AN ABSTRACT OF THE THESIS OF

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Title: Measuring the Sustainability of a Proposed Copper Mine in Arizona: A Temporal Comparison

Abstract Approved:

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A proposed copper mine in Arizona has the potential to be the largest copper producing mine in North America. It is expected to produce over a billion pounds of copper per year, and individually produce more than half of the United State’s demand for copper. The operation claims to be more sustainable than previous operations by being more efficient with their use of water, energy and material resources. An embodied energy, or EMERGY analysis, was used to evaluate the sustainability of the proposed copper mining operation. The post-mining externalized annual energy cost of copper waste management for previous operations had an EMERGY value of 1.50E+22 solar emjoules per year (sej/yr); the proposed mine plans to internalize the cost of waste management during operation by containing and reusing waste, resulting in an estimated annual EMERGY cost of 6.00E+18 sej/yr. These results indicate that the proposed method of waste management will potentially be more sustainable than past mining operations in terms of embodied energy cost savings. A 1992 copper mine required 7.35E+23 sej/yr for annual energy resource investment; the proposed mine is estimated to require

5.85E+20 sej/yr. These results indicated that the proposed mine will use energy resources more efficiently than old copper mining operations. However, these results do not account for the impacts of subsidence on water and land resources, nor do they account for other potential impacts of deep mining extraction that may occur as a result of the proposed mining operation. Further analysis will be necessary to evaluate these impacts.

Measuring the Sustainability of a Proposed Copper Mine in Arizona: A Temporal Comparison

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

John B. Handy, Author

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LIST OF ABBREVIATIONS

RC – Resolution Copper

LCA – Life Cycle Assessment

Sej – solar emjoule

J – Joule

EPS – East Plant Site

WPS – West Plant Site

TSF – Tailings Storage Facility

FPLF – Filter Plant and Loadout Facility

UEV – Unit Emergy Value

CWG – Citizens Working Group

CAP – Central Arizona Canal

PCD – Porphyry Copper Deposit

Mt – One million tonnes (10^9 kg)

LHD – Load, Haul and Dump

NPAG – Not Potentially Acid Generating

PAG – Potentially Acid Generating

gpm – gallons per minute

MARRCO – Magma Arizona Railroad Company

SRP – Salt River Project

AMD – Acid Mine Drainage

FWPCA – Federal Water Pollution Control Act

CWA – Clean Water Act

LIST OF ABBREVIATIONS (continued)

EPA – Environmental Protection Agency

NEPA – National Environmental Protection Agency

CEQ – Council on Environmental Quality

SWDA – Solid Waste Disposal Act

RRA – Resource Recovery Act

RCRA – Resource Conservation and Recovery Act

TSCA – Toxic Substances Control Act

FHSWA – Federal Hazardous and Solid Waste Amendment

SMCRA – Surface Mining Control and Reclamation Act

CERCLA – Comprehensive Environmental Response, Compensation, and Liability Act

SARA – Superfund Amendments and Reauthorization Act

ICMM – International Council of Mining and Metals

MMSD – Mining and Minerals Sustainable Development

WBCSD – World Business Council for Sustainable Development

ADWR – Arizona Department of Water Resources

GNP – Gross National Product

MPO – Mine Plan of Operations

SME – Surface Mining Engineering Handbook, Vol. 1-2, 1992

Dedicated to those seeking fulfillment and a meaningful existence

and to all those who have successfully concluded their search.

DISCLAIMER: Data and results were not intended to be used for decision-making. Calculations were based on the best available information and the author does not claim responsibility for misuse or misinterpretation of the analysis provided.

Chapter 1 – Introduction

1.1 Eco-Efficiency

The International Council on Mining and Metals (ICMM) created a sustainable development charter [33] meant to improve performance in the mining and metals industry. The organization, Mining, Minerals and Sustainable Development North America (MMSD), developed a method for assessing how a mining operation contributes to sustainability [75]. The seven criteria for assessing sustainability included the following: 1) maintain or improve well-being of the local community, 2) assure the long-term integrity of the environment, 3) improve the economy of the community, and 4) take traditional as well as non-market activities into consideration [75]. The term 'sustainability' has an ambiguous interpretation and some have argued that the term sustainability cannot be used to describe any mining of non-renewable resources because resources are extracted without being replaced [8]. For this reason, when 'sustainability' is mentioned within this paper it refers to efficient use of resources, and is also referred to as eco-efficiency for the purposes of this study.

Eco-efficiency was officially defined by the World Business Council for Sustainable Development (WBCSD), and it means achieving delivery of "competitively priced goods and services that satisfy human needs and bring quality of life while progressively reducing environmental impacts of goods and resource intensity…" [93, 95]. Eco-efficiency aims for five specific resource productivity goals: "effective resource utilization and materials efficiency; reduction of process waste…; reduction of water use and impacts; reduction of energy consumption and greenhouse gas emissions; and improved control of minor elements and toxic materials” [8].

1.2 Introduction to Copper Mining

Modern society is increasingly dependent upon metal mining, and, as a result, the volume of metals extracted, especially copper, has increased [38, 44, 31, 24]. Copper is one of the oldest metals ever used and has been one of the major materials in the development of civilization. After iron and aluminum, copper is the third most consumed metal in the world [79]. In 2012, close to nineteen-million tons of copper were globally produced and a little over one-and-a-half-million tons of this copper was consumed in the United States, with a value of \$7,300/ton [79]. The end uses of copper include: building construction—electrical wire, plumbing and heating, air conditioning and refrigeration; electrical and electronic products—wire and equipment for power and telecom utilities, business electronics, and lighting and wiring devices; industrial machinery and equipment—in-plant equipment, industrial valves and fittings, nonelectrical instruments, off-highway vehicles and heat exchangers; transportation equipment—cars, trucks and buses, rail, marine, and air and space vehicles; consumer and general products—appliances, cord sets, military ordnance and commercial ammunition, utensils and cutlery, and consumer electronics [36].

Pure copper metal is generally produced through a multistage process, beginning with the mining and concentrating of low-grade ores containing copper sulfide minerals, followed by smelting and refining. The amount of marketable copper is small when compared to original mined material. Because the copper concentration in ore generally ranges from 0.5 – 1.0%, several hundred tons of ore must be handled for each ton of copper produced, generating large waste quantities [85]. Mining and processing of copper can concentrate and expose harmful pollutants, such as uranium and thorium, in the waste rock or tailings. When exposed to weathering, tailings can contaminate surface water, groundwater and soils. Copper mining waste makes up the majority of metal and processing wastes generated in the United States. Most copper is mined in the arid west, with the majority of production occurring in Arizona. A significant amount of copper is recycled and nearly one half of the copper consumed annually in North America comes from recycled material [76].

Since 1910 copper has been the most valuable mineral commodity in the state of Arizona. The state produces more than half of the United States domestic copper alone. The copper industry provides ten-thousand jobs to the state of Arizona, with an estimated impact of $12.1 billion to the state, and $34.2 billion to the economy of the U.S. per annum [76]. Since the late nineteenth-century, Arizona has been home to prosperous and historic mining towns. Once copper resources became scarce, these towns were deserted and “mining operations were abandoned…leaving scarred and contaminated land across many parts…” of the state [78].

1.3 Brief Background of Resolution Copper

The Resolution Copper Mine Project is a proposed mining operation, owned by Resolution Copper (RC), a subsidiary of Rio Tinto, which would operate close to a historic mine, the Magma Mine, near Superior, Arizona. The major facilities for the project are distributed within Pinal County, Arizona. The ore body is deep (approximately 5,000 ft. to 7,000 ft. below the surface) and possesses an ore grade content of 1.47-1.52%. It has the potential to be the largest copper producing mine in North America and is expected to produce 132,000 tons of ore per day over a forty year period. Given technological advances, it is feasible that the mine could produce twenty-five percent more ore than estimated. The project is also estimated to create 3,700 jobs and generate sixty-one-billion dollars in economic benefits to the state of Arizona alone.

On RC's website it is written that "everything [done] at Resolution Copper is driven by the principle of sustainable development, which takes into account social, environmental and economic considerations in all decisions" [65]. The project promotes land use stewardship by: mining in a long-standing mining district [the Magma Mine], minimizing waste rock by using the panel cave mining method, reduced carbon emissions by transporting ore via an underground conveyer (reduces need for haul trucks) and using renewable energy from the Salt River Project. The project claims to enhance conservation and biodiversity by: rehabilitating legacy mining areas, implementing a conservation and biodiversity strategy, participating in a land exchange, using a limited amount of groundwater, recycling water and returning water to natural drainage systems.

In addition to environmental stewardship, RC is committed to the community of Superior, Arizona. A Citizens Working Group (CWG) was created from more than a dozen individuals representing various community groups. The two organizations meet every two weeks to discuss project details and receive community feedback about plans and mining activities. RC has made philanthropic contributions to the region, such as investing in "community-identified initiatives including math and science education, environment, community and human development, and arts and culture initiatives" [67]. The project is committed to responsibly and respectfully managing the land, "especially those lands found to have culture, historical and religious significance to Native Americans" [66].

1.4 Problem Statement

The cost of copper has nearly doubled over the last decade, rising from three-thousand 1998 dollars per ton to almost six-thousand 1998 dollars per ton [36]. Historic mine operating costs did not include resource conservation and remediation. Modern mines are held to stricter regulations and must have conservation and remediation plans ready *before* any mining occurs. The externalities [cost of waste disposal] of old mines might have been internalized by new mining operations, leading to an increase in costs. Though a logical argument for the copper price increase, we do not know if it is necessarily true.

RC has made it clear they support sustainable development, which, according to their website, means meeting "the needs of the present without compromising the ability of future generations to meet their own needs." In order to shed light on the proposed mining operations, a benefit-cost analysis framework is used to determine if modern copper mining practices are more sustainable than past operations, in terms of resource efficiency. A benefit-cost analysis can compare the environmental and economic costs/benefits of past mining operations to modern copper mining, using RC as proxy.

1.5 Research Questions

The purpose of this thesis is to develop a framework to answer the following research questions:

1. Is Resolution Copper's proposed mining operation *more* sustainable than past mining operations in terms of water, materials, and energy use?
    a. Are the externalities, i.e. waste management, accounted for?
    b. Is RC using energy and water resources more efficiently?

2. What is being done differently and how have copper mining practices changed over time?
    a. Compare environmental and economic benefits of current mining practices to past mining practices

THE FOLLOWING FIGURES WERE CREATED BY RESOLUTION COPPER

AND MADE PUBLICLY AVAILABLE ONLINE AT

WWW.RESOLUTIONCOPPER.COM

Figure 1. RESOLUTION COPPER General Plan of Operations – Vicinity Map

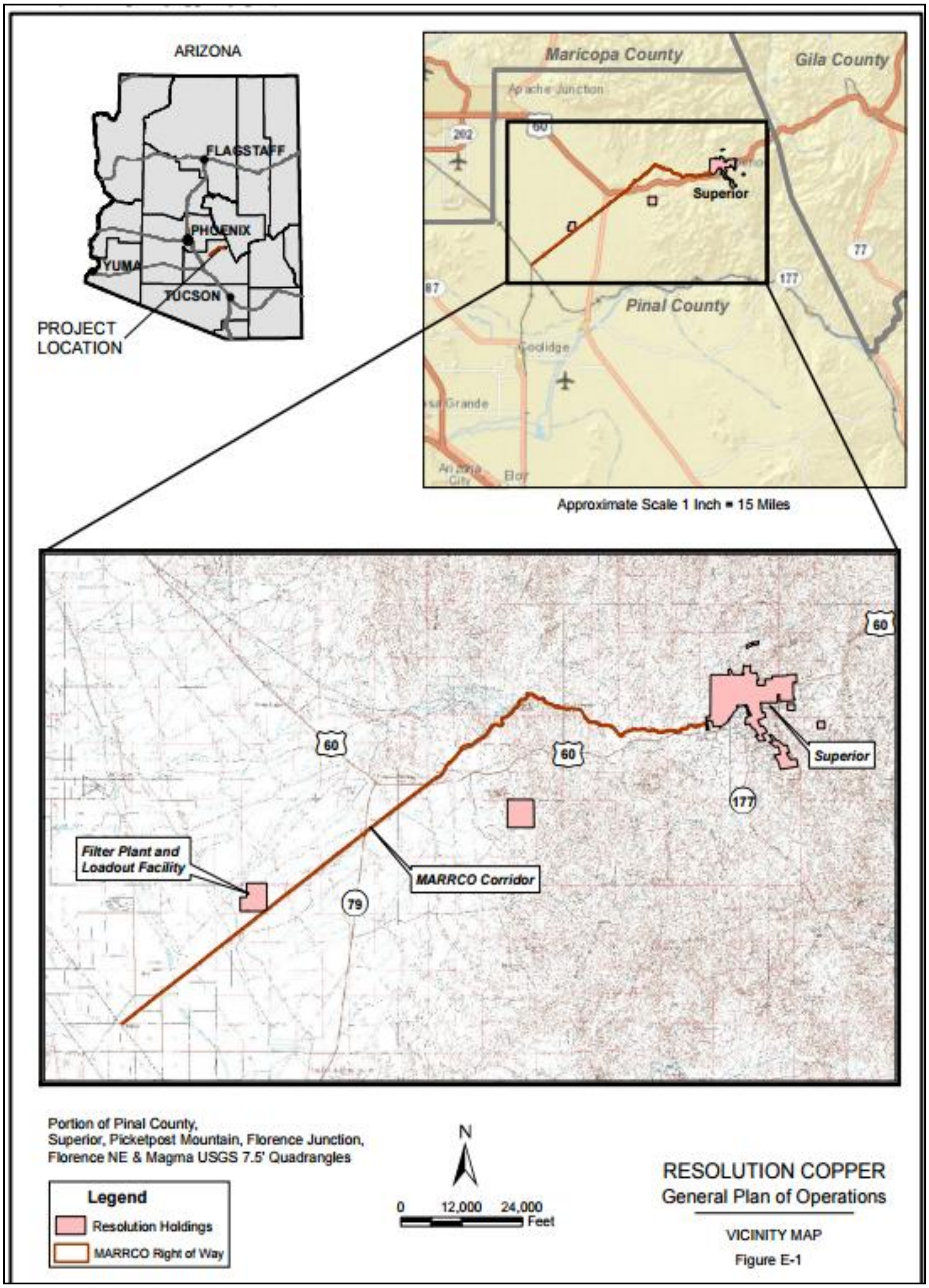


Figure 2. RESOLUTION COPPER General Plan of Operations – East Plant Site Surface Disturbance

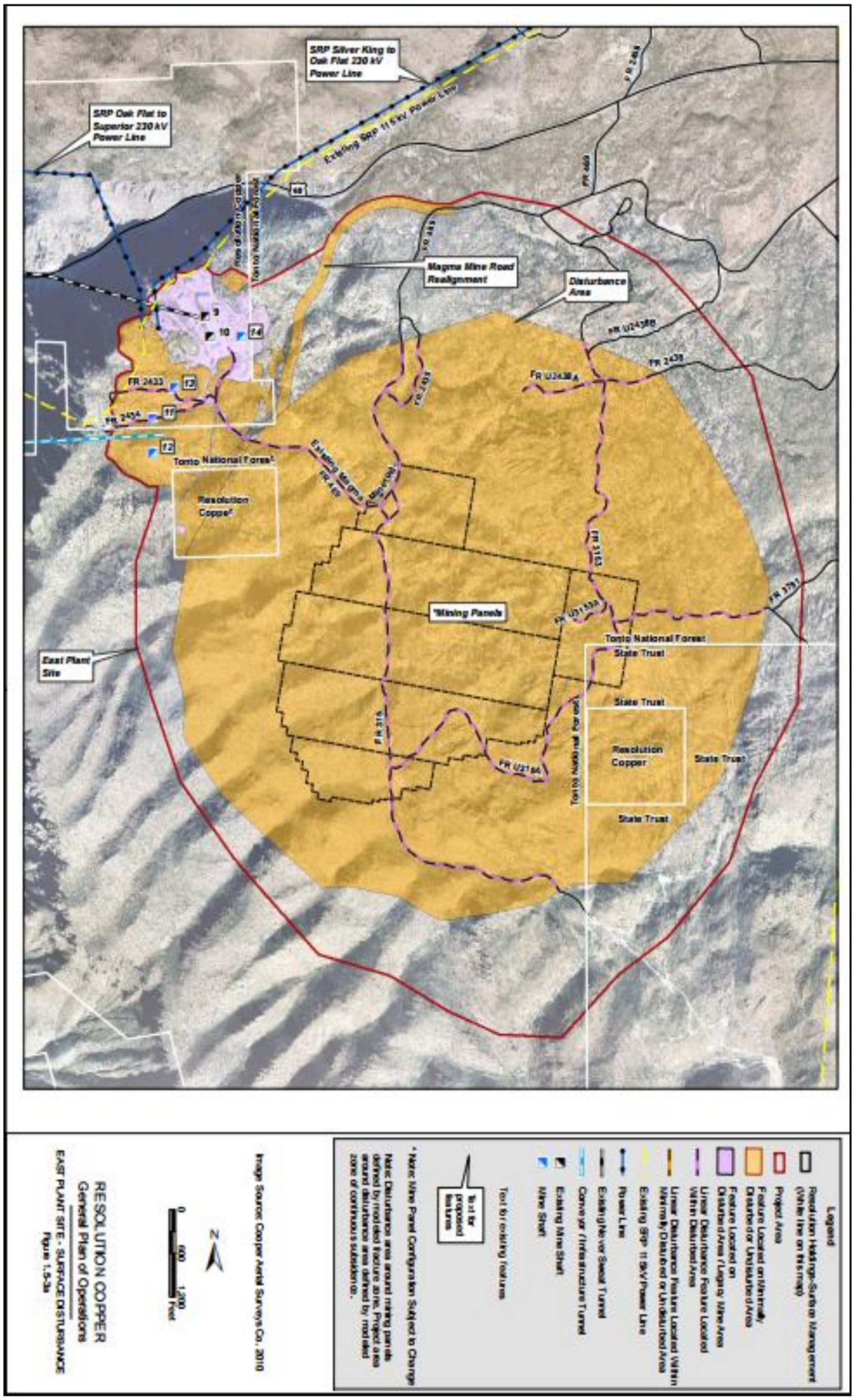


Figure 3. RESOLUTION COPPER General Plan of Operations – West Plant Site Surface Disturbance

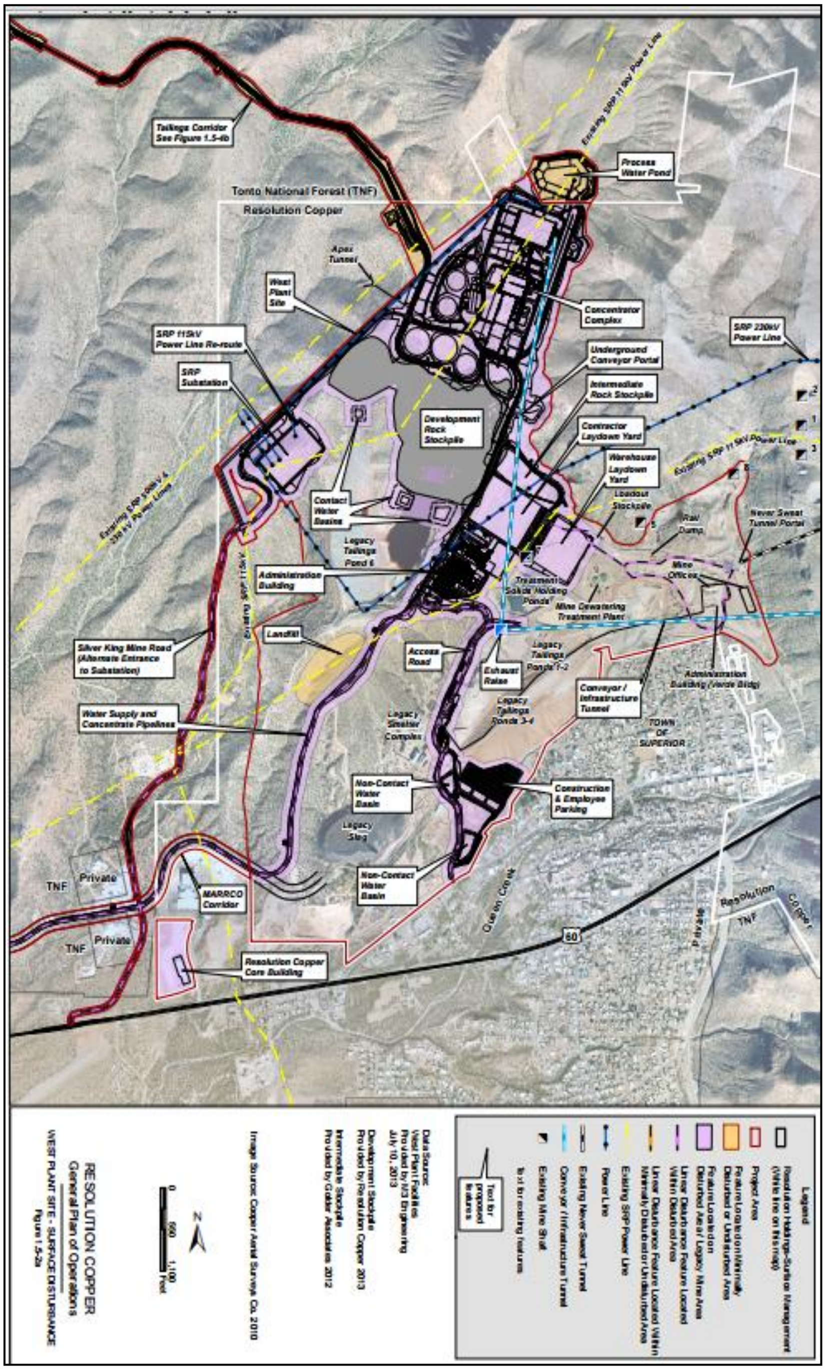


Figure 4. RESOLUTION COPPER General Plan of Operations – Tailings Storage Facility Surface Disturbance

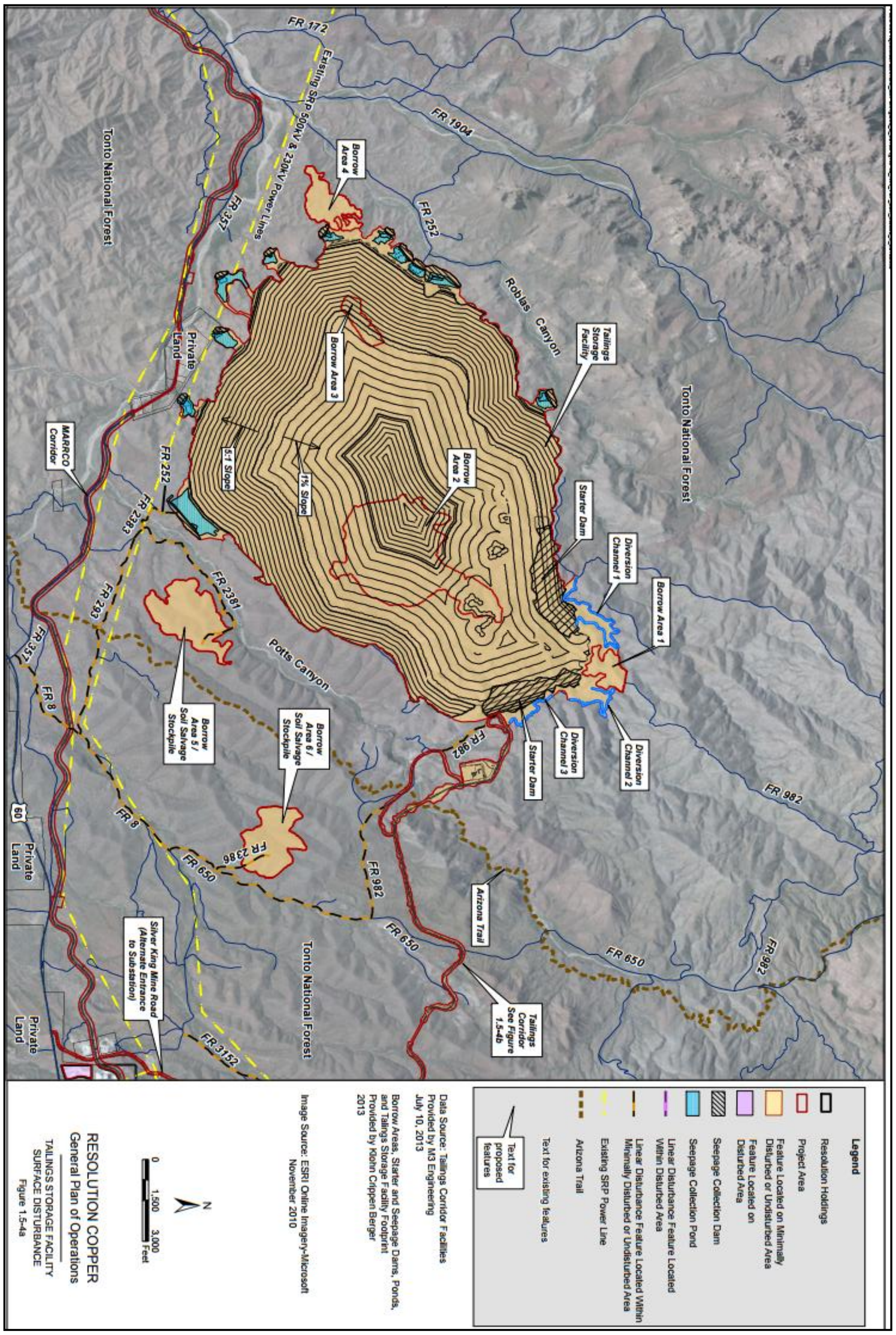
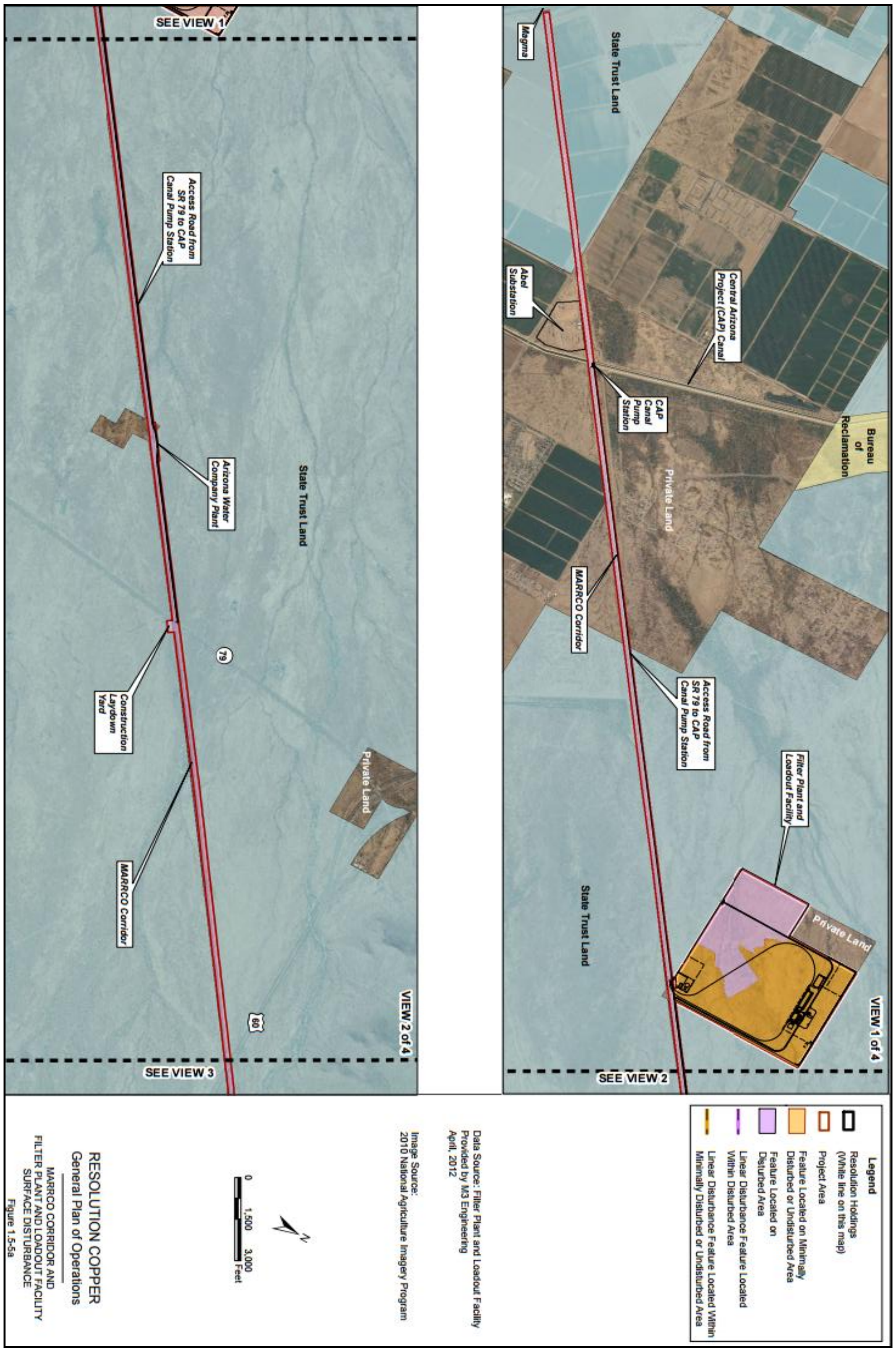


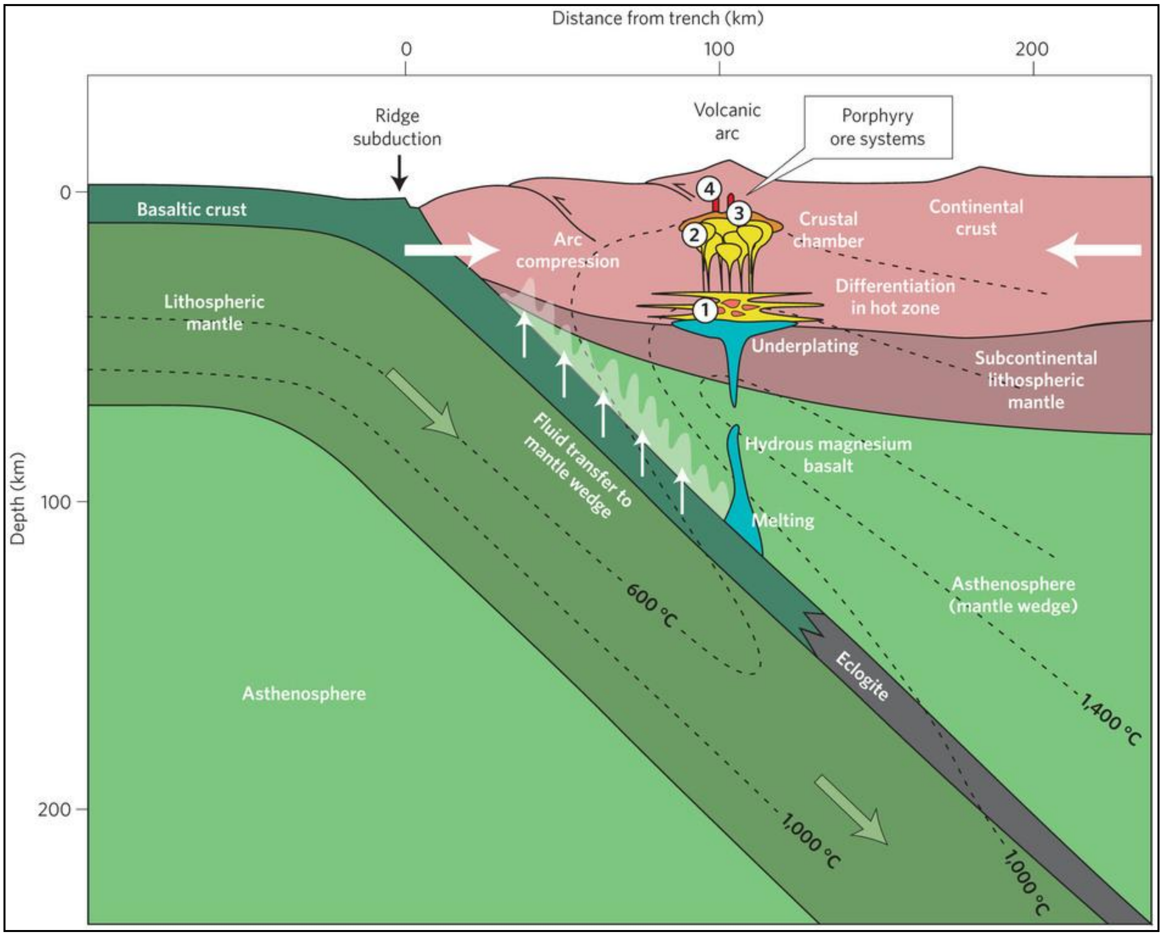
Figure 5. RESOLUTION COPPER General Plan of Operations – MARRCO Corridor and Filter Plant and Loadout Facility Surface Disturbance



Chapter 2 – Background on the Resolution Copper Mining Operation

2.1 Porphyry Copper Deposits Formation Process

Figure 6. Porphyry Copper Deposit Formation [www.nature.com]



Porphyry copper deposits (PCD) are the result of multistage igneous processes and are "characterized by low-grade copper, gold, and/or molybdenum mineralization developed within and around a porphyritic intrusive complex" [20]. Volcanic and sedimentary rock are common hosts of PCD. Deposits form between one and four kilometers below the earth's surface and are related to magma reservoirs in the shallow crust, which are six to eight-plus kilometers deep. They form in magmatic arcs above subduction zones, areas where one tectonic plate is sliding underneath another, and it is in these zones that the underground regional structure controls permeability. Hydrothermal fluids rise and subsequently, with the right temperature and pressure conditions present, react with rocks closer to the surface to form PCD. In the hypogene parts of the PCD, copper occurs predominantly in chalcopyrite; other important copper ore minerals include bornite and enargite. The amount of copper in the ore is small, and is present as small particles dispersed throughout the ore body [7]. The grain size for copper-containing sulfides typically are on the scale of millimeters, but some may reach 1-2 centimeters in diameter. Due to the small amount of copper in the ore, the average amount of waste rock and overburden removed for every ton of ore grade mined is about 1.5 tons [56].

The Resolution Copper PCD is located in Pinal County, Arizona. The deposit was discovered in 1995, and it is estimated to have formed over sixty-million years ago. It is 5000 – 7000 feet deep and almost an entire mile wide [68]. Among other minerals, the deposit contains two important copper ore minerals, chalcopyrite and bornite. It is a part of the Paleozoic sedimentary rock geologic unit [80]; with limestone as the primary rock type and sandstone as the secondary rock type surrounding the deposit. Singer [73] classified deposits as giants if they had >2 megatonnes (Mt, which is equal to one million tonnes (10^9 kg)) copper and they were supergiants if the deposit had >24 Mt copper. The PCD that Resolution Copper plans to mine has an estimated orebody weight of 1,730 Mt, with 1.47-1.52% copper ore grade. This means the deposit has over 26 Mt of copper, making it a supergiant deposit, according to Singer's classification. PCD’s are also classified, arbitrarily, by their grade, or the amount of copper present: low grade (<0.5 wt percent copper), moderate grade (<0.5-0.75 percent copper) and high grade (>0.75 percent copper). So, the Resolution Copper deposit is a high grade, supergiant PCD, and, if Resolution Copper begins operations, the deposit has the potential to produce one-billion pounds of copper annually.

2.2 Resolution Copper Method of PCD Extraction

As high grade copper veins and orebodies become increasingly scarce and copper demand continues to rise, it has become necessary for mining companies to target massive lower grade orebodies, like PCD [42]. Mining the PCD is made practical by an underground method of mining called block caving. This method is characterized by digging underneath the orebody, thereby removing its ability to support itself; as a result, fractures form throughout the area; next, gravity continually forces rock and ore down where it can be gathered and taken away for more processing [64]. There are currently over a dozen active mines globally using the block caving method and, like RC, there are more proposed operations. This method of extraction is currently the only known underground hard rock mining method that is capable of achieving production rates equal to that of surface mines [29]. A characteristic of block cave mining is subsidence, where, due to removal of the orebody and the subsequent void created, the topography of the surface sinks and forms a depression.

RC will use a variation of block cave mining called panel caving. Panel caving involves using explosives to precondition an orebody to cave when removal of the orebody begins, and is used when orebodies do not readily cave [92]. Gravity pulls the blasted rock through a series of passes and chutes, then underground load, haul and dump (LHD) vehicles, which are basically front-end loaders, deliver the rock material to ore passes which brings the rock to the underground rail haulage system [64]. The rail system will use electric semi-autonomous locomotives to pull the rail cars [64]. The ore is then delivered to the underground crushing station, which transports, by way of underground conveyers, the crushed rock to a hoisting station, which then brings the crushed material to the surface where it is stockpiled and processed on site [63].

The crushed ore is brought to the Concentrator Complex, where RC plans to use conventional sulfide processing methods. The Concentrator is expected to process 132,000 tons per day of ore for about forty years. The maximum processing rate is 165,000 tons per day; however, it is likely, that with advances in technology, production rate will increase by 25% as the mining operation progresses. The copper and molybdenum will be recovered by grinding and froth flotation, and it has been estimated that the average metal recovery will be 90-91% for copper and will average about 75% for molybdenum [64]. The produced concentrate will have average copper and molybdenum grades of about 29-31% and 52%, respectively. The amount of concentrate to be shipped for smelting is expected to be 2.20E+06 tons per year [64].

2.3 Resolution Copper and Tailings

The non-economic materials left over after metal ore processing are called tailings. Tailings are comprised of ground rock that range in size from clay and silt to coarse sand, and their elemental composition varies depending upon the geology of the orebody. The small amount of copper dispersed throughout the PCD means large quantities of waste rock must be processed resulting in significant amounts of tailings produced. As a matter of fact, RC's operation is expected to produce approximately 1.5 billion tons of tailings over the mine's lifetime [64]. The potential for environmental contamination from tailings is great, so tailings must be transported and stored in a safe and manageable manner.

RC analyzed multiple sites to determine the best location for storing tailings, and it was decided, after dialogue and cooperation with local communities, the tailings storage facility (TSF) would be stored at the "Lower West" site. Tailings are delivered as thickened slurry from the Concentrator to the TSF, and, as part of the flotation process, two types of tailings are generated, scavenger tailings and cleaner tailings. Scavenger tailings are depleted of pyrite and residual metals, and are not potentially acid generating (NPAG). Cleaner tailings concentrate the sulfides and metals relative to the whole tailings, and are potentially acid generating (PAG). The scavenger tailings will make up approximately 85% of the total tailings volume, and the cleaner tailings will make up about 15% of the total tailings volume [64]. The methods of containment and storage for these tailings have large land requirements and require long-term management.

RC will use a nearby valley as a tailings repository, and will employ an embankment method for the scavenger tailings using an upstream construction method, which allows reclamation and rehabilitation to occur simultaneously. This method involves discharging tailings through spigots along the rim of the southern embankment. As more scavenger tailings are added, the height of the southern embankment will rise. A gentle slope comprised of tailings will develop, with supernatant water flowing to a reclaim pond area downstream [62]. The cleaner tailings will be placed behind a constructed embankment at a slightly higher elevation than the scavenger tailings and will have their own separate pond. The method of deposition and storage will be subaqueous discharge and confinement. After eight years of operations, the scavenger tailings and cleaner tailings ponds will merge. The intent of the design is to keep the cleaner tailings saturated and continuously surrounded by the larger mass of inert scavenger tailings during operation. Seepage and stormwater will be pumped back and recycled in the tailings pond. The total surface area of the TSF at closure will be about 3,583 acres [64].

2.4 Resolution Copper and Reclamation

RC plans to implement several types of reclamation: construction reclamation, interim reclamation, concurrent reclamation, final reclamation and post-closure care and maintenance [64]. Construction reclamation refers to reclamation efforts on lands disturbed during mine site and facilities development. These include growth medium removal, stockpiling and stabilization. Due to the long life of the mine, growth medium material stockpiles will be contoured and seeded to prevent erosion, and to promote revegetation. Interim reclamation is temporary reclamation on lands that are not needed for active operations, and the main goals are to prevent erosion and sediment loading and for dust control. This includes reclaiming roads and fills. Another aspect of interim reclamation is to test revegetation plots to determine which mixture of seeds will be most effective within the area. Concurrent reclamation is final reclamation efforts completed during operations; concurrent reclamation differs from interim reclamation in that it is designed to be permanent. A comprehensive plan for concurrent reclamation is currently in the works, but RC does plan to implement it on the outer slopes of the TSF where practicable.

Final reclamation involves reclaiming surface disturbances, like decommissioning facilities, sealing of shafts, removal and/or closure of structures and facilities, removal and reclamation of roads, recontouring and regrading, growth medium replacement and fertilizing, mulching and seeding. In addition, the final reclamation plan will also deal with geotechnical stability; determining which water structures will be removed (culverts and pipelines, etc.) and those that will remain (surface water diversions, etc.); the management of hazardous material and waste and the removal of potentially impacted soils; restoring the natural hydrologic systems to pre-operation conditions; and protecting surface water and groundwater. All facilities and structures are planned for demolition and removal, but some may remain if the community wishes to preserve the historic mining heritage of the region. RC facility areas will be cross ripped along the contour, re-graded and contoured to blend into the surrounding topography, and to provide erosion control and to collect water for plants and seedlings. A post-closure care and maintenance plan has not been formally created, but RC will monitor sites and continue to ensure erosion is minimized and that revegetation and animal repopulation is occurring.

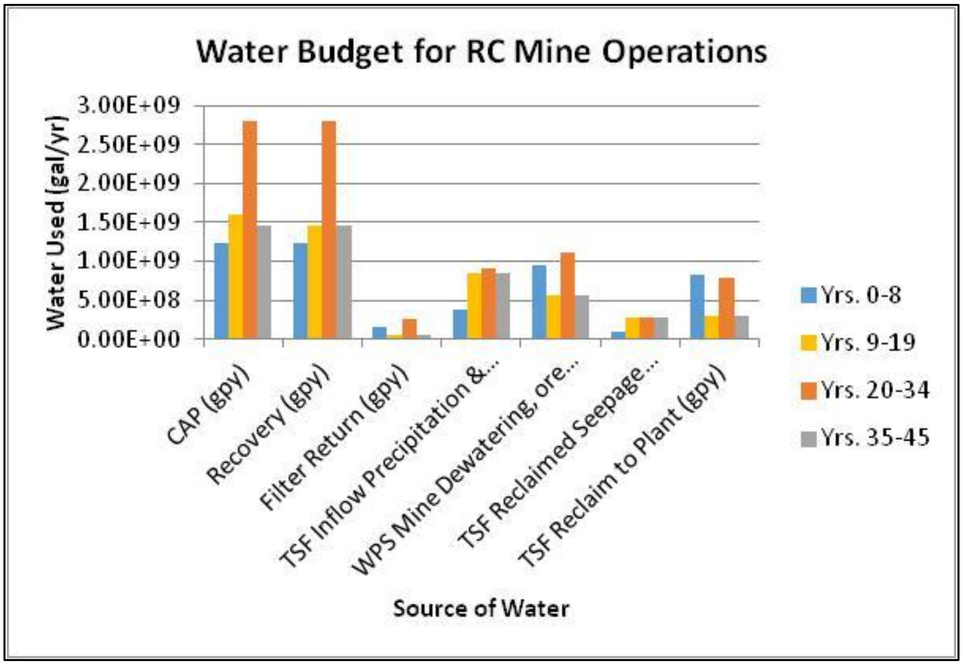
2.5 Resolution Copper and Water Resources

The CAP will be the main source of water for the project. In 2006, RC began purchasing and banking excess CAP water via delivery to a nearby irrigation district. Farmers use water from the CAP for irrigation purposes, which reduces groundwater pumping. The banked CAP water is stored in 30 recovery wells, and each is capable of providing 400 gallons of water per minute (gpm). If there is not enough banked water to meet the project's water demands, water will be extracted directly from the CAP canal. Two pump stations, each able to pump 12,000 gpm, will be constructed, one at the Filter Plant and Loadout Facility (FPLF) and one on the north side of the Magma Arizona Railroad Company (MARRCO) railroad corridor, called Queen Valley Pump Station.

Water pumped directly from the CAP will be transported 4.2 miles to the FPLF. It is around the FPLF that recovery wells used to store the banked water will be located. A 15,000 yd^3 storage tank on the FPLF site will contain CAP canal water, recover well water and filter plant filtrate. Water is then pumped via the pump stations at the FPLF and Queen Valley, and transported 22 miles from the FPLF to the Western Plant Site (WPS). The WPS will have three booster pumps, each with the ability to pump 6,000 gpm. In an effort to reduce the amount of water required for mining operations, RC will reclaim water from the filter plant, concentrator complex and TSF, and, eventually, a large portion of the operation's water will be from recycled sources. In addition to reclaiming water, RC will capture water from precipitation and runoff, and reuse water from mine dewatering, ore moisture and treated effluent.

During years zero through eight of the operation phase, the amount of water from: the CAP and recovery wells will be about 2.5 billion gallons per year; 375 million gallons of runoff and precipitation water will be captured per year; and 1 billion gallons of water will be reclaimed each year from the TSF and FPLF. During years twenty through thirty-four of the operations phase the amount of water from: the CAP and recovery wells will be over 5.5 billion gallons per year; 2 billion gallons of runoff and precipitation water will be captured per annum; and 1.3 billion gallons a year will be reclaimed water from the TSF and FPLF. During years thirtyfive through forty-five of the operations phase, the amount of water from: the CAP and recovery wells will be close to 3 billion gallons per year; almost 1.5 billion gallons of water per year will be captured from runoff and precipitation; and almost 650 million gallons of water per year will be reclaimed water from the TSF and FPLF. [61] The chart below shows the various water sources and the amount of water used during different periods of operations.

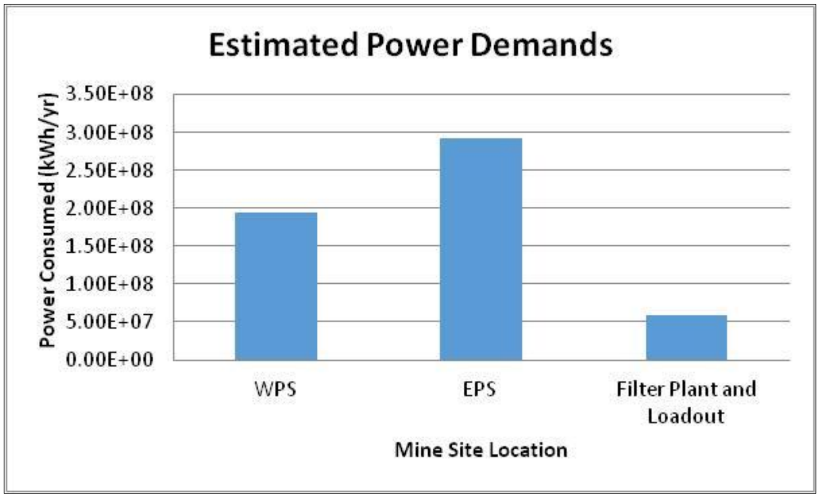
Figure 7. Water Budget for RC Mine Operations.



2.6 Electrical Power Supply

The three primary demands for power at underground mining operations are the operation of hoist motors that bring ore out of the mine, the ventilation and cooling systems for the underground workings and the operation of the grinding and flotation machinery in the Concentrator Complex. Concentrator complexes at surface mines account for about 85% of total power consumption for open pit mines, whereas the concentrator complex accounts for only about 45% of the total power consumption for underground mines hoisting ore to a surface concentrator [28]. Within the EPS, a new 230 kV substation will be built at Oak Flat. At the WPS, a 230 kV substation will be constructed to provide all the power for WPS facilities. The FPLF willhave a 69 kV power supply for all of its facilities, including supply water pumping facilities. The estimated power demands for each site were based on their percentage of total kV requirements.

Figure 8. Estimated Power Demands



The power for the entire project will be supplied by the Salt River Project (SRP), an organization that owns and operates electric, irrigation and water supply systems. The two SRP-owned generating plants closest to Superior, AZ are the Coolidge Generating Station and the Santan Generation Station, located in Coolidge, AZ and Gilbert, AZ, respectively. Both generating stations use natural gas as fuel sources to produce electricity [70, 71]. 15% of RC's energy will be supplied by renewable energy sources. Though it is not explicitly stated in RC documents which source of renewable energy will be used, SRP owns and operates a handful of dams providing hydroelectric power. The dams closest to Superior, AZ are the Theodore Roosevelt Dam and Horse Mesa Dam. An assumption made is that RC's 15% of renewable energy will be supplied by hydroelectric energy sources, and the remaining 85% of electricity will be supplied by natural gas-powered generating stations.

Chapter 3 – Literature Review

3.1 Environmental Impacts of Copper Mining

The majority of heavy metal contamination has its origin from humans, and is linked to metal manufacture and mining industries with storage, disposal and transportation problems [97]. Among metals found the following occur more frequently: cadmium, lead, cobalt, copper, mercury, nickel, selenium and zinc [35]. In low doses, some of these elements pose no risk, but at higher concentrations they become toxic to both animals and plants. When these elements are exposed to weathering they can mobilize [22], thus having the potential to contaminate surface water, ground water, sediment and air, leading to a decrease in the quality of life for plant and animal communities, including humans.

Copper mining and smelting activities pollute to some extent soil, air and water [77]. Metals during extraction are brought from deep within the earth's crust to the surface, where they are exposed to weathering processes. Weathering processes refers to exposure to sun, wind, rain, temperature, etc. Some of these variables affect the chemical composition of the metal, thus determining how the metal interacts with its surrounding environment. Metals are present on the surface as mine tailings and waste rock, both of which are considered mining waste, and both are sources for heavy metal contamination. Mine wastes are "discharged directly into marine environments, rivers and lakes" or discharged "inadvertently as a result of seepage, run-off or flooding, often spreading several [miles] from the source" [23]. Contamination from mining can impact food production, quality of surface and groundwater and damage natural ecosystems, including soil degradation and damage to wildlife and native flora [77]. Human beings also suffer from metal extraction wastes; in general, human populations in “areas of active and historic mineral extraction…are associated with elevated rates of death from disease” [72].

Metal production has increased while the grade of ore has declined [30]. Because of this low copper concentration in ore, several hundred tons of ore must be handled for each ton of copper produced, generating massive amounts of mine wastes. Ores mined for production of metals have trace levels of toxic elements, such as arsenic, mercury, cadmium, uranium and thorium [49].The majority of processed ore is discarded as tailings, usually 90 to 99% of original mined material [44, 24]. Copper and molybdenum mining are responsible for a combined fifty-percent of accumulated mine waste during the twentieth century. Over 24.2 billion tons of mine wastes were produced from 1910 to 1981, just from copper and molybdenum mining activities alone [28].

Mine waste disposal methods include cross valley or hillside dams, raised embankments/impoundments, backfilling into abandoned mines and direct disposal into bodies of water [24]. The most common form of disposal is termed ‘tailings ponds’ or ‘tailings dams’. Tailings are stored underwater for erosion and dust control and, since submersion slows down oxidation, acid mine drainage (AMD) is prevented. Every year two to five tailings dams fail [40], with a rate of failure of one in 700, which is a much higher rate of failure than water-retaining dams, which is approximately one in 10,000. Examples of copper tailings dam failure include the El Cobre Old Dam (Chile, 1965) and the Cerro Negro No. 4 (Chile, 1985), where the volume of tailings released were over 2.48 million and over 2.60 million cubic yards, respectively, and with more than 300 direct fatalities [38]. The sheer volume and toxic nature of the material held within a tailings dam means that a future dam failure could result in discharge into river systems, thus affecting water and sediment quality, and aquatic and human life for potentially hundreds of miles downstream.

When the sulfide-bearing material in tailings is exposed to oxygen and water [89], AMD can take place, causing long-term impairment to waterways and biodiversity [2]. AMD causes metals to be released to surrounding water-soil-sediment, resulting in contamination of ecological systems [89]. Depending upon the chemical composition of the mined material in the tailings, metals can be adsorbed by soil particles, thus contaminating the soil. Runoff generated from precipitation events can transport the contaminated soil to nearby aquatic ecosystems, and, once in the aquatic environment, the heavy metals can be transported much greater distances downstream [5]. In an aquatic environment, the heavy metals can be adsorbed onto streambed sediments or be present as suspended particles [69]. Erosion of tailings or waste rock also introduces metals to aquatic environments [69]. In addition, mobilized heavy metals can potentially leach into groundwater resources, where contamination can slowly spread to other water sources.

The effects of AMD on water quality include: lowering the pH and creating acidic environments; heavy metal contamination; and sedimentation [5, 26]. Sedimentation is caused by heavy metal contamination reducing vegetation cover, which leads to erosion causing a high sediment load [48]. Turbidity also increases due to AMD, thereby reducing light penetration, which impairs photosynthesis of the aquatic plant community [26]. The biological effects of

AMD include problems with respiration and reproduction, death of sensitive species and species migration or avoidance [26]. Ecological effects include habitat modification, bioaccumulation within the food chain, reduction in primary productivity and food chain modification [26]. Commonly associated with AMD are elevated concentrations of arsenic [17], which is a known carcinogen in humans [43]. Some forms of AMD prevention include: diverting surface water flowing towards the site of pollution; prevention of groundwater infiltration into the pollution site; prevention of hydrological water seepage into the affected areas; and controlled placement of acid-generating waste [2].

3.2 Federal Environmental Regulations Affecting Copper Mining's Impact on Water

The Federal Water Pollution Control Act (FWPCA) of 1948 was the first major U.S. law to address water pollution [87]. The objective was to restore and maintain the chemical, physical and biological integrity of waters within the United States [81]. Seeking to eliminate discharge of pollutants into navigable waters by 1985, the FWPCA prohibited the discharge of toxic pollutants in toxic amounts. The FWPCA provided Federal assistance for construction of publicly owned waste treatment plants and the act sought to develop and implement programs aimed at assessing and controlling point and non-point sources of pollution. As amended in 1972, the law became known as the Clean Water Act (CWA) [87]. The CWA gave the United States Environmental Protection Agency (EPA) authority to implement pollution control programs, like wastewater standards for industry. The act made it unlawful for any person to discharge any pollutant from a point source into navigable waters, unless a permit was obtained, and it established the basic structure for regulating pollutant discharge into the waters of the United States [81].

The National Environmental Policy Act (NEPA) of 1969 was created to prevent or eliminate damage to the environment and human welfare, and to further the understanding of ecological systems and natural resources within the United States [83]. NEPA established the Council on Environmental Quality (CEQ), whose responsibilities include reviewing and appraising various programs and activities of the Federal government to ensure these activities are meeting the purpose of NEPA. The CEQ is also responsible for conducting research on ecological systems and their associated environmental quality [83]. NEPA has been immensely successful in accomplishing its mission. In its early history, NEPA was used by environmental and citizen groups to sue government agencies for noncompliance, and courts generally ruled in favor of these groups [89]. NEPA has changed the way government deals with environmental issues, and it has become the model for environmental protection legislation in 23 states [89].

The Solid Waste Disposal Act (SWDA) of 1965 was created to promote the protection of health and the environment and to conserve valuable material and energy resources [82]. The act’s objectives included: assuring hazardous waste management practices were undertaken in a manner protecting human health and the environment; required hazardous waste be managed properly the first time, thereby reducing costly corrective measures in the future; and promoted the construction and application of resource recovery and resource conservation systems, thus preserving and enhancing the quality of air, water and land resources [82]. Hazardous waste is defined by the SWDA as any solid waste that can cause increases in mortality or an increase in irreversible illness, or pose as a potential hazard to human health or the environment when improperly managed [82]. A 1970 amendment to the SWDA created the Resource Recovery Act (RRA). The RRA encouraged waste reduction and resource recovery and created national criteria for hazardous wastes. The RRA was the forerunner of the Resource Conservation and Recovery Act (RCRA) of 1976.

The RCRA gave the EPA authority to control hazardous waste from “cradle-to-grave”. The act created regulations dealing with management of solid wastes, including waste created by the minerals industry. The definitions of solid waste and solid waste management facilities as stated in the RCRA are broad enough that “essentially all mining, minerals processing, and materials recycling operations fall under the jurisdiction of the act” [28]. The RCRA created hazardous waste standards, such as: generators of hazardous waste must have a program in place to reduce the volume and toxicity of their hazardous waste; guidelines and certification processes for transportation of hazardous waste; federal enforcement and fines for violation; and the permitting process for treatment, storage or disposal of hazardous waste. It is also worth nothing that the Toxic Substances Control Act (TSCA) of 1976 was passed in response to reported findings of human beings and the environment being exposed to large amounts of toxic chemicals and substances. The TSCA increased the EPA’s regulatory authority for management of toxic chemicals and substances. The EPA’s enforcement authority of the RCRA was increased by the Federal Hazardous and Solid Waste Amendments (FHSWA) of 1984. The FHSWA required the phasing out of land disposal of certain hazardous wastes and created more stringent hazardous waste management standards [86].

The Surface Mining Control and Reclamation Act of 1977 (SMCRA) was legislation specifically designed to eliminate environmental problems associated with coal mining [28]. The SMCRA was created during a time when the United States was recovering from its 1970's energy crisis [28]. To reduce future dependence on foreign energy sources, coal production within the United States increased, which led to further environmental degradation. This legislation pertains to coal mining, but it did create groundbreaking performance standards that would later influence legislation for metal mining. Some such standards were: restoring the land to pre-mining conditions; restore the approximate original contour of the land; stabilize and protect surface areas to prevent erosion and air and water pollution; treating drainage water; and removing waste piles [30 CFR SS 1265 (b)].

When discussing acid mine drainage, it is important to discuss the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), or more commonly known as Superfund. In 1980, CERCLA was enacted for the purpose of providing broad Federal authority in response to release or potential release of hazardous substances that could endanger the public health or the environment. The act established prohibitions and requirements for closed and abandoned hazardous waste sites; provided liability for owners of these sites; and established a trust fund for cleanup when no responsible party could be identified [90]. CERCLA was amended in 1986 by the Superfund Amendments and Reauthorization Act (SARA). The EPA's experience in administering CERCLA is mirrored in SARA's changes and additions to the program [91]. SARA put an emphasis on permanent solutions to hazardous waste sites; it provided new enforcement authorities; the act increased State involvement; the focus on human health problems by hazardous waste sites was increased; it encouraged greater citizen participation; and it increased the size of the trust fund from $1.6 billion to $8.5 billion.

3.3 Previous Studies on Metal Mining

The application of LCA (life cycle assessment) to mining and mineral processing is well known. Ingwersen [32] used an LCA framework to reveal that the primary sources of energy in the product of a Peruvian gold mine were from chemicals (40%), followed by fossil fuels (30%), electricity (14%) and infrastructure, explosives, and labor. Ingwersen's study determined that the largest environmental contribution during mining occurred during the extraction phase, followed by the leaching and processing stages. Norgate et al. [50] used a LCA approach to determine energy and greenhouse gas emissions of various copper mines in Australia and discovered that crushing and grinding and loading and hauling of copper concentrate constituted about 64% of total energy demands, and that crushing and grinding were responsible for nearly 50% of greenhouse gas emissions. Norgate et al. [49] used LCA to assess the environmental impact of metal production processes. Mudd [45] compiled sources and conducted calculations to show historical trends in water consumption, greenhouse gas emissions and energy consumption associated with gold mining in Australia. Awuah-Offei et al. [4] conducted an LCA study of belt conveyers and truck haulage systems in an open-pit hard rock gold mine and showed that the greenhouse gas emissions were higher for the belt conveyer system. While the above publications included results from actual LCA studies, none of these studies performed a benefit-cost analysis coupled with an embodied energy (EMERGY) analysis to determine the resource eco-efficiency of an underground mining operation, which was a goal of the present thesis research. This method of analysis is explained in the following section.

Chapter 4 – Methods and Results

4.1 Comparison of Methods

In order to answer the research questions posed, the next step is to select an evaluation tool to quantify economic, environmental and social benefits. The tool should provide a method of comparison between alternative mining scenarios. Three methods were examined for this purpose: traditional benefit-cost analysis, life cycle assessment (LCA) and embodied energy (EMERGY) analysis.

Benefit-cost analysis is traditionally used in business decisions. The benefits of a given situation are summed and then the costs associated with taking that action are subtracted. These analyses are reduced to dollars and cents, because one goal of a benefit-cost analysis is to determine the “monetary valuation of the benefits of life, health, and nature itself” [1]; this poses the hardest part of the entire process. What are the benefits of undisturbed land? What is the monetary value of not seeing tailings? How do you quantify the monetary value of nature? It is difficult to quantify nonmarket goods, because “...trade-offs...are not readily observable in the market place” and “many of the valuations necessary do not have readily observable market surrogates available to impute the value of non-market commodities” [12]. Since no natural price tags for environmental goods and services exist (i.e. things which are not bought or sold), benefit-cost analysis requires the creation of proxies. Benefits are often based on estimates of what people would be willing to pay for them, determined from opinion polls and other methods. Benefit-cost analysis has been used to evaluate government policy decisions, including environmental and health and safety regulations. Benefit-cost analysis may present information in a manner inconsistent with the majority of people's view of the world [1], and it slows the decision making process considerably.

LCA is based on the basic idea that "all environmental burdens connected with a product or service have to be assessed, back to the raw materials and down to waste removal" [37]. The message is that all actions related to the production of one function unit have to be analyzed, which includes raw material extracted, intermediate products, the product/service itself, the use phase and finally the waste removal. LCA's have been applied to product development and improvement, strategic planning, public policy making, marketing and many more processes. Currently, there exists "a lack of current standardization" [60] of steps within an LCA. A result from lack of standardization is that conclusions from an LCA could vary due to varying approaches to the same problem, thus causing uncertainty for decision makers. Additionally, "lacking...historical data, traditional life cycle assessment cannot account for environmental and industrial dynamics" [60].

Embodied energy, or EMERGY, analysis is a type of energy analysis. EMERGY can be thought of as energy memory or as a "measure of the available energy that has already been used up (degraded during transformations)" [51] to create a product. Others describe EMERGY as "a cost-of-production theory with all costs carried back to the solar energy [universal energy unit] necessary directly and indirectly to produce them" [21]. EMERGY is recognized by the USEPA, which states on their website that "the EMERGY method incorporates environmental, social, and economic aspects into a common unit of non-monetary measure and objectively assesses the sustainability of systems or processes" [84]. Traditional economic models determine resource and service values by what people are willing to pay. This price tag is not reflective of the amount of work Nature put into creating these resources. EMERGY is able to account for the energy Nature *and* human beings put into making a resource available, thus increasing the awareness of the value of natural resources. EMERGY "is thus a proxy for the environmental cost of making a resource available" and "EMERGY evaluation has the potential to identify and compare the contribution of many inputs to a production process, highlighting the role of the environmental resources supporting human activities" [59].

The tool required for this analysis must be able to estimate impacts of copper mining, must have a relatively easy-to-use procedure, must be relatively easy to understand by the layman/laywoman and must accurately reflect the true cost of an action/resource. For this thesis, EMERGY analysis is the tool that will be used for comparing the economic and environmental benefits of RC's proposed mine practices to mining practices of the past, and to determine if RC's planned mining operations are *more* sustainable than mining operations in the past.

4.2 EMERGY

In traditional terms, energy is thought of the amount of work put into a process, whereby a process requiring more work is seen as having more value. However, the scientific measure of energy is the heat generated when different types of energy are converted. This scientific concept "rates a calorie of sunlight, electricity, nuclear fission, and human thinking as equal" [52], ignoring the fact that different amounts of work went into generating each type of energy. Dr. Howard T. Odum recognized that each type of energy required a different amount of work and as such each type of energy has different values associated with its production.

Since energy of one kind is not equivalent in its ability to do work to energy of another kind, EMERGY uses the universal unit, the solar emjoule (sej) to calculate a system's energy inputs and outputs. To reflect changing energy quality, transformity values are used to express the EMERGY required to make one joule of a service or product; its value is solar emjoule per Joule (sej/J).The farther right on an EMERGY diagram you go, the more the transformity value increases, meaning available energy was used up to produce a lesser amount of higher quality energy. Thus, transformity creates an easy to understand energy hierarchy.

Because EMERGY evaluation uses energy units to understand systems dynamics, it obeys the laws of thermodynamics. The first law of thermodynamics states that energy is neither created nor destroyed; looking at the diagram below, you can see how energy moves from one form to another. The second law of thermodynamics is a principle of universal depreciation, which can be seen in systems as energy losing its concentration and ability to do work and leaving the system in degraded form, i.e. heat sinks.

Most economic models do not consider the free benefits that nature provides which might be lost through environmental degradation. Generally, wastes are an externalized cost of resource extraction, but EMERGY evaluation internalizes the externalities, meaning the costs of wastes are now part of the system. EMERGY "is thus a proxy of the environmental cost of making a resource available" and "EMERGY evaluation has the potential to identify and compare the contribution of many inputs to a production process, highlighting the role of the environmental resources supporting human activities" [59]. In other words, EMERGY analysis can be used to show the environmental AND economic costs associated with RC's mining operation. (Figure 8)

Figure 9. Example of Energy Flow and Market Value of a Resource [46]

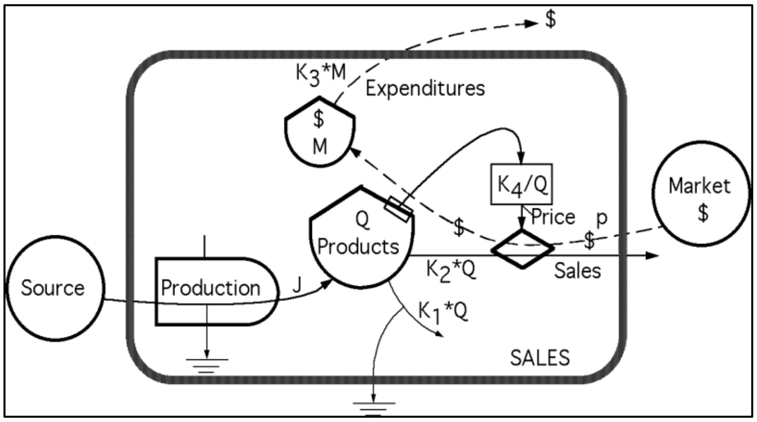
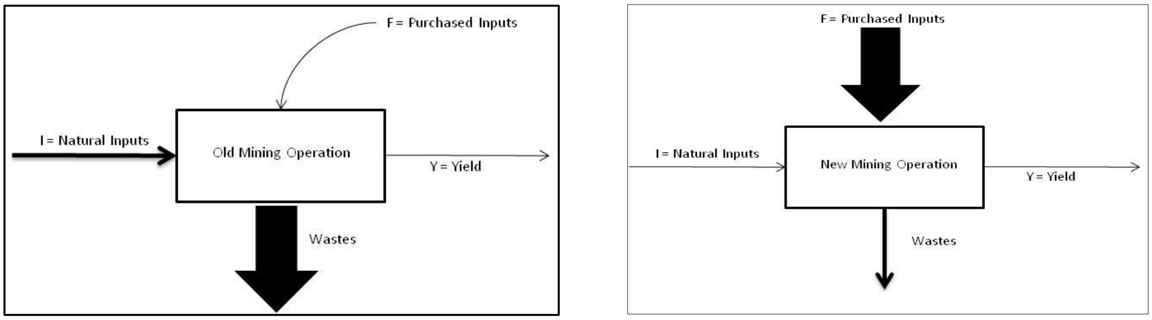


Figure 9 is an example of energy flow and market value of a resource. The energy source sends energy that is concentrated into higher quality energy during production. Production's energy flow, J, is further concentrated in product form, Q. Since transformity increases the further right we go, the market energy source required the most amount of energy to create its product, cash. This is how RC's copper value can be determined with emergy.

4.3 Tradeoffs

Most forms of mining require large quantities of water; copper mining is no exception. Water is used to transport tailings to tailings dams, it is used during the flotation process to separate copper from non-valuable ore materials (400-800 gallons/ton of ore) and water is used at the concentrator plant (200 gallons/ton of ore) [74]. Arizona is mostly desert and does not have an abundant supply of water to meet the demand for mining operations. In response to heightened water awareness, mining companies in Arizona are investing in technologies to reduce the amount of wastewater generated and to decrease their use of freshwater supplies [74]. The Arizona Department of Water Resources (ADWR) developed conservation requirements for metal mines in the state, some of which are listed here: reclaim tailings impoundment and recycle it; reuse runoff storm water that has been harvested on site; and water from pit dewatering should be used [3]. This reduces the amount of freshwater required for consumption and reduces the amount of wastewater. But to reduce water use and wastewater generated, the operation increases purchased inputs, such as energy and labor. [*Please see Figure 10 below]*.

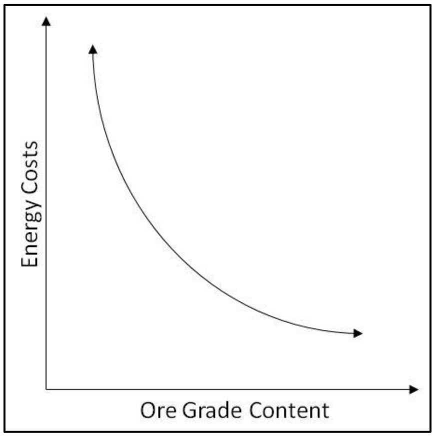
Figure 10. Water Tradeoff



The thickness of the arrow represents the amount of resources: thin is less, thicker is more. (*not to scale*)

To extract and process metal requires significant amounts of energy [49, 58], with fuel and electricity being the major sources of nonrenewable energy [58]. Regardless of the amount of energy consumed, metal production will still result in emissions directly (during mining and processing) and indirectly (associated with consumption of raw materials and utilities) [49]. Ore grade and electricity energy sources are two factors influencing environmental impacts of mining. As mined ore grade gradually decreases more material must be treated [50] and energy consumption will increase [49]. Depending upon the electricity energy source, greenhouse gas emissions will accompany increased electricity consumption [49]. RC's operation uses electricity powered underground conveyers instead of fossil-fuel burning haul trucks. This research attempts to answer the following question regarding energy use: Is the generation of electricity more eco-efficient than diesel combustion in the haul trucks?

Figure 11. Energy Tradeoff



During early excavation of the mine, RC will generate development rock. Development rock is rock generated from excavation that is used somewhere on the mining site. The development rock will be transported from the EPS to the WPS via conveyers and dump truck to stockpiles or used for reclamation or construction purposes. The majority of these stockpiles will be PAG and contain 16,774,000 tons of rock. Once mine production begins, there will be no waste rock generated and all material from the mine will go to the Concentrator for processing. The development rock that is PAG will be removed from the stockpile area and sent to the Concentrator. The NPAG development will be used for reclamation and as construction material.

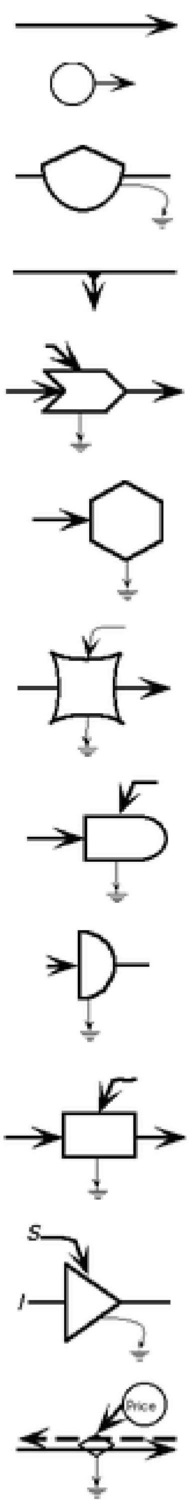
Consequences of processing all rock material as ore includes an increased amount of tailings generated.

4.4 EMERGY Evaluation Procedure

The first step in an EMERGY evaluation is to create an energy systems diagram, which includes an overview of the system, parts and processes, inputs and outputs. Symbols used in the energy systems diagrams are given in Figure 12 [*PLEASE SEE PAGE 43*]. The next step is to set up an EMERGY evaluation table (refer to Table 1). All EMERGY analysis tables follow the following six-column format [53]. Column 1 is the line item to be evaluated. For each line item evaluated, the source of raw data and calculations are indicated by a footnote with the same number as the line item. Column 2 is the where the name of the item is written. Colum 3 is the raw data units, evaluated in raw units of energy, grams, or dollars. Some materials do not have potential energy values, Joules (J), readily available; it is acceptable to express this data in grams or monetary currency in place of Joules. Column 4 is the transformity (sej/J) of an item (the value can also be sej/g or sej/$). Column 5 is the EMERGY of a flow or storage. This value is calculated by multiplying the data in column 3 by the value in column 4. Data in column 5 is expressed with scientific notation, i.e. E10 = 10^{10}. Column 6 is the emvalue (emdollars). The emvalue is calculated by dividing the "EMERGY in column 5 by the EMERGY/money ratio for a particular currency of a particular year to get the emdollar value for column 6" [53]. EMERGY/money ratios are calculated by dividing the solar EMERGY (sej) used in a country from all sources in a year by the gross national product (GNP) for that year [53]. The United States'

2008 GNP was around 14.70 trillion dollars (i.e. 1.47E+13) [94], and the total EMERGY used in 2008 in the United States was 3.60E+25 sej [46]. The EMERGY/money ratio for this analysis is 1.47E+25 sej / 3.60E+13 $2008, which equals 2.45E+12 sej/$2008. Once the EMERGY evaluation table is complete it is possible to make comparisons between the EMERGY of the system's flows and storages. This comparison shows which flows and storages are most important and contribute most to the combined economy of nature and humanity [53]. More complex comparisons can be made by using ratios, known as EMERGY evaluation indices.

Figure 12. EMERGY Symbols and Their Meanings [53]



Energy Circuit: A pathway whose flow is proportional to the quantity in the storage or source upstream

Source: Outside source of energy delivering forces according to a program controlled from outside; a forcing function.

Tank: A compartment of energy storage within the system storing a quantity as the balance of inflows and outflows; a state variable

Heat sink: Dispersion of potential energy into heat that accompanies all real transformation processes and storages; loss of potential energy from further use by the system

Interaction: Interactive intersection of two pathways coupled to produce an outflow in proportion to a function of both; control action of one flow on another; limiting factor action; work gate

Consumer: Unit that transforms energy quality, stores it, and feeds it back autocatalytically to improve inflow

Switching action: A symbol that indicates one or more switching actions

Producer: Unit that collects and transforms low-quality energy under control interactions of high-quality flows.

Self-limiting energy receiver: A unit that has a self-limiting output when input drives are high because there is a limiting constant quality of material reacting on a circular pathway within

Box: Miscellaneous symbol to use for whatever unit or function is labeled

Constant-gain amplifier: A unit that delivers an output in proportion to the input I but is changed by a constant factor as long as the energy source S is sufficient.

Transaction: A unit that indicates a sale of goods or services (solid line) in exchange for payment of money (dashed line). Price is shown as an external source.

Table 1. Tabular Format for EMERGY Evaluation

Tabular Format for Emergy Evaluation					
Note*	Item	Data Units (J, g, or $)	Solar Emergy/unit (sej/unit)	Solar Emergy (sej/yr)	Em$ ($/yr)^
	(One line here for each source, process, or storage of interest.)				
* Footnotes for each line of the table go here.					
^ Solar emergy in column 5 divided by sej/$ for ____ year.					

To calculate indices for interpretation EMERGY flows are aggregated into a three-arm diagram (environmental inputs, purchased feedbacks, and output products) [53]. [*Please see Figure 12 below*]. In the diagram: *R* stands for free *renewable* EMERGY from environmental inputs such as sun, wind and rain; N is free *nonrenewable* resource EMERGY from the local environment such as soil, forest wood, and minerals when used faster than produced; M is purchased EMERGY of *minerals*, fuels, and raw materials brought to an area by an economic system; and S is purchased EMERGY in *services and labor*, the paid work of people [53]. From this diagram, ratios for determining measures of sustainability can be calculated. Some examples of ratios are given in Table 2 below. Ratios can be used to evaluate and compare alternatives, such as alternative mining practices. The ratios are simple to understand and can help decision makers when comparing alternative choices.

Figure 13. Aggregated EMERGY Diagram [53]

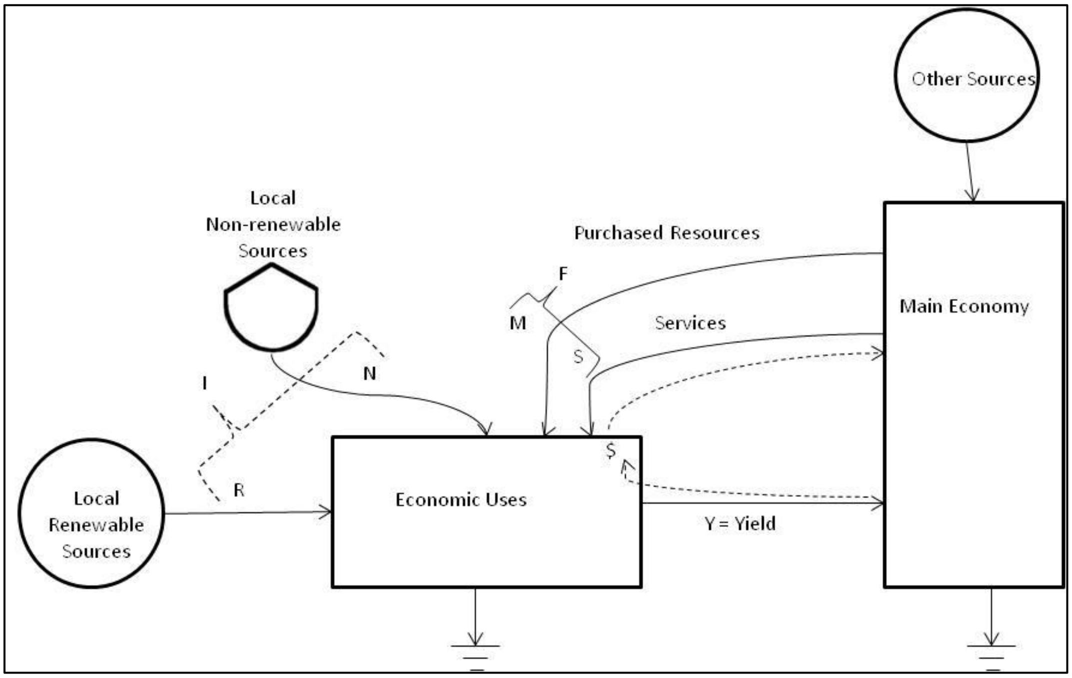


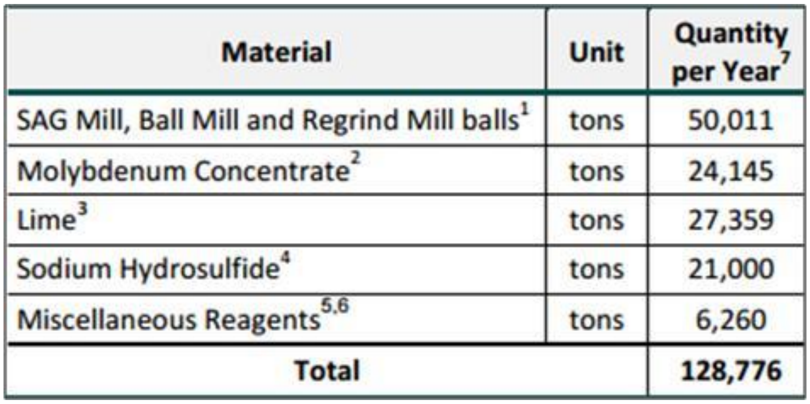
Table 2. Useful EMERGY Ratios [53]

Useful Ratios for Evaluation Economic Uses of Resources	
Name of Index	Definition (Fig. 5.3a)
Purchased/free	(M + S)/(R + N)
Nonrenewable/renewable	(N + M)/R
Service/free	S/(N + R)
Service/resource	S/(R + N + M)
Developed/environmental	(N + M + S)/R

4.5 Data Collection

Data was collected from RC’s proposed Mine Plan of Operations (MPO) (http://resolutioncopper.com/the-project/mine-plan-of-operations/). Within the MPO are tables providing information on the amount of daily personnel per site, quantities of materials required during construction and operation phases, quantities of fuel and chemicals required, etc. Table 3 below was taken directly from the MPO, listing the various reagents required for processing at the WPS. For the purpose of this EMERGY analysis, all measurements of weight were converted into grams. Solar EMERGY/Units (sej/unit) from other EMERGY studies were used to calculate the total amount of EMERGY required for various inputs, i.e. materials, labor, etc, and were cited accordingly.

Table 3. Example of RC Materials Table [64]



Material	Unit	Quantity per Year[7]
SAG Mill, Ball Mill and Regrind Mill balls[1]	tons	50,011
Molybdenum Concentrate[2]	tons	24,145
Lime[3]	tons	27,359
Sodium Hydrosulfide[4]	tons	21,000
Miscellaneous Reagents[5,6]	tons	6,260
Total		**128,776**

Table 4 [*Please see next* page] is an example of converting information from the MPO into an EMERGY evaluation table. If data were not available in the MPO, equations from the SME Mining Engineering Handbook, 1992, were used. Some of these equations resulted in quantities expressed in dollars. Items with a dollar value were converted into solar emjoules using conversions from Odum, 1996. The following sections consist of EMERGY evaluation tables for: the entire mining operation, the EPS, the WPS and TSF, the Filter Plant and Loadout Facility and resource tradeoffs.

Table 4. West Plant Site Materials – Operations Phase – EMERGY Evaluation

West Plant Site - Operations Phase							
Note	**Material**	**Unit**	**Quantity per Year**	**Quantity (g/yr)**	**Specific Emergy (sej/g)**	**Emergy (sej/yr)**	**Source**
1	SAG Mill, Ball Mill and Regrind Mill Balls	tons	50,011	4.54E+10	4.13E+09	1.87E+20	SME, pp. 2201; Brown (2000) and Buranakarn Dissertation (1998)
2	Molybdenum Concentrate	tons	24,145	2.19E+10		0.00E+00	EXPORTING THIS
3	Lime	tons	27,359	2.48E+10	2.56E+09	6.35E+19	Wes Ingersen Dissertation (2010)
4	Sodium Hydrosulfide	tons	21,000	1.91E+10	3.97E+09	7.56E+19	Wes Ingersen (2009)
5	Miscellaneous Reagents	tons	6,260	5.68E+09	3.97E+09	2.25E+19	Wes Ingersen (2009)
	Total		128,775	**1.17E+11**		**3.49E+20**	

4.6 EMERGY Evaluation of the Entire Mine Operation

Figure 14. EMERGY Diagram of Entire Mine Operation

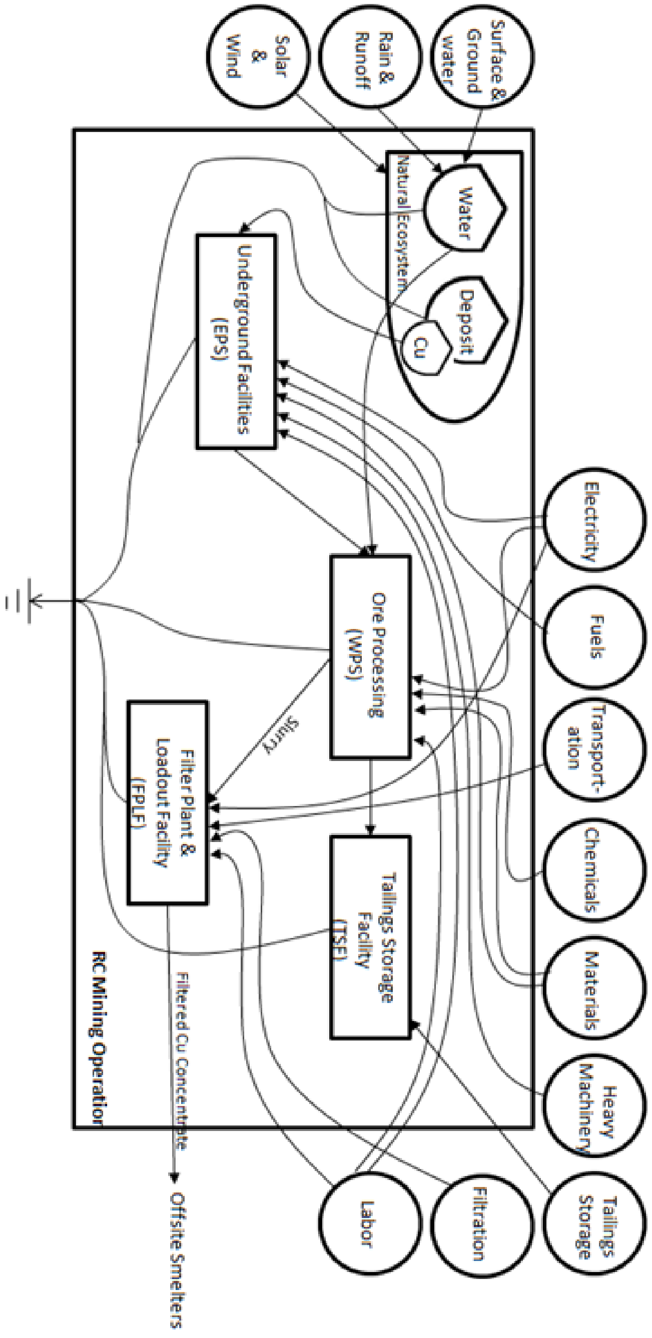


Figure 13 is the EMERGY diagram for RC's entire mining operation. The operation is complex and data sources were incomplete. To simplify, the mine site was divided into three sites: EPS, WPS (includes TSF) and FPLF. Each site had its various inputs quantified and then combined to calculate the entire project area's inputs. The entire mine site does not include the offsite smelters. Table 5 is an accounting table for Figure 13.

Table 5 Entire Mine Project Area EMERGY Evaluation

Entire Mine Project Area						
Note	Renewable Natural Inputs (*R*)	Raw Data	Data Units (J, g, or $)	Solar EMERGY/Unit (sej/unit)	Solar EMERGY (sej/yr)	Em$ (2008 U.S. $/yr)[a]
1	Solar	4.43E+17	J	1.00E+00	4.43E+17	1.81E+05
2	Wind	2.02E+14	J	2.45E+03	4.95E+17	2.02E+05
3	Rain Chemical Potential	4.65E+13	J	3.10E+04	1.44E+18	5.89E+05
4	Runoff	2.21E+13	J	4.70E+04	1.04E+18	4.24E+05
5	Surface Water	5.78E+13	J	8.10E+04	4.68E+18	1.91E+06
	Non-Renewable Natural Inputs (*N*)					
6	Groundwater	1.30E+13	J	3.02E+05	3.93E+18	1.60E+06
7	Geologic Energy of Orebody	1.73E+15	g	4.50E+09	1.73E+23	7.06E+10
8	Geologic Energy of Cu Deposit	2.63E+13	g	1.96E+06	1.15E+18	4.68E+05
	Purchased Inputs (*M* & *S*)					
9	Electricity	1.96E+15	J	2.92E+05	5.73E+20	2.34E+08
10	Fuel [diesel]	4.40E+09	g	2.83E+09	1.25E+19	5.08E+06
11	Heavy Machinery	1.20E+06	$	1.43E+12	1.72E+18	7.00E+05
12	Chemicals	4.95E+10	g	varies	1.62E+20	6.61E+07
13*	Transportation	2.20E+06	ton	5.07E+10	1.12E+17	4.57E+04
14	Labor	1.04E+03	people	3.41E+16	3.56E+19	1.45E+07
15	Materials	2.24E+11	g	varies	1.01E+21	4.14E+08
16	Tailings Storage	2.27E+04	$	1.43E+12	3.25E+16	1.32E+04
17	Filtration	3.04E+06	$	1.43E+12	4.35E+18	1.77E+06
18	Total Solar EMERGY in Filtered Copper Concentrate (sej/yr)			=	1.75E+23	
Solar EMERGY per Unit Calculated by Dividing Total Solar EMERGY Previously Used by the Weight						
Note	Item	Solar EMERGY per Mass (sej/g)				
19[b]	Filtered Copper Concentrate		8.76E+10			

*Transformity is sej/ton-mile

[a] Solar Emergy divided by 2.45E+12 sej/$2008

[b] (2.20E+06 tons of copper concentrate / year)(907,185 grams / ton) = 2.00E+12 grams of copper concentrate per year

Solar EMERGY per Mass (sej/g) = (1.75E+23 sej/yr) / (2.00E+12 g/yr)

Calculations for table items are listed below.

RENEWABLE NATURAL RESOURCES

1 Solar Insolation SOURCES
Sum of Each Site’s Raw Units (J/yr) =
(WPS + EPS + FPLF) =
3.80E+17 + 4.72E+16 + 1.56E+16 =
4.43E+17
Transformity (sej/J) 1.00E+00

2 Wind, Kinetic
Sum of Each Site’s Raw Units (J/yr) =
(WPS + EPS + FPLF) = 1.49E+14 + 3.93E+13 + 1.31E+13) =
2.02E+14
Transformity (sej/J) 2.45E+03 Odum et al, 2000

3 Rain Chemical Potential
Sum of Each Site’s Rain Chemical Potential (J/yr) =
(WPS + EPS + FPLF) =
(3.43E+13 + 9.20E+12 + 3.03E+12) =
4.65E+13
Transformity (sej/J) 3.10E+04 sej/J Odum et al, 2000

4 Runoff
Sum of Each Site’s Runoff (J/yr) =
(WPS + EPS + FPLF) = (1.63E+13 + 4.37E+12 + 1.44E+12) =
2.21E+13
Transformity (sej/J) 4.70E+04 Odum et al, 2000

5 Surface Water
Sum of Each Site’s Surface Water (J/yr) =
(WPS + EPS + FPLF) = (5.78E+13 + 0 + 0) =
5.78E13
Transformity (sej/J) 8.10E+04 Brown and Campbell, 2007

NONRENEWABLE NATURAL RESOURCES

6 Groundwater
Sum of Each Site’s Groundwater (J/yr) =
(WPS + EPS + FPLF) =
(5.78E+13 + 0 + 0) =
5.78E+13
Transformity 3.02E+05 sej/J Brown and Campbell, 2007

7 Geologic EMERGY of Surrounding Orebody
Volume 1.73E+15 grams
Specific EMERGY (sej/g) 4.50E+09 Odum, 1996
Avg. Emergy (sej/yr) = (Volume)(Specific EMERGY) / (45 years)

8 Geologic EMERGY of Copper Deposit
Volume = (1.52% of deposit is Cu)(Volume of Surrounding Orebody)
2.63E+13 grams
UEV of Cu Ore (sej/g) = (*G* of ore, J/g)(UEV of Volcanic Heath, sej/J)
(1.65 J/g)(1.80E+04 sej/J) = 2.97E+04 sej/g Ingwersen, 2009; Odum 1996; Gilliland, 1978
Specific EMERGY (sej/g) = (UEV of Cu Ore)/(copper, g / orebody, g) Ingwersen, 2009
(2.97E+04 sej/g) / (2.63E+13 g / 1.73E+15 g)
= 1.96E+06 sej/g
Avg. Emergy (sej/yr) = (Volume)(Specific EMERGY) / (45 years)

PURCHASED INPUTS

9 Electricity
Sum of Each Site’s Electricity (J/yr) =
(WPS + EPS + FPLF) =
(7.01E+14 + 1.05E+15 + 2.10E+14) =
1.96E+15
Transformity (sej/J) 2.92E05 Brown and Campbell, 2007
10 Fuel (diesel)
Sum of Each Site’s Fuel (g/yr) =
(WPS + EPS + FPLF) =
(0 + 4.40E+09 + 0) =
4.40E+09
Specific EMERGY (sej/g) 2.83E+09 Bastianoni et al, 2009
11 Heavy Machinery
Sum of Each Site’s Heavy Machinery ($/yr) =
(WPS + EPS + FPLF) =
(0 + 1.20E+06 + 0) =
1.20E+06
EMERGY to Money Ratio (sej/$) 1.43E+12 Odum, 1996
12 Chemicals
Sum of Each Site’s Chemicals (g/yr) =
(WPS + EPS + FPLF) =
(4.95E+10 + 0 + 0) =
4.95E+10
EMERGY (sej/yr) = sum of all quantities multiplied by respective solar EMERGY values
= 1.62E+20
13 Transportation
Sum of Each Site’s Transportation (ton/yr) =
(WPS + EPS FPLF) =
(0 + 0 = 2.20E+06) =

2.20E+06
Unit EMERGY Value (sej/ton-mile) 5.07E+10 Buranakarn, 1998

14 Labor
Average Daily Personnel of Each Site (people) =
(EPS + WPS + FPLF) =
(537 + 477 + 30) = 1.04E+03
EMERGY Use per Person (sej/day) 9.35E+13 Odum, 1996
EMERGY (sej/yr) = (Avg. Daily Personnel)(EMERGY/person)(365 days/1 yr) =
3.56E+19

15 Materials
Avg. EMERGY (sej/yr) 1.24E+21

[*SEE NEXT PAGE FOR MATERIALS EVALUATION*]

16 Tailings Storage
Sum of Each Site's Tailings Storage ($/yr) =
(EPS + WPS + FPLF) =
(0 + 2.27E+04 + 0) =
2.27E+04
EMERGY to Money Ratio (sej/$) 1.43E+12

17 Filtration
Sum of Each Site's Filtration ($/yr) =
(EPS + WPS + FPLF) =
(0 + 0 + 3.04E+06) =
3.04E+06
EMERGY to Money Ratio (sej/$) 1.43E+12

OUTPUT

18 Total Solar EMERGY in Filtered Copper Concentrate (sej/yr)
Sum of Items 1 – 17 = 1.75E+23

SPECIFIC EMERGY OF FINAL PRODUCT

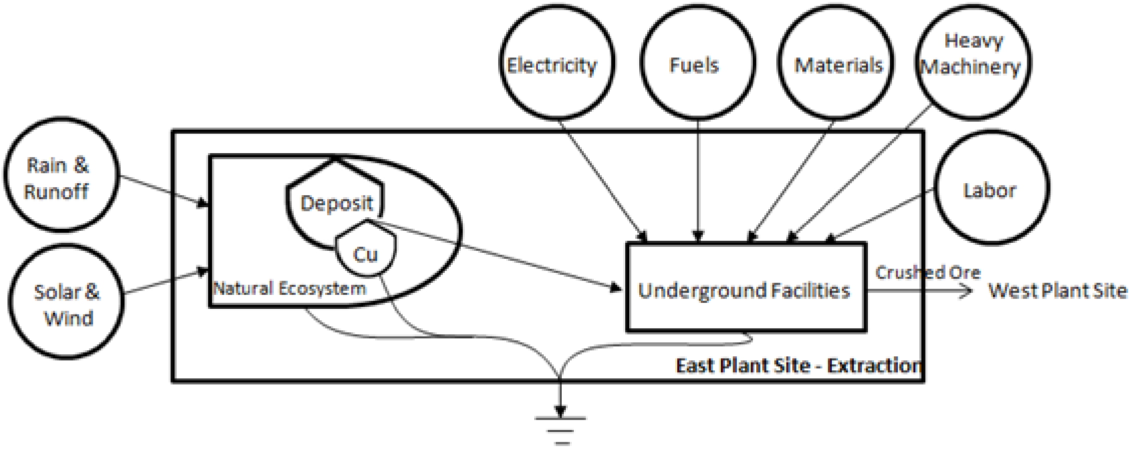
19 Filtered Copper Concentrate (sej/g)
2.20E+06 tons of copper concentrate shipped/yr
907,185 grams / ton
Shipped Copper Concentrate (g/yr)
= (2.20E+06 tons/yr)(907,185 g/ton)
= 2.00E+12 g/yr
Specific EMERGY of Copper Concentrate
= Divide total solar EMERGY by weight of copper concentrate
= (1.75E+23 sej/yr) / (2.00E+12 g/yr)
= 8.76E+10 sej/g

Table 5.1 Materials EMERGY Evaluation

Materials							
Note	Item	Raw Data	Units (J, g, or $)	Emergy/unit (sej/unit)	Emergy (sej)	Em$	Source
EPS - Construction							
1	Underground Concrete	3.57E+11	g	2.12E+09	7.57E+20	3.09E+08	Brown and Campbell, 2007
2	Underground Production Consumables	6.10E+11	g	8.83E+09	5.39E+21	2.20E+09	Wes Ingwersen, 2009
3	Construction Steel	4.99E+10	g	2.99E+09	1.49E+20	6.09E+07	Brown and Campbell, 2007
4	Construction Material	7.50E+11	g	2.99E+09	2.24E+21	9.15E+08	SME, Vol. 1, 1992
5	Construction Material	7.83E+09	g	2.99E+09	2.34E+19	9.56E+06	
6	Construction Concrete	2.92E+11	g	2.12E+09	6.19E+20	2.53E+08	Brown and Campbell, 2007
EPS - Operations							
7	Underground concrete	1.22E+12	g	2.12E+09	2.59E+21	1.06E+09	Odum, 1996 - Solar Voltaic Cells
8	Underground Production Consumables	3.30E+12	g	8.83E+09	2.91E+22	1.19E+10	Wes Ingwersen, 2009
WPS - Concentrator							
9	Concrete	2.96E+11	g	2.12E+09	6.28E+20	2.56E+08	Brown and Campbell, 2007
10	Rebar	1.54E+10	g	4.13E+09	6.36E+19	2.60E+07	Brown, 2000; Buranakarn, 1998
11	Structural Steel	1.50E+10	g	2.99E+09	4.49E+19	1.83E+07	Brown and Campbell, 2007
12	Handrails/stairs	2.17E+08	g	2.99E+09	6.49E+17	2.65E+05	Brown and Campbell, 2007
13	Grating	1.29E+10	g	2.99E+09	3.86E+19	1.57E+07	Brown and Campbell, 2007
14	Prefab Buildings	5.19E+07	g	varies	1.35E+20	5.51E+07	Buranakarn, 2007
15	Liner Plates	2.82E+08	g	2.12E+09	5.98E+17	2.44E+05	Brown and Campbell, 2007; SME, Vol. 2, 1992
16	Chutes/launders, boxes	3.33E+08	g	2.99E+09	9.96E+17	4.06E+05	Brown and Campbell, 2007; SME, Vol. 2, 1992
17	Tanks	5.79E+07	g	2.99E+09	1.73E+17	7.07E+04	Brown and Campbell, 2007
18	Small Diameter Pipe	2.07E+10	g	2.99E+09	6.19E+19	2.53E+07	Brown and Campbell, 2007
19	Large Diameter Pipe	5.92E+10	g	2.12E+09	1.26E+20	5.12E+07	Brown and Campbell, 2007
20	Electrical Equipment	6.64E+07	g	1.13E+10	7.50E+17	3.06E+05	Brown and Campbell, 2007
21	Overhead Transmission Line	2.35E+07	g	1.25E+10	2.94E+17	1.20E+05	Brown, 2000
TSF - Tailings							
22	Large Diameter Pipe	9.36E+08	g	1.13E+10	1.06E+19	4.32E+06	Brown and Campbell, 2007
23	Valves						
24	Concrete	9.08E+10	g	2.12E+09	1.92E+20	7.86E+07	Odum, 1996 - Solar Voltaic Cells
25	Asphalt	1.79E+10	g	2.62E+09	4.69E+19	1.91E+07	Bastianoni et al, 2009
26	Structural Steel	9.07E+07	g	2.99E+09	2.71E+17	1.11E+05	Odum, 1996 - Solar Voltaic Cells
WPS							
27*	SAG Mill, Ball Mill & Regrind Mill Balls	4.54E+10	g/yr	4.13E+09	7.50E+21	3.06E+09	SME, Vol. 2, 1992; Brown, 2000; Buranakarn, 1998
	Avg. Materials (g/yr)#	2.23E+11		Total	4.98E+22	2.03E+10	
				Average (unit/yr)#	1.24E+21	5.08E+08	
* This material is g/yr. Total emergy = (sej/yr) x (40 yrs)							
# Averaged over 40 years							

4.7 EMERGY Evaluation of the East Plant Site [Extraction Phase]

Figure 15. EMERGY Diagram of the East Plant Site



The EPS is the extraction site. It is here that the block panel caving method of mining is employed. Ore is gathered through the chutes and passes, transported by the underground rail haulage system to the underground crushing station, and, after the ore is crushed, it is transported via the electric underground conveyor belts to the hoister that deposits the crushed ore at the WPS. The evaluation table for the EPS is given below.

Table 6. East Plant Site – Extraction Phase EMERGY Evaluation

East Plant Site - Extraction Phase						
Note	Renewable Natural Inputs (*R*)	Raw Data	Data Units (J, g, or $)	Solar Emergy/Unit (sej/unit)	Solar Emergy (sej/yr)	Em$ (2008 U.S. $/yr)[a]
1	Solar	4.72E+16	J	1	4.72E+16	1.93E+04
2	Wind	3.98E+13	J	2.45E+03	9.75E+16	3.98E+04
3	Rain Chemical Potential	9.20E+12	J	3.10E+04	2.85E+17	1.16E+05
4	Runoff	4.37E+12	J	4.70E+04	2.05E+17	8.38E+04
	Non-Renewable Natural Inputs (*N*)					
5	Geologic Energy of Orebody	1.73E+15	g	4.50E+09	1.73E+23	7.06E+10
6	Geologic Energy of Copper Deposit	2.63E+13	g	1.96E+06	1.15E+18	4.68E+05
	Purchased Inputs (*M* & *S*)					
7	Electricity	1.05E+15	J	2.92E+05	3.07E+20	1.25E+08
8	Materials	1.65E+11	g	varies	7.93E+20	3.24E+08
9	Fuels	4.40E+09	g	2.83E+09	1.25E+19	5.08E+06
10	Heavy Machinery	1.20E+06	$	1.43E+12	1.72E+18	7.00E+05
11	Labor	537	people	3.41E+16	1.83E+19	7.48E+06
12	Total Solar EMERGY in Extracted Copper Ore (sej/yr)			=	1.74E+23	
Solar EMERGY per Unit Calculated by Dividing Total Solar EMERGY Previously Used by the Weight						
Note	Item	Solar EMERGY per Mass (sej/g)				
13[b]	Extracted Copper Ore		8.71E+10			
[a] Solar Emergy divided by 2.45E+12 sej/$2008						
[b] (2.20E+06 tons of copper concentrate / year)(907,185 grams / ton) = 2.00E+12 grams of copper concentrate per year						
Solar EMERGY per Mass (sej/g) = (1.74E+23 sej/yr) / (2.00E+12 g/yr)						

Calculations for table items are listed below.

RENEWABLE NATURAL RESOURCES

1 Solar Insolation Sources
Land Area 7,755,362.48 m^2
Insolation 8.70E+09 $J/m^2/yr$ NREL, 2006
Albedo 0.30 pac-ibphys.wikispaces.com
Energy (J) = (area)(insolation)(1-albedo) Brown and Campbell, 2007
4.72E+16
Transformity (sej/J) 1.00E+00

2 Wind, Kinetic
Area 7,755,362.48 m^2
Air Density (kg/m^3) 1.30
Avg. Annual Wind Velocity (mps) 5.96 www.usa.com
Geostrophic Winds 9.93 Brown and Campbell, 2007
Drag Coefficient 2.00E-03 Brown and Campbell, 2007
Energy (J) = (area)(density)(drag coef)(Geos-grnd velocity)^3(31,500,000) =
3.98E+13
Transformity (sej/J) 2.45E+03 Odum et al, 2000

3 Rain Chemical Potential
Land Area 7,755,362.48 m^2
Rain 0.24 m www.usa.com
Volume Rain 1,861,287 m^3
Energy (J) = (volume)(1000 kg/m^3)(4940 J/kg)
= 9.20E+12
Transformity (sej/J) 3.10E+04

4 Runoff
Land Area 7,755,362.48 m^2
Rainfall (m/yr) 0.24
Density of Water (g/m^3) 1E+06
Runoff Coefficient 0.475
Gibbs Free Energy of Water (J/g) 4.94E+00
Energy (J/yr) = (area)(rainfall)(density of water)(*G*)(Runoff Coef.) Odum, 1996
4.37E+12
Transformity (sej/J) 4.70E+04 Odum et al, 2000

NONRENEWABLE NATURAL INPUTS

5 Geologic EMERGY of Surrounding Orebody
Volume 1.73E+15 grams www.resolutioncopper.com
Specific EMERGY (sej/g) 4.50E+09 Odum, 1996
Avg. EMERGY (sej/yr) = (Volume)(Specific EMERGY) / (45 years)

6 Geologic EMERGY of Copper Deposit
Volume = (1.52% of deposit is Cu)(Volume of Surrounding Orebody)

2.63E+13 grams
UEV of Cu Ore (sej/g) = (*G* of ore, J/g)(UEV of Volcanic Heath, sej/J)
(1.65 J/g)(1.80E+04 sej/J) = 2.97E+04 sej/g Ingwersen, 2009;
Odum 1996
Specific EMERGY (sej/g) = (UEV of Cu Ore)/(copper, g / orebody, g)
Odum, 1996
(2.97E+04 sej/g) / (2.63E+13 g / 1.73E+15 g)
= 1.96E+06 sej/g

Avg. EMERGY (sej/yr) = (Volume)(Specific EMERGY) / (45 years)

PURCHASED INPUTS

7 Electricity
Power Consumed (kWh/day) 8.00E+05 SME, Vol. 2, 1992
Conversion (J/kWh) 3.60E+06
Energy (J/yr) = (Power Consumed)(365 days/yr)(Conversion, J/kWh)
1.05E+15
Transformity (sej/J) 2.92E+05 Brown and Campbell, 2007
8 Materials
Avg. EMERGY (sej/yr) 1.02E+21
[*PLEASE SEE TABLE 6.1 ON PAGE 59*]
9 Fuels (diesel)
Total Volume (g) 1.98E+11
Avg. Volume (g/yr) = (total volume)/(45 yrs) = 4.40E+09 g/yr
Specific EMERGY (sej/g) 2.83E+09 Bastianoni et al, 2009
10 Heavy Machinery
Cost of drilling, loading and hauling equipment SME, Vol. 1, 1992
$= \$24,600 \text{ x } T^{0.8} / W^{0.3}$
T is tons of ore per day; *W* is width of ore (ft)
T = 132,000 tons/day *W* = 49,000 ft
= 1.20E+07 ($)
Assuming new equipment must be purchased every ten years and mine operation is 45 years … ($1.20E+07)(45 yrs / 10 yrs) = $5.40E+07
Average Cost ($/yr) = 5.40E+07 / 45 yrs = 1.20E+06 $/yr
EMERGY to Money Ratio (sej/$) 1.43E+12 Odum, 1996
11 Labor
Avg. Daily Personnel (people) 537
EMERGY Use per Person (sej/day) 9.35E+13 Odum, 1996
EMERGY (sej/yr) = (Avg. Daily Personnel)(EMERGY Use/Person)(365 days/1 yr)
1.83E+19

OUTPUT

12 Total Solar EMERGY in Extracted Copper Ore (sej/yr)

Sum of Items 1 – 12
= 1.74E+23

SPECIFIC EMERGY OF EXTRACTED COPPER ORE

13 Extracted Copper Ore (sej/g)

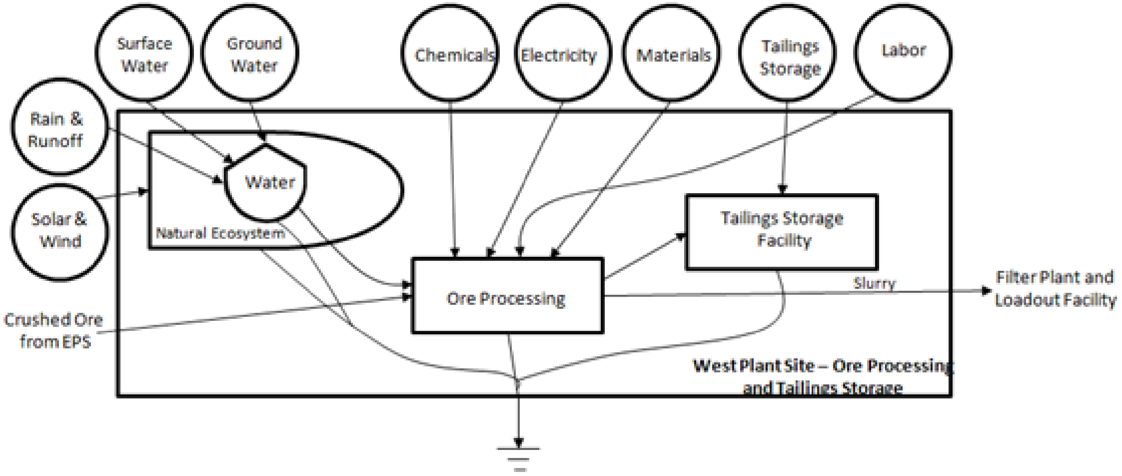
2.20E+06 tons of copper concentrate shipped/yr
907,185 grams / ton
Shipped Copper Concentrate (g/yr)
= (2.20E+06 tons/yr)(907,185 g/ton)
= 2.00E+12 g/yr
Specific EMERGY of Extracted Copper Ore
= Divide total solar EMERGY by weight of copper concentrate
= (1.74E+23 sej/yr) / (2.00E+12 g/yr)
= 8.71E+10 sej/g

Table 6.1 Materials EMERGY Evaluation

Materials							
Note	**Item**	**Raw Data**	**Data Units (J, g, or $)**	**Solar Emergy/unit (sej/unit)**	**Solar Emergy (sej/yr)**	**Em$ (2008 U.S. $/yr)**	**Source**
Construction Phase							
1	Underground Concrete	3.57E+11	g	2.12E+09	7.57E+20	3.09E+08	Brown and Campbell, 2007
2	Underground Production Consumables	6.10E+11	g	8.83E+09	5.39E+21	2.20E+09	Wes Ingwersen, 2009
3	Construction Steel	4.99E+10	g	2.99E+09	1.49E+20	6.09E+07	Brown and Campbell, 2007
4	Construction Material	7.50E+11	g	2.99E+09	2.24E+21	9.15E+08	SME, Vol. 1, 1992
5	Construction Material	7.83E+09	g	2.99E+09	2.34E+19	9.56E+06	
6	Construction Concrete	2.92E+11	g	2.12E+09	6.19E+20	2.53E+08	Brown and Campbell, 2007
Operations Phase							
7	Underground concrete	1.22E+12	g	2.12E+09	2.59E+21	1.06E+09	Odum, 1996 - Solar Voltaic Cells
8	Underground Production Consumables	3.30E+12	g	8.83E+09	2.91E+22	1.19E+10	Wes Ingwersen, 2009
	Avg. Materials (g/yr)$^{\#}$	1.65E+11		Total (sej)	4.09E+22		
				Avg. Emergy (sej/yr)$^{\#}$	1.02E+21		
$^{\#}$ Averaged over 40 years							

4.8 EMERGY Evaluation of the West Plant Site (Includes the Tailings Storage Facility) [Processing Phase]

Figure 16. EMERGY Diagram of the West Plant Site



The WPS is where crushed ore is processed. After ore processing, the uneconomical materials, tailings, are sent to the TSF. The EMERGY evaluation table for the WPS + TSF is located below.

Table 7. West Plant Site (Includes TSF) – Processing Phase EMERGY Evaluation

West Plant Site (Includes Tailing Storage Facility) - Processing Phase					
Note	Renewable Natural Inputs (*R*)	Raw Data	Data Units (J, g, or $)	Solar Emergy/Unit (sej/unit)	Solar Emergy (sej/yr)	Em$ (2008 U.S. $/yr)[a]
1	Solar	3.80E+17	J	1.00E+00	3.80E+17	1.55E+05
2	Wind	1.49E+14	J	2.45E+03	3.65E+17	1.49E+05
3	Rain Chemical Potential	3.43E+13	J	3.10E+04	1.06E+18	4.34E+05
4	Runoff	1.63E+13	J	4.70E+04	7.66E+17	3.13E+05
5	Surface Water	5.78E+13	J	8.10E+04	4.68E+18	1.91E+06
	Non-Renewable Natural Inputs (*N*)					
6	Groundwater	1.30E+13	J	3.02E+05	3.93E+18	1.60E+06
	Purchased Inputs (*M & S*)					
7	Electricity	7.01E+14	J	2.92E+05	2.05E+20	8.35E+07
8	Chemicals	4.95E+10	g	varies	1.62E+20	6.61E+07
9	Labor	4.77E+02	people	3.41E+16	1.63E+19	6.64E+06
10	Materials	5.86E+10	g	varies	2.21E+20	9.02E+07
11	Tailings Storage	2.27E+04	$	1.43E+12	3.25E+16	1.32E+04
12	Extracted Copper Ore	--	--	--	1.74E+23	7.10E+10
13	Total Solar EMERGY in Slurry (sej/yr)			=	1.75E+23	
Solar EMERGY per Unit Calculated by Dividing Total Solar EMERGY Previously Used by the Weight						
Note	Item	Solar EMERGY per Mass (sej/g)				
14[b]	Slurry		8.73E+10			
[a] Solar Emergy divided by 2.45E+12 sej/$2008				Total =	6.15E+20	7.13E+10
[b] (2.20E+06 tons of copper concentrate / year)(907,185 grams / ton) = 2.00E+12 grams of copper concentrate per year						
Solar EMERGY per Mass (sej/g) = (1.75E+23 sej/yr) / (2.00E+12 g/yr)						

Calculations for table items are listed below.

RENEWABLE NATURAL RESOURCES

1 Solar Insolation Sources
Land Area 28,908,957.84 m^2
Insolation 8.70E+09 $J/m^2/yr$ NREL, 2006
Albedo 0.30 pac-ibphys.wikispaces.com
Energy (J) = (area)(avg. insolation)(1-albedo) Brown and Campbell, 2007
3.80E+17 J/yr
Transformity (sej/J) 1.00E+00

2 Wind, Kinetic
Area 28,908,957.84 m^2
Air Density (kg/m^3) 1.30
Avg. Annual Wind Velocity (mps) 5.96 www.usa.com
Geostrophic Winds 9.93 Brown and Campbell, 2007
Drag Coefficient 2.00E-03 Brown and Campbell, 2007
Energy (J) = (area)(density)(drag coef)(Geos-grnd velocity)^3(31,500,000)
1.49E+14
Transformity (sej/J) 2.45E+03 Odum et al, 2000

3 Rain Chemical Potential
Land Area 28,908,957.84 m^2
Rain 0.24 m/yr www.USA.com
Volume Rain 6,938,149.88 m^3/yr
Energy (J) = (volume)(1000 kg/m^3)(4940 J/kg) Brown and Campbell, 2007
3.43E+13 J/yr
Transformity (sej/J) 3.10E+04 Odum et al, 2000

4 Runoff
Land Area 28,908,957.84 m^2
Rainfall (m/yr) 0.24
Density of Water (g/m^3) 1E+06
Runoff Coefficient 0.475
Gibbs Free Energy of Water (J/g) 4.94E+00
Energy (J/yr) = (area)(rainfall)(density of water)(*G*)(Runoff Coef.) Odum, 1996
1.63E+13
Transformity (sej/J) 4.70E+04 Odum et al, 2000

5 Surface Water
Volume 1.17E+07 m^3/yr www.resolutioncopper.com
Density of Water 1000 kg/m^3
Gibbs (G) Free Energy of Water 4940 J/kg
Energy (J/yr) = (volume)(density of water)(G) Odum, 1996
5.78E+13
Transformity (sej/J) 8.10E+04 Brown and Campbell, 2007

NONRENEWABLE NATURAL RESOURCES

6 Groundwater

Volume $2.64E+06\ m^3/yr$ www.resolutioncopper.com
Density of Water $1000\ kg/m^3$
Gibbs (G) Free Energy of Water 4940 J/kg
Energy (J/yr) = (volume)(density of water)(G) Odum, 1996
1.30E+13 J/yr
Transformity (sej/J) 3.02E+05 Brown and Campbell, 2007

PURCHASED INPUTS

7 Electricity

Power Consumed (kWh/day) 5.33E+05 SME, Vol. 2, 1992
Conversion (J/kWh) 3.60E+06
Energy (J/yr) = (power consumed)(365 days/1 yr)(Conversion, J/kWh)
7.01E+14
Transformity (sej/J) 2.92E05 Brown and Campbell, 2007

8 Chemicals

Lime (g/yr) 2.48E+10 www.resolutioncopper.com
Specific EMERGY (sej/g) 2.56E+09 Wes Ingwersen, 2009
Sodium Hydrosulfide (g/yr) 1.91E+10 www.resolutioncopper.com
Specific EMERGY (sej/g) 3.97E+09
Misc. Reagents (g/yr) 5.68E+09 www.resolutioncopper.com
Specific EMERGY (sej/g) 3.97E+09
EMERGY (sej/yr) = sum of all quantities multiplied by respective solar EMERGY values
= 1.62E+20

9 Labor

Average Daily Personnel (people) 477
EMERGY Use per Person (sej/day) 9.35E+13 Odum, 1996
EMERGY (sej/yr) = (Avg. Daily Personnel)(EMERGY/person)(365 days/1 yr) =
1.63E+19

10 Materials

Avg. EMERGY (sej/yr) 2.21E+20

[*SEE TABLE 7.1 ON PAGE 65*]

11 Tailings Storage

Capital Cost of Initial Tailings Storage SME, Vol. 2, 1992
Minimum tailings storage cost (\$) = \$20,000 x $T^{0.5}$
= \$20,000 x $(132{,}000\ tons/day)^{0.5}$
\$7.27E+06
Assuming This Cost Is Reoccurring Every 10 yrs and operations last 40 yrs…
Total Cost (\$) = (initial cost) + (initial cost)(40 yrs / 10 yrs) = 9.09E+05

Avg. Cost ($/yr) = (Total Cost) / (40 yrs) = 2.27E+04
EMERGY to Money Ratio (sej/$) 1.43E+12 Odum, 1996
12 Extracted Copper Ore
Sum of sej/yr from EPS
= 1.74E+23 sej/yr

OUTPUT

13 Total Solar EMERGY in Slurry (sej/yr)
= Sum of Line Items 1 – 12
= 1.75E+23

SPECIFIC EMERGY OF SLURRY

14 Calculating Specific EMERGY =
Solar EMERGY Previously Used / Weight

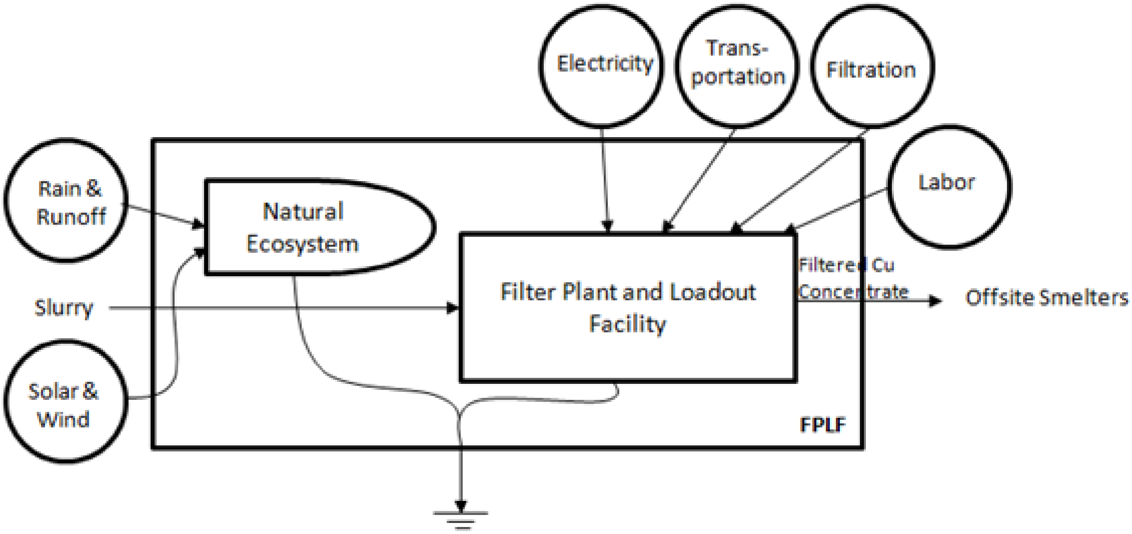
2.20E+06 tons of copper concentrate shipped per year
907,185 grams / ton
Copper concentrate shipped (g/yr)
= (2.20E+06 ton/yr)(907,185 g/ton
= 2.00E+12
Solar EMERGY Previously Used (sej/yr) = 1.75E+23
Specific EMERGY of Slurry (sej/g)
= (1.75E+23 sej/yr) / (2.00E+12 g/yr)
= 8.73E+10

Table 7.1 Materials EMERGY Evaluation

Materials - WPS							
Note	Item	Raw Data	Data Units (J, g, or $)	Solar Emergy/unit (sej/unit)	Solar Emergy (sej/yr)	Em$ (2008 U.S. $/yr)	Source
WPS - Concentrator							
1	Concrete	2.96E+11	g	2.12E+09	6.28E+20	2.56E+08	Brown and Campbell, 2007
2	Rebar	1.54E+10	g	4.13E+09	6.36E+19	2.60E+07	Brown, 2000; Buranakarn, 1998
3	Structural Steel	1.50E+10	g	2.99E+09	4.49E+19	1.83E+07	Brown and Campbell, 2007
4	Handrails/stairs	2.17E+08	g	2.99E+09	6.49E+17	2.65E+05	Brown and Campbell, 2007
5	Grating	1.29E+10	g	2.99E+09	3.86E+19	1.57E+07	Brown and Campbell, 2007
6	Prefab Buildings	5.19E+07	g	varies	1.35E+20	5.51E+07	Buranakarn, 2007
7	Liner Plates	2.82E+08	g	2.12E+09	5.98E+17	2.44E+05	Brown and Campbell, 2007; SME, Vol. 2, 1992
8	Chutes/launders, boxes	3.33E+08	g	2.99E+09	9.96E+17	4.06E+05	Brown and Campbell, 2007; SME, Vol. 2, 1992
9	Tanks	5.79E+07	g	2.99E+09	1.73E+17	7.07E+04	Brown and Campbell, 2007
10	Small Diameter Pipe	2.07E+10	g	2.99E+09	6.19E+19	2.53E+07	Brown and Campbell, 2007
11	Large Diameter Pipe	5.92E+10	g	2.12E+09	1.26E+20	5.12E+07	Brown and Campbell, 2007
12	Electrical Equipment	6.64E+07	g	1.13E+10	7.50E+17	3.06E+05	Brown and Campbell, 2007
13	Overhead Transmission Line	2.35E+07	g	1.25E+10	2.94E+17	1.20E+05	Brown, 2000
TSF - Tailings							
14	Large Diameter Pipe	9.36E+08	g	1.13E+10	1.06E+19	4.32E+06	Brown and Campbell, 2007
15	Valves				0.00E+00	0.00E+00	
16	Concrete	9.08E+10	g	2.12E+09	1.92E+20	7.86E+07	Odum, 1996 - Solar Voltaic Cells
17	Asphalt	1.79E+10	g	2.62E+09	4.69E+19	1.91E+07	Bastianoni et al, 2009
18	Structural Steel	9.07E+07	g	2.99E+09	2.71E+17	1.11E+05	Odum, 1996 - Solar Voltaic Cells
WPS							
19*	SAG Mill, Ball Mill & Regrind Mill Balls	4.54E+10	g/yr	4.13E+09	7.50E+21	#DIV/0!	SME, Vol. 2, 1992; Brown, 2000; Buranakarn, 1998
	Avg. Total (g)	5.86E+10		Total	8.85E+21	5.51E+08	
				Average (unit/yr)$^{\#}$	2.21E+20	1.38E+07	
* This material is g/yr. Total emergy = (sej/yr) x (40 yrs)							
$^{\#}$Averaged over 40 years							

4.9 EMERGY Evaluation of the Filter Plant and Loadout Facility [Part of Processing Phase]

Figure 17. EMERGY Diagram of the Filter Plant and Loadout Facility



The FPLF is where a filter plant separates copper concentrate and sends it to the adjacent loadout facility. At the loadout facility is where a covered stockpile with capacity of 110,000 tons will store the concentrate from the filter plant. The concentrate will be loaded onto railcars and shipped seven miles southwest to Magma, where it will be loaded onto cars for delivery via the Union Pacific Railroad to an off-site smelter. It is estimated that 2.20E+6 tons of concentrate will be shipped per year. The EMERGY evaluation table for the FPLF is shown below.

Table 8. Filter Plant and Loadout Facility – Component of Processing Phase EMERGY Evaluation

Filter Plant and Loadout Facility - Component of Processing Phase						
Note	Renewable Natural Inputs (*R*)	Raw Data	Data Units (J, g, or $)	Solar Emergy/Unit (sej/unit)	Solar Emergy (sej/yr)	Em$ (2008 U.S. $/yr)[a]
1	Sun	1.56E+16	J	1.00E+00	1.56E+16	6.37E+03
2	Wind	1.31E+13	J	2.45E+03	3.21E+16	1.31E+04
3	Rain Chemical Potential	3.03E+12	J	3.10E+04	9.39E+16	3.83E+04
4	Runoff	1.44E+12	J	4.70E+04	6.77E+16	2.76E+04
	Purchased Inputs (*M & S*)					
5	Electricity	2.10E+14	J	2.92E+05	6.13E+19	2.50E+07
6	Labor	30	people	3.41E+16	1.02E+18	4.18E+05
7	Filtration	3.04E+06	$	1.43E+12	4.35E+18	1.77E+06
8*	Transportation (Railcar)	1.54E+07	ton-mile	5.07E+10	7.81E+17	3.19E+05
9	Slurry	--	--	--	1.75E+23	7.14E+10
10	Total Solar EMERGY in Filtered Copper Concentrate (sej/yr)			=	1.75E+23	
Solar EMERGY per Unit Calculated by Dividing Total Solar EMERGY Previously Used by the Weight						
Note	Item	Solar EMERGY per Mass (sej/g)				
11[b]	Filtered Copper Concentrate		8.76E+10			
*Solar EMERGY/Unit is sej/ton-mile						
[a] Solar Emergy divided by 2.45E+12 sej/$2008						
[b] (2.20E+06 tons of copper concentrate / year)(907,185 grams / ton) = 2.00E+12 grams of copper concentrate per year						
Solar EMERGY per Mass (sej/g) = (1.75E+23 sej/yr) / (2.00E+12 g/yr)						

Calculations for the table items are listed below.

	RENEWABLE NATURAL INPUTS		SOURCES
1	Solar Insolation		
	Land Area	2,559,192.20 m^2	
	Insolation	8.70E+09 $J/m^2/yr$	NREL, 2006
	Albedo	0.30	pac-ibphys.wikispaces.com
	Energy (J) = (area)(avg. insolation)(1-albedo)		Brown and Campbell, 2007
		1.56E+16 J/yr	
	Transformity (sej/J)	1.00E+00	
2	Wind, Kinetic		
	Area	2,559,192.20 m^2	
	Air Density (kg/m^3)	1.30	Brown and Campbell, 2007
	Avg. Annual Wind Velocity (mps)	5.96	www.usa.com
	Geostrophic Winds	9.93	Brown and Campbell, 2007
	Drag Coefficient	2.00E-03	Brown and Campbell, 2007
	Energy (J) = (area)(density)(drag coef)(Geos-grnd velocity)^3(31,500,000)		
		1.31E+13	
	Transformity (sej/J)	2.45E+03	Odum et al, 2000
3	Rain Chemical Potential		
	Land Area	2,559,192.20 m^2	
	Rain	0.24 m/yr	www.USA.com
	Volume Rain	614,206.13 m^3/yr	
	Energy (J) = (volume)(1000 kg/m^3)(4940 J/kg)		Brown and Campbell, 2007
		3.03E+12 J/yr	
	Transformity (sej/J)	3.10E+04	Odum et al, 2000
4	Rain Geopotential		
	Land Area	2,559,192.2 m^2	
	Rainfall (m/yr)	0.24	
	Density of Water (g/m^3)	1E+06	
	Runoff Coefficient	0.475	
	Gibbs Free Energy of Water (J/g)	4.94E+00	
	Energy (J/yr) = (area)(rainfall)(density of water)(*G*)(Runoff Coef.)		Odum, 1996
		1.44E+12	
	Transformity (sej/J)	4.70E+04	Odum et al, 2000
	PURCHASED INPUTS		
5	Electricity		
	Power Consumed (kWh/day)	1.60E+05	SME, Vol. 2, 1992
	Energy (J/kWh)	3.60E+06	
	Energy (J/yr) = (Power Consumed)(365 days/1 yr)(Energy, J/kWh)		
		2.10E+14	
	Transformity (sej/J)	2.92E+05	Brown and Campbell, 2007

6 Labor

Avg. Daily Personnel (people) 30

EMERGY Use per Person (sej/day) 9.35E+13 Odum, 1996

EMERGY (sej/yr) = (Avg. Daily Personnel)(EMERGY/person)(365 days/1 yr)

1.02E+18

7 Goods

Cost of Processing (includes equipment and tanks for thickening, filtering, precipitation, leaching, etc., plus all process piping, electrical wiring and process control

Process Capital Costs = \$20,600 x $T^{0.6}$, where *T* is tons mined per day

SME, Vol. 2, 1992

= \$20,600 x (132,000 tons/day)$^{0.6}$

\$2.43E+07

Assuming that new equipment must be bought every 10 years and that mine operations last 40 years…

= (initial cost of processing)+(cost of processing)(40 years / 10 yrs)

\$1.22E+08

Avg. Cost of Processing (\$/yr) = (\$1.22E+08) / (40 yrs)

\$3.04E+06

EMERGY to Money Ratio (sej/\$) 1.43E+12

8 Transportation by Rail

Unit EMERGY Value (sej/ton-mile) 5.07E+10 Buranakarn, 1998

Distance to be Traveled (miles) 7

Concentrate to be Shipped (ton/yr) 2.20E+06

EMERGY (sej/yr) = (Transformity)(Distance)(Concentrate shipped)

7.81E+17

9 Slurry

Sum of sej/yr from WPS

= 1.75E+23

OUTPUT

10 Total Solar EMERGY in Filtered Copper Concentrate (sej/yr)

= Sum of Items 1 – 9

= 1.75E+23

SPECIFIC EMERGY OF FILTERED COPPER CONCENTRATE

11 Calculating Specific EMERGY =

Solar EMERGY Previously Used / Weight

2.20E+06 tons of copper concentrate shipped per year

907,185 grams / ton

Copper concentrate shipped (g/yr)

= (2.20E+06 ton/yr)(907,185 g/ton

= 2.00E+12

Solar EMERGY Previously Used (sej/yr) = 1.75E+23
Specific EMERGY of Filtered Copper Concentrate (sej/g)
= (1.75E+23 sej/yr) / (2.00E+12 g/yr)
= 8.76E+10

4.10 EMERGY Evaluation of the Refining Phase

After the FPLF, the filtered copper concentrate is to be shipped seven miles via rail. It is estimated that 2.2 million tons/yr of copper concentrate will be shipped over the project's lifetime (40 yrs) [64]. The refining process for the copper concentrate was not mentioned in the MPO. Using other EMERGY studies, it was possible to create a hypothetical refining process [58]. The stages of refining include: smelting, converting, electrorefining and gas cleaning. Various methods of refining were examined, but this analysis only calculated the emergy for the refining method involving an electric furnace. The emergy evaluation table and calculations are listed below.

Table 9. Refining Method – Electric Furnace EMERGY Evaluation

Refining Method - Electric Furnace				EMERGY/unit	Solar Emergy	Em$ (2008
Stage of Refining	Primary Energy Sources	Btu/yr	J/yr	(sej/unit)	(sej/yr)	U.S.$/yr)[a]
Smelting						
	Electricity	4.19E+13	4.42E+16	2.92E+05	1.29E+22	5.26E+09
Converting						
	Electricity	6.42E+12	6.78E+15	2.92E+05	1.98E+21	8.08E+08
	Fuel [diesel]	7.88E+12	8.31E+15	6.60E+04	5.48E+20	2.24E+08
Electrorefining						
	Electricity	4.50E+10	4.75E+13	2.92E+05	1.39E+19	5.66E+06
Gas Cleaning						
	Gas [Natural]	2.82E+13	2.98E+16	4.35E+04	1.30E+21	5.29E+08
[a] Solar Emergy divided by 2.45E+12 sej/$2008				Total =	1.67E+22	6.83E+09

STAGE OF REFINING SOURCES

Smelting
Energy Requirement (Btu/ton) 19.03E+06 [55]
Energy Requirement (Btu/yr) =
(Energy Requirement)(Cu Concentrate Shipped) =
(19.03E+6 Btu/ton)(2.20E+06 ton/yr) =
4.19E+13
1 Btu = 1055 Joules
Energy Requirement (J/yr) = (Energy Requirement, Btu/yr)(1055 J / 1 Btu) =
4.42E+16
Transformity (sej/J) 2.92E+05 Brown and Campbell, 2007

Converting
Electricity Requirement (Btu/ton) 2.92E+06 Princeton
Electricity Requirement (Btu/yr) =
(Electricity Req.)(Cu Concentrate Shipped) =
(2.92E+06 Btu/ton)(2.20E06 ton/yr) =
6.42E+12
1 Btu = 1055 Joules
Electricity Requirement (J/yr) = (Energy Requirement, Btu/yr)(1055 J / 1 Btu) =
6.78E+15
Transformity (sej/J) 2.92E+05 Brown and Campbell, 2007
Fuel Requirement (Btu/ton) 3.58E+06 Princeton
Fuel Requirement (Btu/yr) =
(Fuel Requirement)(Cu Concentrate Shipped) =
(3.58E+06 Btu/ton)(2.20E+06 ton/yr) =
7.88E+12
1 Btu = 1055 Joules
Fuel Requirement (J/yr) = (Fuel Requirement, Btu/yr)(1055 J / 1 Btu) =
8.31E+15
Transformity (sej/J) [Diesel] 6.60E+04 Bastianoni et al, 2009

Electrorefining
Energy Requirement (Btu/ton) 56.1 Princeton
Energy Requirement (Btu/yr) =
(Energy Req.)(Cu Concentrate Shipped) =
(56.1 Btu/ton)(2.20E+06 ton/yr) =
4.50E+13
1 Btu = 1055 Joules
Energy Requirement (J/yr) = (Energy Requirement, Btu/yr)(1055 J / 1 Btu) =
4.75E+13
Transformity (sej/J) 2.92E+05 Brown and Campbell, 2007

Gas Cleaning
Energy Requirement (Btu/ton) 1.28E+07 Princeton
Energy Requirement (Btu/yr) =
(Energy Req.)(Cu Concentrate Shipped) =
(1.28E+07 Btu/ton)(2.20E+06 ton/yr) =
2.82E+13
1 Btu = 1055 Joules
Energy Requirement (J/yr) = (Energy Req., Btu/yr)(1055 J / 1 Btu) =
2.98E+16
Transformity (sej/J) [Natural Gas] 4.35E+04 Bastianoni et al, 2009

4.11 EMERGY Evaluation of Resolution Copper Water Resources

Water budget data for the mining operation was gathered from three figures provided by RC. These figures detailed the various mining processes and distribution of water throughout the mining operation and the mine's lifetime (years 0 – 45). Figure 17 is the water budget for years 0 – 8. No data was provided for years 9 – 19. This incomplete data was remedied by the assumption that because it was a period of 10 years, the years 9 – 19 would have the same water budget as years 35 – 45. The water budget is given in gallons per minute (gpm), which was converted into gallons per year (gpy) for each time period. The gpy were multiplied by the years for each time period to determine total amount of water in gallons required for operations. The sum of all time period's total water amount was divided by the length of operations (45 years), to create an average amount of water in gallons used per year.

It was determined, from RC's water budget figures, that there were seven water flows of interest within the mining operation, and they were: CAP, Recovery Well, Filter Return, TSF Inflow Precipitation and Runoff, WPS Mine Dewatering and Ore Moisture and Treated Effluent, TSF Reclaimed Seepage and TSF Reclaim to Plant. Below, Table10 shows the water budget for the seven flows during each time period. 1 gal of liquid equals 0.0038 m^3, so the total water volume (m^3/yr) was calculated by multiplying the average gpy by 0.0038 m^3. The energy (J/yr) of each water flow was calculated the same way the energy of the surface water was calculated earlier, energy (J/yr) = (water volume)(water density)(Gibbs free energy of water). Water has a density of 1000 kg/m^3 and a Gibb's free energy of 4940 J/kg.

Figure 18. RESOLUTION COPPER General Plan of Operations – Process Water Supply and Balance – Years 1 – 8

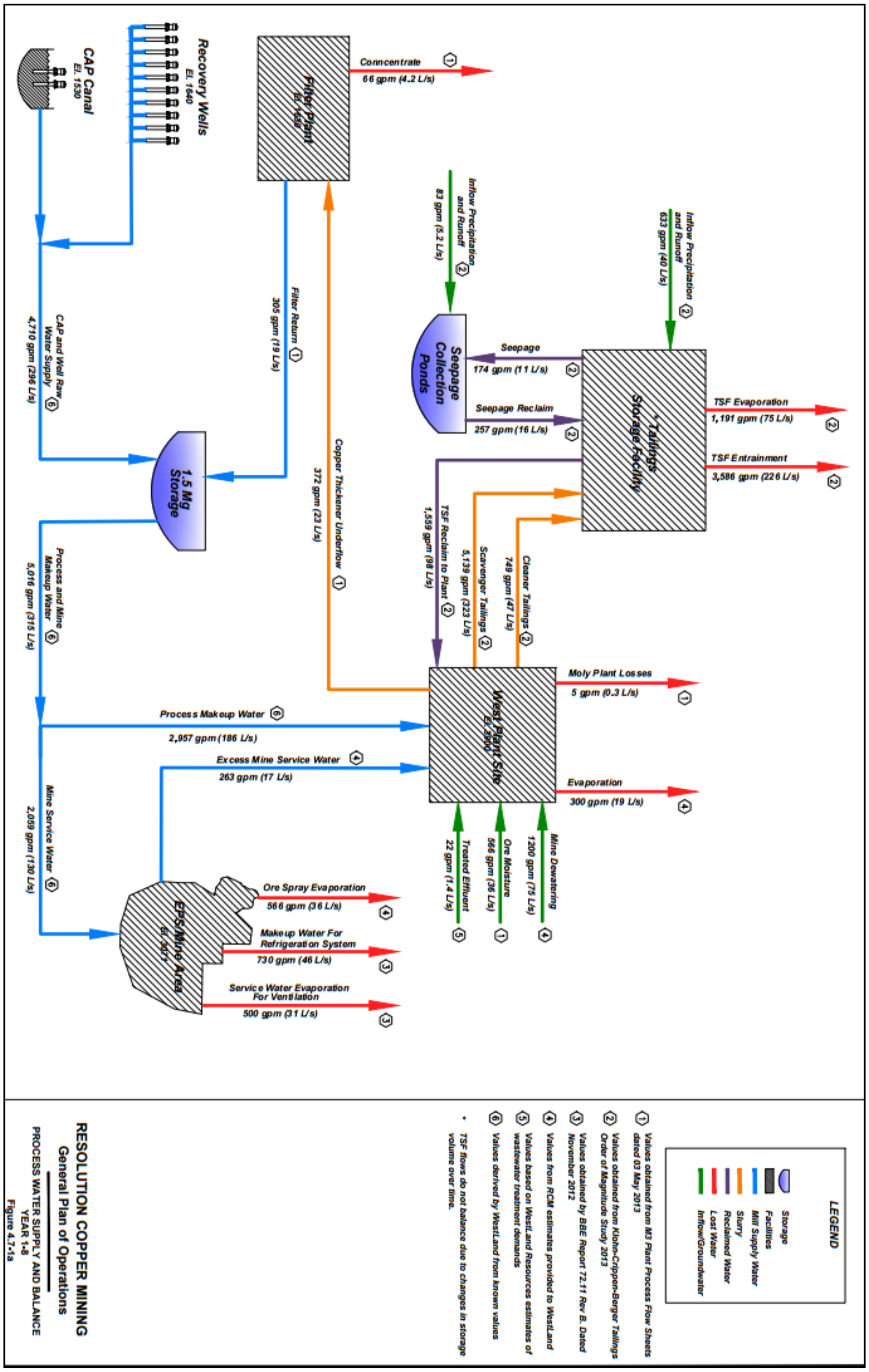


Table 10. Resolution Copper Water Budget

Resolution Copper Water Budget							
Years	CAP (gpy)	Recovery (gpy)	Filter Return (gpy)	TSF Inflow Precipitation & Runoff (gpy)	WPS Mine Dewatering, ore moisture, treated effluent (gpy)	TSF Reclaimed Seepage (gpy)	TSF Reclaim to Plant (gpy)
0-8	1.24E+09	1.24E+09	1.60E+08	3.76E+08	9.40E+08	9.15E+07	8.19E+08
9-19	1.61E+09	1.46E+09	5.73E+07	8.48E+08	5.59E+08	2.83E+08	3.07E+08
20-34	2.80E+09	2.80E+09	2.52E+08	9.15E+08	1.11E+09	2.68E+08	7.95E+08
35-45	1.46E+09	1.46E+09	5.73E+07	8.48E+08	5.59E+08	2.83E+08	3.07E+08
Average GPY	1.54E+09	1.54E+09	1.30E+08	5.87E+08	6.95E+08	1.77E+08	5.04E+08
Total Water (m^3/yr)	5.86E+06	5.85E+06	4.95E+05	2.23E+06	2.64E+06	6.71E+05	1.92E+06
Energy (J/yr)	2.89E+13	2.89E+13	2.44E+12	1.10E+13	1.30E+13	3.31E+12	9.46E+12
Transformity (sej/unit)	8.10E+04	2.79E+05	3.80E+05	3.10E+04	3.02E+05	3.80E+05	3.80E+05
Emergy (sej/yr)	2.34E+18	8.06E+18	9.28E+17	3.42E+17	3.94E+18	1.26E+18	3.60E+18

The recovery wells are full of water taken from the CAP, which meant, during calculations, the recovery well water was combined with the CAP water to form one water flow, Surface Water (blue in the above table). The Filter Return, TSF Reclaimed Seepage and TSF Reclaim to Plant were combined to form one water flow, Reclaimed Water (purple in the above table). TSF Inflow Precipitation and Runoff (green in the above table) was divided into two categories, Rain and Runoff. The volumes for Rain and Runoff, respectively, are simply TSF Inflow Precipitation and Runoff divided by two. WPS Mine Dewatering, Ore moisture and Treated effluent (red in the above table) was considered groundwater. The majority (99%) of this water is from mine dewatering and ore moisture, treated effluent's water contribution is negligible, i.e. it is too small to have its own separate category. The diagram below is the EMERGY diagram for the RC water budget. Goods and Services represent the following items: Water Supply System, Mine Pumping System, Mine Dewatering and Human Labor. The accompanying table is the EMERGY evaluation table for RC's operation. Remember, RC's operation is the proxy for new copper mining water resource efficiency.

Figure 19. EMERGY Diagram of Resolution Copper Water Budget

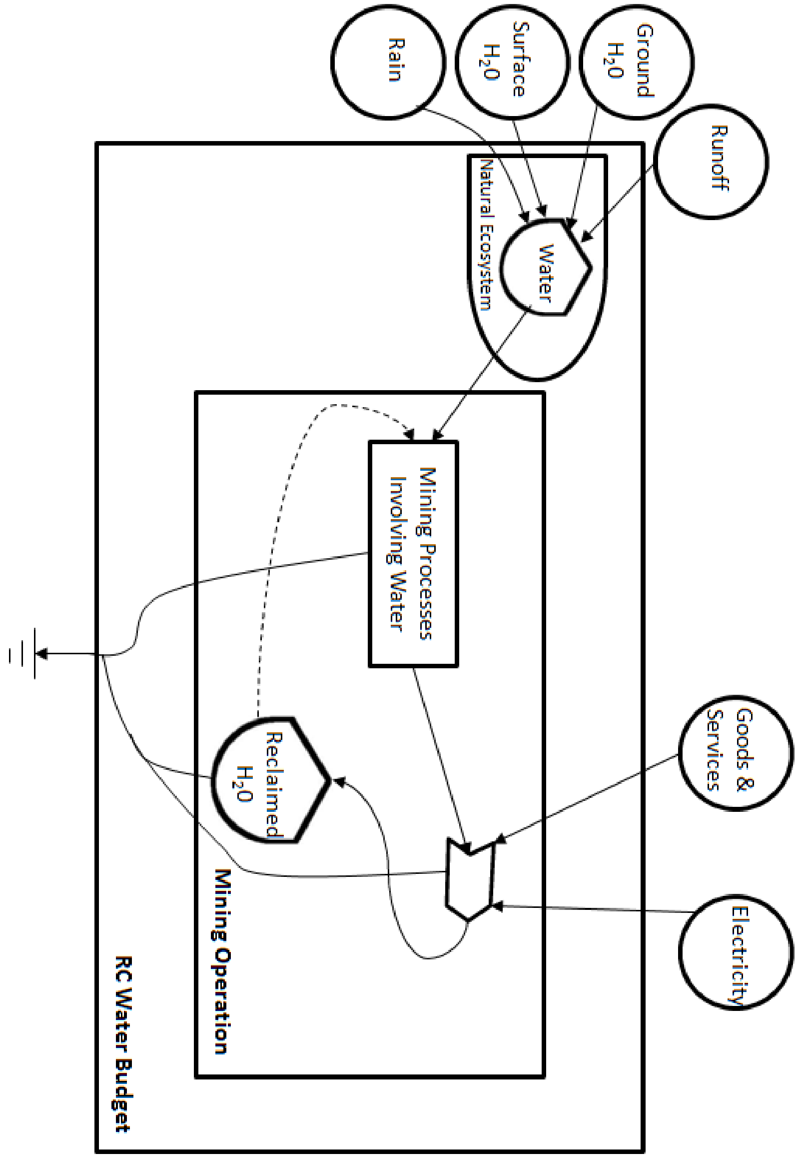


Table 11. Mine Site Water Budget for Entire Mine Life (Construction + Operations) EMERGY Evaluation

Mine Site Water Budget for Entire Mine Life (Construction + Operations)						
Note	Ren. Natural Inputs (*R*)	Data	Units/yr	UEV (sej/unit)	Emergy (sej/yr)	Em$ (2008 U.S. $/yr)[a]
1	Surface Water	5.78E+13	J	8.10E+04	4.68E+18	1.91E+06
2	Rain Chemical Potential	5.51E+12	J	3.10E+04	1.71E+17	6.98E+04
3	Runoff	5.51E+12	J	4.70E+04	2.59E+17	1.06E+05
	NonRen. Natural Inputs (N)					
4	Groundwater	1.30E+13	J	3.02E+05	3.93E+18	1.61E+06
	Purchased Inputs (*M*)					
5	Electricity	6.50E+11	J	2.92E+05	1.90E+17	7.76E+04
6	Reclaimed Water	6.85E+10	g	3.80E+05	2.60E+16	1.06E+04
7	Water Supply System	5.92E+05	$	1.43E+12	8.47E+17	3.46E+05
8	Mine Pumping System	6.46E+06	$	1.43E+12	9.24E+18	3.78E+06
9	Mine Dewatering	5.30E+14	J	2.92E+05	1.55E+20	6.33E+07
	Services (S)					
10	Human Labor	3.80E+09	J	7.38E+06	2.80E+16	1.15E+04
[a] Solar Emergy divided by 2.45E+12 sej/$2008				Total =	1.74E+20	7.12E+07

Calculations for table items are listed below.

RENEWABLE NATURAL INPUTS

1	Surface Water		SOURCES
	Volume (m^3/yr)	1.17E+07	www.resolutioncopper.com
	Energy (J/yr) = (Volume)(Density)(G)		
	(1.17E+07)(1000 kg/m^3)(4940 J/kg)		
	= 5.78E+13		
	Transformity (sej/J)	8.10E+04	Brown and Campbell, 2007
2	Rain Chemical Potential		
	Volume (m^3/yr)	1.12E+06	www.resolutioncopper.com
	Energy (J/yr) = (Volume)(Density)(G)		Brown and Campbell, 2007
	(5.51E+12)(1000 kg/m^3)(4940 J/kg)		
	= 5.51E+12		
	Transformity (sej/J)	3.10E+04	Odum, 1996
3	Rain Geopotential		
	Volume (m^3/yr)	1.12E+06	www.resolutioncopper.com
	Energy (J/yr) = (Volume)(Density)(G)		Brown and Campbell, 2007
	= (5.51E+12)(1000 kg/m^3)(4940 J/kg)		
	= 5.51E+12		
	Transformity (sej/J)	4.70E+04	Brown and Campbell, 2007

NONRENEWABLE NATURAL INPUTS

4	Groundwater		
	Volume (m^3/yr)	2.64E+06	www.resolutioncopper.com
	Energy (J/yr) = (Volume)(Density)(G)		Brown and Campbell, 2007
	= (2.64E+06)(1000 kg/m^3)(4940 J/kg)		
	= 1.30E+13		
	Transformity (sej/J)	3.02E+05	Brown and Campbell, 2007

PURCHASED INPUTS

5	Electricity		
	Electricity Required to Operate Waste Treatment Plant (J/yr) = 6.50E+11		Siracusa and Rosa, 2006
	Transformity (sej/J)	2.92E+05	Brown and Campbell, 2007
6	Reclaimed Water		
	Total Volume (m^3/yr)	3.08E+06	
	Total Water (g/yr) = (Volume)(1000 kg/m^3)(1000 g/kg)		
	= 6.85E+10		
	Specific EMERGY (sej/g)	3.80+05	Siracusa and Rosa, 2006
7	Water Supply System		
	Cost of Water Supply System ($/yr) =		SME, Vol. 2, 1992

$5,300 x $T^{0.4}$, where *T* is tons of ore mined daily
= $5,300 x $(132{,}000)^{0.4}$ = 5.92E+05
EMERGY to Money Ratio (sej/$1992) 1.43E+12 Odum, 1996
The transformity is for $1992 due to SME's
equations being from 1992

8 Mine Pumping System
Cost of Mine Pumping System ($/yr) = SME, Vol. 2, 1992
$5,800 x HP$^{0.7}$, where HP is horsepower
$5,800 x $(2.25\text{E}+04)^{0.7}$ = 6.46E+06
EMERGY to Money Ratio (sej/$1992) 1.43E+12 Odum, 1996
The transformity is for $1992 due to SME's
equations published in 1992

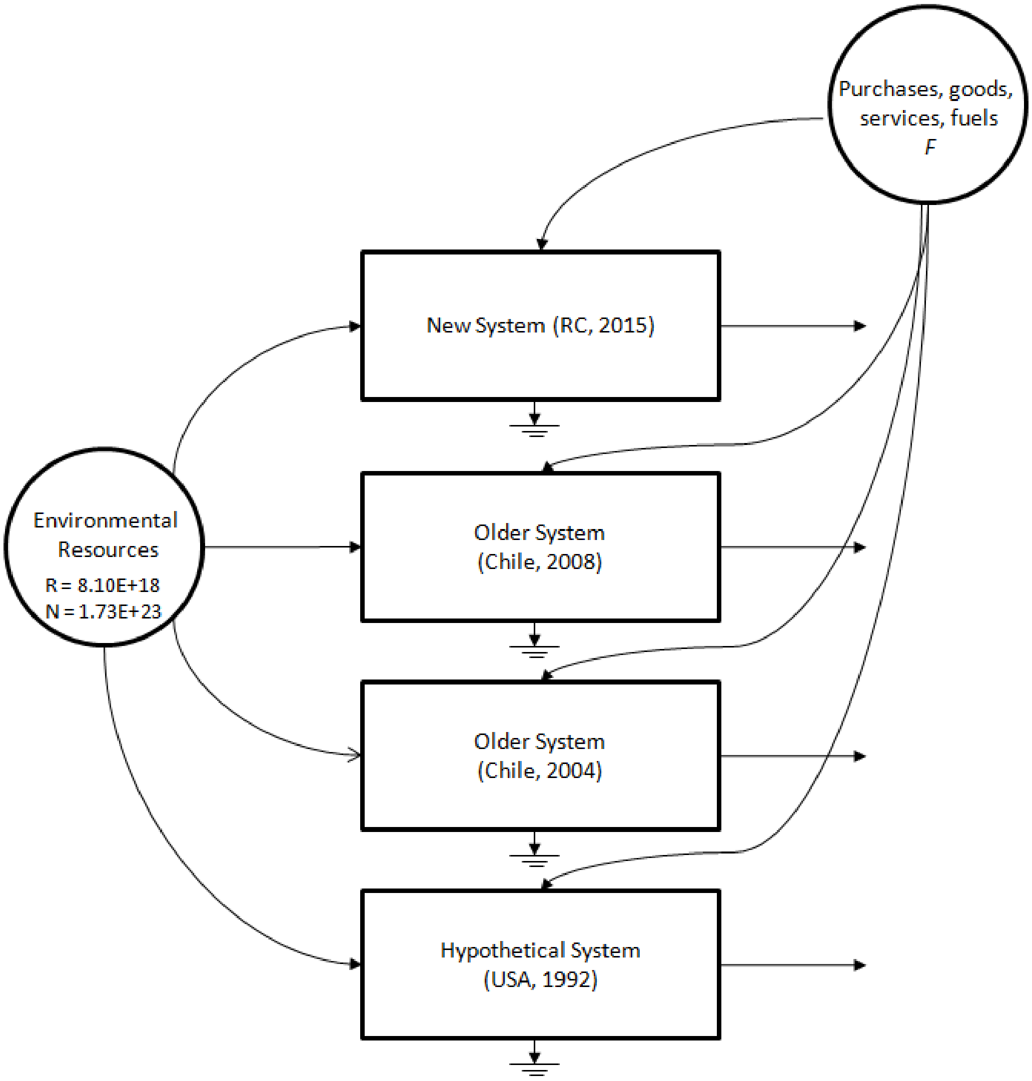
9 Mine Dewatering
Underground Mine Drainage System (HP) = SME, Vol. 2, 1992
62 x $T^{0.5}$, where *T* is tons of ore mined/day
62 x $(132{,}000)^{0.5}$ = 2.25E+04
Conversion 1 HP = 746 J/s
Energy (J/yr) = (HP)(Conversion)(60 sec / 1 min)(60 min / 1 hr)(24 hr / 1 day)(365 days / 1 yr) = 5.30E+14
Transformity (sej/J) 2.92E+05
Assuming electricity is used to dewater

10 Human Labor
Labor required for
treating wastewater for reuse (J/yr) = 3.80E+09 Siracusa and Rosa, 2006
Transformity (sej/J) 7.83E+06 Siracusa and Rosa, 2006

4.12 EMERGY Evaluation of Energy Tradeoffs

The electricity for the entire mine site has already been calculated. The EMERGY of an operation that uses other quantities of electricity and fuel can be calculated. Figure 19 below compares the energy efficiency of RC and earlier mining operations.

Figure 20. EMERGY Diagram for Energy/Fuel Alternatives



It was assumed that the environmental resources for each operation were the same as RC and that the only differing variables were fuel and electricity. Table 12 is an EMERGY comparison of each operation's energy efficiency.

Table 12. EMERGY Energy Comparison of Mining Operations

EMERGY Energy Comparison of Mining Operations[a]						
Resolution Copper (2015)		Raw Data	Unit	EMERGY/Unit	EMERGY (sej/yr)	Em$ (2008 U.S.$/yr)*
	Fuel	4.40E+09	g	2.83E+09	1.25E+19	5.08E+06
	Electricity	1.96E+15	J	2.92E+05	5.72E+20	2.34E+08
Chile (2008)						
	Fuel	2.60E+16	J	6.60E+04	1.72E+21	7.00E+08
	Electricity	4.20E+16	J	2.92E+05	1.23E+22	5.01E+09
Chile (2004)						
	Fuel	2.00E+16	J	6.60E+04	1.32E+21	5.39E+08
	Electricity	2.52E+16	J	2.92E+05	7.36E+21	3.00E+09
Hypothetical Operation (USA, 1992)						
	Fuel	2.43E+11	g	2.83E+09	6.88E+20	2.81E+08
	Gas [Natural]	1.67E+19	J	4.35E+04	7.26E+23	2.97E+11
	Electricity	2.69E+16	J	2.92E+05	7.85E+21	3.21E+09

* Solar Emergy divided by 2.45E+12 sej/$2008

[a] Assumed that each operation produced 2.20E+06 tons of copper concentrate per year

Calculations for table items are listed below. Resolution Copper’s inputs have already been quantified; please see Section 4.4 to review calculations.

Source

2 Chile (2004) [18]

Fuel Consumption (MJ/MTF) 1000.60
1 MJ = 1.00E+07 J
1 MTF = 1.1 ton of refined copper
Fuel Consumption (J/ton) = (Fuel, MJ/MTF)(1.00E+07 J/1MJ)(1MTF / 1.1ton) =
9.10E+09
Assuming 2.20E+06 tons of refined copper are shipped each year
Fuel Consumption (J/yr) =
(9.10E+09 J/ton)(2.20E+06 tons/yr) =
2.00E+16
Transformity (sej/J) 6.60E+04 Martin et al, 2006
Electricity Consumption (MJ/MTF) 1257.9 [18]
1 MJ = 1.00E+07 J
1 MTF = 1.1 ton of refined copper
Electricity Consumption (J/ton) = (Fuel, MJ/MTF)(1.00E+07 J/1 MJ)(1 MTF/1.1ton) =
1.14E+10
Assuming 2.20E+06 tons of refined copper are shipped each year
Electricity Consumption (J/yr) =
(1.14E+10 J/ton)(2.20E+06 tons/yr) =
2.52E+16
Transformity (sej/J) 2.92E+05 Brown and Campbell, 2007

3 Chile (2008) [18]

Fuel Consumption (MJ/MTF) 1297.60
1 MJ = 1.00E+07 J
1 MTF = 1.1 ton of refined copper
Fuel Consumption (J/ton) = (Fuel, MJ/MTF)(1.00E+07 J/1MJ)(1MTF/1.1ton) =
1.18E+10
Assuming 2.20E+-6 tons of refined copper are shipped each year
Fuel Consumption (J/yr) =
(1.18E+10 J/ton)(2.20E+06 tons/yr) =
2.60E+16
Transformity (sej/J) 6.60E+04 Brown and Campbell, 2007
Electricity Consumption (MJ/MTF) 2099.40 [18]
1 MJ = 1.00E+07 J
1 MTF = 1.1 ton of refined copper

Electricity Consumption (J/ton) = (Elec. MJ/MTF)(1.00E+07 J/1MJ)(1MTF/1.1ton)
= 1.91E+10
Assuming 2.20E+06 tons of refined copper are shipped each year
Electricity Consumption (J/yr) =
(1.91E+10 J/ton)(2.20E+06 tons/yr) =
4.20E+16
Transformity (sej/J) 2.92E+05 Brown and Campbell, 2007

4 Hypothetical Operation (USA, 1992) www.energy.gov
United States Copper Production 1992 (tons) 1.94E+06
Total Fuel Oil (barrels) Consumed in the
US for Copper Production 1.50E+16
Fuel Oil (barrels/ton) = (Total Fuel Oil, barrels) / (1.94E+06 tons) =
7.73E-01
1 barrel = 42 US gallons
1 US gallon = about 7.5 lbs
1 lb = 453.6 g
Fuel Oil (g/ton of refined copper) =
(Fuel Oil, bbls/ton)(1bbl/42 gal)(1 gal/7.5 lbs)(1lb/453.6 g) =
= 1.10E+05
Assuming 2.20E+06 tons of refined copper are shipped each year
Total Fuel Oil (g/yr) = (Fuel Oil, g/ton)(2.20E+06 tons/yr) =
2.43E+11
Specific EMERGY (sej/g) 2.83E+09 Bastianoni et al, 2009

Total Gas [Natural](ft^3) Consumed by US Copper www.energy.gov
Production 2.40E+09
Gas (ft^3/ton) = (Total gas, ft^3) / (1.94E+06 tons) =
1.24E+03
1 ft^3 Natural Gas = 5.80E+06 BTU
Gas (BTU/ton of refined copper) = (1.24E+03 ft^3/ton)(5.80E+06 BTU/ft^3) =
7.17E+09
1 BTU = 1055 J
Gas (J/ton of refined copper) = (7.17E+09 BTU/ton)(1055 J/1 BTU) =
7.57E+12
Assuming 2.20E+06 tons of refined copper are shipped each year
Total Gas (J/yr) = (7.57E+12 J/ton)(2.20E+06 tons) =
1.67E+19
Transformity (sej/J) 4.35E+04

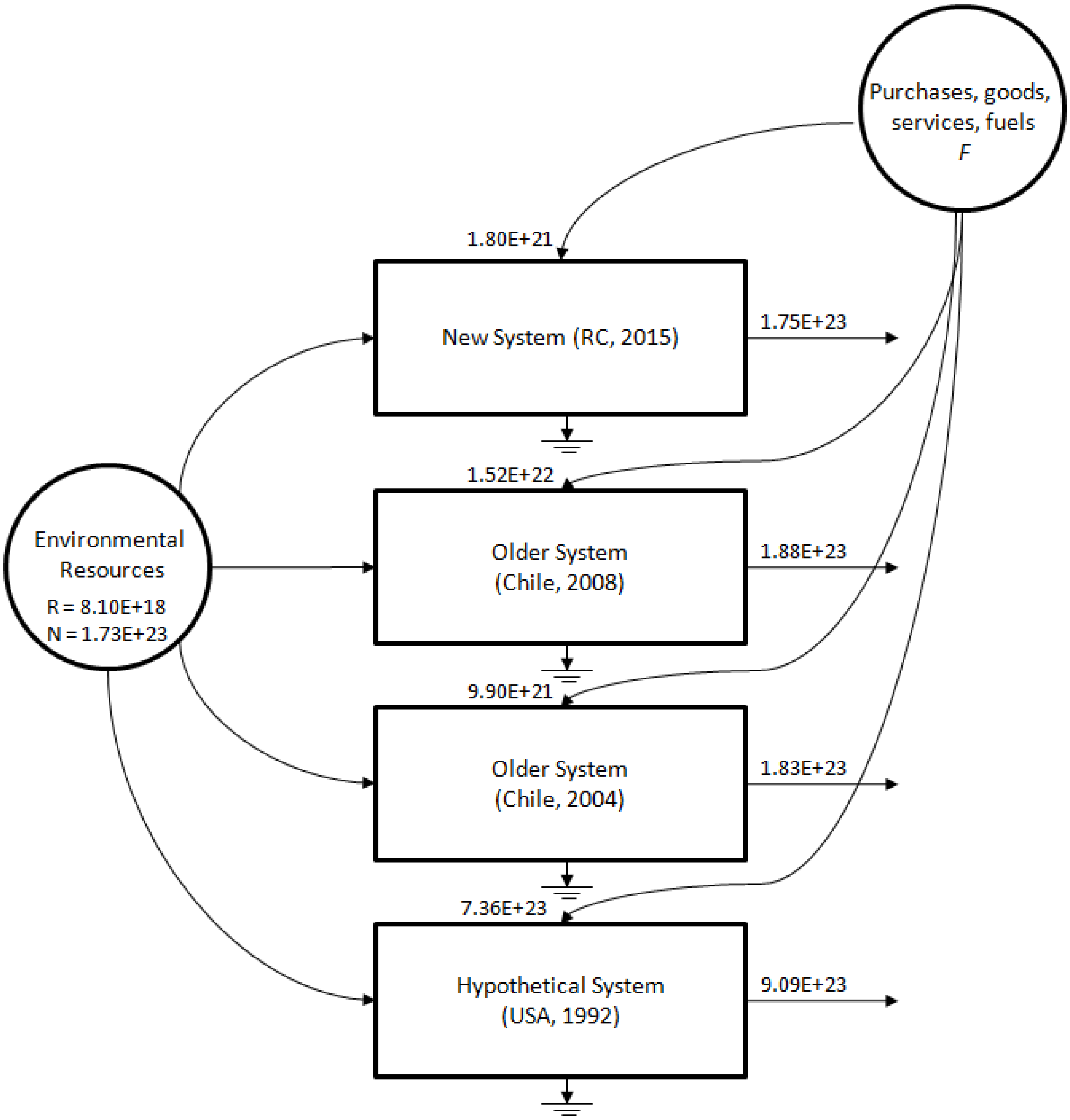
Total Electricity Purchased by the US 1992
Copper Industry (kWh) 6.60E+09 www.energy.gov
Electricity (kWh/ton of refined copper) = (Total Electricity)/(6.60E+09) =

3.40E+03
1 kWh = 3.60E+06 J
Electricity (J/ton of refined copper) = (3.40E+03 kWh/ton)(3.60E+06 J/kWh) =
1.22E+10
Assuming 2.20E+06 tons of refined copper are shipped each year
Total Electricity (J/yr) = (1.22E+10 J/ton)(2.22E+10 tons/yr) =
2.69E+16

Transformity (sej/J)	2.92E+05	Brown and Campbell, 2007

Figure 20 [*Please see next page*] compared the EMERGY flow for each operation, which allowed a comparison of each operation's energy efficiency.

Figure 21. EMERGY Flows for Comparison of Energy Efficiency

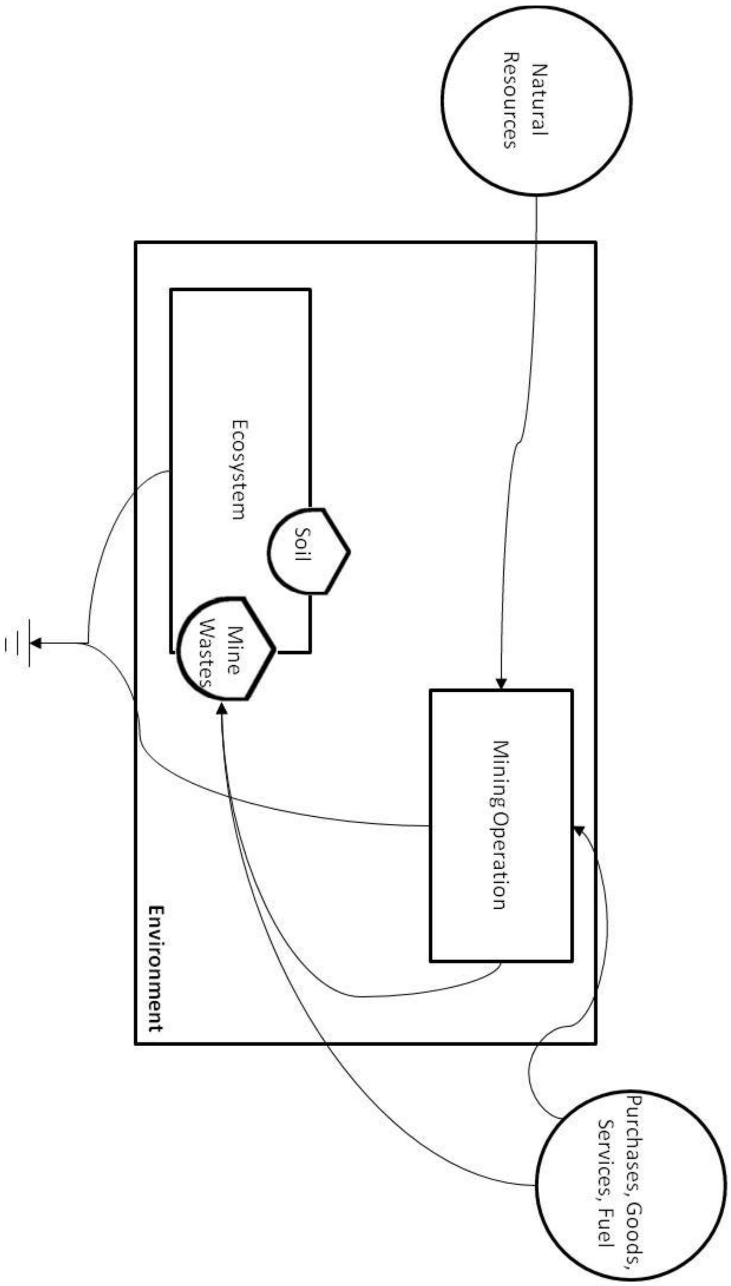


4.13 EMERGY Evaluation of Reclamation Alternatives

4.13.1 Externalized Cost of Mine Waste Clean Up – Hypothetical Copper Mine [Old Practice]

Instead of incorporating the cost of cleanup into the mining business model, old mining operations relied on nature for cleanup. Mining operations polluted waterways and ecosystems by discharging untreated effluent and mine waste directly into these systems. If cleanup was required, it occurred outside the mining system and post-mining operations. Figure 21 below was for visual purposes only.

Figure 22. EMERGY Diagram for Old Method of Mine Cleanup



It was assumed that all inputs, except cleanup of mine wastes, were the same as RC's proposed mining operation. A report on mine cleanup for Shiny Rock Mine (SRM), Marion County, Oregon, was used to estimate the amount of money it would cost for site cleanup caused by waste rock. Investigations discovered that soils were contaminated by metals, primarily lead and cadmium. The chosen method of mine site cleanup consisted of stabilizing soil in a cement mixture and then off-site disposal. The total cost (i.e. analyses, stabilization, trucking and disposal) for 680 cubic yards of metal-contaminated soil was between \$140,600 – \$381,500 [34]. It was assumed that the waste rock produced from the hypothetical old copper mine will equal the amount of tailings produced from RC, i.e. 1.5 billion tons. It was assumed that the mining company would not bear the burden of waste removal. The calculations for cleanup of the hypothetical copper mine are given below.

CALCULATIONS SOURCES
Amount of Waste Rock (tons) 1.50E+9
1 ton = 2000 lbs
Waste Rock (lbs) = (1.5E+09 tons)(2000 lbs/1 ton)
3.00E+12
Moist Excavated Soil (lbs / yd^3) 2430 www.reade.com
Contaminated Soil (yd^3) = (Waste Rock) / (Moist Excavated Soil)
1.23E+09
Cost to Clean Up 680 yd^3 (\$) 140,600 – 381,500 ITRC, 2010
Cost to Clean up 1.50E+09 Tons of Contaminated Soil =
[Low (\$)] ((Contaminated Soil) / (680 yd^3)) x (\$140,600)
2.55E+11
[High (\$)] ((Contaminated Soil) / (680 yd^3)) x (\$381,500)
6.93E11
The Avg. Cost (\$/yr) = (Low) / 45 years
5.67E+09
The Avg. Cost (\$/yr) = (High) / 45 years
1.54E+10
The Avg. Costs (\$/yr) = (Low + High) / 2
1.05E+10

EMERGY to Money Ratio (sej/\$1992) 1.43E+12
Tailings Cost (sej/yr) 1.50E+22

4.13.2 Internalized Cost of Mine Waste Clean Up – Resolution Copper [New Practice]

The cost of tailings for RC was calculated using an equation from SME, Vol. 2, 1992. The tailings cost per day = \$0.92 x $T^{0.8}$ for each concentrators, where T is tons of ore mined per day. It was assumed RC will have one concentrator. The cost of tailings is calculated below.

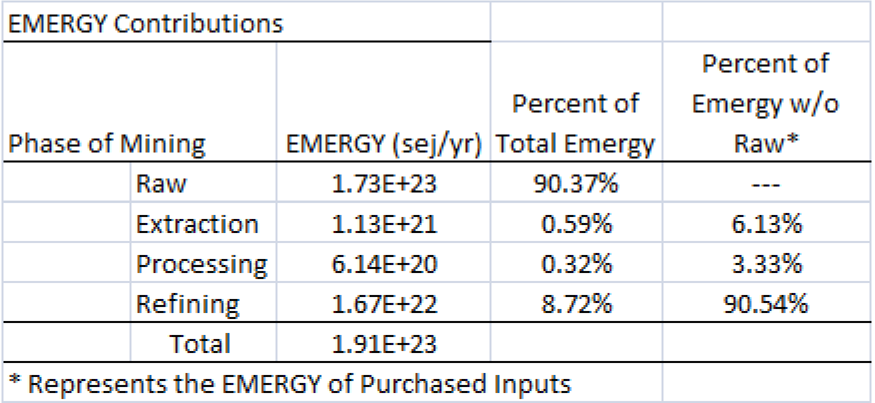
Tailings Cost (\$/day) = \$0.92 x $T^{0.8}$ = \$0.92 x $(132{,}000 \text{ tons/day})^{0.8}$ =
1.15E+04
Tailings Cost (\$/year) = (1.15E+04 \$/day)(365 days/1 yr) =
4.19E+06
EMERGY to Money Ratio (sej/\$1992) 1.43E+12
Tailings Cost (sej/yr) 6.00E+18

Chapter 5 –Discussion

5.1 EMERGY Evaluation of Resolution Copper

The orebody was the single greatest contributor of EMERGY (99%) for the entire mine site operations (note: excludes refining of copper concentrate). Ignoring the EMERGY value of the orebody, purchased inputs comprised almost all of the EMERGY during the mining operation (99%). The four highest contributors of EMERGY were: Materials (56%); Electricity (32%); Chemicals (9%); and Labor (2%). The majority of Materials EMERGY is contributed during the ore processing stage, at the WPS. Since RC will use electricity instead of fuel, it was not surprising that electricity contained a third of the total EMERGY. At the EPS, the EMERGY of the orebody contributed 99% of the total EMERGY during the extraction phase. Ignoring the orebody's EMERGY, the two highest EMERGY contributors at the EPS were Materials (70%) and Electricity (27%). This was an unexpected result. Materials may constitute such a large amount of EMERGY due to underground mining requiring large amounts of steel and cement for infrastructure. At the WPS, the three greatest contributors of EMERGY were: Materials (36%); Electricity (33%); and Chemicals (26%). The EMERGY of WPS Materials was the largest contributor to EMERGY due to the yearly requirements of steel SAG Mill, Ball Mill and Regrind Balls. More likely than not, Chemicals contribute a larger amount of EMERGY than is shown in this analysis. One UEV was used for all chemicals; so calculating the EMERGY of each individual reagent might result in a higher EMERGY contribution. At the FPLF, the two greatest contributors of EMERGY were Electricity (91%) and the process of filtering copper from the slurry (6%). During the refining process, the greatest EMERGY contributors were: Smelting (77%); Converting (12%); and Gas Cleaning (8%). Calculating the EMERGY for each site allowed the evaluation of EMERGY during different mining stages. [*Please see Table 13 below*]. The sites corresponding to mines phases were: geologic energy of the orebody equaled the raw phase; the EPS (without the orebody and copper deposit EMERGY) equaled the extraction phase; the WPS and FPLF equaled the processing phase; and the smelting, converting, electrorefining and gas cleaning represented the refining phase. The raw phase of mining, meaning no interaction between natural and human systems had occurred, accounted for 90.37% of the total EMERGY, meaning the true value of copper comes from the amount of work Nature put into the resource. Ignoring the ore's raw EMERGY, the extraction phase and refining phase constituted approximately 6% and 91%, respectively, of the total EMERGY.

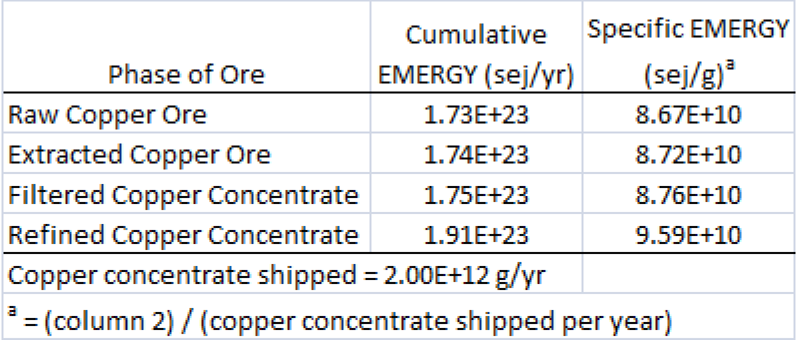
Table 13. EMERGY Contribution of Phases of Mining



EMERGY Contributions			
Phase of Mining	EMERGY (sej/yr)	Percent of Total Emergy	Percent of Emergy w/o Raw*
Raw	1.73E+23	90.37%	---
Extraction	1.13E+21	0.59%	6.13%
Processing	6.14E+20	0.32%	3.33%
Refining	1.67E+22	8.72%	90.54%
Total	1.91E+23		
* Represents the EMERGY of Purchased Inputs			

By evaluating the EMERGY inputs for the stages of mining, it was possible to track changes in Specific EMERGY for the various states of copper. This evaluation showed how the phases of mining contributed to the EMERGY of the finished product, refined copper concentrate. [*Please see Table 14 on the next page]*.

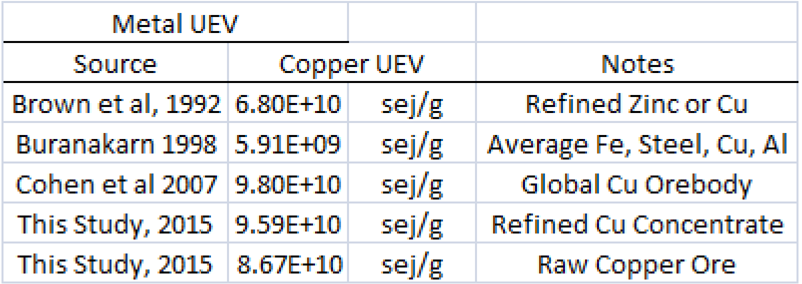
Table 14. Specific EMERGY Changes of Copper



Phase of Ore	Cumulative EMERGY (sej/yr)	Specific EMERGY (sej/g)[a]
Raw Copper Ore	1.73E+23	8.67E+10
Extracted Copper Ore	1.74E+23	8.72E+10
Filtered Copper Concentrate	1.75E+23	8.76E+10
Refined Copper Concentrate	1.91E+23	9.59E+10
Copper concentrate shipped = 2.00E+12 g/yr		
[a] = (column 2) / (copper concentrate shipped per year)		

The Specific EMERGY of a resource is the equivalent solar energy that would be required to create a unit of that resource efficiently and rapidly. A higher Specific EMERGY is reflective of more available energy being used up to create a product. A high Specific EMERGY value indicates a product that requires more purchased inputs, and vice versa for lower Specific EMERGY values. It was important to calculate the Specific EMERGY for RC copper so a comparison could be made to earlier EMERGY studies. Some earlier copper UEVs are listed below.

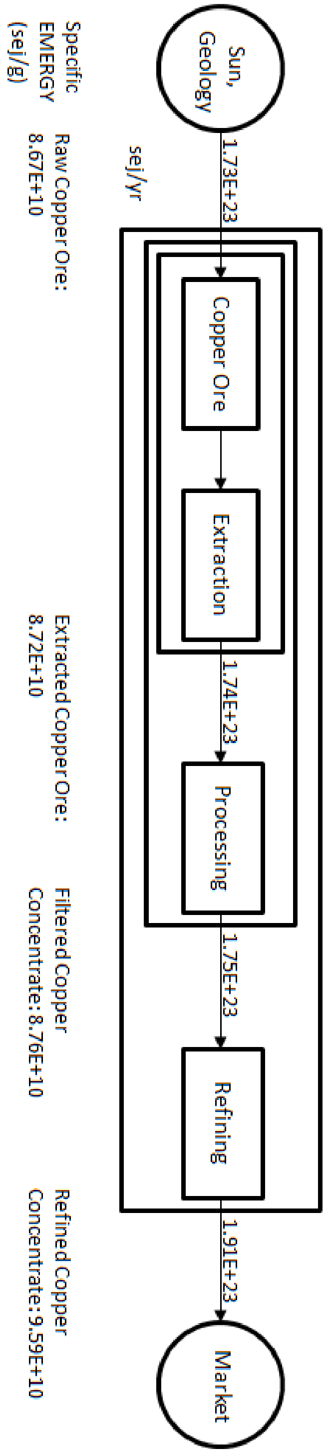
Table 15. Comparison of Copper Specific EMERGIES



Metal UEV			
Source	Copper UEV		Notes
Brown et al, 1992	6.80E+10	sej/g	Refined Zinc or Cu
Buranakarn 1998	5.91E+09	sej/g	Average Fe, Steel, Cu, Al
Cohen et al 2007	9.80E+10	sej/g	Global Cu Orebody
This Study, 2015	9.59E+10	sej/g	Refined Cu Concentrate
This Study, 2015	8.67E+10	sej/g	Raw Copper Ore

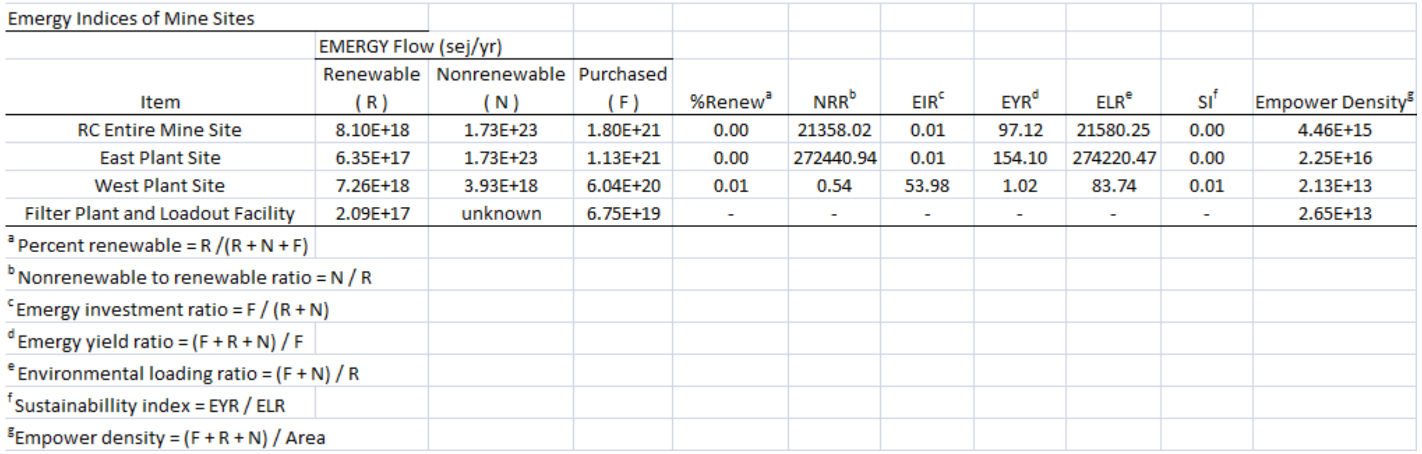
The reported copper UEVs from this analysis were close to previously reported copper UEVs. This thesis used a method of calculation that resulted in a site-specific UEV. This thesis calculated the Specific EMERGY for the raw copper ore and the Specific EMERGY of the refined copper concentrate, with values of 8.67E+10 sej/g and 9.59E+10 sej/g, respectively. Brown et al [14] calculated a UEV that could be used for refined zinc or copper. Buranakarn [16] averaged pig iron, steel ore, copper ore and unrefined aluminum. Cohen et al [19] calculated a Specific EMERGY for copper orebody; his value was meant to be used for all copper deposits, regardless of rock type or geographic location.

Figure 23. EMERGY Changes During Various Phases of Mining



A goal of this thesis was to measure the sustainability of RC’s mining operation and compare it to older copper mining operations. Toward this end, it was possible to use EMERGY evaluation indices to quantify measures of sustainability for the various phases of mining and for RC’s mine site overall. The FPLF data was incomplete so evaluation ratios were not calculated for the site. [*Please see Table 16 on next page*].

Table 16. EMERGY Indices for Mine Sites



Emergy Indices of Mine Sites

	EMERGY Flow (sej/yr)									
Item	Renewable (R)	Nonrenewable (N)	Purchased (F)	%Renew[a]	NRR[b]	EIR[c]	EYR[d]	ELR[e]	SI[f]	Empower Density[g]
RC Entire Mine Site	8.10E+18	1.73E+23	1.80E+21	0.00	21358.02	0.01	97.12	21580.25	0.00	4.46E+15
East Plant Site	6.35E+17	1.73E+23	1.13E+21	0.00	272440.94	0.01	154.10	274220.47	0.00	2.25E+16
West Plant Site	7.26E+18	3.93E+18	6.04E+20	0.01	0.54	53.98	1.02	83.74	0.01	2.13E+13
Filter Plant and Loadout Facility	2.09E+17	unknown	6.75E+19	-	-	-	-	-	-	2.65E+13

[a] Percent renewable = R /(R + N + F)

[b] Nonrenewable to renewable ratio = N / R

[c] Emergy investment ratio = F / (R + N)

[d] Emergy yield ratio = (F + R + N) / F

[e] Environmental loading ratio = (F + N) / R

[f] Sustainabillity index = EYR / ELR

[g] Empower density = (F + R + N) / Area

Percent Renewable (%Renew) is the percent of the total energy driving a process that is derived from renewable sources. Only processes with high %Renew are sustainable [15]. RC's entire mine site's %Renew was 0.00005, which indicated that RC's operation was unsustainable in the long run. This result was not surprising since the copper was being extracted at a much faster rate than natural rates of copper replenishment (millions of years). The Nonrenewable to Renewable Ratio (NRR) is the ratio of nonrenewable energy to the renewable energy used during a process. A high ratio indicates processes that use large amounts of nonrenewable energy to relatively small amounts of renewable energy. The NRR for the entire mine site was approximately 21,358 meaning much more nonrenewable resources were consumed than renewable. The EMERGY Investment Ratio (EIR) is a ratio of EMERGY from outside the system to the EMERGY within the system. It evaluates if the process is a good user of the EMERGY invested, in comparison to alternatives. Overall, the entire mine site had an EIR of approximately 0.01. The EIR for the EPS was 0.01, meaning that, during the extraction phase, much less EMERGY came from outside the mining system than inside. This is to be expected, because the orebody contains almost all the EMERGY. Whereas, at the WPS, the EIR was approximately 54, which reflected the increased amount of purchased inputs required to process the ore. The EMERGY Yield Ratio (EYR) is a ratio of the EMERGY of a processes' output divided by the EMERGY of the inputs to the process. It is an indicator of the yield compared to nonlocal inputs and gives a measure of the ability of a process to exploit local resources [15]. The EYR for the entire mine site was approximately 97; the EPS was 154; and the WPS was about 1. These values are to be expected. The mine operation and EPS exploit local resources, whereas the WPS relies on nonlocal inputs for processing. The Environmental Loading Ratio (ELR) is an indicator of the pressure the mining operation is “putting on the local ecosystem and can be considered a measure of ecosystem stress due to production activity” [15]. The ELR for the entire mine site was approximately 21,580; it is exerting a massive amount of pressure on the surrounding ecosystem. The Sustainability Index (SI) is a measure of a processes’ long-term position relative to other processes. A low SI indicates that a large fraction of the EMERGY used was imported from outside the system, meaning large percentages of total EMERGY are from nonrenewable sources. The SI for RC’s operation was 0.005; this is not a sustainable operation. The Empower Density ratio shows the concentration of EMERGY in an area, and, for RC’s operation, the Empower Density was very high, 4.46E+15 sej per square meter.

5.2 EMERGY Evaluation of Mine Site Water Budget

Mine dewatering was the largest contributor to the water budget’s overall EMERGY (89%), followed by the mine pumping system (5%). The renewable and nonrenewable natural inputs only constituted 5% of the total EMERGY. On the next page, Table 17 gives an account of the EMERGY indices for the RC Water Budget. The %Renew value of 0.03 indicates that RC’s water budget was not sustainable. The NRR of 0.77 indicates that more local renewable sources of water were being used than local nonrenewable sources of water. The EIR of 18.25 indicates that non-local sources of EMERGY were more heavily relied upon than local renewable sources of EMERGY. The EYR of 1.05 indicates that the EMERGY output was approximately equal to the EMERGY inputs for the water budget. The ELR of 33.06 indicates that the mining operation’s use of water was putting large amounts of stress on the local ecosystem. The ELR is particularly pertinent to the state of Arizona, since the state often experiences severe drought. The SI agrees with the %Renew ratio; RC’s use of water resources was not sustainable. The Empower Density was 4.44E+12 sej per square meter.

Table 17. EMERGY Indices for RC Water Budget

EMERGY Indices of RC Water Budget										
	EMERGY Flow (sej/yr)									
Item	Renewable (R)	Nonrenewable (N)	Purchased (F)	%Renew[a]	NRR[b]	EIR[c]	EYR[d]	ELR[e]	SI[f]	Empower Density[g]
RC Water Budget	5.11E+18	3.93E+18	1.65E+20	0.03	0.77	18.25	1.05	33.06	0.03	4.44E+12

[a] Percent renewable = R /(R + N + F)

[b] Nonrenewable to renewable ratio = N / R

[c] Emergy investment ratio = F / (R + N)

[d] Emergy yield ratio = (F + R + N) / F

[e] Environmental loading ratio = (F + N) / R

[f] Sustainabillity index = EYR / ELR

[g] Empower density = (F + R + N) / Area

5.3 EMERGY Evaluation of Alternative Energy Options

RC had a much lower EIR (0.01), meaning RC is not having to invest as much purchased EMERGY as the Hypothetical Operation in 1992 (EIR of approximately 4.25). RC's ELR was approximately 21,580, much lower than the Hypothetical Operation's ELR of approximately 112,000. As time progresses, there appears to be a descending trend in the EIR and ELR. This evidence supports RC's claim of being more sustainable, in terms of energy efficiency, than older operations.

Table 18. EMERGY Indices for Energy Alternatives

EMERGY Indices for Energy Alternatives

	EMERGY Flow (sej/yr)									
Operation (Year)	Renewable (R)	Nonrenewable (N)	Purchased (F)	%Renew[a]	NRR[b]	EIR[c]	EYR[d]	ELR[e]	SI[f]	Empower Density[g]
Resolution Copper (2015)	8.10E+18	1.73E+23	1.80E+21	0.00	21358.02	0.01	97.12	21580.25	0.00	4.46E+15
Chile (2008)	8.10E+18	1.73E+23	1.52E+22	0.00	21358.02	0.09	12.38	23234.57	0.00	4.80E+15
Chile (2004)	8.10E+18	1.73E+23	9.90E+21	0.00	21358.02	0.06	18.48	22580.25	0.00	4.66E+15
Hypothetical (USA, 1992)	8.10E+18	1.73E+23	7.36E+23	0.00	21358.02	4.25	1.24	112222.22	0.00	2.32E+16

[a] Percent renewable = R /(R + N + F)

[b] Nonrenewable to renewable ratio = N / R

[c] Emergy investment ratio = F / (R + N)

[d] Emergy yield ratio = (F + R + N) / F

[e] Environmental loading ratio = (F + N) / R

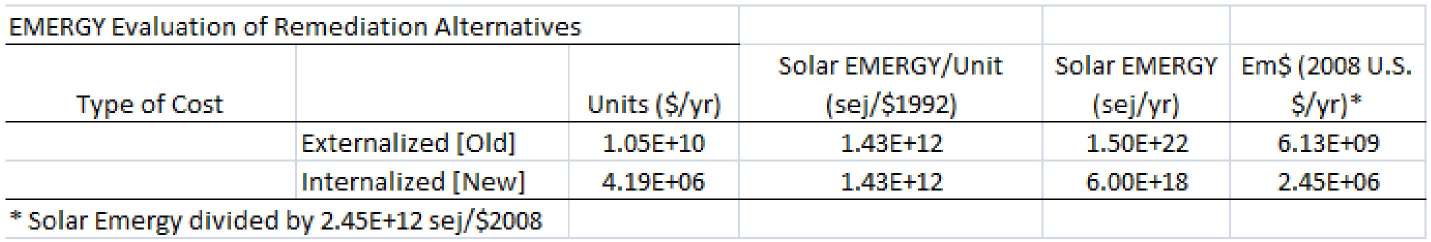
[f] Sustainabillity index = EYR / ELR

[g] Empower density = (F + R + N) / Area ; Assumes area is 39,223,513 m^2

5.4 EMERGY Comparison of Alternative Mine Waste Management Strategies

The externalized cost of mine waste cleanup required 1.50E+22 sej/yr, or 6.13E+09 (billion) $2008/yr. The internalized cost of mine waste cleanup required 6.00E+18 sej/yr, or 2.45E+06 (million) $2008/yr. The internalized cost of cleanup required a fraction of the emergy (less than 1%) than that of the externalized cost. [*Please see Table 19 on the next page*]. The results of this study support the idea that managing mine wastes during mining operations is a more efficient means of controlling pollution than cleanup after operations have ceased. This evaluation does not take into account the environmental damage caused by mine wastes pollution. If environmental damage were included in the cost of cleanup, it is expected that the externalized cost of environmental cleanup and remediation would be even higher. This was a simple comparison and one of extremes; it is unlikely that 1.5 billion tons of waste rock would be left on the surface. In addition, past underground copper mining operations were not as large as RC's proposed mine, meaning the cost of cleanup might be exaggerated. Odum [53] stated that more energy is stored in environmental products than in paid services. Using money as a measure of environmental resources often results in an underrepresentation of said resources.

Table 19. EMERGY Evaluation of Remediation Alternatives



EMERGY Evaluation of Remediation Alternatives					
Type of Cost		Units ($/yr)	Solar EMERGY/Unit (sej/$1992)	Solar EMERGY (sej/yr)	Em$ (2008 U.S. $/yr)*
	Externalized [Old]	1.05E+10	1.43E+12	1.50E+22	6.13E+09
	Internalized [New]	4.19E+06	1.43E+12	6.00E+18	2.45E+06
* Solar Emergy divided by 2.45E+12 sej/$2008					

5.5 Summary

This analysis sought to answer several questions. The first question was: Is Resolution Copper's proposed mining operation more sustainable than past mining operations? The first part of this question consisted of determining if externalities, i.e. waste cleanup, were accounted for in the operation. The old method of waste management, i.e. externalization, had an EMERGY value of 1.50E+22 sej/yr. The new method of waste management as represented by RC, i.e. internalization, had an EMERGY value of 6.00E+18 sej/yr. Internalizing the cost of waste management required only 0.04% of the solar emjoules per year than the externalized cost. These results indicated that RC's operation which internalized the cost of waste management was more sustainable than past mining operations.

The second part of the question consisted of determining if RC was using energy resources more efficiently. The hypothetical 1992 copper mine in the United States, using natural gas, fuel and electricity as energy sources, had an EMERGY value of 7.35E+23 sej/yr. The 2004 copper mine in Chile, using fuel and electricity as energy sources, had an EMERGY value of 8.68E+21 sej/yr. The 2008 copper mine in Chile, using fuel and electricity as energy sources, had an EMERGY value of 1.40E+22; the cause for the increase between the 2004 and 2008 Chile operations was not determined. The 2015 Resolution Copper mine, using fuel and electricity as energy sources, had an EMERGY value of 5.85E+20 sej/yr. RC's 2015 operation required 0.07% of the solar emjoules per year for energy resources than the 1992 operation. The results from this study indicated that RC's use of electricity was more efficient than past mining operations use of fossil fuels.

The second question was: What is being done differently and how have copper mining practices changed over time? Copper mining operations have reduced freshwater consumption by reusing and reclaiming water within the mining operation. The utilization of precipitation, runoff and mine water are all relatively new practices designed to reduce an operation's load on water supplies. However, these water diversions reduce the amount of water available to the local ecosystem and could adversely affect local plant and animal communities. The trend for copper mining has been to rely less on natural gas and diesel fuel and to rely more on electricity. The source of electricity is important for determining secondary impacts on the environment, such as greenhouse gas emissions. New operations have also begun to make use of uneconomical excavated rock for mine site development, thus reducing the amount of waste rock on the surface.

5.6 Future Research

Conducting an EMERGY analysis of an old mining operation would allow a comparison of old and new mining operation's measures of sustainability. Having EMERGY indices for an old mining operation, and comparing to RC's EMERGY indices, will provide insight into how the copper mining industry has changed with the progression of time. In addition, an EMERGY analysis of an old copper mine operation's use of water would shed light on the water efficiency of RC's mining operation. It would be interesting to determine if processing all ore, regardless of copper concentrations, and producing a larger amount of tailings, is more efficient than processing ore only with certain copper concentrations and producing more waste rock. It would also be interesting to study the effects the subsidence might have on local hydrology, such as ephemeral streams and drainage networks.

In order for RC to begin operations a Federal Land Swap (FLS) agreement had to be approved. At the end of 2014, President Obama signed the FLS. The FLS involves the Federal government swapping federal lands for parcels of private land owned by RC. These parcels are noted for their biodiversity and contribution to species protection. The land of each party in an FLS is appraised and, if determined to be of equal value, the Federal government must accept the trade. The tool used for appraisal states that a land's value cannot be derived from a non-market purpose, i.e. conservation. Using EMERGY to measure the market and non-market values of the Federal government's land and RC's land would allow an objective comparison of land values, and help create a new method of evaluating land swap values for future trade negotiations.

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