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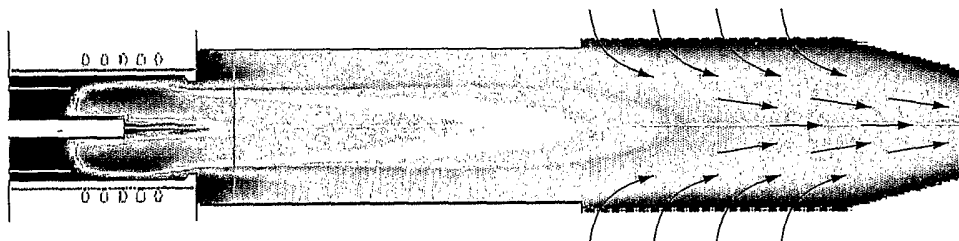
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(54) Title: INDUCTION PLASMA SYNTHESIS OF NANOPOWDERS



(57) Abstract: A process and apparatus for synthesizing a nanopowder is presented. In particular, a process for the synthesis of nanopowders of various materials such as metals, alloys, ceramics and composites by induction plasma technology, using organometallic compounds, chlorides, bromides, fluorides, iodides, nitrites, nitrates, oxalates and carbonates as precursors is disclosed. The process comprises feeding a reactant material into a plasma torch in which is generated a plasma flow having a temperature sufficiently high to yield a superheated vapour of the material; transporting said vapour by means of the plasma flow into a quenching zone; injecting a cold quench gas into the plasma flow in the quenching zone to form a renewable gaseous cold front; and forming a nanopowder at the interface between the renewable gaseous cold front and the plasma flow.

TITLE OF THE INVENTION**INDUCTION PLASMA SYNTHESIS OF NANOPOWDERS****FIELD OF THE INVENTION**

[0001] The present invention relates to the plasma synthesis of nanopowders using induction plasma technology. More specifically, but not exclusively, the present invention relates to a process for the synthesis of nanopowders of various materials such as metals, alloys, ceramics and composites by induction plasma technology, using organometallic compounds, chlorides, bromides, fluorides, iodides, nitrites, nitrates, oxalates and carbonates as precursors.

BACKGROUND OF THE INVENTION

[0002] The plasma synthesis of nanopowders has attracted increasing attention over the past few years. Numerous processes have been developed for preparing metal, alloy and ceramic-based nanopowders using a wide variety of technologies including plasma discharge, arc discharge, electro-explosion, self propagating high temperature synthesis, combustion synthesis, electric discharge, spray pyrolysis, sol-gel, and mechanical attrition.

[0003] High temperature plasma processing routes are based on the concept of heating the reactant precursors (in solid, liquid or vapor/gaseous form), to relatively high temperatures followed by rapid cooling of the reaction products through their mixing with a cold gas stream as in the "*high intensity turbulent quench technique*" or through their contacting with a cold surface on which the nanoparticles form and deposit. The use of a "highly turbulent gas quench zone" has been previously described by Boulos *et al.* in U.S. 20050217421 and U.S. 20030143153 as filed on March 25, 2005

and December 6, 2002 respectively. A common objective to all of these processes is the desire to closely control the particle morphology, the particle size distribution, and the agglomeration of the powders obtained. However, a drawback of the use of traditional "cold-surface" condensation techniques is that the nature and the temperature of the condensation surface changes with the build-up of the condensed nanopowder layer.

[0004] U.S. Patent 6,379,419 issued to Celik *et al.* on April 30, 2002 discloses a transferred arc thermal plasma based vapor condensation method for the production of fine and ultra fine powders. The method calls upon a condensation procedure involving an indirect cooling step and a direct cooling step. The indirect cooling step involves a cooling surface whereas the direct cooling step involves the injection of a cooling gas directly onto the vapor. The use of a cooling surface suffers from the drawback of particle build-up on the condensation surface.

[0005] It has been shown theoretically that by controlling the initial vapor concentration and temperature, residence time of particle nucleation and growth, and cooling profile, one may have some control on the particle size distribution and crystallinity. This is shown by Okuyama *et al.* in *AIChE Journal*, 1986, 32 (12), 2010-2019 and Girshick *et al.* in *Plasma Chem. and Plasma Processing*, 1989, 9 (3), 355-369. However, these references remain silent as to an efficient method for producing nanopowders of well defined particle size distribution and morphology.

[0006] There remains a need for an improved process for the preparation of nanopowders in which the particle morphology, the particle size distribution, and the agglomeration of particles is readily controlled and that it easily scalable.

[0007] The present invention seeks to meet these and other needs.

[0008] The present invention refers to a number of documents, the content of which is herein incorporated by reference in their entirety.

SUMMARY OF THE INVENTION

[0009] The present invention relates to the plasma synthesis of powders calling upon an induction plasma apparatus comprising an induction plasma torch and a quenching chamber in which a renewable "gaseous cold front" is generated, through the injection of a quench gas, and on which the gaseous reactants/reaction products nucleate. The nucleation generates a nanopowder which is rapidly transported to a collection chamber by the moving cold front. It was surprisingly discovered that by generating a renewable gaseous cold front for nucleating (*i.e.* condensing) the reactants/reaction products present in the plasma flow, excellent control of the morphology and particle size distribution of the resulting nanopowder could be achieved. Moreover, the use of the renewable gaseous cold front offers a close control over particle agglomeration.

[0010] More specifically, as broadly claimed, the present invention relates to a process for synthesizing a nanopowder comprising feeding a reactant material into a plasma torch in which is generated a plasma flow having a temperature sufficiently high to yield a superheated vapour of the material; transporting the vapour by means of the plasma flow into a quenching zone; injecting a cold quench gas into the plasma flow in the quenching zone to form a renewable gaseous cold front; and forming a nanopowder at the interface between the renewable gaseous cold front and the plasma flow.

[0011] The present invention also relates to an apparatus for synthesizing nanopowders comprising a plasma torch to generate a plasma flow and to produce a superheated vapour from reactant material supplied to the plasma torch in the plasma flow; and a quenching chamber mounted to the plasma torch downstream therefrom and in fluid communication with said plasma torch to receive the superheated vapour from the plasma torch, the quenching chamber being structured to receive a quench gas and to generate from said quench gas a renewable gaseous cold front to rapidly cool the superheated vapour, yielding nanopowder.

[0012] The foregoing and other objects, advantages and features of the present invention will become more apparent upon reading of the following non restrictive description of illustrative embodiments thereof, given by way of example only with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] In the appended drawings:

[0014] **FIG. 1** is a schematic cross-sectional elevation view of an induction plasma assembly in accordance with the present invention;

[0015] **FIG. 2** is a schematic cross-sectional elevation view of an induction plasma assembly of **FIG. 1** without reactor component ;

[0016] **FIG. 3** is an illustration of the temperature isocontours in the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz] for **(3A)** a quench gas (Ar) flow rate of 400 slpm and **(3B)** a quench gas (Ar) flow rate of 800 slpm, respectively;

[0017] **FIG. 4** is an illustration of the stream lines in the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz] for **(4A)** a quench gas (Ar) flow rate of 400 slpm and **(4B)** a quench gas (Ar) flow rate of 800 slpm, respectively;

[0018] **FIG. 5** is graph illustrating temperature profiles along the centerline of the induction plasma torch/reactor sections **(5A, 5B)** and in the radial direction at different axial locations within the reactor/quench sections of the induction plasma assembly of **FIG.1** **(5C, 5D)** using an Ar/H₂ plasma gas [65kW; 3MHz] for a quench gas (Ar) flow rate of 400 slpm **(5A, 5C)** and a quench gas (Ar) flow rate of 800 slpm, respectively **(5B, 5D)**;

[0019] **FIG. 6** is an illustration of the “gaseous cold front” showing the quench gas concentration isocontours in the quench section of the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz] for **(6A)** a quench gas (Ar) flow rate of 400 slpm and **(6B)** a quench gas (Ar) flow rate of 800 slpm, respectively;

[0020] **FIG. 7** is an illustration of the reaction product cooling rate isocontours (darker areas are representative of cooling rates in the range of 10⁵ to 10⁶ K/s) in the quench section of the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz] for **(7A)** a quench gas (Ar) flow rate of 400 slpm and **(7B)** a quench gas (Ar) flow rate of 800 slpm, respectively;

[0021] **FIG. 8** is a graph showing the particle size distribution for an aluminum nanopowder as obtained using the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz];

[0022] **FIG. 9** is a graph showing the particle size distribution for a nickel nanopowder as obtained using the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz];

[0023] **FIG. 10** is a graph showing the particle size distribution for a tungsten nanopowder as obtained using the induction plasma assembly of **FIG.1** using an Ar/H₂ plasma gas [65kW; 3MHz];

[0024] **FIG. 11** is an illustration of the quench gas flow within the quench section of the induction plasma assembly of **FIG.1**;

[0025] **FIG. 12** is a graph showing the mean particle size (**12A**) and the specific surface area (**12B**) of a nanometric nickel powder as produced by a process according to the present invention as a function of the quench gas (Ar) flow rate;

[0026] **FIG. 13** is a graph showing the mean particle size (**13A**) and the specific surface area (**13B**) of a nanometric cupric oxide (CuO) powder as produced by the process of the present invention (starting with micrometric-sized copper powder) as a function of the quench gas (Ar/O₂) flow rate;

[0027] **FIG. 14** is a graph showing the particle size distribution of a cupric oxide nanopowder (BET = 23.08 m²/g (**14A**) and 22.11 m²/g (**14B**) respectively) as produced by the process of the present invention (starting with micrometric-sized copper powder);

[0028] **FIG. 15:** is a graph showing the mean particle size (**15A**) and the specific surface area (**15B**) of a nanometric germanium dioxide

(GeO₂) powder as produced by the process of the present invention (starting with liquid GeCl₄) as a function of the quench gas (Ar/O₂) flow rate.

DETAILED DESCRIPTION OF ILLUSTRATIVE EMBODIMENTS

[0029] In order to provide a clear and consistent understanding of the terms used in the present specification, a number of definitions are provided below. Moreover, unless defined otherwise, all technical and scientific terms as used herein have the same meaning as commonly understood to one of ordinary skill in the art to which this invention pertains.

[0030] The use of the word “a” or “an” when used in conjunction with the term “comprising” in the claims and/or the specification may mean “one”, but it is also consistent with the meaning of “one or more”, “at least one”, and “one or more than one”. Similarly, the word “another” may mean at least a second or more.

[0031] As used in this specification and claim(s), the words “comprising” (and any form of comprising, such as “comprise” and “comprises”), “having” (and any form of having, such as “have” and “has”), “including” (and any form of including, such as “include” and “includes”) or “containing” (and any form of containing, such as “contain” and “contains”), are inclusive or open-ended and do not exclude additional, unrecited elements or process steps.

[0032] The term “about” is used to indicate that a value includes an inherent variation of error for the device or the method being employed to determine the value.

[0033] The present invention relates to a novel process for the plasma synthesis of nanopowders using induction plasma technology and calling upon a renewable "gaseous cold front", for example a laminar "gaseous cold front" which serves to rapidly quench the reactants/reaction products present in the plasma flow. According to a first alternative, the gaseous cold front may be generated in a quenching chamber comprising a porous metal or ceramic wall through which is uniformly injected a cold quench gas. According to a second alternative, the gaseous cold front may be generated in a quenching chamber comprising a perforated refractory wall.

[0034] FIG. 1 shows an illustrative embodiment of the induction plasma assembly, generally identified by the reference **10**. The induction plasma assembly **10** of FIG. 1 comprises an upper section consisting of an inductively coupled radio frequency (rf) plasma torch **12** in which the reactants are substantially axially introduced at the feed upper end of the torch **12** and dispersed into the center of the plasma flow using techniques well known to those of ordinary skill in the art. A reactor **14**, mounted to a quenching chamber **16**, is affixed to the lower end of the plasma torch **12**, generally coaxial with the induction plasma assembly **10** between the plasma torch **12** and the quenching chamber **16**. The induction plasma assembly **10** further comprises a collection chamber **18** coaxially mounted to the lower end of the quenching chamber **16**. Of course, the plasma torch **12**, the reactor **14**, the quenching chamber **16** and the collection chamber are in fluid communication with each other.

[0035] The plasma is generated using any suitable gas that will ionize when subject to a high frequency electromagnetic field, such as a radio frequency field. It is believed to be within the skill of an expert in the art to select a suitable gas. Suitable inductively coupled radio frequency (rf) plasma torches are disclosed in U.S. Patent No. 6,919,527 issued to Boulos *et al.* on

July 19, 2005. Other suitable plasma torches as contemplated by the process of the present invention include high performance induction plasma torches such as the one disclosed in U.S. Patent No. 5,200,595 issued to Boulos *et al.* on April 6, 1993.

[0036] The reactant feed may be in the form of fine solid particles, liquid droplets or in the vapor/gaseous phase. In the case of a solid feed, the reactant, upon entering the plasma flow, is melted and vaporized forming a vapor cloud which is superheated to a reaction temperature. In the case of a liquid feed, the heat load on the plasma is substantially limited to that required to heat up the liquid droplets to the vaporization temperature and superheating the vapor to a reaction temperature. In the case of a gaseous feed, the heat load on the plasma is substantially limited to that required to superheat the gaseous feed to the reaction temperature. The plasma flow axially delivers the vapor cloud to the reactor **14** in which it may be further mixed with other components present in the vapor/gaseous phase. In an embodiment of the present invention, a further component may be an oxidizing agent such as oxygen, a carburizing agent such as methane or acetylene, or a nitrating agent such as ammonia. Of course, the other components may be concomitantly introduced into the plasma torch **12** with the reactant feed, or introduced in the reactor section **14**, or in the quench section **16**, using techniques well known to those of ordinary skill in the art.

[0037] The plasma flow carries the reactants/reaction products emerging from the plasma torch **12** into a reactor **14** in fluid communication therewith. In an embodiment of the present invention, the reactor **14** may be a high temperature graphite/refractory lined reactor. It is believed to be within the skill of an expert in the art to select other suitable reactors and reactor configurations. In the event that the feed was concomitantly introduced into the plasma torch **12** mixed with other components, the reactor **14** allows for

any reaction to be completed. Alternatively, the superheated feed exits the plasma torch **12** at a reaction temperature and is carried by the plasma flow into the reactor **14** where it is mixed and reacted with other components.

[0038] Upon exiting the reactor **14**, the reactants/reaction products are carried into a quenching chamber **16**. In an embodiment of the present invention, the quenching chamber **16** may comprise a porous metal or ceramic wall section **17** through which a cold quench gas and/or reactants are injected. Alternatively, the quenching chamber **16** may comprise a perforated or slotted refractory wall section through which the cold quench gas and/or reactants may be injected. It is believed to be within the skill of an expert in the art to determine and select other suitable quenching chamber configurations. The injection of the cold quench gas, mixed with or without other reactants, generates a mobile and continuously renewable laminar "gaseous cold front" on which the gaseous reactants/reaction products condense. Such a condensation results in a nucleation of reactants/reaction products generating a nanopowder. The "gaseous cold front" is renewable since it is in movement; the movement being imparted by the continuous injection of cold quench gas and by the movement of the plasma flow. The physical separation of the reaction section (*i.e.* the plasma torch **12** and/or the reactor **14**) and the quench section (quenching chamber **16**) provides for a better means of controlling the location of the condensation front over which nanopowder formation occurs. The gaseous cold front is further illustrated in FIGS. **3**, **4**, **6** and **7**. In an embodiment of the present invention, argon was used as the quench gas. It is believed to be within the skill of an expert in the art to determine and select other suitable quench gases.

[0039] The quench rate to which the gaseous reactants/reaction products are exposed will depend on the temperature of the quench gas and its flow rate. The flow rate of the quench gas also affects the position of the

cold front within the quenching chamber **16** and the manner in which the cold front interacts with the hot flow of plasma gases emerging from the reactor **14** and comprising the reactants/reaction products. The nanopowder is carried away on the mobile cold front into the collection chamber **18**. Of course, the plasma gases will also be at significantly lower temperatures, due to their interaction with the cold front, upon reaching the collection chamber **18**.

[0040] The process according to the present invention involves the concept of a renewable "gaseous cold front" as an effective means of controlling the uniformity and particle size distribution of the produced nanopowder. Furthermore, the possibility for condensed nanoparticle agglomeration is significantly reduced since the nanopowder is rapidly evacuated, substantially upon its formation, from the quenching chamber **16** to the collection chamber **18** by the gaseous cold front at present comprised of plasma gases and the quench gas. Moreover, by using a high volume quench gas flow rate, it is possible to maintain the generated nanopowder in dilute suspension while it is being evacuated from the quenching chamber **16** into the collection chamber **18**. Additionally, by maintaining a dilute suspension, both the deposition of the nanopowder on the walls of the quenching chamber **16** and nanoparticle agglomeration through inter-particle collision are substantially eliminated. Typical temperature and flow fields as observed in the plasma torch **12**, the reactor **14** and the quenching chamber **16** respectively, are illustrated in FIGS. **3** and **4** for quench gas flow rates of 400 and 800 standard liters per minute (slpm). These figures clearly demonstrate the constricting effect of the "gaseous cold front" on the hot plasma gas stream. The more intense the gaseous cold front, the greater the constricting effect. Moreover, as may be observed from FIGS. **3** and **6**, an increase in the quench gas flow rate results in a significant increase in the thickness of the cold boundary layer and a gradual displacement of the cold front toward the center of the plasma flow. Furthermore, the increase in the

thickness of the cold boundary layer is accompanied by the development of steep temperature gradients at the interface of the cold front and the plasma flow, where the nucleation of the reactants/reaction products takes place. While not shown in these figures, changing the length of the reactor, combined with a close control of the quench gas flow rate offers tangible means of controlling the position of the cold front in the reactor assembly and accordingly the exact moment at which the reactants/reaction products are subjected to rapid cooling. In the case wherein the reactor **14** is absent, the reactants/reaction products are substantially immediately exposed to the cold front following their vaporization in the plasma torch **12**. In the illustrative embodiment as shown in FIGS. **3** and **4**, the plasma gas was composed of an argon/hydrogen mixture (80%vol /20%vol) whereas the gaseous cold front was created using argon which was injected through the porous metal wall of the quenching chamber **16**.

[0041] A typical "gaseous cold front" and the associated quench gas concentration isocontours as observed in the quenching chamber **16** is illustrated in FIG. **6**. Furthermore, typical isocontours of reaction product cooling rate, as produced when the hot plasma gases comprising the reaction products collide with the gaseous cold front, are illustrated in FIG. **7**. These figures illustrate a substantially uniform, renewable and mobile cooling gas front across which the reaction products are exposed to high cooling rates in the order of about 10^5 to about 10^6 K/s. Such a gaseous cold front allows for particle nucleation to occur at the interface with the hot plasma gases and the formation of a nanopowder having a substantially uniform particle size distribution, representative examples of which are illustrated in FIGS. **8-10**.

[0042] The process of the present invention offers the additional advantages of being compact, scalable and simple to operate. Moreover, the reactor assembly **10** can be readily modified depending on the needs and

type of nanopowder to be produced. Vapor, liquid or solid precursors may be used in the process according to the present invention with the produced nanopowder being either of identical or different chemical composition as that of the precursor. In the case wherein the produced nanopowder is of identical chemical composition, the process is limited to the vaporization and condensation of the feed generating nanoparticles thereof. In the case wherein the produced nanopowder is of different chemical composition, the feed was reacted with a second reactant which can be either injected in the plasma torch **12** or introduced in the reactor **14**. Alternatively, the quench gas may react with the vaporized feed in which case it serves a dual function. As illustrated in FIG. 2, the reactor **14** can be removed such that the plasma feed comprising the gaseous reactants or alternatively the gaseous reactants/reaction products, are brought directly into the quenching chamber **16**. If the feed material is to be chemically modified, a non-limiting example of which is oxidation, the presence of the reactor might be required. It is believed to be within the skill of an expert to select an appropriate reactor assembly depending on the type of nanopowder to be produced.

EXPERIMENTAL

[0043] A number of examples are provided hereinbelow, illustrating the efficiency of a *renewable laminar gaseous cold front* in the synthesis of a number of metallic and ceramic nanopowders using induction plasma technology.

[0044] **Synthesis of nanopowders using solid precursors.**

[0045] An argon/hydrogen induction plasma flow is generated using a 50 mm internal diameter induction plasma torch with an oscillator frequency of 3 MHz, a plasma plate power of 65 kW, and a reactor pressure of approximately 500 Torr. Different metals, in the form of a micron-sized metallic powder, were axially injected into the center of the plasma discharge and vaporized. As the hot plasma gases comprising the vaporized metal emerge from the reactor, they are intercepted by the gaseous cold front which is created by means of injecting argon through the porous walls of the quenching chamber. The interaction of the hot plasma gases with the gaseous cold front gives rise to a nucleation phenomenon at the interface hot plasma gases/gaseous cold front, leading to the formation of a nanopowder having a well defined particle size distribution. The continuously moving gaseous cold front, now also made-up of cooled plasma gases, rapidly evacuates the nanopowder to a collection chamber where it can be collected on standard sintered metal or cloth filter elements. The experimental results as obtained for aluminum, nickel and tungsten powders are summarized hereinbelow in Table 1. Data regarding plasma plate power, precursor feed rates, quench gas rates, and physical characteristics of the collected nanopowder such as their Specific Surface Area (as measured using the BET method) and particle mean diameter are also provided. The Specific Surface Area is expressed in terms of m^2/g of collected powder. The mean particle

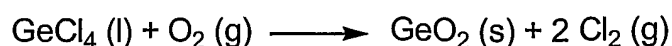
diameter of the collected powder can be calculated assuming a spherical particle shape having an equivalent surface area to volume ratio. The particle size distributions, obtained by light scattering analysis using a Malvern Mastersizer™ instrument are illustrated in FIGS. 8-10 respectively.

[0046] **Table 1:** Examples of metallic nanopowders as obtained using the process of the present invention.

Metal	Sample	Plate Power	Feed Rate	Quench Rate	BET	Mean Diam.
	Number	kW	g/min	slpm	m ² /g	nm
Al	04-1113-02	60	20	1300	61.66	36
Ni	04-1116-03	60	19	1300	15.07	44.7
W	04-1110-04	70	20	1100	11.83	26.2

[0047] **Synthesis of nanopowders using liquid precursors.**

[0048] As illustrated in **FIG. 15** and in Table 2 below, the process according to the present invention lends itself to the synthesis of nanopowders using liquid feeds. Liquid germanium tetrachloride (GeCl₄, b.p. = 83 °C) was sent by a Masterflex™ pump into an oxygen plasma. The liquid was vaporized and oxidized. The produced germanium dioxide (GeO₂) vapor was condensed to nanometric powders by injection of cold quench gas flow generating the “gaseous cold front”. The process as occurring in **Fig. 15** can be illustrated by the following reaction:



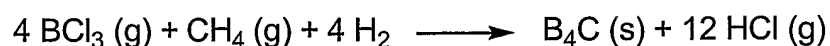
[0049] **Table 2:** Examples of process parameters* for producing GeO₂ (g) starting with GeCl₄ (l).

GeCl ₄ feed rate (g/min)	Quench gas flow rate, O ₂ (lpm)	Feed time (min)
67,2	50	15
21,9	150	15
33,2	400	15
30,0	Variable	15

*Plasma power: 65 kW; Plasma sheath: 18 Ar + 82 O₂ (slpm); Plasma central: 30Ar (slpm); Injection probe: SA953; Atomization gas: 8O₂ (slpm); Reactor pressure: 80 kPa.

[0050] **Synthesis of nanopowders using gaseous precursors.**

[0051] The process of the present invention also lends itself to the synthesis of nanopowders using gaseous feeds as illustrated by the following reaction:



[0052] It is to be understood that the invention is not limited in its application to the details of construction and parts as described hereinabove. The invention is capable of other embodiments and of being practiced in various ways. It is also understood that the phraseology or terminology used herein is for the purpose of description and not limitation. Hence, although the present invention has been described hereinabove by way of illustrative embodiments thereof, it can be modified, without departing from the spirit, scope and nature of the subject invention as defined in the appended claims.

WHAT IS CLAIMED IS:

1. A process for synthesizing a nanopowder comprising:
 - a) feeding a reactant material into a plasma torch in which is generated a plasma flow having a temperature sufficiently high to yield a superheated vapour of said material;
 - b) transporting said vapour by means of said plasma flow into a quenching zone;
 - c) injecting a cold quench gas into the plasma flow in the quenching zone to form a renewable gaseous cold front; and
 - d) forming a nanopowder at the interface between the renewable gaseous cold front and the plasma flow.
2. The process of claim 1 further comprising collecting the nanopowder in a collection zone.
3. The process of claim 2, wherein the gaseous cold front exerts a constricting effect on the plasma flow.
4. The process of claim 3, wherein the constricting effect is proportional to the quench gas flow rate.
5. The process of claim 4, comprising injecting the cold quench gas in the quenching zone by means of a plurality of openings in a wall section of said quenching zone.
6. The process of claim 5, wherein the plurality of openings define a porous wall section.
7. The process of claim 5, wherein the plurality of openings define a slotted wall section.

8. The process of claim 5, wherein the plurality of openings define a perforated wall section.

9. The process of any one of claims 5, 6, 7 or 8, wherein the quenching zone is a quenching chamber.

10. The process of claim 1, wherein the reactant material is selected from the group consisting of solid, liquid and gaseous feeds.

11. The process of claim 1, wherein said superheated vapour is at a reaction temperature capable of reacting with said plasma flow and/or said quench gas.

12. The process of claim 10, wherein the reactant material is selected from the group consisting of metals, alloys, organometallic compounds, chlorides, bromides, fluorides, iodides, nitrites, nitrates, oxalates, carbonates, oxides and composites.

13. The process of claim 1, further comprising:
e) feeding a second reactant in the plasma flow; and
f) reacting the second reactant with the reactant material to produce a nanopowder of chemical composition different from the reactant material.

14. The process of claim 13, comprising injecting the second reactant into the plasma torch.

15. The process of claim 13, comprising injecting the second reactant into a reactor between the plasma torch and the quenching zone.

16. The process of claim **13**, wherein the second reactant is the quench gas.

17. An apparatus for synthesizing nanopowders comprising:

a) a plasma torch to generate a plasma flow and to produce a superheated vapour from reactant material supplied to the plasma torch in the plasma flow; and

b) a quenching chamber mounted to the plasma torch downstream therefrom and in fluid communication with said plasma torch to receive the superheated vapour from the plasma torch, said quenching chamber being structured to receive a quench gas and to generate from said quench gas a renewable gaseous cold front to rapidly cool the superheated vapour, yielding nanopowder.

18. The apparatus of claim **17**, further comprising a collection chamber to collect the nanopowder.

19. The apparatus of claim **17**, wherein the gaseous cold front exerts a constricting effect on the plasma flow.

20. The apparatus of claim **19**, wherein the constricting effect is proportional to the quench gas flow rate.

21. The apparatus claim **17**, wherein the quenching chamber comprises a wall section with a plurality of openings for injecting the quench gas in the quenching chamber.

22. The apparatus of claim **21**, wherein the wall section is a porous wall section.

23. The apparatus of claim **21**, wherein the wall section is a slotted wall section.

24. The apparatus of claim **21**, wherein the wall section is a perforated wall section.

25. The apparatus of claim **17**, wherein the reactant material is selected from the group consisting of solid, liquid and gaseous feeds.

26. The apparatus of claim **17**, wherein said superheated vapour is at a reaction temperature capable of reacting with said plasma flow and/or said quench gas.

27. The apparatus of claim **17**, wherein the reactant material is selected from the group consisting of metals, alloys, organometallic compounds, chlorides, bromides, fluorides, iodides, nitrites, nitrates, oxalates, carbonates, oxides and composites.

28. The apparatus of claim **17**, further comprising:
means for feeding a second reactant in the plasma flow:
and
means for reacting the second reactant with the reactant material to produce a nanopowder of chemical composition different from the reactant material.

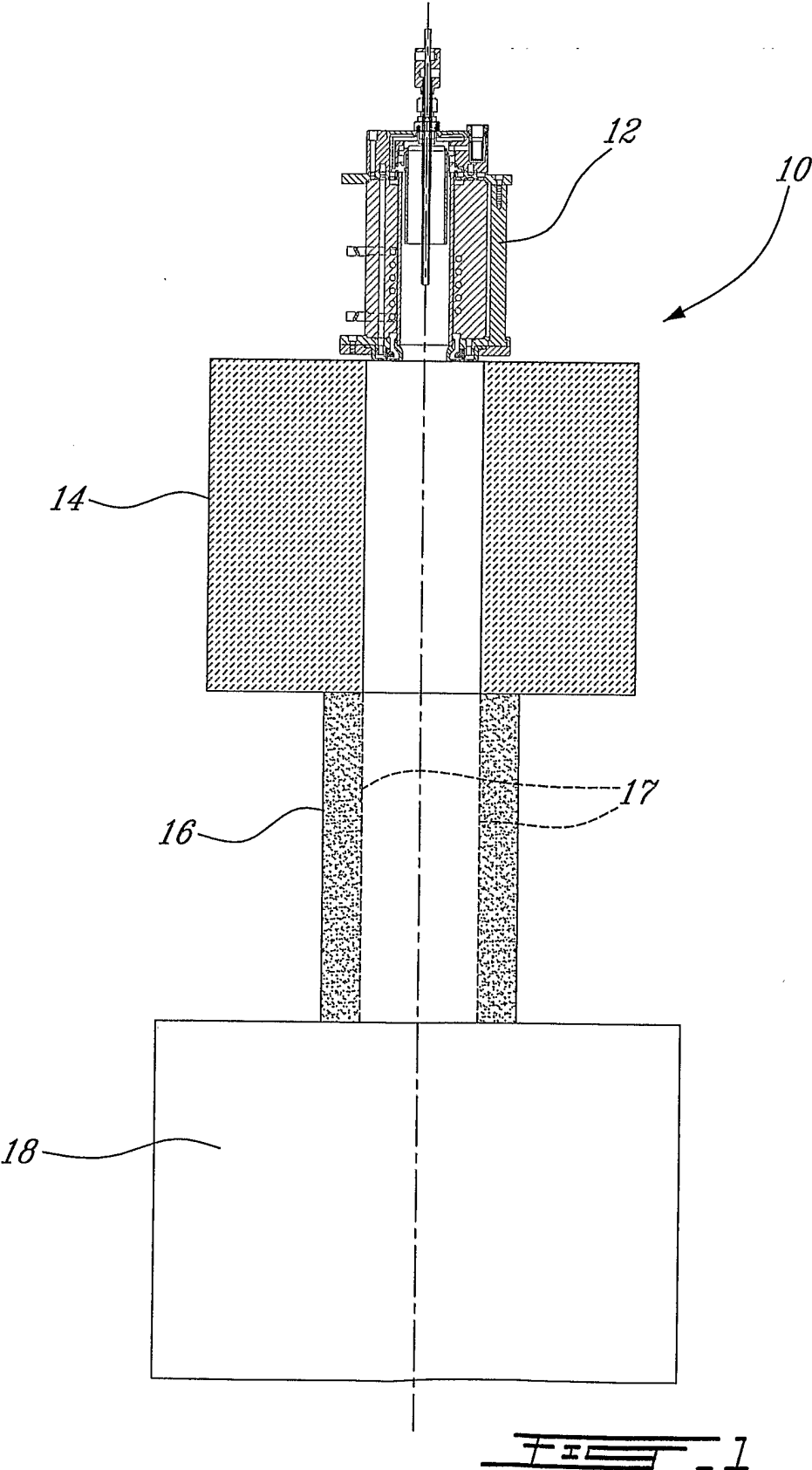
29. The apparatus of claim **28**, comprising means for injecting the second reactant into the plasma torch.

30. The apparatus of claim **28**, comprising means for injecting the second reactant into a reactor between the plasma torch and the quenching zone.

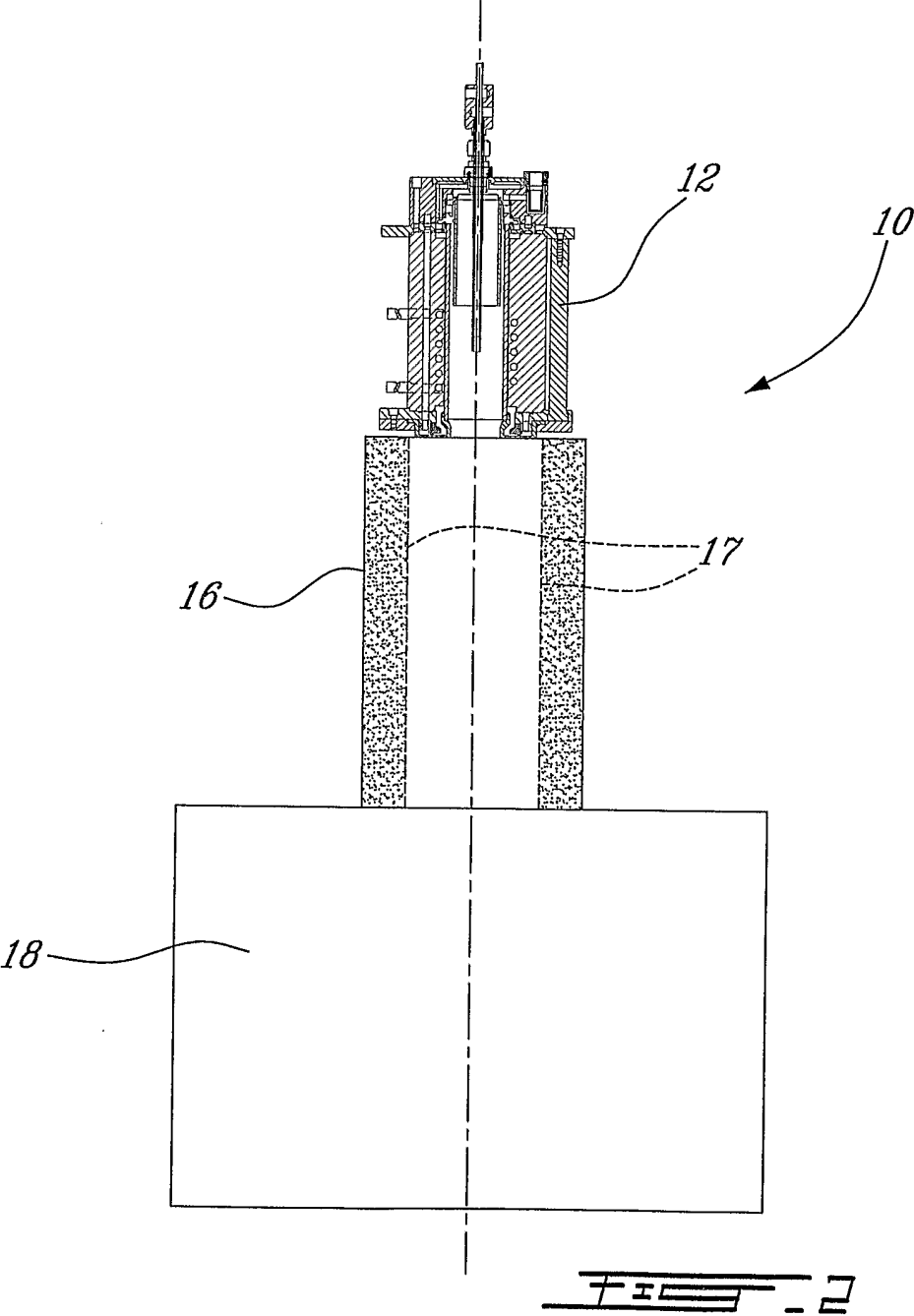
31. The apparatus of claim **28**, wherein the second reactant is the quench gas.

32. The apparatus of claim **17**, further comprising a reactor to react the reactant material with a second reactant, said reactor being in fluid communication with the plasma torch and the quenching chamber, and said reactor being disposed between the plasma torch and the quenching chamber.

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FIG. 3A

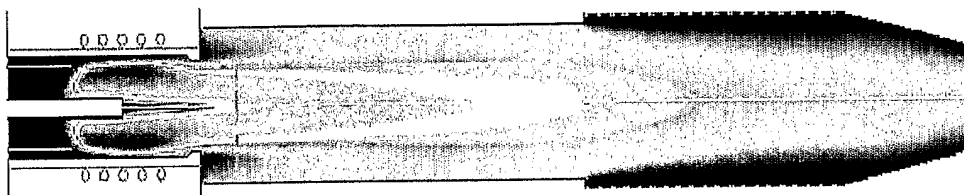


FIG. 3B

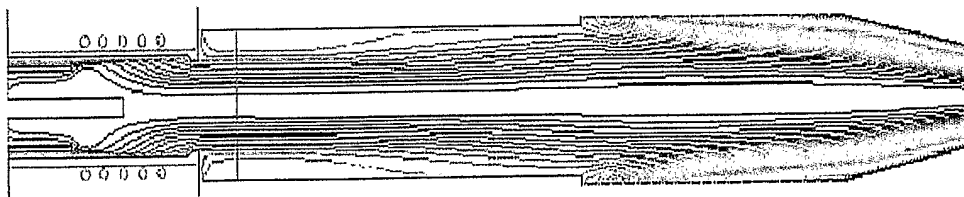


FIG. 4A

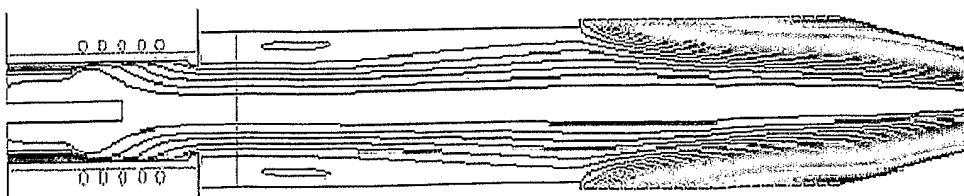


FIG. 4B

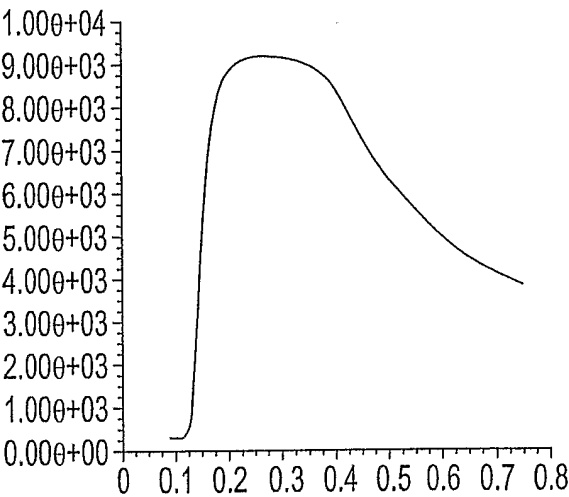


FIG. 5A

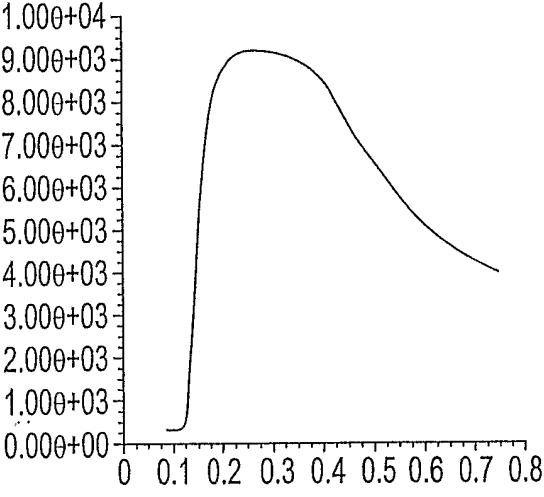


FIG. 5B

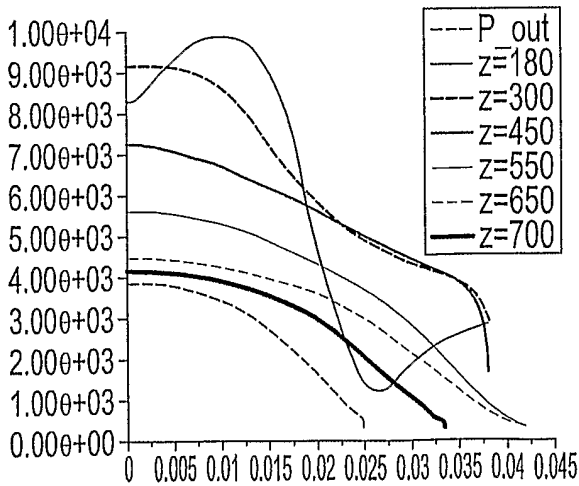


FIG. 5C

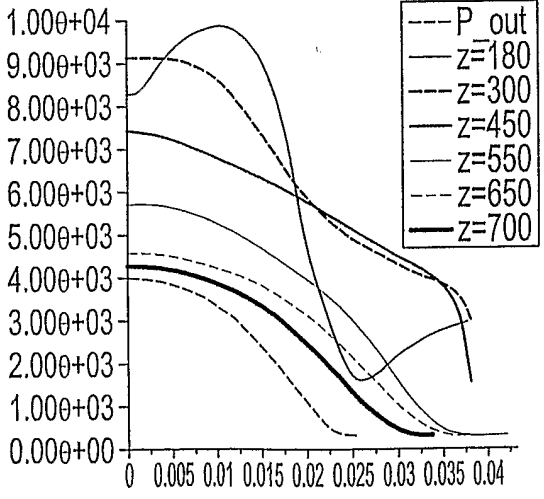
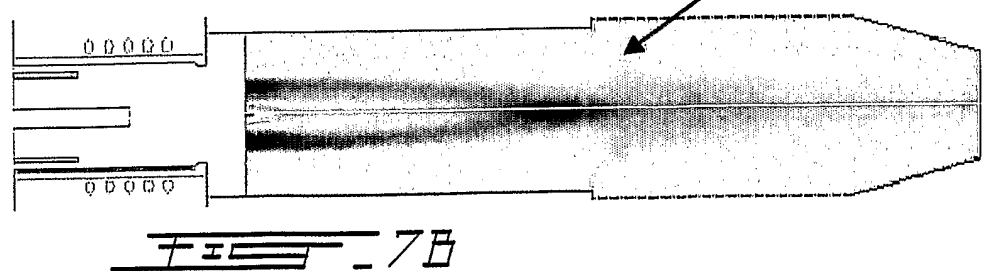
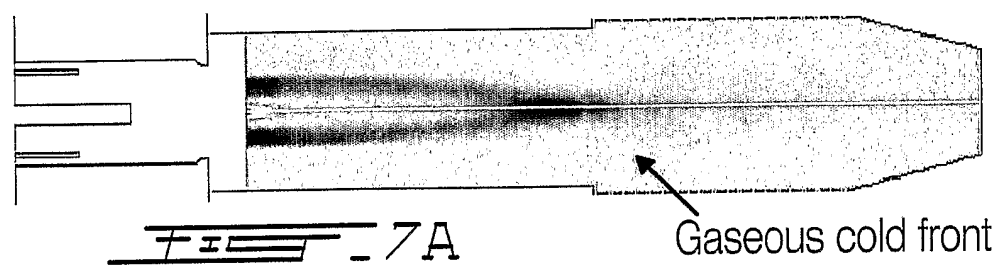
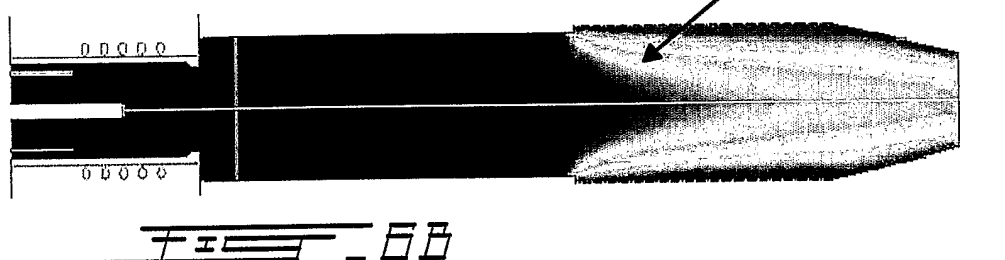
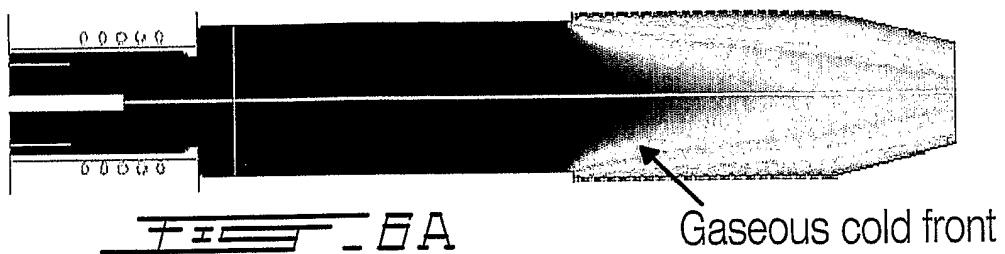


FIG. 5D

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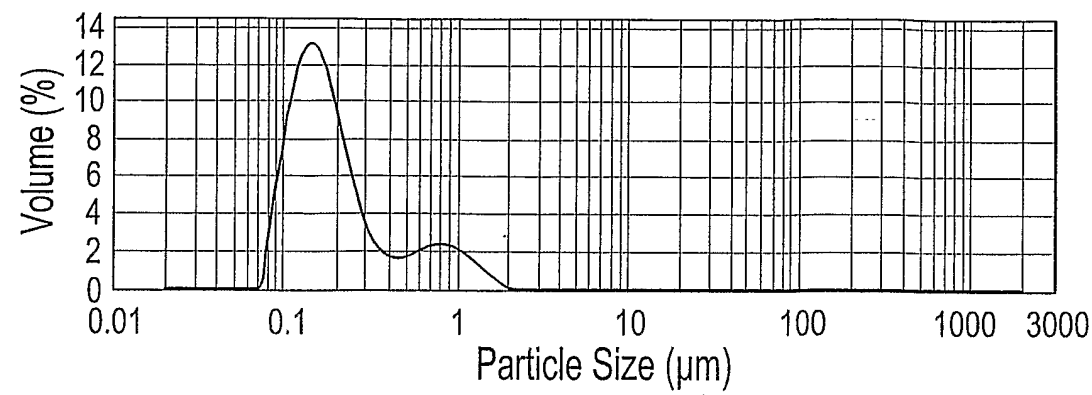


Figure 1

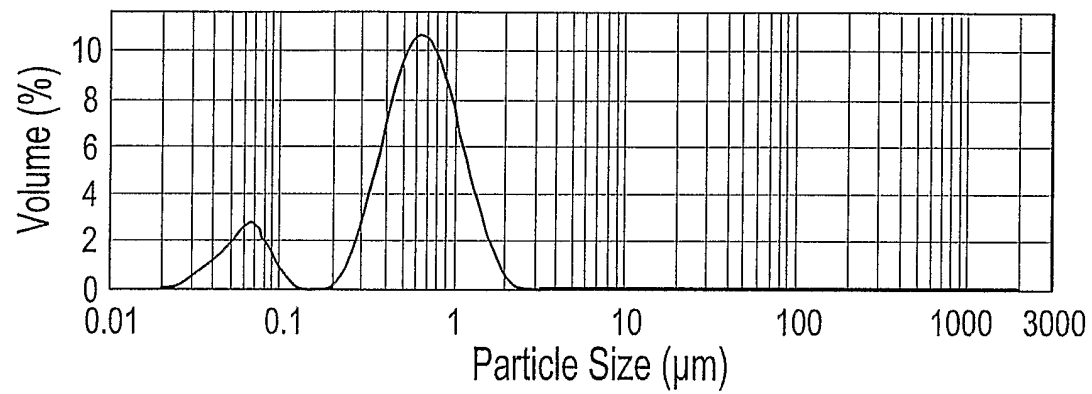


Figure 2

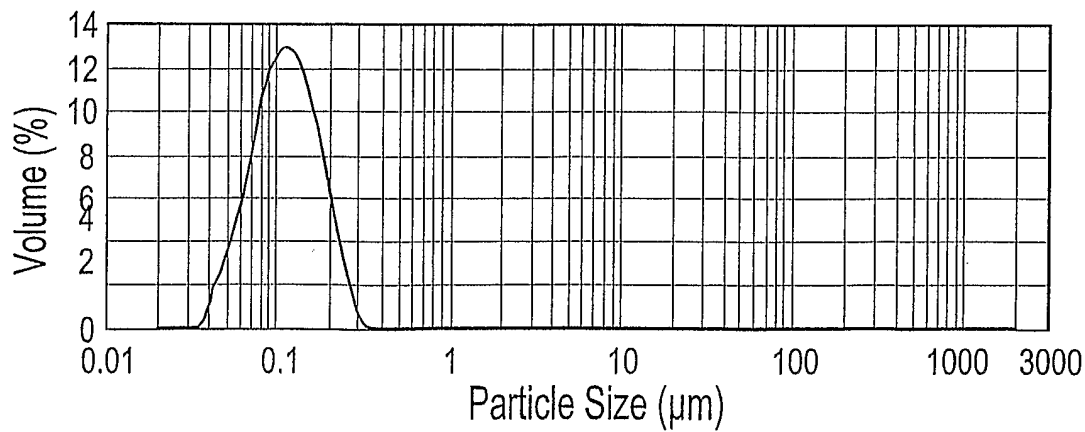


Figure 3

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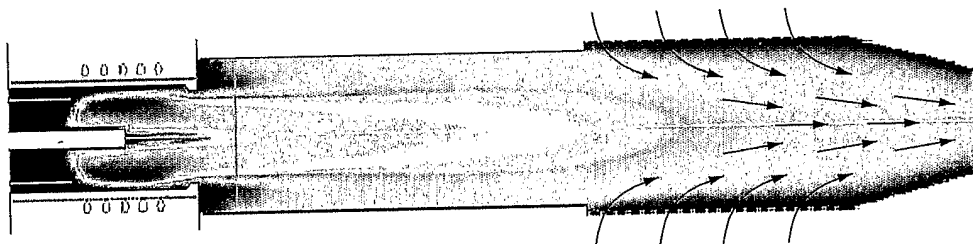
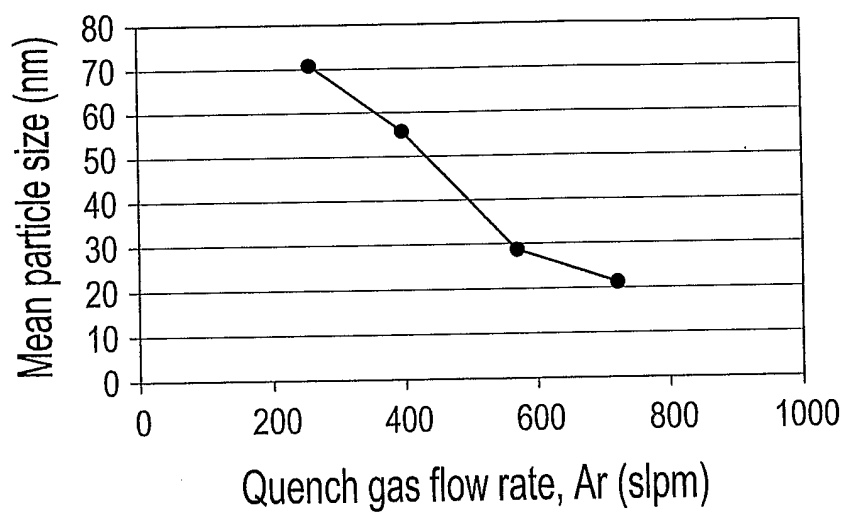
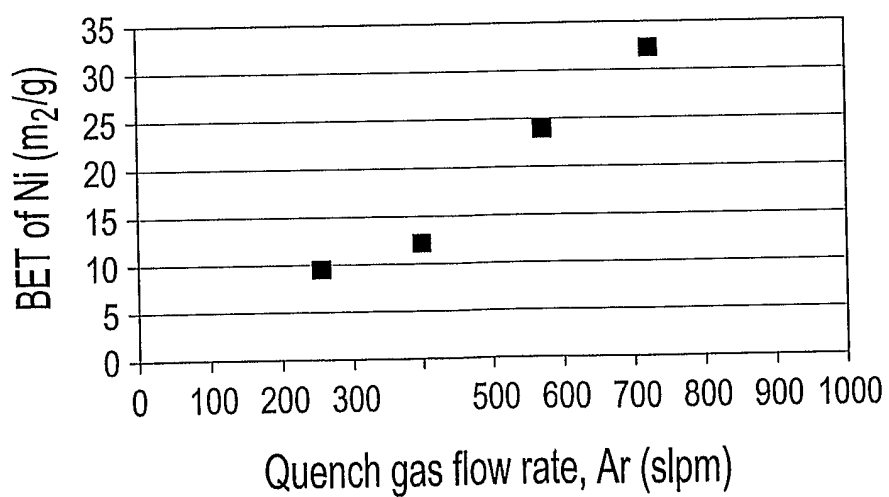
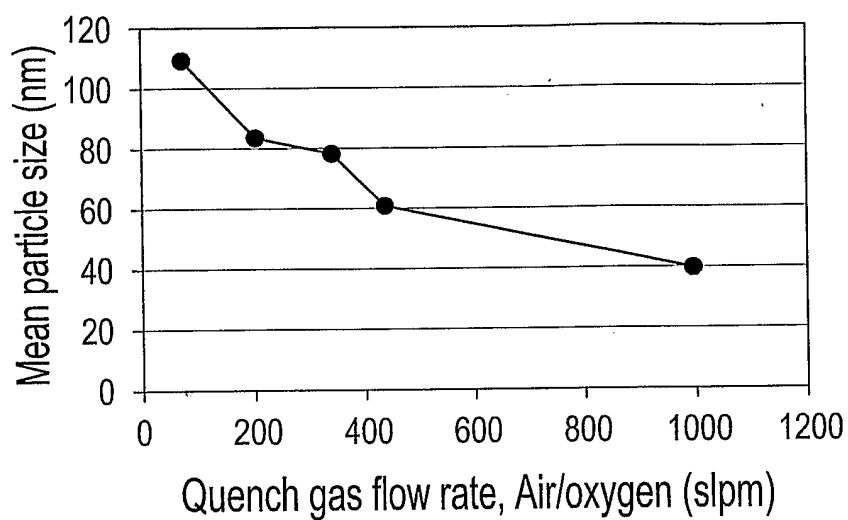
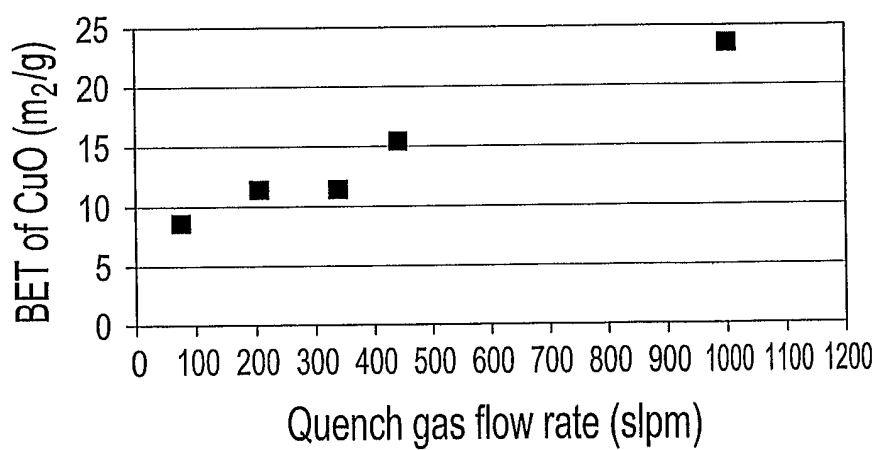


FIG. 11

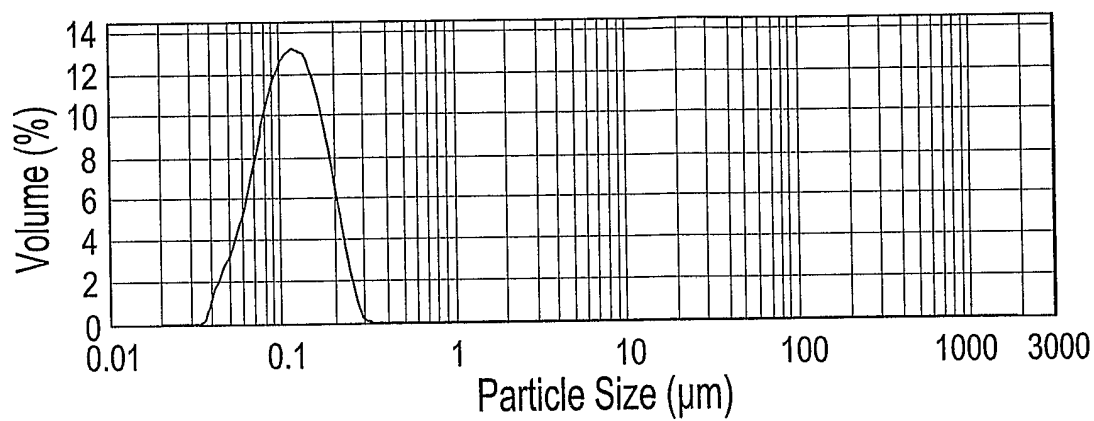
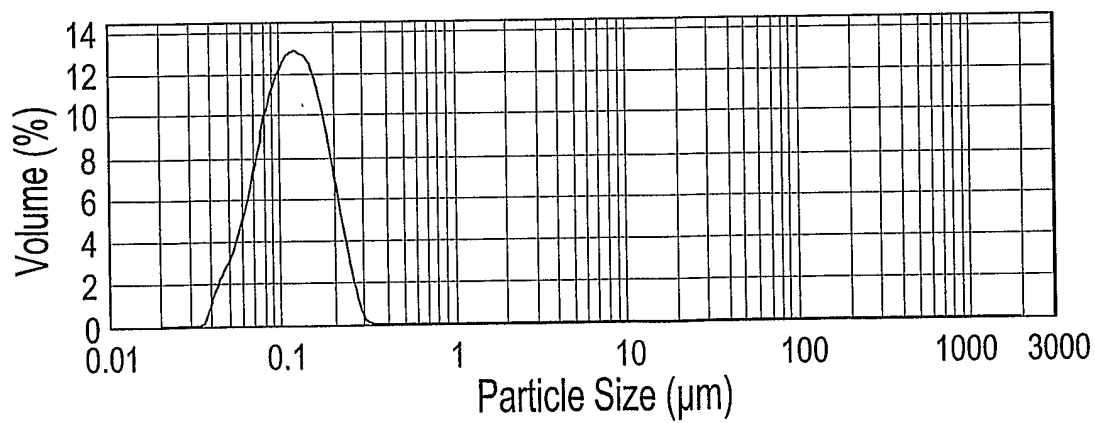
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FIG. 12AFIG. 12B

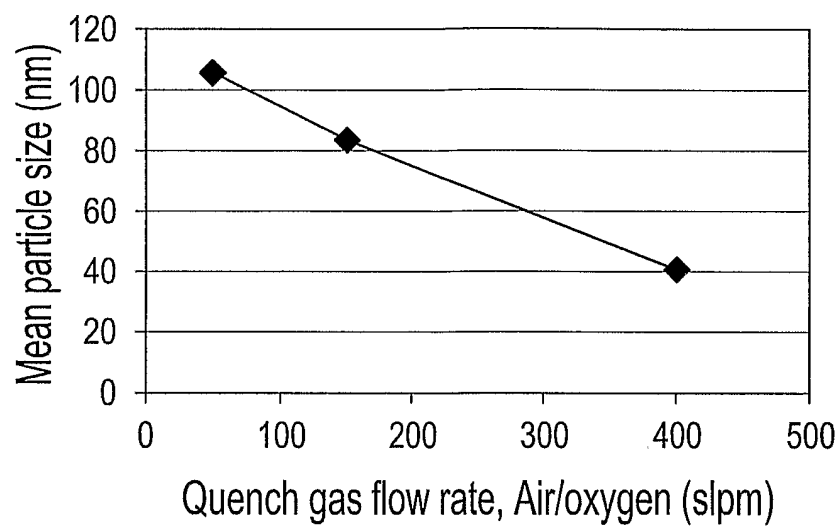
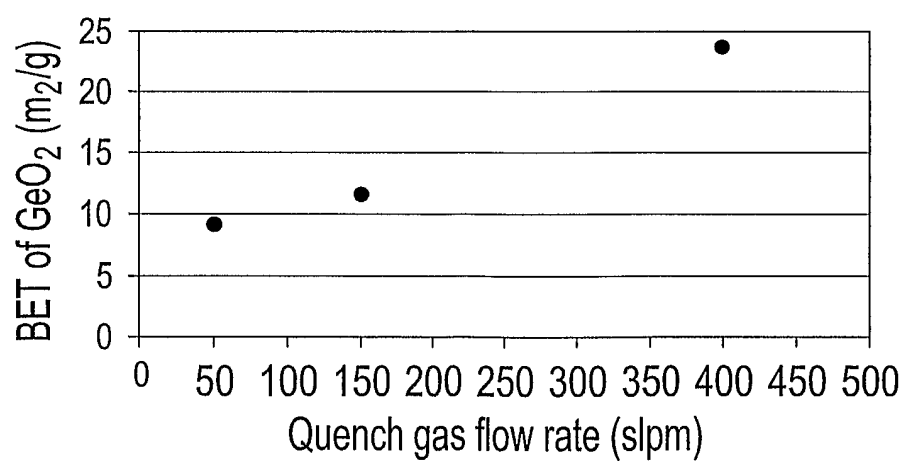
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FIG. 13AFIG. 13B

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FIGURE 14AFIGURE 14B

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FIG. 15AFIG. 15B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2006/000110

A. CLASSIFICATION OF SUBJECT MATTER IPC: B01J 2/04 (2006.01) , B22F 9/08 (2006.01) , B22F 9/00 (2006.01), C01B 13/30 (2006.01), C01G 17/2 (2006.01), C01G 3/02 (2006.01) According to International Patent Classification (IPC) or to both national classification and IPC		
B. FIELDS SEARCHED Minimum documentation searched (classification system followed by classification symbols) IPC: B01J 2/04 (2006.01) , B22F 9/08 (2006.01) , C01G 23/07 (2006.01) , C01B 13/30 (2006.01) Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used) Canadian Patent Database, West, Esp@cenet, Qweb		
C. DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	Ca2445169 (TEKNA PLASMA SYSTEMS INC.) 31 October 2002 (31-10-2002) See whole document	1 to 32
P, X	Ca2481152 (E.I. DU PONT DE NEMOURS and COMPANY) 11 March 2005 (11-03-2005) See whole document	1 to 32
P, X	Ca2512317 (E.I. DU PONT DE NEMOURS and COMPANY) 20 January 2006 (20-01-2006) See whole document	1 to 32
☐ Further documents are listed in the continuation of Box C. ☒ See patent family annex.		
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Date of the actual completion of the international search 7 March 2006 (07-03-2006)		Date of mailing of the international search report 29 March 2006 (29-03-2006)
Name and mailing address of the ISA/CA Canadian Intellectual Property Office Place du Portage I, C114 - 1st Floor, Box PCT 50 Victoria Street Gatineau, Quebec K1A 0C9 Facsimile No.: 001(819)953-2476		Authorized officer Mark Hantke (819) 953-5773

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International application No.
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