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 STABILIZING MOLTEN MATERIAL DURING MAGNETIC
 LEVITATION AND HEATING THEREOF
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Fig. 1.

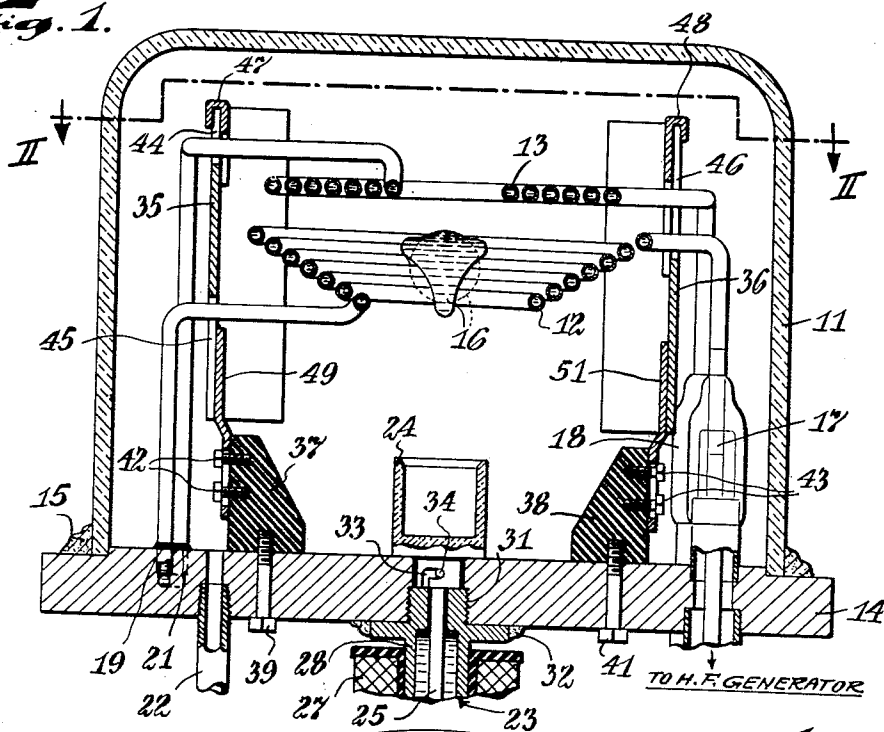


Fig. 2.

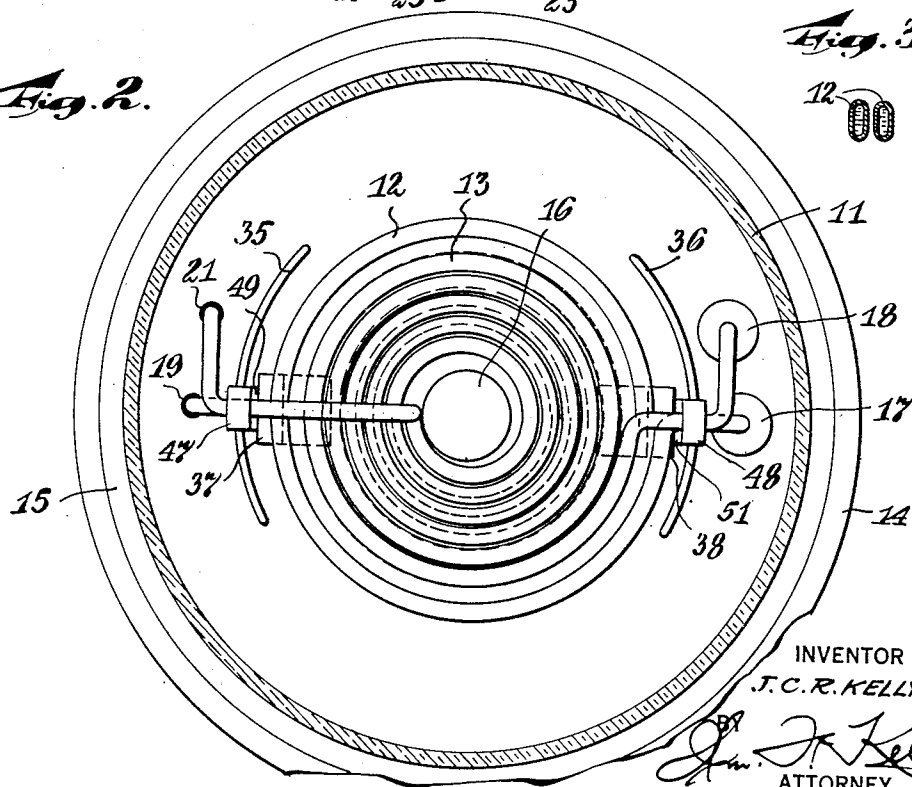


Fig. 3.



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STABILIZING MOLTEN MATERIAL DURING
MAGNETIC LEVITATION AND HEATING
THEREOF

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7 Claims. (Cl. 219—1)

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This invention relates to heating and/or melting of electrically conductive materials in any form and shape while levitated by a properly distributed alternating magnetic field or fields in air, vacuum or inert gas atmosphere, without a confining container or crucible. The required levitating field, which may be obtained by various configurations of coils, is shielded from undesired distortion by the current in the power supply leads. The frequency of the alternating magnetic field is preferably such that relatively thin skin depth of field penetration occurs in the conductive object.

The principal object of my invention, generally considered, is to provide apparatus for heating conductive materials, comprising at least one, but preferably a system of electrical circuits or coils, means for supplying an alternating magnetic field or fields, whereby a conductive object interposed above a coil or between coils on the common axis thereof may be levitated thereat by the alternating current fields, means to prevent undesired distortion of the field or fields, and means for moving such an object into the influence of said fields whereby it may be levitated and heated to the desired extent, out of contact with a potentially contaminating crucible or other container at the elevated temperature involved.

Other objects and advantages, relating to the particular arrangement and the construction of the various parts, will become apparent as the description proceeds.

Referring to the scale drawings:

Figure 1 is a vertical sectional view of apparatus for producing alternating current fields, in air, a vacuum, or an inert atmosphere, for levitating conductive material to be melted and/or heated, means for shielding the fields from the effects of current in the leads or coil extensions, together with means for raising supporting means for such material to a position between two coaxial coil systems where the fields will exert the desired levitation, and then withdrawing the supporting means immediately.

Figure 2 is a horizontal sectional view on the line II—II of Fig. 1, in the direction of the arrows.

Figure 3 is an enlarged sectional view of the metal tubing forming the coils of the illustrated embodiment of the invention, showing how closer spacing of the turns of said coils is effected by flattening, or forming the tubing oval rather than circular in section.

In melting metals, particularly in melting the more reactive high-melting-point metals, such as titanium, zirconium, vanadium, tantalum, 55

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molybdenum and other metals of similar chemical and physical characteristics, difficulty is usually encountered in the selection of crucible materials. When such metals are melted they react with the material of the crucible to some extent, or other reactions occur which adversely affect the quality of the melt. For example, titanium, when melted in a graphite crucible, may contain several tenths to 1% or more of carbon. When zirconium is melted in contact with beryllium oxide, it becomes embrittled because of absorbing oxygen from the refractory. When molybdenum is melted in a crucible of water-cooled copper, the ingot thereafter formed has a very rough surface and often possesses holes or voids.

In order to overcome such difficulties, I have devised an improved apparatus wherein such metal is heated and melted out of contact with any solid material with which it might react, whereby no refractory crucibles are necessary to hold the metal for melting. The invention comprises levitating the metal to be melted in air, a vacuum or inert atmosphere confined by a suitable vessel, such as a quartz, or a 96% silica glass bell jar manufactured by the Corning Glass Works under the name "Vycor," by means of an alternating magnetic field or fields.

The levitating magnetic fields are so distributed between, for example, two coaxial coils, that the metal to be melted does not touch any physical material and, while so levitating the metal, melting it by alternating current energy from the surrounding coil system. The levitating magnetic field, which I protect from undesired distortion in accordance with my invention, is preferably supplied by the same coil system which provides the high frequency electrical energy for heating and melting the levitated material. Besides keeping the metal out of contact with any material which might react therewith and contaminate the melt, volatile materials which may vaporize from the metal when it is melted, will condense upon the walls of the confining vacuum or inert gas vessel and not again contaminate the metal upon cooling.

In previous applications using levitation melting, see the Wroughton and Okress application, Ser. No. 206,344, filed January 17, 1951, it has been observed that although a solid object of regular geometric configuration is supported in a stable manner in the sinusoidally varying electromagnetic field, the molten aggregation resulting from the induction heating and melting occasioned by said field demonstrates irregulari-

ties of form which are suitably designated as "wings" or "pseudopodia." These wings, after formation, tend to induce an instability in the molten mass causing it to move toward the device creating the electromagnetic field and this phenomenon ultimately may result in a short-circuiting of those elements creating said electromagnetic field.

It has been observed that the aforementioned "wings" demonstrated a predictable tendency to incline or direct themselves toward those elements of the field-producing device which were unsymmetrical with respect to the vertical axis of said device. These unsymmetrical elements were the conductors or media by which the field-producing current must be introduced to the device from a current source and are, therefore, an indispensable evil associated with the method.

To obviate the difficulty two alternatives are acceptable:

(a) The asymmetry-producing current elements may be directed from their respective points of origin at the field producing device radially away from the vertical axis of the coil to such a degree of separation, theoretically infinite—but practically several feet, that any modification of their direction of travel will not materially affect the configuration of the alternating electromagnetic field in the reaction space. However the customary practical considerations of space required for such an assembly, especially in vacuum technology, make this device unsuitable for most applications.

(b) The second device consists of placing, at certain suitable sites adjacent the customary device for "levitation melting," formed plates of copper or other good or better electrically conducting material of thickness dictated by known formulas depending upon frequency and so disposed as to shield the metal object, whether molten or solid, within the reaction space from those electromagnetic fields or the effects thereof which are created by unsymmetrical disposition of conductors. Said device will eliminate the troublesome perturbations within the reaction space or reduce them to levels of energy that will have a negligible effect upon said reaction field. The device is illustrated in the drawing as applied to one of the possible modifications of a "levitation" producing device.

Now referring to the drawings illustrating an embodiment of my invention, there is shown a bell jar 11 formed large enough, if this is convenient, to enclose coils 12 and 13, which are to be used for levitating conductive material or metal to be melted or heated. This jar rests on a preferably metal base 14 and may be sealed gas or vacuum-tight thereto, preferably by means of suitable wax 15.

In the present embodiment, the coils 12 and 13, desirably of copper tubing (conveniently of 1/4" dia.) flattened to facilitate close coiling, as shown in detail of Figure 3, although drawn unflattened in the other figures to avoid drafting difficulties, the lower coil 12 being helically coiled into frusto-conical formation, as illustrated. The upper coil 13 is formed as a spiral lying in a horizontal plane, instead of being helically coiled into frusto-conical formation. However, such constructions are contemplated as correspond with Figures 1 to 4 and the other forms disclosed in the Wroughton et al. application referred to. The outside diameter of the lower coil 12 is larger than that of upper coil 13, in order to more effectively stabilize the support of the mass 16 of metal

or other conductive material to be heated. Alternating current is supplied to the coils 12 and 13 by means of coaxial lines or cables 17 and 18, respectively extending to one end of each coil, the other ends being supportingly connected to and through the efficiently conducting base 14, as indicated at 19 and 21.

The enclosure provided by the bell jar 11, and the supporting base 14, may be evacuated through pipe 22 and, if desired, thereafter supplied with inert gas thereby. In order to place the mass 16 of metal, here shown generally spherical in dotted lines as unmelted, into the influence of the supporting and heating coils 12 and 13, we have provided a lifting device 23. Said device comprises a cup 24, desirably formed of low-loss material or alumina and of a size sufficient to hold the material to be subsequently levitated and heated, connected to the upper end of a rod 25, the lower end of which is connected to the armature of a solenoid 27. The armature reciprocates in an oil-containing cylinder 28, and is provided with one or more grooves therealong, so that the oil in said cylinder leaks thereby during operation, exerting a dash-pot action and preventing jerky operation, as in the first embodiment disclosed in the Wroughton et al. application referred to. The cylinder is desirably threadably connected to the lower portion of the base 14, as indicated at 31, and sealed thereto by means of suitable wax 32. The cup 24 may be detachably connected to the upper end of the rod 25 by having a bayonet slot 33 engaging an out-standing pin 34 on said rod.

The shielding means of the present embodiment comprises a sheet or plate of copper, or other highly conductive metal 35, and a similar sheet or plate 36. Both of these sheets are desirably cylindrically curved about the axis of the coils 12 and 13, and connected to the base 14 by means of insulating blocks 37 and 38, secured to said base by bolts or the like 39 and 41. These blocks 37 and 38 are desirably made of not only insulating but refractory material, such as porcelain, and the plates 35 and 36 are connected respectively thereto by means of screws or the like 42 and 43.

The plates 35 and 36 are so positioned that they clear or lie beyond the coils 12 and 13, being however apertured or slotted, as indicated at 44, 45 and 46, to allow the leads or extensions from the coils to pass therethrough while substantially shielding the space between the plates 35 and 36 from the magnetic effects of the current in the vertical portions of the coil extensions.

The upper edges of the slots 44 and 46 may be subsequently closed by angular caps or clips 47 and 48, and the lower end of the slot 45 may be closed by a supporting or stem member 49, secured to the plate 35 by brazing or other desired means, the lower end of which member 49 receives the supporting screws 42. In a similar way, the lower portion of the plate 36 may have depending therefrom a stem or supporting portion 51, similarly secured thereto, and the lower end of which receives the connecting screws 43.

In order to effect heating or melting of the material, using the apparatus of Figures 1 and 2, material 16 is placed in the cup 24 while the bell jar 11 is removed. This may be done either when the cup is elevated, as upon energization of the solenoid 27, or when the cup is lowered, as shown in Figure 1 upon deenergization thereof. After this has been accomplished the bell jar may be placed in position, as shown in Figure 1,

and sealed to the base by the wax 15. The space inside the jar 11, may then be evacuated through pipe 22, and said vacuum either maintained or the exhausted air replaced by inert gas, such as argon, nitrogen, or other gas not reactive with the material to be heated.

If the cup 34 is initially in the position of Figure 1, power is then applied to energize the solenoid 27 and raise said cup where the matter therein will be under the influence of the magnetic fields to be generated by the coils 12 and 13. High frequency or other alternating current is then supplied to the coils 12 and 13 to create a field of such nature and magnitude, that upon lowering the cup 24, the metal mass or sphere 16 stays in place in the field as shown in Figure 1. Alternating current, usually of high frequency, is needed for simultaneous levitation, heating and melting the conductive material 16. The frequency is such that the resultant skin depth in the material is a small fraction of the dimension of the material. The two coils 12 and 13 may be connected in series in such a way that the fields produced thereby are in opposition, that is, so that current always flows around the helix of the top coil in one direction, and through the bottom coil in the opposite direction. A variable condenser bank 45, shown diagrammatically in Figure 6 of the Wroughton et al. application referred to, is connected across the two coils, as there shown, so that the power factor may be adjusted as desired.

The coil-condenser combination may be powered from a 50 kva., 10,000 cycle generator. The voltage on the leads to the generator is substantially the voltage across the coils, but the current readings in the line will be smaller than the circulating current in the coils, because of the resonance effect of the parallel condenser coil combination.

With a preferred spacing between the coils 12 and 13, of about $1\frac{1}{4}$ " for a particular case and generator output readings of about 200 volts, 25 amps., a piece of aluminum roughly spherical, about $1\frac{1}{4}$ " in diameter, and weighing about 60 grams, was raised to the position shown in Figure 2, and remained suspended as illustrated, supported by the high frequency field and without solid support or restraint of any other physical kind. Theoretically, the restoring force on the levitated material will maintain it at an equilibrium position between the coils, on or near the common axis as shown. Actually the piece resisted any effort to move it in any direction away from said equilibrium position.

With the metal suspended as indicated in Figure 1, continued operation of the system caused heating of the metal by induction, the same current which provided the supporting field also serving to heat the piece. After a few minutes, with the power setting noted, the metal started to melt. As it melted, it assumed and maintained the shape like a top, illustrated in full lines in Figure 1, with the tip of the molten matter reaching downward toward the center of the lower turn of the lower coil. When it is desired to remove the molten metal from the field, it is merely necessary to decrease the strength of the field, whereupon the metal will drain into the cup 24, therebelow. This drain may be at a controlled rate in accordance with the variation in the field strength. No physical confining funnel or vessel is needed to drain the molten levitated metal. As an alternative, the field strength may be reduced merely enough to allow

the metal to solidify, while still supported by the field. Also, the field may be reduced quickly so as to permit the molten metal to drop as a whole.

Although it is desirable to have an upper coil as well as a lower coil for supporting the metal prior to and after melting, yet it is possible to support it and melt a mass of metal with a single lower supporting coil, like that indicated at 12 in Figure 1, provided said coil is shaped frusto-conical as there shown or when other alternatives, discussed in the Wroughton et al. application referred to, are employed. In such a case, the metal when molten drops slightly from the levitated position when solid.

With an arrangement such as shown in Figure 1, we used 7 turns of $\frac{1}{4}$ " outside diameter copper tubing in each of the coils 13 and 12 and cooled them by water. The conical angle subtended by the turns of the coil 12 was 120° , and the distance between the plane of the coil 13 and that of the lower turn of the coil 12 was $1\frac{1}{2}$ ", with a 1" opening in the centers of both of said coils. Using an aluminum sphere 1" in diameter weighing 21.5 grams, the levitating circulating current necessary was 630 amps. at a frequency of 10 kilocycles/sec., when the currents in the two coils were in opposition. The stability of levitation of both solid and molten metal with this coil combination is better, as compared with that in which the coil 12 is formed as a flat spiral like the upper coil.

With generally circular, although slightly spiral, coils 12 and 13 arranged as in Figure 1 of the Wroughton et al. application referred to, using 7 turns of $\frac{1}{4}$ " outside diameter water-cooled copper tubing for both of said coils, with the conical angle 120° , the distance between planes of the coils $1\frac{1}{2}$ ", and 1" openings through the lower turns of each coil, a solid 1" diameter aluminum sphere weighing 215 grams was supported when circulating current of 426 amps. at a frequency of 10 kilocycles/sec. was passed through the coils in opposition to one another. This was with a 8.1 kilowatt input to the circuit and provided good stable levitation of both solid and molten metal.

Although in all forms, the coils are, for convenience, shown generally circular or spiral in plan, or cylindrically helical, I contemplate other forms, such as those generally square or otherwise polygonal in plan, or prismatically helical.

Although a conductive sphere was considered for simplicity, other conductive forms may be used with effectiveness. The previous comments hold for magnetic solids as well as non-magnetic solid or molten objects. The inherent agitation of the molten matter of the levitation object is due to the thermal and electrical forces therein. Although from 20 to 550 grams of metals such as copper, brass, tin, and pressed titanium powder were successfully levitated and heated in the alternating magnetic fields, obtained by various configurations of coils, most of the work was done initially with small aluminum spheres for convenience, economy and within the limitations of available power supply. Later other metals of much greater weight were successfully levitated and heated to the desired degree.

Although I have illustrated for simplicity hollow coils, circular in section, yet it is preferred to flatten such coils, as illustrated in Fig. 3, so that they may be positioned closer to one another and thereby improve efficiency and coupling

to the levitated object. It will be understood that I contemplate in all forms of my invention, where desired, effecting melting in a protective atmosphere or vacuum, either in the manner disclosed in Figures 1 and 2, or in any other desirable way which will occur to those skilled in the art.

It is also within the province of this invention to include some instances where heating and melting may be effected by coils, similarly shielded as in the illustrated embodiment but separate from those which create the levitation and with electrical power of frequency the same or different from that producing said field. The heating may take place in the atmosphere without protection against oxidation, as when melting material which is either not readily oxidized or in which oxidation is not undesirable. It is also understood that in all forms the supporting and/or heating coils are desirably cooled by passing water therethrough.

Although preferred embodiments of my invention have been disclosed, it will be understood that modifications may be made within the spirit and scope of the appended claims.

I claim:

1. Apparatus for levitating, heating and melting electrically conductive materials, comprising a coil having a substantially vertical axis, means comprising leads to and extending beyond said coil for supplying alternating current to generate a levitating magnetic field, means shielding the space within said coil from the electromagnetic effects of current in the leads beyond said coil, and means for moving a conductive object to a position on said axis, above said coil, and in the influence of said field, whereby it may be levitated while heated to the desired extent and held out of contact with any physical supporting means.
2. Apparatus for levitating, heating, and melting electrically conductive materials, comprising a plurality of isolated coils with a common axis, means comprising leads to and extending beyond said coils for supplying alternating current to generate opposing levitating magnetic fields therebetween, means shielding the space within said coils from the electromagnetic effects of current in the leads beyond said coils, and means for moving said object to a position between said coils, on their axis, and in the influence of said fields, whereby it may be levitated while heated to the desired extent and held out of contact with any physical supporting means.
3. Apparatus for levitating, heating, and melting electrically conductive materials, comprising a plurality of isolated coaxial coils each with a substantially vertical axis, means comprising leads to and extending beyond said coils for supplying high frequency power to generate opposing magnetic fields therebetween, whereby an electrically conductive object may be levitated in the so-produced alternating fields, means shielding the space within said coils from the electromagnetic effects of current in the leads beyond said coils, means providing a protective atmosphere around said object, and means for moving said object into the influence of said fields, whereby it may be levitated between said coils at their common axis while being heated to the desired extent and held out of contact with any physical supporting means.
4. Apparatus for levitating, heating, and melting electrically conductive materials, comprising a conductive tube helically coiled to upwardly

frusto-conical form, means comprising extensions of said tube beyond said coil for supplying alternating current to generate a levitating magnetic field thereabove, means for internally cooling the turns of said coil and said extensions, means comprising a conductive plate disposed between each extension and the adjacent portion of the coil to shield the space therewithin from the electromagnetic effects of current in said extensions, and means for moving a conductive object into the influence of said field, whereby it may be levitated while heated to the desired extent and held out of contact with any physical supporting means.

5. Apparatus for levitating, heating, and melting electrically conductive materials, comprising a conductive tube helically coiled to upwardly expanding frusto-conical form, a similar tube spirally coiled with its turns lying in a plane over said first tube and coaxial therewith, means comprising extensions on said tubes beyond said coils for supplying alternating current in series to generate a levitating magnetic field therebetween, means comprising a conductive plate disposed between each extension and the adjacent portion of the coil to shield the space therewithin from the electromagnetic effects of current in said extensions, and means for moving a conductive object to a position on the axis of said coils in the influence of said field, whereby it may be levitated while heated to the desired extent and held out of contact with any physical supporting means.

6. Apparatus for levitating, heating, and melting electrically conductive materials, comprising a conductive tube flattened transversely for close spacing of the turns thereof and helically coiled to upwardly expanding frusto-conical form, a similar tube spirally coiled with its turns lying in a plane over said first tube and having said spiral coaxial with the frusto-conical coil, a conductive base, extensions on said tubes beyond said coils for supplying alternating current thereto, said extensions first passing radially away from the axis of said coils and then down and parallel to said axis, two of said extensions passing through said base and the other two supportingly engaged by said base for connecting said coils in series to generate opposed levitating magnetic fields therebetween, and means for shielding the space between said coils from the effects of current in said extensions comprising highly-conductive metal in sheet form, cylindrical about the axis of said coils, and disposed between said coils and said parallel extensions, said sheet metal being supported on said base from insulating means upstanding therefrom and connected thereto and provided with slots through which said radial portions of the extensions pass, means connected to said sheet metal and closing said slots about said extensions, and means passing through said base, coaxial with said coils, for moving a conductive object to a position on the axis of said coils in the influence of said field, whereby it may be levitated while heated to the desired extent, said means comprising a cup formed of low-loss material, a rod passing through said base and on the upper end of which said cup is supported, the lower end of said rod beneath said base carrying an armature, a cylinder mounted on the lower surface of said base and in which said rod and its armature are reciprocatingly mounted, a solenoid surrounding said cylinder, and means for energizing and deenergizing said solenoid to effect

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operation of said cup through said rod, means mounted on said base for enclosing said levitating apparatus, and a pipe connected to an aperture in said base beneath said enclosing means for evacuating the space under said enclosing means or supplying a protective atmosphere to said coils.

7. Apparatus for levitating, heating, and melting electrically conductive materials, comprising a conductive tube helically coiled to upwardly expanding frusto-conical form, a similar tube spirally coiled with its turns lying in a plane over said first tube and having said spiral coaxial with the frusto-conical coil, a conductive base, extensions on said tubes beyond said coils for supplying alternating current thereto, said extensions first passing radially away from the axis of said coils and then down and parallel to said axis, two of said extensions passing through said base and the other two supportingly engaged by said base for connecting said coils in series to generate opposed levitating magnetic fields therebetween, and means for shielding the space between said coils from the effects of current in said extensions comprising highly-conductive metal in sheet form, cylindrical about the axis of said coils, and disposed between said coils and said parallel extensions, said sheet metal being supported on said base from insulating

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means upstanding therefrom and connected thereto and provided with slots through which said radial portions of the extensions pass, means connected to said sheet metal and closing said slots about said extensions, means mounted on said base for enclosing said levitating apparatus, and a pipe connected to an aperture in said base beneath said enclosing means for evacuating the space under said enclosing means or supplying a protective atmosphere to said coils.

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