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(54) **DEVICES, METHODS, AND SYSTEMS FOR COMBINED ORE REDUCTION AND METALS STRIPPING**

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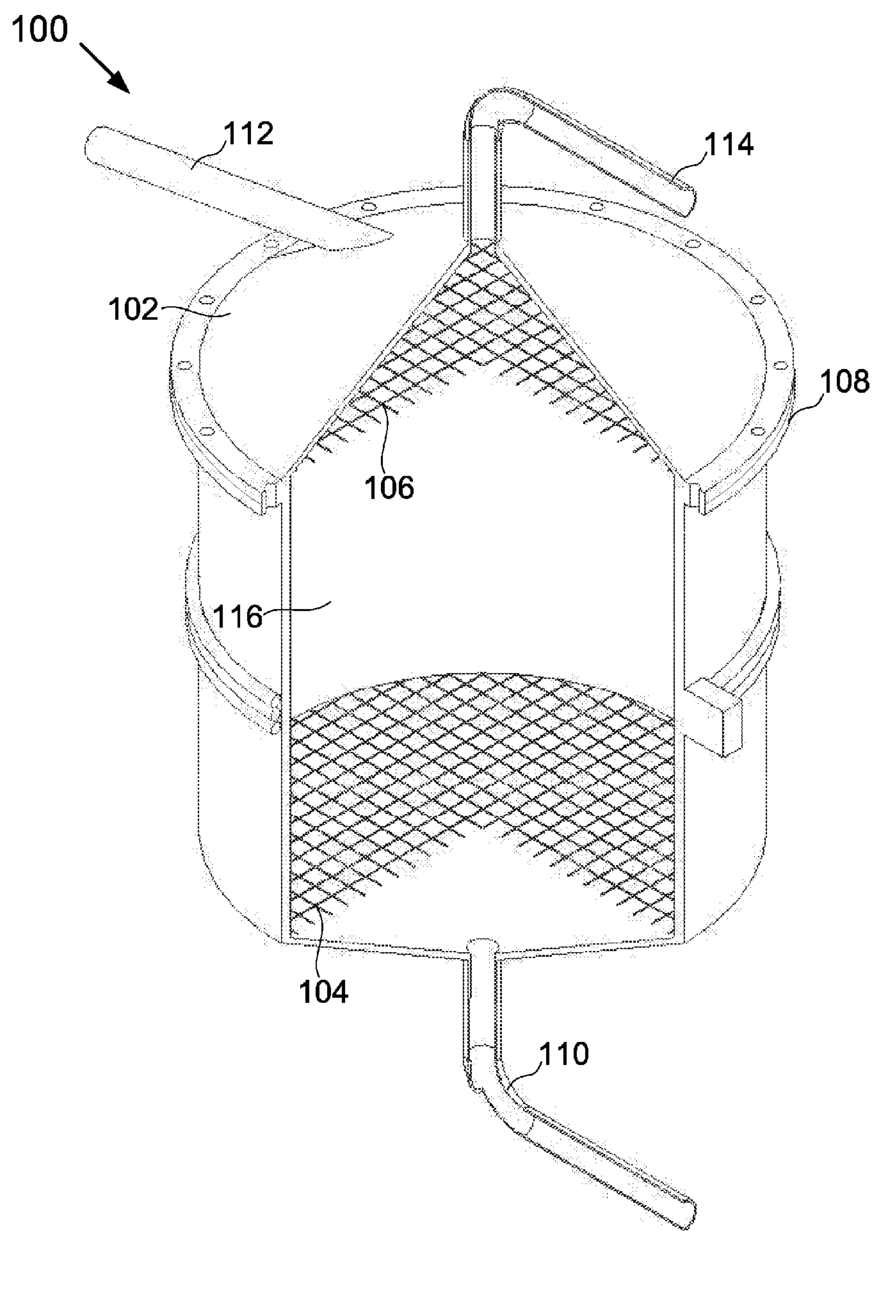
(57) **ABSTRACT**

Devices, systems, and methods for metals production are disclosed. In a first embodiment, a first portion of an ore is reduced, producing metals. A portion of the metals are stripped, complexed, or a combination thereof, into a supercritical carbon dioxide stream.



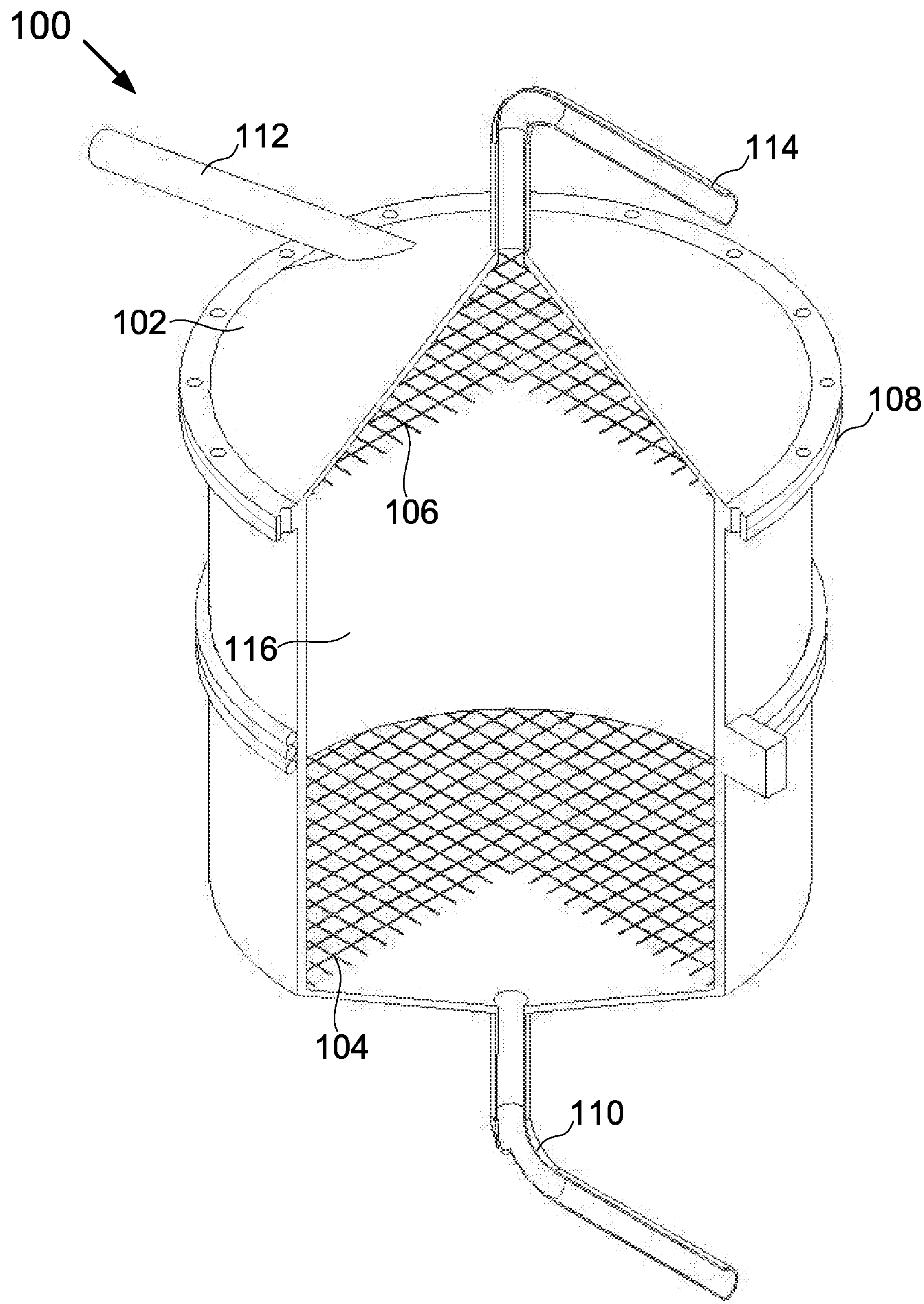


FIG. 1

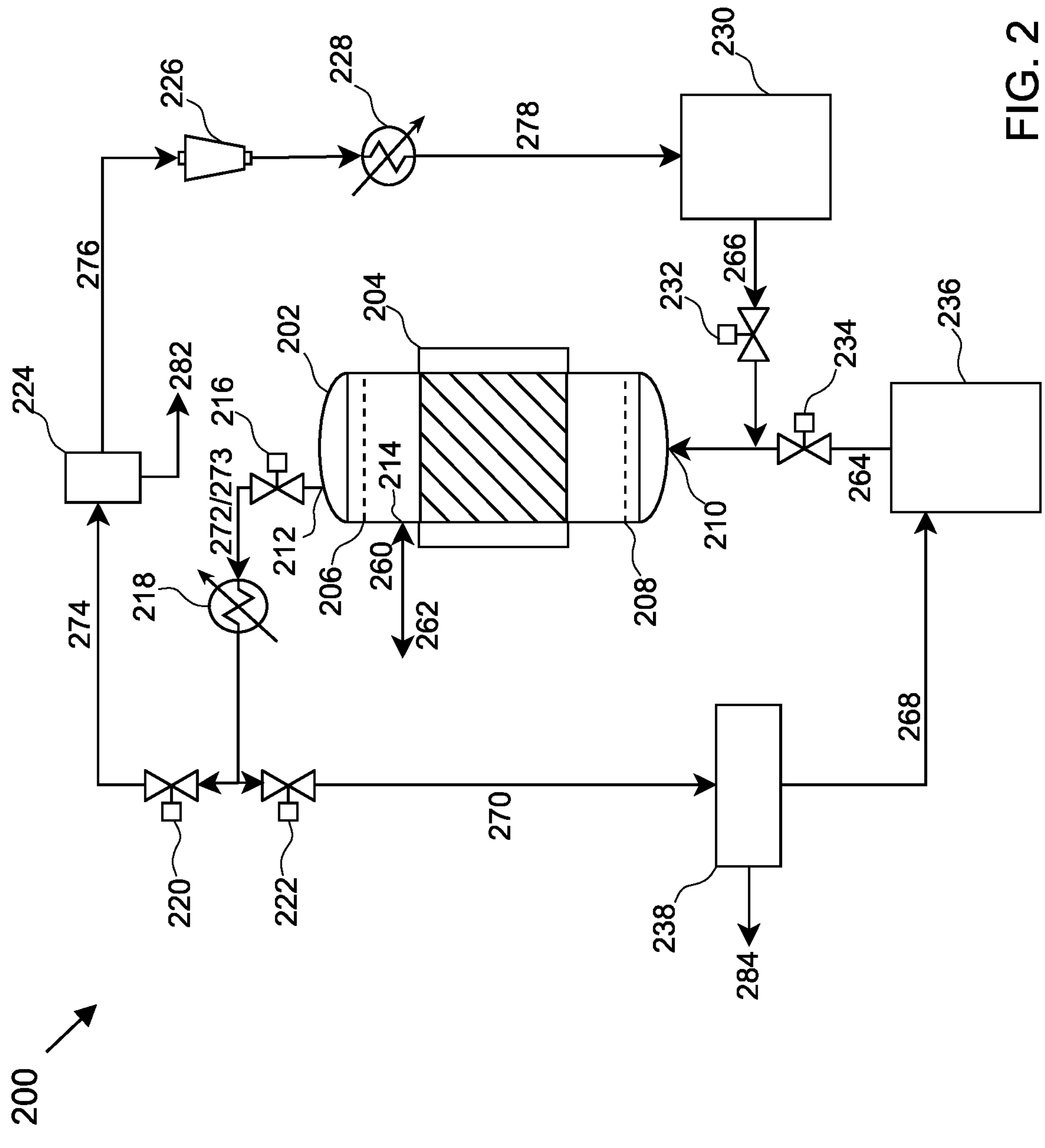

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FIG. 2

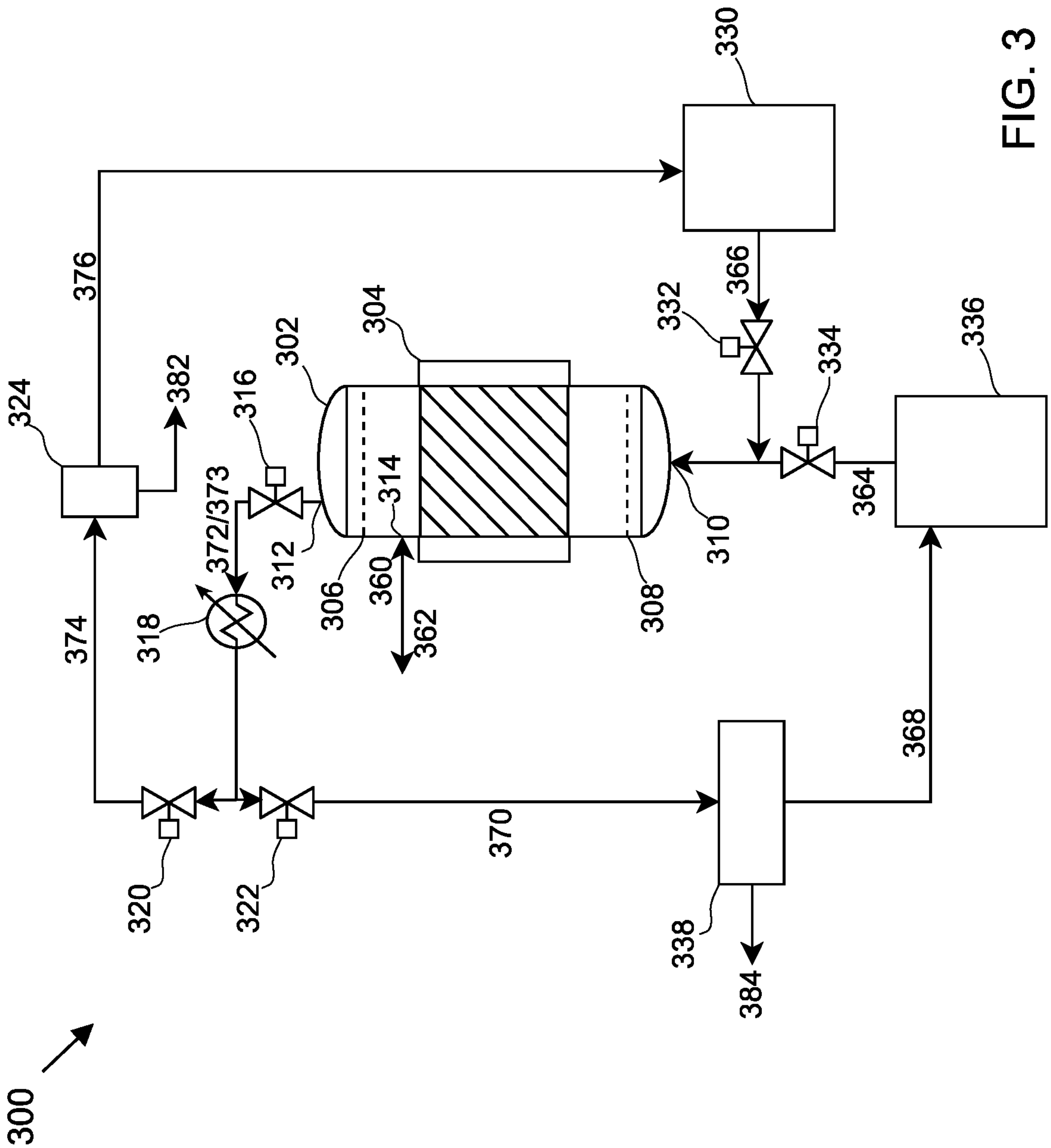
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FIG. 3

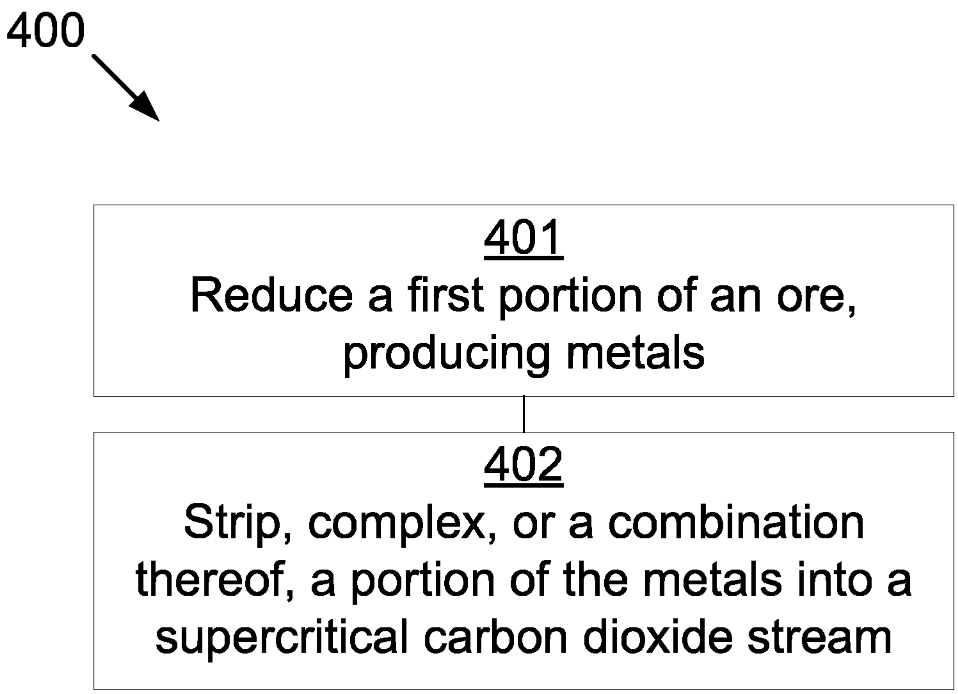
400
401
Reduce a first portion of an ore, producing metals
402
Strip, complex, or a combination thereof, a portion of the metals into a supercritical carbon dioxide stream

FIG. 4

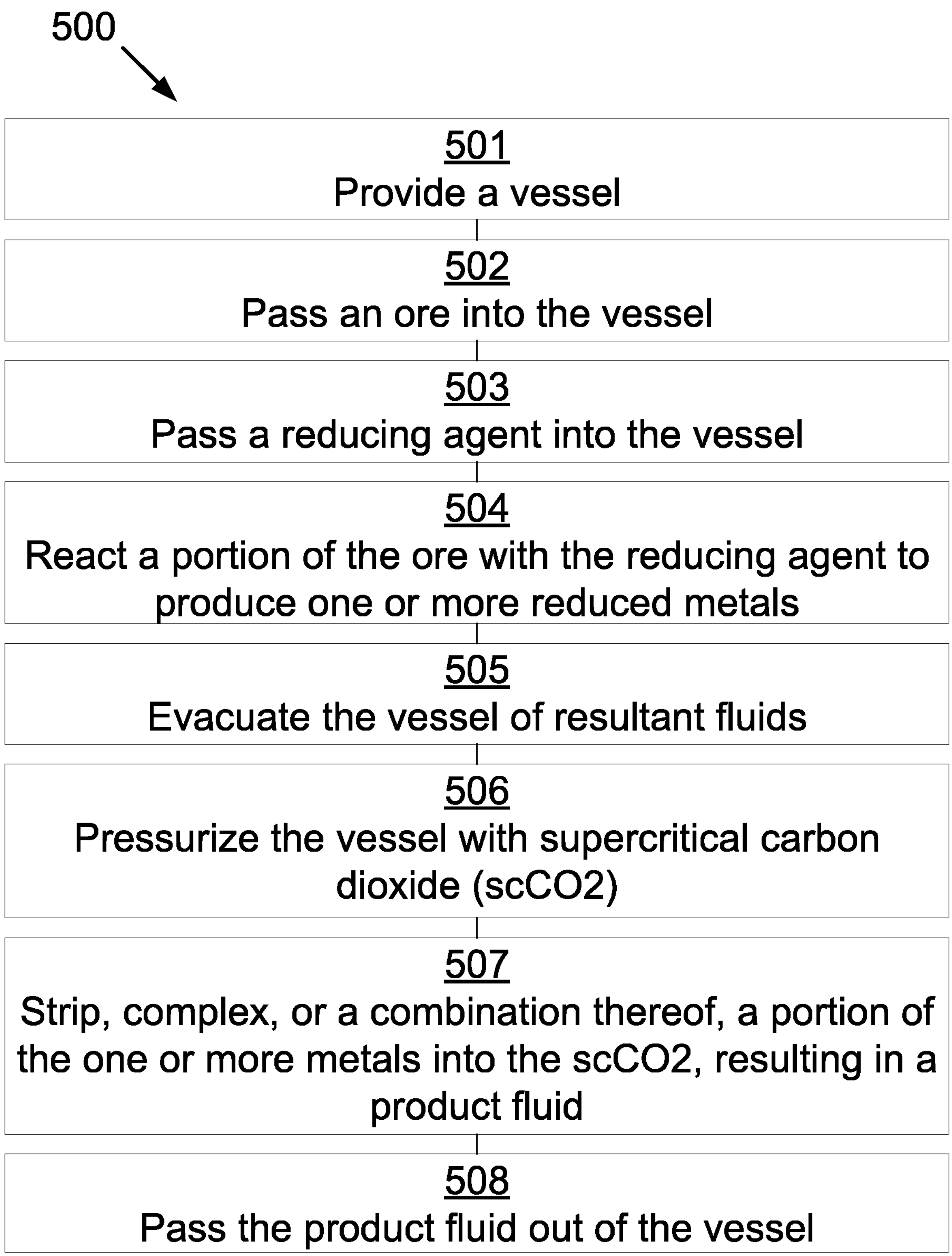
500
501
Provide a vessel
502
Pass an ore into the vessel
503
Pass a reducing agent into the vessel
504
React a portion of the ore with the reducing agent to produce one or more reduced metals
505
Evacuate the vessel of resultant fluids
506
Pressurize the vessel with supercritical carbon dioxide (scCO2)
507
Strip, complex, or a combination thereof, a portion of the one or more metals into the scCO2, resulting in a product fluid
508
Pass the product fluid out of the vessel

FIG. 5

DEVICES, METHODS, AND SYSTEMS FOR COMBINED ORE REDUCTION AND METALS STRIPPING

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. provisional patent application No. 62/674,157.

FIELD OF THE INVENTION

[0002] The devices, systems, and methods described herein relate generally to ore processing. More particularly, the devices, systems, and methods described herein relate to ore reduction and metals stripping.

BACKGROUND

[0003] Terrestrial ore processing is not often directly translatable to extraterrestrial ore processing. Many known technologies are not viable on earth because of issues such as the toxic nature of the chemicals used, the energy costs of unit operations, and the low abundance of key metals in terrestrial deposits. As these technologies are, generally, poorly suited to terrestrial application, the technologies known are not sufficiently developed for immediate application in extraterrestrial situations. Devices, systems, and methods are needed for better developing these and other technologies to process extraterrestrial ore in a manner that can also be applied terrestrially.

SUMMARY

[0004] Devices, systems, and methods for metals production are disclosed. In a first embodiment, a first portion of an ore is reduced, producing metals. A portion of the metals are stripped, complexed, or a combination thereof, into a supercritical carbon dioxide stream ($scCO_2$). In a preferred embodiment, the reduction and the $scCO_2$ treatment occur in the same vessel.

[0005] A second embodiment consists of a vessel with a porous plate, a fluid port, and an ore port. An ore is passed through the ore port into the vessel onto the porous plate. A reducing agent is passed through the fluid port. The reducing agent reduces a first portion of the ore, producing metals. Resultant fluids are removed from the vessel through the fluid port. A supercritical carbon dioxide stream is passed through the fluid port into the vessel. The supercritical carbon dioxide stream strips, complexes, or a combination thereof, a portion of the metals.

[0006] In a third embodiment, a first portion of an ore is reduced, producing metals. A portion of the metals is amalgamated with a mercury stream. The metals and the mercury stream are separated. In some embodiments, separating involves boiling off the mercury by reduced pressure, heat, or a combination thereof.

[0007] The ore may include an oxide ore, a sulfide ore, a sulfate ore, a silicate ore, a carbonate ore, a phosphate ore, or a combination thereof.

[0008] Reducing the ore may include passing a reducing agent across the ore. The reducing agent may be hydrogen, hydrogen plasma, carbon monoxide, an alkaline metal, an alkaline earth metal, or a combination thereof.

[0009] Reducing the ore may produce a water stream from the oxide ore and silicate ore and a hydrogen sulfide stream from the sulfide ore. The water stream may be electrolyzed, producing hydrogen and oxygen.

[0010] The vessel may have a porous plate onto which the ore is passed. The vessel may have a microwave emitter that induces the hydrogen plasma.

[0011] The supercritical carbon dioxide stream may have reagents in solution that complex the metals, unreduced metals from a second portion of the ore, or a combination thereof. The reagents may include organic amines, organic acids, ketones, diketones, ethers, alcohols, dithiocarbamates, organophosporous reagents, macrocyclic compounds, halogenated organic amines, halogenated organic acids, halogenated ketones, halogenated diketones, halogenated ethers, halogenated alcohols, halogenated dithiocarbamates, halogenated organophosporous reagents, cyanide compounds, or a combination thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] In order that the advantages of the described devices, systems, and methods will be readily understood, a more particular description of the devices, systems, and methods briefly described above will be rendered by reference to specific embodiments illustrated in the appended drawings. Understanding that these drawings depict only typical embodiments of the described devices, systems, and methods and are not therefore to be considered limiting of its scope, the devices, systems, and methods will be described and explained with additional specificity and detail through use of the accompanying drawings, in which:

[0013] FIG. **1** is an isometric cutaway view of a vessel for metals production.

[0014] FIG. **2** is a process flow diagram for metals production.

[0015] FIG. **3** is a process flow diagram for metals production.

[0016] FIG. **4** shows a method for metals production.

[0017] FIG. **5** shows a method for metals production.

DETAILED DESCRIPTION

[0018] The following description recites various aspects and embodiments of the inventions disclosed herein. No particular embodiment is intended to define the scope of the invention. Rather, the embodiments provide non-limiting examples of various compositions, and methods that are included within the scope of the claimed inventions. The description is to be read from the perspective of one of ordinary skill in the art. Therefore, information that is well known to the ordinarily skilled artisan is not necessarily included.

[0019] The following terms and phrases have the meanings indicated below, unless otherwise provided herein. This disclosure may employ other terms and phrases not expressly defined herein. Such other terms and phrases shall have the meanings that they would possess within the context of this disclosure to those of ordinary skill in the art. In some instances, a term or phrase may be defined in the singular or plural. In such instances, it is understood that any term in the singular may include its plural counterpart and vice versa, unless expressly indicated to the contrary.

[0020] As used herein, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. For example, reference to "a substituent" encompasses a single substituent as well as two or more substituents, and the like.

[0021] As used herein, "for example," "for instance," "such as," or "including" are meant to introduce examples that further clarify more general subject matter. Unless otherwise expressly indicated, such examples are provided only as an aid for understanding embodiments illustrated in the present disclosure and are not meant to be limiting in any fashion. Nor do these phrases indicate any kind of preference for the disclosed embodiment.

[0022] Reduction of ores using reducing agents, such as hydrogen or hydrogen plasma, is a process that has been studied at the laboratory scale but which has not been applied to large scale mining application, as far as the Applicants have been able to determine. Supercritical carbon dioxide is used to strip heavy metals from soil and has been studied by the Bureau of Mines and others for rare earth metal stripping, but no installations in large scale processing facilities exist, as far as the Applicants have been able to determine. The combination of these two technologies, either in sequence or in the same vessel, is disclosed herein. Individually, each process requires solids handling. By eliminating solids handling, the combined processes become simpler, more energy efficient, and more productive than they are separately. In conjunction with the devices disclosed herein, the process can even be used effectively in low gravity or microgravity.

[0023] Referring now to the figures, FIG. **1** is an isometric cutaway view **100** of a vessel for metals production that may be used in the described devices, methods, and systems herein. A vessel **102** includes a bottom porous plate **104**, a top porous plate **106**, an ore port **108**, a first fluid port **110**, a second fluid port **112**, and a third fluid port **114**. The fluid ports **110**, **112**, and **114** have valves (not shown) controlling fluid flow into or out of the vessel **102**. The ore port **108** is a flange that, when opened, allows ore to be placed onto the bottom porous plate **104**. The ore port **108** is then closed.

[0024] In a first embodiment, a reducing agent is passed through the first fluid port **110**. The reducing agent reduces a first portion of the ore, producing metals. Any unused reducing agent and any fluids produced during reduction are pulled out of the vessel **102** through the second fluid port **112** by vacuum. A supercritical carbon dioxide stream ($scCO_2$) is then passed through the first fluid port **110** into the vessel. Once the vessel **102** is up to pressure that keeps the carbon dioxide in the supercritical phase, the $scCO_2$ strips, complexes, or both strips and complexes a portion of the metals, and optionally a portion of the unreduced metals, in the vessel **102** in a batch. Once a time period has passed, the $scCO_2$, now containing metals, is passed out of the second fluid port **112** and sent for further processing. The ore port **108** is then opened and the leftover solids are removed in preparation for the next batch.

[0025] In a second embodiment, after pressurizing the vessel **102** with the $scCO_2$, the valve on the fluid port **112** is opened and $scCO_2$ with a reducing agent added are passed together into vessel **102** through fluid inlet **110**. The reducing agent reduces a first portion of the ore, producing metals. Concurrently, the $scCO_2$ strips, complexes, or both strips and complexes a portion of the metals, and optionally a portion of the unreduced metals, in the vessel **102** in a semi-batch manner, until the ore is sufficiently stripped of metals. At that point the remainder of the fluids are removed, the ore port **108** is opened, and the leftover solids are removed in preparation for the next batch of ore.

[0026] In either embodiment, a complexing agent may be added to aid in complexing the metals or unreduced metals.

[0027] Referring now to FIG. **2**, FIG. **2** is a process flow diagram for metals production that may be used in the described devices, methods, and systems herein. Ore feed stream **260** is passed through ore port **214** into vessel **202**, settling on porous plate **208**. Reducing agent **264**, in this embodiment, hydrogen gas, is passed from hydrogen tank **236** through valve **234** and into vessel **202** through fluid port **210**. Reducing agent **264** is turned into a hydrogen plasma by microwave radiation induced by microwave emitter **204**. The hydrogen plasma reduces a portion of the ore feed stream **260** into metals, leaving spent ore stream **262** with water as a side product. The water and any unreacted hydrogen gas are pulled out of vessel **102** through fluid port **212** and valve **216** as stream **272**. Stream **272** is cooled across exchanger **218**, producing mixed water stream **270**, which passes through valve **222** and into electrolysis unit **238**. Electrolysis produces hydrogen and oxygen from the water in mixed water stream **270**. Any hydrogen from mixed water stream **270** combines with the hydrogen produced to make hydrogen product stream **268**, which is sent to hydrogen tank **236**.

[0028] Supercritical carbon dioxide ($scCO_2$) stream **266** is passed through valve **232** and fluid port **210** into vessel **202**. The $scCO_2$ stream **266** strips, complexes, or strips and complexes a portion of the metals, and optionally, a portion of the unreduced metals, into solution. In some embodiments, this is assisted by the use of reagents. The pregnant $scCO_2$ stream **273** is passed out valve **216**, and through heat exchanger **218**, which heats pregnant $scCO_2$ stream **273** to form separator feed stream **274**. Separator feed stream **274** passes through valve **220** and into separator **224**, where the metals **282** are separated from the carbon dioxide **276**. The carbon dioxide is compressed and cooled through compressor **226** and heat exchanger **228**, respectively, to produce a $scCO_2$ feed stream **278**, which is passed to $scCO_2$ tank **230**. The spent ore stream **262** is then removed from the vessel **202**.

[0029] In microgravity environments, ore feed stream **260** floats between porous plate **206** and porous plate **208**.

[0030] In some embodiments, vessel **202** includes a heater.

[0031] Referring now to FIG. **3**, FIG. **3** is a process flow diagram for metals production that may be used in the described devices, methods, and systems herein. Raw ore feed stream **350** is passed into comminution unit **354**. In this embodiment, the raw ore is crushed in a gyratory crusher. The crushed ore exits the crusher in crushed ore stream **352**. The crushed ore stream is passed into separation unit **355**. In this embodiment, the separation unit is a gravity separator. The separated oxide ore leaves the separation unit and becomes ore feed stream **360**. Ore feed stream **360** is passed through ore port **314** into vessel **302**, settling on porous plate **308**. Reducing agent **364**, in this embodiment, hydrogen gas, is passed from hydrogen tank **336** through valve **334** and into vessel **302** through fluid port **310**. Reducing agent **364** is turned into a hydrogen plasma by microwave radiation induced by microwave emitter **304**. Microwave emitter **304** also includes a heater for heating vessel **302**. The hydrogen plasma reduces a portion of the ore feed stream **360** into metals, with water as a side product. The water and any unreacted hydrogen gas are pulled out of vessel **102** through fluid port **312** and valve **316** as stream **372**. Stream **372** is cooled across exchanger **318**, producing mixed water stream **370**, which passes through valve **322** and into electrolysis unit **338**. Electrolysis produces hydrogen and oxygen from the water in mixed water stream **370**. Any hydrogen from mixed water stream **370** combines with the hydrogen produced to make hydrogen product stream **368**, which is sent to hydrogen tank **336**.

[0032] A mercury stream **366** is passed through valve **332** and fluid port **310** into vessel **302**. The mercury stream **366** amalgamates with a portion of the metals. The amalgam **373** is passed out valve **316**, and through heat exchanger **318**, which heats amalgam **373** to form separator feed stream **374**. Separator feed stream **374** passes through valve **320** and into separator **324**, where the metals **382** are separated from the mercury **376**. The mercury **376** is returned to mercury tank **330**. The metals are further purified, in this embodiment, in a smelter (not shown). The spent ore stream **362** is then removed from the vessel **302**.

[0033] In some embodiments, separating the metals from them mercury consists of boiling off the mercury by reduced pressure, heat, or a combination thereof.

[0034] Referring now to FIG. **4**, FIG. **4** shows a method **400** for metals production that may be used with the described devices, systems, and methods herein. At **401**, a first portion of an ore is reduced, producing metals. At **402**, a portion of the metals is stripped, complexed, or a combination thereof, into a supercritical carbon dioxide stream.

[0035] Referring now to FIG. **5**, FIG. **5** shows a method **400** for metals production that may be used with the described devices, systems, and methods herein. At **501**, a vessel is provided. At **502**, an ore is passed into the vessel. At **503**, a reducing agent is passed into the vessel. At **504**, a portion of the ore is reacted with the reducing agent to produce one or more reduced metals. At **505**, the vessel is evacuated of the resultant fluids. At **506**, the vessel is pressurized with supercritical carbon dioxide. At **507**, a portion of the one or more reduced metals is stripped, complexed, or a combination thereof into the supercritical carbon dioxide, resulting in a product fluid. At **508**, the product fluid is passed out of the vessel.

[0036] In some embodiments, the ore may include oxide ores, sulfide ores, sulfate ores, silicate ores, carbonate ores, phosphate ores, or a combination thereof.

[0037] In some embodiments, the reducing agent may include hydrogen, hydrogen plasma, carbon monoxide, an alkaline metal, an alkaline earth metal, or a combination thereof.

[0038] In some embodiments, the ore produces a water stream from oxide ores and silicate ores and a hydrogen sulfide stream from sulfide ores.

[0039] In some embodiments, the supercritical carbon dioxide stream comprises reagents in solution that complex the metals, unreduced metals from a second portion of the ore, or a combination thereof. These reagents may include organic amines, organic acids, ketones, diketones, ethers, alcohols, dithiocarbamates, organophosporous reagents, macrocyclic compounds, halogenated organic amines, halogenated organic acids, halogenated ketones, halogenated diketones, halogenated ethers, halogenated alcohols, halogenated dithiocarbamates, halogenated organophosporous reagents, cyanide compounds, or a combination thereof.

[0040] In some embodiments, the metals are purified by smelting, refining, or a combination thereof. In some embodiments, the ore is comminuted before passing the ore to the reactor. Comminuting may include passing the oxide ore through sag mills, ball mills, cone crushers, roll crushers, impact crushers, hammer mills, jaw crushers, gyratory crushers, rotary breakers, other comminution devices known to those of normal skill in the art, or a combination thereof.

[0041] In some embodiments, separating includes gravity separation, vibration separation, flotation separation, magnetic separation, or a combination thereof.

[0042] In some embodiments, reducing occurs simultaneously with stripping, complexing, or a combination thereof, in the same vessel.

[0043] In some embodiments, the oxygen produced by electrolysis may be stored for fuel or air. Metals may be fed into a 3D Printer and replacement parts printed as needed. A 3D printer can be used to fuse alumina powder into castings for use in parts making. Metals may then be poured into the castings to make a variety of parts.

[0044] Fluids may be used for forced ore and product flow (slurries) in low/micro gravity environments.

[0045] Rocket fuel may be produced from the products of this process. Powdered aluminum and oxygen can be used as a rocket fuel. Once aluminum is separated from other metals produced in this process and is ground into a fine powder (by other parts made from other metals produced by this process) it may be loaded into rockets for transport into lunar orbit. A lunar fuel depot may be created thereby to allow for cheaper travel to Mars and the outer solar system.

[0046] Hydrogen is the preferred reducing agent as it is easily recyclable through electrolysis. The disadvantage of this is that electrolysis is an energy intensive process. This tradeoff is justified as the cost to transport regular shipments of reducing agent is orders of magnitude greater than the one-time cost of sending up greater power production capability in the form of solar panels and batteries or even small, modular, nuclear reactors.

[0047] This process may help pave the way for greater colonization of the moon. One of the issues of building the first moon colonies will be sourcing building materials. The devices, systems, and methods detailed in this patent could be used to produce some of the structural materials needed to build a viable base on the moon. The first colonies will likely be built underground, but structural material will be needed for walls, flooring, and reinforcement.

1. A method for metals production comprising:
reducing a first portion of an ore, producing metals in a vessel; and
stripping, complexing, or a combination thereof, a portion of the metals into a supercritical carbon dioxide stream in the vessel.

2. The method of claim **1**, wherein the ore comprises an oxide ore, a sulfide ore, a sulfate ore, a silicate ore, a carbonate ore, a phosphate ore, or a combination thereof.

3. The method of claim **1**, wherein reducing an ore comprises passing a reducing agent across the ore.

4. The method of claim **3**, wherein the reducing agent comprises hydrogen, hydrogen plasma, carbon monoxide, an alkaline metal, an alkaline earth metal, or a combination thereof.

5. The method of claim **4**, wherein reducing the ore produces a water stream from the oxide ore and silicate ore and a hydrogen sulfide stream from the sulfide ore.

6. The method of claim **5**, further comprising electrolyzing the water stream, producing hydrogen and oxygen.

7. The method of claim **1**, wherein the vessel further comprises a porous plate onto which the ore is passed.

8. The method of claim **1**, wherein the vessel further comprises a microwave emitter that induces the hydrogen plasma.

9. The method of claim **1**, wherein the supercritical carbon dioxide stream comprises reagents in solution that complex the metals, unreduced metals from a second portion of the ore, or a combination thereof.

10. The method of claim **9**, wherein the reagents comprise organic amines, organic acids, ketones, diketones, ethers, alcohols, dithiocarbamates, organophosporous reagents, macrocyclic compounds, halogenated organic amines, halogenated organic acids, halogenated ketones, halogenated diketones, halogenated ethers, halogenated alcohols, halogenated dithiocarbamates, halogenated organophosporous reagents, cyanide compounds, or a combination thereof.

11. The method of claim **1**, further comprising separating the supercritical carbon dioxide stream and the portion of the metals by evaporating off the supercritical carbon dioxide stream.

12. The method of claim **11**, further comprising purifying the portion of the metals.

13. The method of claim **12**, wherein the purifying step comprises smelting, refining, or a combination thereof.

14. The method of claim, further comprising comminuting the ore before the reactor, wherein comminuting comprises passing the oxide ore through sag mills, ball mills, cone crushers, roll crushers, impact crushers, hammer mills, jaw crushers, gyratory crushers, rotary breakers, or a combination thereof.

15. The method of claim **14**, further comprising separating the oxide ore from contaminants before passing the oxide ore to the reactor.

16. The method of claim **15**, wherein separating comprises gravity separation, vibration separation, flotation separation, magnetic separation, or a combination thereof.

17. The method of claim **1**, wherein reducing and stripping, complexing, or a combination thereof, occur simultaneously in the same vessel.

18. A method for ore processing comprising:

providing a vessel;

passing an ore into the vessel;

passing a reducing agent into the vessel;

reacting at least a portion of the ore with the reducing agent to produce one or more reduced metals;

evacuating the vessel of resultant fluids;

pressurizing the vessel with supercritical carbon dioxide;

stripping, complexing, or a combination thereof at least a portion of the one or more reduced metals into the supercritical carbon dioxide, resulting in a product fluid; and

passing the product fluid out of the vessel.

19. A device for metals production comprising:

a vessel comprising a porous plate, one or more fluid ports, and an ore port;

wherein:

an ore is passed through the ore port into the vessel onto the porous plate;

a reducing agent is passed through the one or more fluid ports;

the reducing agent reduces a first portion of the ore, producing metals;

fluids are removed from the vessel through the one or more fluid ports; and

a supercritical carbon dioxide stream is passed through the fluid port into the vessel;

the supercritical carbon dioxide stream strips, complexes, or a combination thereof, a portion of the metals.

20. The device of claim **19**, wherein the reducing agent comprises hydrogen gas.

* * * * *