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Singh

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(54) **CONTAINER AND SYSTEM FOR HANDLING DAMAGED NUCLEAR FUEL, AND METHOD OF MAKING THE SAME**

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(73) Assignee: **Holtec International**

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G21F 5/012 (2006.01)
G21C 19/26 (2006.01)

(52) **U.S. Cl.**

CPC ***G21F 5/008*** (2013.01); *G21C 19/26* (2013.01); *G21F 5/012* (2013.01)

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CPC G21F 5/008; G21F 5/012

(Continued)

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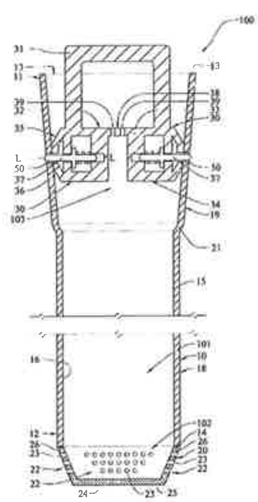
(57) **ABSTRACT**

A container and system for handling damaged nuclear fuel, and a method of making the same. In one embodiment, the invention is a damaged fuel container having a specially designed top cap that can be detachably coupled to the elongated tubular wall by simply translating the top cap into proper position within, the elongated tubular wall, wherein biased locking elements automatically lock the top cap to the elongated tubular wall. In another embodiment, the vent screens of the damaged fuel container are integrally formed rather than being separate components. In still other embodiments, the lower vent screens are arranged on an upstanding portion of the damaged fuel container. In an even further embodiment, the elongated tubular wall is formed by an extrusion process.

15 Claims, 12 Drawing Sheets



(58) **Field of Classification Search**
USPC 376/272, 285, 313; 250/507.1
See application file for complete search history.

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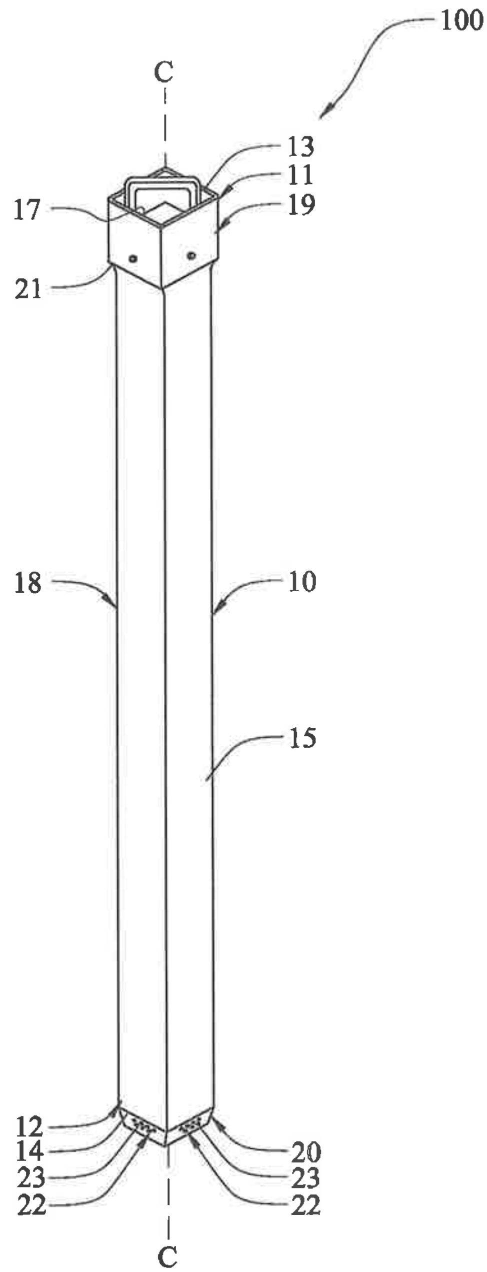

FIGURE 1

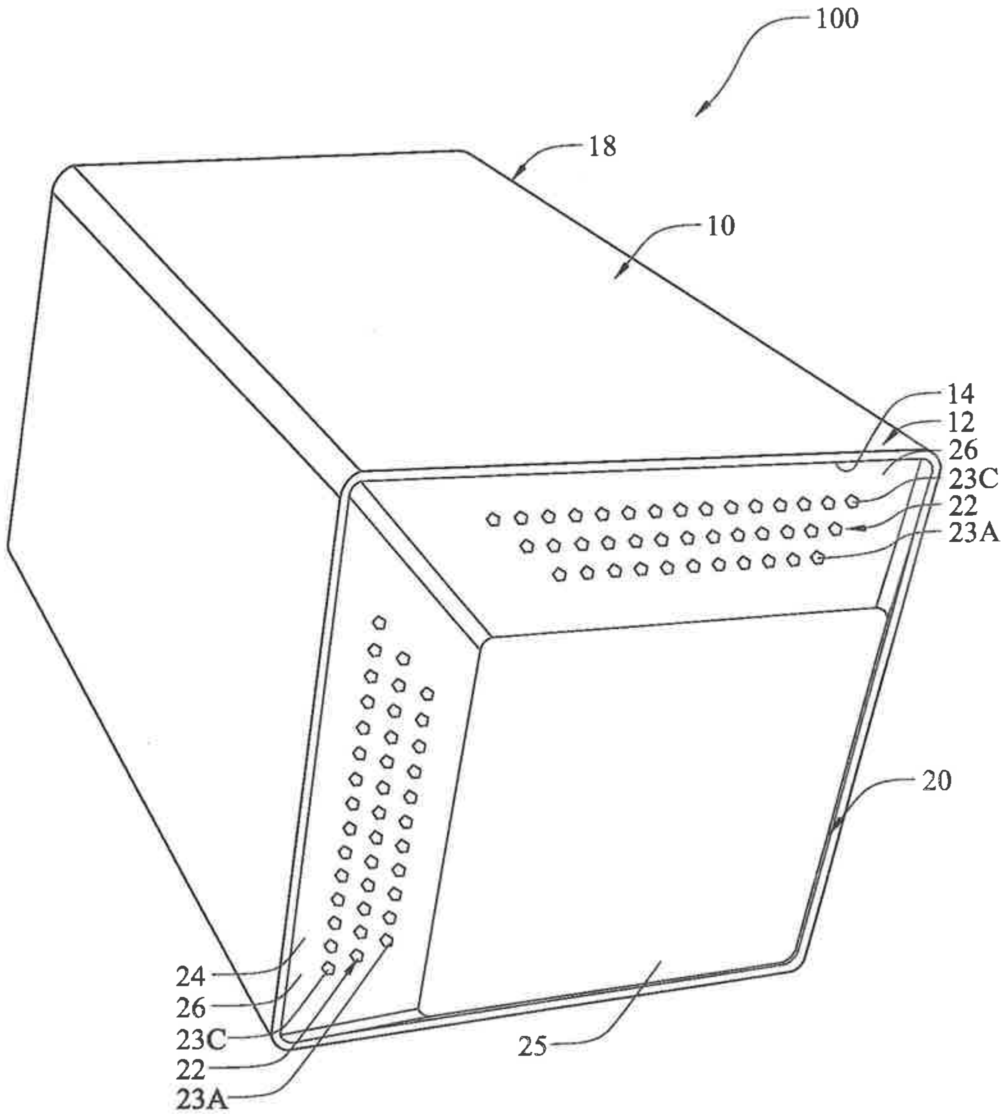

FIGURE 2

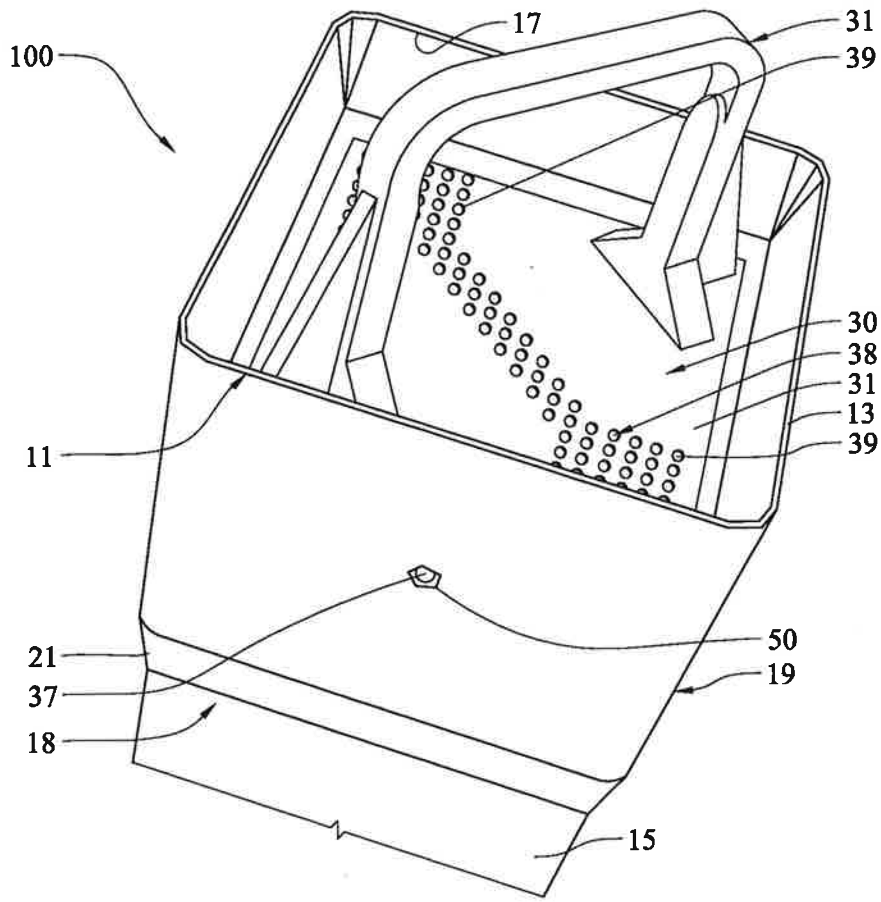

FIGURE 3

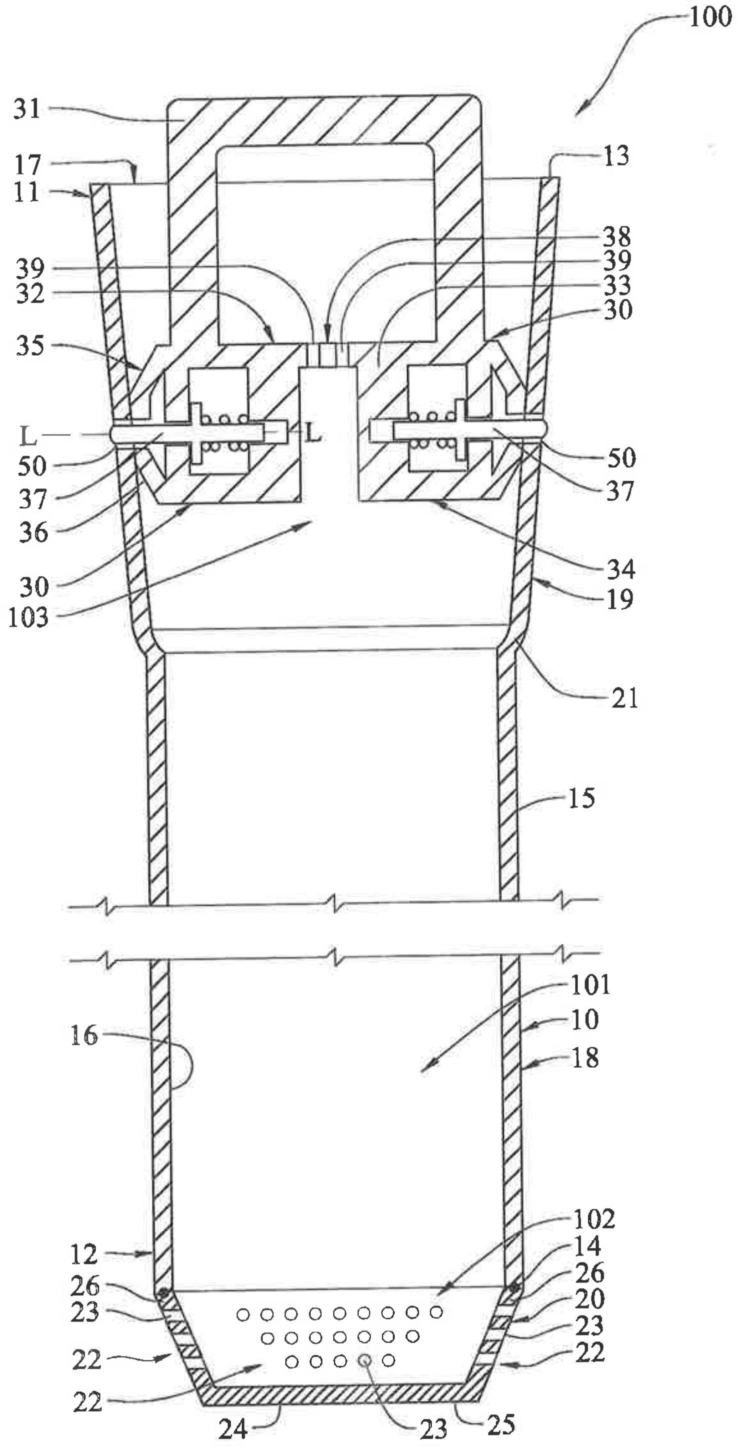
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FIGURE 4

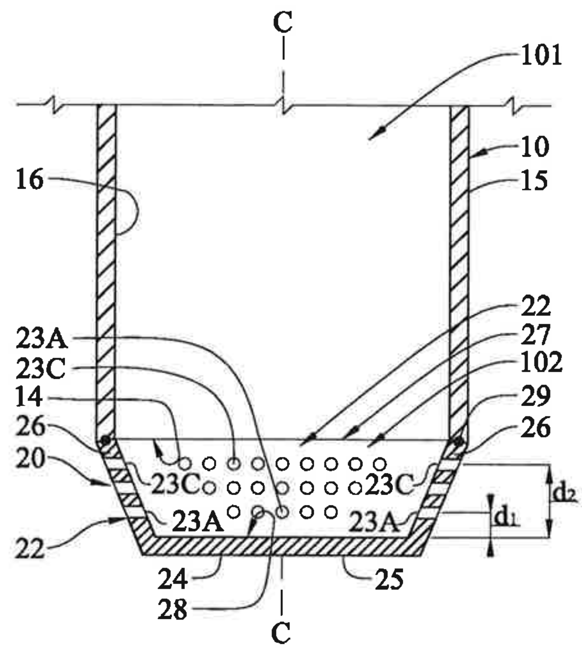

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FIGURE 5

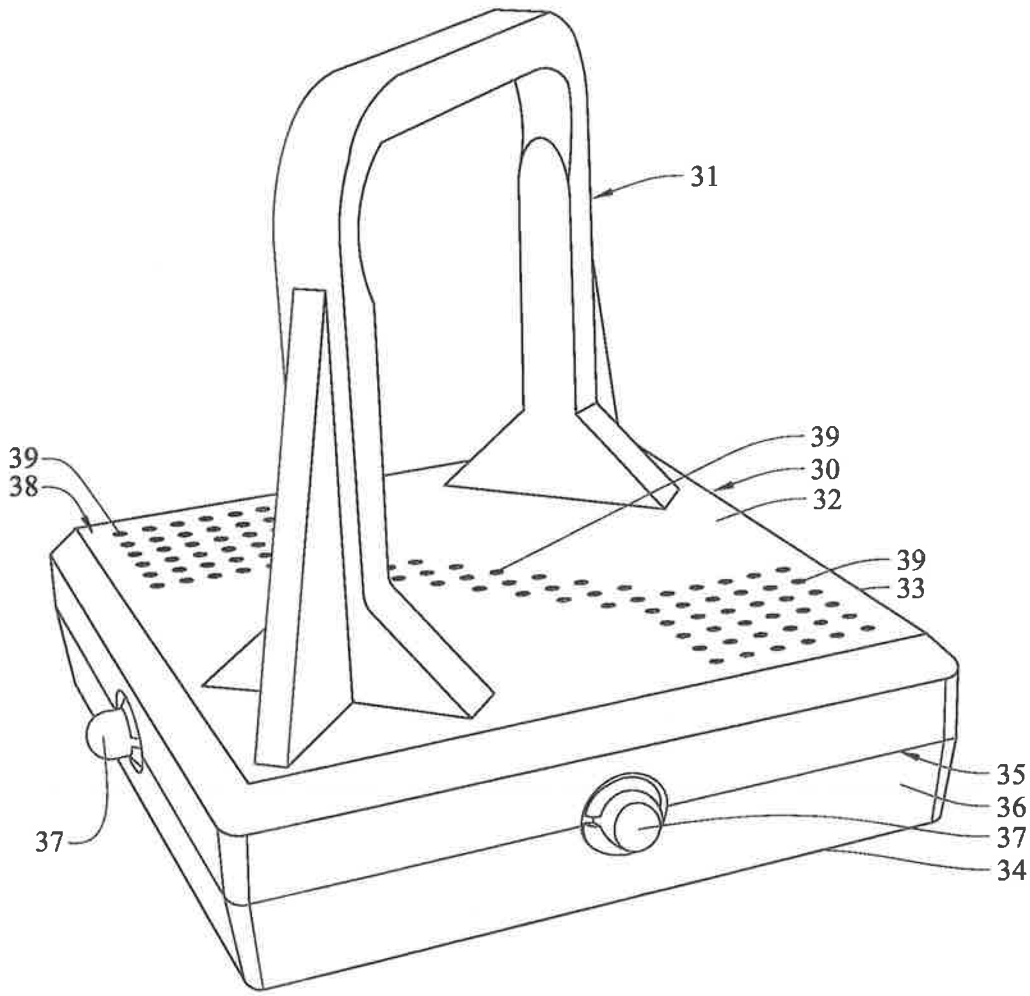

FIGURE 6

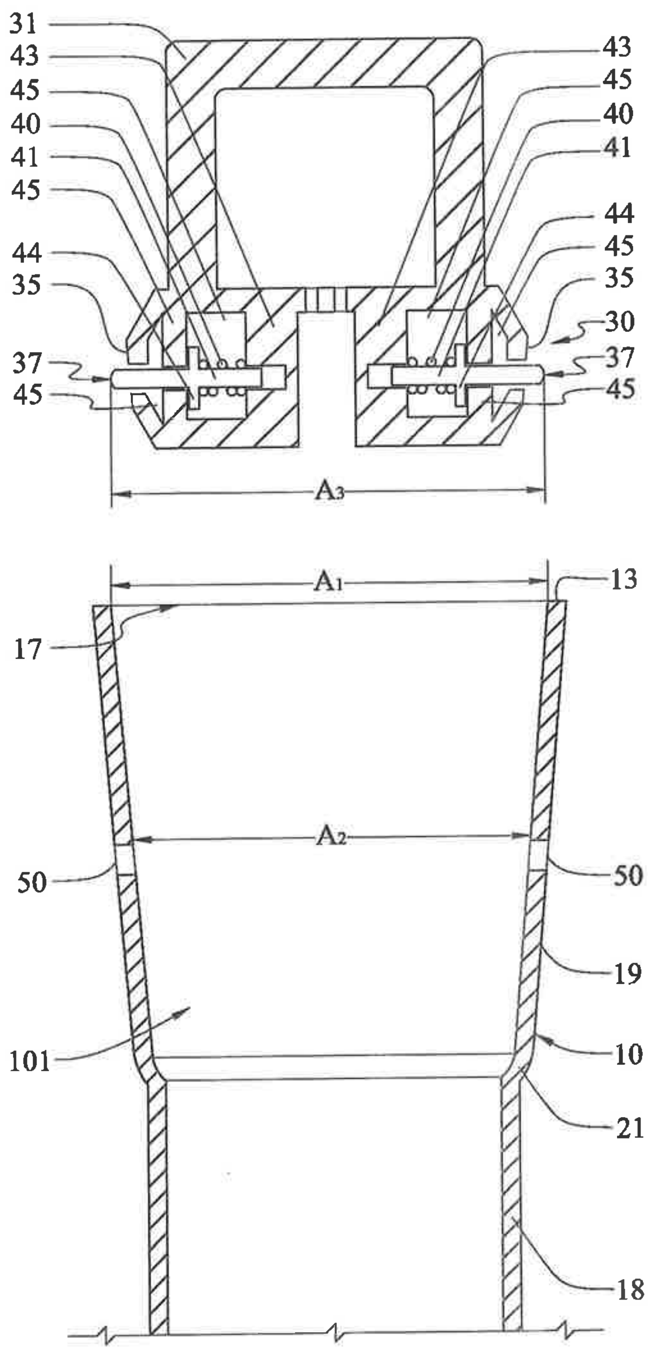
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FIGURE 7

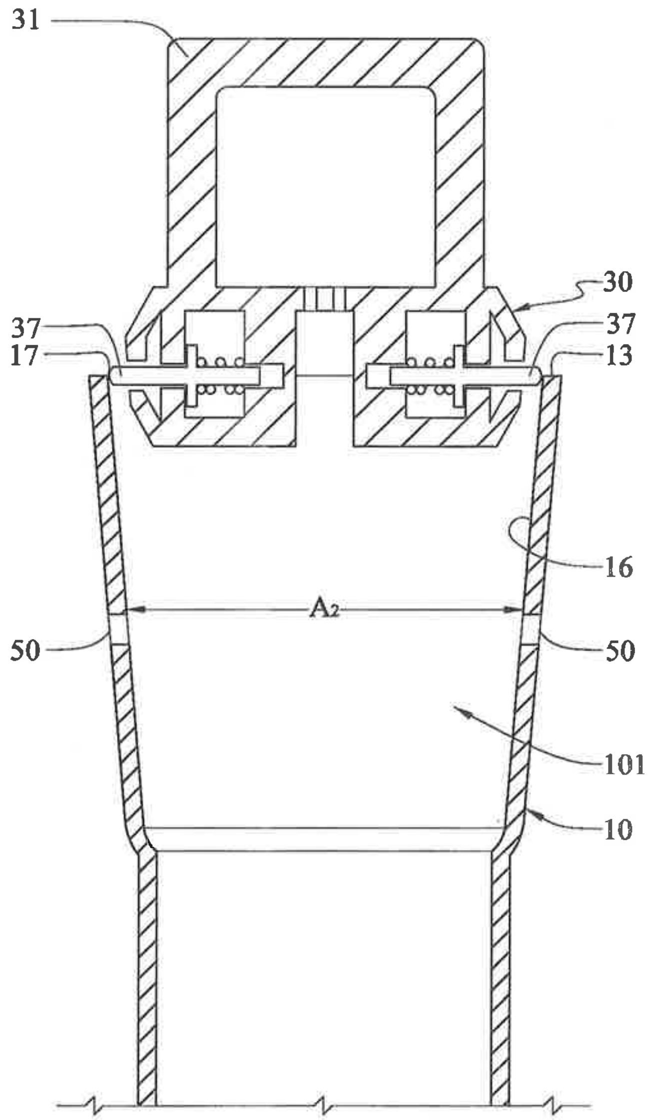

FIGURE 8

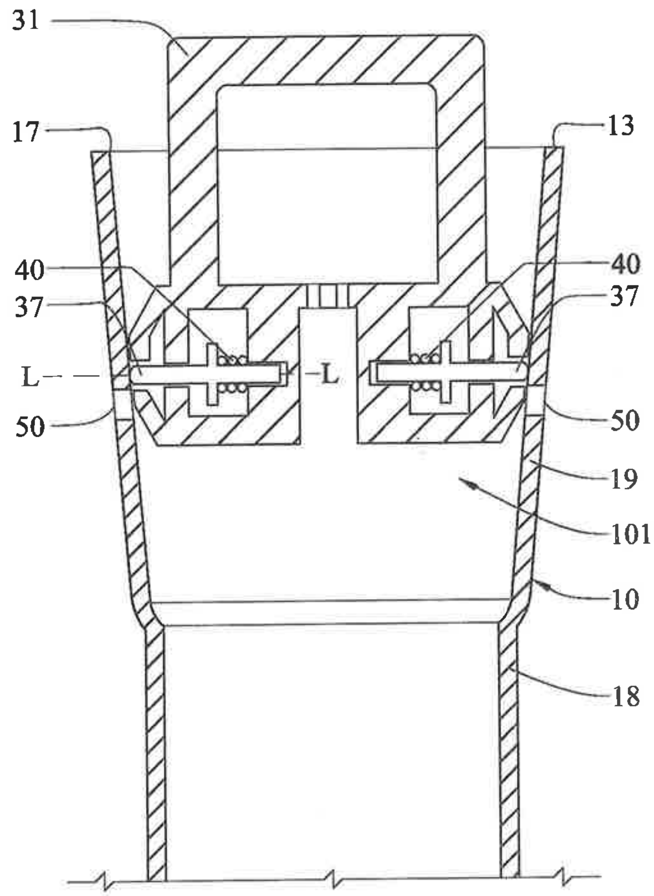

FIGURE 9

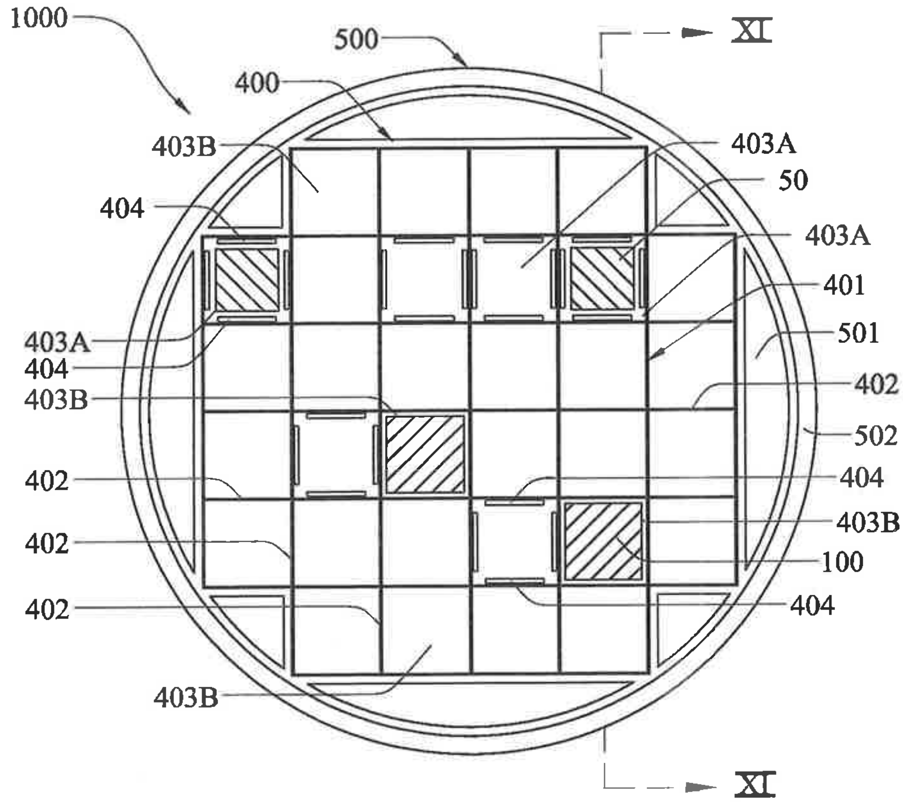
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FIGURE 10

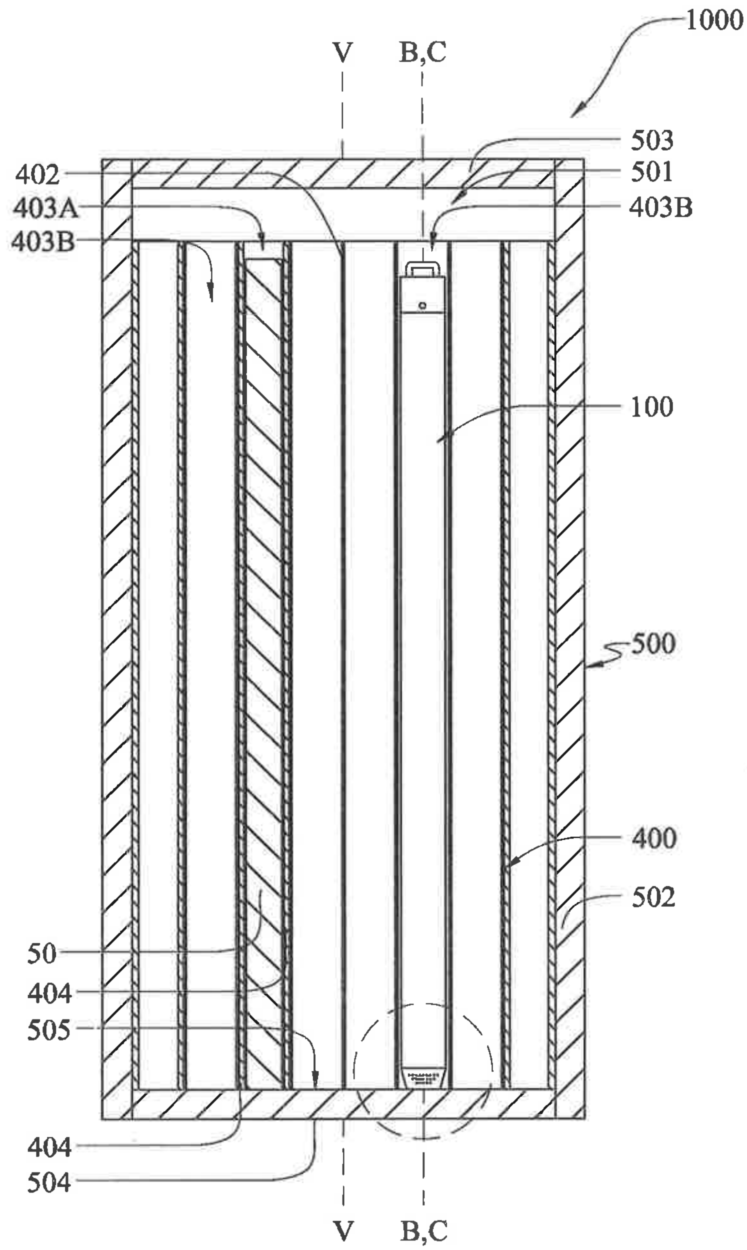
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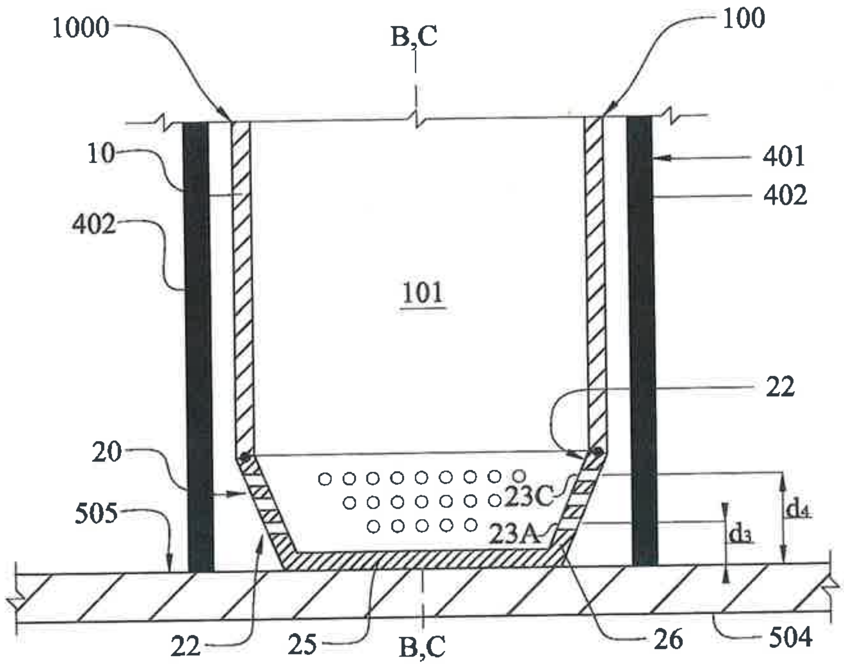
FIGURE 11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101
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FIGURE 12

CONTAINER AND SYSTEM FOR HANDLING DAMAGED NUCLEAR FUEL, AND METHOD OF MAKING THE SAME

This application is a U.S. national stage application under 35 U.S.C. §371 of PCT Application No. PCT/US12/51634, filed on Aug. 20, 2012, which claims the benefit of U.S. Provisional Patent Application No. 61/525,583, filed Aug. 19, 2011, the entireties of which are incorporated herein by reference.

FIELD OF THE INVENTION

The present invention relates generally to containers and systems for handling nuclear fuel, and specifically to containers and systems for handling nuclear fuel whose physical integrity has been compromised, and methods of making the same.

BACKGROUND OF THE INVENTION

Damaged nuclear fuel is nuclear fuel that is in some way physically impaired. Such physical impairment can range from minor cracks in the cladding to substantial degradation on various levels. When nuclear fuel is damaged, its uranium pellets are no longer fully contained in the tubular cladding that confines the pellets from the external environment. Moreover, damaged nuclear fuel can be distorted from its original shape. As such, special precautions must be taken when handling damaged nuclear fuel (as compared to handling intact nuclear fuel) to ensure that radioactive particulate matter is contained. Please refer to USNRC's Interim Staff Guidance #2 for a complete definition of fuel that cannot be classified as "intact" and, thus, falls into the category of damaged nuclear fuel for purposes of this application. As used herein, damaged nuclear fuel also includes nuclear fuel debris.

Containers and systems for handling damaged nuclear fuel are known. Examples of such containers and systems are disclosed in U.S. Pat. No. 5,550,882, issued Aug. 27, 1996 to Lehnart et al., and U.S. Patent Application Publication No. 2004/0141579, published Jul. 22, 2004 to Methling et al. While the general structure of a container and system for handling damaged nuclear fuel is disclosed in each of the aforementioned references, the containers and systems disclosed therein are less than optimal for a number of reasons, including inferior venting capabilities of the damaged nuclear fuel cavity, difficulty of handling, inability to be meet tight tolerances dictated by existing fuel basket structures, lack of adequate neutron shielding, and/or manufacturing complexity or inferiority.

Thus, a need exists for an improved container and system for handling damaged nuclear fuel, and methods of making the same.

SUMMARY OF THE INVENTION

In one embodiment, the invention can be a method of forming an elongated tubular container for receiving damaged nuclear fuel, the method comprising: a) extruding, from a material comprising a metal and a neutron absorber, an elongated tubular wall having a container cavity; b) forming, from a material comprising a metal that is metallurgically compatible with the metal of the elongated tubular wall, a bottom cap comprising a first screen having a plurality of openings; and c) autogenously welding the bottom cap to a bottom end of the elongated tubular wall, the

plurality of openings of the first screen forming vent passageways to a bottom of the container cavity.

In another embodiment, the invention can be a container for receiving damaged nuclear fuel, the method comprising: an extruded tubular wall forming a container cavity about a container axis, the extruded tubular wall formed of a metal matrix composite having neutron absorbing particulate reinforcement; a bottom cap coupled to a bottom end of the extruded tubular wall; a top cap detachably coupled to a top end of the extruded tubular wall; a first screen comprising a plurality of openings that define lower vent passageways into a bottom of the container cavity; and a second screen comprising a plurality of openings that define upper vent passageways into a top of the container cavity.

In yet another embodiment, the invention can be a system for storing and/or transporting nuclear fuel comprising: a vessel comprising defining a vessel cavity and extending along a vessel axis; a fuel basket positioned within the vessel cavity, the fuel basket comprising a grid forming a plurality of elongated cells, each of the cells extending along a cell axis that is substantially parallel to the vessel axis; and at least one elongated tubular container comprising a container cavity containing damaged nuclear fuel positioned within one of the cells, the elongated tubular container comprising: an extruded tubular wall forming a container cavity about a container axis, the extruded tubular wall formed of a metal matrix composite having neutron absorbing particulate reinforcement; a bottom cap coupled to a bottom end of the extruded tubular wall; a top cap detachably coupled to a top end of the extruded tubular wall; a first screen comprising a plurality of openings that define lower vent passageways into a bottom of the container cavity; and a second screen comprising a plurality of openings that define upper vent passageways into a top of the container cavity.

In still another embodiment, the invention can be a system for storing and/or transporting nuclear fuel comprising: a vessel defining a vessel cavity and extending along a vessel axis; a fuel basket positioned within the vessel cavity, the fuel basket comprising a plurality of elongated cells; an elongated tubular container positioned within one of the cells, the elongated tubular container comprising: an elongated tubular wall forming a container cavity about a container axis, the tubular wall comprising a top portion having a plurality of locking apertures and a top edge defining a top opening into the container cavity; a bottom cap coupled to a bottom end of the elongated tubular wall; a top cap comprising a plurality of locking elements that are alterable between a retracted state and an extended state, the locking elements biased into the extended state; a first screen comprising a plurality of openings that define lower vent passageways between the vessel cavity and a bottom of the container cavity; a second screen comprising a plurality of openings that define upper vent passageways between the vessel cavity and a top of the container cavity; and the top cap and the elongated tubular wall configured so that upon the top cap being inserted through the top opening, contact between the locking element and the elongated tubular wall forces the locking elements into a retracted state, and wherein upon the locking element becoming aligned with the locking apertures, the locking elements automatically returning the extended state such that the locking member protrude into the locking apertures, thereby detachably coupling the top cap to elongated tubular wall.

In a further embodiment, the invention can be a system for storing and/or transporting nuclear fuel comprising: a vessel defining a vessel cavity and extending along a vessel axis; a fuel basket positioned within the vessel cavity, the fuel basket comprising a plurality of elongated cells; an elongated tubular container comprising a container cavity for containing damaged nuclear fuel positioned within one of the cells, the elongated tubular container comprising: a first screen comprising a plurality of openings that define lower vent passageways between the vessel cavity and a bottom of the container cavity, the plurality of openings of the first screen comprising a lowermost opening that is a first distance from a floor of the vessel cavity and an uppermost opening that is a second distance from the floor of the vessel cavity, the second distance being greater than the first distance; and a second screen comprising a plurality of openings that define upper vent passageways between the vessel cavity and a top of the container cavity.

In an even further embodiment, the invention can be a system for storing and/or transporting nuclear fuel comprising: a vessel defining a vessel cavity and extending along a vessel axis; a fuel basket positioned within the vessel cavity, the fuel basket comprising a plurality of elongated cells; an elongated tubular container comprising a container cavity for containing damaged nuclear fuel positioned within one of the cells, the elongated tubular container comprising: a first screen comprising a plurality of openings that define lower vent passageways between the vessel cavity and a bottom of the container cavity, the first screen located on an upstanding portion of the elongated tubular container that is substantially non-perpendicular to the vessel axis; and a second screen comprising a plurality of openings that define upper vent passageways between the vessel cavity and a top of the container cavity.

In a still further embodiment, the invention can be a damaged fuel container, or system incorporating the same, in which the one or more of the screens of the container are integrally formed into the body of the container.

Further areas of applicability of the present invention will become apparent from the detailed description provided hereinafter. It should be understood that the detailed description and specific examples, while indicating the preferred embodiment of the invention, are intended for purposes of illustration only and are not intended to limit the scope of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

The present invention will become more fully understood from the detailed description and the accompanying drawings, wherein:

FIG. **1** is an isometric view of a damaged fuel container according to an embodiment of the present invention;

FIG. **2** a bottom perspective view of a bottom portion of the damaged fuel container of FIG. **1**;

FIG. **3** is a top perspective view of a top portion of the damaged fuel container of FIG. **1**;

FIG. **4** is a longitudinal cross-sectional schematic of the damaged fuel container of FIG. **1** taken along the container axis, wherein a middle portion of the damaged fuel container has been omitted;

FIG. **5** is a close-up longitudinal cross-sectional schematic of the bottom portion of the damaged fuel container of FIG. **1**;

FIG. **6** is an isometric view of the top cap of the damaged fuel container of FIG. **1**, wherein the top cap has been removed;

FIG. **7** is a longitudinal cross-sectional schematic of the top cap of FIG. **5** positioned above the elongated tubular wall of the damaged fuel container for detachable coupling thereto;

FIG. **8** is a longitudinal cross-sectional schematic wherein the top cap of FIG. **5** has been partially inserted through a top opening of the elongated tubular wall of the damaged fuel container;

FIG. **9** is a longitudinal cross-sectional schematic wherein the top cap of FIG. **5** has been slidably inserted into the container cavity of the elongated tubular wall, and wherein the locking elements of the top cap have been forced into a fully retracted state due to contact with the elongated tubular wall;

FIG. **10** is a top view of a system according to an embodiment of the present invention, wherein a loaded damaged fuel container of FIG. **1** and intact fuel assemblies are schematically illustrated therein;

FIG. **11** is cross-sectional view taken along view XI-XI of FIG. **10**; and

FIG. **12** is a close-up view of area XII-XII of FIG. **11**.

DETAILED DESCRIPTION OF THE DRAWINGS

The following description of the illustrated embodiment(s) is merely exemplary in nature and is in no way intended to limit the invention, its application, or uses.

The description of illustrative embodiments according to principles of the present invention is intended to be read in connection with the accompanying drawings, which are to be considered part of the entire written description. In the description of embodiments of the invention disclosed herein, any reference to direction or orientation is merely intended for convenience of description and is not intended in any way to limit the scope of the present invention. Relative terms such as "lower," "upper," "horizontal," "vertical," "above," "below," "up," "down," "top" and "bottom" as well as derivatives thereof (e.g., "horizontally," "downwardly," "upwardly," etc.) should be construed to refer to the orientation as then described or as shown in the drawing under discussion. These relative terms are for convenience of description only and do not require that the apparatus be constructed or operated in a particular orientation unless explicitly indicated as such. Terms such as "attached," "affixed," "connected," "coupled," "interconnected," and similar refer to a relationship wherein structures are secured or attached to one another either directly or indirectly through intervening structures, as well as both movable or rigid attachments or relationships, unless expressly described otherwise. Moreover, the features and benefits of the invention are illustrated by reference to the exemplified embodiments. Accordingly, the invention expressly should not be limited to such exemplary embodiments illustrating some possible non-limiting combination of features that may exist alone or in other combinations of features; the scope of the invention being defined by the claims appended hereto.

Referring first to FIGS. **1-4** concurrently, a damaged fuel container ("DFC") **100** according to an embodiment of the present invention is illustrated. The DFC **100** incorporates an inventive design (and is formed by an inventive method) that allows high density packaging of damaged fuel in pressure vessels, such as metal casks or multi-purpose canisters (described in greater detail below). The DFC **100** can be used to package damaged nuclear fuel at nuclear reactors, such as the Fukushima Daiichi site. The DFC **100** can be used to safely containerize nuclear fuel of compromised cladding integrity and is a unitary waste package for the fuel that may be in various stages of dismemberment ranging from minor cracks in the cladding to its substantial degradation. As described in greater detail below, the DFC **100** is designed to be loaded with damaged nuclear fuel and positioned within a fuel basket which, in turn, is housed in a pressure vessel such as a metal cask or a multi-purpose canister.

The DFC **100** is an elongated tubular container that extends along a container axis C-C. As will become more apparent from the description below, the DFC **100** is specifically designed so as to not form a fluid-tight container cavity **101** therein. This allows the container cavity **101** of the DFC **100**, and its damaged nuclear fuel payload, to be adequately dried for dry storage using standard dry storage dehydration procedures. Suitable dry storage dehydration operations and equipment that can be used to dry the DFC **100** (and the system **1000**) are disclosed in, for example: U.S. Patent Application Publication No. 2006/0288607, published Dec. 28, 2006 to Singh; U.S. Patent Application Publication No. 2009/0158614, published Jun. 2, 2009 to Singh et al.; and U.S. Patent Application Publication No. 2010/0212182, published Aug. 22, 2010 to Singh. While a fluid-tight boundary is not formed by the DFC **100**, the DFC **100** (when fully assembled as shown in FIGS. **1-4**) creates a particulate confinement boundary for its damaged nuclear fuel payload, thereby preventing radioactive particles and debris from escaping the container cavity **101**.

The DFC **100** generally comprises an elongated tubular wall **10**, a bottom cap **20** and a top cap **30**. In one embodiment, the elongated tubular wall **10** is formed of a material comprising a metal and a neutron absorber. As used herein the term "metal" includes metals and metal alloys. In certain embodiments, suitable metals may include without limitation aluminum, steel, lead, and titanium while suitable neutron absorbers may include without limitation boron, boron carbide and carborundem. As used herein, the term "aluminum" includes aluminum alloys. In one specific embodiment, the metal is an aluminum and the neutron absorber material is boron or boron carbide. In other embodiments, the elongated tubular wall **10** is formed entirely of a metal matrix composite having neutron absorbing particulate reinforcement. Suitable metal matrix composites having neutron absorbing particulate reinforcement include, without limitation, a boron carbide aluminum matrix composite material, a boron aluminum matrix composite material, a boron carbide steel matrix composite material, a carborundum aluminum matrix composite material, a carborundum titanium matrix composite material and a carborundum steel matrix composite material. Suitable aluminum boron carbide metal matrix composites are sold under the name Metamic® and Boralyn®. The use of an aluminum-based metal matrix composite ensures that the DFC **100** will have good heat rejection capabilities.

The boron carbide aluminum matrix composite material of which the elongated tubular wall **10** is constructed, in one embodiment, comprises a sufficient amount of boron carbide so that the elongated tubular wall **10** can effectively absorb neutron radiation emitted from the damage nuclear fuel loaded within the container cavity **101**, thereby shielding adjacent nuclear fuel (damaged or intact) in the fuel basket **400** from one another (FIG. **10**). In one embodiment, the elongated tubular wall **10** is constructed of an aluminum boron carbide metal matrix composite material that is greater than 25% by volume boron carbide. In other embodiments, the elongated tubular wall **10** is constructed of an aluminum boron carbide metal matrix composite material that is between 20% to 40% by volume boron carbide, and more preferably between 30% to 35%. Of course, the invention is not so limited and other percentages may be used. The exact percentage of neutron absorbing particulate reinforcement required to be in the metal matrix composite material will depend on a number of factors, including the thickness of the elongated tubular wall **10**, the spacing/pitch between adjacent cells within the fuel basket **400** (FIG. **10**), and the radiation levels of the damaged nuclear fuel. As will be discussed in greater detail below, the elongated tubular wall **10** is formed by an extrusion process in certain embodiments and, thus, the DFC **100** can be considered an extruded tubular container in such embodiments. Extrusion is preferred because it results in an elongated tubular wall **10** that is free of bending or warping that can be caused by welding processes that are used to create tubes.

The elongated tubular wall **10** extends along the container axis C-C from a top end **11** to a bottom end **12**. The top end **11** terminates in a top edge **13** while the bottom end **12** terminates in a bottom edge **14**. The elongated tubular wall **10** also comprises an outer surface **15** and an inner surface **16** that forms a container cavity **101**. The top edge **13** defines a top opening **17** that leads into the container cavity **101**.

The elongated tubular wall **10** comprises a top portion **18** and a bottom portion **19**. In the exemplified embodiment, the bottom portion **19** extends from the bottom edge **14** to a transition shoulder **21** while the top portion **18** extends from the transition shoulder **21** to the top edge **13**. The top portion **19**, in the exemplified embodiment, is an upper section of the elongated tubular wall **10** that flares slightly outward moving from the transition shoulder **21** to the top edge **13**. Thought of another way, the top portion **19** of the elongated tubular wall **10** has a transverse cross-section that gradually increases in size moving from the transition shoulder **21** to the top edge **13**. The bottom portion **18**, in the exemplified embodiment, has a substantially constant transverse cross-section along its length, namely from the bottom edge **14** to the transition shoulder **21**. In other embodiments, the top portion **19** can also have a transverse cross-section that is substantially constant along its length from the transition shoulder **21** to the top edge **13**. In such an embodiment, the transverse cross-section of the top portion can be larger than the transverse cross-section of the bottom portion **18**. In still other embodiments, the elongated tubular wall **10** may have a substantially constant transverse cross-section along its entire length from the bottom edge **14** to the top edge **13**. In such an embodiment, the elongated tubular wall **10** will be devoid of a transition shoulder **21** and the top and bottom portions **18**, **19** would have no physical distinction.

In the exemplified embodiment, the elongated tubular wall **10** has a substantially constant thickness along its entire length. In one embodiment, the elongated tubular wall **10** has a wall thickness between 1 mm to 3 mm, with about 2 mm being preferred. Of course, the invention is not so limited and the elongated tubular wall **10** can have wall thickness that is variable and of different empirical values and ranges.

The inner surface **16** of the elongated tubular wall **10** defines the container cavity **101**. In the exemplified embodiment, the portion of the container cavity **101** defined by the bottom portion **18** has a transverse cross-section that is substantially constant in size while the portion of the container cavity **101** defined by the top portion **19** has a transverse cross-section that increases in size moving from the transition shoulder **21** to the top edge **13**.

In the exemplified embodiment, the elongated tubular wall **10** has a transverse cross-section that is substantially rectangular in shape along its entire length from the bottom edge **14** to the top edge **13**. Similarly, the container cavity **101** also has a transverse cross-section that is substantially rectangular in shape along its entire length. Of course, the transverse cross-sections can be other shapes in other embodiments, and can even be dissimilar shapes between the top and bottom portions **18**, **19**.

The bottom cap **20** is fixedly coupled to the bottom end **12** of the elongated tubular wall **10** while the top cap **30** is detachably coupled to the top end **11** of the elongated tubular wall **10**. More specifically, the bottom cap **20** is coupled to the bottom edge **14** of the elongated tubular wall **10**. As will be described in greater detail below, in the exemplified embodiment, the bottom cap **20** is fixedly coupled to the bottom end **12** of the elongated tubular wall **10** by an autogenous welding technique, such as by friction stir welding. In other embodiments, the bottom cap **20** is fixedly coupled to the bottom end **12** of the elongated tubular wall **10** using other connection techniques.

The bottom cap **20**, in certain embodiments, is formed of a material comprising a metal that is metallurgically compatible with the metal of the elongated tubular wall **10** for welding. In one embodiment, the bottom cap is formed of aluminum. The bottom cap **20**, in a preferred embodiment, is formed by a casting process.

The bottom cap **20** comprises a plurality of first screens **22**. Each of the first screens **22** comprises a plurality of openings **23** that define lower vent passageways into a bottom **102** of the container cavity **101**. While in the exemplified embodiment the first screens **22** are incorporated into the bottom cap **20**, the first screens **22** can be incorporated into the bottom end **12** of the elongated tubular wall **10** in other embodiments. Furthermore, while the exemplified DFC **100** comprises four first screens in the exemplified embodiment, more or less first screens **22** can be included in other embodiments.

In one embodiment, the openings **23** of the first screens **22** are small enough so that radioactive particulate matter cannot pass therethrough but are provided in sufficient density (number of openings/area) to allow sufficient venting of air, gas or other fluids through the container cavity **101**. In one embodiment, the openings **23** have a diameter in a range of 0.03 mm to 0.1 mm, and more preferably a diameter of about 0.04 mm. The openings **23** may be provided for each of the first screens **22**, in certain embodiments, to have a density of 200 to 300 holes per square inch. The invention, however, is not limited to any specific dimensions or hole density unless specifically claimed.

In the exemplified embodiment, the first screens **22** are integrally formed into a body **24** of the bottom cap **20** by creating the openings **23** directly into the body **24** of the bottom cap **20**. The openings **23** can be formed into the body **24** of the bottom cap **20** by punching, drilling or laser cutting techniques. In one embodiment, it is preferred to form the openings using a laser cutting technique. Laser cutting allows very fine openings **23** to be formed with precision and efficiency. In alternate embodiments, the openings of the first screens **22** may not be integrally formed into the bottom cap **20** (or the elongated tubular wall **10**). Rather, larger through holes can be formed in the bottom cap **20** that are then covered by separate first screens **22**, such as wire mesh screens.

Referring now to FIGS. **2** and **5** concurrently, the bottom cap **20** generally comprises a floor plate **25** and an oblique wall **26** extending upward from a perimeter of the floor plate **25**. In the exemplified embodiment, the oblique wall **26** is integrally formed with the floor plate **25**, for example, during the casting formation process. The oblique wall **26** is a rectangular annular wall that forms a tapered end of the DFC **100**, which helps with inserting the DFC **100** into a cell **403B** of the fuel basket **400** (FIGS. **10** and **11**). The oblique wall **26** extends oblique to the container axis C-C and terminates in an upper edge **27**. The upper edge **27** of the oblique wall **26** is coupled to the bottom edge **14** of the elongated tubular wall **10** by an autogenous butt weld **29** that seals the interface and integrally couples the components together so as to produce a junction that is smooth with the outer surface **15**.

The floor plate **25** comprises a top surface **28** that forms a floor of the container cavity **101**. As can be seen in FIG. **5**, one of the first screens **22** is located on each of the four sections of the oblique wall **26**, which collectively form its rectangular transverse cross-sectional shape. The oblique wall **26** is an upstanding portion of the DFC **100**. By locating the first screens **22** on an upstanding portion of the DFC **100** (rather than a portion that only has a horizontal component, such as the floor plate **25**), the openings **23** of the first screens **23** are less susceptible to becoming clogged from particulate matter from the damaged nuclear fuel. Moreover, the openings **23** do not become choked-off (i.e., blocked) when the DFC **100** is supported upright in a fuel basket **400** and the floor plate **25** is in surface contact with a floor **505** of the vessel **500** (FIG. **12**). In certain embodiments, an additional first screen **22** may be added to the floor plate **25** of the bottom cap **20** to ensure adequate leakage of retained water.

The openings **23** of each of the first screens **22** comprise a lowermost opening(s) **23A** and an uppermost opening(s) **23C**. The lowermost opening **23A** is located a first axial distance d_1 above the floor **28** of the container cavity **101** while the uppermost most opening **23C** is located a second distance d_2 above the floor **28** of the container cavity **101**. The second distance d_2 is greater than the first distance d_1. As discussed below, the DFC **100**, in certain embodiments, is intended to be oriented so that the container axis C-C is substantially vertical when the DFC **100** is positioned within the fuel basket **400** of the vessel **500** for transport and/or storage. Thus, in the exemplified embodiment, both the lowermost and uppermost openings **23A**, C are located a vertical distance above the floor **28** of the container cavity **101**. As a result, the first screens **22** are unlikely to become clogged by settling particulate debris as each of d_1 and d_2 are vertical distances.

As mentioned above, it is beneficial to have the first screens **22** located on an upstanding portion of the DFC **100**, which in the exemplified embodiment is the oblique wall **26** of the bottom cap **20**. In other embodiments, the bottom cap **20** is designed so that the wall **26** is not oblique to the container axis C-C but rather substantially parallel thereto. In such and embodiment, the first screens **22** are located on this vertical annular wall of the bottom cap **20**. In still another embodiment, the bottom cap **20** may simply be a floor plate without any significant upstanding potion. In such an embodiment, the first screens **22** can be located on the bottom end **12** of the elongated tubular wall **10** itself, which would be considered the upstanding portion that is substantially parallel to container axis C-C. Of course, in such embodiments, the upstanding portion of the elongated tubular wall **10** on which the first screens **22** are located can be oriented oblique to the container axis C-C.

Referring now to FIGS. **3-4** and **6** concurrently, the details of the top cap **30**, along with its detachable coupling to the elongated tubular body **10** will be discussed in greater detail. The top cap **30** is shaped to provide a strong attachment location for lifting the loaded DFC **100**. A handle **31** is fixedly coupled to the top cap **30** and extends upward from a top surface **32** of the top cap **30** so that the DFC **100** can be easily handled by a crane or other handling equipment. As can be seen, when the top cap **30** is detachably coupled to the elongated tubular wall **10** (shown in FIGS. **3-4**), the entirety of the top cap **30** is disposed within the top portion **19** of the elongated tubular wall **10**. A portion of the handle **31**, however, protrudes axially from the top edge **13** of the elongated tubular wall **13**. Nonetheless, the entirety of the handle **31** is located fully within a transverse perimeter defined by the top edge **13** of the elongated tubular wall **10** (viewed from a plane that is substantially perpendicular to the container axis C-C). As a result, the handle **31** can be easily grabbed by lifting mechanisms when the DFC **100** is fully inserted into a fuel cell of a fuel rack, without the grid **401** of the fuel basket **400** interfering with the lifting mechanism (FIGS. **10** and **11**).

The top cap **30** comprises a body **33**. In one embodiment, the body **33** is formed of any of the materials described above for the elongated tubular wall **10**. In another embodiment, the body **33** is formed of any of the materials described above for the bottom cap **20**.

The top cap **30** has a bottom surface **34**, a top surface **32** and a peripheral sidewall **35**. The peripheral sidewall **35** comprises a chamfered portion **36** at a lower edge thereof to facilitate insertion into the top opening **17** of the elongated tubular wall **10**. The top cap **30** has a transverse cross-sectional shape that is the same as the transverse cross-sectional shape of the container cavity **101**.

A plurality of locking elements **37** protrude from the peripheral sidewall **35** of the top cap **30** and, as discussed in greater below, are alterable between a fully extended state (shown in FIGS. **3-4** and **6**) and a fully retracted state (shown in FIG. **9**) to facilitate repetitive coupling and uncoupling of the top cap **30** to the elongated tubular wall **10**. In the exemplified embodiment, the locking elements **37** are spring-loaded pins. In other embodiments, the locking elements **37** can be tabs, protuberances, clamps, tangs, and other known mechanisms for locking components together.

The top cap **30** also comprises a second screen **38**. The second screen **38** comprises a plurality of openings **39** that define upper vent passageways into a top **103** of the container cavity **101**. While in the exemplified embodiment the second screen **38** is incorporated into the top cap **30**, the second screen **38** can be incorporated into the elongated tubular wall **10** at a position below where the top cap **30** couples to the elongated tubular wall **10** in other embodiments.

In one embodiment, the openings **39** of the top cap are small enough so that radioactive particulate matter cannot pass therethrough but are provided in sufficient hole density (number of openings/area) to allow sufficient venting of air and gases (or other fluids) through the container cavity **101**. In one embodiment, the openings **39** have a diameter in a range of 0.03 mm to 0.1 mm, and more preferably a diameter of about 0.04 mm. The openings **39** may be provided for the second screen **38**, in certain embodiments, to have a density of 200 to 300 holes per square inch. The invention, however, is not limited to any specific dimensions or hole density of the openings **39** unless specifically claimed.

In the exemplified embodiment, the second screen **38** is integrally formed into the body **33** of the top cap **30** by creating the openings **39** directly into the body **33** of the bottom cap **20**. The openings **39** can be formed into the body **33** of the top cap **30** by punching, drilling or laser cutting techniques. In one embodiment, it is preferred to form the openings **39** using a laser cutting technique. Laser cutting allows very fine openings **39** to be formed with precision and efficiency. In alternate embodiments, the openings **39** of the second screen **38** may not be integrally formed into the top cap **30** (or the elongated tubular wall **10**). Rather, larger

through holes can be formed in the top cap **30** that are then covered by a separate second screen(s), such as a wire mesh screen(s).

Referring now to FIGS. **7-9**, additional details of the locking elements **37** of the top cap **30**, and the coupling of the top cap **30** to the elongated tubular wall **10**, will be described. As mentioned above, the locking elements **37** are alterable between a fully extended state (FIG. **7**) and a fully retracted state (FIG. **9**).

Referring solely now to FIG. **7**, each of the locking elements **37** is biased into the fully extended state by a resilient element **40**, which in the exemplified embodiment is a coil spring that is fitted over a shaft portion **41** of the locking element **37**. In the exemplified embodiment, the springs **40** bias the locking elements **37** into the extended state through contact with a first wall **43** of the top cap **30** on one end and a flange **44** of the shaft portion **41** of the locking element **37** on the other end. Overextension of the locking elements **37** out of the peripheral sidewall **35** is prevented by contact interference between the flanges **44** of the shaft portions **41** and second walls **45** of the top cap. Upon the application of adequate force to the locking elements **37**, the spring force of the springs **40** is overcome and each of the locking elements **37** will translate along its locking element axis L-L (FIG. 4) to the fully retracted state. In the exemplified embodiment, the locking element axes L-L are substantially perpendicular to the container axis C-C. In certain embodiments, the internal chambers **45** in which the springs **40** and portions of the locking elements **37** nest are hermetically sealed. This can be accomplished by incorporating a suitable gasket about the shaft portion **41** of the locking element at the peripheral sidewall **35**. In the exemplified embodiment, a locking element **37** is provided on each one of the four sections of the peripheral sidewall **35** and are centrally located thereon at the cardinal points.

As described in greater detail below, the locking elements **37** are forced from the fully extended state to the fully retracted state due to contact between the extruded tubular wall **10** and the locking elements **37** during insertion of the top cap **30** into the container cavity **101**. As can be seen in FIG. **7**, the portion of the container cavity **101** defined by the top portion **19** of extruded tubular wall has a transverse cross-section that gradually tapers (i.e. decreases in size) moving away (i.e., downward in the illustration) from a top edge **13** of the elongated tubular wall **10**. Thus, the container cavity **101** has a transverse cross-section A_1 at the top opening **17** that is greater than the transverse cross-section A_2 of the container cavity **101** at an axial position immediately above locking apertures **50** formed into the elongated tubular wall **10**.

As mentioned above, the locking elements **37** are biased into a fully extended state and, thus, protrude from all four sections of the peripheral sidewall **35**. As a result of the protruding locking elements 37, the top cap **37** has an effective transverse cross-section A_3 when the locking elements **37** are in the fully extended state. The DFC **100** is designed, in the exemplified embodiment, so that the effective transverse cross-section A_3 of the top cap **30** is the same as or smaller than the transverse cross-section A_1 of the top opening **17** of the internal cavity **101**. The effective transverse cross-section A_3 of the top cap **30**, however, is greater than the transverse cross-section A_2 of the container cavity **101** at the axial position immediately above locking apertures **50**.

Referring now to FIG. **8**, as a result of the relative dimensions described immediately above, when the top cap **30** is initially aligned with and lowered into the top opening

17 of the container cavity **101**, the top cap **70** (including the locking elements **70**) can pass through the top opening **17** while the locking elements **37** remain in the fully extended state. Thought of another way, the top edge **13** defines the top opening **17** so as to have a transverse cross-section through which the top cap **30** can be inserted while the locking elements **37** are in the fully extended state.

As the top cap **30** continues to be inserted (i.e., lowered in the illustration), the locking elements **37** come into contact with the inner surface **16** of the top portion **19** of the elongated tubular wall **10** that defines that portion of the container cavity **101**. Due to the fact that the inner surface **16** is sloped such that the transverse cross-section of the container cavity **101** continues to decrease with distance from the top edge **13**, the locking elements **37** are further forced into retraction by the inner surface **16** of the elongated tubular wall **10** until a fully retracted state is achieved at the axial position immediately above locking apertures **50** (FIG. **9**).

Referring to FIG. **9**, the locking elements **37** are at the axial position immediately above locking apertures **50** of the elongated tubular wall **10** and are in the fully retracted state. In the fully retracted state, the springs **40** are fully compressed and the locking elements **37** have been translated inward along the locking element axis L-L. As lowering of the top cap **30** is continued, the locking elements **37** become aligned with the locking apertures **50** of the elongated tubular wall **10** and are automatically returned back into the fully extended state in which the locking elements **37** protrude into the locking apertures **50** due to the bias of the springs **40** (shown in FIG. **4**). As a result of the locking elements **37** protruding into the locking apertures **50**, the top cap **30** is coupled to the elongated tubular wall **10** so that the DFC **100** can be lifted by the handle **31**. The locking elements **37** cannot be forced back into the retracted state due to contact with the edges that define the locking apertures **50**. In other words, once the top cap **30** is coupled to the elongated tubular wall **10** as described above, the locking elements **37** cannot be retracted by applying a lifting or pulling force (i.e. an axial force along the container axis C-C) to the top cap **30**. Thus, a secure connection between the top cap **30** and the elongate tubular wall **10** is provided. In order to remove the top cap **30** from the elongated tubular wall **10**, a tool is required to unlock the top cap **30** from the elongated tubular wall **10** by pressing the locking elements **37** radially inward along their locking element axes L-L. In the exemplified embodiment, the locking apertures **50** are through-holes and, thus, the locking elements **37** can be pressed inward by the access provided to the locking elements **37** by the locking apertures **50**.

The exemplified embodiment is only one structural implementation in which the top cap **30** and the elongated tubular wall **10** are configured so that upon the top cap **30** being inserted through the top opening **17**, contact between the locking elements **37** and the elongated tubular wall **10** forces the locking elements **37** into a retracted state. In other embodiments, the effective transverse cross-section A_3 of the top cap **30** may be larger than the transverse cross-section A_1 of the top opening **17** of the internal cavity **101**. In such an embodiment, the lower edges of the locking elements **37** can be appropriately chamfered and/or rounded so that upon coming into contact with the top edge **13** of the elongated tubular wall **10** during lowering, contact between the lower edges of the locking elements **37** and the top edge **13** of the elongated tubular wall **10** forces the locking elements **37** to translate inward along their locking element axes L-L. In other embodiments, the top edge **13** of the elongated tubular wall **10** may be appropriately chamfered to achieve the desired translation of the locking elements **37**.

Referring now to FIGS. **10-12** concurrently, a system **1000** for storing and/or transporting damaged nuclear fuel is illustrated according to an embodiment of the present invention. The system **1000** generally comprises a vessel **500**, a fuel basket **400** and at least one of the DFCs **100** described above. The vessel **500**, when fully assembled, forms a fluid-tight vessel cavity **501** in which the fuel basket **400**, the DFC **100** containing damaged nuclear fuel and intact nuclear fuel **50** are housed (in FIG. **10**, the loaded DFC **100** and the intact nuclear fuel **50** are schematically illustrated for simplicity). Thus, the vessel **500** can be considered a pressure vessel that forms a fluidic containment boundary about the vessel cavity **501**. In the exemplified embodiment, the vessel **500** is a canister, such as a multi-purpose canister. In embodiments, where the vessel is an MPC, the system **100** may also comprises an overpack cask, such as an above-ground or below-ground ventilated vertical overpack. In other embodiments, the vessel **500** may be a metal cask.

The vessel **500** comprises a cylindrical shell **502**, a lid plate **503** and a floor plate **504**. The lid plate **503** and the floor plate **504** are seal welded to the cylindrical shell **502** so to form the hermetically sealed vessel cavity **501**. A top surface **505** of the floor plate **504** forms a floor of the vessel cavity **501**. The vessel **500** extends along a vessel axis V-V, which is arranged substantially vertical during normal operation and handling procedures.

The fuel basket **400** is positioned within the vessel cavity **502** and comprises a gridwork **401** forming a plurality of elongated cells **403A-B**. In the exemplified embodiment, the gridwork **401** is formed by a plurality of intersecting plates **402** that form the cells **403A-B**. In one embodiment, the plates **402** that form the gridwork **401** are formed of stainless steel. Because the elongated tubular wall **10** of the DFC **100** is made of a boron carbide aluminum matrix composite material, or a boron aluminum matrix composite material, and the gridwork **401** is made of stainless steel, there is no risk of binding from the cohesion effect of materials of identical genre.

Each of the elongated cells **403A-B** extend along a cell axis B-B that is substantially parallel to the vessel axis V-V. The plurality of cells **403A-B** comprises a first group of cells **403A** that are configured to receive intact nuclear fuel **50** and a second group of cells **403B** configured to receive DFCs **100** containing damage nuclear fuel. Each of the cells **403A** of the first group comprise neutron absorbing liner panels **404** while the each of the cells **403B** of the second group are free of the neutron absorbing liner panels **404**. In one embodiment, the neutron absorbing liner panels **404** can be constructed of the same material that is described above for the elongated tubular wall **10**.

Because the elongated tubular wall **10** of the DFC **100** incorporate neutron absorber as described above, the cells **403B** of the fuel basket **400** that are to receive the DFCs **100** do not require such neutron absorber plates **404**, leading to an increased cell cavity size which is large enough to enable free insertion or extraction of the DFC **100** from the fuel basket **400**. In certain embodiments, the cell opening of the cells **403B** is 6.24 inches, which means that there is a ¼ inch lateral gap between the DFC **100** and the grid that forms the storage cell **403B**. Moreover, because the DFC **100** is extruded and the cells **403A-B** of the fuel basket **400** are of honeycomb construction made of thick plate stock (¼ inch wall), there is a high level of confidence that the DFCs **100** can be inserted into the storage cells **403B** without interference. In the exemplified embodiment, all of the cells **403**A-B have the same pitch therebetween.

Referring now to FIGS. **11** and **12**, each of the DFCs **100** is loaded into one of the cells **403**B by aligning the DFC **100** with the cell **403**B and lowering the DFC **100** therein until the floor plate **25** of the DFC **100** comes into surface contact with and rests on the top surface **505** of the floor plate **504** of the vessel **500**. When positioned within the cell **403**B, the container axis C-C of the DFC **100** is substantially parallel to the cell axis B-B and, in certain embodiments, substantially coaxial therewith.

As mentioned above, the cell axis B-B is substantially parallel to the vessel axis V-V. Thus, when the DFC **100** is loaded within the cell **403**B, the oblique wall **26** of the bottom cap **20** is oblique to both the cell axis B-B and the vessel axis V-V. As mentioned above, the top surface **505** of the floor plate **504** forms a floor of the vessel cavity **501**. Thus, when the DFC **100** is loaded within the cell **403**B, the lowermost opening(s) **23**A of the first vent(s) **22** is a distance d_3 above the floor **505** of the vessel **500** while the uppermost opening(s) **23**C of the first vent(s) **22** is a distance d_4 above the floor **505** of the vessel **500**.

In summary, the DFC **100** of the present invention fits in the storage cell **403**B with adequate clearance. The DFC **100** also provides adequate neutron absorption to meet regulatory requirements. The DFC **100** also confines the particulates but allow water and gases to escape freely. The DFC **100** also features a robust means for handling and includes a smooth external surface to mitigate the risk of hang up during insertion in or removal from the storage cell **403** B. The DFC also provides minimal resistance to the transmission of heat from the contained damaged nuclear fuel. The loaded DFC **100** can be handled by a grapple from the Fuel Handling Bridge. All lifting appurtenances are designed to meet ANSI 14.6 requirements with respect to margin of safety in load handling. Specifically, the maximum primary stress in any part of the DFC **100** will be less than its Yield Strength at 6 times the dead weight of the loaded DFC, W. and less than the Ultimate Strength at 10 times W.

The table below provides design data for one embodiment of the DFC **100**.

DFC: Design Data	
Outer Dimension	152 mm (5.99")
Corner Radius	6 mm (0.24" nominal)
Wall Thickness	2.0 mm (0.079")
DFC Cell I.D.	148 mm (5.83")
Total Height	4680 mm (184.25")
Boron Carbide Concentration	32% (nominal)
Empty Weight, Kg	25 (55 lbs)
Permissible Planar Average Enrichment	4.8%

A method of manufacturing the DFC **100** according to an embodiment of the present invention will now be described. First, the elongated tubular wall **10** is formed via an extrusion process using a metal matrix composite having neutron absorbing particulate reinforcement. A boron carbide aluminum matrix composite material is preferred. At this stage, the extruded elongated tubular wall **10** (and the container cavity **101**) has a substantially constant transverse cross-section, with the elongated tubular wall **10** also having a substantially uniform wall thickness. The elongated tubular wall **10** is then taken and a portion thereof is expanded so that the container cavity **101** has an increased transverse cross-section, thereby forming the top portion **19** and the bottom portion **18** elongated tubular wall **10**. Expansion of

the container cavity **101** (which can also be considered expansion of the elongated tubular wall **10**) can be accomplished using a swaging process using an appropriate mandrel, die and/or press. Said swaging process can be a hot work in certain embodiments. In an alternate embodiment, the difference sizes in transverse cross-section of the container cavity **101** can be accomplished by performing a drawing process to reduce the bottom portion **18** of the elongate tubular wall **10**.

The locking apertures **50** are then formed into the top portion of the elongated tubular wall **10** via a punching, drilling, or laser cutting technique.

The bottom cap **20** is then formed. Specifically, the bottom cap **20** is formed by casting aluminum to form the cap body **24**. The plurality of openings **23** are then integrally formed therein using a laser cutting process to form the first screens **22** on the oblique wall **26**.

The bottom cap **20** is then autogenously welded to the bottom end **12** of the elongated tubular wall **10**. More specifically, the bottom cap **20** is butt welded to the bottom end **12** of the elongated tubular wall **10** to produce a weld junction that is smooth with the outer surface **15** of the elongated tubular wall **10**. A friction stir weld technique may be used.

The top cap **30** is then formed and coupled to the elongated tubular wall **10** as described above.

While the invention has been described with respect to specific examples including presently preferred modes of carrying out the invention, those skilled in the art will appreciate that there are numerous variations and permutations of the above described systems and techniques. It is to be understood that other embodiments may be utilized and structural and functional modifications may be made without departing from the scope of the present invention. Thus, the spirit and scope of the invention should be construed broadly as set forth in the appended claims.

What is claimed is:

1. A system for storing and/or transporting nuclear fuel comprising:
  - a vessel comprising a vessel cavity and extending along a vessel axis;
  - a fuel basket positioned within the vessel cavity, the fuel basket comprising a grid forming a plurality of elongated cells, each of the cells extending along a cell axis that is substantially parallel to the vessel axis; and
  - an elongated tubular container comprising a container cavity containing damaged nuclear fuel, the elongated tubular container positioned within one of the cells, the elongated tubular container further comprising:
    - an extruded tubular wall forming a container cavity about a container axis, the extruded tubular wall formed of a metal matrix composite having neutron absorbing particulate reinforcement;
    - a bottom cap coupled to a bottom end of the extruded tubular wall, the bottom cap comprising a body including a floor plate and plurality of oblique walls arranged obliquely to the container axis, the oblique walls extending upward from a perimeter of the floor plate to define an annular wall structure forming a tapered bottom end of the container;
    - a top cap detachably coupled to a top end of the extruded tubular wall;
  - each oblique wall including a first screen comprising a plurality of openings that define lower vent passageways into a bottom of the container cavity; and

a second screen comprising a plurality of openings that define upper vent passageways into a top of the container cavity.

2. The system according to claim **1** wherein a top portion of the extruded tubular wall comprises locking apertures, and the top cap comprises locking elements that are alterable between a retracted state and an extended state, the locking elements biased into the extended state, and wherein the top cap is detachably coupled to the extruded tubular wall when the locking elements are in the extended state and protrude into the locking apertures.

3. The system according to claim **2** wherein contact between the extruded tubular wall and the locking elements forces the locking elements into the retracted state during insertion of the top cap into the container cavity until the locking elements become aligned with the locking apertures.

4. The system according to claim **1** wherein the bottom cap comprises the first screen and the top cap comprises the second screen.

5. The system according to claim **1** further comprising a floor of the container cavity, and wherein at least one of the plurality of openings of the first screen is located an axial distance above the floor of the container cavity.

6. The system according to claim **1**, wherein the vessel further comprises a cylindrical vessel shell and a vessel floor plate having a solid structure free of openings, the vessel floor plate seal welded to the vessel shell for hermetically sealing the vessel cavity.

7. The system according to claim **6**, wherein the floor plate of the bottom cap of the container abuttingly contacts the vessel floor plate when the container is positioned in the one of the cells.

8. The system according to claim **7**, wherein the floor plate of the bottom cap has a solid structure free of openings.

9. The system according to claim **1**, wherein the floor plate of the bottom cap has a solid structure free of openings.

10. A system for storing and/or transporting nuclear fuel comprising:

a vessel comprising a vessel cavity and extending along a vessel axis;

a fuel basket positioned within the vessel cavity, the fuel basket comprising a grid forming a plurality of elongated cells, each of the cells extending along a cell axis that is substantially parallel to the vessel axis; and

an elongated tubular container comprising a container cavity containing damaged nuclear fuel, the elongated tubular container positioned within one of the cells, the elongated tubular container further comprising:

an extruded tubular wall forming a container cavity about a container axis, the extruded tubular wall formed of a metal matrix composite having neutron absorbing particulate reinforcement;

a bottom cap fixedly coupled to a bottom end of the extruded tubular wall;

a top cap detachably coupled to a top end of the extruded tubular wall;

the bottom cap including a plurality of first screens each comprising a plurality of openings that define lower vent passageways in fluid communication with a bottom of the container cavity; and

the top cap including a second screen comprising a plurality of openings that define upper vent passageways in fluid communication with a top of the container cavity;

wherein a top portion of the extruded tubular wall comprises locking apertures, and the top cap comprises locking elements in the form of laterally and linearly movable pins each arranged for insertion into a corresponding one of the locking apertures when the top cap is coupled to the extruded tubular wall;

each of the pins being laterally movably alterable between a laterally inward retracted state and a laterally outward extended state, the locking elements biased outward into the extended state via a spring, and wherein the top cap is detachably locked to the extruded tubular wall when the pins are in the extended state and protrude into the locking apertures.

11. The system according to claim **10**, wherein contact between the extruded tubular wall and the pins forces the pins into the retracted state when engaged by the extruded tubular wall during insertion of the top cap into the container cavity until the pins each become aligned with one of the locking apertures and move to the extended state engaged with the apertures.

12. The system according to claim **11**, wherein the locking apertures are disposed in an upper section of the extruded tubular wall having a configuration that flares outward moving from a transition shoulder upwards to a top edge of the extruded tubular wall, the pins engaging the upper section and forced into the retracted state when the top cap is inserted into the container cavity.

13. The system according to claim **10**, wherein the bottom cap comprises a body including a floor plate and plurality of oblique walls arranged obliquely to the container axis, the oblique walls extending upward from a perimeter of the floor plate to define an annular wall structure forming a tapered bottom end of the container.

14. A system for storing and/or transporting nuclear fuel comprising:

a vessel comprising a vessel cavity and extending along a vessel axis;

a fuel basket positioned within the vessel cavity, the fuel basket comprising a grid forming a plurality of elongated cells, each of the cells extending along a cell axis that is substantially parallel to the vessel axis; and

an elongated tubular container comprising a container cavity containing damaged nuclear fuel, the elongated tubular container positioned within one of the cells, the elongated tubular container further comprising:

an extruded tubular wall forming a container cavity about a container axis, the extruded tubular wall formed of a metal matrix composite having neutron absorbing particulate reinforcement;

a bottom cap fixedly coupled to a bottom end of the extruded tubular wall;

a top cap detachably coupled to a top end of the extruded tubular wall;

the bottom cap including a plurality of first screens each comprising a plurality of openings that define lower vent passageways in fluid communication with a bottom of the container cavity; and

the top cap including a second screen comprising a plurality of openings that define upper vent passageways in fluid communication with a top of the container cavity;

wherein a top portion of the extruded tubular wall comprises locking apertures, and the top cap comprises locking elements in the form of laterally and linearly movable pins each arranged for insertion into a corresponding one of the locking apertures when the top cap is coupled to the extruded tubular wall;

each of the pins being movably alterable between a retracted state and an extended state, the locking elements biased into the extended state, and wherein the top cap is detachably locked to the extruded tubular wall when the pins are in the extended state and protrude into the locking apertures;

wherein the bottom cap comprises a body including a floor plate and plurality of oblique walls arranged obliquely to the container axis, the oblique walls extending upward from a perimeter of the floor plate to define an annular wall structure forming a tapered bottom end of the container;

wherein each of the oblique walls includes one of the first screens.

15. The system according to claim **14**, wherein the floor plate of the bottom cap has a solid structure free of openings.

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