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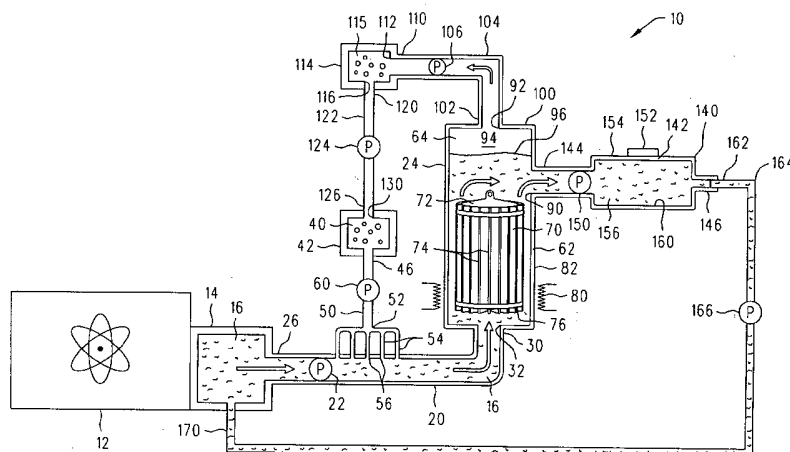
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(54) Title: METHOD AND APPARATUS FOR DECONTAMINATING MOLTEN METAL COMPOSITIONS



(57) Abstract: A method and apparatus for decontaminating molten metal compositions. A molten metal composition (typically containing elemental lead or a lead alloy) is initially provided which also includes various inorganic contaminants. The composition is placed in contact with a specialized decontamination member which actively allows diffusion of the contaminants therein. As a result, the contaminants are removed from the molten metal composition. Contaminants of particular interest in lead-based molten metal compositions include arsenic, tin, antimony, tellurium, and combinations thereof. A reducing agent is optimally combined with the molten metal composition to prevent oxide formation on the decontamination member. The decontamination member preferably contains iron in the form of an iron alloy (for example, steel). Additional preferred components in the decontamination system include an iron trap for removing iron-containing contaminants from the molten metal composition. As a result, the composition is rapidly and effectively decontaminated.

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METHOD AND APPARATUS FOR DECONTAMINATING MOLTEN METAL COMPOSITIONS

Related Applications

5 This application is related to U.S. Patent Application Serial Number 10/995,829 entitled METHOD AND APPARATUS FOR DECONTAMINATING MOLTEN METAL COMPOSITIONS, filed on 22 November 2004.

U.S. Government Rights

10 The United States Government has certain rights in this invention pursuant to Contract No. DE-AC07-99ID13727, and Contract No. DE-AC07-05ID14517 between the United States Department of Energy and Battelle Energy Alliance, LLC

Field of the Invention

15 The present invention generally relates to the decontamination and purification of molten metal compositions and, more particularly, to the processing and treatment of lead-containing molten metal compositions in order to remove contaminants therefrom. The molten metal compositions being treated are particularly useful in cooling systems for nuclear power generating units and related applications, with the claimed decontamination apparatus
20 and method facilitating the safe, continuous, and efficient operation of these systems in a rapid and effective manner.

Background of the Invention

 Most modern power generation systems produce significant quantities of heat as a by-
25 product. Efficient heat removal is therefore a high priority in order to extract useful energy to ensure safe and continuous operation of these systems. Heat removal is of particular concern

in nuclear reactor-based power generating facilities which have extensive cooling requirements. Various methods have been developed for removing and otherwise dissipating heat from nuclear reactors. A heat removal method of particular interest has involved the use of molten heavy metal compositions (for example, those which contain elemental lead [Pb] or lead-containing alloys with particular reference to, for example, lead-bismuth [Pb-Bi] alloys). Lead-containing molten metal compositions are characterized by high levels of heat conductivity and heat transfer efficiency. They therefore continue to be of significant interest in the nuclear power generating industry. Additional background information concerning the use of lead-containing molten metal compositions in nuclear reactor cooling systems is available from numerous sources and literature articles including but not limited to, for example, Gromov, B., et al., "Inherently Safe Lead-Bismuth-Cooled Reactors", Atomic Energy, 76(4):323 - 330 (1994) which is incorporated herein by reference.

Notwithstanding the usefulness of lead-containing molten metal compositions as efficient coolants in nuclear reactor systems, various difficulties have likewise been encountered when these materials are employed which will now be discussed. Specifically, lead-containing molten metal compositions (especially lead-bismuth alloys) have demonstrated an ability to significantly corrode various metal components (conduits, containment vessels, heat-transfer surfaces, and the like) in reactor cooling systems and related structures. This corrosion (caused by a variety of complex chemical and physical interactions) can significantly degrade the operating components of the cooling systems, thereby leading to costly damage, leaks, and general system failures (including interruptions in reactor operation). The corrosion problems discussed above are primarily caused by various inorganic contaminants in the lead-containing molten metal compositions including but not limited to the following materials in elemental form and/or various combinations thereof (alloys, compounds, complexes, and the like without limitation): antimony [Sb],

arsenic [As], tin [Sn], and tellurium [Te]. The presence of these materials (in even relatively small quantities, namely, 0.1% by weight or less) can cause significant corrosion of the cooling system under consideration and its operating components.

The corrosion problems discussed above have been extensively investigated and, in view of these difficulties, alternative cooling systems using different coolant media have been studied and, in some cases, implemented. These alternative cooling systems involve, for instance, the use of liquid sodium [Na] which is characterized by significantly lower corrosive activity compared with lead-based molten metal cooling compositions. Nonetheless, lead-based cooling systems continue to have numerous advantages over other cooling methods and, for this reason, they continue to be of interest. These advantages include but are not limited to: (1) a high degree of thermal conductivity (and heat removal efficiency); (2) a favorable level of thermal stability; (3) low neutron capture cross-section (resulting in relatively uniform power distributions); (4) self-shielding from reactor gamma-rays; (5) high boiling points (which enable low-pressure operation at high temperature levels without boiling); (6) a fast neutron spectrum which makes it possible to burn radioactive wastes; (7) low chemical reactivity at high temperatures compared with, for example, liquid sodium-based cooling systems; and (8) a high specific heat value which allows the cooling systems of interest to be significantly smaller than conventional systems that employ water, various gases, air, and the like. Accordingly, a number of important benefits are provided by lead-based molten metal cooling systems. A continued interest in this technology therefore exists for cooling nuclear reactors and other related devices (including but not limited to accelerator-driven radioactive waste transmutators and the like) notwithstanding the corrosion problems discussed above.

In accordance with the many beneficial features and characteristics of lead-based molten metal cooling systems in nuclear applications, various attempts have been made to

control or otherwise mitigate corrosion problems. For example, prior research has demonstrated that a stable oxide film on the metallic components employed in the cooling systems will control the corrosion of ferrous metals. However, if the lead-containing molten metal compositions being used in the cooling systems are too oxidizing (which is

5 characterized by the production of, for example, lead oxide [PbO] within the systems), reduced flow rates will occur as the oxide materials form. Even under highly-oxidizing conditions, if one or more of the above-mentioned contaminants are present (namely, arsenic, antimony, tin, tellurium, and/or combinations thereof), corrosion will still occur. If the reverse condition is implemented within the systems (namely, if a reducing environment is

10 created therein which is characterized by a lack of oxygen [O₂]), corrosion will nonetheless occur in the presence of the foregoing contaminants since any previously-formed protective oxide layers (e.g. lead oxide) will be removed from the metal surfaces in the cooling systems. Thus, while the active control of the overall environment in the cooling systems (from an oxidation-reduction perspective) remains a potentially viable approach for mitigating

15 corrosion-based damage, the amount of oxygen in the systems must be precisely controlled in order to achieve this goal which can be difficult and complex.

From a historical standpoint, the purification of lead to remove contaminants therefrom (including but not limited to antimony, arsenic, sulfur, and tin) has been addressed in various patents including U.S. Patent Nos. 50,800; 786,581, 1,640,486; 1,640,487,

20 1,950,388; 2,062,838; and 3,335,569. U.S. Patent Nos. 3,300,043; 3,393,876; and 3,689,253 disclose hydrometallurgical processes for purifying lead compositions. U.S. Patent No. 4,194,904 involves the purification of lead and antimony oxide by partial oxidation (namely, via the introduction of air into molten alloy materials at controlled temperatures). As a result, the antimony is preferentially oxidized to form antimony trioxide. U.S. Patent No. 4,496,394

25 involves a method for removing tin from a molten lead-containing composition by

introducing chlorine and oxygen into the composition (which contains tin therein as an impurity) in order to form a tin-containing "dross" (e.g. an oxide composition typically located on the surface of the molten metal composition). Thereafter, the lead is physically separated from the dross. Finally, U.S. Patent No. 5,100,466 discloses a method wherein lead
5 is purified using a reactive mixture comprised of sodium and calcium. In accordance with this process, the resulting mixture is allowed to cool which yields three equilibrium phases, one of which (located on the bottom of the product) involves refined lead.

Notwithstanding the processes and techniques generally discussed above, the present invention offers a considerable advance in the art of metal purification with particular
10 reference to the decontamination of lead-containing molten metal compositions. The claimed invention provides numerous benefits which, particularly from a collective standpoint, have not been achieved prior to the present invention. Accordingly, the processes and systems described below satisfy a long-felt need for a decontamination method and apparatus which accomplishes the following benefits and goals simultaneously (with the foregoing list not
15 necessarily being considered exhaustive): (1) the ability to remove inorganic compositions (particularly arsenic, antimony, tin, and tellurium) in a highly efficient manner from lead-containing molten metal compositions; (2) rapid and highly effective decontamination rates; (3) the implementation of an efficient decontamination process using a minimal amount of operating equipment and materials; (4) the ability to remove contaminants without the need to
20 employ hazardous, caustic, or expensive chemical reagents; (5) a high level of versatility with particular reference to the types of lead-containing molten metal compositions which can be treated; (6) improved decontamination efficiency resulting from the ability of the system to operate in a substantially continuous fashion; (7) compatibility with a considerable number of heat generating devices including but not limited to a wide variety of nuclear power
25 generating systems, accelerator-driven radioactive waste transmutators, and the like which

employ lead-containing molten metal compositions as coolants; (8) the ability to achieve decontamination without requiring highly oxidizing conditions (which avoids the problems associated therewith as discussed above); (9) a considerable degree of versatility regarding the types of contaminants which may be removed from the lead-containing molten metal compositions; (10) the overall implementation of a procedure which is cost effective, readily controllable (e.g. customizable on-demand to various cooling systems and devices), easily scaled up or down as needed, and capable of rapid integration into the cooling systems of interest; (11) the capacity to decontaminate lead-containing molten metal compositions in a manner whereby destructive corrosion of the cooling systems is eliminated, thereby avoiding excessive maintenance requirements, system failures, and other operational problems; and (12) an accomplishment of the above-listed goals in a manner which is superior to prior decontamination techniques and represents a considerable advance in molten metal processing technology.

As outlined above, the claimed invention is characterized by a multitude of specific benefits in combination, with the foregoing list not necessarily being exhaustive. These benefits include but are not limited to items (1) - (12) recited above both on an individual and simultaneous basis which are attainable in a substantially automatic manner (with the simultaneous achievement of such goals being of particular importance and novelty). The decontamination method and apparatus described herein perform all of the functions mentioned above in a uniquely effective and simultaneous fashion while using a minimal quantity of reactants, reagents, equipment, labor, and operational requirements. As a result, a decontamination system of minimal complexity and high effectiveness is created that nonetheless exhibits a substantial number of beneficial attributes in an unexpectedly efficient manner. In this regard, the developments disclosed herein represent an important advance in molten metal decontamination technology (with particular reference to lead-containing

molten metal compositions). Specific information concerning the novel process steps, reaction conditions, operating components, equipment configurations, and other elements associated therewith will be presented below in the following Summary, Brief Description of the Drawing, and Detailed Description sections.

5

Summary

The following discussion shall constitute a brief and non-limiting general overview. More specific details concerning particular embodiments and other important features (including a recitation of preferred reaction conditions, operational parameters, processing equipment, and other aspects of the claimed technologies) will again be recited in the Detailed Description section set forth below.

In accordance with the present invention, a highly efficient method and apparatus are disclosed for removing inorganic contaminants from molten metal compositions, particularly those which contain in whole or in part lead. While the claimed invention shall not be restricted to the treatment of any particular lead-containing molten metal compositions, representative compositions of particular interest include those which are made from elemental lead [Pb], lead-bismuth [Pb-Bi] alloys, or combinations thereof in a variety of proportions without limitation. Furthermore, the present invention shall not be restricted regarding the particular inorganic contaminants which can be removed from the lead-containing molten metal compositions discussed above. However, in a preferred embodiment, the following contaminants shall be considered of primary interest in the claimed invention: antimony, arsenic, tin, tellurium, or combinations thereof. As outlined further below in the Detailed Description section, the term "combinations thereof" as employed herein and as claimed shall be construed (wherever it appears) to encompass any combination of two or more of the materials recited in connection therewith and possibly others, with

“combinations” being further defined to encompass mixtures, alloys, compounds, and complexes of the listed materials in any amounts, arrangements, or proportions without limitation.

With continued reference to the claimed method, it is optional (but preferred) to introduce at least one reducing agent into the lead-containing molten metal composition in order to substantially avoid and otherwise prevent an oxidation layer (e.g. comprised of lead oxide and related compounds) from forming on the decontamination member used in the claimed treatment process as discussed further below. In a preferred and non-limiting embodiment, the reducing agent will comprise a material selected from the group consisting of solid particulate carbon [C_(s)], hydrogen [H_{2(g)}], methane [CH_{4(g)}], acetylene [C₂H_{2(g)}], propane [C₃H_{8(g)}], or combinations thereof without limitation. The use of at least one reducing agent shall be considered a “default” process step employed in order to obtain optimum results and, in this regard, shall be used unless countervailing circumstances exist which would make it unnecessary as determined by routine preliminary pilot tests. These tests would take into account the particular chemical nature of the lead-containing molten metal composition being treated, the contaminant content thereof, and the environmental conditions which exist within the decontamination system (along with other related factors). It should likewise be noted that the introduction of the reducing agent into the molten metal composition can occur at a variety of intervals or locations in the claimed process and system including before and during decontamination using the decontamination member discussed below.

Next, the molten metal composition having the inorganic contaminants therein is placed in contact with at least one decontamination member which is comprised of a composition that will allow the inorganic contaminants in the molten metal composition to diffuse into the decontamination member. In a preferred embodiment, the decontamination

member will comprise iron [Fe] therein, with optimum results being achieved when an iron-containing alloy is employed (preferably steel). As extensively discussed below, the term “diffuse” shall be construed in the broadest possible sense to involve: (1) entry of the inorganic contaminants into and beneath the surface of the decontamination member to various depths without limitation; (2) interaction of the inorganic contaminants with the decontamination member at the surface thereof without necessarily passing beneath the surface; and/or (3) a combination of [1] and [2] above. Irrespective of the manner in which diffusion occurs, the decontamination member is of a type that will have a selective affinity for the inorganic contaminants of interest while avoiding affinity (and diffusion therein as defined above) of the various lead-containing materials (e.g. elemental lead, alloys, compounds, or complexes thereof) that are associated with the lead-containing molten metal composition. As a result (and as more fully described in the Detailed Description section), the inorganic contaminants can be efficiently removed from the lead-containing molten metal composition in order to effectively decontaminate it.

With continued reference to the decontamination process, specific operating parameters associated therewith (including preferred residence times and the like) will be presented in detail below. However, in order to obtain optimal results, it is preferred that the lead-containing molten metal composition be maintained at a temperature of about 400 - 600°C during placement of the composition in contact with the decontamination member. This temperature level promotes favorable reaction kinetics and otherwise facilitates the decontamination process.

In accordance with the procedure discussed above wherein direct physical contact occurs between the decontamination member and the lead-containing molten metal composition, the inorganic contaminants in the molten metal composition are allowed to diffuse into the decontamination member and consequently be removed from the molten

metal composition. In this manner, rapid and effective decontamination of the molten metal composition takes place as stated above. Further information will again be provided in the Detailed Description section regarding other operational parameters associated with the decontamination procedure including residence times, material quantities, and the like.

5 As stated above and in accordance with the claimed process, the inorganic contaminants of concern will diffuse into the decontamination member for removal thereof from the lead-containing molten metal composition. However and during this procedure, it is possible under some (but not necessarily all) circumstances that placement of the molten metal composition in contact with the decontamination member will cause at least one iron-
10 containing contaminant (e.g. elemental iron [Fe], alloys, mixtures, compounds, and/or complexes containing iron) to be introduced into the molten metal composition. Removal of at least some (and preferably all) of the iron-containing contaminant is desired in order to preserve and maintain the overall purity, cooling efficiency, and non-corrosivity of the lead-containing molten metal composition and to likewise avoid undesired precipitation of the iron
15 within the cooling system (which can cause flow restrictions and related problems).

Removal of the iron-containing contaminant may be accomplished in various ways without limitation. However, in a preferred and representative embodiment, elimination of the iron-containing contaminant is achieved using at least one iron trap. In particular, effective results are attained through the use of an iron trap system which supplies a magnetic field.
20 The molten metal composition is placed within this magnetic field in order to draw the iron-containing contaminant out of the lead-containing molten metal composition. It should be noted that a decision to employ an iron trap in a given operational environment shall be determined in accordance with routine preliminary pilot tests taking into account the chemical and physical nature of the molten metal compositions being treated, the structural
25 configuration of the decontamination member (and the materials from which it is made), and

other operational parameters associated with the decontamination system. However, in a preferred embodiment, this step will be employed as a “default” procedure unless countervailing circumstances indicate otherwise. Additional information concerning this particular aspect of the invention will likewise be outlined in greater detail below.

5 It should likewise be recognized that in some (but not necessarily all) circumstances where a reducing agent is employed, the lead-containing molten metal composition will contain (after decontamination) at least some of the reducing agent therein which remains in an unreacted state. In particular, this reducing agent will be present (at least temporarily) within the molten metal composition after placement of the molten metal composition in
10 contact with the decontamination member. This situation typically results in accordance with the use of excess quantities of reducing agent within the system as a “default” procedure in order to ensure that oxide formation on the decontamination member does not occur. In a preferred embodiment to be discussed in greater depth below, an additional feature of the claimed process can involve the step of removing at least some of the unreacted reducing
15 agent from the molten metal composition (and the system as a whole). This step enables maximum operating efficiency to be maintained within the decontamination and cooling systems (namely, the minimization of corrosion and improved economic performance by the recycling of recovered quantities of reducing agent). As previously stated, additional information concerning the process discussed above and its various embodiments will be
20 provided in the Detailed Description section below.

 Regarding the apparatus to be used in implementing the claimed process, all of the information, definitions, and other data set forth above in connection with the claimed method shall be incorporated by reference in the current discussion of the apparatus. Specifically, a supply of the lead-containing molten metal composition described above is
25 initially provided which includes the previously-listed contaminants therein. Should the use

of a reducing agent within the system be needed and desired as indicated above (with representative and preferred reducing agents being discussed earlier in this section), a supply of the reducing agent is also provided which is in fluid communication with the supply of the molten metal composition. As a result, the reducing agent can be introduced into the molten metal composition on demand.

A containment vessel is also provided which is in fluid communication with the supply of the molten metal composition so that the composition can enter the vessel when decontamination is desired. In an exemplary and preferred embodiment, the containment vessel comprises therein the decontamination member outlined above. As previously stated, the decontamination member comprises iron therein (preferably an iron-containing alloy with optimum results being achieved when steel is used for this purpose). In accordance with the general information provided above, the decontamination member is of a type that will allow the inorganic contaminants of concern within the lead-containing molten metal composition to diffuse into the decontamination member when the molten metal composition comes in contact with the decontamination member. In this manner, the contaminants can be removed rapidly and effectively from the molten metal composition.

The containment vessel will further comprise at least one outlet port therein for passage of the molten metal composition out of the vessel after the composition comes in contact with the decontamination member. Likewise and in an exemplary embodiment, at least one additional outlet port is provided in the containment vessel for the passage of unreacted quantities of the reducing agent out of the vessel (with such quantities being previously combined with the molten metal composition as outlined above). In order to avoid corrosion and maintain structural stability, the containment vessel (and other components associated with the claimed decontamination apparatus) are optimally produced from a composition which is highly resistant to corrosion, chemical degradation, and the like. In a

representative embodiment designed to provide optimum results, the containment vessel (along with the various conduits and other components of the decontamination system) are produced from a composition which comprises zirconium [Zr] therein (e.g. elemental zirconium or alloys, compounds, mixtures, and complexes which contain at least some
5 zirconium).

If it is desired that iron-containing contaminants be removed from the system as previously described (which should again be considered a “default” procedure unless countervailing circumstances exist which would indicate otherwise), at least one iron trap is provided which is able to receive the molten metal composition after contact with the
10 decontamination member. The iron trap will again remove iron-containing contaminants from the molten metal composition which were introduced into the composition during contact thereof with the decontamination member. Furthermore and in a preferred embodiment, the iron trap will comprise at least one magnet which is able to generate a magnetic field in order to draw the iron-containing contaminants out of the molten metal
15 composition.

Finally, in an exemplary and preferred (e.g. non-limiting) version of the invention, the decontamination apparatus may likewise include at least one heater which is used to provide heat to the molten metal composition so that optimum temperature levels can be maintained therein during decontamination. The heater can be located in a variety of positions inside and
20 outside the apparatus without limitation although it is preferred that it be positioned on or adjacent the exterior surface of the containment vessel so that direct heating thereof can be accomplished.

It shall be recognized that the apparatus which may be used to implement the claimed methods and processes shall not be restricted by the description provided herein. Various
25 additional components, systems, and sub-systems may be employed in connection with the

containment vessel and the other sections of the claimed decontamination apparatus without limitation provided that the main functional capabilities of the system can be implemented in an effective and cost-efficient manner. In this regard, the apparatus associated with the claimed invention shall not be restricted to any particular equipment types, arrangements, capacities, materials, operational parameters, and the like unless otherwise expressly stated herein.

As previously indicated, the Summary provided above shall not limit the invention in any respect and is instead being presented as a brief overview of the claimed technology from a general standpoint. The Detailed Description section set forth below will offer explicit and enabling information regarding the foregoing subject matter including data involving the materials being used, the reaction conditions of interest, and the operating components associated with the claimed invention which achieve the goals outlined above.

Brief Description of the Drawing

The drawing figure provided herein is schematic and not necessarily drawn to scale. It shall not limit the scope of the invention in any respect. Any physical components or structures shown in the drawing are representative only and are not intended to restrict the invention or its implementation. In particular, the claimed treatment methods are not limited to any specific hardware, processing equipment, arrangements of components, orders and sequences in which processing steps occur, and the like, with the invention being useful in a variety of applications (including the incorporation thereof in various nuclear reactors and cooling systems without limitation). Accordingly, the claimed technology shall not be considered "environment-specific" or "application-specific" in any fashion. Likewise and as previously noted, the current invention is not restricted to any particular order or sequence in which the desired operating procedures are implemented and is also not limited to any

specific equipment arrangements or configurations unless otherwise expressly stated herein, with any representations of the same in the drawing figure being presented for example purposes only. The use of any symbolic elements in Fig. 1 regarding various materials, reactants, structures, components, and the like which are employed in the claimed invention shall also be considered exemplary and non-restrictive.

Fig. 1 is a schematically-illustrated view of a representative decontamination system for lead-containing molten metal compositions which may be used to implement the process of the claimed invention. No scale or size relationships shall be construed from the drawing or other limitations implied therefrom.

10

Detailed Description

As described above, the present invention involves a highly efficient method and apparatus for removing inorganic contaminants from lead-containing molten metal compositions. The technology discussed herein represents a significant advance in the field of molten metal decontamination technology. Likewise, the claimed method and apparatus are further characterized by an unexpectedly high degree of operational efficiency as previously noted.

At this point, the claimed techniques and devices will be discussed in depth with particular reference to the preferred materials, components, equipment, quantities, operational parameters, equipment configurations, reaction conditions, and the like. All of the various embodiments disclosed herein shall not be limited to any specific equipment, components, material quantities, reactants, starting materials, and the like unless otherwise expressly stated herein. Likewise, all scientific terms used throughout this discussion shall be construed in accordance with the traditional meanings attributed thereto by individuals skilled in the art to which this invention pertains unless a special definition is provided below. The numerical

25

values listed in this section and in the other sections of the present description constitute preferred embodiments designed to offer optimum results and shall not limit the invention in any respect. In particular, it shall be understood that the specific embodiments, components, and methods disclosed herein and illustrated in the drawing figure constitute special versions
5 of the claimed method and apparatus which, while non-limiting in nature, can offer excellent results and are highly distinctive. All recitations of chemical formulae, structures, alloys, compounds, mixtures, complexes, and the like in the following discussion are intended to generally indicate the types of materials which may be used. The listing of specific chemical compositions which fall within the general formulae and classifications presented below are
10 offered for example purposes only and shall be considered non-limiting unless explicitly stated otherwise.

The invention discussed herein and all of its various embodiments shall likewise not be restricted with particular reference to the order in which the claimed process steps are implemented unless otherwise expressly indicated below.

15 Finally, any and all recitations of structures, materials, chemicals, and components in the singular throughout the Claims, Summary, and Detailed Description sections (for example, by using “a”, “an”, or other comparable words) shall also be construed to encompass a plurality of such items unless otherwise explicitly noted herein. Employment of the phrase “at least one” shall be construed in a conventional fashion to involve “one or
20 more” of the listed items, with the term “at least about” being defined to encompass the listed numerical value and values in excess thereof. Use of the word “about” in connection with any numerical terms or ranges shall be interpreted to offer at least some latitude both above and below the listed parameter(s) with the magnitude of such latitude being construed in accordance with current and applicable legal decisions pertaining to this terminology.
25 Furthermore, all of the definitions, terms, and other information recited above in the

Background and Summary sections are applicable to and incorporated by reference in the current Detailed Description section. In order to facilitate a full and complete explanation of the invention and its various embodiments, the best mode associated with the method and apparatus that are claimed herein will be described in a sequential fashion beginning with the starting materials under consideration, followed by an explanation as to how these materials are decontaminated on a step-by-step basis along with detailed technical information and definitions where needed.

I. The Lead-Containing Molten Metal Composition

With reference to Fig. 1, a system for decontaminating the lead-containing molten metal composition of interest in the present invention is generally shown at reference number 10 which will now be discussed in substantial detail. Operatively associated with the system 10 is a nuclear reactor 12 which is being cooled using the lead-containing molten metal composition. It shall be understood that, while a nuclear power-generating reactor 12 is shown in Fig. 1 and described herein, the lead-containing molten metal composition to be decontaminated may be associated with any heat-generating apparatus or facility without limitation that is capable of being cooled using materials of this nature. For example, instead of the nuclear reactor 12 discussed above, an accelerator-driven radioactive waste transmutator may likewise be cooled using the lead-containing molten metal composition being described herein. Accordingly, the present invention shall not be limited regarding the particular apparatus, device, or system being cooled, or the cooling system in general which would employ the lead-containing molten metal composition of interest.

As shown in Fig. 1, the nuclear reactor 12 includes a cooling system 14 of conventional design which is associated therewith. The cooling system 14 includes a variety of conduits, components, and structures (not shown) which enable the lead-containing molten

metal composition to be effectively circulated throughout the heat-generating regions of the nuclear reactor 12 in order to remove fission energy in the form of heat for use in electrical generation, H₂ production, etc. Lead-containing molten metal cooling systems for nuclear applications are again known in the art to which this invention pertains and have been used
5 for decades, with general information involving these systems being disclosed in a variety of articles and references including but not limited to Gromov, B., et al., "Inherently Safe Lead-Bismuth-Cooled Reactors", Atomic Energy, 76(4):332 - 330 (1994) which is incorporated herein by reference. Accordingly, the lead-containing molten metal composition being discussed herein (as well as the processes and devices which are used for decontamination
10 purposes as disclosed below) shall not be considered "reactor-specific" or "cooling system-specific" and may be employed in connection with a number of conventional and non-conventional heat-generating devices and cooling systems without restriction.

Within the cooling system 14 associated with the nuclear reactor 12 is a supply 16 of a lead-containing molten metal composition (also characterized in an equivalent fashion as a
15 molten metal composition comprising lead therein). The terms "lead-containing molten metal composition" and "molten metal composition comprising lead therein" shall be broadly construed and defined to encompass alloys, compounds, mixtures, complexes, and other combinations of materials (including the use of pure elemental lead [Pb]) which contain in part or in whole at least some lead therein. As previously explained, a significant number of
20 benefits are achieved through the use of lead-based materials in connection with the cooling system 14 and other comparable cooling systems for nuclear applications and like. These benefits specifically include but are not limited to: (1) a high degree of thermal conductivity (and heat removal efficiency); (2) a favorable level of thermal stability; (3) low neutron capture cross-section (resulting in relatively uniform power distributions); (4) self-shielding
25 from reactor gamma-rays; (5) high boiling points (which enable low-pressure operation at

high temperature levels without boiling); (6) a fast neutron spectrum which makes it possible to burn radioactive wastes; (7) low chemical reactivity at high temperatures compared with, for example, liquid sodium-based cooling systems; and (8) a high specific heat value which allows the cooling systems of interest to be significantly smaller than conventional systems that employ water, various gases, air, and the like. Accordingly, a number of important benefits are attributable to lead-based molten metal cooling systems which have resulted in a continued interest in this technology for cooling nuclear reactors and related systems as outlined herein.

At this point, the lead-based molten metal composition associated with supply 16 will be discussed in greater detail. In accordance with the definition of this material provided above, a number of different lead-based compositions (in molten/liquid form) can be employed in connection with the cooling system 14 and the present invention in general. However, in a preferred embodiment, the lead-based molten metal composition will be produced from: (1) elemental lead, (2) a lead-containing alloy; or (3) mixtures of [1] and [2]. Regarding the lead-containing alloy, this composition will contain at least some lead therein which is alloyed with one or more other metals or non-metals. For example, some representative examples of metals and non-metals which may be alloyed with lead in the lead-containing molten metal composition include but are not limited to bismuth [Bi], tin [Sn], zinc [Zn], or combinations of two or more of the above elements. It should likewise be noted that, within the lead-containing alloys associated with the supply 16 of the molten metal composition, the various individual materials therein can be used in a wide variety of proportions without limitation provided that at least some lead (optimally at least about 45% by weight or more) is present in the alloys so that the beneficial cooling effects associated with lead can be achieved.

One composition of particular interest is the use of a lead-bismuth [Pb-Bi] alloy which

is characterized by a high degree of cooling capacity and is therefore of considerable interest in nuclear applications. A number of different lead-bismuth alloys can be employed wherein differing amounts of lead and bismuth are present therein. For example, two representative lead-bismuth alloys which are suitable for use in the cooling system 14 are as follows:

5

(1) Pb (89% by weight) + Bi (10% by weight) [with the balance involving various impurities as discussed in greater detail below]; and

(2) Pb (45% by weight) and Bi (54% by weight) [with the balance involving various
10 impurities as likewise discussed in further depth below].

While the lead-bismuth alloys of interest in the present situation can involve many different lead and bismuth quantity values without limitation, preferred lead-bismuth alloys which are suitable for cooling purposes will include therein about 45 - 89% by weight Pb
15 (optimum sub-range = about 45 - 55% by weight) and about 10 - 54% by weight Bi (optimum sub-range = about 40 - 54% by weight). Again, the claimed invention shall not be restricted to these or any other numerical parameters unless otherwise expressly stated herein.

II. The Inorganic Contaminants

20 As indicated above, the supply 16 of the lead-containing molten metal composition will likewise contain at least some inorganic contaminants therein which are naturally present in the raw ore materials associated with the lead. The presence of these contaminants contributes to increased corrosion problems in the cooling system 14 which can adversely impair the operating efficiency and safety of the nuclear reactor 12 or other heat-generating
25 devices as previously discussed. Regarding the particular inorganic contaminants which

reside within the lead-containing molten metal composition, a variety of metals, non-metals, or combinations thereof may be involved. Accordingly, the term "combinations" as employed in connection with the inorganic contaminants (and other materials associated with the claimed invention) shall be broadly construed to encompass mixtures, compounds, alloys, and complexes of two or more of the listed materials and possibly others without limitation. Regarding the inorganic contaminants, a typical supply 16 of the lead-containing molten metal composition can include therein the following metals and/or non-metals alone or combined (typically in elemental form but possibly in other forms in accordance with the definition of "combinations" recited above): arsenic [As], antimony [Sb], tin [Sn], tellurium [Te], or combinations of two or more of the above-mentioned elements (or with other materials). These compositions are, for the most part, naturally occurring impurities in lead-containing ores that will need to be removed in order to avoid the problems discussed above including those associated with corrosion and the like.

Regarding typical quantities of the above-mentioned and other inorganic impurities in the supply 16 of the lead-containing molten metal composition, these quantities will vary depending on the type of ore from which the lead was derived, the geographic location and grade associated with the ore, and other extrinsic factors. However, in a representative and non-limiting embodiment, typical amounts of the above-listed inorganic contaminants (in elemental form in this example) are as follows: (A) arsenic (about 0.1 - 0.2% by weight); (B) antimony (about 0.5 - 2% by weight); (C) tin (about 0.1 - 1% by weight); and (D) tellurium (about 0.1 - 0.5% by weight). However, these numbers may again vary and otherwise fluctuate without limitation and should therefore be considered representative only. For example purposes, TABLE I below lists some representative molten metal compositions associated with the supply 16 (and contaminants therein) which may be effectively treated in accordance with the claimed invention:

TABLE I

	<u>Composition Type</u>	<u>Components (% by weight)</u>
	Pb-Bi alloy	Pb (89%) Bi (10%) As (0.2%) Sb (0.8%)
5	Pb-Bi alloy	Pb (45%) Bi (54%) As (0.2%) Sb (0.8%)
	Pb (elemental)	Pb (98%) Bi (0%) As (0.2%) Sb (1.8%)

Again, the above-listed compositions (which do not include appreciable amounts of tin and tellurium, with such materials and possibly others being present in other lead-containing molten metal compositions) constitute representative examples and shall not restrict the invention in any manner. In this regard, the invention as claimed shall not be limited to the treatment of any particular lead-containing molten metal compositions, with a wide variety of such materials being subject to rapid and effective decontamination as discussed below.

It should also be noted that, for general information purposes, the supply of lead-containing molten metal composition is typically maintained at a temperature of about 125 - 1000°C during use within the cooling system 14 (for example, about 125 - 1000°C for lead-bismuth alloy cooling systems and about 320 - 1000°C for cooling systems 14 which employ molten elemental lead). Regarding the optimum temperature levels which are maintained during the decontamination process, the higher the temperature of the lead-containing molten metal composition, the more efficient the decontamination process will be (with faster processing times) as outlined further below. This temperature-efficiency relationship is the result of improved reaction kinetics at higher temperatures (although such temperatures will likewise need to be balanced against energy costs and the structural materials that are

employed within the decontamination system 10 as likewise discussed later in this section). A preferred operating temperature range in the decontamination system 10 which facilitates rapid and effective treatment of the lead-containing molten metal composition will likewise be presented below.

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III. Representative Decontamination System Construction Materials and Components

With continued reference to the schematic illustration of Fig. 1, the supply 16 of the molten metal composition is then routed into and through conduit 20 (using one or more conventional pumps 22) and into a containment vessel 24. In particular, the conduit 20
10 includes a first end 26 operatively connected to the cooling system 14 and a second end 30 which is operatively connected to an inlet port or opening 32 in the containment vessel 24. The pump 22 will involve, for example, a standard centrifugal type that is known in the art for molten metal transfer or other comparable pump devices which are suitable for this purpose. At this point, however, some additional discussion is warranted concerning the construction
15 materials that are employed in connection with the conduits, vessels, and other structures which contain or allow the passage therethrough of the molten-metal composition before, during, and after decontamination. While these structures (including conduit 20, containment vessel 24, and the other components described herein) may be produced from any materials which are sufficiently durable to resist corrosion, thermal deterioration, or other potentially-
20 damaging effects caused by the molten metal composition, certain construction materials are preferred. In particular, effective results may be achieved through the use of a composition which comprises at least some zirconium [Zr] therein (including but not limited to elemental zirconium or zirconium-containing alloys). Representative zirconium-containing alloys that are suitable for this purpose include but are not limited to the following materials: (A)
25 "Zircaloy-2" (with the approximate content of this alloy being [in % by weight]: tin [1.5%],

iron [0.12%], chromium [0.01%], and nickel [0.05%]) with the balance being zirconium; and

(B) "Zircaloy-4" (with the approximate content of this alloy being [in % by weight]: tin [1.5%], iron [0.18%], and chromium [0.01%] with the balance being zirconium) wherein the

foregoing values for both alloys are subject to a certain degree of variance. Zirconium-

5 containing compositions of the types listed above (and others) are particularly useful in that they form a self-protective zirconium oxide [ZrO_2] layer on the internal surfaces of the components discussed above. This oxide layer can assist in avoiding corrosion and other related problems (especially at operating temperatures within the decontamination system 10 of about 550°C or less).

10 While the foregoing zirconium-containing compositions are preferred as previously discussed, various other materials can likewise be employed in connection with the conduits, vessels, etc. of the claimed decontamination system 10 including but not limited to molybdenum [Mo], tantalum [Ta], tungsten [W], and alloys or other combinations of two or more of the above-listed materials (or with other compositions). These alternative materials
15 are particularly effective at temperatures greater than 550°C. They will likewise form a protective oxide layer on the internal surfaces of the structural components of the decontamination system 10 and (like zirconium) will have an insignificant degree of solubility within the lead-containing molten metal compositions of interest (including those made from elemental lead or a lead-bismuth alloy). As a result, the supply 16 of the lead-
20 containing molten metal composition will not be further contaminated by the above-mentioned materials.

Additional compositions which can be used effectively as construction materials in
/ connection with the operating components of the decontamination system 10 (namely, the conduits and vessels associated therewith) include iron-chromium-silicon alloys (with these
25 materials being present in varying proportions without limitation) and a Russian alloy known

as "EP-823". It should be recognized that a number of different construction materials may be used in connection with the decontamination system 10, with all of the above-mentioned compositions being effective and suitable at the temperature ranges and operational conditions associated with the claimed apparatus and method. The selection of any given structural materials in connection with the conduits, vessels, and the like of the present invention shall therefore be undertaken in accordance with routine preliminary pilot tests taking into account the type of lead-containing molten metal composition being treated (including the particular chemical nature thereof), the operating temperatures of the decontamination system 10, and other related factors.

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IV. The Reducing Agent

Next and with continued reference to Fig. 1, it is preferred that a supply 40 of a reducing agent (optimally in gaseous form as indicated below) be provided which is in fluid communication with the supply 16 of the lead-containing molten metal composition so that the reducing agent can be introduced into the molten metal composition on demand. In the representative embodiment of Fig. 1, the supply 40 of the reducing agent is retained within a storage vessel 42 having an outlet 44 therein to which the first end 46 of a conduit 50 is operatively attached. In a preferred and non-limiting embodiment, the second end 52 of the conduit 50 will include multiple distributor portions 54 (e.g. in the form of, for example, "tuyeres" or lances) which are in operative connection with openings 56 in the conduit 20. In this manner, the reducing agent can be effectively distributed or otherwise delivered into the lead-containing molten metal composition within the conduit 20.

As noted above, it is preferred that the supply 40 of the reducing agent be in a gaseous form which facilitates the delivery thereof into the supply 16 of the lead-containing molten metal composition in a rapid, cost-effective, and efficient manner. Delivery of the reducing

25

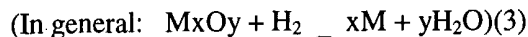
agent to the molten metal composition may be achieved in a number of different ways without limitation. For example, the reducing agent 40 within the storage vessel 42 can be maintained in a pressurized state which will allow the reducing agent to be spontaneously and automatically transferred into the conduits 20, 50 (and the molten metal composition) in an effective fashion. Use of the reducing agent in a pressurized state is, in fact, preferred in that this delivery approach is highly efficient and rapid, especially since the cooling system 14 and the claimed decontamination system 10 operate at relatively low pressure levels (e.g. about 1 - 1400 torr). Alternatively, an in-line gas flow pump 60 of a conventional type (for example, of a vacuum/diaphragm variety) that is known in the art for gas transfer can be used to deliver the supply 40 of the reducing agent into the molten metal composition. It should therefore be recognized that the claimed invention shall not be restricted to any materials, devices, or components which may be used to deliver or transfer the various compositions associated with the invention into, through, and out of the decontamination system 10. A wide variety of different transfer devices and equipment may therefore be employed for these and other purposes without limitation.

Regarding the reducing agent, its purpose will now be generally discussed. The employment of a reducing agent within the decontamination system 10 should be considered preferred in that it can provide a number of important benefits. Specifically, by creating a reducing environment within the system 10, the formation of oxide layers (for example, one or more layers comprised of lead oxide [PbO] or other oxide materials) on the internal operating surfaces of the decontamination system 10 (especially the decontamination member discussed below) is effectively prevented. If not prevented, oxide layers of this type can coat the decontamination member and thereby prevent access to the surface of this important structure by the lead-containing molten metal composition. As a result, the decontamination process will be blocked and otherwise substantially impeded, with the overall

decontamination procedure being discussed in extensive detail below.

For the reasons given above (including the overall maintenance of a high level of decontamination efficiency), it is therefore preferred that the reducing agent be employed. While the use of a reducing agent should nonetheless be considered "optional" (since, under certain circumstances as determined by routine preliminary pilot testing, the decontamination system 10 may operate without it), it should nonetheless be employed as a "default" procedure unless compelling reasons exist to the contrary. It should also be recognized that the claimed invention shall not be restricted to any location, interval, or point at which the supply 40 of reducing agent is added or otherwise introduced into the supply 16 of lead-containing molten metal composition. While the point-of-introduction shown in Fig. 1 is preferred, the reducing agent can be added into the decontamination system 10 at any point upstream or downstream thereof provided that the reducing agent is introduced into the lead-containing molten metal composition in a manner which prevents oxide layer formation as previously discussed.

Regarding the materials which can be employed in connection with the supply 40 of the reducing agent, a number of different compositions can be used for this purpose without limitation. However, in a preferred embodiment designed to provide optimum results, the reducing agent will be in gaseous form (in order to facilitate rapid and efficient introduction into the molten metal composition) and will involve the following exemplary materials: hydrogen [$H_{2(g)}$], methane [$CH_{4(g)}$], acetylene [$C_2H_{2(g)}$], propane [$C_3H_{8(g)}$], or combinations of two or more of the above without limitation. Within this group of materials, hydrogen is preferred in accordance with its ability to significantly reduce the oxygen potential of the molten metal composition. With respect to the ability of hydrogen to function as an effective reducing agent in the present invention, the following chemical reactions occur when hydrogen is combined with the lead-containing molten metal composition:



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Regarding the overall quantity of the reducing agent to be employed in the claimed decontamination apparatus and method, the present invention shall not be restricted to any particular amount for this purpose. The exact quantity of the reducing agent to be used in a given application or situation is again determined in accordance with routine preliminary pilot tests taking into account numerous parameters including the overall size and capacity of the decontamination system 10, the amount of lead-containing molten metal composition being treated, and other related parameters. However, in a representative, preferred, and non-limiting embodiment designed to provide optimum results, the reducing agent (namely, one or more of the gaseous compositions listed above) will be used in an amount equal to about 0.1 - 10% by weight of the mass flow rate of the decontamination system 10. By way of example, if 100 lb./hour of lead-containing molten metal composition was flowing through the system 10, the addition of approximately 1 lb./hour of the chosen reducing agent would provide effective results. However, it should again be emphasized that the above-listed data (and the foregoing example) are representative only and, in this regard, the claimed invention shall not be limited to any particular quantities of reducing agent which may vary in accordance with a variety of parameters as outlined above.

It should likewise be recognized that, in a preferred embodiment, an excess amount of reducing agent should be used over and above the level which would theoretically be needed to prevent oxide layer formation. This approach should specifically be implemented as a “default” measure in order to be certain that the above-listed goal is effectively achieved.

Regarding the flow rate associated with the reducing agent, this may likewise be determined using routine preliminary pilot studies, with the claimed invention not being restricted in this regard. The particular flow rate to be selected should be sufficient to introduce the chosen amount of reducing agent into the decontamination system 10 over a desired time period, and
5 is therefore readily determined once the desired reducing agent quantity is selected (again taking into account system size and other related parameters). Furthermore and in view of the relatively high temperature of the lead-containing molten metal composition as it leaves the cooling system 14 (and the fairly large volumes thereof which are employed in most reactor applications), pre-heating of the supply 40 of reducing agent is typically not necessary (unless
10 otherwise indicated by routine preliminary tests).

It should likewise be noted that, in an alternative embodiment, solid particulate carbon [$C_{(s)}$] can be employed in connection with the supply 40 of reducing agent (although gaseous materials are again preferred for the reasons given above). Solid carbon compositions will function effectively in the claimed decontamination system 10, especially if temperatures
15 above about 600°C exist. This material would be physically combined (e.g. mixed) with the lead-containing molten metal composition preferably within conduit 20 (or at any point upstream or downstream therefrom in the same fashion as the gaseous reducing agents discussed above). Regarding the quantity of this material to be used, the amount thereof would again be determined by routine preliminary pilot tests taking a number of factors into
20 account including the overall size of the decontamination system 10, the metallurgical nature and content of the molten metal composition, and the like. While this alternative embodiment is not restricted to any particular amount of solid carbon reducing agent, a representative and non-limiting preferred quantity would involve an amount of solid carbon which would be sufficient to produce an exposed carbon surface area in the range of about 5 - 15% of the
25 cross-sectional flow area of the conduit 20 to ensure contact between the lead-containing

molten metal composition and the solid carbon reducing agent. Individuals skilled in the art will recognize that the internal flow configuration of the solid carbon reducing agent (if used) can be modified as needed and desired in order to enhance the contact between the solid carbon reducing agent and the lead-containing molten metal composition.

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V. The Decontamination Process

At this point, the decontamination process associated with the claimed invention will now be discussed in detail. With continued reference to Fig. 1, the supply 16 of the lead-containing molten metal composition is thereafter routed through the second end 30 of conduit 20 and into the containment vessel 24 via the opening 32 therein. Transfer of the molten metal composition will occur using the pump 22 or possibly other auxiliary or supplemental pumping devices (not shown), the need for which will be determined by the overall size and configuration of the decontamination system 10 under consideration. Likewise, transfer of the molten metal composition can take place using the differential pressure across the core of the reactor 12. The containment vessel 24 includes a side wall 62 which is produced from the materials discussed above (optimally a material which comprises at least some zirconium therein including but not limited to elemental zirconium, a zirconium-containing alloy, or combinations thereof).

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Once the lead-containing molten metal composition is present within the interior region 64 of the containment vessel 24, it comes in direct physical contact with at least one decontamination member 70 which will now be discussed in detail. The central location of the decontamination member 70 within the interior region 64 of the containment vessel 24 as illustrated in Fig. 1 (namely, in the direct flow path of the incoming lead-containing molten metal composition) ensures direct physical contact between the molten metal composition and the decontamination member 70. This process (which generally involves the intentional

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placement of the lead-containing molten metal composition in contact with the decontamination member 70) constitutes an important development which facilitates the effective removal of the inorganic contaminants (as defined above) from the molten metal composition.

5 The decontamination member 70 involves a structure of varying overall configuration which is separate and distinct from any other structures within the cooling system 14 and decontamination system 10. In particular, it is separate from the conduits, walls, vessels, and other components associated with the foregoing systems 10, 14 and is an independently-functioning structure. The decontamination member 70 again resides in a central location
10 within the interior region 64 of the containment vessel 24 and is surrounded by the side wall 62 thereof. It is particularly positioned within the flow path of the molten lead-containing composition which enters the interior region 64 of the containment vessel 24 so that the molten metal composition may directly contact the decontamination member 70.

 The decontamination member 70 can involve many different structural configurations,
15 shapes, sizes, surface areas, and the like without limitation. The present invention shall therefore not be limited to any particular dimensions, sizes, and designs in connection with the decontamination member 70. As long as the decontamination member 70 is present in some form (irrespective of size, shape, etc.), it will remove at least some of the inorganic contaminants from the lead-containing molten metal composition and will therefore
20 accomplish the goals of the present invention. The exact size, shape, and structural configuration of the decontamination member 70 will depend on the overall size and capacity of decontamination system 10 in general (and the amount of molten metal composition to be treated) which can be determined in accordance with routine preliminary pilot tests.

 With reference to Fig. 1, the particular decontamination member 70 shown therein is
25 comprised of an upper cap-like retaining structure 72 having secured thereto a plurality of

individual rod or plate-like elements 74. The elements 74 are produced from the particular materials that accomplish the actual decontamination of the molten metal composition as discussed extensively below. In accordance with Fig. 1, the elements 74 are elongate in character, arranged in an annular (e.g. circular) configuration, and are further retained in position using a bottom-mounted retaining structure 76. In the exemplary configuration presented in Fig. 1, the molten metal composition can flow around and between the elements 74 in order to achieve a maximum degree of contact therebetween. It should likewise be noted that, in a preferred embodiment, the elements 74 which are produced from the chosen decontamination material are readily removable from the system 10 once they become sufficiently "loaded" with contaminants that they are no longer operationally effective as discussed further below.

It should therefore be recognized that the structure set forth in Fig. 1 in connection with the decontamination member 70 constitutes a single representative example thereof, with a number of other structures and overall configurations being possible without limitation.

Likewise, the number of decontamination members 70 in the system 10 may vary from a single unit to multiple units in combination. These units may be elongate, spherical, round, square, or in any other configuration as determined in accordance with the overall configuration of the entire decontamination system 10 and its capacity (with a maximum degree of surface area being desired as a "default" condition). However and in general, removal of the inorganic contaminants from the lead-containing molten metal composition using the decontamination member 70 is dependent on the following variables: (1) temperature; (2) oxygen potential; (3) surface area; and (4) the types of materials associated with the decontamination member 70 and the lead-containing molten metal composition. The following mathematical correlation is provided in order to explain and otherwise quantify the degree of impurity removal relative to the physical characteristics of the decontamination

member 70 (e.g. size, shape, surface area, etc.) and may therefore be used to produce a decontamination member 70 having desired characteristics:

$$I = BmAe^{(RT/[PO_2]AL)}$$

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[I = Degree of contaminant removal (mass [kgs]/hour);

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B = A constant dependant on the substrate of the decontamination member 70 (1/meters²);

T = Temperature of the molten metal composition (K);

PO₂ = Partial pressure of oxygen [O₂] in the molten metal composition (atm or force/area);

R = Gas constant (joules/mole/K);

15

L = Length of the decontamination member 70 (meters);

A = Surface area of the decontamination member 70 (meters²);

m = mass flow rate of the lead-containing molten metal composition through the decontamination system 10 (kgs/hour); and

e = natural log].

20

The above-listed formula can generally be employed to determine the overall structural characteristics of the decontamination member 70 with particular reference to surface area and the like. However, it should again be recognized that routine preliminary pilot testing can likewise be employed to determine these characteristics (and other features thereof) without limitation. At this point, the materials which are used to produce the decontamination member 70 will be discussed in detail. As previously stated, the decontamination member 70 is produced from a composition that will allow the above-

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mentioned inorganic contaminants to diffuse into the decontamination member 70 (while allowing lead in the molten metal composition to remain unaffected so that it does not diffuse into the decontamination member 70 or otherwise react therewith). As previously stated, the term “diffuse” shall be construed in the broadest possible sense to involve: (1) entry of the

5 inorganic contaminants into and beneath the surface of decontamination member 70 to various depths without limitation; (2) interaction of the inorganic contaminants with the decontamination member 70 at the surface thereof without passing beneath the surface; and/or (3) a combination of [1] and [2] above. Irrespective of the manner in which diffusion occurs, the decontamination member 70 is again of a type that will have an affinity for the

10 inorganic contaminants of interest while avoiding an affinity for the various lead-containing materials (e.g. elemental lead, alloys, compounds, or complexes thereof) which are associated with the lead-containing molten metal composition. As a result, the inorganic contaminants can be removed in a selective manner from the lead-containing molten metal composition in order to effectively decontaminate it.

15 To accomplish the goals outlined above, the decontamination member 70 will be made from a material which comprises or otherwise contains at least some iron therein (e.g. elemental iron or iron-containing alloys, compounds, complexes, or combinations thereof). However, in a preferred and inventive embodiment designed to yield unexpectedly superior results, the decontamination member will be comprised entirely or partially of steel (namely,

20 an iron-based alloy). A number of different steel materials can be employed for this purpose without limitation including stainless steels (for example, both austenitic and ferritic stainless steels) and carbon-based steels. Representative steel compositions which can be used to produce the decontamination member 70 (for example, the elements 74 as shown in Fig. 1) are as follows:

1. "310-stainless steel" (with the approximate content of this material in % by weight being as follows: C = 0.25%; Cr = 26%; Mn = 2%; Ni = 22%; P = 0.045%; Si = 1.5%; and S = 0.03%, with the balance involving Fe).
2. "316L-stainless steel" (with the approximate content of this material in % by weight being as follows: C = 0.01%; Cr = 16.3%; Cu = 0.34%; Mn = 1.5%; Mo = 2.1%; Ni = 10.1%; and Si = 0.6%, with the balance involving Fe).
3. "410-stainless steel" (with the approximate content of this material in % by weight being as follows: Cr = 12.5%; Mn = 0.7%; and Si = 0.8%, with the balance involving Fe).
4. "F-22 carbon steel" (with the approximate content of this material in % by weight being as follows: C = 0.1%; Cr = 2.1%; Cu = 0.1%; Mn = 0.4%; and Mo = 0.9%, with the balance involving Fe).

It should again be noted that the steel materials recited above constitute representative examples which shall not restrict the invention in any respect since various other steel and iron-containing compositions can likewise be employed. For example, a wide variety of other steel materials may be used including but not limited to the group of austenitic stainless steels in the "300-series", the group of ferritic stainless steels in the "400-series", and "mild" carbon steels in general.

In accordance with the direct physical contact which is made between the lead-containing molten metal composition and the decontamination member 70, the inorganic contaminants recited above (and possibly others not expressly set forth herein) will diffuse into or onto (as previously defined) the decontamination member 70. As a result, the inorganic contaminants are effectively removed from the lead-containing molten metal composition while allowing lead materials within the molten metal composition to remain therein and not be removed (by diffusion into the decontamination member 70 or otherwise).

While the exact physical and chemical mechanisms associated with the decontamination process are not fully understood, it is theorized that a number of specialized reaction processes take place which will now be generally discussed with primary reference to arsenic-based impurities for example purposes.

5 Under normal or oxidizing conditions, the dissolution of oxygen into the iron-containing decontamination member 70 (e.g. made from steel or the like) forms a protective layer of metal oxide that prevents the dissolution of metals (e.g. iron, nickel, and/or chromium) from the decontamination member 70 into the lead-containing molten metal composition. This situation likewise prevents the above-listed inorganic contaminants from
10 being “exchanged” with the metals set forth above so that they can diffuse into the decontamination member 70. The oxide material discussed above primarily consists of spinelles of iron-chrome oxides with a magnetite layer on the surface of the decontamination member 70. A reducing environment (which may be induced by the addition of a reducing agent as discussed herein) removes these oxides, thereby allowing elements from the
15 decontamination member 70 (e.g. iron, nickel, and/or chromium) to diffuse and dissolve into the molten metal composition. As a result, inorganic contaminants (for example, arsenic) can diffuse into the surface of the decontamination member 70 as previously discussed and react with iron therein (which becomes more “available” in accordance with the diffusion of other materials such as chromium and nickel out of the member 70). Diffusion of the inorganic
20 contaminants into the decontamination member 70 in the manner described above forms metallic combinations (e.g. alloys) within the surface of the decontamination member 70. For example, elemental iron and arsenic react to form an iron-arsenic [Fe-As] alloy (e.g. iron arsenide). It should also be noted that iron from the decontamination member 70 likewise diffuses into the lead-containing molten metal composition, but at a much lower level than,
25 for example, nickel and chromium which are typical elements that reside within steel-based

decontamination members 70 of the type discussed above. This situation occurs in accordance with the much lower solubility of iron in the molten metal composition compared with, for instance, chromium and nickel. Specifically and for general information purposes, the solubility limit for iron in molten lead is approximately 1 ppm at 500°C. In contrast, 5 solubility limits for arsenic, nickel, and chromium in molten lead are approximately 31,000 ppm, 32,000 ppm, and 16 ppm, respectively.

The high temperature of the lead-containing molten metal composition (with particular but not necessarily exclusive reference to the preferred operating temperature range listed below) serves to anneal the decontamination member 70. It is theorized that iron 10 migrates during these elevated temperatures, especially within gaps in the crystalline structure of the decontamination member 70 caused by the dissolution of other components from the member 70 (including chromium, nickel, and/or possibly other elements). Arsenic, when present as an inorganic contaminant in the lead-containing molten metal composition, has a lower mobility compared with iron, thereby allowing a layer of iron-arsenide to be formed at 15 the surface of the steel-based decontamination member 70 as the iron migrates to the surface and becomes exposed to the slowly, inwardly-diffusing contaminants (e.g. arsenic in this example). The relative purity of the resulting iron-arsenide layer decreases as the distance from the surface of the decontamination member 70 increases. This situation is caused by the diminished migration of, for example, chromium and/or nickel from the decontamination 20 member 70 as the distance from the surface increases. At these levels (e.g. depths), materials such as nickel and chromium are unable to exchange positions with the contaminants (for example, arsenic). This situation generally reduces the purity of the resulting alloys (e.g. iron-arsenide) as the distance from the surface of the decontamination member 70 increases. It should also be noted that cracks will typically form in the structures associated with the 25 newly-formed contaminant-based layers in the decontamination member 70 (iron-arsenide in

the present example). Cracks form for many reasons including the relatively high activity of the layer-creation mechanism, tensile layer-substrate stresses caused by lattice mismatches, high thermal stress gradients which result from rapid cooling (at the point at which cooling is permitted to occur), and the preparation process that is typically associated with analysis of the decontamination member 70 using scanning electron microscope ("SEM") techniques and the like. Furthermore, the thickness of the resulting layer which occurs when contaminants diffuse into the decontamination member 70 is expected to increase as the time-of-contact between the molten metal composition and the decontamination member 70 increases, and will likewise increase when higher temperatures are employed.

10 In a representative decontamination system 10 which employs, for example, (1) a decontamination member 70 that is made from 316L, 410, or F-22 steel materials; and (2) a lead-containing molten metal composition of the type discussed above which includes arsenic and antimony as inorganic contaminants, the following layer (e.g. film) structures are typically produced in connection with the member 70: [A] a first (e.g. outermost) layer which
15 approaches the stoichiometric composition of iron-arsenide [Fe-As]; and [B] a second (e.g. inner) layer which involves a mixture (e.g. alloy) of iron, arsenic, antimony, and lead [Fe-As-Sb-Pb]. It is believed that these layers result in accordance with the migration of chromium and/or nickel from the decontamination member 70 into the lead-containing molten metal composition, thereby allowing the contaminants (e.g. arsenic) to come in contact with
20 exposed iron as previously discussed. As chromium and/or nickel continue to diffuse from the decontamination member 70 into the molten metal composition, an "exchange" occurs in connection with the arsenic, thereby permitting it to diffuse (along with antimony and possibly other contaminants) into the member 70. With particular reference to arsenic (which is of primary concern in this example), the resulting iron-arsenide layer or layers in the
25 decontamination member 70 are characterized by reduced levels of chromium and/or nickel

compared with the quantities of these materials that were initially present in the member 70.

In the above-listed example, the diffusion/ decontamination process produces a relatively pure layer (e.g. film) of iron-arsenide at the surface of the decontamination member 70, with the purity of this material again decreasing as the distance from the surface of the member 70 increases (characterized by inner layers of iron-arsenic-antimony-lead as previously indicated). However, it should also be recognized that, notwithstanding the formation of these layers, there is negligible dimensional change in the decontamination member 70 in most cases. Structural defects in the foregoing layers are normally attributed to the relatively favorable production of these layers from a chemical and physical standpoint and the fact that a "pure" iron (e.g. iron-only) decontamination member 70 is not being used. As indicated earlier in the current discussion, a highly reducing environment (produced, for example, through the combination of at least one reducing agent with the lead-containing molten metal composition) is beneficial in the production of an iron-contaminant layer (for example, iron-arsenide) on the steel-based decontamination member 70. Such a reducing environment will typically involve an oxygen partial pressure of about 10 - 40 atm in a representative embodiment. In contrast and when oxidizing conditions are present, there is a higher chemical affinity of various components in the steel (e.g. iron, chromium, and/or nickel) to oxygen compared with lead. This situation typically results in surface passivation that prevents the "exchange" of inorganic contaminants (e.g. arsenic and antimony) into the steel associated with the decontamination member 70. Thus, as a "default" condition in the present invention, the introduction of a reducing agent into the lead-containing molten metal composition should be employed unless special reaction conditions exist which would dictate otherwise.

It should again be recognized that the description of the reaction mechanisms set forth above represents a current understanding of the manner in which they function to achieve

decontamination of the lead-containing molten metal composition. In this regard, the explanations presented herein concerning these mechanisms shall not limit or otherwise restrict the invention in any manner and are being presented for information purposes only.

It should likewise be noted that, in a representative embodiment designed to provide optimum results, the decontamination system 10 (preferably the containment vessel 24) will include at least one heater 80 associated therewith as schematically illustrated in Fig. 1. The heater 80 may involve a number of different types, structures, and configurations without limitation including but not limited to those that employ at least one or more electric resistive heating elements, as well as heating systems powered by other fuel sources including natural gas, and the like. Furthermore, the claimed invention shall not be restricted to any particular locations in connection with the heater 80 which may be placed at any position on or within the decontamination system 10 provided that the desired degree of heat is imparted to the lead-containing molten metal composition as discussed further below. In a representative and non-limiting embodiment, the heater 80 (optimally comprising at least one or more electrically resistive elements) will at least partially surround the exterior surface 82 of the side wall 62 associated with the containment vessel 24 as schematically illustrated in Fig. 1. Alternatively, an internal heating system can be provided within the containment vessel 24. For example, one or more laminate layers of graphite (not shown) can be provided on at least a portion of the decontamination member 70. Heat is then applied using a chosen heating source (e.g. an induction coil) positioned outside of the containment vessel 24. The graphite then becomes inductively heated (in accordance with its favorable thermal susception characteristics) which, in turn, heats the decontamination member 70.

It should therefore be understood that: (1) many different type of systems and components may be used in connection with the heater 80; and (2) the heater 80 can be positioned in a variety of locations. Furthermore, use of the heater 80 should be considered

“optional” in that the additional heat generated by the heater 80 may not be necessary depending on a variety of factors as determined by routine preliminary pilot testing (including the overall size associated with the decontamination system 10, the temperature of the incoming molten metal composition, and other related factors). Nonetheless, the use of at least one heater 80 should be considered preferred and employed as a “default” component in the claimed decontamination system 10 unless operating conditions specifically indicate otherwise.

Regarding the temperatures to be maintained during decontamination of the lead-containing molten metal composition using the decontamination member 70, the claimed invention shall not be restricted to any particular values. However, in a preferred embodiment designed to obtain optimum results, the molten metal composition will be maintained at a temperature of about 400 - 600°C during contact thereof with the decontamination member 70. This temperature level is designed to promote favorable reaction kinetics and maximum operating efficiency. The temperature conditions set forth above may be maintained and otherwise achieved using the heater 80 as previously described or, alternatively, the molten metal composition will have a temperature within the foregoing range as a natural consequence of the heat transfer process which occurs in the cooling system 14. Thus, a number of different approaches may be employed in order to achieve the preferred temperature characteristics recited above without limitation. Likewise, in certain circumstances, different (e.g. higher or lower) temperatures may be desired which would be determined on a case-by-case basis using routine preliminary pilot tests taking into account a number of factors including the quantity of lead-containing molten metal composition being treated, the nature and chemical make-up of the composition, the type and configuration of the decontamination system 10, and other factors.

Regarding the "residence time" in the claimed decontamination system 10 (namely, the amount of time during which the lead-containing molten metal composition is maintained in direct physical contact with the decontamination member 70), this time period may be varied as needed and desired. In particular, it may be determined in accordance with routine preliminary pilot tests taking into account the particular size, surface area, and configuration of the decontamination member 70, the compositional characteristics of the molten metal composition, and other related factors. Accordingly, the claimed invention shall not be restricted to any particular residence time parameters. However, it should be generally understood that the overall residence time as defined herein is a function of temperature and the oxygen potential of the molten metal composition. For example purposes, TABLE II below provides some representative and non-limiting estimated residence times for a decontamination member 70 made from any of the specific steel compositions recited above. The decontamination member 70 associated with the data in TABLE II will have a single elongate bar-like configuration that is approximately 1 meter long with a surface area of about 1000 cm² (wherein a primary goal is to remove arsenic as a contaminant):

TABLE II

<u>Molten Metal</u>	<u>O₂ Potential</u>	<u>Temp.</u>	<u>Residence Time</u>
Pb	10 ⁻²⁰ to 10 ⁻⁴⁰ atm	400 - 600°C	2 min. to 20 hr.
Pb-Bi	10 ⁻²⁰ to 10 ⁻⁴⁰ atm	400 - 600°C	1 min. to 10 hr.

Again, the values recited above are provided for example purposes only and shall not limit the invention in any respect.

Finally and in an exemplary embodiment designed to achieve optimum decontamination efficiency, the decontamination member 70 should be of a type that is readily removable from the system when it becomes saturated (e.g. "loaded") with the inorganic contaminants to a point where it is of diminished operational effectiveness. As to when this point is reached will vary depending on many factors including but not limited to the overall size, surface area, and shape of the decontamination member 70, the level of contamination within the lead-containing molten metal composition, and other related factors.

One method for deciding when to remove the decontamination member 70 from the system 10 would be to conduct analytical tests on the member 70 which would generally involve a periodic analysis of the member 70 during system operation using SEM analysis and other related techniques. These tests (and possibly others as discussed below) could then be used to determine the amount of time that it takes for the decontamination member 70 to become unable to form any additional layers (through diffusion and the like) of the desired contaminants therein. Once this time period is determined for a given type and quantity of the molten metal composition and decontamination member 70, it may then be applied as a "standard" for subsequent use in the decontamination of additional quantities of the molten metal composition. Alternatively, other methods for determining when the decontamination member 70 is fully "loaded" with contaminants include diffraction pressure measurements across the member 70, ultrasonic probe tests, resistive measurements, and the like.

In any event, the claimed invention shall not be restricted to any particular methods or time intervals in connection with the saturation and removal of the decontamination member 70 from the system 10, with a number of different options being available.

VI. Other Features and Sub-Systems

Having discussed the basic operational capabilities of the decontamination member 70 and other parameters of the decontamination system 10, some additional features thereof will now be discussed. While these additional items should be considered “optional” and not mandatory in all cases (as determined by routine preliminary pilot investigations), it is preferred that they be employed as “default” measures in the methods and systems of the present invention in order to achieve maximum operating efficiency. First and with reference to Fig. 1, the side wall 62 of the containment vessel 24 includes at least one main or primary outlet port 90 therein for passage of the decontaminated lead-containing molten metal composition as discussed further below. Furthermore and in a preferred embodiment, the side wall 62 of the containment vessel 24 will likewise include at least one additional or secondary outlet port 92 therein, the function of which will now be discussed.

Should a reducing agent be used in the decontamination system 10 and if the molten metal composition contains excess (e.g. unreacted) quantities of the reducing agent therein after contact between the molten metal composition and the decontamination member 70, it is usually desirable to remove this excess reducing agent from the molten metal composition and containment vessel 24. This is particularly important when the gaseous reducing agents listed above are employed, with the current discussion being primarily directed to these particular reducing agents. In most cases (namely, as a “default” condition), excess gaseous reducing agents will be used in the claimed process for the reasons given above (e.g. to ensure complete, continuous, and maximum operational efficiency and to likewise avoid the oxidation problems discussed herein). Typically, the excess/residual reducing agent will involve about 1 - 5% more than is consumed or otherwise needed in the process. Removal of the excess reducing agent is particularly desired since, if allowed to remain in the lead-containing molten metal composition, it can contribute to additional corrosion of the cooling

system 14 once the decontaminated molten metal composition is recycled back into the cooling system 14 for reuse. Furthermore, removal, recovery, and reuse of the excess reducing agent can significantly improve the overall cost-efficiency and economic performance of the entire decontamination process.

5 To accomplish the removal (and recovery if desired) of the excess gaseous reducing agent, it is preferred that the decontamination system 10 (with particular reference to the containment vessel 24) be configured and operated so that an open region 94 exists above the supply 16 of molten metal composition. As a result, an exposed (e.g. top) surface 96 associated with the molten metal composition exists within the interior region 64 of the

10 containment vessel 24. This exposed surface 96 represents an “interface” between the molten metal composition and the open region 94. In accordance with the particular chemical and physical nature of the gaseous reducing agents discussed above, the limited solubility thereof in the molten metal composition, and the high temperature conditions within the containment vessel 24, the unreacted (e.g. excess/residual) quantities of reducing agent will spontaneously

15 diffuse out of the molten metal composition and reside (in gaseous form) in the open region 94. In order to remove this material from the containment vessel 24 (for reuse or otherwise), the vessel 24 will include the outlet port 92 through the upper wall 100 which optimally resides at the top of the vessel 24. Operatively connected to the outlet port 92 is the first end 102 of a conduit 104 which, in a representative embodiment, will contain an in-line vacuum

20 pump 106 of conventional design (or other comparable device) which will draw the excess reducing agent out of the containment vessel 24 and through the conduit 104. The conduit 104 will have a second end 110 that is operatively connected to an opening 112 in a storage vessel 114 which can be used to retain the excess (e.g. withdrawn) reducing agent therein (shown at reference number 115 in Fig. 1). This reducing agent may then be used for any

25 purpose, discarded, or (optimally) recycled back into the decontamination system 10 for

reuse.

With continued reference to Fig. 1, the storage vessel 114 preferably has an additional opening 116 therein which is operatively connected to the first end 120 of a conduit 122 which, in a representative embodiment, will have another in-line vacuum pump 124 of conventional design (or other comparable device) therein. The conduit 122 further includes a second end 126 that is operatively connected to an opening 130 within the storage vessel 42 which contained the initial supply 40 of the reducing agent. In this manner, effective recycling of the reducing agent can occur in order to achieve the significant benefits listed above.

It should be recognized that the reducing agent removal sub-system discussed herein and shown schematically in Fig. 1 is being presented for example purposes only and shall not limit the invention in any respect. Instead, a variety of different components, conduits, and other structures may be used to remove excess (e.g. residual) quantities of the reducing agent from the molten metal composition and the containment vessel 24. Nonetheless, the methods and procedures outlined above represent a viable and practical approach by which the removal of excess/residual quantities of reducing agent from the molten metal composition and the containment vessel 24 can occur.

It should also be noted that at least some residual water (e.g. in the form of steam - not shown) may be generated and spontaneously released from the molten metal composition in accordance with the decontamination procedures discussed herein. This water may be eliminated from the containment vessel 24 in a number of different ways without limitation. For example, it is possible that the water (e.g. steam) can be withdrawn along with the excess reducing agent discussed above (e.g. using the same components and techniques) so that it is routed through the conduit 104 into the storage vessel 114. The storage vessel 114 would then include a water trap/separatory system of conventional design (not shown) that could be

used to collect water from the materials in the vessel 114. Again, however, a number of different techniques and components can be used to accomplish water removal from the containment vessel 24 without limitation, with the techniques outlined above being representative only. It should also be noted that, while the removal of water from the molten metal composition and the containment vessel 24 may be considered "optional" in nature, it is preferably employed as a "default" procedure unless countervailing circumstances indicate otherwise. Water removal is generally considered to be desirable so that the overall oxygen potential in the decontamination and cooling systems 10, 14 is not adversely affected.

Finally and as previously discussed, placement of the molten metal composition in contact with the decontamination member 70 will typically cause at least one iron-containing contaminant to be introduced into the molten metal composition. The iron-containing contaminant can involve, for instance, elemental iron and iron-containing alloys, compounds, complexes, or combinations thereof without limitation. In a preferred embodiment, a process step will be initiated in which at least some of the iron-containing contaminants will be removed from the lead-containing molten metal composition after decontamination. While this step (and the components associated therewith) should nonetheless be considered "optional" (with the need thereof ultimately being determined by routine preliminary pilot studies), it should be implemented as a "default" procedure unless compelling reasons exist to do otherwise.

Many different methods and techniques can be employed in order to remove the iron-containing contaminant materials from the molten metal composition without limitation. Since the majority of these materials will be in the form of solid particulate compositions, a representative removal method and apparatus will involve the use of one or more magnetic iron trap systems which will now be explained in greater depth. With reference to Fig. 1, an exemplary and non-limiting iron trap 140 is schematically illustrated (with a number of other

configurations and types also being possible). The iron trap 140 involves a tubular member 142 having a first end 144 and a second end 146, with the tubular member 142 optimally being designed so that it is readily removable from the decontamination system 10. The first end 144 in the embodiment of Fig. 1 is operatively connected to the main outlet port 90 in the side wall 62 of the containment vessel 24. Furthermore, the tubular member 142 may include a pump 150 associated therewith of conventional design (e.g. the same type as pump 22 or otherwise). As a result, the decontaminated lead-containing molten metal composition can readily pass from the interior region 64 of the containment vessel 24 into the tubular member 142 associated with the iron trap 140.

10 The tubular member 142 will preferably be produced from an iron-containing composition (e.g. an iron alloy including but not limited to stainless steel) and will have at least one magnet 152 preferably located on the exterior surface 154 of the tubular member 142. A single magnet 152 can be used as shown in Fig. 1 or multiple magnetic elements can instead be employed (not shown) without limitation. Likewise, the size, shape, capacity, and other characteristics of the tubular member 142, the magnet 152, and the iron trap 140 in general can be varied as needed and desired in accordance with routine preliminary pilot testing and shall not restrict the invention in any respect.

 Regarding the magnet 152, preferred and non-limiting magnetic strength values associated therewith will be about 0.1 - 10 gauss. As the molten metal composition enters the interior region 156 of the tubular member 142, the magnetic field generated by the magnet 152 will cause the solid iron-containing contaminants in the molten metal composition to be drawn out of the composition and become magnetically adhered to the interior surface 160 of the tubular member 142. In this manner, the iron-containing contaminants are effectively removed from the molten metal composition in a rapid and efficient manner. It should be understood that removal of the iron-containing contaminant materials from the molten metal

composition is desirable as a “default” procedure for various reasons. For example, if the iron-containing contaminants are not removed from the molten metal composition, they can precipitate within lower-temperature regions of the cooling system 14 when the molten metal composition is recirculated for use therein. This precipitation process can, in fact, cause
5 significant flow restrictions in the cooling system 14 and substantially degrade its performance.

As needed and desired, the tubular member 142 associated with the iron trap 140 can be removed for cleaning or replacement at any desired interval. One method for determining when to remove the tubular member 142 from the decontamination system 10 would be to
10 conduct pilot tests on the member 142 which would involve a periodic analysis of the member 142 during system operation using manual inspection techniques, flow pressure measurements, and other related procedures. These techniques could then be used to determine when the interior surface 160 of the tubular member 142 has become sufficiently “loaded” with iron-containing contaminants to no longer be optimally effective. Once this
15 time period is determined for a given type and quantity of the molten metal composition, it may then be applied as a “standard” for subsequent use in the overall operation of the iron trap 140. Regarding flow pressure measurements, these measurements will generally involve a determination of the pressure levels of the molten metal composition moving through the tubular member 142, with diminished pressure levels indicating that the tubular member 142
20 has become sufficiently “loaded” to warrant its replacement or cleaning. It should also be noted that, aside from the approach outlined above, an on-line “real-time” flow pressure measurement system of a type which is conventional and known in the art may be used in connection with the tubular member 142. Once the flow pressure in the tubular member 142 decreases to a predetermined level, the member 142 can be removed from the
25 decontamination system 10 for replacement or cleaning. It shall therefore be understood that

a number of different methods and components may be used to monitor the activity of the iron trap 140 without limitation.

In the exemplary embodiment of Fig. 1, the second end 146 of the tubular member 142 associated with the iron trap 140 is operatively connected to the first end 162 of a conduit 164 which includes, for example, an in-line pump 166 of conventional design therein (e.g. of the same type as pump 22 or otherwise). The second end 170 of the conduit 164 is operatively connected to the cooling system 14 so that the decontaminated lead-containing molten metal composition may be transferred through the conduit 164 (using, for example, pump 166) for delivery into cooling system 14 to be reused therein as desired.

As previously stated, the claimed invention provides many key benefits in a simultaneous fashion. In particular, it is able to effectively and economically decontaminate a wide variety of lead-containing molten metal compositions and can likewise remove a significant number of metallic and non-metallic contaminants with a high level of efficiency. For example, it is expected that implementation of the claimed invention using the processes and equipment discussed above can remove a given contaminant (e.g. arsenic, antimony, etc.) down to 10 ppm levels or below depending on the manner in which the overall process is implemented, the particular materials being decontaminated, and the like. Accordingly, the present invention is capable of a significant level of decontamination and, in this regard, can provide the benefits listed above. These benefits again include, without limitation: (1) the ability to remove inorganic compositions (particularly arsenic, antimony, tin, and tellurium) in a highly efficient manner from lead-containing molten metal compositions; (2) rapid and highly effective decontamination rates; (3) the implementation of an efficient decontamination process using a minimal amount of operating equipment and materials; (4) the ability to remove contaminants without the need to employ hazardous, caustic, or expensive chemical reagents; (5) a high level of versatility with particular reference to the

types of lead-containing molten metal compositions which can be treated; (6) improved decontamination efficiency resulting from the ability of the system to operate in a substantially continuous fashion; (7) compatibility with a considerable number of heat generating devices including but not limited to a wide variety of nuclear power generating systems, accelerator-driven radioactive waste transmutators, and the like which employ lead-containing molten metal compositions as coolants; (8) the ability to achieve decontamination without requiring highly oxidizing conditions (which avoids the problems associated therewith as discussed above); (9) a considerable degree of versatility regarding the types of contaminants which may be removed from the lead-containing molten metal compositions; (10) the overall implementation of a procedure which is cost effective, readily controllable (e.g. customizable on-demand to various cooling systems and devices), easily scaled up or down as needed, and capable of rapid integration into the cooling systems of interest; (11) the capacity to decontaminate lead-containing molten metal compositions in a manner whereby destructive corrosion of the cooling systems is eliminated, thereby avoiding excessive maintenance requirements, system failures, and other operational problems; and (12) an accomplishment of the above-listed goals in a manner which is superior to prior decontamination techniques and represents a considerable advance in molten metal processing technology.

Having set forth herein preferred embodiments of the invention, it is anticipated that various modifications may be made thereto by individuals skilled in the relevant art to which this invention pertains which nonetheless remain within the scope of the invention. For example, the invention shall not be limited to any particular equipment, operating components, reactant types and quantities, contaminants to be removed, lead-containing molten metal composition types and quantities, operating conditions and parameters, decontamination system sizes and capacities, and other related items unless otherwise

expressly stated herein. The present invention shall therefore only be construed in accordance with the following claims:

THE INVENTION THAT IS CLAIMED IS:

1. A method for decontaminating a molten metal composition comprising:
providing a supply of a molten metal composition comprising lead therein, said molten metal composition further comprising at least one inorganic contaminant in said composition;
placing said molten metal composition in contact with at least one decontamination member that will allow said inorganic contaminant to diffuse into said decontamination member, said decontamination member comprising iron therein; and
allowing said inorganic contaminant to diffuse into said decontamination member for removal thereof from said molten metal composition.
2. The method of Claim 1 wherein said molten metal composition is comprised of a material selected from the group consisting of elemental lead, a lead-containing alloy, and combinations thereof.
3. The method of Claim 2 wherein said lead-containing alloy comprises a lead-bismuth alloy.
4. The method of Claim 1 wherein said inorganic contaminant is comprised of a material selected from the group consisting of arsenic, tin, antimony, tellurium, and combinations thereof.
5. The method of Claim 1 wherein said decontamination member is comprised of an iron-containing alloy.

6. The method of Claim 5 wherein said iron-containing alloy comprises steel.

7. The method of Claim 1 further comprising maintaining said molten metal composition at a temperature of about 400 - 600°C during said placing of said molten metal composition in contact with said decontamination member.

8. The method of Claim 1 wherein said placing of said molten metal composition in contact with said decontamination member causes at least one iron-containing contaminant to be introduced into said molten metal composition, said method further comprising removing at least some of said iron-containing contaminant from said molten metal composition.

9. The method of Claim 8 wherein said removing of said iron-containing contaminant from said molten metal composition comprises placing said molten metal composition having said iron-containing contaminant therein within a magnetic field in order to draw said iron-containing contaminant out of said molten metal composition.

10. A method for decontaminating a molten metal composition comprising:
providing a supply of a molten metal composition comprising lead therein, said molten metal composition further comprising at least one inorganic contaminant in said composition;

introducing at least one reducing agent into said molten metal composition;

placing said molten metal composition in contact with at least one decontamination member that will allow said inorganic contaminant to diffuse into said decontamination member, said decontamination member comprising iron therein; and

allowing said inorganic contaminant to diffuse into said decontamination member for removal thereof from said molten metal composition.

11. The method of Claim 10 wherein said molten metal composition is comprised of a material selected from the group consisting of elemental lead, a lead-containing alloy, and combinations thereof.

12. The method of Claim 10 wherein said reducing agent is comprised of a material selected from the group consisting of $C_{(s)}$, $H_{2(g)}$, $CH_{4(g)}$, $C_2H_{2(g)}$, $C_3H_{8(g)}$, and combinations thereof.

13. The method of Claim 10 wherein, after said placing of said molten metal composition in contact with said decontamination member, said molten metal composition comprises at least some of said reducing agent therein which remains in an unreacted state, said method further comprising removing at least some of said reducing agent in said unreacted state from said molten metal composition.

14. The method of Claim 13 wherein said placing of said molten metal composition in contact with said decontamination member causes at least one iron-containing contaminant to be introduced into said molten metal composition, said method further comprising removing at least some of said iron-containing contaminant from said molten metal composition.

15. A method for decontaminating a molten metal composition comprising:
providing a supply of a molten metal composition comprised of a material selected from the group consisting of elemental lead, a lead-bismuth alloy, and combinations thereof,

said molten metal composition further comprising at least one inorganic contaminant therein, said inorganic contaminant comprising a material selected from the group consisting of arsenic, tin, antimony, tellurium, and combinations thereof;

introducing at least one reducing agent into said molten metal composition, said reducing agent comprising a material selected from the group consisting of $C_{(s)}$, $H_{2(g)}$, $CH_{4(g)}$, $C_2H_{2(g)}$, $C_3H_{8(g)}$, and combinations thereof;

placing said molten metal composition in contact with at least one decontamination member that will allow said inorganic contaminant to diffuse into said decontamination member, said decontamination member being comprised of steel;

allowing said inorganic contaminant to diffuse into said decontamination member for removal thereof from said molten metal composition, said placing of said molten metal composition in contact with said decontamination member further causing at least one iron-containing contaminant to be introduced into said molten metal composition, said molten metal composition further comprising at least some of said reducing agent therein which remains in an unreacted state within said molten metal composition after said placing of said molten metal composition in contact with said decontamination member;

removing at least some of said reducing agent in said unreacted state from said molten metal composition; and

removing at least some of said iron-containing contaminant from said molten metal composition.

16. An apparatus for decontaminating a molten metal composition comprising:
a supply of a molten metal composition comprising lead therein, said molten metal composition further comprising at least one inorganic contaminant in said composition; and
a containment vessel in fluid communication with said supply of said molten metal

composition so that said molten metal composition can enter into said containment vessel, said containment vessel comprising:

at least one decontamination member therein that will allow said inorganic contaminant to diffuse into said decontamination member when said molten metal composition comes in contact with said decontamination member so that said contaminant can be removed from said molten metal composition, said decontamination member comprising iron therein; and

at least one outlet port in said containment vessel for passage of said molten metal composition out of said containment vessel after said composition comes in contact with said decontamination member.

17. The apparatus of Claim 16 further comprising at least one heater which is used to provide heat to said molten metal composition.

18. The apparatus of Claim 16 wherein said molten metal composition is comprised of a material selected from the group consisting of elemental lead, a lead-containing alloy, and combinations thereof.

19. The apparatus of Claim 18 wherein said lead-containing alloy comprises a lead-bismuth alloy.

20. The apparatus of Claim 16 wherein said inorganic contaminant is comprised of a material selected from the group consisting of arsenic, tin, antimony, tellurium, and combinations thereof.

21. The apparatus of Claim 16 wherein said containment vessel is produced from a composition which comprises zirconium therein.

22. The apparatus of Claim 16 further comprising at least one iron trap which receives said molten metal composition after contact thereof with said decontamination member.

23. The apparatus of Claim 22 wherein said iron trap comprises at least one magnet.

24. An apparatus for decontaminating a molten metal composition comprising:
a supply of a molten metal composition comprising lead therein, said molten metal composition further comprising at least one inorganic contaminant in said composition;
a supply of at least one reducing agent which is in fluid communication with said supply of said molten metal composition so that said reducing agent can be introduced into said molten metal composition; and

a containment vessel in fluid communication with said supply of said molten metal composition so that said molten metal composition can enter into said containment vessel, said containment vessel comprising:

at least one decontamination member therein that will allow said inorganic contaminant to diffuse into said decontamination member when said molten metal composition comes in contact with said decontamination member so that said contaminant can be removed from said molten metal composition, said decontamination member comprising iron therein; and

at least one outlet port in said containment vessel for passage of said

molten metal composition out of said containment vessel after said composition comes in contact with said decontamination member.

25. The apparatus of Claim 24 wherein said containment vessel further comprises at least one additional outlet port therein for passage of unreacted quantities of said reducing agent out of said containment vessel.

26. The apparatus of Claim 25 further comprising at least one iron trap which receives said molten metal composition after contact thereof with said decontamination member.

27. An apparatus for decontaminating a molten metal composition comprising:
a supply of a molten metal composition comprised of a material selected from the group consisting of elemental lead, a lead-bismuth alloy, and combinations thereof, said molten metal composition further comprising at least one inorganic contaminant therein, said inorganic contaminant comprising a material selected from the group consisting of arsenic, tin, antimony, tellurium, and combinations thereof;

a supply of at least one reducing agent which is in fluid communication with said supply of said molten metal composition so that said reducing agent can be introduced into said molten metal composition, said reducing agent comprising a material selected from the group consisting of $C_{(s)}$, $H_{2(g)}$, $CH_{4(g)}$, $C_2H_{2(g)}$, $C_3H_{8(g)}$, and combinations thereof;

a containment vessel in fluid communication with said supply of said molten metal composition so that said molten metal composition can enter into said containment vessel, said containment vessel comprising:

at least one decontamination member therein that will allow said

inorganic contaminant to diffuse into said decontamination member when said molten metal composition comes in contact with said decontamination member so that said contaminant can be removed from said molten metal composition, said decontamination member being comprised of steel;

at least one outlet port in said containment vessel for passage of said molten metal composition out of said containment vessel after said composition comes in contact with said decontamination member; and

at least one additional outlet port in said containment vessel for passage of unreacted quantities of said reducing agent out of said containment vessel; and

at least one iron trap which receives said molten metal composition after contact thereof with said decontamination member, said iron trap comprising at least one magnet.

28. The apparatus of Claim 27 further comprising at least one heater which is used to provide heat to said molten metal composition.

29. The apparatus of Claim 27 wherein said containment vessel is produced from a composition which comprises zirconium therein.

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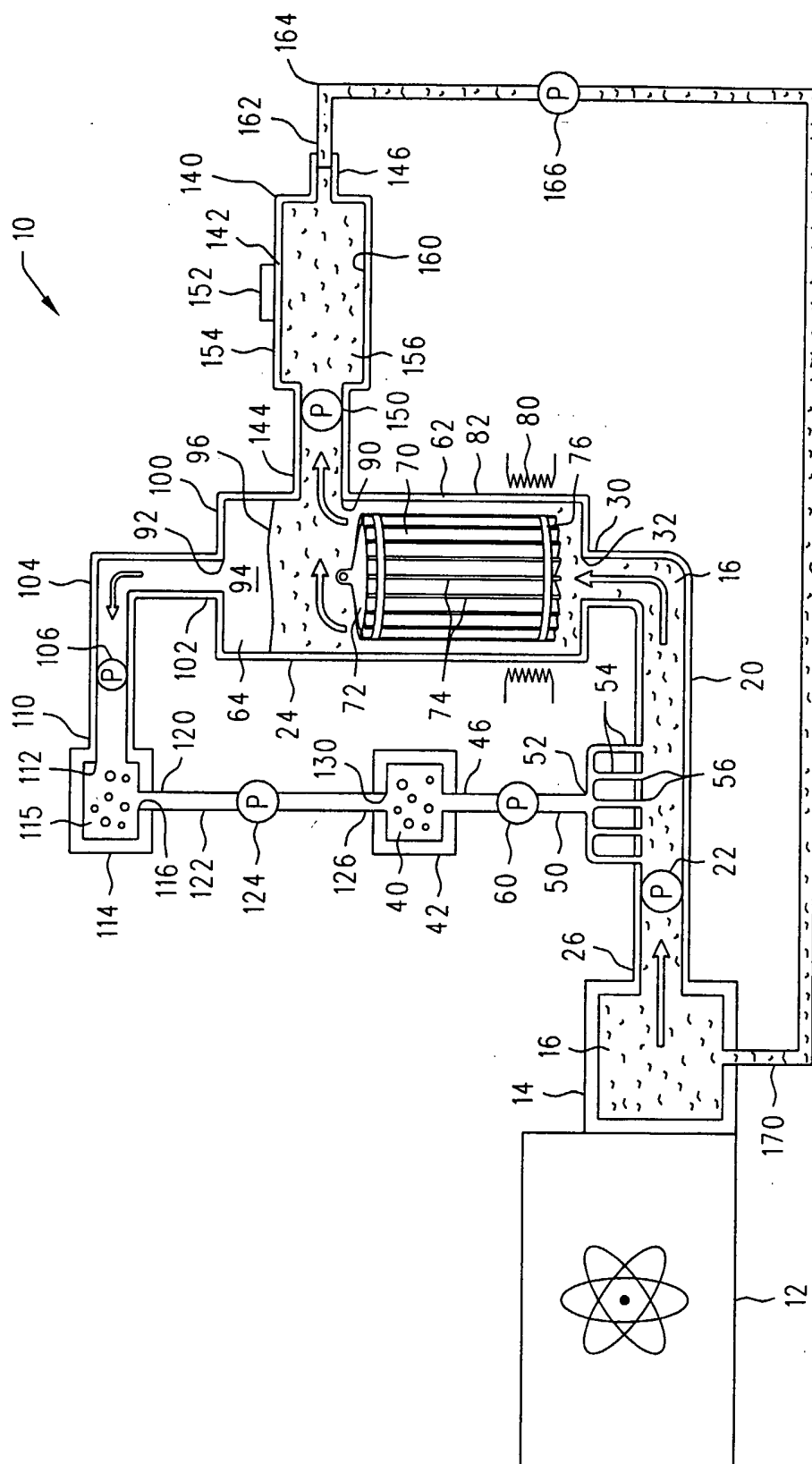


FIG. 1