Social Implications [1,3]

Solution mining of uranium may prove to be very socially desirable. In this time of uranium shortages, which will probably not ease to a significant degree in the near future, it is important to note that the lead time for getting an in situ plant into operation, once an amiable ore body is discovered, is a little over one year. This is significantly shorter than for conventional systems. This could help ease the present uranium shortage and help in the future by adjusting more quickly to supply-demand pressures of the market system. Also, since the financial participation by a company is much smaller, more companies will be inclined to get involved in uranium mining and help supply more uranium to the market. Recoverable reserves would additionally be increased by increasing adoption of the in situ leaching technology. Ore bodies which are bypassed now as uneconomic, using conventional methods, are economically attractive, using solution mining methods. This allows the social desirability of the use of all uranium resources. Further, solution mining can be used at cut-off grades that conventional systems leave behind and accordingly make more efficient use of our nation's limited resources.

STATE-OF-THE-ART

Solution mining requires some specific geological conditions to allow recovery of uranium. These conditions are the following:

1) The ore body generally must be a horizontal bed underlain by impermeable strata for containment of solution.
2) The ore body must be located below the static water table so the solutions may flow.
3) The mineralogy of the deposit must be amenable to the process.
4) Even though the uranium content requirement for profitable operation is much lower than in conventional operations, it must be ascertained whether the mineral content is enough for the geological conditions of the site to repay all exploration, development, and extraction costs.

Further information is needed on the direction and velocity of the groundwater flow and the porosity and permeability of the aquifer. These last items of information are needed to design the well field.[7]

Well Field

Below is a figure showing a typical sandstone roll front which pictorially describes the solution mining method. Most of the leachable uranium deposits are of this type. Of all the western uraniferous deposits, it appears quite possible that 30 to 50 percent are amenable to recovery by in situ leaching technology.[3]

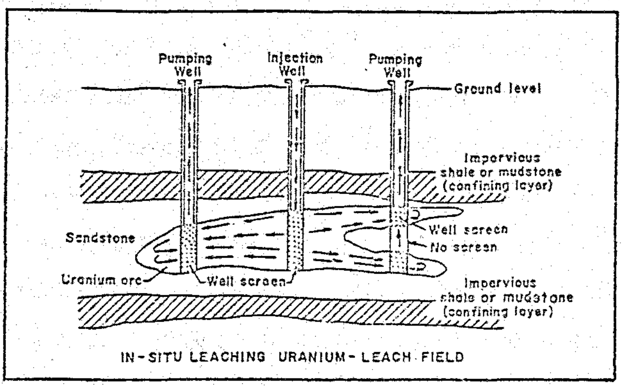

Figure 1 - Solution Mining a Sandstone Roll Front[8]

Solution mining of uranium has many of the technical aspects of secondary recovery of oil, in that fluids are injected into the area desired, and are pumped out from other wells. It requires that the fluid pass through the ore zone and then come into contact with the solubilizable uranium values and be pumped out and processed. Although industry has also tried three- and nine-spot well patterns, the five-spot has been generally favored.

The five-spot pattern is usually set up in a square configuration, with the injection wells at the corners, and the production (output) well in the center. This configuration, although not the most efficient in flooding an ore zone, affords usually sufficient control of the injected fluids. Research and development conducted at the present time will promote increased efficiency and control. This will be discussed later; for now we will use the five-spot pattern for simplicity of illustration.

Most commonly a 50-foot spacing between injection wells is used. The injection wells are cased with four inch diameter PVC pipe which is cemented to the surface. Production wells usually have an inside diameter of four or six inches, also cased with PVC pipe and cemented. All connections and surface lines must be made of a non-corrodible material. Standard steel, for example, cannot be used in in situ leaching operations because of the corrosive solution used; it would dissolve the pipes and then plug the injection wells and contaminate the yellowcake.[4] All leaching operations require an oxidant to promote leaching. Of all the materials suited for use, plastics (PVC in particular) are the most practical and economical. Stainless steel has been used for the screened sections of the pipe in the ore zones, but its cost is quite high, so PVC is used as screening material also.

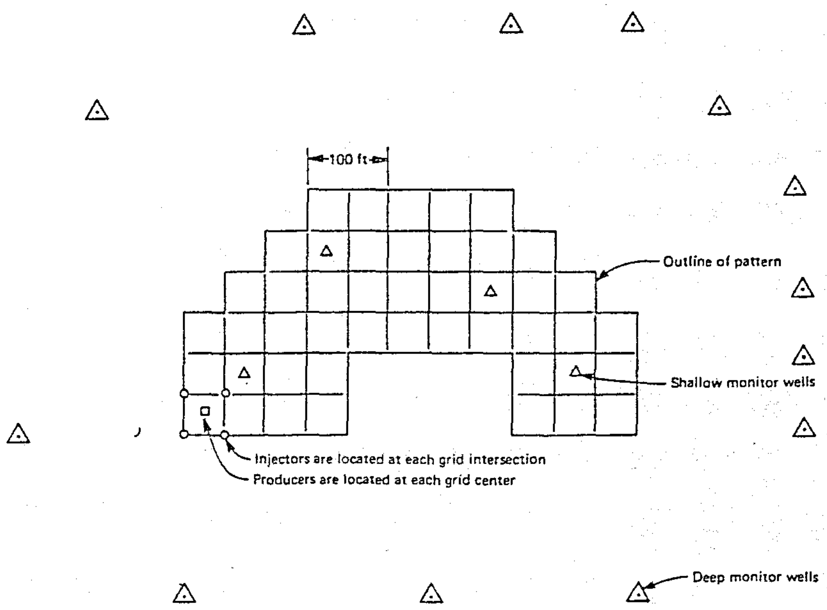

Figure 2 - ARCO-U.S. Steel-Dalco Leaching Pattern[4]

Hydraulic gradients formed in the aquifer by input pump pressures and volumes in conjunction with production pump downdraw determine the direction and velocity of the solution flow. The hydraulic head is much greater at the injection wells than the production well so the solution flow will be toward the production well. The well field design and the pumping rates and pressures are engineered to confine the solution to the desired leaching area and to obtain efficient solution sweep and leach contact time.[3] Normally, more fluid is pumped out than is injected to realize and maintain appropriate pressure gradients.

Shallow monitor wells placed in the uraniferous aquifer are used for purposes of detection of escaping solution. Deeper monitor wells outside of the ore zone are used to detect loss of leaching solution and deterioration of the groundwater quality. If escaping solution is noted, then the solution can be pulled back into the well area by increased pumping of the production well or increased pumping of the injection wells to increase the hydraulic gradient which will pull the solution back into the well area.

Well Development[9]

It is important that the wells be properly drilled and cased to ensure proper permeability within the aquifer. This is of major concern to many companies that are developing in situ leaching, as it has caused many problems in the past.

One of the major problems which arises in well development is in the use of drilling muds. It is of utmost importance that the muds used do not plug up the aquifer near the well. Organic muds are made to order to eliminate this earlier problem. Once used, the remaining mud in the well decomposes, through bacterial action, into CO_2 and H_2O, all within days. This just about nullifies any reduction in permeability due to plugging of sand grain interstitial spaces by the mud. The most popularly used organic mud is a guar gum based mud known commercially as Revert.[10]

Another problem which can considerably reduce permeability is the swelling of clays caused by hydration from the use of other than natural groundwater. There are two ways of possibly attacking this problem, which can be considerable if much clay is present. The first way is, naturally, to use the native groundwater in the muds. Because clays are in equilibrium (with respect to their ion exchange capabilities) with the groundwater, they will not hydrate to a significant degree due to equilibrium changes. Another way of attacking the problem is by using a mud with an additive added to prevent swelling. Cyfloc 326[11] is a mud which contains a polyacrylamide flocculant, which helps settle out clays on the surface during drilling to prevent their migration into the sandstone, and potassium cloride which helps prevent hydration and swelling of the clays. In a few days the well area is at equilibrium with the aquifer groundwater again.

It was found to be a good practice to put a tail pipe on at the end of the casing. This is to allow sands and clays to settle out inside the pipes below the level of the screen. This could avoid many problems, particularly with the production wells, with material filling up inside the screen. Also, it should be noted that production wells should be gravel-packed in low permeability aquifers to increase capacity.

Well development is one area that cannot be taken too lightly by companies in solution mining. It has been a source of many problems, and improperly drilled holes lengthen the mining schedule or worse, may require drilling new wells. The wells are the crux of the solution mining system, and great care in their design and development must be observed.

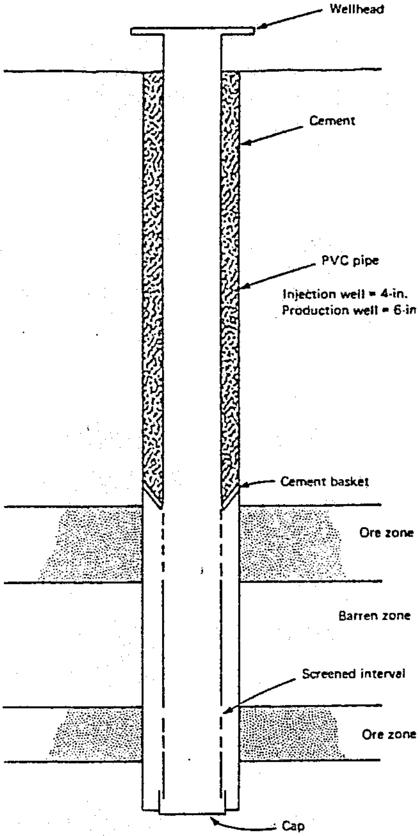

Figure 3 - Generalized Section of an In Situ Leaching Well[4]

Leaching Solutions

The two principle lixiviants (leachants) used in leaching uranium are acids and alkaline carbonates. The acids used are mainly nitric and sulfuric acids. Their advantages are high yields and fairly efficient recoveries. However, because large amounts of impurities are also solubilized and the acid cannot be regenerated,[12] which results in high reagent consumption, carbonate lixiviants have found widespread use in the uranium solution mining industry.

The most popular carbonate used is ammonium bicarbonate. It is non-corrosive, shows high selectivity in solubilizing uranium, requires simple procedures for recovering high grade uranium, and the reagent consumption can be kept low because the reagent may be regenerated. In a conglomerate ore, carbonate lixiviants would not be effective in recovering uranium because it could not dissolve other minerals encasing particles of uranium. However, in sandstone-type ores, the uranium is usually a precipitate on grain surfaces, which are exposed to solution flow.[13] This makes ammonium bicarbonate an ideal lixiviant in uranium solution mining.

Ammonium bicarbonate is easily formed on site by addition of ammonia to water and bubbling CO_2 gas through the water. Before pumping the solution into the aquifer, an oxidant is added to oxidize the uranium into the soluble hexavalent state. The commonly used oxidants are liquid O_2 and hydrogen peroxide with hydrogen peroxide gaining wider and wider acceptance in the industry.[14]

Hydrogen peroxide dissociates into O_2 within a few feet of the injection well, but its advantages lie in the ease of storage and the ease in which it can be added to the solution and pumped into the well. The lixiviant concentration in the injected solution ranges from approximately one to seven percent; whereas the oxidant concentration is a few tenths of a percent. This is to minimize the oxidation of minerals other than uranium. The chemical reaction which takes place is: $9(NH_4)_2CO_3 + U_3O_8 + \frac{1}{2}O_2 + 9H_2O$ $\rightarrow 3[(NH_4)_4 \cdot UO_2(CO_3)_3 \cdot 2H_2O] + 6NH_4(OH)$

The ammonium bicarbonate - O_2 (or H_2O_2) combination has been quite successful. It causes fewer irreversible effects on the aquifer and surrounding environment and performs well in recovering uranium.

Recovery of Uranium and Waste Disposal

Depending upon the size of the orebody, the uranium can be recovered on site, or a concentrated uranium solution can be produced which can be shipped to a central site for processing into yellowcake. For large orebodies, such as the Atlantic Richfield-U.S. Steel-Dalco Clay West in situ leaching operation (at George West, Texas), leach solution is pumped to a central plant where it is processed into dried yellowcake.[4] In smaller orebodies, or those orebodies which are located at the periphery of a main mineralized zone mined by conventional means, the solution may be concentrated by ion exchange and then shipped to the mill of the main operations. In this way, in situ leaching can scavenge the lower grade zone and take advantage of mill facilities present. Figure 4 shows a flowchart of the Clay West uranium recovery scheme.

The Clay West operation will dispose of their chemical wastes in deep disposal wells. Presently, these wastes are stored on land in large surface reservoirs. However, once the wells are complete, solution will be pumped down 4500 feet into a sandstone layer at an expected rate of 150 gallons per minute. In addition to the mill wastes being disposed of in such deep underground wells, in orebody restoration following leaching, the final leach solutions will be pumped out of the orebody to be disposed 4500 feet underground.[6]

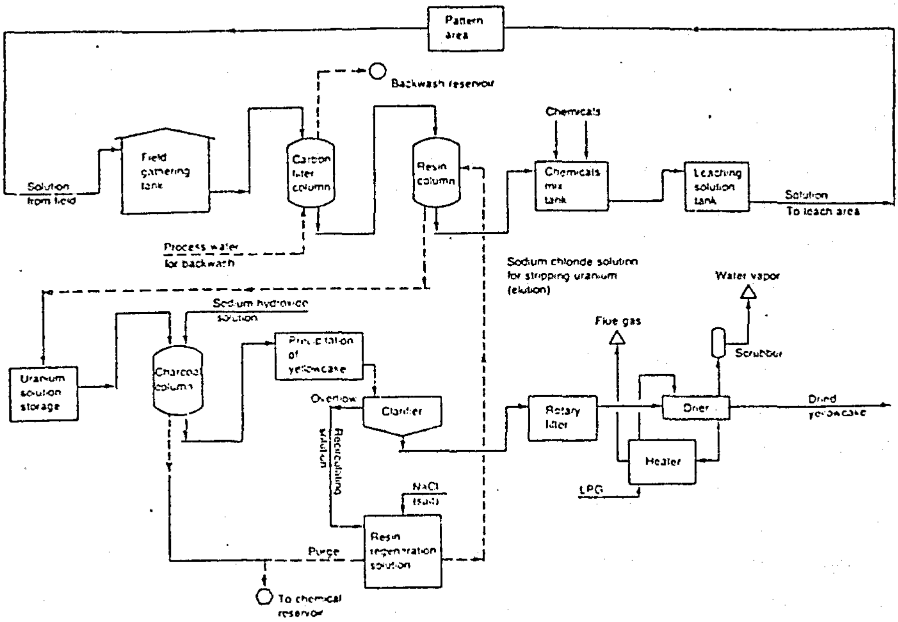

Figure 4 - Block Flow Diagram of ARCO Clay West, Texas Uranium Leaching Plant[6]

PROBLEMS WITH IN SITU LEACHING[15]

Despite the attractive picture displayed so far, uranium solution mining does have its problems. Many companies experience decreased injectivity of their injection wells as leaching progresses. This is thought to be the result of precipitation of minerals or the swelling of clays. Companies have flushed their wells with solutions of strong acids which have helped increase production for a time, but the wells still seem to lose most of their permeability over time. Reverse pumping does help out in some cases also, but is not totally effective. This is a major problem of concern to many companies and research is being conducted to discover the problem (or problems) and to find solutions.

A second area of concern is the usage of reagents by minerals other than uranium. Indications of leaching studies seem to show that feldspars may be a consumer of carbonates which, depending upon the minerology of the feldspar, can give different leaching rates and reagent consumption.[2] Calcite and pyrite dissolution are always problems which need to be controlled. Further, other minerals may be interferring in the process which are not yet suspected and need to be identified in order to get optimal results in leachant usage.

If uranium is in the aquifer, it may never be recovered because of the refractory tendencies of the minerals, or because of its association with organic carbon and with pyrites which initially caused its precipitation from uraniferous waters. Even if the uranium is leachable, it may be later absorbed by montmorillonite (which shows an ion exchange preference to uranium over many other ions) or co-precipitated with other elements.[2] This is a bane to solution mining -- to leach the mineral yet never recover it.

Much research needs to be done to help control these aspects so that optimization may be realized. However, as control of a complicated and delicate natural system such as a water aquifer is attempted, the problem becomes very complex and multifaceted.

COMPUTER SIMULATION[16]

In an attempt to optimize leaching technology, computer simulation of the hydrology has been done and the mass transport and chemistry will be in the future. The thrust of simulation is to help determine the optimal well spacing, input and out put flow rates, and other parameters characteristic to the individual orebodies. This information is computed using the inputs of aquifer, well, and inherent flow characteristics.

The Bureau of Mines' Twin Cities Mining Research Center has developed a five-spot simulation program (5-SISL program). The model was developed directly from solutions to the Hantush and Jacob hydrology equations in various closed forms. These equations describe fluid flow in a variety of aquifer types. The 5-SISL program has some options to handle the many different aquifer characteristics. The output is in the form of numerical and graphic representation of streamline isovelocity, isotime, and isopressure gradients. This helps the uranium producer to see what would occur and to determine the best well field design for a pilot 5-spot operation.

The 5-SISL program is under continual development to make it fit the needs of the producers. Leaching chemical kinetic considerations will be incorporated into the program in the future. These kinetic considerations are being studied and will model the uranium leaching kinetics dependent upon the many variables discussed earlier. Below are isovelocity and isotime streamline plots of a quadrant in a five-spot pattern worked out by the 5-SISL program.

Realizing the inefficiencies of the five-spot pattern, but aware of the unknowns uranium producers face from deviating very much from it, Dr. Chester McKee, now with the University of Wyoming, developed a multi-well computer simulation program. Multi-well patterns are well field designs which follow the orebody contours in no set geometrical well pattern such as the five-spot configuration. Through the program, the well field can be designed efficiently, avoiding the spots between injection wells where little or no solution will sweep which lowers overall recovery. Given the leaching rates, the program will compute the amount of time required to leach an orebody to a desired degree. The user can pick different well configurations and determine which well field design will optimize the recovery and economics of leaching a uranium-bearing aquifer.

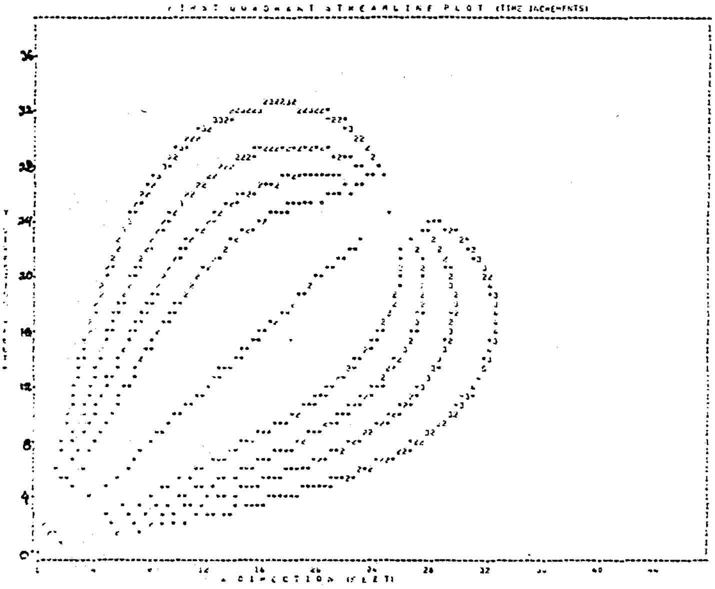

Figure 5 - An Isotime Plot by the U.S.B.M. 5-SISL Program[16]

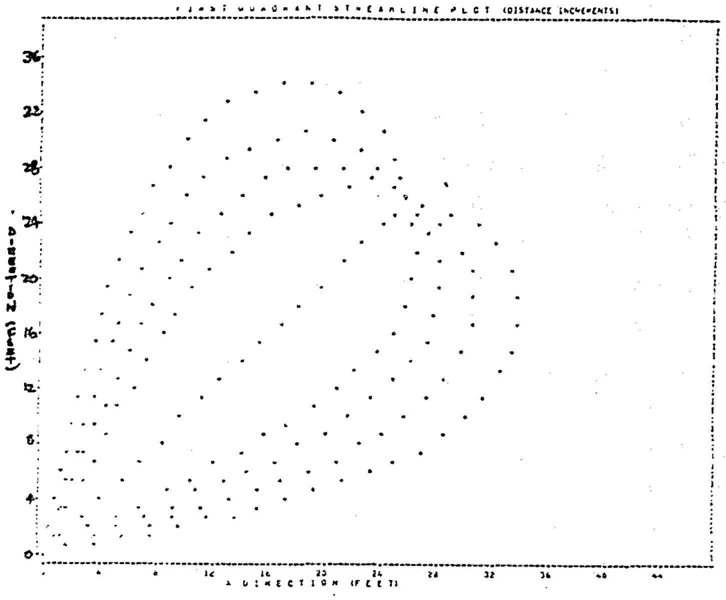

Figure 6 - An Isovelocity Plot by the U.S.B.M. 5-SISL Program[16]

CONCLUSION

Since 1957, when Clifton Livingston first proposed a mining system[17] which required no shafts, tunnels, or slurry handling systems, solution mining has progressed and developed to the point of its commercial use. Considerable capital has been spent on research and development to evolve it to where it is today. In southern Texas, there are large amounts of low grade uranium ore which are beginning to be mined on a pilot plant or commercial scale by six companies. It is the same story in the Powder River, Gas Hills, and Shirley Basin areas in Wyoming. Many companies now recognize the potential value of in situ leaching for recovering low grade uranium.

As with all new technologies, in situ leaching will require continual development in the near future to overcome the many present problems. However, with the amounts of research and development going on, in high probability eventual solutions to many of these problems will be found. A relatively short period has passed since in situ leaching was first conceived until the present time, but it has proved to be a viable mining technique which can be applied economically on ores with which many commercial systems cannot economically or environmentally handle.

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