Abstract: A shutdown rod for liquid lead or lead-bismuth cooled nuclear reactors comprising a column of ceramic boride absorber pellets enclosed in a steel cladding tube, wherein the cross sectional area of the steel cladding tube comprises at least 10% of the cross sectional area of the shutdown rod and the average density of the shutdown rod at a temperature of 400°C is larger than 10.7 g/cm³.
SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG). Published: — with international search report (Art. 21(3))
SHUTDOWN ROD FOR LEAD-COOLED REACTORS

Technical field
[001] This disclosure relates generally to the field of nuclear reactors and reactor safety, and concerns in particular a shutdown rod for lead-cooled and lead-bismuth cooled reactors.

Background
[002] The majority of nuclear reactors use shutdown rods containing a neutron absorbing material to allow the initiation of a controlled chain reaction of fission events, or to rapidly halt a controlled or uncontrolled chain of such events. During operation of the reactor, the shutdown rod is parked above or below the core, and when the need to halt the operation arises, the rod is vertically displaced until it absorbs a sufficient fraction of neutrons to make the reactor permanently sub-critical. The insertion mechanism can be active, for example by using electrical motors, hydraulic devices or gas expansion systems. In case the insertion mechanism is based on the use of gravity, shutdown can be accomplished in a so called passive mode. For reasons of safety, the ability to shut down a reactor using passive mechanisms, such as gravity, is a desired feature in modern reactor design.

[003] In nuclear power reactors utilizing a thermal neutron spectrum, boron carbide, enriched boron carbide, cadmium, silver-indium-cadmium alloys or hafnium may be used as neutron absorbing material in shutdown rods. However, in fast spectrum reactors, the neutron absorbing materials that have been under consideration are limited to boron and europium compounds since other elements have a much reduced ability to absorb fast neutrons [Mahagin 1979, Dunner 1984].

[004] In fast spectrum reactors cooled with lead or lead-bismuth, shutdown rods comprising of boron carbide, europium oxides or europium hexaborides must be parked below the reactor core, if gravity (or rather buoyancy) is to be used to achieve passive shutdown, since the density of the aforementioned absorbers is much lower than that of the coolant. This location increases the height of the reactor vessel and complicates the design of the core support structure. Conversely, in order to place the shutdown rods above the core, the density of the absorbing material must be
significantly higher than that of liquid lead or lead-bismuth, in order to achieve passive shutdown by means of gravity.

[005] It may be noted that hafnium diboride based absorber materials are known in the art. For example, US 3,565,762, issued in 1971, discloses an absorber element for nuclear reactors having a core of high-melting-point boride selected from the group which consists essentially of the diborides of zirconium, vanadium, hafnium and tantalum. US 6,334,963, issued in 2002, discloses a neutron adsorbent material being a composite material comprising hafnium diboride and hafnium dioxide.

**Summary of invention**

[006] One object of the present disclosure is to provide an improved shutdown rod for liquid lead or lead-bismuth cooled reactors permitting passive shutdown after parking the shutdown rod above the core. The rod consists essentially of a column of ceramic pellets enclosed in a steel cladding tube.

[007] This and other objects are achieved by the aspects and embodiments defined in the independent claims. Further advantageous embodiments have been specified in the dependent claims.

[008] A first aspect relates to a shutdown rod for liquid lead or lead-bismuth cooled nuclear reactors comprising a column of ceramic boride absorber pellets enclosed in a steel cladding tube, wherein the cross sectional areal of the steel cladding tube comprises at least 10% of the cross sectional area of the shutdown rod and the average density of the shutdown rod at a temperature of 400°C is at least 10.7 g/cm³.

[009] According to a first embodiment of said aspect, the ceramic absorber pellets consist essentially of ReB₂ (rhenium diboride). Preferably the boron is enriched to at least 90% in boron-10.

[0010] According to a second embodiment of said aspect, the ceramic absorber pellets consist essentially of (W, Re)B₂ (tungsten-rhenium diboride) in the hexagonal ReBe₂-phase. Preferably the boron is enriched to at least 90% in boron-10.
According to a third embodiment, the ceramic absorber pellets consist essentially of OsB2 (osmium diboride). Preferably, the boron is enriched to at least 90% in boron-10.

**Short description of the drawing**

The invention and embodiments thereof is now described, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows a schematic cross section of a shutdown rod or cartridge according to an embodiment.

**Detailed description**

Before the present invention is described, it is to be understood that the terminology employed herein is used for the purpose of describing particular embodiments only and is not intended to be limiting, since the scope of the invention will be limited only by the appended claims and equivalents thereof.

It must be noted that, as used in this specification and appended claims, the singular forms "a", "an" and "the" also include plural referents unless the context clearly dictates otherwise.

The expression "consists essentially of" is consciously used in the present disclosure and claims instead of the conventional and closed expression "consists of" in order to underline that minor amounts or trace amounts of other substances and impurities may be present, provided that the overruling characteristics are fulfilled, i.e. a minimum density of 10.7 g/cm³ at a temperature of about 400 °C is achieved.

The purpose of the present invention is to provide a shutdown rod for liquid lead or lead-bismuth cooled reactors permitting passive shutdown after parking the shutdown rod above the core. The rod consists essentially of a column of ceramic boride absorber pellets enclosed in a steel cladding tube. The cross sectional areal of the steel cladding tube comprises at least 10% of the cross sectional area of the shutdown rod.
[0018] A shutdown rod or cartridge (A) with absorption rods (B) according to an embodiment of the present disclosure is shown in Figure 1. The ceramic boride (1) is shown as dotted, and the steel cladding (2) as dashed surfaces in the figure. The rod or cartridge is shown here having a hexagonal cross section, and comprising 37 absorption rods. This is however only an example, and a rod or cartridge can have different shapes depending on the design of the reactor core. A cartridge can also contain different numbers of absorption rods, and these can be arranged in different configurations, again provided that the overruling characteristics are fulfilled, i.e. a minimum density of 10.7 g/cm³ at a temperature of about 400 °C is achieved.

[0019] In a preferred embodiment the ceramic absorber pellet consists essentially of ReB₂ (rhenium diboride) and is manufactured with a porosity of less than 11%. Preferably, the boron is enriched to at least 90% in boron-10.

[0020] In another preferred embodiment, the ceramic absorber pellet consists essentially of (W, Re)B₂ (tungsten-rhenium diboride) with a tungsten to rhenium molar ratio of 48% or less, and is manufactured with a porosity of less than 8%. Preferably, the boron is enriched to at least 90% in boron-10.

[0021] In a third preferred embodiment, the ceramic absorber pellet consists essentially of OsB₂ (osmium diboride) and is manufactured with a porosity of less than 12%. Preferably, the boron is enriched to at least 90% in boron-10.

[0022] By manufacturing ReB₂, (W, Re)B₂ or OsB₂ pellets with a sufficiently low porosity, the effective density of the shutdown rod including the steel cladding tube, can be made higher than that of liquid lead or lead-bismuth at operating temperatures. The latter densities are approximately 10.6 g/cm³ for liquid lead and 10.2 g/cm³ for liquid lead-bismuth. The theoretical densities (at zero porosity and room temperature) of ReB₂, (W₅₋₄.₈Re₀.₅₂)B₂ or OsB₂ are 12.7 g/cm³, 12.3 g/cm³; and 12.9 g/cm³; respectively. A requirement for the present applications is however that the density of the resulting shutdown rod is at least 10.7 g/cm³ at a temperature of about 400 °C.

[0023] Fabricating HfB₂ pellets with a porosity of less than 5%, such pellets would have a density higher than liquid lead. However, when taking into account that the average density of the absorber rod is significantly lower than that of bare pellets, hafnium diboride is not a suitable material for the present use.
[0024] It may also be noted that pure tungsten diboride exists only in the hexagonal AIB$_2$ phase, which is of considerably lower density than if it would exist in the high density hexagonal ReB$_2$ phase. Hence, tungsten diboride must be dissolved into ReB$_2$ in order to obtain a sufficiently high density to serve the purpose of the present invention. The solubility limit of tungsten diboride in rhenium diboride has been determined at 48% [Lech 2014].

[0025] Whereas the cost of rhenium is high, it is less than that of boron carbide enriched above 90%, which is often used for shutdown rod applications in fast reactors. The cost of osmium is also very high, and the application of OsB$_2$ would be considered in the case that highest possible density differential density between the shutdown rod and the coolant is desired.

[0026] A shutdown rod according to any of the aspects and embodiments presented herein, as well as any combinations thereof, offers the possibility to construct shutdown systems, in particular passive shutdown systems with high density and excellent shutdown reactivity. This is important both in normal shutdown and in safety shutdown situations. Further advantages will become apparent to a skilled person upon study of the example and the appended claims.

Example

[0027] In this example, the shutdown worth (i.e. the reduction in reactivity) was calculated for the lead-cooled SEALER reactor [Wallenius 2014]. The shutdown reactivity (per cent per cent mille) resulting from inserting three shutdown elements was calculated for each of the preferred embodiments of the present invention, using the Serpent Monte-Carlo code (Serpent is a three-dimensional continuous-energy Monte Carlo reactor physics burnup calculation code, developed at VTT Technical Research Centre of Finland since 2004. The publicly available Serpent 1 has been distributed by the OECD/NEA Data Bank and RSICC since 2009, and later versions of the code are available to registered users by request).

[0028] It was assumed that the boron in each boride compound was enriched to 96% in boron-10. As shown in Table 1, the shutdown reactivity of the presently disclosed shutdown rod is 100-200 per cent smaller than for the reference boron carbide rod, but it still meets the requirement of making the core sub-critical by at least 1000
pcm.

Table 1. Comparison of shutdown reactivity in the lead-cooled SEALER reactor for different neutron absorbers

<table>
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<tr>
<th>Absorber material</th>
<th>B₄C</th>
<th>ReB₂</th>
<th>(W, Re)B₂</th>
<th>OsB₂</th>
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<tr>
<td>Pellet density (g/cm³)</td>
<td>2.1</td>
<td>11.2</td>
<td>11.2</td>
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<td>Shutdown reactivity (pcm)</td>
<td>-1350</td>
<td>-1250</td>
<td>-1230</td>
<td>-1180</td>
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[0029] Without further elaboration, it is believed that a person skilled in the art can, using the present description, including the examples, utilize the present invention to its fullest extent. Also, although the invention has been described herein with regard to its preferred embodiments, which constitute the best mode presently known to the inventors, it should be understood that various changes and modifications as would be obvious to one having the ordinary skill in this art may be made without departing from the scope of the invention which is set forth in the claims appended hereto.
References


AT. Lech, Synthesis, Structure, and Properties of Refractory Hard-Metal Borides, PhD thesis, UCLA, 2014 (Permalink: [http://escholarship.org/uc/item/1hv5m731](http://escholarship.org/uc/item/1hv5m731))


Claims

1. A shutdown rod for liquid lead or lead-bismuth cooled nuclear reactors comprising a column of ceramic boride absorber pellets enclosed in a steel cladding tube, wherein the cross sectional areal of the steel cladding tube comprises at least 10% of the cross sectional area of the shutdown rod and the average density of the shutdown rod at a temperature of 400°C is at least 10.7 g/cm³.

2. A shutdown rod according to claim 1, where the ceramic absorber pellets consist essentially of ReB₂ (rhenium diboride).

3. A shutdown rod according to any one of claims 1 and 2, where the boron is enriched to at least 90% in boron-10.

4. A shutdown rod according to claim 1, where the ceramic absorber pellets consist essentially of (W,Re)B₂ (tungsten-rhenium diboride) in the hexagonal ReBe₂-phase.

5. A shutdown rod according to claim 4, where the boron is enriched to at least 90% in boron-10.

6. A shutdown rod according to claim 1, where the ceramic absorber pellets consist essentially of OsB₂ (osmium diboride).

7. A shutdown rod according to claim 6, where the boron is enriched to at least 90% in boron-10.
### Basis of the report

- **a.** With regard to the **language**, the international search was carried out on the basis of:
  - X: the international application in the language in which it was filed.
  - I: a translation of the international application into [language], which is the language of the translation furnished for the purposes of international search (Rules 12.3(a) and 23.1(b)).

- **b.** This international search report has been established taking into account the **rectification of an obvious mistake** authorized by or notified to this Authority under Rule 91 (Rule 43.6bis(a)).

- **c.** With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, see Box No. I.

### Certain claims were found unsearchable

(See Box No. II).

### Unity of invention is lacking

(See Box No. III).

### With regard to the title,

- X: the text is approved as submitted by the applicant.
- I: the text has been established by this Authority to read as follows:

### With regard to the abstract,

- X: the text is approved as submitted by the applicant.
- I: the text has been established, according to Rule 38.2, by this Authority as it appears in Box No. IV. The applicant may, within one month from the date of mailing of this international search report, submit comments to this Authority.

### With regard to the drawings,

- a. the figure of the drawings to be published with the abstract is Figure No. 1
  - X: as suggested by the applicant.
  - X: as selected by this Authority, because the applicant failed to suggest a figure.
  - I: as selected by this Authority, because this figure better characterizes the invention.

- b. X: none of the figures is to be published with the abstract.
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

IPC: see extra sheet
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC: C04B, G21 C

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE, DK, FI, NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal, PAJ, WPI data, COMPENDEX, INSPEC

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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Further documents are listed in the continuation of Box C. See patent family annex.

Date of the actual completion of the international search 10-03-2017
Date of mailing of the international search report 13-03-2017

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International Patent Classification (IPC)

G21C 7/24 (2006.01)
C04B 35/58 (2006.01)
G21C 7/12 (2006.01)
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