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Jackson

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(54) **CARBON DIOXIDE SNOW APPARATUS**

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(51) **Int. Cl.**
B08B 3/02 (2006.01)

(52) **U.S. Cl.** **134/94.1**; 134/198; 239/589

(58) **Field of Classification Search** 134/198, 134/102.1, 94.1; 239/132.5, 589
See application file for complete search history.

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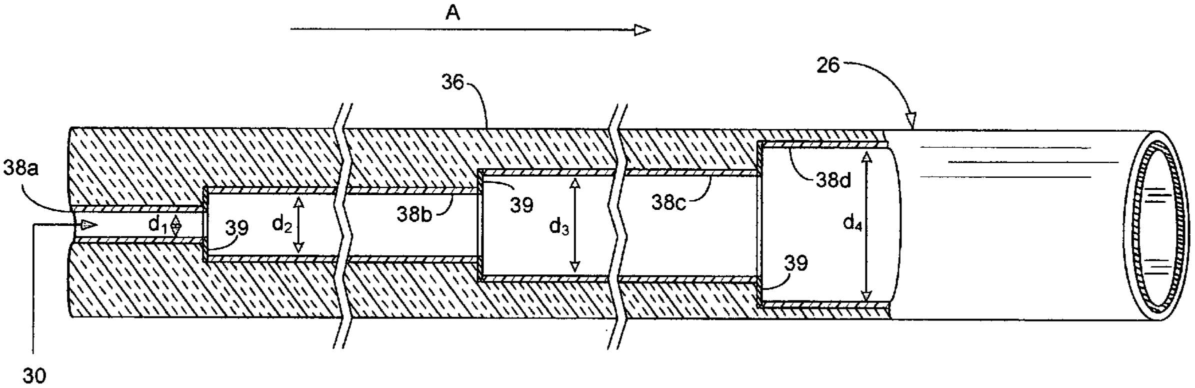
(57) **ABSTRACT**

A carbon dioxide snow apparatus of the present invention includes a carbon dioxide snow generation system and a propellant generation system connected to a common carbon dioxide gas source. The carbon dioxide snow generation system includes a condenser having a at least two connected segments, wherein a first segment has a lesser diameter than the a second segment to provide a stepped expansion cavity for cooling and condensing liquid carbon dioxide into solid carbon dioxide snow. Several snow generation systems, each separately controllable with separate condensers, may be integrated with the propellant generation system and common carbon dioxide source to provide for a multiplicity of carbon dioxide snow applicators for integration into both manual and automated machining processes.

21 Claims, 13 Drawing Sheets



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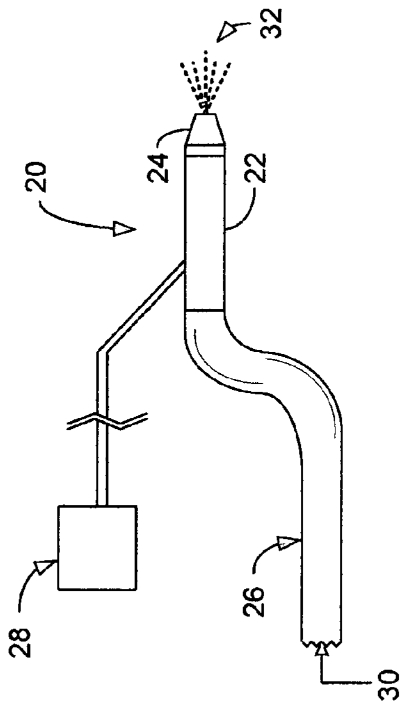


Figure 1

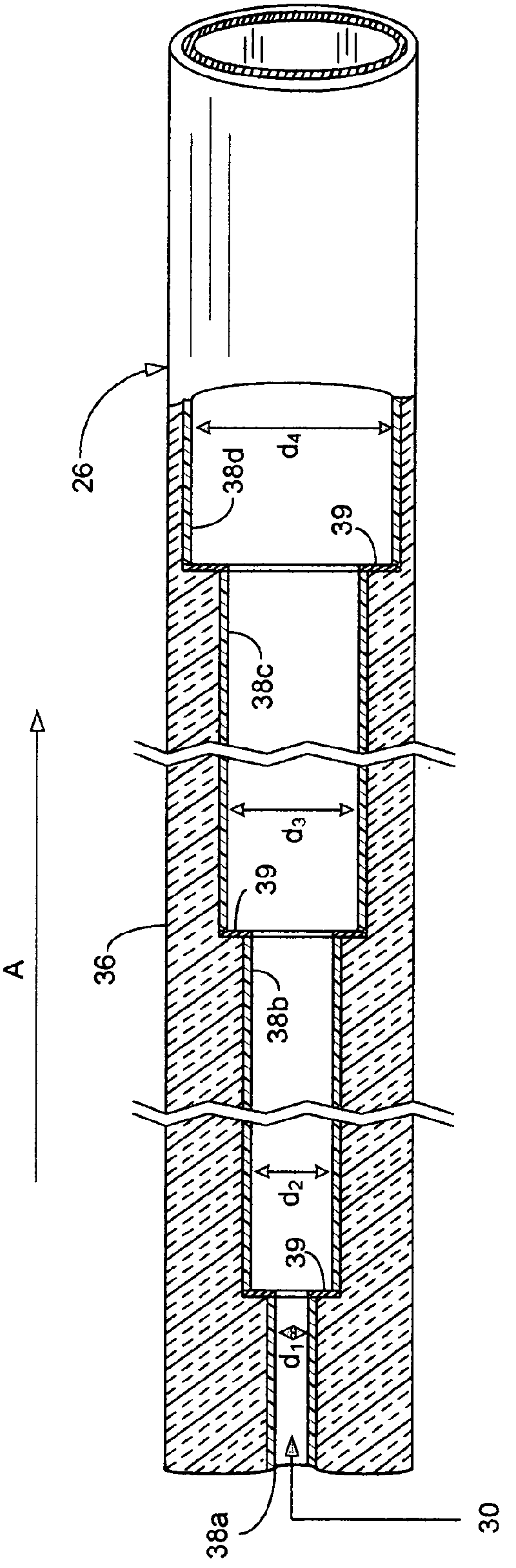


Figure 2

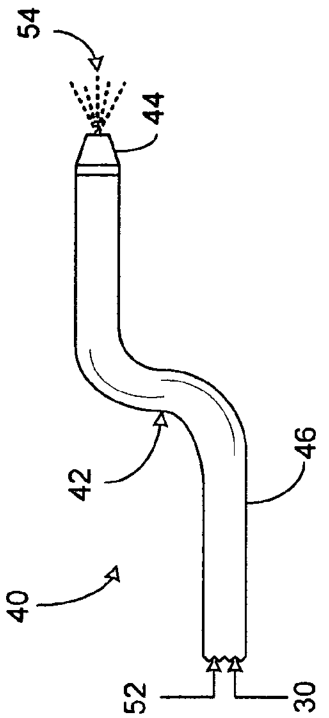


Figure 3

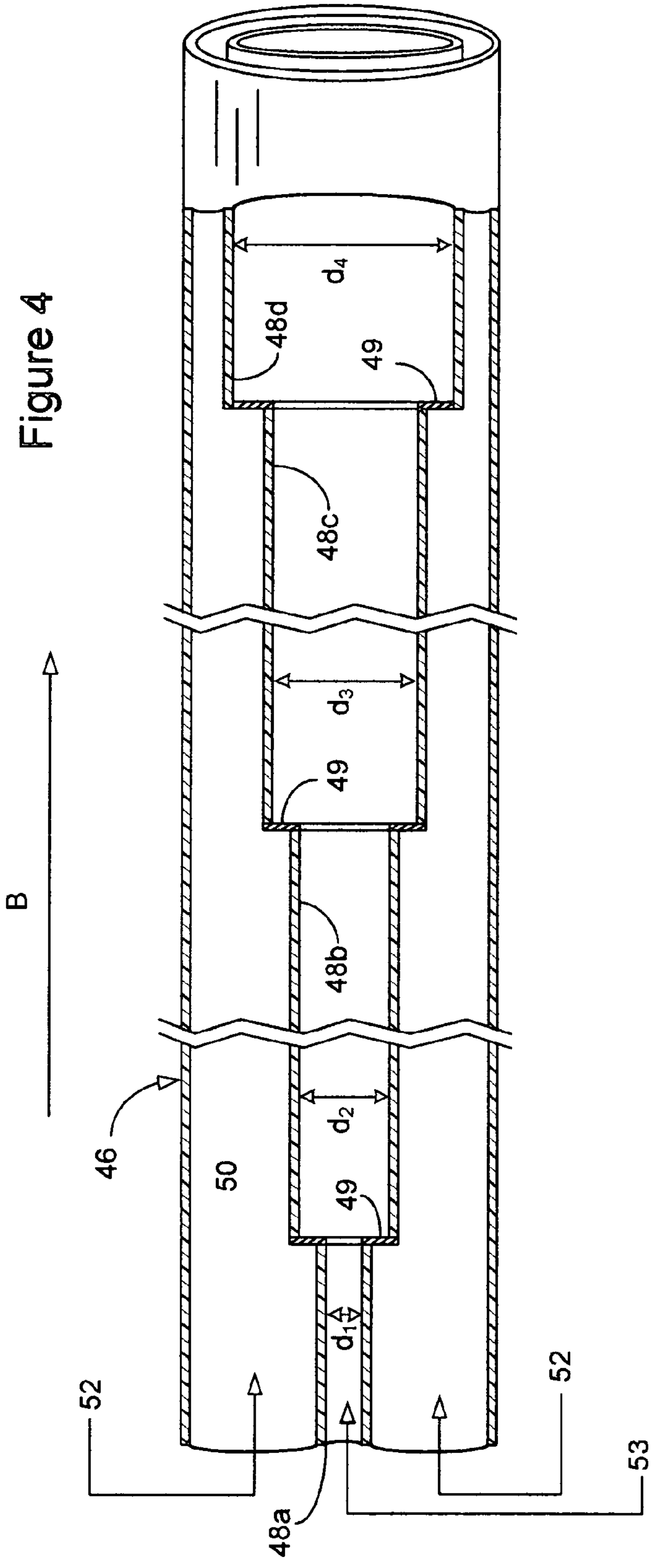


Figure 4

Figure 5

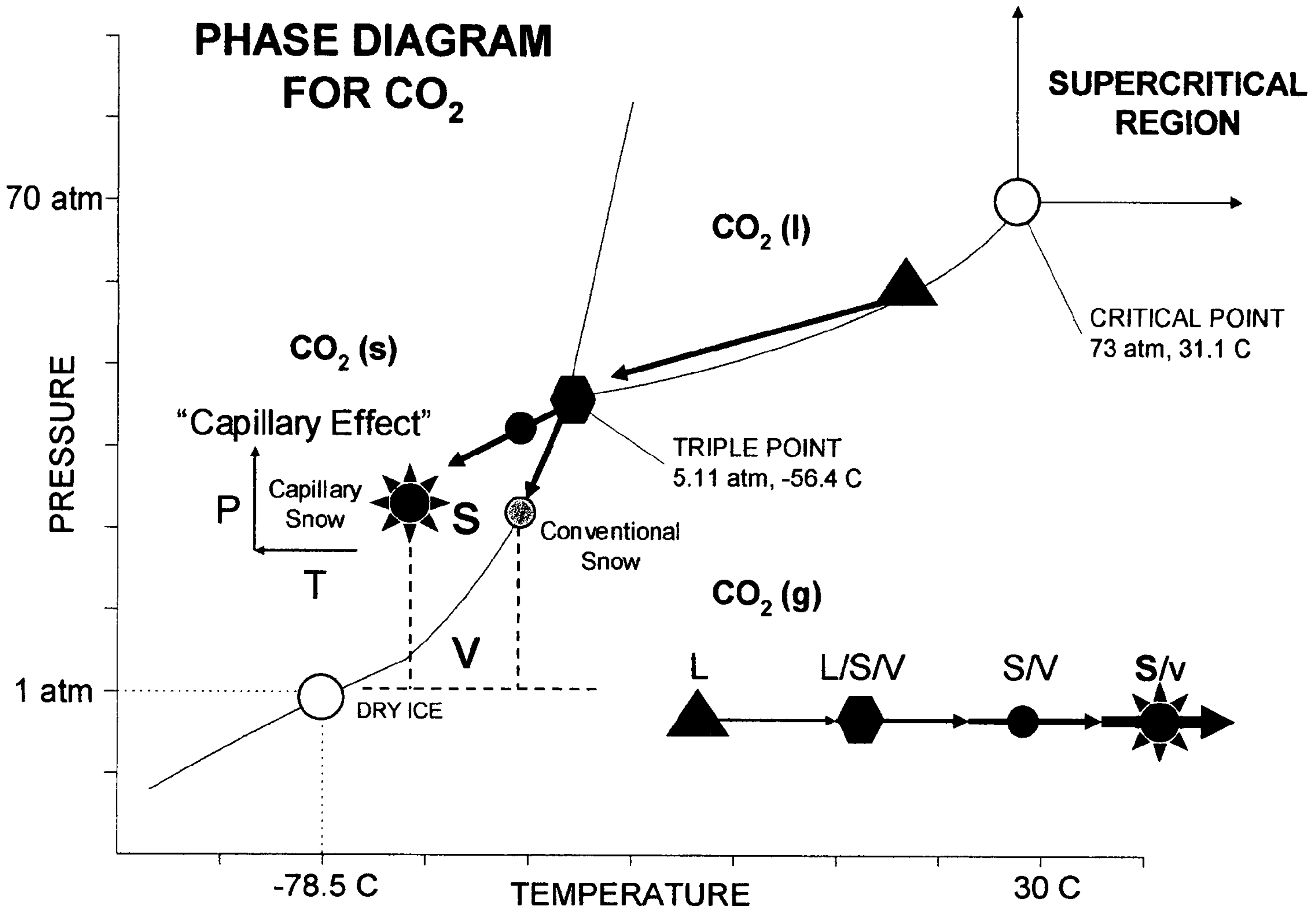

PHASE DIAGRAM FOR CO$_2$
SUPERCRITICAL REGION
70 atm
1 atm
PRESSURE
CO$_2$ (l)
CO$_2$ (s)
CO$_2$ (g)
CRITICAL POINT
73 atm, 31.1 C
TRIPLE POINT
5.11 atm, -56.4 C
"Capillary Effect"
P
T
Capillary Snow
S
Conventional Snow
V
DRY ICE
L
L/S/V
S/V
S/v
-78.5 C
TEMPERATURE
30 C

Figure 6

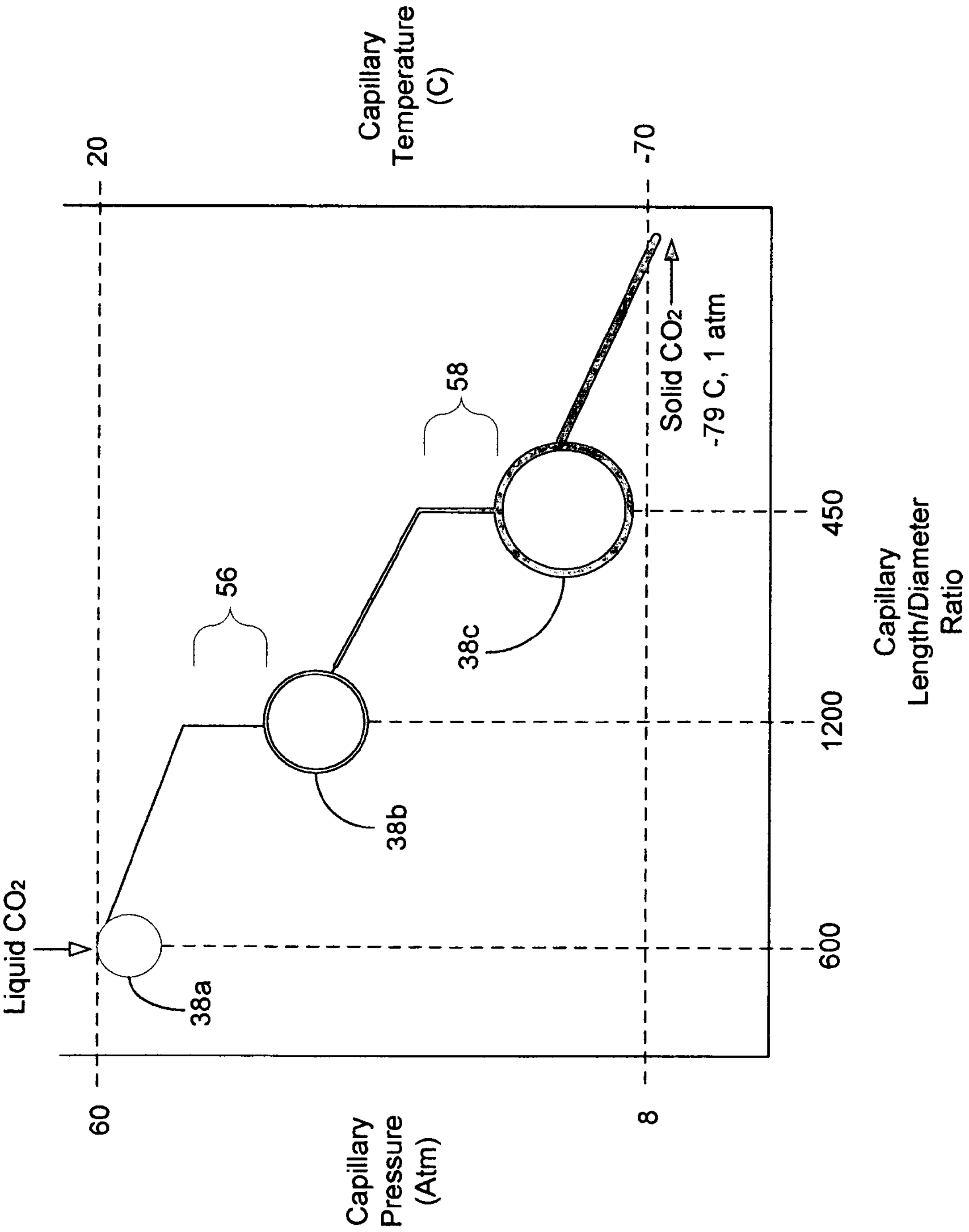
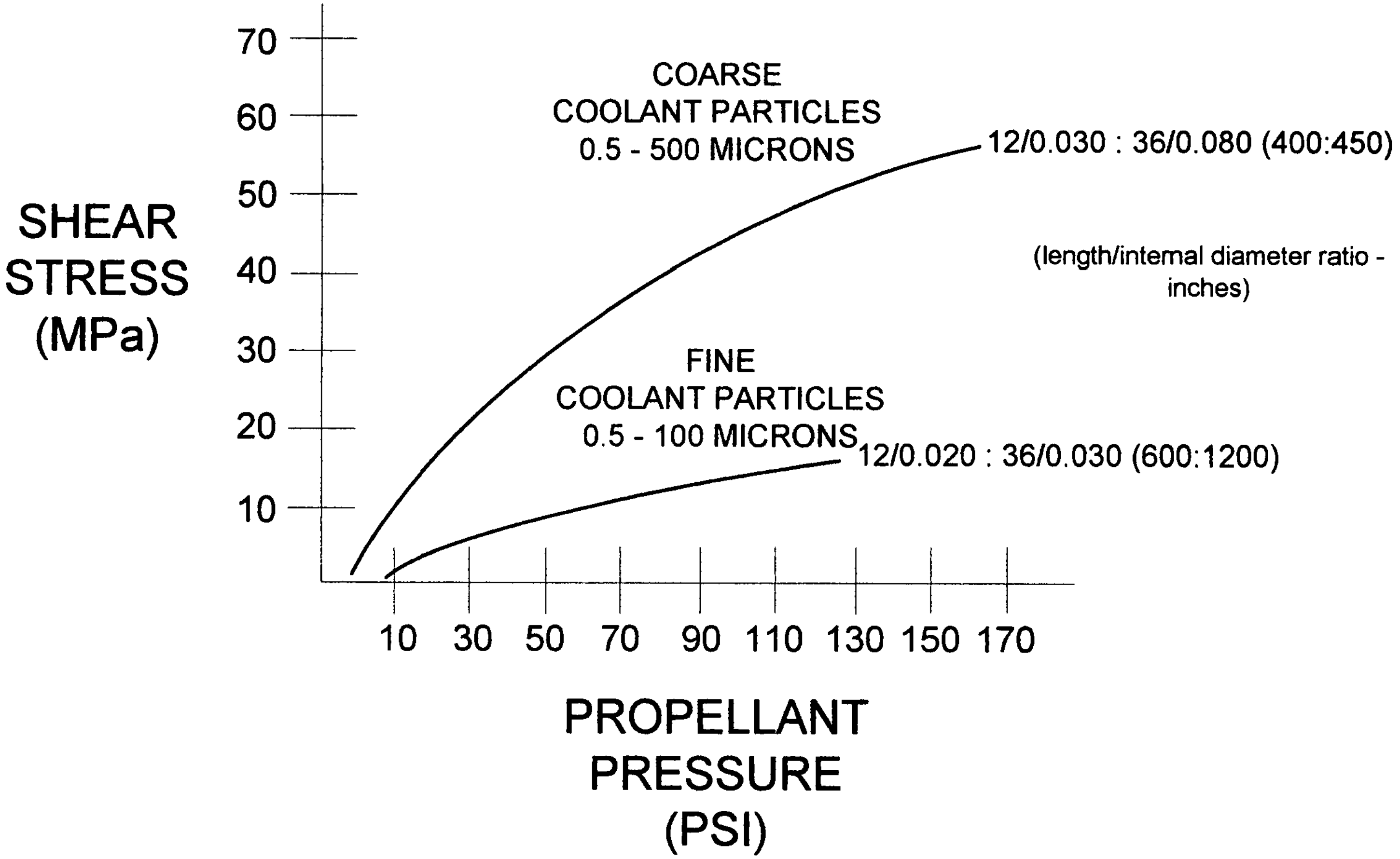
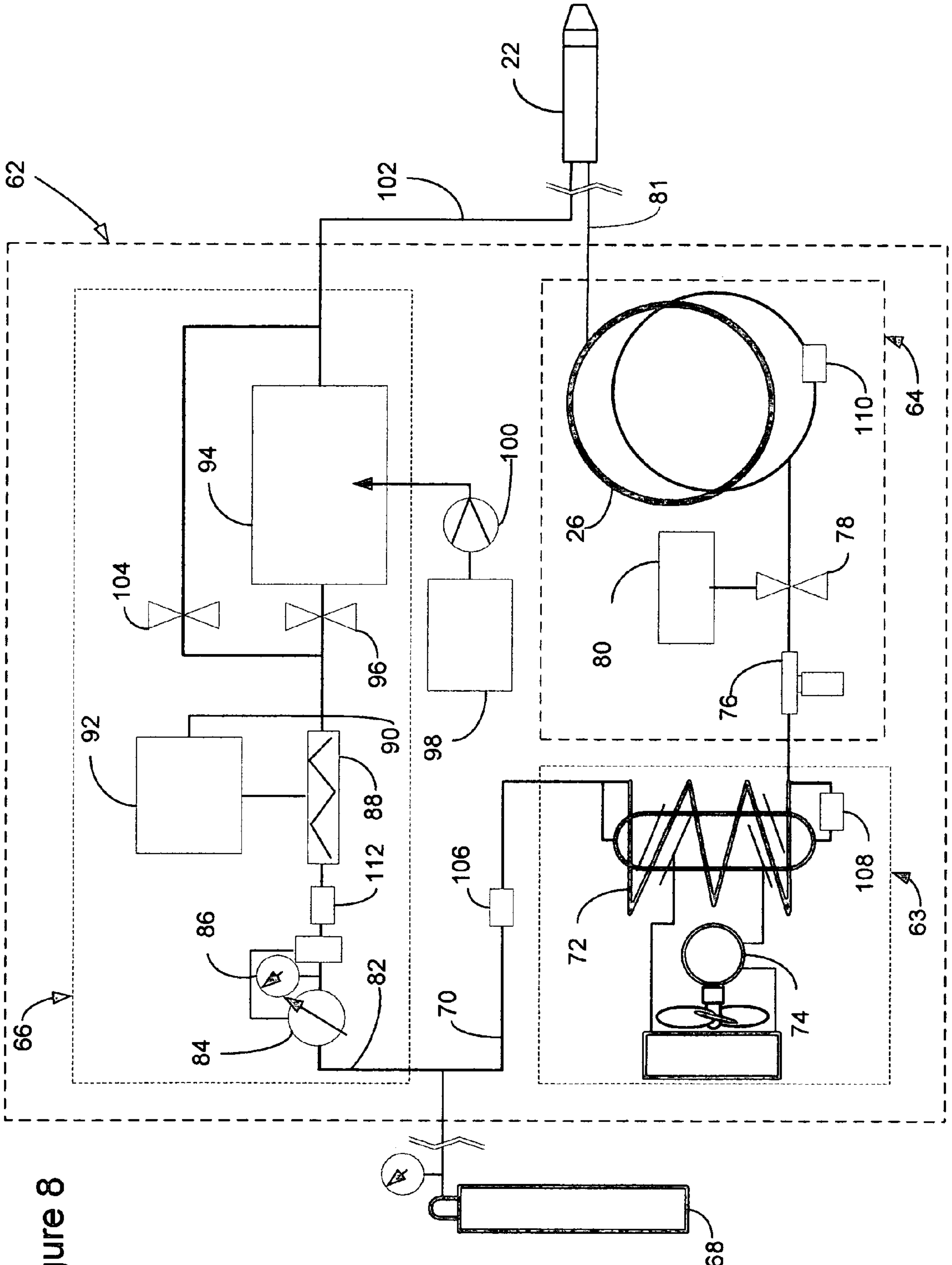

Capillary Temperature (C)
20
-70
Liquid CO_2
38a
38b
38c
56
58
Solid CO_2
-79 C, 1 atm
600
1200
450
Capillary Length/Diameter Ratio
60
8
Capillary Pressure (Atm)

Figure 7

Spray Impact Pressure
(Shear Stress)




62
22
102
81
66
94
100
104
96
92
90
88
98
112
86
82
84
106
70
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110
64
78
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76
72
108
63
74
68

Figure 8

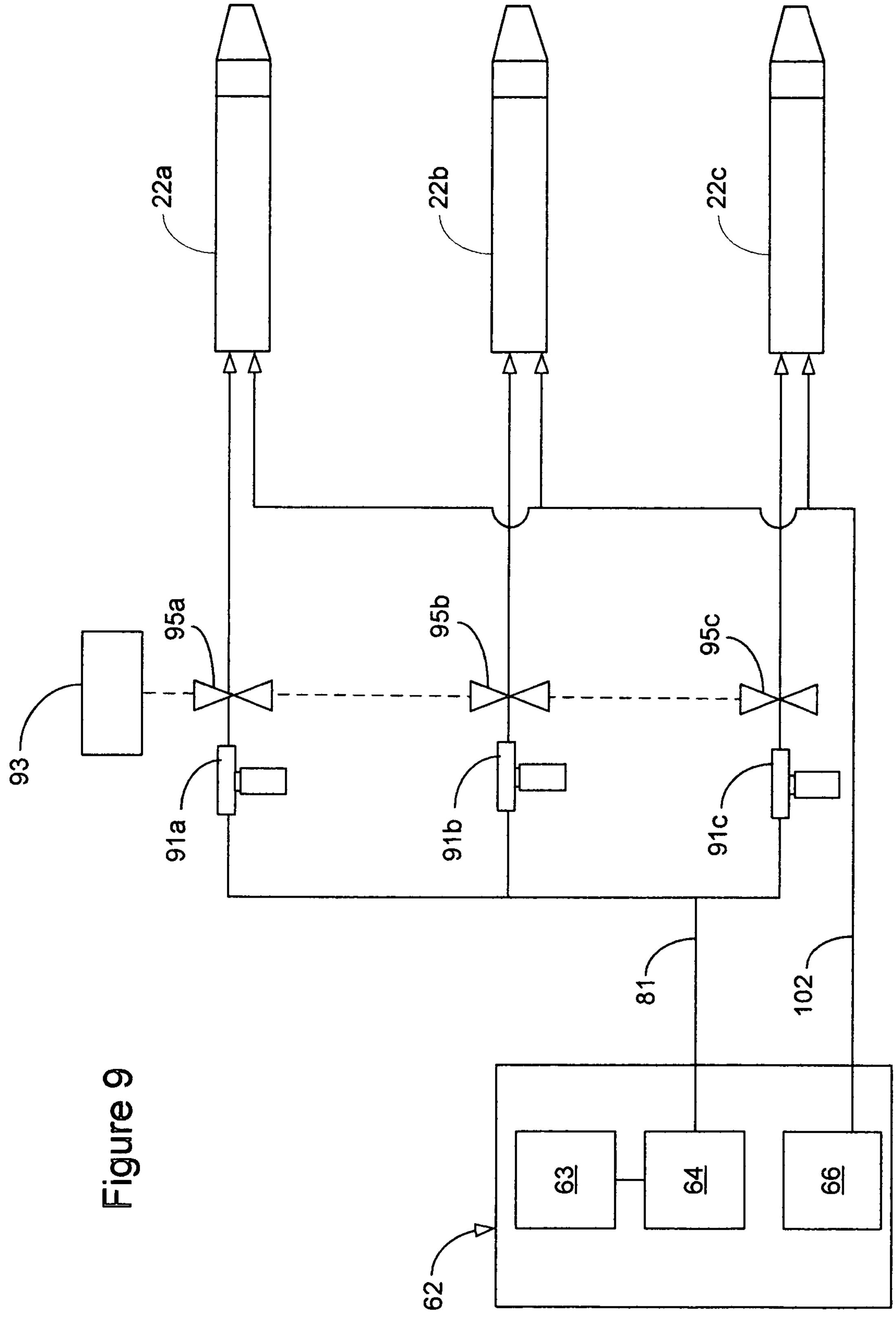


Figure 9

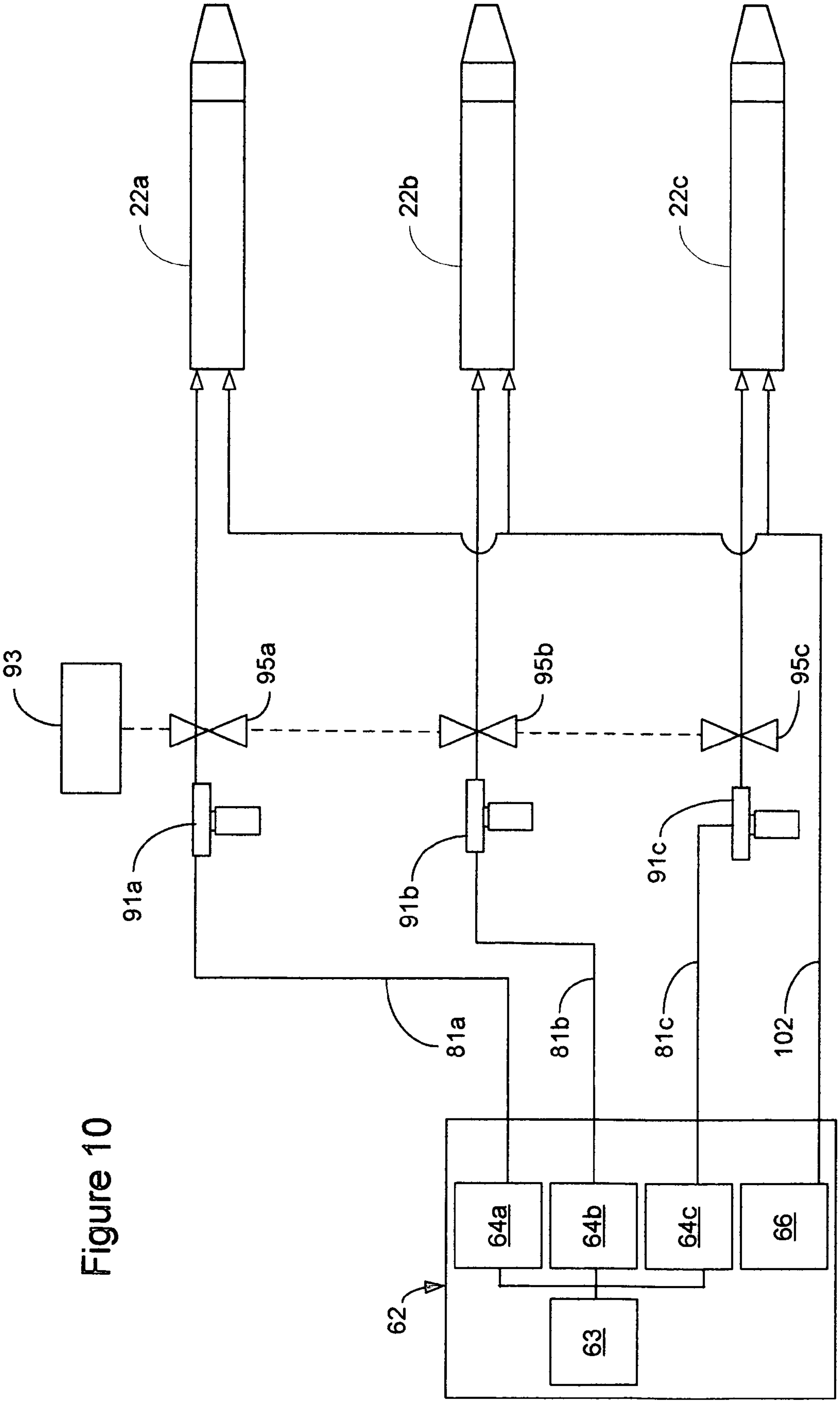

22a
22b
22c
93
95a
95b
95c
91a
91b
91c
81a
81b
81c
102
64a
64b
64c
66
63
62

Figure 10

Figure 11

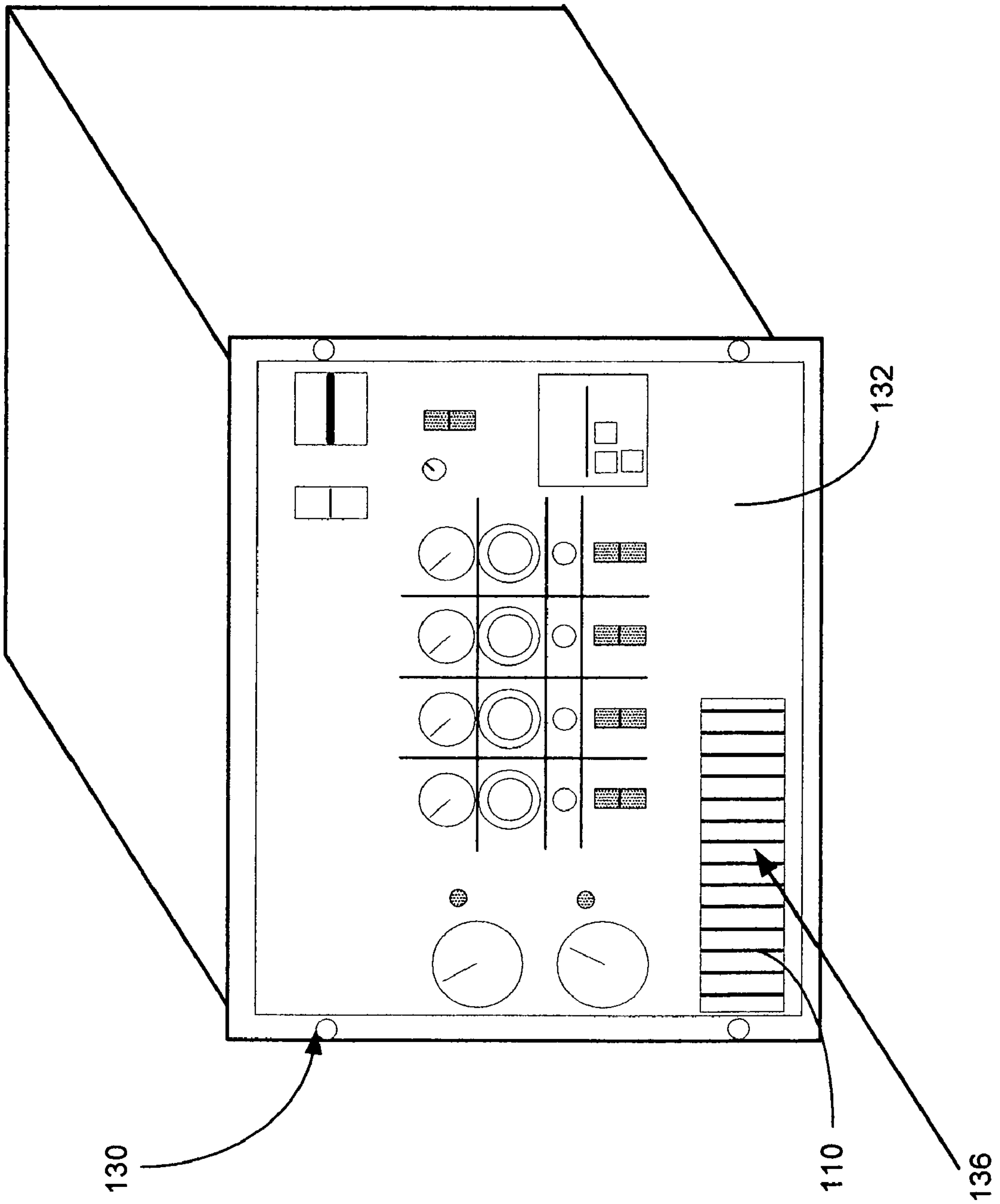


Figure 12

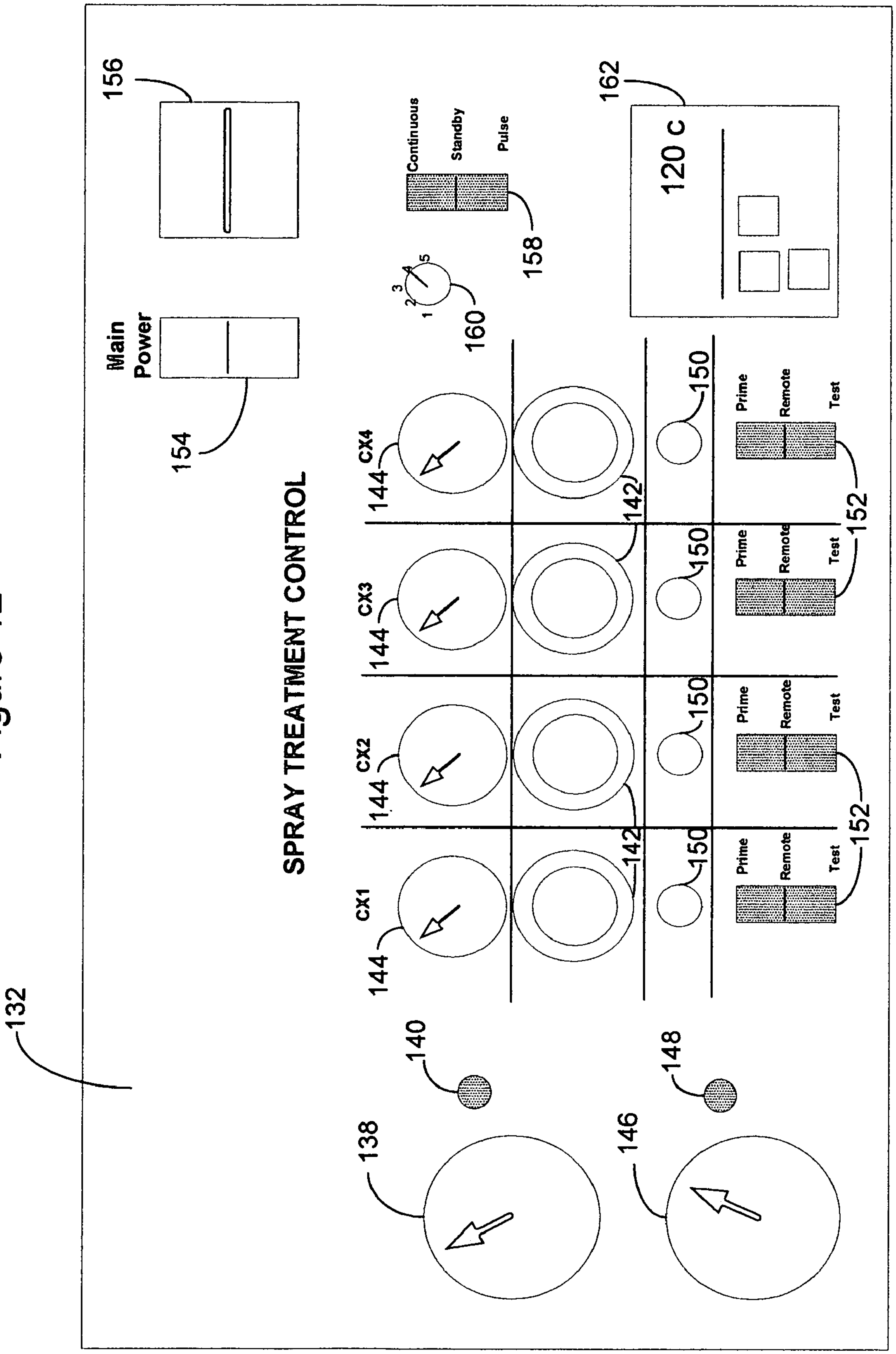

132
SPRAY TREATMENT CONTROL
Main Power
154
156
138
140
146
148
144
CX1
CX2
CX3
CX4
142
150
152
Prime
Remote
Test
160
1
2
3
4
5
Continuous
Standby
Pulse
158
162
120 c

Figure 13

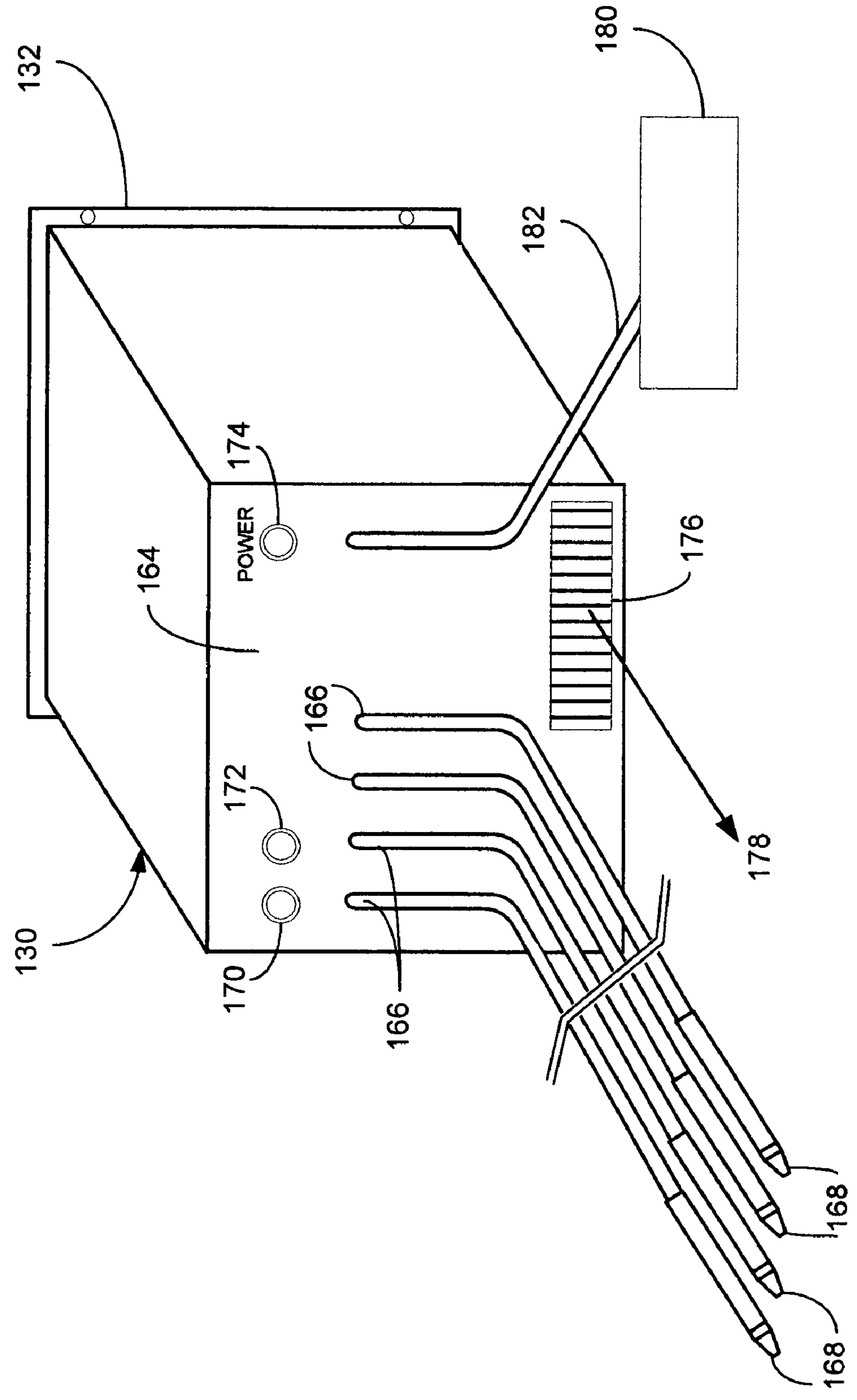
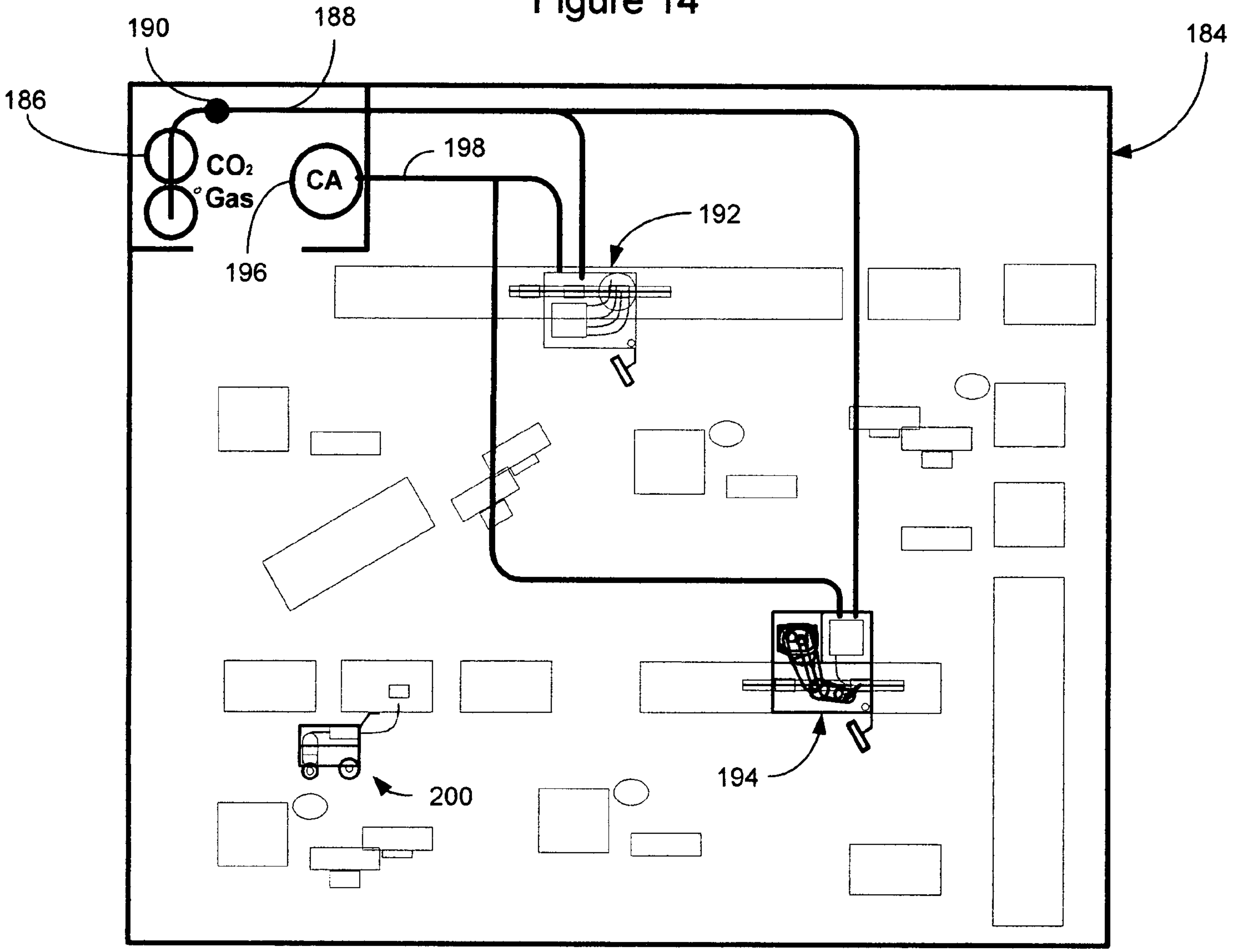

132
180
182
174
POWER
164
176
166
166
172
170
166
130
178
168
168
168

Figure 14



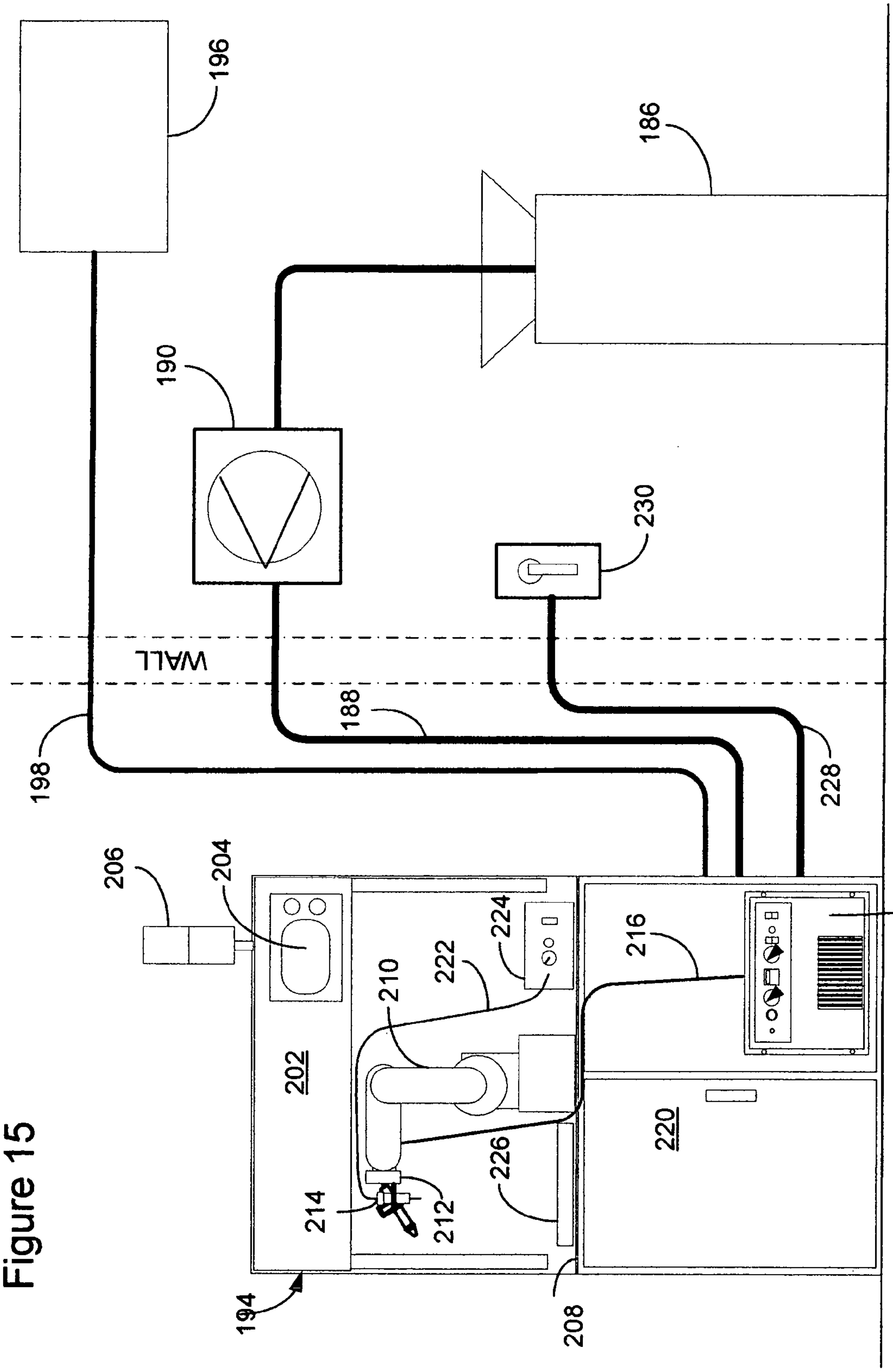

196
186
190
230
WALL
198
188
228
206
204
224
222
210
216
218
202
220
226
214
212
194
208

Figure 15

CARBON DIOXIDE SNOW APPARATUS

CROSS-REFERENCE TO RELATED APPLICATION(S)

This application claims the benefit of U.S. Provisional Patent Application No. 60/635,230 entitled METHOD AND APPARATUS FOR SELECTIVE CLEANING AND TREATMENT WITHIN A MANUFACTURING PROCESS filed on 13 Dec. 2004 and which is hereby incorporated herein by reference.

BACKGROUND OF INVENTION

The present invention generally relates to manufacturing tools and procedures. More specifically, the present invention relates to a precision cleaning apparatus and process that can be integrated directly into various manufacturing tools and processes. Manufacturing tools and processes requiring precision cleaning include, among others, die attachment, machining, board cutting, wafer singulation, assembly, rework, inspection, wire bonding, adhesive bonding, soldering, underfilling, dispensing, sealing, dicing, coating and trimming tools. These tools may be designed and developed as stand-alone tools, located on automation lines or integrated into existing Original Equipment of Manufacturers (OEM) tools.

In-situ cleaning processes practiced in the prior art involve a variety of cleaning methods including solvent bathes, aqueous cleaning, ultrasonic cleaning, and liquid spraying. Due to there inherent incompatibilities with process tools, the aforementioned methods are typically performed as a step before or after a manufacturing tool or process. For example, U.S. Pat. No. 4,832,753 issued to Cherry et al., suggests a fully enclosed environmental chamber containing a Freon® 113 solvent sprayer with a high-efficiency particulate air (HEPA) filter and dry air re-circulated within a closed chamber. The apparatus is typical of what would be commonly used as a stand-alone cleaning tool within a manufacturing operation.

There are several examples of the prior art suggesting techniques to integrate carbon dioxide snow into substantially stand-alone cleaning systems to control thermal and electrostatic effects during the use of cryogenic impingement sprays. These techniques include using secondary heated or ionized jets or sprays directed at the substrate surface and delivered either independently or as a component of the cryogenic spray. For example, U.S. Pat. No. 5,354,384 issued to Sneed et al. suggests the use of a heated gas, such as filtered nitrogen, to provide both a pre-heat cycle and a post-heat cycle to a portion of a substrate in a snow spray cleaning process. This approach relies on "banking heat" into the substrate portion prior to the cryogenic spray cleaning by delivering a heated gas stream to a portion of the substrate to prevent moisture deposition and adding heat from a heated gas following cryogenic spray treatment. Another example includes U.S. Pat. No. 5,409,418 issued to Krone-Schmidt et al., which suggests an apparatus for surrounding an impinging cryogenic spray stream with an ionized inert gas. It is proposed by surrounding a stream of solid-gas carbon dioxide with a circular stream of ionized gas and applying the two components to the substrate simultaneously, resulting in controlling or eliminating the electrostatic discharge at the surface during impingement. However, in practice, entrainment and deposition of atmospheric contaminants onto substrate surfaces being treated with the cryogenic spray is resulted. As such, cryogenic spray cleaning applications of the prior art necessitate that the housing of the cryogenic spray applicator, the substrate and the secondary gas jets be enclosed in large, bulky and complex environmental enclosures employing HEPA filtration and dry inert atmospheres.

Another approach is to integrate the cryogenic spray cleaning process into a production tool. For example U.S. Pat. No. 5,001,873 teaches a method for cleaning small Excimer LASER optics in-situ within the sealed chamber comprising the LASER cavity itself Using this invention, each optical surface is provided an individual carbon dioxide spray nozzle, as well as purge gas nozzles, as a means for cleaning particle debris from the optical surfaces between LASER operations. Such an invention provides in-situ cleaning of the production tool components, in this case the LASER optical surfaces. However, the '873 invention does not teach an apparatus for generating and controlled such a cleaning spray. More importantly, '873 does not teach providing in-situ spray cleaning of Excimer LASER processed substrates and does not provide a means for integrating cryogenic spray cleaning into the LASER production process.

The failure in the prior art to effectively provide a technology capable of operating within the production process, the same workcell or process tool to provide clean-in-place capability results in a number of disadvantages and limitations in manufacturing operations. As discussed herein, overall productivity is limited by many factors including environmental control challenges for cryogenic spray cleaning, carbon dioxide cleaning machine's ability to operated autonomously, adaptability to different manufacturing processes and tools, cleaning complex surfaces, and cleaning multiple surfaces at one time.

This is particularly disadvantageous in flexible manufacturing systems in which the entire machining operation is intended to be completely automated. Flexible manufacturing systems are designed to operate without human assistance, or greatly reduced human assistance, and it substantially limits their efficiency if a worker must regularly remove substrates, clean them and return them to the manufacturing tool or line.

In another invention by the present inventor, U.S. Pat. No. 5,725,154, the use of a coaxial solid spray generator to spray clean critical surfaces is taught. The '154 invention suffers from the same limitations of other prior art discussed herein including the need for environmental control as well as the need for utilitarian improvements necessary for integration into and control by a production tool. For example, significant improvements in the present invention over '154 include a gas-to-liquid phase condenser and purification system which allows the present invention to be used anywhere in the manufacturing environment with just a single source supply of carbon dioxide gas. This is a particular advantage in manufacturing environments where the transport or storage of high pressure liquid carbon dioxide supply tanks would be cumbersome or pose a risk to workers. Moreover, gas supply lines may be brought from a single supply tank to multiple production tools incorporating the present invention.

Moreover, a new type of capillary condenser technology is taught herein called a "stepped capillary condenser", which achieves solid carbon dioxide particle types (i.e., particle size and coarseness) heretofore not possible using '154. Conventional snow cleaning devices produce fine gas-filled solid particles, of which a significant quantity of particles are needed to efficiently clean a surface. Moreover, fine particles require extremely high velocities to dislodge tenacious surface contaminants. By contrast, the more coarse particles generated by the stepped capillary condenser embodiment of present invention provide increased physicochemical cleaning action and fewer of these types of particles required to remove very tenacious surface residues.

Still moreover, further research by the present inventor has shown that oscillating the snow particle stream at greater than 1 Hertz significantly improves surface cleaning action (i.e., scouring) with the added benefit of not interrupting the generation and flow of solid carbon dioxide particles. Finally, a means for multiplexing coaxial spray applicators is taught, which provides a method for cleaning multiple sides of a complex article.

Unlike the prior art, the present invention provides the ability to seamlessly integrate cryogenic spray cleaning into a production process. There are many manufacturing applications where such a capability as in the present invention would improve quality and performance, provide a lower cost of ownership and longer tool life (i.e., cutting and dicing blades), smaller footprint, less cleanroom floor space, and provide an increase in process efficiency. One such example is described as follows.

The growing variety and complexity of matrix array packages present a true challenge to many back end processes. The singulation (i.e., dicing a wafer into discrete dies) of these arrays into individual packages is an important step in the manufacturing process, and as in many cases, needs to be optimized to minimize the overall cost of package. The continuous reduction in package size, along with the demand for increased throughput has resulted in a shift to advanced dicing processes for many matrix array packages, for example copper-ceramic and copper-plastic packages. Quality issues associated with conventional dicing of such devices using water-based coolant include chipping along the edges of the diced kerf, smearing of the ductile copper, and the formation of burrs. Using the selective impingement cleaning apparatus of the present invention, a dicing-cleaning hybrid system improves cutting quality, reduces chipping, reduces smearing and burr formation. Another advantage is increased tool life as well since the tool itself is continuously cleaned during the process.

Today's production environment demands fairly autonomous operation and standard control and communication between production controls and equipment to improve efficiency, increase quality and reduce manufacturing costs. These so-called plug and play manufacturing tools utilize standards such as the Generic Model for Communications and Control of Semi Equipment, the Semiconductor GEM standard. No prior art teaches a module which combines all the necessary elements for efficient use of solid phase carbon dioxide spray cleaning in production tools and on the manufacturing line.

As such there is a present need for a plug and play process, apparatus and chemistry that reduces air pollution, eliminates worker exposure hazards, eliminates liquid hazardous waste production, and enables the widespread implementation of in-situ precision cleaning or more specifically clean-during-processing capability.

In many manufacturing operations a product is cleaned prior to or following a particular assembly process, sometimes many times through the production cycle. Conventional parts cleaning operations are performed as an independent operation prior to or following a manufacturing process using, for example, a spray cleaner, vapor degreaser or ultrasonic cleaning system. Segregation of the cleaning process has been due to the inherent chemical and physical incompatibilities between conventional cleaning operations and most assembly tools. Manufacturing operations requiring a cleaning or surface treatment process may include cutting, drilling, trimming, micro-machining, bonding, dicing, abrasive finishing, polishing, stamping and welding, among many other operations. There is a present need for an alternative cleaning model for the manufacturing process. This alternative integrated cleaning into the production process to produce a range of new assembly tools—hybridized cleaning and manufacturing tools. Hybrid tools are much more productive because two or more assembly processes can be performed simultaneously within the same work cell. Substrates being treated don't have to be removed, cleaned and returned to the production line—resulting in reduced human interaction, higher throughput and decreased cost-of-ownership. In the traditional manufacturing model, precision parts cleaning is not considered a value-added operation. The present invention incorporates the cleaning process into the value-added assembly and manufacturing operations, which enhances both product yield and tool productivity. The present invention is suitable for integration into original equipment manufacturer (OEM) tools as well as serving as a stand-alone tool for manufacturing production lines. The present invention enables the creation of unique and useful hybrid manufacturing technology, providing cleaning during manufacturing and assembly operations.

BRIEF SUMMARY OF INVENTION

The carbon dioxide snow apparatus of the present invention generally includes a snow generation subsystem and a diluent or propellant subsystem connected to a delivery line and applicator. The snow generation subsystem includes a stepped capillary condenser comprising at least two connected segments of differing diameters. The stepped capillary condenser provides increased Joule-Thompson cooling in the conversion of liquid carbon dioxide to solid carbon dioxide, reduces clogging and sputtering, improves jetting, and allows for greater spray temperature control. Moreover, the stepped capillary condenser produces coarser particles than a single step capillary.

Another aspect of the present invention is the ability to provide several snow generation subsystems, each with a stepped capillary condenser, in communication with a single carbon dioxide source and diluent or propellant subsystem. This allows for the generation of snow particles of differing sizes and physical qualities to fit the need of treating a single substrate or multiple substrates. The several snow generation subsystems, diluent or propellant subsystem and respective delivery lines and applicators can be independently controlled and fitted within a console or mobile unit.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is an illustrated perspective view of a carbon dioxide snow treatment apparatus of the present invention.

FIG. **2** is a partial cross sectional view of the carbon dioxide snow treatment apparatus of FIG. **1**.

FIG. **3** is an illustrated perspective view of an alternative embodiment of a snow treatment apparatus of the present invention.

FIG. **4** is a partial cross sectional view of the alternative embodiment of a snow treatment apparatus of FIG. **3**.

FIG. **5** is a phase diagram of carbon dioxide.

FIG. **6** is a graphical diagram of the physical characteristics of a stepped capillary condenser of the present invention.

FIG. **7** is a graphical diagram of shear impact stresses of the present invention.

FIG. **8** is a flow-diagram of a carbon dioxide snow treatment system of the present invention.

FIG. **9** is a flow-diagram of an alternative embodiment of the carbon dioxide snow treatment system of the present invention.

FIG. **10** is a flow-diagram of an alternative embodiment of the carbon dioxide snow treatment system of the present invention.

FIG. **11** is a perspective view of an apparatus employing the carbon dioxide snow treatment system of the present invention.

FIG. **12** is a frontal side-view of the apparatus illustrated in FIG. **11**.

FIG. **13** is a perspective rear-view of the apparatus illustrated in FIG. **11**.

FIG. **14** is a top-view of an exemplary plant floor design incorporating embodiments of the present invention.

FIG. **15** is a side-view of a control scheme between the present invention and a machine controller.

DETAILED DESCRIPTION

A carbon dioxide snow treatment apparatus for selectively treating a substrate within a manufacturing process is generally indicated at **20** in FIG. **1**. The apparatus **20** includes a dense fluid spray applicator **22**, with a mixing spray nozzle **24**, connected to a flexible capillary condenser **26**. Preferably, the dense fluid spray applicator **22**, used in conjunction with a connected propellant gas source, is either a co-axial dense fluid spray applicator as taught by the present inventor and fully disclosed in U.S. Pat. No. 5,725,154 or a tri-axial type delivering apparatus as taught by the present inventor and fully disclosed in U.S. Provisional Application No. 60/726,466, both of which are hereby incorporated herein by reference. Employing either fluid spray applicator **22**, a dense fluid **30**, preferably liquid carbon dioxide, enters the capillary condenser **26** whereupon passing therethrough, or in conjunction with the applicator **22**, is condensed and solid carbon dioxide snow **32** exits the mixing spray nozzle along with the propellant gas **28** or any uncondensed carbon dioxide.

Referring to FIG. **2**, the capillary condenser **26** includes a capillary tube **34** covered by suitable insulation **36**, such as for example, 0.318 cm (0.125 inch) of self-adhering polyurethane insulation foam tape as supplied by Armstrong World Industries, Inc. of Lancaster, Pa., which is wrapped about the capillary tube **34** in a helical fashion with 50% overlap. The capillary tube **34** includes segmented capillaries **38** that have step-wise increasing diameters, indicated by d_1, d_2, d_3 and d_4, respectively, which increase in a feed-wise direction, indicated by arrow A. Thus, $d_1<d_2<d_3<d_4$. It should be noted, though, that capillary tube **34** of FIG. **2** is for illustrative purposes only, and that the capillary tube **34** of the present invention need only include at least two segments **38**, and it is well within the scope of the present invention to provide a capillary tube **34** with three or more segments **38** as well, depending upon the particular application. The capillary **34** is preferably constructed of a PolyEtherEtherKetone (PEEK) polymer. However, other suitable tubular materials are well within the scope of the present invention including, but not limited to, Teflon®, Stainless Steel, or other clean and flexible materials. As stated, the capillary condenser tube **34** includes at least two segments **38**, with each segment **38** preferably having a length ranging from 0.3 m (1 foot) to 7.32 m (24 feet) and inside diameters ranging from 0.127 mm (0.005 inches) to 3.175 mm (0.125 inches). Such tubing should be able to withstand propellant gas pressures ranging up to about 7 MPa (1000 psi) and temperatures ranging between 203 K and 473 K. The interconnections **39** between the segments may be Swagelok or finger-tight compression fittings.

FIGS. **3** and **4** illustrate an alternative carbon dioxide snow treatment apparatus **40** of the present invention including a flexible capillary condenser **42** connected to a divergent/convergent nozzle **44**. The capillary condenser **42** similarly includes a capillary tube **46** having segmented capillaries **48***a*, **48***b*, **48***c* and **48***d* that have step-wise increasing diameters d_1, d_2, d_3 and d_4, respectively, which increase in a feed-wise direction, indicated by arrow B. The capillary **42** is preferably constructed of PEEK polymer. However, other suitable tubular materials are well within the scope of the present invention including, but not limited to, Teflon®, Stainless Steel, or other clean and flexible materials. As stated, the capillary condenser tube **42** includes at least two segments **48**, with each segment **48** preferably having a length ranging from 0.3 m (I foot) to 7.32 m (24 feet) and inside diameters ranging from 0.127 mm (0.005 inches) to 3.175 mm (0.125 inches). Such tubing should be able to withstand propellant gas pressures ranging up to about 7 MPa (1000 psi) and temperatures ranging between 203 K and 473 K. The interconnections **49** between the segments may be Swagelok or finger-tight compression fittings. The capillary tube **42** is positioned within a propellant gas tube **50**. A heated propellant gas **52** is carried within the flexible propellant delivery tube **50** to the nozzle **44**. The propellant tubing **50** may be constructed of any number of suitable tubular materials including Teflon, Stainless Steel overbraided Teflon®, Polyurethane, Nylon, among other clean and flexible materials having lengths ranging from 0.3 cm (1 foot) to 7.3 m (24 feet) or more and inside diameters ranging from about 0.65 cm (0.25 inches) to about 1.3 cm (0.50 inches). Such tubing **46** should be able to withstand propellant gas pressures ranging between about 0.07 MPa (10 psi) and 1.72 MPa (250 psi) and temperatures ranging between 293 K and 473 K. The exemplary flexible condenser **42** of the alternative embodiment **40** is terminated with the rigid mixing spray nozzle **44** which contains a convergent mixing nozzle portion and a divergent expansion nozzle portion (not shown) as is known in the art. Dense fluid **53**, preferably liquid carbon dioxide, enters the capillary assembly **46** and forms carbon dioxide snow particles as the carbon dioxide progresses through the at least two capillary segments **48**. Upon entering the nozzle **44**, carbon dioxide snow particles discharge from the capillary condenser assembly **46**, mixing with propellant gas **52** discharged from the propellant aerosol tube **50**, thus forming a solid-gas carbon dioxide spray **54**. The carbon dioxide aerosol spray **54** discharges from the nozzle **44** and is selectively directed at a substrate surface (not shown).

Being that both embodiments **20** and **40** include similar stepped capillary assemblies **34** and **46**, respectively, reference to one shall include reference to the other and all their like parts, for purposes of convenience, unless stated otherwise. Capillary segments **38** are constructed to have increasing, or stepped, diameters in the direction of flow because it has been discovered that by providing stepped capillaries of increasing diameter, certain performance advantages over single capillary diameters are resulted. For instance, when employing carbon dioxide as the dense fluid, larger and harder snow particles can be generated from a relatively smaller feed supply of carbon dioxide. Also, starting with an internal capillary diameter as little as about 0.5 mm (0.020

inches) in the first capillary segment, restricted flow into and down the capillary condenser tube is resulted. It has also been discovered that by manipulating the number of steps and incrementally increasing the capillary step diameters, various ranges of solid phase particle size distribution can be produced. Stepped capillary condensation more efficiently condenses the liquid and vapor to solid through sharp near-isobaric expansion cooling while also producing a more desirable range of impact shear stresses.

Referring to FIG. **5**, using a non-stepped capillary, liquid carbon dioxide at approximately 6 MPa (60 atmospheres) and 293 K enters the capillary condenser **26** and begins to boil at the triple point. Pressure builds instantly within the condenser causing the boiling mixture to subcool below the triple point, traversing deeply into the solid phase region. Temperature continues to decrease within the capillary while pressure is maintained at a pressure above the vapor phase. This capillary effect is an optimized Joule-Thompson process which efficiently produces an aerosol composition rich in solid phase carbon dioxide.

Referring now to FIG. **6**, liquid carbon dioxide enters the first segment **38***a* of the stepped capillary condenser **34** of the present invention. The liquid carbon dioxide almost instantly pressurizes the entire capillary tube **34** with a mixture of sub-cooled gas, solids and liquid. The pressure within the capillary condenser **34** builds rapidly causing the gas phase to re-condense to solid phase and/or liquid phase. After traversing the first capillary segment **38***a*, the mixture encounters a sharp step in the second capillary segment **38***b* which increases the expansion volume considerably. This sharp change in volume causes the mixture temperature to drop rapidly **56** to near-isobaric expansion, forming relatively coarse and large crystals of solid phase carbon dioxide. The mixture continues to condense along the second capillary segment until encountering the third capillary segment **38***c*, again rapidly expanding and cooling **58** the mixture to form additional coarse crystals of solid phase carbon dioxide. The mixture continues to condense in further segments **38***d* and so on.

By contrast, conventional snow spray processes using less efficient Joule-Thompson condensation means, such as expansion upon exiting a spray nozzle, do not build pressure or lower temperature along a progressive gradient. The mixture thus exists for a very short time along the solid-vapor line which produces snow composition having as much as 30% to 40% less solid phase produced from the liquid phase, and much more vapor phase.

Another aspect of providing a stepped capillary condenser **34** is the ability to optimize spray composition **32** with respect to snow particle size distribution. This is important because the cleaning energy, defined by the force, pressure and stress of the snow particle directed onto the substrate, is directly proportional to the size or mass of the snow particle. Referring to FIG. **7**, a stepped capillary condenser comprising a 30 cm (12 inch) long section of 0.8/1.6 mm (0.030/0.0625 inch) inside/outside diameter PEEK capillary segment coupled with a 91 cm (36 inch) long section of 2.0/3.2 mm (0.080/0.125 inch) inside/outside diameter PEEK capillary tube produces variable shear stress pressures of between 0 and 50 MPa for propellant pressures of between 0 and 1 MPa (150 psi). By contrast, the stepped capillary condenser of the present invention comprising a 30 cm (12 inch long) section of 0.5/1.6 mm (0.020/0.0625 inch) inside/outside diameter PEEK capillary segment coupled with a 91 cm (36 inch) long section of 0.8/1.6 mm (0.030/0.0625 inch) inside diameter PEEK capillary segment produces variable shear stress pressures of between 0 and 10 MPa for propellant pressures of between 0 and 0.9 MPa (130 psi). It can be seen that for an approximate doubling of the capillary step volume, for a given capillary condenser length, propellant pressure and temperature, a five-fold increase in shear stress pressure can be exerted. In accordance with the following equation:

$$\text{Kinetic Energy}=\tfrac{1}{2}(\text{Mass})(\text{Velocity})^2$$

the solid carbon dioxide particles impacting the surface appear to have a particle size distribution having about a five-fold difference. Spray impact stress experiments performed using Prescale Series contact pressure measuring films, manufactured by FujiFilm USA, show that spray impact pressures may be selectively altered using stepped capillary condensers **34** to produce a mass of sublimable particles and coupling the particle stream with a propellant phase. The present invention can produce solid carbon dioxide particles having diameters ranging 0.5 microns (fine) to 500 microns (coarse) which are able to produce variable impact stresses. A fine particle spray can produce a range of impact stresses from less than 0.1 MPa to approximately 15 MPa at propellant phase pressures of between 0 and 1 MPa. A coarse particle spray can produce a range of impact stresses from less than 0.1 MPa to approximately 50 MPa at propellant phase pressures of between 0 and 1 MPa. Higher impact stresses are imparted at higher propellant pressures and lower impact stresses are imparted at lower propellant pressures. Propellant pressure and temperature can be used selectively to alter both the impact stress and impact particle density.

A preferred capillary combination **34** for use with the present invention includes a 31 cm (12 inches) of 4.2/0.3 mm (0.010/0.167 inch) inside/outside diameter capillary coupled with a 46 cm (18 inches) of 0.5/1.6 mm (0.020/0.062 inch) inside/outside diameter capillary and a 91 cm (36 inches) of 1.0/1.6 mm (0.040/0.062 inch) inside/outside diameter PEEK capillary. The initial 61 cm (24 inch) section of the capillary condenser is wrapped up, while the third segment is run down the coaxial propellant tube **46** to form the coaxial spray applicator **44**. A more preferred capillary combination **34** for use with the present invention includes the first capillary segment **38***a* comprising approximately 31 cm (12 inches) of 0.76 mm (0.030 inch) inside diameter PEEK, followed by the second capillary segment **38***b* being approximately 92 cm (36 inches) to 122 cm (48 inches) of 2 mm (0.080 inch) inside diameter PEEK tubing. The entire PEEK stepped capillary assembly **34**, with the exception of the portion traversing the coaxial line **50**, is wrapped in insulating material **36** to prevent heat transfer during the condensation process. Other lengths, diameters and stepwise constructions are possible to form various desired spray compositions therein.

Alternatively, the dense fluid composition is that as taught by the present inventor and fully disclosed in U.S. application Ser. No. 11/301,466 entitled CRYOGENIC FLUID COMPOSITION filed concurrently herewith and claiming benefit from U.S. Provisional Application No. 60/635,399, both of which are hereby incorporated by reference.

Having thus described the preferred method for generating carbon dioxide snow particles within a stepped-capillary condenser **34**, the following is a discussion of exemplary apparatuses for creating a stepped capillary condenser **26** in a carbon dioxide snow treatment system. Referring to FIG. **8**, a carbon dioxide snow treatment system is indicated at **62** and includes carbon dioxide liquification subsystem **63**, a carbon dioxide snow generation subsystem **64** and the carbon dioxide propellant aerosol generation subsystem **66** connected to a high-pressure carbon dioxide supply **68**. The high pressure carbon dioxide gas **68** preferably has a pressure range of between 2 MPa (300 psi) and 6 MPa (900 psi). The carbon dioxide snow generation subsystem **64** and propellant aerosol subsystem **66** are each connected to a dense fluid spray applicator.

The high pressure carbon dioxide gas is fed into the liquification subsystem **63** via a pipe **70** to a tube-in-tube heat exchanger **72**, wherein a compressor-refrigeration unit **74** re-circulates sub-cooled refrigerant countercurrent with the heat exchanger **72**, condensing the carbon dioxide gas into a liquid carbon dioxide base stock. Liquid carbon dioxide base stock flows from the heat exchanger **72** into the snow generation subsystem **64** through a micro-metering valve **76**, a base cleaning stock supply ball valve **78** and then into the stepped capillary condenser unit **26**. Optionally, a supply ball valve **78** may be oscillated between opened and closed at a cycle rate of one or more cycles per second using an electronic pulsing timer **80**. In the present embodiment, the stepped capillary condenser **26** is constructed first using a 61 cm (24 inch) segment of 0.8/1.6 mm (0.030/0.0625) inside/outside diameter PEEK tubing and then a second 91 mm (36 inch) segment of 1.5/3.2 mm (0.060/0.125 inch) inside/outside diameter PEEK tubing. As described, the stepped capillary condenser **26** boils liquid carbon dioxide base stock under a controlled pressure gradient to produce a solid phase carbon dioxide base stock which is fed to the applicator **22** via delivery line **81**.

In the propellant generation subsystem **66**, the high pressure carbon dioxide gas **68** is therein via a pipe **82** and into a pressure reducing regulator **84** and gauge **86** capable of regulating the carbon dioxide gas propellant pressure between 0.07 MPa (10 psi) and 1.72 MPa (250 psi) or more. The regulated carbon dioxide gas is then fed into a resistance heater **88** controlled by a thermocouple **90** and temperature controller **92** at a temperature between 293 K and 473 K. Following this, temperature-controlled carbon dioxide gas is fed into either the spray applicator **22** or into an aerosol generator **94**. When employing the aerosol generator **94**, temperature-regulated carbon dioxide propellant is fed via an aerosol generator inlet valve **96** into the aerosol generator **94**. The aerosol generator **94** is supplied by a additive supply tank **98** and injection pump **100** which can inject cleaning additives, such as acetone, into the temperature-regulated carbon dioxide propellant gas preferably at a rate of between 0 liters per minute and 0.02 liters per minute or more, thus forming a temperature-regulated carbon dioxide propellant aerosol which may be fed into a propellant aerosol feed line **102**. Alternatively, temperature-regulated carbon dioxide propellant gas may be fed via an aerosol generator bypass valve **104**, thus by-passing the aerosol generator **94**, and connecting directly into the propellant aerosol feed line **102**. It should be noted, though, that pressure-regulated clean dry compressed air (CDA) or nitrogen gas may be used in place of pressure-regulated carbon dioxide gas on piping connection **82** described above to produce a propellant aerosol stream supply.

Another aspect of the carbon dioxide treatment system **62** is that a means is provided for monitoring and controlling the operation of each subsystem **64** and **66**. Such process intelligence is accomplished by using various pressure and temperature sensors along strategic points within each subsystem **64** and **66**. To accomplish this, a pressure switch or transducer **106** is used to measure the input CO_2 pressure to provide and on/off signal with respect to the carbon dioxide gas supply **98**. A thermocouple or thermometer **108** is used within the condenser coil **72** to determine if the carbon dioxide gas is being condensed to liquid. Finally, a thermocouple or thermometer **110** is employed within the stepped capillary condenser assembly **26** to determine if the liquid carbon dioxide is being converted from liquid carbon dioxide to the solid phase. Table 1 lists the preferable operating range parameters for the solid carbon dioxide subsystem **64**.

TABLE 1

Exemplary Solid CO_2 System Sensors and Operating Ranges

Sensor	Lower Limit	Upper Limit
Pressure Sensor 106	2 MPa (300 psi)	6 MPa (850 psi)
Temperature Sensor 108	273 K	283 K
Temperature Sensor 110	213 K	253 K

Referring now to the propellant supply subsystem **66**, a pressure switch or transducer **112** is used to measure the regulated carbon dioxide (or CDA) pressure to provide an on/off signal with respect to the propellant gas supply **68**. Finally, the thermocouple or thermometer **90** is used with the propellant heater **88** and temperature controller **92** to determine if the carbon dioxide (or CDA) propellant gas is being heated to a proper operating temperature. Table 2 lists the preferred operating range parameters for the propellant subsystem **66**

TABLE 2

Exemplary Propellant Gas System Sensors and Operating Ranges

Sensor	Lower Limit	Upper Limit
Pressure Sensor 112	207 kPa (30 psi)	1.7 MPa (250 psi)
Temperature Sensor 90	293 K	473 K

Industrial cleaning or surface treatment applications may require multiple treatment spots on a substrate or multiple treatment spots in close proximity. Any desired number of independent carbon dioxide snow treatment applicators **22** may be provided by multiplexing each applicator **22** with the carbon dioxide snow treatment system **62**. Referring to FIG. **9**, the carbon dioxide snow treatment system **62** is connected, for exemplary purposes, to three carbon dioxide snow applicators **22***a*, **22***b* and **22***c*, respectively. Carbon dioxide snow is fed from the carbon dioxide generation subsystem **64** via delivery line **81** to respective discrete lines **81***a*, **81***b* and **81***c*. Respective discrete line control valves **91***a*, **91***b* and **91***c* control the flow rate of the carbon dioxide snow into the respective applicator **21***a*, **21***b* and **21***c*. Optionally, a pulse generator **93** operatively connects to respective ball valves **95***a*, **95***b* and **95***c* to oscillate each ball valve **95***a*, **95***b* and **95***c* between opened and closed at a cycle rate of one or more cycles per second. Likewise, propellant from propellant subsystem **66** is fed via delivery line **102** to each of the discrete spray applicators **22***a*, **22***b* and **22***c*. Alternatively, and as illustrated in FIG. **10**, if varying particle sizes of carbon dioxide snow is simultaneously desired for a single or multiple applications, the carbon dioxide snow system **62** can be modified to include several snow generation subsystems **64***a*, **64***b* and **64***c*. Each subsystem **64***a*, **64***b* and **64***c* is independently controlled and connected to the corresponding spray applicator **22***a*, **22***b* and **22***c*, respectively, via corresponding snow delivery line **81***a*, **81***b* and **81***c*, respectively. Flow rates for each line are again controlled by corresponding control valves **91***a*, **91***b* and **91***c*, respectively, along with pulse generator **93** and corresponding ball valves **95***a*, **95***b* and **95***c*. Propellant line **102** again connects the propellant generation subsystem **66** to each spray applicator **22***a*, **22***b* and **22***c*.

Another aspect of the present invention is the incorporation of the previous embodiments into a single enclosed unit. An exemplary product design using the present invention is illustrated in FIGS. **11-13**. Referring to FIG. **11**, the carbon dioxide snow treatment system **62** is integrated within an electronic console **130**, such as a rack-mount configuration. The control system **62** may include a single snow generation subsystem **64** as illustrated in FIG. **9**, or several snow generation subsystems **64***a*, **64***b* and **64***c*, as illustrated in FIG. **10**. The electronic console includes a front control panel **132** having an air inlet grill **134** to allow cooling air to enter, indicated by the line arrow segment **136**, to cool the carbon dioxide snow treatment system **62** contained therein.

Referring to FIG. **12**, the exemplary control panel **132** contains operator controls for controlling the propellant subsystem and the snow generation subsystem(s) contained within the electronic console **130**. The controls include a propellant supply pressure gauge **138**, a low propellant supply pressure indicator light **140**, an individual coaxial propellant pressure regulators **142** and pressure gauges **144**. The front panel **132** also contains a carbon dioxide gas supply pressure gauge **146**, low carbon dioxide gas supply indicator light **148** and discrete liquid carbon dioxide metering valves **150**. An operational mode selector switch **152** allows an operator to prime each system **64** by sub-cooling the respective capillary condensers, test the spray cleaning operation, and place the exemplary cleaning system into remote or external machine control mode. A main power switch **154** provides electrical power to the cleaning system through a circuit breaker **156**. Preferably, continuous or pulsed spray treatments are implemented in the present invention. Each are enabled using a treatment spray selector switch **158** which upon actuation provides for continuous spray by by-passing the pulse timer, pulse spray cleaning by enabling the pulse timing circuit **80**, and an standby mode for preventive maintenance operations. A pulse cycle switch **160** provides a means for increasing and decreasing a pulse cycle period if that mode has been selected using the exemplary cleaning spray switch **158**. Finally, a propellant temperature controller **162** provides the operator with a means for adjusting and monitoring propellant gas temperature.

Referring to FIG. **13**, the exemplary enclosure **130** also has a rear panel **164** which contains a bank of multiplexed flexible coaxial spray lines **166** with spray applicators **168**. Each applicator is individually controlled and supplied by either a single snow generation subsystem or several discrete snow generation subsystems. A rear-mounted plumbing connection **170** for high pressure carbon dioxide gas, an optional CDA gas connection **172** and an electrical power connection **174** are also provided. A rear-mounted vent grille **176** is used to direct heat-laden airflow out of the enclosure **130** as shown by the line arrow segment **178** to remove heat from the carbon dioxide base stock condenser unit **40**. Finally, a suitable and remote machine tool controller **180** communicates via a monitoring and control cable assembly **182** with each system **62** to monitor and control functions such as valve actuation, temperature measurement, and oscillation. Machine controllers **180** are those that control the manufacturing tool such as a machining center, lathe, LASER drill, singulation saw, among any variety of other tools requiring in-situ cleaning include, for example, a footswitch, a finger switch, a program logic controller, computer or embedded controllers, and machine tool controllers.

The present invention as described herein may be used as a stand-alone tool or designed and developed as an "integration module" for various machine tools. An integration module is especially useful since it "hybridizes" the manufacturing tool or process. Many commercial manufacturing tools and processes may be hybridized with the present invention. A few examples are described in the following sections.

Clean-Dispense-Cure and Clean-Bond Processes: Adhesive joining of polymethylmethacrylate (PMMA) surface portions.

A commercially available robotic dispensing and curing machine such as that produced by I & J Fisnar of Fair Lawn, N.J. is integrated with the present invention, including operational control interfacing, to form a new hybrid surface preparation, adhesive dispensing and UV curing system. Both portions of a substrate surface are precision treated using at least of the carbon dioxide snow treatment systems of the present invention. Upon treatment, an adhesive is dispensed onto the cleaned surfaces, mechanically contacted, and cured using a UV curing light. A manufacturer using such a product would not require a separate off-line or in-line cleaning and surface pre-treatment system.

Clean-Assemble and Clean-Attach Processes: Mechanically joining surface portions of polyethylene (PE) substrates.

A commercially available automated assembly machine, such as that produced by Automated Tool Systems of Cambridge, Ohio is integrated with the present invention, including operational control interfacing, to form a new hybrid surface preparation and mechanical assembly tool. Firstly, one or both substrate surfaces are precision treated using at least one carbon dioxide treatment systems of the present invention. Upon such treatment, the substrates are mechanically assembled (screwed, riveted, clipped) to form a clean-assembled substrate. A manufacturer using such a product would not require a separate off-line or in-line cleaning and surface pre-treatment system prior to automated assembly.

Drill-Clean and Clean-Inspect Processes: A stainless steel substrate having multiple surface portions to be drilled.

A commercially available automatic drilling machine, such as that produced by Steinhauer Elektromachinen AG of Wurselen, Germany, is integrated with the present invention, including operational control interfacing, to form a new hybrid drilling and cleaning tool. In an automated and sequential process, a portion of the substrate surface is precision drilled, which is followed by spray treatment at least one carbon dioxide treatment system of the present invention to remove residual drilling oils and chips from each hole to form a clean dilled hole. A manufacturer using such a product would not require a separate off-line or in-line cleaning and surface pre-treatment system. A substrate could be machined continuously without interruption. Moreover, no further cleaning is required and the machined surfaces can be inspected directly. Thus this example serves as an example of a clean-inspect aspect as well.

Deburr-Clean Processes: A stainless steel substrate having a surface portion to be robotically deburred.

A commercially available robotic deburring machine, such as that produced by TEC Automation of Canton, Ga., is integrated with the present invention, including operational control interfacing, to form a new hybrid precision deburring and cleaning tool. In an automated and sequential process, a portion of the substrate surface is first precision de-burred, which is followed by a spray treatment with at least one carbon dioxide treatment system of the present invention to remove residual cutting chips and other debris to form a clean, de-burred substrate. A manufacturer using such a product would not require a separate off-line or in-line cleaning process tool or step.

Clean-Weld Processes: Two polypropylene (PPE) substrates having surface portions to be acoustically welded together.

A commercially available automated acoustic welding machine, such as that produced by Branson North America of Danbury, Conn., is integrated with the present invention, including operational control interfacing, to form a new hybrid surface preparation and plastics welding tool. Firstly, both substrate surfaces to be joined are precision treated using at least one carbon dioxide treatment system of the present invention. The substrates are then mechanically assembled to form a clean-assembled substrate. Finally, the clean-assembled substrate is acoustically welded to form a clean-welded substrate. A manufacturer using such a product would not require a separate off-line or in-line cleaning and surface pre-treatment system or process step prior to welding.

Clean-Solder and De-solder-Clean Processes: An electro-optical board having one or more bonding requirements is to be laser soldered following placement of one or more electro-optical components.

A commercially available automated laser soldering machine, such as that produced by Palomar Technologies of Carlsbad, Calif., is integrated with the present invention, including operational control interfacing, to form a new hybrid surface preparation and laser soldering tool. Firstly, the surface to be soldered is precision treated using at least one carbon dioxide treatment system of the present invention. The substrate, with electro-optical component in place, is then laser soldered to form a clean-soldered substrate. A manufacturer using such a hybrid tool would not require a separate off-line or in-line cleaning and surface pre-treatment system prior to soldering. Alternatively, an electro-optical component may be de-soldered using the same hybrid laser soldering and cleaning tool, following which the de-soldered substrate surface may be precision cleaned to remove laser soldering residues and particles. Thus the present invention may be used form a de-solder-clean hybrid tool.

Clean-Coat Processes: A glass substrate having surface portion to be coated with anti-reflectance coating.

A commercially available optical coating system, such as that produced by Leybold Optics GmbH of Alzenau, Germany, is integrated with the present invention, including operational control interfacing, to form a new hybrid surface preparation and optical coating tool. Firstly, optical surfaces to be coated are precision treated using at least one carbon dioxide treatment system of the present invention. The substrates are then coated with an optical coating material to form a particle-free and clean-coated substrate. A manufacturer using such a product would not require a separate off-line or in-line cleaning and surface pre-treatment system or process step prior to coating.

Dice-Clean, Saw-Clean, and Trim-Clean Processes: A ceramic substrate is diced into smaller ceramic chips.

A commercially available dicing machine, such as that produced by Kulicke and Soffa of Willow Grove, Pa., is integrated with the present invention, including operational control interfacing, to form a new hybrid dicing and cleaning tool. Firstly, a ceramic surface is diced to form smaller ceramic chip packages. Prior to removal from the dicing machine, the small chip packages are treated with at least one carbon dioxide treatment system of the present invention to remove dicing debris. A manufacturer using such a product would not require a separate off-line or in-line cleaning and surface pre-treatment system or process step following dicing operations. Similarly, manufacturers producing or utilizing precision sawing equipment would benefit from the integration of the present invention into such a tool.

The present invention may also be deployed in a number of configurations to provide unique factory cleaning solutions. FIG. **14** illustrates an exemplary factory floor layout **184** showing three possible configurations for the implementation of the present invention. A remote supply of carbon dioxide gas **186** having a pressure of 2.1 MPa (300 psi) is distributed throughout the factory using a network of stainless steel or copper tubing **188** and a pressure distribution pump **190**. The pressure distribution pump **190** elevates the carbon dioxide gas supply **186** pressure from 2.1 MPa (300 psi) to a relatively constant distribution carbon dioxide cleaning fluid supply pressure within the network **188** ranging between 5.5 MPa (800 psi) and 6.0 MPa (850 psi). The carbon dioxide cleaning fluid supply network **188** may be connected to one or more carbon dioxide enabled factory tools such as an exemplary in-line tool **192** and robotic spray cleaning tool **194**. In addition to and optionally as described herein, a remote source of CDA **196** having a preferred pressure range of between 0.6 MPa (90 psi) and 1.0 MPa (150 psi) may be distributed to these same carbon dioxide enabled tools using a CDA plumbing network **198** comprising stainless steel or copper tubing. Finally, mobile carbon dioxide enabled cleaning tools **200** may be developed using the present invention to provide transportable carbon dioxide cleaning processes within a factory environment for needs such as tool block cleaning.

Referring now to FIG. **15**, an exemplary robotic clean-dispensing system **194** includes a workstation **202** having an operator interface panel **204** and process indicator light **206**. The exemplary workstation **202** has a work platform **208** which contains articulating robot **210** and robot end-effector **212**. The robot end-effector **212** is a combinational tool comprising a carbon dioxide snow treatment apparatus, **20** or **40**, and automated dispensing syringe **214**. The carbon dioxide snow treatment apparatus, **20** or **40**, is connected via a coaxial spray delivery line **216** to the exemplary cleaning module **218** described herein and contained within a lower compartment **220** within the workstation **202**. Finally, the dispensing syringe **214** is connected via a pneumatic pressure hose **222** to a dispensing control unit **224**.

The exemplary system, including robot articulation, surface cleaning and dispensing operations, as illustrated in FIG. **14** is controlled via an internal PLC or PC control system (both not shown) and associated software. A conveyance system **226** may be used to bring substrates to be processed using the present invention into and out of the exemplary workstation **202**, which itself is controlled by same PLC or PC control system.

Also illustrated in FIG. **15** are the exemplary process fluids supplies and connections to the exemplary factory tool. A remote supply of CDA **196** is communicated to the factory tool **194** through a suitable plumbing network **198** which provides pneumatic power to the exemplary workstation **202** as well as propellant supply to the exemplary cleaning module **218**. A remote supply of carbon dioxide cleaning fluid **186** is communicated to the exemplary cleaning module **218** via a suitable plumbing network **188** and pressure distribution pump **190**. Finally, electrical power is delivered via a suitable line connection **228** and circuit breaker **230**.

Although the present invention has been described with reference to preferred embodiments, workers skilled in the art will recognize that changes may be made in form and detail without departing from the spirit and scope of the invention.

The invention claimed is:

1. A carbon dioxide snow generation system comprising a condenser having a first flexible capillary segment connectable to a liquid carbon dioxide feed line and a second flexible capillary segment attached to the first capillary segment, the second capillary segment having a greater inner diameter than the first capillary segment, wherein liquid carbon dioxide enters the first capillary segment from the liquid carbon dioxide feed line and progresses toward the second segment, whereupon entering the second segment, at least a portion of the liquid carbon dioxide condenses into solid carbon dioxide particles.

2. The snow generation system of claim **1** and further comprising a third capillary segment attached to the second capillary segment, the third capillary segment having a greater inner diameter than the second capillary segment, whereupon the liquid carbon dioxide and solid carbon dioxide particles pass from the second capillary segment to the third capillary segment at least a portion of the liquid carbon dioxide further condenses.

3. The snow generation system of claim **1** and further comprising an insulator contacting an outer surface of each capillary segment.

4. The snow generation system of claim **1** and further comprising a conduit, the condenser positionable therein, wherein a gas or fluid is transportable through the conduit and about the condenser.

5. The snow generation system of claim **1** wherein each capillary segment includes an inner diameter ranging from about 0.12 millimeters to about 3.18 millimeters.

6. The snow generation system of claim **1** wherein at least one capillary segment is constructed from a polymer material to provide an insulating effect.

7. The snow generation of claim **1** wherein each segment includes a length ranging from about 0.3 meters to about 7.3 meters.

8. An apparatus for producing solid carbon dioxide particles from liquid carbon dioxide, the carbon dioxide particles deliverable to a nozzle, the nozzle independently positionable relative to the apparatus, the apparatus comprising:

a first flexible tube; and

a second flexible tube adjoined to the first tube, the second tube having a greater inner diameter than the first tube, whereupon introducing liquid carbon dioxide into the first tube, the liquid carbon dioxide progresses to the second tube, whereupon entering the second tube at least a portion of the liquid carbon dioxide condenses to form the solid carbon dioxide particles prior to entering the nozzle.

9. The apparatus of claim **8** and further comprising a third tube adjoined to the second tube, the third tube having a greater inner diameter than the second tube, whereupon the liquid carbon dioxide and solid carbon dioxide particles passing from the second tube to the third tube at least a portion of the liquid carbon dioxide further condenses onto to the solid carbon dioxide particles prior to entering the nozzle.

10. The apparatus of claim **9** wherein the third tube is flexible.

11. The apparatus of claim **8** and further comprising an insulator contacting an outer surface of each tube.

12. The apparatus of claim **8** and further comprising a conduit, the first and second tube positionable therein, wherein a gas or fluid is transportable through the conduit and about the first and second tubes.

13. The apparatus of claim **8** wherein the inner diameter of each tube ranges from about 0.12 millimeters to about 3.18 millimeters.

14. The snow generation system of claim **8** wherein each tube has a length ranging from about 0.3 meters to about 7.3 meters.

15. The snow generation system of claim **8** wherein at least one tube includes a polymeric construction to provide an insulating effect.

16. A carbon dioxide snow generation system comprising:

a first tube;

a second tube connected to the first tube, the second tube having a greater inner diameter than the first tube; and

a third tube connected to the second tube, each tube constructed from a flexible material, the third tube having a greater inner diameter than the second tube, wherein liquid carbon dioxide enters the first tube and progresses toward the second tube, whereupon entering the second tube at least a portion of the liquid carbon dioxide condenses into solid carbon dioxide particles, whereupon passing from the second tube to the third tube at least a portion of the remaining liquid carbon dioxide further condenses onto to the solid carbon dioxide particles.

17. The snow generation system of claim **16** and further comprising an insulator contacting an outer surface of each capillary segment.

18. The snow generation system of claim **16** and further comprising a conduit, each tube positionable therein, wherein a gas or fluid is transportable through the conduit and about each tube.

19. The snow generation system of claim **16** wherein each tube has a length ranging from about 0.3 meters to about 7.3 meters.

20. The snow generation system of claim **19** wherein the inner diameter of each tube ranges from about 0.12 millimeters to about 3.18 millimeters.

21. The snow generation system of claim **16** wherein the system is coilable.

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