FINAL TECHNICAL REPORT

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BREAKTHROUGH ENERGY SAVINGS WITH WATERJET TECHNOLOGY

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Executive Summary

Experiments performed at the University of Missouri-Rolla's Waterjet Laboratory have demonstrated clearly the ability of waterjets to disaggregate, in a single step, four different mineral ores, including ores containing iron, lead and copper products. The study focused mainly on galena-bearing dolomite, a lead ore, and compared the new technology with that of traditional mining and milling to liberate the valuable constituent for the more voluminous host rock. The technical term for the disintegration of the ore to achieve this liberation is comminution. The potential for energy savings if this process can be improved, is immense. Further, if this separation can be made at the mining face, then the potential energy savings include avoidance of transportation (haulage and hoisting) costs to move, process and store this waste at the surface. The waste can, instead, be disposed into the available cavities within the mine. The savings also include the elimination of the comminution, crushing and grinding, stages in the processing plant. Future prototype developments are intended to determine if high-pressure waterjet mining and processing can be optimized to become cheaper than traditional fragmentation by drilling and blasting and to optimize the separation process.

The basic new mining process was illustrated in tests on two local rock types, a low-strength sandstone with hematite inclusions, and a medium to high-strength dolomite commonly used for construction materials. Illustrative testing of liberation of minerals, utilized a lead-bearing dolomite, and included a parametric study of the optimal conditions needed to create a size distribution considered best for separation. The target goal was to have 50 percent of the mined material finer than 100 mesh (149 microns). Of the 21 tests that were run, five clearly achieved the target. The samples were obtained as run-of-mine lumps of ore, which exhibited a great deal of heterogeneity within the samples. This, in turn, reduced the ability to apply detailed statistical tests to the product outcomes. Nonetheless, a regression analysis showed that operating pressures between 105 (10,000psi) and 140 (15,000psi) MegaPascals (MPa) at traverse speeds no greater than 10 cm/min (4 in/min), best generated the target result. Variation in other parameters, rotation speed, nozzle diameter, and nozzle separation angle, during the preliminary tests did not substantially change the product, and so were kept fixed during the ore mining tests. The experimental protocols were developed to include proper treatment of the lead-bearing materials, which may be considered hazardous.

In anticipation of the creation of a mineral processing design for separation of the concentrates from the tailings (waste), assays were made of the metal content of each screen size for each of the 21 runs; with three screens and a pan for undersize, to give a total of 84 assays. This information will enable Dr. McNulty, project consultant, to create a flow sheet for the prototype mining machine. As a preliminary component to such a system, the experimental layout included a product-recovery system that delivered all of the fragmented product to the nest of screens which allowed study of the liberation at the different size levels.

Where incomplete liberation is found, a secondary process was demonstrated for using pressurized cavitation to further comminute the material. This concept was

successfully demonstrated, with a small cavitation chamber illustrating the much smaller space that such a tool requires, relative to conventional ball and rod mills. Additional testing is ongoing, external to this program, to find whether an one-step process using higher jet pressures and longer dwell times to achieve all the required comminution in mining, is more efficient than a two-step process in which normal jet pressures and feed rates do the initial mining, but full particle liberation is achieved only through secondary processing of the product in a cavitation chamber. Subsequent testing is also planned, to determine preferred methods for separating ore minerals from the waste. Tests with this system have included both the galena samples, and copper ores from Poland.

The development of this tool lies within an expanding market for the use of high-pressure waterjet equipment across a broad spectrum of applications. As the industry develops new tools, it is anticipated that the research team will investigate the development of a prototype machine based on these tools, since this will simplify and speed up equipment development. It is hoped that once this is developed that can be taken into an active mine. Such a machine should be able to produce large enough samples to allow assessment of optimal operating conditions.

Accomplishments Compared with Goals

In the project narrative that is part of the initial proposal for this research, the team said the following as part of a section on "the Competitive Position of the Proposed Project."

> "This will include the development of a series of experiments on samples of mineral ore to evaluate the parameters best suited to disintegration of that ore; and an evaluation of the product to determine how best to separate out the components. Concurrently, based on the results of these experiments, a basic design for a preliminary head, and a process plan for mining with this tool will be developed. The process plan will include a more accurate basis for prediction of the savings in energy and other costs that can be anticipated from this project."

Additionally, the team said in the proposal section on "Project Objectives,"

> "The overall objective therefore will be the design of a mining module, based on laboratory experiments that will optimize ore disintegration and component separation, together with a report that will more accurately predict the energy and other cost savings achievable with this change in technology over that currently prevailing."

The laboratory experiments have been completed and statistically sound suggestions have been made for operating parameters to be used on the Missouri lead ore found in the Doe Run Company's mines. Assays of the metal content of varying splits of product size have been run and are providing the basis for several proposed mineral processing flow sheets. Discussions on the creation of a prototype mining machine have shown that tools are being developed within the waterjet industry that will facilitate construction of a mining machine.

Essentially, the team has delivered that which was promised for Phase I of the research project.

Summary of Project Activities (DOE Final Technical Report Item 5.)

As will be detailed in the next section, the accomplishments of the project are substantial reported in the Master of Science thesis of Jorge Garcia-Joo. A copy of that thesis, both in print and in digital format, has been submitted. Material from that thesis is summarized in sufficient detail to validate the statements of progress made above.

Introduction

The underlying premise of this work relates to how minerals are found in the ground, and how, most effectively, to separate the valuable constituents of such deposits from the surrounding host rock, which has no useful value. In conventional mining of valuable mineral deposits it is most common practice to mine the entire volume of rock, transport it to the surface, and then crush it down to a small enough particle size as to ensure that the valuable mineral particles (pay) are broken free (liberated) from the surrounding rock (waste). This process, by its nature, requires that all material be crushed to a fine particle size, at a considerable cost in energy, time and materials.

When valuable minerals are deposited they lie, in many cases, as discrete particles within the rock body, itself made up of discrete particles of other, less valuable minerals. The boundaries of these intergrown particles outline particles that are, quite frequently, larger in size than the product size from the grinding process (comminution) that is used to conventionally liberate the pay. Energy costs for comminution increase significantly as particle size is reduced, due to the increase in surface area that must be generated for the smaller particles.

Experimental evidence has shown that high-pressure waterjets remove material by first entering the small surface flaws in a target, then pressurizing the water within the flaw inducing it to grow. Where these grown cracks intersect particles of material are then liberated. If the crack growth can be controlled so that it grows around the individual constituents of an ore, then the pay particles can be separated from the waste particles as part of the process of mining. It has been shown, in earlier studies, that the grain boundaries of the rock constituents form the likely starting flaws by which the waterjets can penetrate, and thereby disaggregate the rock.

Where this disintegration of ore into its constituent grains of different minerals occurs at the mining machine, then there is no additional need to transport and process the waste rock. If it can effectively therefore be separated from the pay, then it can be left in a site adjacent to current mining (perhaps filling a void from previous mining) and will no longer incur the transportation, comminution and disposal costs that are a part of current mining practice. Given the reduced volume of material that must be removed (normally the pay is less than 5% of the total rock volume) the potential savings can be very significant, across the mining process. Experiments that have been carried out serve to demonstrate that the underlying concept is valid, and to establish some preliminary parameters for the operation of a mining machine to achieve this purpose.

Equipment

The High-Pressure Waterjet Laboratory (HPWL) is a part of the Rock Mechanics and Explosives Research Center (RMERC) at the University of Missouri-Rolla (UMR). The HPWL has, for the past 40-years, been involved in the useful application of high-pressure waterjets for a variety of purposes, many of which have related to the removal of geotechnical materials. As a necessary part of the support to that endeavor, the Laboratory has acquired a number of high-pressure pumps and support equipment, which were made available for use with this project. In addition to the pumps, an existing traversing rig (which moves the nozzle over the target surface) was modified to hold large blocks of rock or ore and contain the material removed from the cut. This provided a test bed for a parametric study that was performed to determine the best way to extract and comminute the ore. During this study, a debris recovery system was devised to capture the mined product and feed it to a nest of sizing screens. These emulate the post-mining separation unit that will be required in the mining machine, and provided size-segregated samples that could be evaluated to determine liberation and mineral content.

The waterjet was anticipated to simultaneously mine and mill the rock. Thus, it would fragment the rock, not into the coarse sizes expected from conventional mining, but into sizes small enough to liberate the valuable constituent from its surrounding waste allowing the segregation of concentrates at the mine face and the disposal of the remaining wastes in the underground mine cavities. Based on advice from the team's mineral processing expert, Dr. McNulty, it was felt that if the product was produced in a size range where fifty percent or more of the material was finer than 100 mesh (149 microns), then it could be fed directly into a compact separator. The recovery system that was used was designed to collect the output of the experiments directly onto sizing screens and thus make efficient the determination of size range for each parameter tested.

The prime mover for this system was a portable Freemeyer M12 pump capable of producing, at maximum, 245 MPa (35,000 psi) with a flow rate of 38 liter/min (10 gpm). It is a type and size of pump that is generally commercially available and is not pictured.

Figures 1and 2 illustrate the waterjet rig and a sample in place before testing. The sample in the latter picture is partially obscured by a steel template that as placed over each sample to ensure that each test covered the same relative area and that there were extraneous inputs through events such as the cutting head approaching the end of the sample, causing large chips to break free from the sample, and bias the distributions of the collected material.

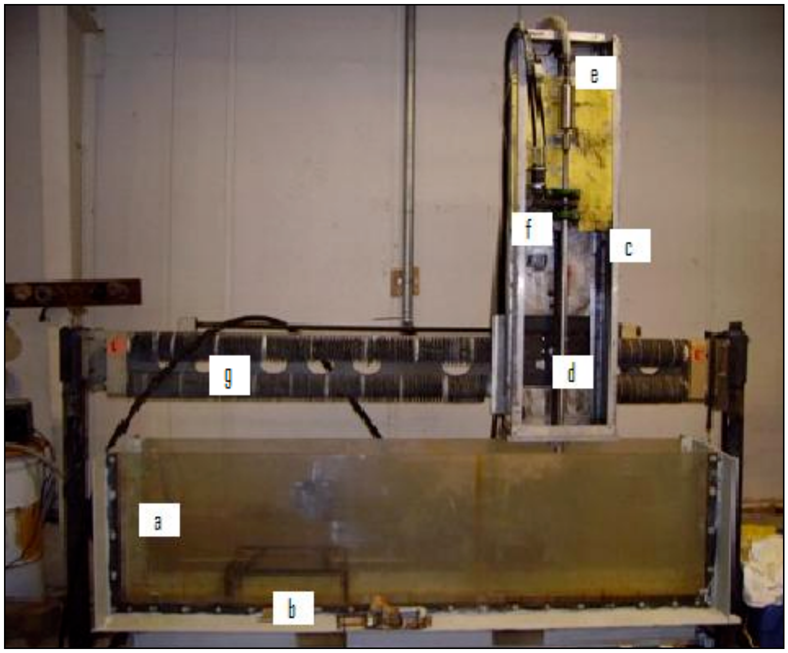

Figure 1. Cutting Apparatus used in the Series of Experiments (a. Tank, b. Sample Holder, c. Cross-Head, d. Rotating Lance, e. Pressure Hose, f. Hydraulic Motor, g. Screw)

By sweeping the same relative area of coverage each time, the differences in recovered mass could be assumed to be significant indicators of the efficacy of the parameter being tested, rather than being a variable imposed by the sample geometry.

Figure 2. Steel Sample Holder Placed over a Dolomite Rock Sample

Figure 3. is a line drawing of the design of the equipment emphasizing the recovery and prototype separation system. Figure 4. is a photograph of the interior of the recovery drum showing the location of the sizing screen set.

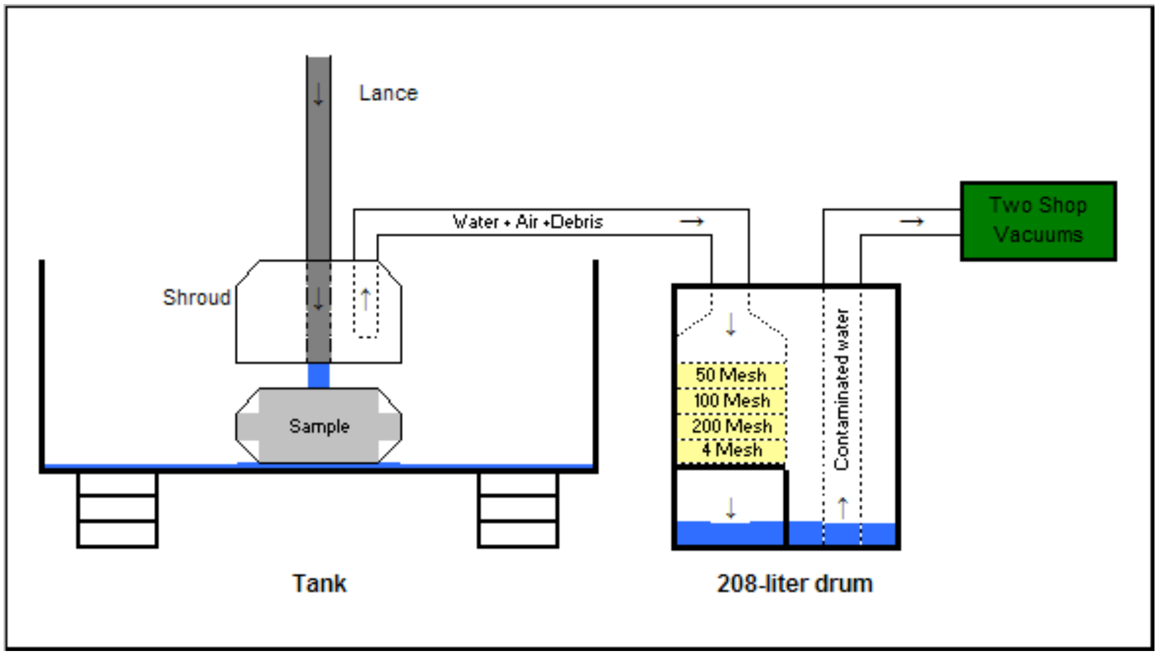

Figure 3. Design of the Recovery System

Figure 4. Large Containment Drum with a Nest of Sizing Screens Used in the Product Recovery System.

Experiments to optimize Mining Parameters

The objective of this work was to illustrate, through a specific example, that a designated ore, the Missouri mined, galena-bearing dolomites of the Doe Run Company, (a project co-sponsor) can be disaggregated by a waterjet, and consequently processed. Unfortunately, lead, even as lead sulphide, is considered to be a hazardous material and requires careful handling with strict adherence to an experimental protocol that ensures total recovery of the product. Therefore, in the early phases of the research, two other rocks were used to establish experimental procedures, to help illustrate the proposed process, and to optimize the parameters of cutting.

The first rock was Roubidoux Sandstone, a low-strength sedimentary rock containing natural inclusions of hematite. Because this fragmented so readily into its individual sand grains and the hematite, it did not give much opportunity for optimization. Tests on this rock did, however, give encouragement that the process would achieve the goals. Figure 5. shows a block of sandstone after a test run and Figure 6. shows the coarse debris that was recovered from the screens.

Figure 5. Slot Produced by the Waterjet Process on Sandstone Test 01.

Figure 6. Coarse Debris from the Sandstone Tests Showing the difference in size between the two constituents (sand and hematite), which would facilitate separation. Note the incomplete cleaning of sand particles, due to lack of optimization.

Test results of these from the initial evaluation are included in Table 1. Even with pressures as low as 35 MPa (5,000 psi), the sandstone was almost completely disintegrated into its constituent grains. Because the natural size of these grains was above 100 mesh, and that of the hematite very much larger, very little of the product reached the desired size range. But this work emphasized, given the nature of the result, the simplicity of the approach, and the potential for material mining and separation that it demonstrates. It was not felt necessary, with this ore, to optimize the process. Subsequent testing, and the combination of sand and hematite in some of the fragments points out one of the needs for the mining tool, however.

Given the large size of the hematite particles, these can act as a protective cover to the underlying sandstone that has to be disintegrated and removed to release the hematite. If the geometry of the cutting head is not such that the jets can undermine the particles, then a bridge of sand will hold them in place (Figure 7). The revolving waterjet head that was used in these tests had a very shallow angle of inclination (Figure 8), and the result shows the need for an increase in this angle, as a function of the maximum grain size of the material that is to be mined. As an alternative the head must be moved forward and run along non-coincident traverse lines to ensure that the jets have the access to mine all around the particles in the target surface.

Figure 7. The protection afforded by the larger hematite particles to the underlying sand, and the failure, in consequence to achieve better mining practice.

Figure 8. The angle of the jets to the axis of the cutting head, at the start of a cutting pass. Note that the jets are also tilted in the plane of the head, so that the reaction force from the jets, also provides a motive force to cause the head to rotate. Thus there is no external rotary drive for the head, which spins under the pressure (5,000 psi) of the jet.

Table 1. Experimental Parameters and Outcomes for tests on Roubidoux Sandstone with Nodules of Hematite

SANDSTONE WITH INTRUSIONS OF HEMATITE (CRITICAL PARAMETERS)									
Test number	**Waterjet pressure (MPa)**	**Traverse speed (cm/min)**	**Nozzle diameter (mm)**	**Standoff distance (mm)**	**Rotational speed (RPM)**	**Angle between jets (°)**	**Number of replications**	**% passing 100 Mesh (- 147 micrins)**	**Mass of material (gr)**
1	35	40	0.78	50	120	34	1	5.58	484
2	35	20	0.78	32	120	34	1	5.36	612
3	35	40	0.78	10	120	34	1	5.39	634

The local predominant rock in Rolla is a dolomite. Samples of this non-mineralized dolomite from the Jefferson City Formation were therefore tested; it was of medium strength, fine grained, and is close in constitution and properties to the dolomite gangue of the Doe Run ore deposits. Because of its strength and hardness, a variety of test conditions could be applied in the search for optimal operating conditions. Figure 9 is an illustration of a slot that was cut during test run number 24; it should be noted that changes in cutting parameters yielded a wide variety of patterns in the slot cut.

Figure 9. Slot Cut into Jefferson City Dolomite During Test Run 24

In Table 2., the operating conditions are listed with output for 24 tests on dolomite. Four tests that had promising results are highlighted; the last three of these produced substantial fragmentation. It was these tests that showed that higher pressures and lower traverse speeds would work best in giving us the mining product and performance that is needed for this process to be successful.

Table 2. Experimental Parameters and Outcomes for the Jefferson City Dolomite

JEFFERSON CITY DOLOMITE (CRITICAL PARAMETERS)									
Test number	**Waterjet pressure (MPa)**	**Traverse speed (cm/min)**	**Nozzle diameter (mm)**	**Standoff distance (cm)**	**Rotational speed (RPM)**	**Angle between jets (°)**	**Number of replications**	**% passing 100 Mesh (- 147 micrins)**	**Mass of material (gr)**
1	105	30	0.78	2.5	120	34	2	5.67	811
2	70	40	0.53	2.5	110	31	1	28.36	342
3	70	30	0.53	2.5	110	31	1	47.60	1061
4	70	30	0.53	1.9	110	31	1	76.92	39
5	105	30	0.53	1.9	110	31	2	24.40	525
6	140	30	0.53	1.9	100	31	1	17.57	962
7	140	30	0.53	1.9	112	45	1	20.42	1043
8	140	20	0.53	2.5	112	45	1	10.08	982
9	140	30	0.53	2.5	30	45	1	31.27	854
10	140	30	0.53	2.5	60	45	1	24.32	296
11	140	30	0.53	2.5	182	45	1	6.67	1140
12	140	30	0.53	2.5	182	45	1	17.60	608
13	140	20	0.53	2.5	182	45	1	50.46	753
14	140	10	0.53	2.5	180	45	1	26.25	1341
15	140	10	0.53	2.5	180	45	1	63.88	825
16	140	10	0.53	2.5	240	45	1	27.52	1875
17	140	10	0.53	2.5	240	45	1	39.88	1640
18	140	10	0.53	2.5	271	45	1	15.70	1987
19	140	10	0.53	2.5	271	45	1	23.81	315
20	140	20	0.53	1.9	240	45	1	44.44	333
21	140	20	0.53	1.9	240	45	1	41.78	304
22	140	30	0.53	1.9	240	45	1	25.47	1072
23	140	30	0.53	1.9	240	45	1	16.15	910
24	140	5	0.53	2.5	185	45	1	48.75	1327

Lead Ore

With these results in hand and an assurance that the waterjet would disintegrate an ore with strength characteristics similar to those of the dolomite, a series of 21 tests was run on the galena-bearing ore of the Bonneterre Formation. The recovery system was now fully operational and the disintegrated product – the water and rock fragments coming from the waterjet – was captured on the nest of screens in the sealed drum. As before, the product on each screen and the undersize pan was weighed and the size distribution plotted. In addition, each product, by run and screen size, was sent to the Doe Run Analytical Laboratory to obtain the value of its metal content.

Table 3. Experimental Parameters and Outcomes for the Galena found in Dolomite (Bonneterre Formation)

DOE RUN LEAD ORE (CRITICAL PARAMETERS)									
Test number	**Waterjet pressure (MPa)**	**Traverse speed (cm/min)**	**Nozzle diameter (mm)**	**Standoff distance (cm)**	**Rotational speed (RPM)**	**Angle between jets (°)**	**Number of replications**	**% passing 100 Mesh (- 147 micrins)**	**Mass of material (gr)**
1	35	5	0.53	2.5	60	20	1	35.72	42
2	35	5	0.53	2.5	120	20	1	15.63	128
3	35	5	0.53	2.5	180	20	1	30.00	30
4	35	5	0.53	2.5	180	20	1	32.55	43
5	70	5	0.53	2.5	180	20	1	33.33	33
6	70	10	0.53	2.5	180	20	1	53.84	13
7	70	15	0.53	2.5	180	20	1	38.64	44
8	70	20	0.53	2.5	180	20	1	21.05	19
9	105	5	0.53	2.5	180	20	1	41.03	39
10	105	10	0.53	2.5	180	20	1	67.60	463
11	105	15	0.53	2.5	180	20	1	23.71	135
12	105	20	0.53	2.5	180	20	1	55.44	36
13	140	5	0.53	2.5	180	20	1	24.67	227
14	140	10	0.53	2.5	180	20	1	20.10	184
15	105	10	0.53	2.5	180	20	1	62.79	868
16	140	15	0.53	2.5	180	20	1	25.00	144
17	140	20	0.53	2.5	180	20	1	17.79	118
18	140	15	0.53	2.5	180	20	1	38.23	204
19	140	20	0.53	2.5	180	20	1	14.76	61
20	140	5	0.53	2.5	180	20	1	41.21	199
21	140	10	0.53	2.5	180	20	1	67.74	155

In the following two tables, the particle size distribution for each galena-ore run is given (Table 4.), and the metal content found in each size range for each run (Table 5.)

Table 4. Analysis of Particle Size Results (Galena - Bonneterre Formation)

DOE RUN LEAD ORE (CRITICAL PARAMETERS AND OUTCOMES)							
Test number	**Mass of material (gr)**	**Sieve No**	**Sieve size (µm)**	**Weight retained (gr)**	**Weight % retained**	**Weight fraction retained (gr)**	**Cumulative undersize (gr)**
1 *	42	**50**	300	23	54.76	23	19
		100	149	4	9.52	27	15
		200	74	6	14.29	33	9
		-200	-74	9	21.43	42	0
2 *	128	**50**	300	95	74.22	95	33
		100	149	13	10.16	108	20
		200	74	7	5.47	115	13
		-200	-74	13	10.16	128	0
3 *	30	**50**	300	18	60.00	18	12
		100	149	3	10.00	21	9
		200	74	3	10.00	24	6
		-200	-74	6	20.00	30	0
4 *	43	**50**	300	24	55.81	24	19
		100	149	5	11.63	29	14
		200	74	6	13.95	35	8
		-200	-74	8	18.60	43	0
5 *	33	**50**	300	18	54.55	18	15
		100	149	4	12.12	22	11
		200	74	3	9.09	25	8
		-200	-74	8	24.24	33	0
6 *	13	**50**	300	5	38.46	5	8
		100	149	1	7.69	6	7
		200	74	1	7.69	7	6
		-200	-74	6	46.15	13	0
7 *	44	**50**	300	20	45.45	20	24
		100	149	7	15.91	27	17
		200	74	7	15.91	34	10
		-200	-74	10	22.73	44	0
8 *	19	**50**	300	14	73.68	14	5
		100	149	1	5.26	15	4
		200	74	1	5.26	16	3
		-200	-74	3	15.79	19	0
9 *	39	**50**	300	20	51.28	20	19
		100	149	3	7.69	23	16
		200	74	5	12.82	28	11
		-200	-74	11	28.21	39	0

Table 4. Analysis of Particle Size Results (Galena - Bonneterre Formation) (cont.)

DOE RUN LEAD ORE (CRITICAL PARAMETERS AND OUTCOMES)							
Test number	**Mass of material (gr)**	**Sieve No**	**Sieve size (µm)**	**Weight retained (gr)**	**Weight % retained**	**Weight fraction retained (gr)**	**Cumulative undersize (gr)**
10 **	463	**50**	300	97	20.95	97	366
		100	149	53	11.45	150	313
		200	74	66	14.25	216	247
		-200	-74	247	53.35	463	0
11 *	135	**50**	300	86	63.70	86	49
		100	149	17	12.59	103	32
		200	74	23	17.04	126	9
		-200	-74	9	6.67	135	0
12 *	36	**50**	300	14	38.89	14	22
		100	149	2	5.56	16	20
		200	74	4	11.11	20	16
		-200	-74	16	44.44	36	0
13 *	227	**50**	300	162	71.37	162	65
		100	149	9	3.96	171	56
		200	74	16	7.05	187	40
		-200	-74	40	17.62	227	0
14 *	184	**50**	300	138	75.00	138	46
		100	149	9	4.89	147	37
		200	74	10	5.43	157	27
		-200	-74	27	14.67	184	0
15 **	868	**50**	300	234	26.96	234	634
		100	149	89	10.25	323	545
		200	74	99	11.41	422	446
		-200	-74	446	51.38	868	0
16 *	144	**50**	300	101	70.14	101	43
		100	149	7	4.86	108	36
		200	74	13	9.03	121	23
		-200	-74	23	15.97	144	0
17 *	118	**50**	300	93	78.81	93	25
		100	149	4	3.39	97	21
		200	74	6	5.08	103	15
		-200	-74	15	12.71	118	0
18 *	204	**50**	300	114	55.88	114	90
		100	149	12	5.88	126	78
		200	74	19	9.31	145	59
		-200	-74	59	28.92	204	0

Table 4. Analysis of Particle Size Results (Galena - Bonneterre Formation) (cont.)

DOE RUN LEAD ORE (CRITICAL PARAMETERS AND OUTCOMES)							
Test number	**Mass of material (gr)**	**Sieve No**	**Sieve size (µm)**	**Weight retained (gr)**	**Weight % retained**	**Weight fraction retained (gr)**	**Cumulative undersize (gr)**
19 *	61	**50**	300	48	78.69	48	13
		100	149	4	6.56	52	9
		200	74	5	8.20	57	4
		-200	-74	4	6.56	61	0
20 *	199	**50**	300	103	51.76	103	96
		100	149	14	7.04	117	82
		200	74	24	12.06	141	58
		-200	-74	58	29.15	199	0
21 *	155	**50**	300	45	29.03	45	110
		100	149	5	3.23	50	105
		200	74	7	4.52	57	98
		-200	-74	98	63.23	155	0

The asterisks in Table 4. refer to a visual assessment that was made on the relative amount of galena found in each sample. A single asterisk (*) refers to a lean sample while a double asterisk (**) was judged to be a rich one. The presumption is the evaluation was that the pressure of the jet was sufficient to break down the galena preferentially into smaller fragments, which will, in consequence, be clean of gangue. A subsidiary result is that that rich samples will also produce relatively more product. The Garcia Joo thesis contains plots of each size distribution. Referring to Table 5., it should be noted that the laboratory reported only values for metal, therefore the ore mineral amounts were calculated based on molecular weights for the ore versus its metal and the dolomite content was found by the difference in the mass balance.

This result also highlights one of the debatable issues in the evolution of this new technology. There are two ways to mine the ore by waterjet, one being to set the cutting parameters so that individual grains are removed, without further comminution. The second is to use the power of the jet to reduce the size of the softer component, making it easier to liberate from the surrounding waste, while concurrently providing the jet with sufficient pressure to ensure that a clear path is cut into the rock, so that the mining tool can continue to move forward on successive passes, following the vein into the face.

When the project began it was anticipated that the method of attack would use the first concept, however it has become clear, that for this rock, and under these conditions, the second approach will be a more effective one.

Table 5. Laboratory Analysis Results for Galena

DOE RUN LEAD ORE (MINERALOGICAL ANALYSIS)											
Test number	**Sieve No**	**Percentage of each component (%)**					**Weight of each component (gr)**				
		Dolomite	**PbS**	**ZnS**	**Cu_2S**	**FeS_2**	**Dolomite**	**PbS**	**ZnS**	**Cu_2S**	**FeS_2**
1 *	**50**	37.00	59.68	0.22	0.02	3.07	20.26	32.68	0.12	0.01	1.68
	100	30.00	65.16	1.45	0.02	3.38	2.86	6.21	0.14	0.00	0.32
	200	50.74	45.10	1.15	0.00	3.01	7.25	6.44	0.16	0.00	0.43
	-200	65.88	28.39	2.49	0.04	3.20	14.12	6.08	0.53	0.01	0.69
2 *	**50**	12.46	83.25	0.27	0.00	4.02	9.25	61.79	0.20	0.00	2.98
	100	16.32	80.20	0.30	0.00	3.18	1.66	8.15	0.03	0.00	0.32
	200	24.63	72.09	0.36	0.00	2.92	1.35	3.94	0.02	0.00	0.16
	-200	67.07	27.48	1.04	0.04	4.36	6.81	2.79	0.11	0.00	0.44
3 *	**50**	83.69	12.47	1.04	0.04	2.75	50.22	7.48	0.63	0.02	1.65
	100	74.62	19.66	0.15	0.00	5.57	7.46	1.97	0.01	0.00	0.56
	200	73.32	20.51	0.69	0.06	5.48	7.33	2.05	0.07	0.01	0.55
	-200	77.48	16.66	0.75	0.06	5.05	15.50	3.33	0.15	0.01	1.01
4 *	**50**	31.12	64.44	0.16	0.00	4.28	17.37	35.97	0.09	0.00	2.39
	100	25.73	69.36	0.28	0.00	4.62	2.99	8.07	0.03	0.00	0.54
	200	35.64	60.04	0.28	0.00	4.04	4.97	8.38	0.04	0.00	0.56
	-200	61.87	31.43	0.55	0.02	6.13	11.51	5.85	0.10	0.00	1.14
5 *	**50**	88.96	7.49	0.04	0.00	3.50	48.52	4.09	0.02	0.00	1.91
	100	73.92	19.64	0.30	0.00	6.15	8.96	2.38	0.04	0.00	0.75
	200	70.62	22.87	0.55	0.02	5.96	6.42	2.08	0.05	0.00	0.54
	-200	75.70	18.24	1.45	0.02	4.60	18.35	4.42	0.35	0.00	1.12
6 *	**50**	92.04	5.11	0.31	0.04	2.49	35.40	1.97	0.12	0.02	0.96
	100	81.44	10.13	3.87	0.04	4.52	6.26	0.78	0.30	0.00	0.35
	200	80.44	12.39	2.07	0.02	5.10	6.19	0.95	0.16	0.00	0.39
	-200	81.34	11.34	1.88	0.04	5.40	37.54	5.24	0.87	0.02	2.49
7 *	**50**	96.50	1.10	0.06	0.00	2.34	43.86	0.50	0.03	0.00	1.07
	100	91.02	4.56	0.66	0.00	3.76	14.48	0.73	0.10	0.00	0.60
	200	85.90	10.05	0.51	0.00	3.55	13.67	1.60	0.08	0.00	0.56
	-200	89.38	6.94	0.49	0.00	3.18	20.31	1.58	0.11	0.00	0.72
8 *	**50**	89.35	0.84	0.09	0.00	9.72	65.84	0.62	0.07	0.00	7.16
	100	78.50	9.80	2.99	0.02	8.69	4.13	0.52	0.16	0.00	0.46
	200	73.48	18.63	2.91	0.04	4.99	3.87	0.98	0.15	0.00	0.26
	-200	92.17	4.83	0.52	0.02	2.45	14.55	0.76	0.08	0.00	0.39
9 *	**50**	97.34	0.18	0.03	0.00	2.45	49.92	0.09	0.02	0.00	1.26
	100	89.55	2.42	0.63	0.00	7.40	6.89	0.19	0.05	0.00	0.57
	200	90.70	3.59	0.66	0.00	5.05	11.63	0.46	0.08	0.00	0.65
	-200	92.44	3.04	0.57	0.00	3.96	26.07	0.86	0.16	0.00	1.12

Table 5. Laboratory Analysis Results for Galena (cont.)

DOE RUN LEAD ORE (MINERALOGICAL ANALYSIS)											
Test number	Sieve No	Percentage of each component (%)					Weight of each component (gr)				
		Dolomite	PbS	ZnS	Cu_2S	FeS_2	Dolomite	PbS	ZnS	Cu_2S	FeS_2
10 **	50	47.78	31.48	19.74	0.06	1.00	26.27	40.00	28.53	0.12	2.09
	100	44.03	28.54	26.59	0.04	0.84	11.19	19.82	21.00	0.04	0.96
	200	42.65	28.51	28.20	0.02	0.64	12.68	24.65	27.73	0.03	0.91
	-200	43.61	34.81	20.96	0.02	0.62	53.93	112.63	77.14	0.00	3.29
11 *	50	90.65	7.97	0.31	0.07	1.00	74.65	8.98	0.40	0.12	1.85
	100	85.22	12.00	1.52	0.07	1.19	13.48	2.67	0.39	0.02	0.43
	200	83.92	13.72	1.10	0.07	1.19	17.87	4.13	0.38	0.03	0.59
	-200	91.09	6.50	0.70	0.05	1.66	7.81	0.77	0.09	0.01	0.32
12 *	50	96.89	1.62	0.22	0.01	1.26	13.27	0.30	0.05	0.00	0.38
	100	92.80	4.07	1.54	0.02	1.57	1.78	0.11	0.05	0.00	0.07
	200	90.79	5.93	1.73	0.02	1.53	3.45	0.31	0.10	0.00	0.13
	-200	87.51	9.38	1.34	0.04	1.73	13.11	1.97	0.32	0.01	0.60
13 *	50	98.91	0.11	0.02	<.01	0.96	158.37	0.23	0.05	0.00	3.34
	100	98.02	0.56	0.22	0.03	1.17	8.67	0.07	0.03	0.01	0.23
	200	97.77	0.81	0.25	0.03	1.14	15.37	0.17	0.06	0.01	0.39
	-200	96.93	1.42	0.31	0.01	1.33	37.92	0.74	0.18	0.01	1.14
14 *	50	98.98	0.03	<.01	<.01	0.99	135.01	0.05	0.00	0.00	2.94
	100	97.35	0.42	0.16	<.01	2.07	8.53	0.05	0.02	0.00	0.40
	200	97.23	0.71	0.16	0.01	1.89	9.47	0.09	0.02	0.00	0.41
	-200	97.15	0.73	0.20	0.02	1.90	25.55	0.26	0.08	0.01	1.10
15 **	50	43.93	42.74	12.56	0.12	0.65	55.36	131.02	43.79	0.56	3.27
	100	32.52	44.27	22.73	0.03	0.45	6.33	51.61	30.14	0.05	0.86
	200	32.28	49.57	17.80	0.02	0.33	7.71	64.29	26.26	0.04	0.70
	-200	26.70	61.24	11.73	0.01	0.32	7.09	357.80	77.95	0.09	3.07
16 *	50	98.73	0.28	0.07	<.01	0.92	98.53	0.37	0.11	0.00	2.00
	100	94.14	2.89	1.13	<.01	1.84	6.34	0.27	0.12	0.00	0.28
	200	91.91	4.75	1.04	0.01	2.29	11.35	0.81	0.20	0.00	0.64
	-200	87.25	9.41	0.98	0.02	2.34	18.66	2.84	0.34	0.01	1.16
17 *	50	99.14	0.11	0.02	<.01	0.73	91.38	0.13	0.03	0.00	1.46
	100	96.86	1.36	0.39	<.01	1.39	3.79	0.07	0.02	0.00	0.12
	200	96.65	1.40	0.30	<.01	1.65	5.65	0.11	0.03	0.00	0.21
	-200	95.96	1.46	0.35	0.01	2.22	13.92	0.29	0.08	0.00	0.72
18 *	50	99.11	0.07	0.02	<.01	0.80	111.90	0.10	0.03	0.00	1.96
	100	98.65	0.27	0.18	<.01	0.90	11.69	0.04	0.03	0.00	0.23
	200	99.01	0.10	0.05	<.01	0.84	18.62	0.02	0.01	0.00	0.34
	-200	98.11	0.61	0.13	<.01	1.15	56.96	0.47	0.11	0.00	1.46

Table 5. Laboratory Analysis Results for Galena (cont.)

DOE RUN LEAD ORE (MINERALOGICAL ANALYSIS)											
Test number	**Sieve No**	**Percentage of each component (%)**					**Weight of each component (gr)**				
		Dolomite	**PbS**	**ZnS**	**Cu_2S**	**FeS_2**	**Dolomite**	**PbS**	**ZnS**	**Cu_2S**	**FeS_2**
19 *	**50**	99.23	0.02	<.01	<.01	0.75	47.21	0.01	0.00	0.00	0.77
	100	97.73	0.66	0.28	<.01	1.33	3.83	0.03	0.02	0.00	0.11
	200	98.07	0.38	0.16	<.01	1.39	4.81	0.02	0.01	0.00	0.15
	-200	90.48	6.24	1.40	0.02	1.86	3.43	0.33	0.08	0.00	0.16
20 *	**50**	97.90	1.00	0.02	0.02	1.06	99.23	1.35	0.03	0.04	2.35
	100	96.54	1.94	0.05	<.01	1.47	13.19	0.36	0.01	0.00	0.44
	200	97.42	1.08	0.10	<.01	1.40	22.90	0.34	0.04	0.00	0.72
	-200	94.75	3.43	0.09	<.01	1.73	53.16	2.61	0.08	0.00	2.16
21 *	**50**	99.02	0.09	0.04	<.01	0.85	44.10	0.05	0.03	0.00	0.82
	100	96.82	1.65	0.07	<.01	1.46	4.73	0.11	0.01	0.00	0.16
	200	97.82	0.81	0.18	<.01	1.19	6.73	0.07	0.02	0.00	0.18
	-200	95.96	2.20	0.42	0.01	1.41	91.57	2.82	0.61	0.02	2.97

Optical Observations of the Particles generated by Waterjet-Mining

One of the final observational steps was to examine the comminuted product under an optical microscope. While it was reassuring to see that ore minerals and waste gangue appeared to exist in separate and discrete particles, implying a potentially high separation efficiency, it was clear that many more observations of this type will be needed to give significance to the observation. Figure 10. is a picture of coarse debris taken from a 4-mesh screen and Figure 11. is a picture of minus-100 mesh material. In each case, discrete particles of galena can be seen.

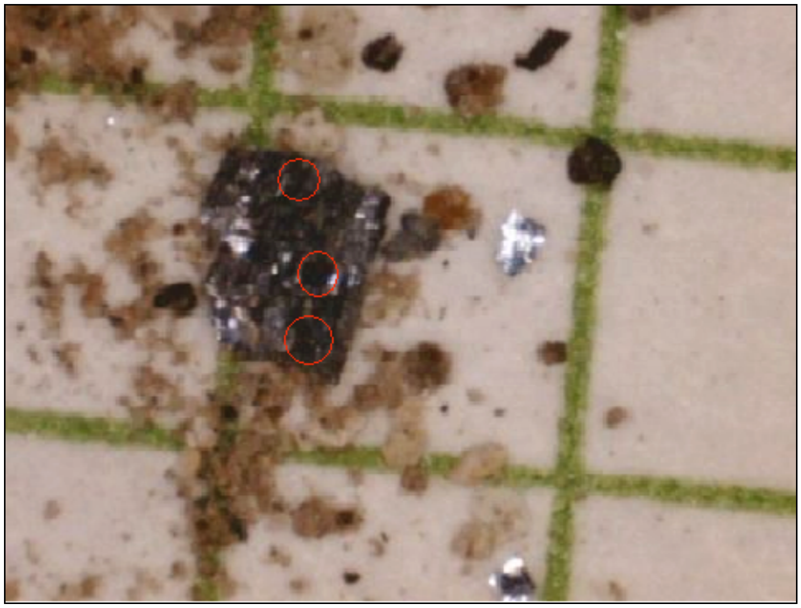

Figure 10. Recovered Particles greater than 4760 microns, showing Individual Liberation; the Square is 2.5 mm across. Circles identify grains that are potentially waste on the galena particle.

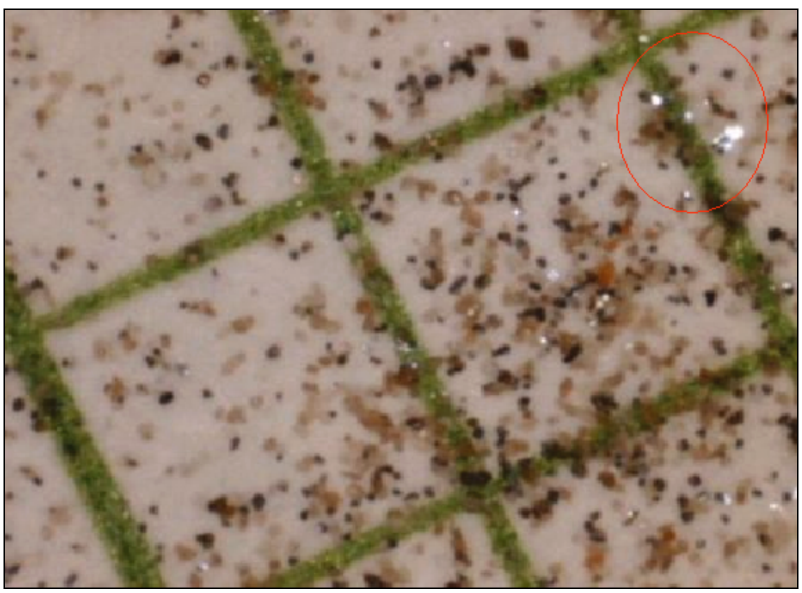

Figure 11. Recovered Particles less than 147 microns and greater than 74 microns, showing Individual Liberation; the Square is 2.5 mm across. The circle illustratively locates some of the particles that appear to be wholly galena.

Secondary crushing and separation – the use of cavitation

The fragmentation of rock by waterjet, as described above, occurs through the penetration of a jet into a fracture in the rock, and then the pressurization of that water. It thereby fails the rock in tension. As particle sizes get smaller the need for larger jets, and longer exposure times becomes less. Earlier studies at UMR have shown that the deliberate induction of cavitation into a jet flow can also induce rock failure at lower than conventional pressures. If the cavitation is "enhanced" by a change in the cavitation number, most easily achieved by raising the chamber back pressure to a value of around 0.01, then the rock fragmentation effect is further enhanced.

One of the significant problems in particle comminution is to ensure that the particle in question is exposed to the comminution process. Studies of autogenous grinders have shown that for much of the time the particle is not subject to comminution impact, thereby reducing the efficiency of the mill. However, when the particle is passed through the cavitation cloud generated around a jet flow, the density of collapsing bubbles is high, and the propensity of these bubbles to attach to, and then collapse on, any existing surface further ensures that each particle is subject to multiple impacts on an almost continuous basis. The process works more efficiently with smaller particles given that although the cavitation jets can induce impact pressures of up to 10,000 MPa, their very small size makes the duration of the pulse every short. Thus the cavitation process works more efficiently in secondary comminution than it would as the primary crushing agent for the ore.

On the basis of this earlier research at UMR a special cavitation test cell, given the acronym WASP, was constructed (Figure 12) and used to evaluate and demonstrate the effectiveness of "pressurized" cavitation for secondary comminution. One of the early demonstrated advantages of this approach was the significant reduction in size that could be achieved with this new tool. Because the power of the cell lies in the jet produced, which issues through an orifice that is less than 2 mm in diameter, a cell using some 100 kW of power will measure no more than 10 cm in diameter and be some 15 cm long.

In the initial evaluation of the concept, a mix of sample particles each measuring roughly 1.25 cm in diameter, were placed in a sleeve that would hold them within the jet path. (In subsequent designs the flow through the sleeve will be continuous – this was an illustrative batch process test series). A 100-mesh screen over the open end of the sleeve retained the particles in position. The sleeve was then fitted over the jet nozzle, itself held centrally within the end plate of the cell. Sample sizes were approximately 20 grams each. The operation can be described with reference to Figure 12.

The sleeve, or sample holder, is held inside of the tank immediately in front of the waterjet, which is identified by the letter d. Because the tank, basically a Plexiglas cylinder with a centrally mounted sample holder, is a sealed unit, each experimental repetition was run as an individual test. Pressures used in the jet ranged from 21 MPa (3000 psi) to 35 MPa (5000 psi). At these lower pressures, a smaller Hammelmann pump was used rather than the Freemeier. Once the jet had reached operating pressure, and the cell was filled with water, the exhaust valve for the cylinder was slowly closed until the desired chamber pressure was reached. At this point the comminuted product was leaving the sleeve, through the screen, as a fine cloud of particles (Figure 13). The test was continued until the cloud was no longer being formed at which time the sleeve was found to be empty, after the apparatus had been disassembled. The time of the test was varied to establish over what interval of time all the rock had been reduced.

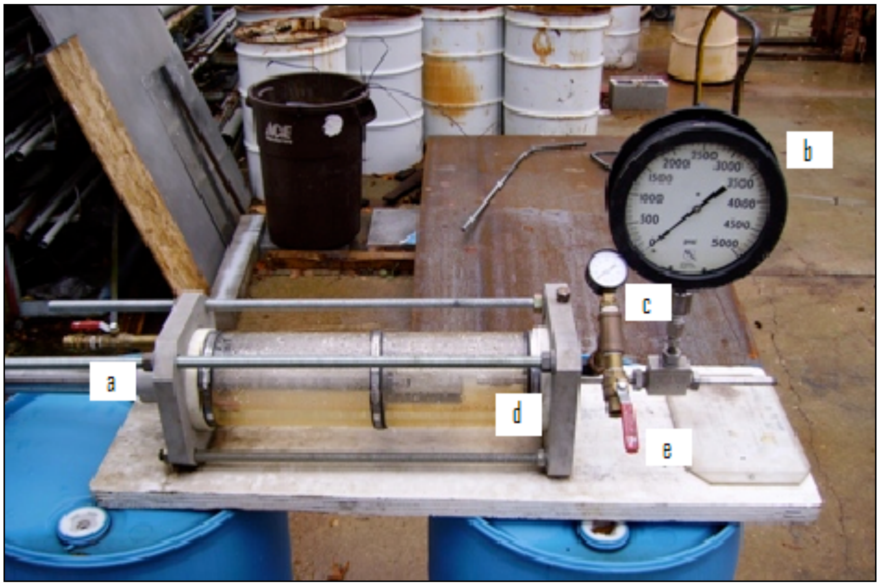

Figure 12. Cavitation Chamber used in the Series of Experiments (a. Back Pressure Valve, b. Waterjet Pressure Gauge, c. Back Pressure Gauge, d. Jet, e. Emergency Valve)

Tables 6, 7, and 8 present the results of a series of cavitation tests on Jefferson City Dolomite. Each of these three tables contains only one set of operating conditions but with a variation in the duration of the test.

Table 6. Experimental Parameters and Outcomes for the Jefferson City Dolomite applying the Cavitation Concept (WP = 21 MPa, BP = 0.40 MPa)

CAVITATION TESTS (JEFFERSON CITY DOLOMITE)									
Test Number	**Jet Pressure (MPa)**	**Back Pressure (MPa)**	**Weight of sample (gr)**	**Time (minutes)**	**Size of material used**	**Weight of debris not passing 100 Mesh**	**Weight of debris passing 100 Mesh**	**% not passing the 100 Mesh (-147 um)**	**% passing the 100 Mesh (-147 um)**
1	21	0.40	20	1	+4760 um	6	14	30	70
2	21	0.40	20	2	+4760 um	1	19	< 5	95
3	21	0.40	20	3	+4760 um	1	19	5	95
4	21	0.40	20	4	+4760 um	< 1	19	< 5	95
5	21	0.40	20	5	+4760 um	1	19	5	95
6	21	0.40	20	6	+4760 um	< 1	19	< 5	95

Table 7. Experimental Parameters and Outcomes for the Jefferson City Dolomite applying the Cavitation Concept (WP = 28 MPa, BP = 0.55 MPa)

CAVITATION TESTS (JEFFERSON CITY DOLOMITE)									
Test Number	**Jet Pressure (MPa)**	**Back Pressure (MPa)**	**Weight of sample (gr)**	**Time (minutes)**	**Size of material used**	**Weight of debris not passing 100 Mesh**	**Weight of debris passing 100 Mesh**	**% not passing the 100 Mesh (-147 um)**	**% passing the 100 Mesh (-147 um)**
1	28	0.55	20	1	+4760 um	7	13	35	65
2	28	0.55	20	2	+4760 um	1	19	5	95
3	28	0.55	20	3	+4760 um	1	19	5	95
4	28	0.55	20	4	+4760 um	1	19	5	95

Table 8. Experimental Parameters and Outcomes for the Jefferson City Dolomite applying the Cavitation Concept (WP = 35 MPa, BP = 0.70 MPa)

CAVITATION TESTS (JEFFERSON CITY DOLOMITE)									
Test Number	**Jet Pressure (MPa)**	**Back Pressure (MPa)**	**Weight of sample (gr)**	**Time (minutes)**	**Size of material used**	**Weight of debris not passing 100 Mesh**	**Weight of debris passing 100 Mesh**	**% not passing the 100 Mesh (-147 um)**	**% passing the 100 Mesh (-147 um)**
1	35	0.70	20	1	+4760 um	4	16	30	70
2	35	0.70	20	2	+4760 um	0	20	0	100
3	35	0.70	20	3	+4760 um	< 1	19	< 5	95

In all three cases, just over a minute of test duration was all that was needed to reduce the input material to less than 100 mesh (147 microns). This was shorter than originally anticipated (which is why some of the tests took longer than necessary). It should be noted that the only screening was the restrictive one to hold particles in the WASP. Other studies with different materials indicate that where a natural particle size is dominant the particles will crush to this size, where that is not the case (such as with coal) the end product particle size can be in the 5 μm range.

The final sequence of experiments in the initial series was made with Bonneterre Formation lead ore. In four runs, the jet pressure was varied from 21 to 35 MPa (3000 to 5000 psi) and the back pressure was varied from 0.40 to 0.83 MPa (60 to 120 psi). Table 9. presents the data from this sequence of tests.

Table 9. Experimental Parameters and Outcomes for the Galena (Bonneterre Formation) applying the Cavitation Concept

CAVITATION TESTS (DOE RUN LEAD ORE)									
Test Number	**Jet Pressure (MPa)**	**Back Pressure (MPa)**	**Weight of sample (gr)**	**Time (minutes)**	**Size of material used**	**Weight of debris not passing 100 Mesh**	**Weight of debris passing 100 Mesh**	**% not passing the 100 Mesh (-147 um)**	**% passing the 100 Mesh (-147 um)**
1	21	0.40	20	5	+4760 um	6	14	30	70
2	35	0.70	20	3	+4760 um	1	19	< 5	95
3	35	0.75	20	3	+4760 um	6	14	30	70
4	35	0.83	20	3	+4760 um	8	12	40	60

Figure 13 shows one of the dolomite runs and the cloud of minus 100 mesh material can be seen streaming from the sample holder. A tray of input material is seen also.

Figure 13. Chips of Dolomite being disintegrated by Cavitation: Feed is shown on Right and Fine Cloud in Center is the Product.

Mining Machine design

The process required to liberate the particles of ore from the solid has been shown to require the movement of a high-pressure waterjet over the surface at a relatively high speed. To balance the reaction forces exerted on the support, this tool should contain at least two balanced jets. While these can be inclined to provide the motive force required to induce rotation about a bearing, this was not found to be a useful feature for a mining head. For, although it allows for a simpler design, self-drive systems have limited capacity for speed control, and have little force to overcome any transient blockage of the nozzle path. For these reasons a motor should be included in the cutting head design (hollow core motors are available for this purpose from, for example, Kollmorgen). By locating the motor around the high pressure line, with a rotary coupling mounted just above the motor mount, it is possible to create a very small footprint for the head.

One additional feature is required to make the system operative, and that is a means to extract the product as it is mined, including both the water and all the mineral. This is a little more complex than might at first appear, given that the jets are traveling at around 300 m/sec as they leave the nozzle. Experience in the cleaning industry has, however shown that such tools can effectively contain such jets, and when married to a vacuum extraction system, can collect all the debris from a high-pressure jet traverse.

UMR has previous experience in developing such a tool for an application that has some similarities to that of the current need. The Department of Energy needed a device that could be fitted on the end of a remotely operated arm (similar to that used by the Space Shuttle) and which could then be lowered into a tank containing high-level radioactive waste. The need was to have a device that could mine around 4 cu.ft/min of this waste (which had a strength of up to 70 MPa) and evacuate it, and all the water used in mining, out of a tank that could be some 20 m below the ground. The HPWL team developed such a design (Figure 14) and validated the performance in a clean above-ground program, before transferring the design to a commercial vendor.

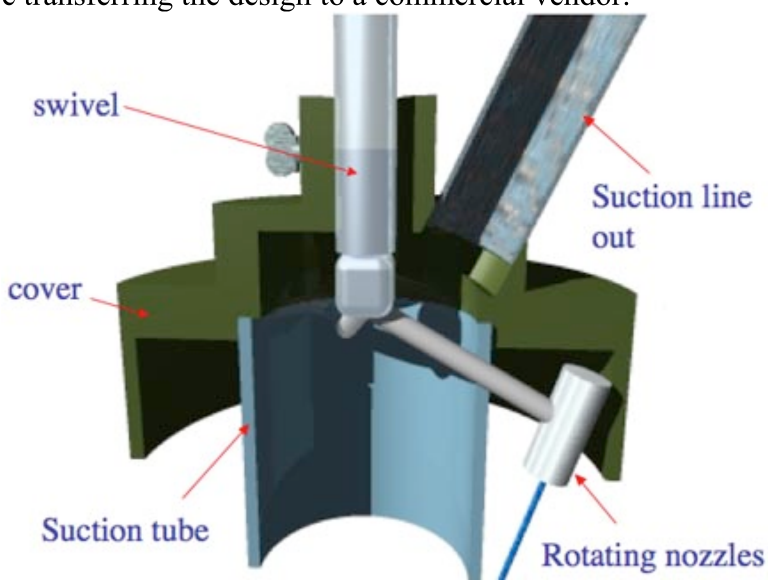

Figure 14. Representation of the Confined Sluicing End Effector developed by UMR for PNNL.

This vendor built the tool that was successfully used to remove the high-level waste from eight underground storage tanks at Oak Ridge National Laboratory. The evacuation of waste was achieved by the development of a small high-pressure jet pump (> 5 cm in diameter, 0.5 m long) that proved capable of collecting the product and delivering it up over the required height.

In an alternate embodiment of this concept (that of waterjet mining and concomitant vacuum waste removal) a tool has been developed for the rapid, gentle removal of soil from above landmines. It has also been successfully demonstrated. The commercial application of high pressure waterjets with vacuum removal of material has also become useful in the excavation of civil engineering sites. This new technology, which is now becoming known under the generic title of "Hydro-excavation" is capable of disaggregating soil down to depths of 40 m in such a gentle and discriminatory manner that it can mine around fiber-optic cables, ceramic sewer pipes, and unexploded bombs, without inducing any damage or reaction.

Thus it can be anticipated that a mining machine, of the type required (Figure 15), will contain a number of remotely controlled cutting arms, each with its own drive motor. These will be controlled to move over a given path removing ore from the surface, and feeding it back, through a small secondary comminution cell, to ensure that all the material is reduced to constituent particle size, before sending it to a processing section.

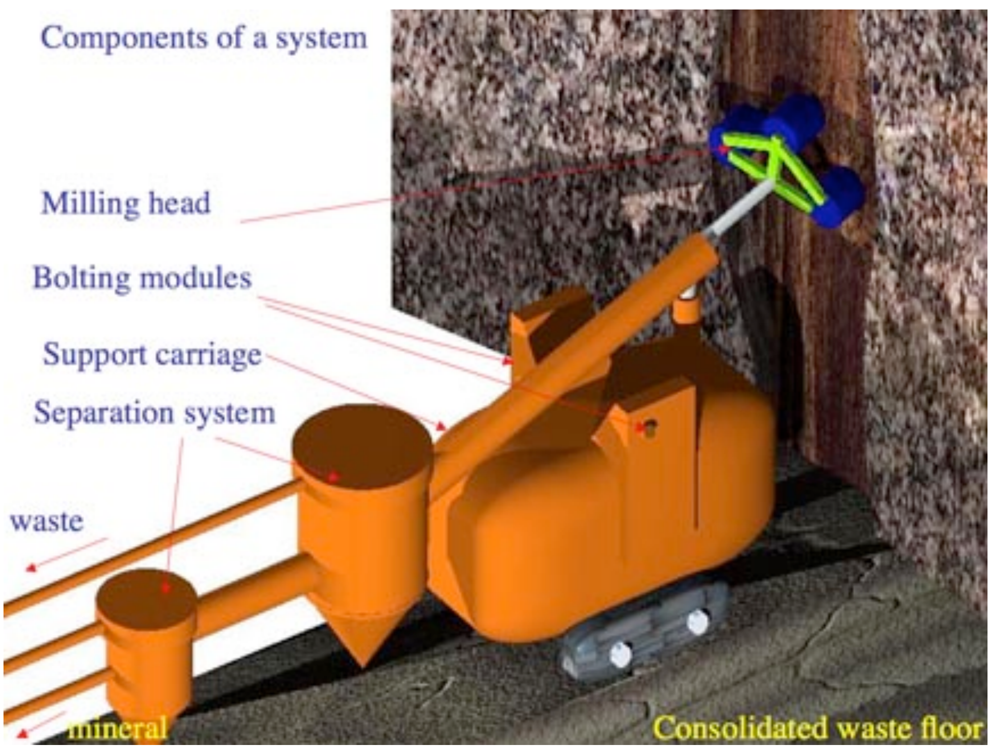

Figure 15. Representational model of a possible mining machine configuration.

It will largely depend on the type of host and valuable mineral content which separation system would then be most effective for pay recovery. In the case where the particles have separated into two distinct size ranges (for example the sand and hematite) then adequate separation and pay recovery may be achieved through simple screening separation. In other work we have found that sand:galena can also be separated in this way. For the more common situation, however, where the ore is a complex mixture, and separation by particle size is impractical, then a simple separation system, material specific, will be required . The simplification can be achieved given that the particles will have been liberated, one mineral from another, during earlier processes.

The differences between the two types of separation might, perhaps, be illustrated through consideration of Polish copper ore. Two different samples were obtained. The first is a fine grained deposit in shale (similar in appearance to the Mahogany oil shale) where jet pressure alone does not effectively break the rock into individual particles. This was better achieved by the secondary processing through the cavitation cell (product shown in Figure 16).

Figure 16. Fragmented copper (in shale) ore, after cavitation comminution. Note the flakes (orange) of metallic copper among the liberated particles. The wire is 0.01 inches (0.2 mm) in diameter.

In contrast, where the copper was found in a granular sandstone, it was easier to disintegrate the sand into its constituent grains, with the copper particles at a much finer level (Figure 17). Note that each grain is separated from the rest.

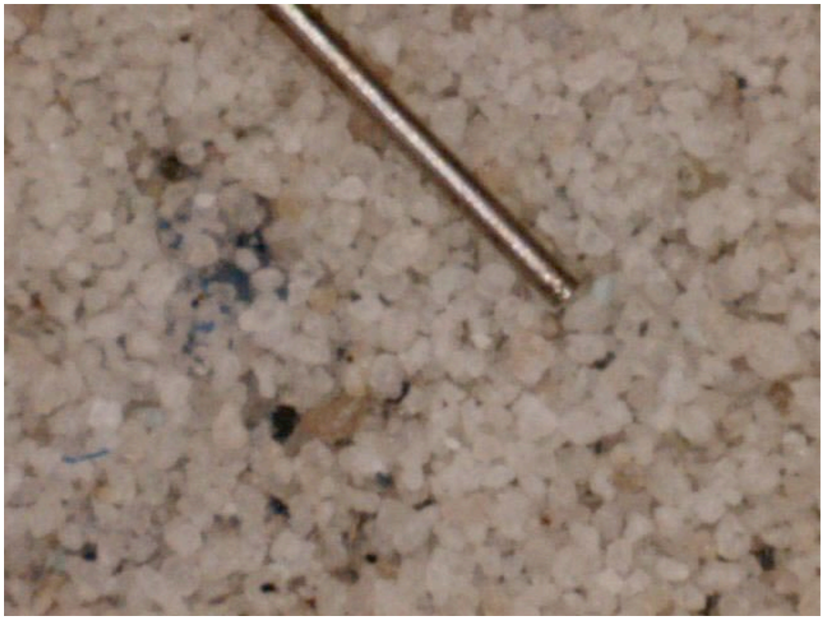

Figure 17. Copper (in sandstone) ore disintegrated. The wire is 0.01 inches (0.2 mm) in diameter.

Conclusions

The work done during this Phase I study demonstrates that it is possible to liberate, capture, and comminute mineral ores in the vicinity of an underground face using a high-pressure waterjet. Operating parameters can be set to produce a finely ground product amenable to simple mineral processing separation techniques. Cavitation processes can be employed to further reduce coarse oversize into minus 100-mesh material, which is in a size range able to be processed. The size of both systems is sufficiently small that they can be integrated into a machine that can maneuver within the restricted space of the mine volume. The potential for using this process to save large amounts of energy now expended in the current mining and milling processes is great.

In his thesis, Jorge Garcia Joo (2006) writes the following. "According to the outcomes of the regression analysis conducted for dolomite data at the significance level of 0.05 using the backwards elimination criteria, the independent variables that are significant to the model (rock cutting and disintegration) are waterjet pressure and traverse speed. The other parameters such as nozzle diameter, rotational speed, included jet angle, and traverse speed are not significant to the model at this significance level." When the significance level was moved to 0.10, all operating parameters except for nozzle diameter became significant.

Because of the high variability of lead content in the ore samples, hence of their inherent strength, a similar regression analysis for the results of the lead-ore test was less conclusive. Nonetheless, the tests show "that there is a tendency to obtain the finest debris (particles less than 147 microns) when a waterjet pressure (P) between 100 and 140 MPa is used, along with a traverse speed (T) of 10.0 cm/min and a rotational speed (R) of 180 RPM." (Garcia Joo, 2006)

It is apparent to the research team that a commercial prototype using this waterjet technology with or without an additional cavitation comminution chamber is possible. Based on the research results presented here, such a machine should be capable of varying its water pressure from 35 MPa (5,000 psi) to a high of 140 MPa (20,000 psi) and its traverse speeds from a high of 3 m/min (10 ft/min) to a low of 5 cm/min (2 in/min). These ranges will allow the machine to operate in weak rock up to medium-strong rock. If a rotating lance is used, then 180 rpm appears to be best. Other parameters such as nozzle diameter and twin-nozzle included angle do not seem to affect the outcome when they are varied and remain in the province of the machine designer.

Cavitation-based comminution is possible at relatively low waterjet and chamber (back pressure) pressures. Further experimentation will help to determine optimal conditions for comminution of any particular ore.

Projected Energy Savings

The methods of mining that have been demonstrated in a laboratory environment during this research program, are readily easily scaled to industrial operations. To illustrate the practicality of this step, consider that the use of a high-pressure spinning waterjet assembly with attached vacuum line is, for example, becoming the tool of choice for removal of paint from large ships, prior to repainting. The waterjet device used is (referring without recommending) known as a Mini-Scrubber. These devices contain an array of high-pressure nozzles (Figure 18), that are rotated at high speed to strip paint from the substrate.

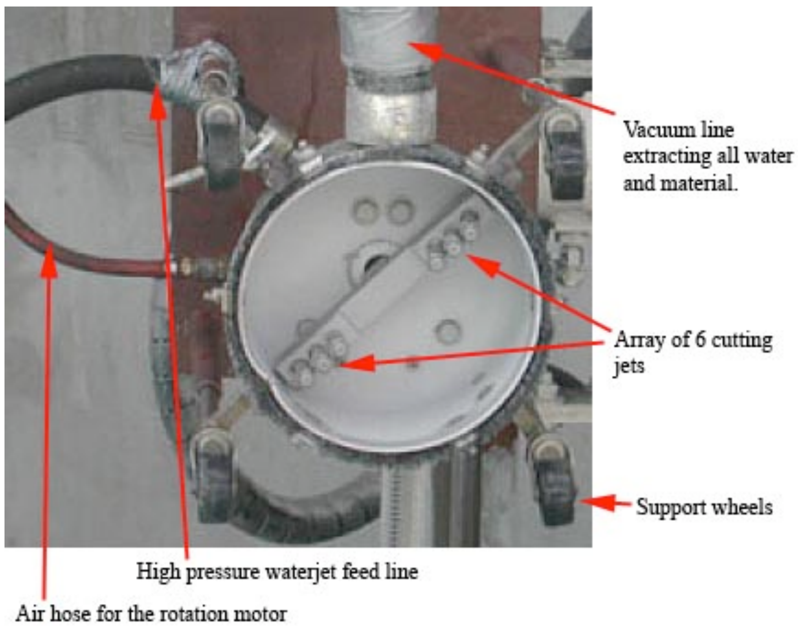

Figure 18. A six-inch diameter mini-scrubber of the type that could be used as a mining head. (Source, on Aug. 31, 2007, the web page at http://www.iuoeiettc.org/Old%20files/HFA/Mini-Scrubber.pdf).

Operating pressures for this type of system are in the 30,000 psi (210 MPa) range, and they are becoming more widely adopted. As an illustration of how this might fit into a mining operation, consider the marriage of the tool with a robotic manipulator developed while testing the head for operational safety (Figure 19). The low levels of reactive force are at levels that are easily held by hand, although controls are more effective when the tool is machine manipulated.

The understanding of energy savings with the tool are sometimes difficult to perceive, since initially when one discusses the mining rate individuals assume that what gets delivered to the shaft/preparation plant is still the valuable mineral in combination with the host rock. Thus the volumes that are reported as being produced by the machine, and transported out, seem small to an operation that is oriented to moving large volumes of rock to produce significantly lower quantities of mineral. However it is in the reduction of the overall volume to be moved, and processed, rather than in the savings during mining itself, that the technology comes to the fore.

Figure 19. A robotic tool manipulating a mini-scrubber head during evaluation. (Source, on Aug. 31, 2007, the web page at http://www.iuoeiettc.org/Old%20files/HFA/Mini-Scrubber.pdf).

If, for example, the data cited in the "Energy and Environmental Profile of the Mining Industry", is adopted for an exemplary lead mine, then the initial division of energy for that operation can be summarized as follows:

It takes, approximately 1 million Btu's to mine and beneficiate the ore in a conventional mine (this does not include the subsequent processing to a refined product, which will utilize roughly twice this amount of energy). Of this amount some 43,000 Btu/ton is required for processing. If the mining machine can separate the valuable mineral from the waste at the machine, (as demonstrated above) then neither the crushing nor flotation at the surface will be required, saving some 30,000 Btu/ton or roughly 70% of the processing cost (not to mention the capital and installation costs for the equipment).

The savings extend considerably beyond this point, since, if one examines the breakdown of energy distribution across the mining operation (Figure 20) the two biggest operational energy consumers are the ventilation and transportation sectors of the process. While it can be argued that the use of a small, mobile mining machine will allow smaller drifts to be run, and the immediate back-filling of the open, and un-used mined out voids will limit the volume of the ventilated space, thereby significantly reducing the ventilation costs of mining, the more obvious and immediate gain will be in the reduction in the haulage costs for the material that is moved from the mining face to the processing plant.

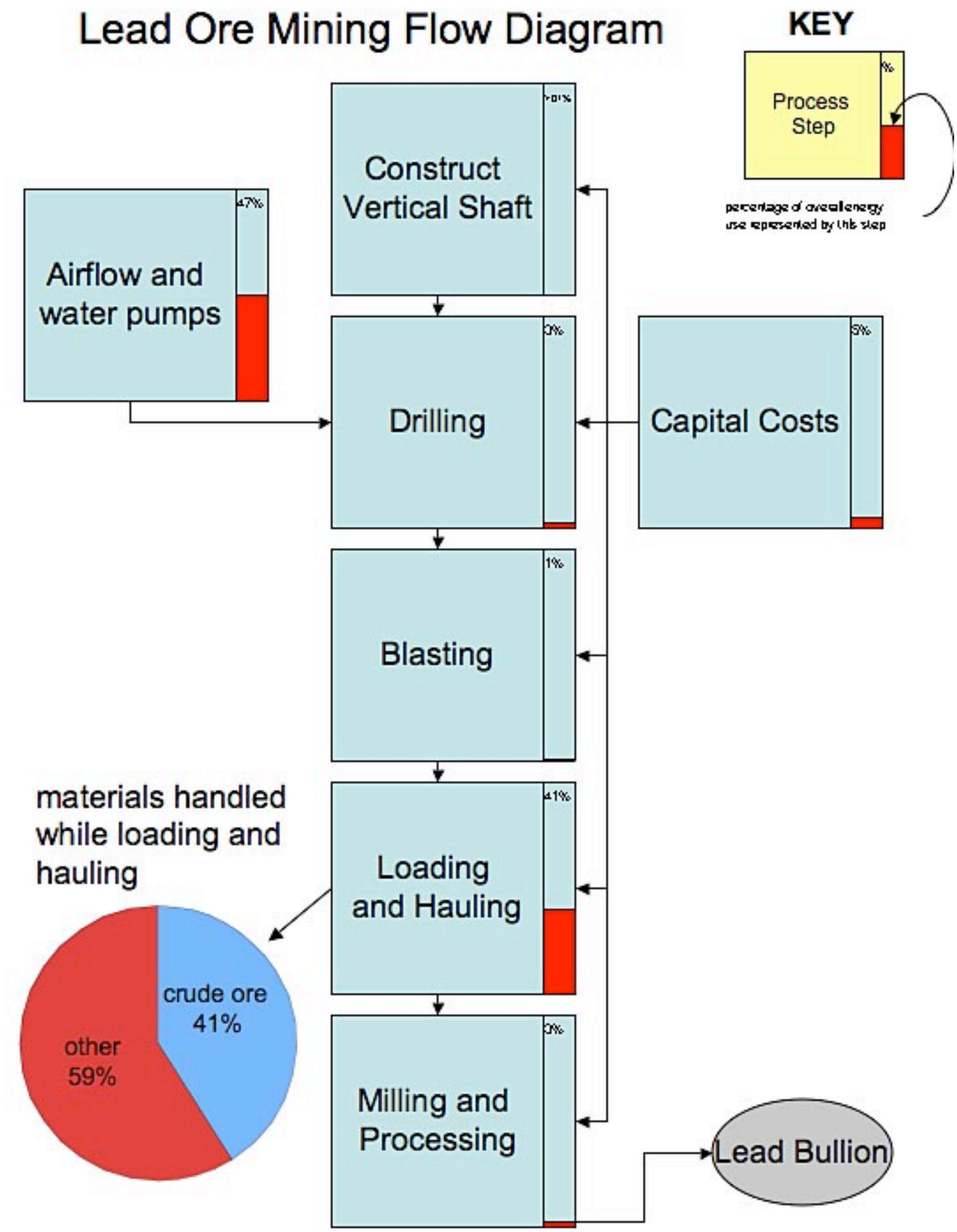

Figure 20. Energy distribution in lead mining (after information at the Web page, http://www1.eere.energy.gov/industry/mining/pdfs/lead_zinc.pdf, as it existed on August 31, 2007).

If the volume of material that must be transported is reduced to the mineral content of the ore, and this is assumed to be[1] 6%, then the volume of material that must be transported any significant distance from the mining operation (assuming immediate back-stowing of the waste) will reduce transport volumes by roughly 94%. Allowing some cost for the waste stowing (though this could be recovered in energy cost by the reduced ventilation needs), and related issues it is still likely that the transportation energy costs could be reduced by 75%. If this loading and hauling cost is assumed to be 410,000 Btu/ton currently, then this will save roughly 300,000 Btu/ton. When this is combined with the savings in reduced processing operations, then the overall reduction in energy that can be anticipated will be from 1,000,000 Btu/ton to 670,000 Btu/ton or a savings of 33% of the energy currently used in mining lead. (Note that this discounts ventilation savings, which are a significant component of current costs).

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[1] From information on the Web page http://sec.edgar-online.com/2004/07/30/0001047469-04-024877/Section10.asp, on August 31, 2007

Research Products (DOE Final Technical Report Item 6.)

In a substantial Master of Science Thesis, Jorge Gerardo Garcia Joo presented the results of the first, full year of experimentation (Garcia Joo, 2006). This may be consulted for a fuller explanation of the material presented in this report. The full analysis of results needed to support the conclusions that are given here can be found in the thesis. The thesis contains a substantial bibliography of background literature.

In addition, a short summary paper of results and conclusions was presented before the BHR 18th International Conference on Water Jets, held in Gdansk, Poland, on September 13-15, 2006 (Garcia Joo, Saperstein, and Summers, 2006). A compact disk of the proceedings is available as is a printed version.

1. Garcia Joo, Jorge Gerardo, Energy Conversation and Integrated Waterjet Mining and Milling, A Master of Science Thesis in Mining Engineering, University of Missouri-Rolla, 2006, 229p. (an electronic and a printed copy of this thesis have been given to the DOE).

2. Garcia Joo, Jorge Gerardo, Lee W. Saperstein, and David A. Summers, "Energy Conservation and Integrated Water Jet Mining and Milling," Proceedings of the 18th International Conference on Water Jetting, Gdansk, Poland, paper 42, pages 139-149, BHR Group Limited, The Fluid Engineering Centre, Cranfield, Bedfordshire, MK43 0AJ, England, September 13-15, 2006, 11p.

Rolla, Missouri
August 12, 2007