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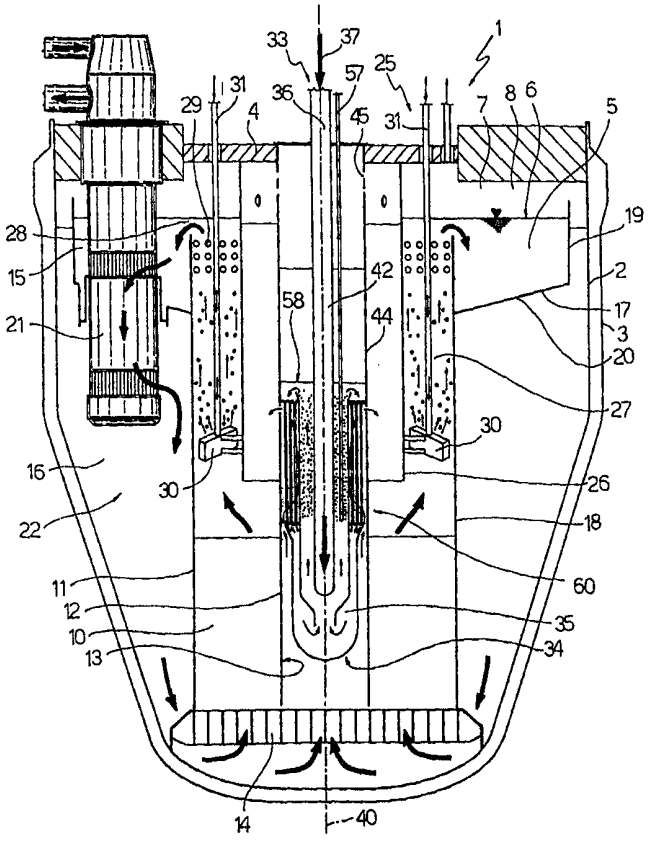
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(57) Abstract

Inside a vessel (2) of a nuclear reactor (1, 1a), e.g. a subcritical liquid–metal reactor, a hydraulic circuit (22) is defined to circulate a coolant (5) between a core (10) and a heat exchanger (21); the nuclear reactor (1, 1a) also features a device (33, 33a) for producing neutrons by interaction of a beam of high–energy particles (37) with an operating fluid (35) defined by a heavy–nucleus material; the device (33, 33a) has a supply conduit (36) in which a vacuum is substantially maintained, which directs the beam of high–energy particles (37) onto the operating fluid (35) inside the core (10) of the reactor (1, 1a), and which is separated from the operating fluid (35) by an interface (41, 93); the device (33, 33a) also has containing means (34) for containing the operating fluid (35) and defining a closed fluid dynamic circuit (43) in no way communicating hydraulically with the hydraulic circuit (22) of the coolant (5); carrier–gas circulating means (25) for keeping the operating fluid (35) moving in the closed fluid dynamic circuit (43); and heat–exchange means (49, 77) for withdrawing heat from the operating fluid (35).



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DEVICE FOR PRODUCING NEUTRONS, IN PARTICULAR FOR A SUBCRITICAL NUCLEAR REACTOR, AND NUCLEAR REACTOR FEATURING SUCH A DEVICE

TECHNICAL FIELD

The present invention relates to a device for producing neutrons, in particular for a subcritical nuclear reactor, and to a nuclear reactor featuring such a device.

BACKGROUND ART

As is known, in "subcritical" nuclear reactors, the fuel mass in the core is less than the so-called "critical" mass required to produce a self-supporting nuclear fission reaction, which is maintained by an auxiliary device producing the quantity of neutrons required by the system, so that the external neutron supply need simply be cut off to arrest the nuclear reaction and so "turn off" the reactor, with obvious advantages in terms of safety.

In particular, the neutrons required by the reaction system are known to be produced by interaction

of a beam of high-energy particles (typically protons) with heavy nuclei in the system itself, e.g. in the core of the reactor, so that the neutrons produced are multiplied in subcritical conditions by the fission process in the core. International Patent Application PCT/EP94/02467, for example, describes a reactor wherein a beam of high-energy particles, produced by an accelerator, is fed into the core along a supply conduit in which a vacuum is substantially maintained, and which is closed at the bottom end by a hemispherical bottom wall or so-called "window". The bottom end of the conduit housed inside the core is immersed in a fluid comprising heavy-nucleus material (liquid metals or molten metal salts) and which, in particular, is the coolant of the reactor itself. At the end of the conduit, the high-energy particles travel through, and yield part of their energy to, the bottom wall, and so interact with the heavy-nucleus fluid to initiate neutron production. Such a system subjects the bottom wall of the supply conduit to particularly severe operating conditions : besides being damaged by the high-energy particles traveling though it, the bottom wall of the conduit is also subjected to severe temperature gradients - severe internal heating by the particles, and external cooling by the heavy-nucleus fluid - alongside an already high operating temperature. Moreover, on account of the vacuum in the conduit, the

external pressure of the heavy-nucleus fluid on the bottom wall is not balanced by the pressure inside the conduit. Finally, radioactive products, which may possibly diffuse outside the reactor, are formed in the supply conduit by the interaction between the high-energy particles and the heavy-nucleus fluid (so-called "spallation" process).

In one possible variation of the above technique, the high-energy particle beam, after traveling through the bottom wall of the supply conduit, interacts with a confined portion of heavy-nucleus fluid separated from the reactor coolant, in which the radioactive products of the "spallation" process are therefore not diffused. This, however, gives rise to the further problem of drawing off the power accumulated in the confined portion of fluid following interaction with the high-energy particle beam.

One known solution provides, using appropriate circulating means, for feeding the heavy-nucleus fluid from the region of interaction with the high-energy particle beam back up to the top of the reactor where it is cooled by appropriate heat exchangers. In the case of heavy-nucleus fluid, however, the considerable height of the cooling circuit, especially if the circulating means are located outside the reactor, would obviously result in severe pressure precisely on the bottom wall of the supply conduit, already subjected to thermal and neutron

stress. As such, the thickness of the bottom wall would have to be increased, which in turn would result in a greater release of energy in, and consequently an undesired increase in the temperature of, the bottom wall.

DISCLOSURE OF INVENTION

It is an object of the present invention to eliminate the above problems typically associated with known subcritical reactors, by providing a reactor featuring a neutron-producing device designed to eliminate or reduce the drawbacks of such reactors.

According to the present invention, there is provided a device, in particular for a subcritical nuclear reactor, for producing neutrons by interaction between a beam of high-energy particles and an operating fluid defined by a heavy-nucleus material, the device comprising a supply conduit whereby said beam of high-energy particles is directed onto said operating fluid; and containing means for containing said operating fluid and located at a first end of said supply conduit; characterized in that said supply conduit comprises at least one vacuum portion in which a vacuum is substantially maintained, and has, at said first end, an interface separating said vacuum portion and said operating fluid; and in that said containing means for containing said operating fluid define a closed fluid dynamic circuit; the device also comprising circulating

means for circulating said operating fluid in said closed fluid dynamic circuit to keep said operating fluid moving at said interface; and heat-exchange means for withdrawing heat from said operating fluid moving in said closed fluid dynamic circuit.

In particular, said circulating means for circulating said operating fluid comprise an infeed circuit for feeding a carrier gas into said closed fluid dynamic circuit of said operating fluid; the device also comprising separating means for separating said carrier gas from a first free surface of said operating fluid; and conducting means for conducting said carrier gas to prevent the carrier gas from circulating in said vacuum portion of said supply conduit.

According to a first embodiment of the invention, said interface is defined by a bottom wall of said supply conduit; said containing means comprising a conducting conduit terminating at the bottom with an opening preferably in the shape of an inverted bottle neck; and said operating fluid being fed into said containing conduit up to a predetermined level defined by said first free surface.

In one variation, said interface is defined by a second free surface of said operating fluid; said first end of said supply conduit being an open end defined by a circular edge; said second free surface being located at a higher level with respect to said first free

surface, at which said carrier gas is separated from said operating fluid; said separating means for separating said carrier gas from said operating fluid, and said containing means for containing said operating fluid being such as to maintain a predetermined pressure difference over said first and said second free surface, so that said second free surface is maintained at a higher level than said first free surface.

The invention also applies to nuclear reactors, in particular subcritical nuclear reactors, featuring the neutron-producing device described briefly.

The device according to the invention therefore provides for obtaining nuclear reactors in which the liquid and solid radioactive spallation products are confined within the operating fluid with no contamination of the reactor coolant. At the same time, the operating fluid is kept constantly moving in the closed fluid dynamic circuit in which it circulates, thus enabling removal of the heat generated in the operating fluid by bombardment with the high-energy particles. Moreover, the operating fluid may be circulated using the same carrier-gas circulating means already provided for circulating the reactor coolant, thus eliminating, for example, the need for, and any problems connected with the installation of, high-performance mechanical pumps. The operating fluid is cooled using a portion of the reactor coolant itself,

thus eliminating the need for additional complex cooling circuits : the particular construction characteristics of the heat-exchange means also prevent the onset of structural hyperstatics of components at different temperature.

When interaction with the heavy-nucleus operating fluid calls for the high-energy particle beam to travel through a mechanical wall (the bottom wall of the supply conduit), the invention provides for significantly reducing stress on the wall, which is undoubtedly lower than that imposed by known solutions. According to the invention, in fact, the head of heavy-nucleus fluid acting on the bottom wall of the supply conduit is significantly less than that of the reactor coolant, so that the wall need not be excessively thick.

Conversely, if the supply conduit terminates with a free surface of operating fluid, there is no need at all for a mechanical wall subjected to severe operating conditions. In this case, too, the operating fluid is kept moving and cooled, to dissipate the power absorbed in the spallation process, using an auxiliary carrier-gas circulation device requiring no mechanical pumps. Despite this, the particular construction characteristics of the invention provide for substantially zero pressure (at most equal to the vapour pressure of the operating fluid) over the free surface defining the particle beam interaction interface; and

the carrier gas is separated from the operating fluid at a further free surface, at a different level from the previous one. As such, a vacuum may substantially be maintained in the supply conduit, which need not be filled with pressurized gas - as would otherwise be necessary to exploit the auxiliary carrier-gas circulation device, thus reducing the power of the particle beam and increasing stress on the supply conduit : in particular, a partition inserted inside the supply conduit at a predetermined distance from the end with the operating fluid interface (e.g. for preventing radioactive leakage from the supply conduit) could easily be made very thin, with no technical problems, by virtue of being subjected to little stress.

BRIEF DESCRIPTION OF THE DRAWINGS

A number of non-limiting embodiments of the present invention will be described by way of example with reference to the accompanying drawings, in which:

Figure 1 shows a schematic longitudinal section of a nuclear reactor featuring a neutron-producing device in accordance with the invention;

Figure 2 shows a schematic, larger-scale longitudinal section of a detail of the Figure 1 nuclear reactor;

Figure 3 shows a schematic longitudinal section of a variation of the Figure 1 nuclear reactor;

Figure 4 shows a schematic, larger-scale

longitudinal section of a detail of the Figure 3 variation;

Figure 5 shows a schematic, larger-scale longitudinal section of a further detail of the Figure 3 variation;

Figures 6 and 7 show two cross sections along lines VI-VI and VII-VII of the Figure 4 detail.

BEST MODE FOR CARRYING OUT THE INVENTION

Number 1 in Figures 1 and 2 indicates as a whole a natural-coolant-circulation nuclear reactor employing a liquid metal, e.g. lead, as the coolant.

Reactor 1 comprises, in known manner, an inner vessel 2 and an outer vessel 3, both substantially cylindrical and closed at the top by a cover 4. Vessel 2 contains a predetermined quantity of a coolant 5 - in the example shown, a liquid metal (e.g. lead) - up to a free surface 6; and a predetermined quantity of an inert gas 7 contained in a chamber 8 located over free surface 6 of coolant 5 and beneath cover 4.

The bottom of vessel 2 houses the so-called core 10 containing, as is known, the nuclear fuel. Core 10 has a substantially annular structure, is defined externally by an enclosure 11, and is defined internally by an inner ring 12 of known fuel elements (not shown in detail) internally coaxial with enclosure 11 and defining a substantially cylindrical seat 13 inside core 10. Further fuel elements are arranged in a number of

concentric rings (not shown) between inner ring 12 and enclosure 11; and core 10 is supported at the bottom by a known grille 14 for conveying coolant 5 inside core 10.

According to a known construction solution particularly suitable for liquid-metal reactors, reactor 1 houses an upper manifold 15 and lower manifold 16 separated by a known structure 17 comprising a first cylindrical portion 18 coaxial with vessel 2 and substantially defining an extension of enclosure 11 of core 10, and a second cylindrical portion 19 also coaxial with vessel 2 and which is radially outwards of and connected to portion 18 by a substantially truncated-cone-shaped connecting portion 20. Reactor 1 also comprises at least one known heat exchanger 21 located at separating structure 17 between manifolds 15 and 16, and which provides for withdrawing heat from coolant 5. In actual use, the upper ("hot") manifold 15 feeds hot liquid metal to heat exchanger 21, while the lower ("cold") manifold 16 feeds cold liquid metal from exchanger 21 to core 10, thus defining a cooling circuit 22.

According to a known solution described in Italian Patent Application n. TO96A001081 filed by the present Applicant, reactor 1 preferably, though not necessarily, also comprises an auxiliary-circulation device 25 for assisting natural circulation of coolant 5 in reactor 1.

For this purpose, cylindrical portion 18 of separating structure 17 extends upwards beyond connecting portion 20 up to a predetermined distance beneath free surface 6 of coolant 5; a cylindrical element 26 of predetermined diameter is housed coaxially inside cylindrical portion 18, at a predetermined distance from core 10, and extends vertically above free surface 6 of coolant 5, where it is secured to cover 4; and cylindrical element 26 and cylindrical portion 18 define an annular conduit 27 inside hot manifold 15 and communicating hydraulically with hot manifold 15 via an annular passage 28 defined by the predetermined distance between cylindrical portion 18 and free surface 6 of coolant 5, and by a number of holes 29 formed through the lateral wall of cylindrical portion 18. Annular conduit 27 houses a number of diffusers 30, which are fed by respective connecting conduits 31 and blowers (not shown) with a stream of compressed gas drawn, for example, from the inert cover gas 7 of reactor 1 in chamber 8, and which, as illustrated in Italian Patent Application n. TO96A001081, assists natural circulation of coolant 5 inside reactor 1 by lightening the column of hot liquid metal from core 10.

Reactor 1 is a subcritical reactor - that is, the quantity of nuclear fuel in core 10 is less than that required to maintain a self-supporting fission reaction of the fuel - and therefore comprises a device 33 for

producing the neutrons required to sustain the reaction. In particular, neutron-producing device 33 comprises containing means 34 for containing an operating fluid 35 comprising heavy-nucleus material (and hereinafter referred to also as "heavy-nucleus operating fluid"); and a supply conduit 36 by which a controlled beam of high-energy particles (e.g. protons) - indicated by arrow 37 in Figure 1 - is directed against heavy-nucleus operating fluid 35 to generate, in known manner, a predetermined number of neutrons by the interaction of beam 37 with operating fluid 35. In the example shown, supply conduit 36 is a substantially cylindrical conduit, which is located at the central longitudinal axis 40 of reactor 1, extends through cover 4, and terminates at the bottom end 39 with a substantially hemispherical bottom wall 41 housed inside seat 13 of core 10. A vacuum is substantially maintained in supply conduit 36, including, in particular, an end portion 42 extending from bottom wall 41.

According to the present invention, means 34 for containing operating fluid 35 define, for operating fluid 35, a closed fluid dynamic circuit 43 in no way communicating hydraulically with cooling circuit 22 of the reactor : despite comprising the same type of fluid as the coolant of reactor 1 (e.g. molten lead), operating fluid 35 is therefore a confined portion of, and in no way mixes with, the coolant during operation

of reactor 1.

In the example shown, containing means 34 comprise a substantially cylindrical containing conduit 44, which extends downwards from, and is supported by, cover 4 of reactor 1, is concentric and coaxial with supply conduit 36, and comprises, above free surface 6 of coolant 5, holes 45 enabling communication with chamber 8 of reactor 1, containing inert gas 7, so that containing conduit 44 prevents coolant 5 from entering fluid dynamic circuit 43 of operating fluid 35.

Containing conduit 44 comprises a top portion 46 extending from cover 4 to a predetermined distance over core 10; and a bottom portion 47 smaller in diameter than top portion 46 and terminating at the bottom - beneath bottom wall 41 of supply conduit 36 and also inside seat 13 of core 10 - with a hemispherical bottom wall 48.

Top portion 46 and bottom portion 47 of containing conduit 44 are connected hydraulically by a pipe bundle 49 comprising a number of heat-exchange pipes arranged, for example, in a number of concentric rings and welded at opposite longitudinal ends to two annular pipe plates 50, 51. Annular pipe plate 50 is located at the bottom end of top portion 46; annular pipe plate 51 is located at the top end of bottom portion 47, just above core 10; the top annular pipe plate 50 is welded to a radially-outer edge of top portion 46 of containing conduit 44;

the bottom annular pipe plate 51 is welded to a radially-outer edge of bottom portion 47 of containing conduit 44; respective inner edges of annular pipe plates 50, 51 are welded to a substantially cylindrical conducting conduit 52 coaxial with, and a predetermined radial distance from, supply conduit 36; and conducting conduit 52 projects at the top by a predetermined portion from annular pipe plate 50, and, at the bottom, projects from annular pipe plate 51 to a point beneath bottom wall 41 of supply conduit 36, where conducting conduit 52 terminates with a circular opening 53 preferably in the shape of an inverted bottle neck.

A further enclosure 54 extends downwards, as an extension of top portion 46 of containing conduit 44, from top annular pipe plate 50 to core 10. In the preferred embodiment shown in Figures 1 and 2, enclosure 54 is so shaped as to fit partially inside seat 13 of the core, but may, alternatively, extend the full height of core 10 to define, for example, an inner containing structure of core 10. Whichever the case, enclosure 54 has radial through openings 55 close to annular pipe plate 50.

An annular gap 56, defined inwards by supply conduit 36 and outwards by conducting conduit 52, houses a number of infeed conduits 57 (only one shown in Figures 1 and 2 for the sake of simplicity) for injecting a stream of gas, and the bottom ends of which

are located just over the active portion of core 10. As explained later on, and according to the principle described in Patent Application n. TO96A001081 filed by the present Applicant, infeed conduits 57 provide for assisting circulation of operating fluid 35 along fluid dynamic circuit 43; and, in this case also, the circulation gas used may advantageously be drawn from inert gas 7 in chamber 8, possibly by the same auxiliary-circulation device 25 used to assist circulation of coolant 5.

In actual use, containing conduit 44 is filled with a predetermined quantity of operating fluid 35 up to a predetermined level defined by a free surface 58 : free surface 58 of operating fluid 35 is at a significantly lower level than free surface 6 of coolant 5 in reactor 1, but is above conducting conduit 52 inside containing conduit 44.

As is known, during operation of reactor 1, particle beam 37 - after traveling along supply conduit 36 and through bottom wall 41 (which therefore defines an interface between vacuum portion 42 of supply conduit 36 and operating fluid 35) - interacts with the operating fluid 35 beneath bottom wall 41 to generate neutrons by which to support the nuclear reaction in core 10; and the operating fluid 35 heated by particle beam 37 flows up along annular gap 56, which therefore defines an annular upflow conduit for operating fluid

35. The upflow of operating fluid 35 along annular conduit 56 is assisted by infeed conduits 57 injecting a carrier gas drawn, for example, from chamber 8 by appropriate known blowers (not shown), and which provides for further lightening, and so assisting the upflow of, the column of hot operating fluid 35 inside annular conduit 56.

Operating fluid 35 therefore flows up annular conduit 56, inside conducting conduit 52, up to free surface 58 where the carrier gas is separated from operating fluid 35 and flows along containing conduit 44 back into chamber 8. Operating fluid 35, on the other hand, separated from the carrier gas, flows down through pipe bundle 49 in which it is cooled by a portion of coolant 5 issuing from core 10 at a lower temperature than operating fluid 35. The operating fluid 35 cooled in pipe bundle 49 then flows along an annular downflow conduit 59 defined outwards by bottom portion 47 of containing conduit 44 and inwards by conducting conduit 52; and, on reaching bottom wall 48 of containing conduit 44, operating fluid 35 flows back up through opening 53 of conducting conduit 52, and is again subjected to particle beam 37.

In the meantime, coolant 5 obviously circulates along cooling circuit 22 of reactor 1. In particular, a portion of coolant 5 - entering core 10 and at a lower temperature than operating fluid 35 following

interaction with particle beam 37 - flows through seat 13 of core 10, flows up inside enclosure 54 and over pipe bundle 49 to remove heat from operating fluid 35, and then flows out through radial openings 55 and back into the stream of coolant 5 flowing up from core 10.

In other words, pipe bundle 49 combines with enclosure 54 to define a heat exchanger 60 : as stated, in the non-limiting example shown in Figures 1 and 2, operating fluid 35 flows inside the heat-exchange pipes in pipe bundle 49, while coolant 5 of reactor 1 circulates on the outside. The same function, however, may obviously be performed by a heat exchanger of a different configuration from the one described.

For example, in one possible variation (not shown in detail for the sake of simplicity, but by now clear to an experienced technician), operating fluid 35 is cooled by an auxiliary coolant, as opposed to the same coolant 5 circulating in reactor 1; and enclosure 54 and top portion 46 and bottom portion 47 of containing conduit 44 are connected continuously to one another to define one containing system for operating fluid 35, into which coolant 5 does not flow. In which case, pipe bundle 49 is advantageously separated from the containing system and connected to a closed circuit for circulating the auxiliary coolant supplied, for example, from outside reactor 1, so that the auxiliary coolant flows inside the heat-exchange pipes in pipe bundle 49,

while operating fluid 35 circulates on the outside.

In a further variation (not shown for the sake of simplicity), the carrier gas separated from operating fluid 35 at free surface 58 may - as opposed to being fed directly back into chamber 8 - be fed to an external cooling and purifying circuit for condensing and so separating and preventing any radioactive products (e.g. mercury) in the gas from being fed back into reactor 1.

Neutron-producing device 33 according to the invention therefore provides for confining liquid and solid radioactive spallation products within operating fluid 35, and so preventing contamination of coolant 5 of reactor 1. Moreover, the head of operating fluid 35 acting on bottom wall 48 of supply conduit 36 is no more than that defined by the different levels of bottom wall 48 and free surface 58 of operating fluid 35 inside containing conduit 44, and is significantly less than the head coolant 5 would have if in contact with wall 48.

Figures 3 to 7 - in which any details similar or identical to those already described are indicated using the same reference numbers - show a reactor 1a comprising a vessel 2 closed at the top by a cover 4 and defining internally a cooling circuit 22 for circulating a coolant 5 (e.g. liquid metal) between a core 10 and at least one heat exchanger 21. In the example shown, the reactor comprises a substantially cylindrical structure

17 coaxial with vessel 2 and extending upwards from an enclosure 11 of core 10 to a predetermined distance beneath free surface 6 of coolant 5; and a cylindrical element 26 housed coaxially inside structure 17 and extending from cover 4 to a predetermined distance over core 10. As such, cylindrical element 26 and structure 17 define an inner annular conduit 27; and structure 17 and vessel 2 define an outer annular conduit 32 communicating hydraulically with inner annular conduit 27 via an annular passage 28 defined by the predetermined distance between structure 17 and free surface 6 of coolant 5, and by a number of holes 29 formed through the lateral wall of structure 17. In this case, too, annular conduit 27 houses a number of connecting conduits 31 for supplying a stream of compressed gas drawn, for example, from the inert cover gas 7 of reactor 1a contained in chamber 8.

Reactor 1a is also a subcritical reactor, and therefore comprises a device 33a for producing the neutrons required to maintain the reaction, and which in turn comprises containing means 34 defining a closed fluid dynamic circuit 43 for a heavy-nucleus operating fluid 35, and a supply conduit 36 by which a beam 37 of high-energy particles (e.g. protons) is directed against heavy-nucleus operating fluid 35 inside a seat 13 of core 10.

Supply conduit 36 is again a substantially

cylindrical conduit located at the central longitudinal axis 40 of reactor 1a and extending through cover 4, but in this case comprises an open bottom end 39 defined by a circular edge 62 and housed inside seat 13 of core 10.

Circular edge 62 of supply conduit 36 is connected to a shaped conduit 64, each section of which is larger in diameter than supply conduit 36, and which comprises, as of a first end 65 connected to circular edge 62 of supply conduit 36, a cylindrical first portion 66 and a diverging second portion 67 possibly connected to each other by a short converging portion 68. Diverging portion 67 terminates at an open second end 69 of shaped conduit 64, opposite end 65 and located close to a bottom edge 70 of core 10.

As described with reference to Figures 1 and 2, in this case also, supply conduit 36 is surrounded by a containing conduit 44, albeit of a different conformation. In the example shown, containing conduit 44 comprises three successive, substantially cylindrical portions 71, 72, 73 connected to one another : a first portion 71 closely surrounds supply conduit 36; a second portion 72 surrounds cylindrical first portion 66 of shaped conduit 64; and a third portion 73, larger in diameter than portions 71 and 72, surrounds diverging portion 67 of shaped conduit 64, extends downwards beyond end 69 of shaped conduit 64 to a predetermined distance beneath bottom edge 70 of core 10, and

terminates with a pipe plate 74.

Beneath and a predetermined distance from circular edge 62 of supply conduit 36, a conducting conduit 52 is inserted inside shaped conduit 64, defines a separate extension of supply conduit 36, and terminates at the bottom, beyond end 69 of shaped conduit 64, with a diverging portion 76 anchored to an inner lateral wall of third portion 73 of containing conduit 44. Conducting conduit 52 defines an annular conduit 59 inside containing conduit 44; and shaped conduit 64, housed inside annular conduit 59, divides annular conduit 59 longitudinally into an inner annular conduit 59' and an outer annular conduit 59".

A number of heat-exchange pipes 77 extend from pipe plate 74, are arranged, for example, in concentric rings, and are connected to a hemispherical bottom portion 78 located beneath a second pipe plate 79.

A number of angularly-spaced upflow conduits 80, larger in diameter than heat-exchange pipes 77, are fitted through close to the peripheral edge of pipe plate 79.

Upflow conduits 80 are fitted, inside guide pipes 82, through pipe plates 74 and 79; are not welded to and so are movable vertically with respect to pipe plates 74 and 79; are secured (e.g. welded) to diverging portion 76 of conducting conduit 52; extend along conducting conduit 52 and a predetermined distance into annular

conduit 59" (defined inwards by shaped conduit 64 and outwards by containing conduit 44); and terminate with respective flared ends 83.

Heat-exchange pipes 77 are housed inside an enclosure 84, which, from a predetermined point just over bottom pipe plate 79, extends into and along the full vertical height of core 10 to define seat 13. More specifically, enclosure 84 comprises a first portion 85 radially enclosing heat-exchange pipes 77, and a second portion 86 larger in diameter than first portion 85 and defining seat 13 of core 10. At top pipe plate 74, to which it is secured radially, enclosure 84 comprises a portion 87 connecting different-diameter portions 85 and 86.

Heat-exchange pipes 77 and enclosure 84 define a heat exchanger 60. As stated with reference to Figures 1 and 2, in this variation also, use may obviously be made of a heat exchanger of a different configuration to the one described (in particular, employing an auxiliary coolant separate from coolant 5 of reactor 1a).

Respective infeed conduits 88, supported by known fasteners and for injecting a carrier gas drawn, for example, from chamber 8, are housed concentrically inside upflow conduits 80 and connected to chamber 8. From an intermediate section, between pipe plates 74 and 79, of upflow conduits 80, infeed conduits 88 extend beyond containing conduit 44 into seat 13 of core 10,

where, inside guide pipes 89, they extend up to cover 4 of reactor 1a (from which they are connected by a circuit (not shown) to chamber 8 containing inert gas 7).

Supply conduit 36 is connected in known manner to a vacuum pump 90 for substantially maintaining a vacuum in supply conduit 36, and in particular in end portion 42.

Together with cylindrical portion 66 of shaped conduit 64 and supply conduit 36 connected to shaped conduit 64, containing conduit 44 defines an annular passage 91 connected at the top to chamber 8 of inert gas 7 (by a circuit not shown for the sake of simplicity).

In actual use, a predetermined quantity of operating fluid 35 is fed into containing conduit 44 to define, inside annular conduits 59" and 59', two different levels defined by respective free surfaces 92, 93 located respectively at converging portion 68 of shaped conduit 64 and at bottom end 39 of supply conduit 36. That is, whereas a vacuum is substantially maintained in supply conduit 36, so that free surface 93 of operating fluid 35 in annular conduit 59' is substantially at zero pressure, free surface 92 in annular conduit 59" is at the same pressure (e.g. atmospheric pressure) as chamber 8 of the reactor, to which it is connected hydraulically by annular passage 91; which difference in pressure results in a difference

in the levels of free surfaces 92, 93. Moreover, free surface 93 is located inside core 10, at a significantly lower level than the free surface 6 of coolant 5 in reactor 1a.

During operation of reactor 1a, particle beam 37 travels along vacuum supply conduit 36 and interacts with the operating fluid 35 directly beneath free surface 93; operating fluid 35 is kept moving along closed fluid dynamic circuit 43 - defined by containing means 34 - by the carrier gas injected into upflow conduits 80 by infeed conduits 88; the operating fluid 35 lightened by the carrier gas therefore flows up upflow conduits 80 to flared ends 83 beneath free surface 92; and, at free surface 92, the carrier gas is separated from operating fluid 35 and flows along annular passage 91 back into chamber 8. Operating fluid 35 separated from the carrier gas, on the other hand, flows along the path indicated by the arrows in Figure 4: first down into annular conduit 59" defined between shaped conduit 64 and containing conduit 44, and then up into annular conduit 59' defined between shaped conduit 64 and conducting conduit 52; along the annular passage defined by the gap between conducting conduit 52 and supply conduit 36, operating fluid 35 flows up to free surface 93, where it is bombarded by particle beam 37, then down along conducting conduit 52 to heat-exchange pipes 77, through heat-exchange pipes 77 to bottom

portion 78, and then back up into upflow conduits 80.

In the meantime, coolant 5 circulates inside cooling circuit 22 of reactor 1a. In particular, coolant 5 from heat exchanger 21 is fed to the bottom of reactor 1a, where a portion of coolant 5 flows radially beneath enclosure 84 and between enclosure 84 and pipe plate 79 into enclosure 84 itself, and then up towards core 10 over the outside of heat-exchange pipes 77 to cool the operating fluid 35 circulating in pipes 77 (coolant 5 being at a lower temperature than operating fluid 35). The portion of coolant 5 then flows up inside enclosure 84 to core 10 where it mixes with and is again circulated with the rest of coolant 5 from core 10.

As shown in Figure 7, at portion 86 defining seat 13 of core 10, enclosure 84, as opposed to being substantially cylindrical, may be so shaped as to define a guide structure for fuel elements 100 in core 10. In particular, if fuel elements 100 are hexagonal and arranged in a typical pattern of concentric rings, and if seat 13 is formed by removing, for example, the three innermost rings, portion 86 of enclosure 84 will reproduce the outline of the remaining fuel elements.

Clearly, further changes may be made to the device as described above without, however, departing from the scope of the accompanying Claims.

CLAIMS

1) A device (33, 33a), in particular for a subcritical nuclear reactor, for producing neutrons by interaction between a beam of high-energy particles (37) and an operating fluid (35) defined by a heavy-nucleus material, the device comprising a supply conduit (36) whereby said beam of high-energy particles (37) is directed onto said operating fluid (35); and containing means (34) for containing said operating fluid (35) and located at a first end (39) of said supply conduit (36); characterized in that said supply conduit (36) comprises at least one vacuum portion (42) in which a vacuum is substantially maintained, and has, at said first end (39), an interface (41, 93) separating said vacuum portion (42) and said operating fluid (35); and in that said containing means (34) for containing said operating fluid (35) define a closed fluid dynamic circuit (43); the device (33, 33a) also comprising circulating means (25) for circulating said operating fluid (35) in said closed fluid dynamic circuit (43) to keep said operating fluid (35) moving at said interface (41, 93); and heat-exchange means (60) for withdrawing heat from said operating fluid (35) moving in said closed fluid dynamic circuit (43).

2) A device as claimed in Claim 1, characterized in that said circulating means (25) for circulating said

operating fluid (35) comprise an infeed circuit (57, 88) for feeding a carrier gas into said closed fluid dynamic circuit (43) of said operating fluid (35); the device (33, 33a) also comprising separating means for separating said carrier gas from a first free surface (58, 92) of said operating fluid (35); and conducting means for conducting said carrier gas to prevent the carrier gas from circulating in said vacuum portion (42) of said supply conduit (36); said circulating means (25) circulating said operating fluid (35) continuously in said closed fluid dynamic circuit (43) between said interface (41, 93) and said heat-exchange means (60) and via said first free surface (58, 92).

3) A device as claimed in Claim 2, characterized in that said containing means (34) for containing said operating fluid (35) comprise a containing structure (44) concentrically and coaxially surrounding said supply conduit (36), at a predetermined radial distance from the supply conduit, and into which is fed a predetermined quantity of said operating fluid (35); said heat-exchange means comprising at least one heat exchanger (60) in which heat is removed from said operating fluid (35) by a coolant (5).

4) A device as claimed in Claim 3, characterized in that said at least one heat exchanger (60) is a shell-and-pipe exchanger comprising a number of heat-exchange pipes (49, 77) forming part of said closed fluid dynamic

circuit (43) of said operating fluid (35); said heat-exchange pipes (49, 77) being traveled along internally by said operating fluid (35), and being immersed in a cooling circuit (22) in which said coolant (5) circulates.

5) A device as claimed in Claim 3 or 4, characterized in that said containing means (34) comprise a containing conduit (44) substantially concentric and coaxial with said supply conduit (36); and a conducting conduit (52) located radially inwards of said containing conduit (44) and defining, with the containing conduit, a first annular conduit (59) traveled along by said operating fluid (35).

6) A device as claimed in Claim 5, characterized in that said interface is defined by a bottom wall (41) of said supply conduit (36); said operating fluid (35) being fed into said containing conduit (44) up to a predetermined level defined by said first free surface (58); said conducting conduit (52) being interposed radially between said containing conduit (44) and said supply conduit (36), and respectively defining, with said containing conduit and said supply conduit, said first annular conduit (59) and a second annular conduit (56) radially inwards with respect to said first annular conduit (59); said conducting conduit (52) extending from a predetermined distance beneath said first free surface (58) of said operating fluid (35) to a point

beneath said bottom wall (41) of said supply conduit, where said conducting conduit terminates with an opening (53) preferably in the shape of an inverted bottle neck.

7) A device as claimed in Claim 6, characterized in that said containing conduit (44) comprises a top portion (46), and a bottom portion (47) smaller in diameter than said top portion (46) and terminating at the bottom, beneath said bottom wall (41) of said supply conduit (36), with a hemispherical bottom wall (48); said top portion (46) and said bottom portion (47) of said containing conduit (44) being connected hydraulically by said number of heat-exchange pipes (49) extending longitudinally between two annular pipe plates (50, 51); said conducting conduit (52) extending through said annular pipe plates (50, 51).

8) A device as claimed in Claim 7, characterized in that said circulating means (25) for circulating said operating fluid (35) comprise a number of infeed conduits (57) for feeding a stream of gas into said second annular conduit (56).

9) A device as claimed in Claim 5, characterized in that said interface is defined by a second free surface (93) of said operating fluid (35); said first end (39) of said supply conduit (36) being an open end defined by a substantially circular edge (62); said second free surface (93) being located at a higher level with respect to said first free surface (92), at which said

carrier gas is separated from said operating fluid (35); said separating means for separating said carrier gas from said operating fluid (35), and said containing means (34) for containing said operating fluid (35) being such as to maintain a predetermined pressure difference over said first (92) and said second (93) free surface, so that said second free surface (93) is maintained at a higher level than said first free surface (92).

10) A device as claimed in Claim 9, characterized in that said containing means (34) also comprise a shaped conduit (64) connected to said substantially circular edge (62) of said supply conduit (36) and interposed radially between, and substantially coaxial and concentric with, said conducting conduit (52) and said containing conduit (44); said conducting conduit (52) extending inside said shaped conduit (64) from a predetermined distance beneath said substantially circular edge (62) of said supply conduit (36), and terminating at the bottom, beyond a bottom end (69) of said shaped conduit (64), with a diverging portion (76) anchored to an inner lateral wall of said containing conduit (44); said shaped conduit (64) dividing said first annular conduit (59) longitudinally, and defining, in said first annular conduit, a second (59') and a third (59") annular conduit substantially concentric and coaxial with each other and traveled along in opposite

directions by said operating fluid (35); said operating fluid (35) being fed into said second annular conduit (59') up to a level corresponding to said second free surface (93), and into said third annular conduit (59") up to a level corresponding to said first free surface (92).

11) A device as claimed in Claim 10, characterized in that, as of a first end (65) connected to said substantially circular edge (62) of said supply conduit (36), said shaped conduit (64) comprises a substantially cylindrical first portion (66) and a diverging second portion (67); said diverging second portion (67) terminating at an open second end (69), opposite said first end (65), of said shaped conduit (64).

12) A device as claimed in Claim 11, characterized in that said containing conduit (44) extends so as to surround, with respective successive mutually-connected portions (71, 72, 73), said supply conduit (36), said substantially cylindrical first portion (66) of said shaped conduit (64) and said diverging second portion (67) of said shaped conduit (64); said containing conduit (44) defining, together with said substantially cylindrical first portion (66) of said shaped conduit (64) and with said supply conduit (36), an annular passage (91) for the upflow of said carrier gas from said first free surface (92) of said operating fluid (35).

13) A device as claimed in Claim 12, characterized in that said containing conduit (44) extends downwards beyond said second end (69) of said shaped conduit (64), and terminates with a first pipe plate (74); said number of heat-exchange pipes (77) extending from said first pipe plate (74) to a second pipe plate (79), and connecting said conducting conduit (52) hydraulically to a bottom portion (78) located beneath said second pipe plate (79); said containing means (34) for containing said operating fluid also comprising a number of upflow conduits (80) extending through said first and said second pipe plate (74, 79); said upflow conduits (80) extending a predetermined distance inside said containing conduit (44) from said bottom portion (78), and terminating with respective flared ends (83) a predetermined distance beneath said first free surface (92).

14) A device as claimed in Claim 13, characterized in that said upflow conduits (80) extend, inside respective guide pipes (82), through said first and second pipe plate (74, 79), and are movable axially with respect to said first and second pipe plate; said upflow conduits (80) being anchored to said conducting conduit (52).

15) A device as claimed in Claim 14, characterized in that said circulating means (25) for circulating said operating fluid (35) comprise a number of infeed

conduits (88) for supplying a carrier gas and housed in said upflow conduits (80).

16) A device as claimed in any one of the foregoing Claims, characterized by also comprising a vacuum pump (90) for substantially maintaining a vacuum in said vacuum portion (42) of said supply conduit (36).

17) A nuclear reactor, in particular a subcritical type employing a liquid metal as coolant, characterized by comprising a device for producing neutrons in accordance with any one of the foregoing Claims.

18) A nuclear reactor (1, 1a), in particular a subcritical nuclear reactor, comprising a vessel (2) in which is defined a primary cooling circuit (22) for circulating a first coolant (5) between a core (10) and at least one first heat exchanger (21); first circulating means (25) for circulating said first coolant (5) in said primary cooling circuit (22); and a device (33, 33a) for producing neutrons by a beam of high-energy particles (37) interacting with an operating fluid (35) comprising a heavy-nucleus material; said device (33, 33a) for producing neutrons in turn comprising a supply conduit (36) by which to direct said beam of high-energy particles (37) onto said operating fluid (35); and containing means (34) for containing said operating fluid (35) and located at a first end (39) of said supply conduit (36); said nuclear reactor being characterized in that said containing means (34)

for containing said operating fluid (35) define a closed fluid dynamic circuit (43) in no way communicating hydraulically with said primary cooling circuit (22) of said first coolant (5); said supply conduit (36) comprising at least one vacuum portion (42) in which a vacuum is substantially maintained, and, at said first end (39), an interface (41, 93) separating said vacuum portion (42) and said operating fluid (35); said device (33, 33a) for producing neutrons also comprising second circulating means (57, 88) for circulating said operating fluid (35) in said closed fluid dynamic circuit (43) to keep said operating fluid (35) moving at said interface (41, 93) during interaction of said beam of high-energy particles (37) with said operating fluid (35); and heat-exchange means (60) for withdrawing heat from said operating fluid (35) moving in said closed fluid dynamic circuit (43).

19) A nuclear reactor as claimed in Claim 18, characterized in that said interface (41, 93) separating said vacuum portion (42) of said supply conduit (36) and said operating fluid (35) is located inside said core (10); said heat-exchange means comprising at least one second heat exchanger (60) inserted in said closed fluid dynamic circuit (43) of said operating fluid (35), and in which a second coolant (5) removes heat from said operating fluid (35).

20) A nuclear reactor as claimed in Claim 19,

characterized in that said second coolant is defined by a portion withdrawn continuously from said first coolant (5) circulating in said primary cooling circuit (22) of the reactor; said at least one second heat exchanger (60) being a shell-and-pipe exchanger (60) comprising a number of heat-exchange pipes (49, 77) in which said operating fluid (35) circulates, and which are immersed in said primary cooling circuit (22) of said first coolant (5) of the reactor, and are located outside, either above or below, said core (10).

21) A nuclear reactor as claimed in Claim 19, characterized in that said heat-exchange means (60) comprise an auxiliary cooling circuit distinct and separate from said primary cooling circuit (22) of the reactor, and which houses said at least one second heat exchanger (60), and in which said second coolant circulates distinctly and separately from said first coolant (5).

22) A nuclear reactor as claimed in one of Claims 18 to 21, characterized in that said second circulating means (57, 88) for circulating said operating fluid (35) are circulating means employing a carrier gas; said carrier gas being drawn from a cover gas (7) of said reactor.

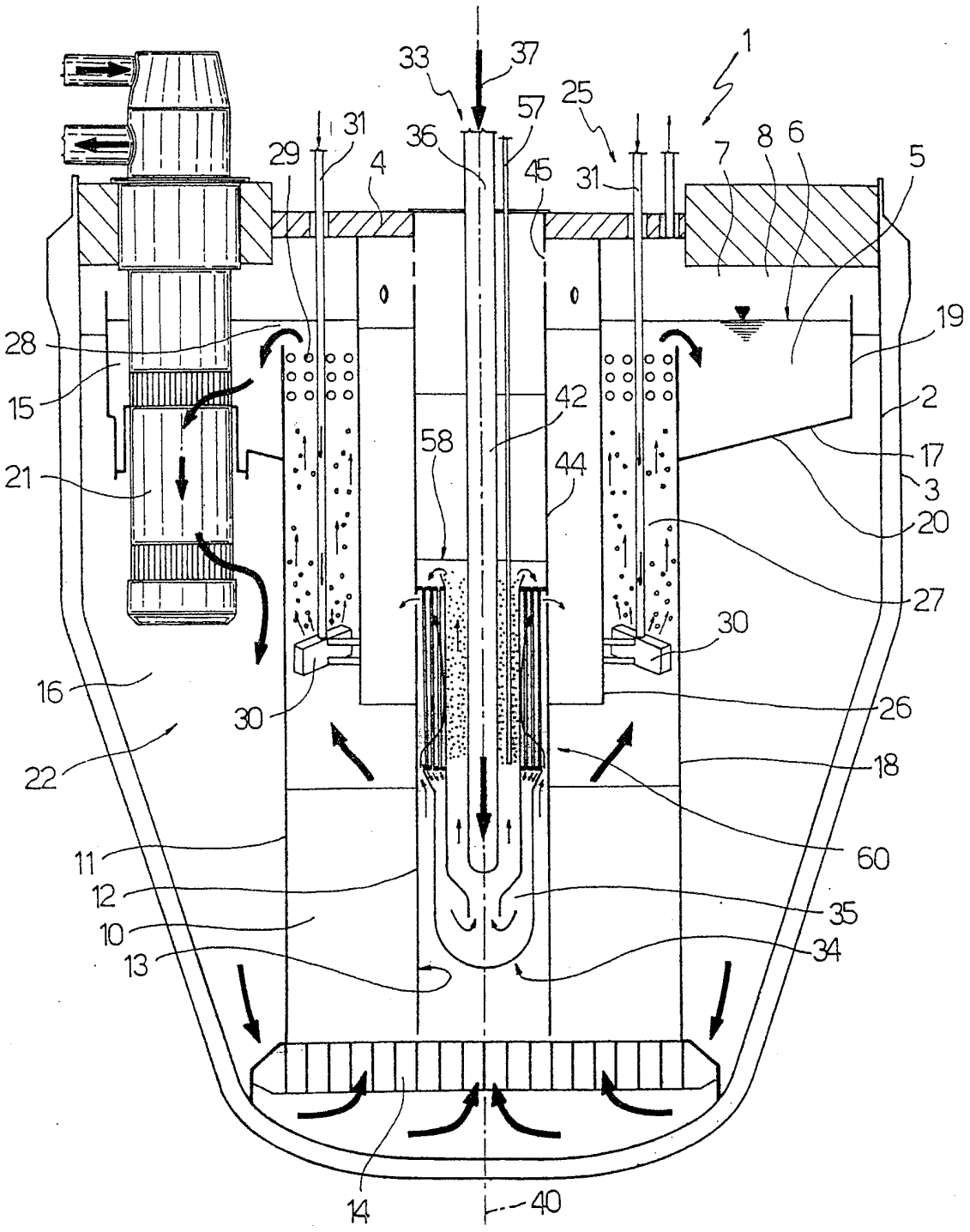

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Fig.1

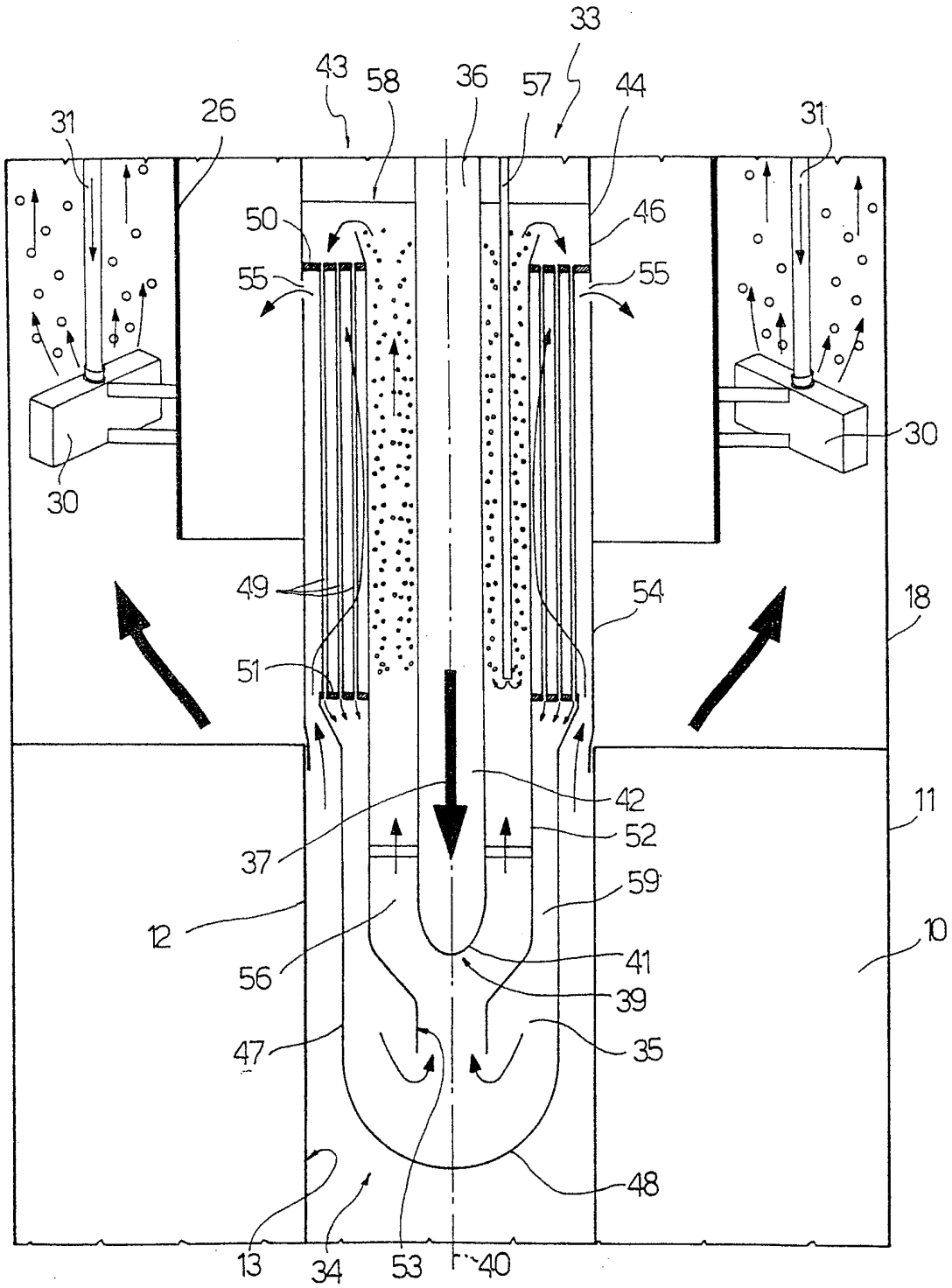

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Fig.2

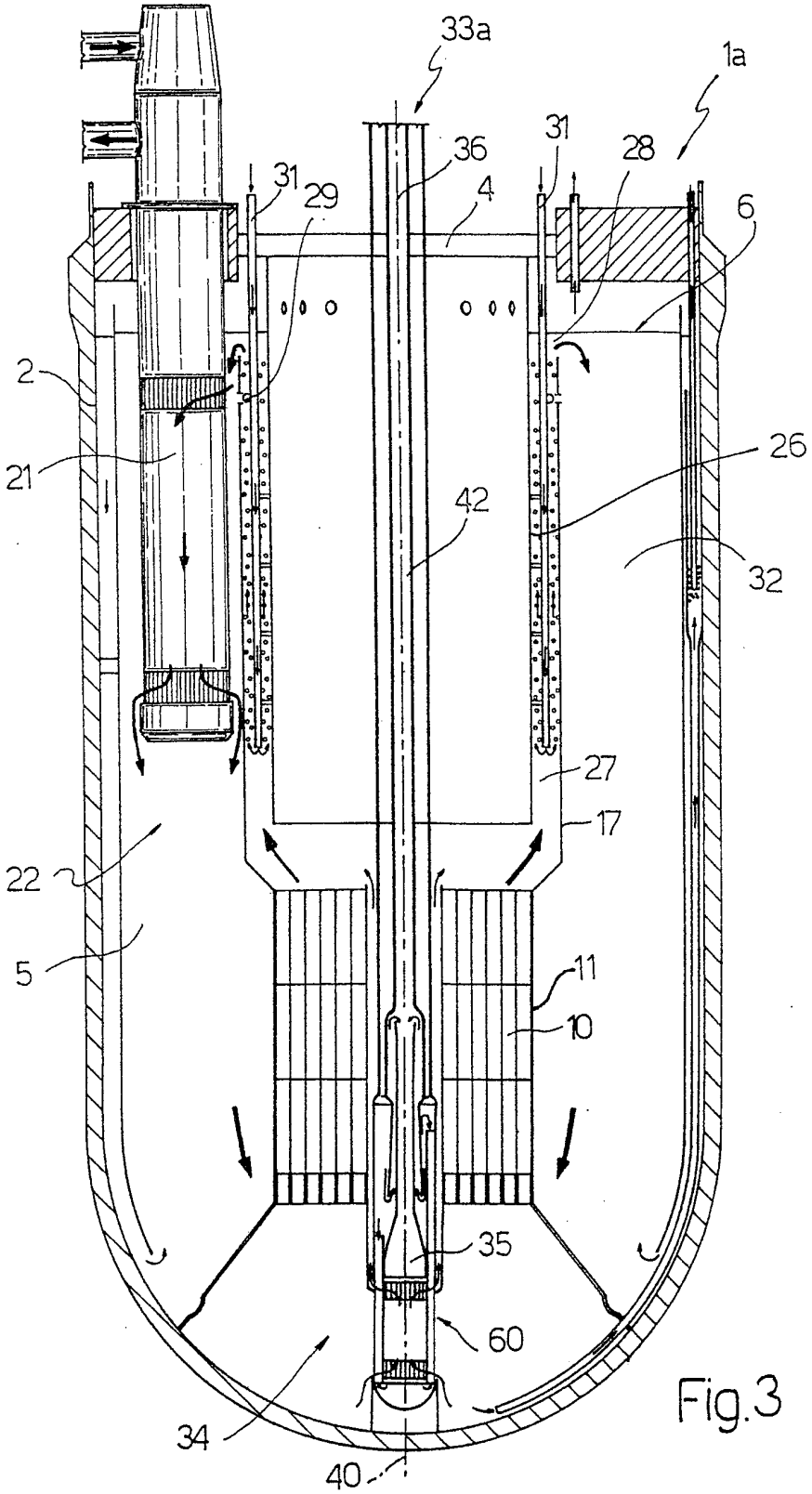


Fig.3

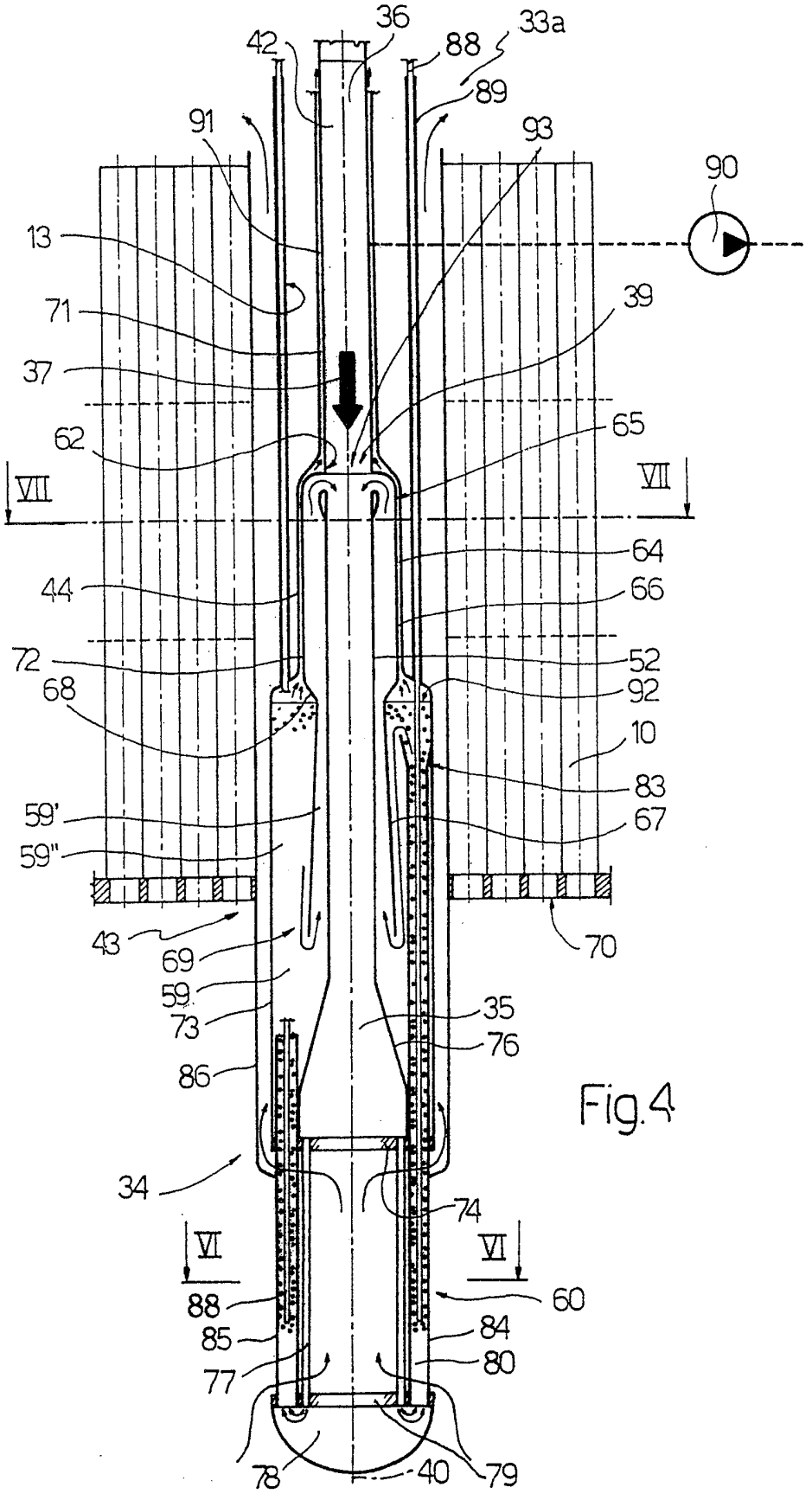

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Fig.4

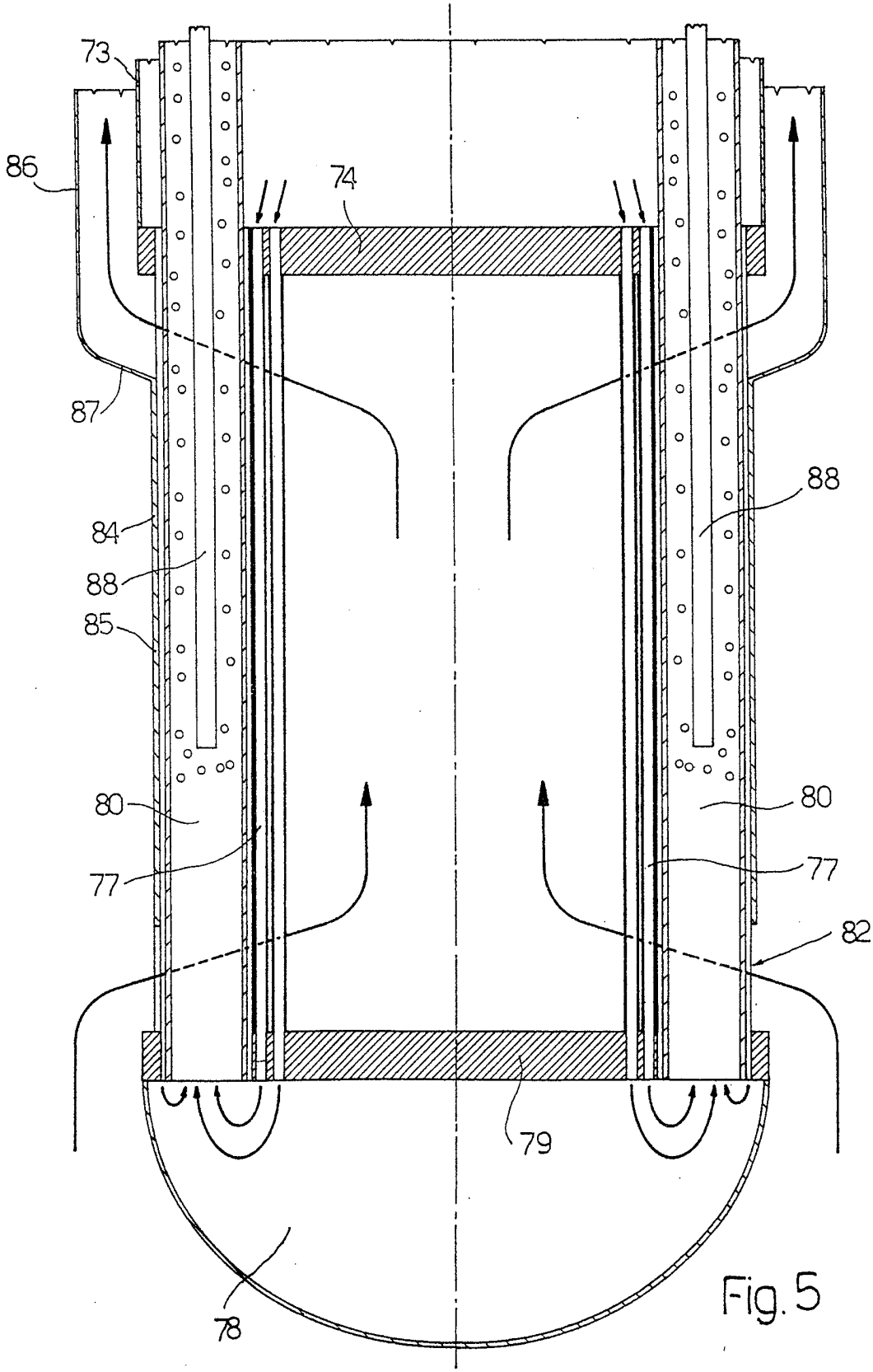


Fig. 5

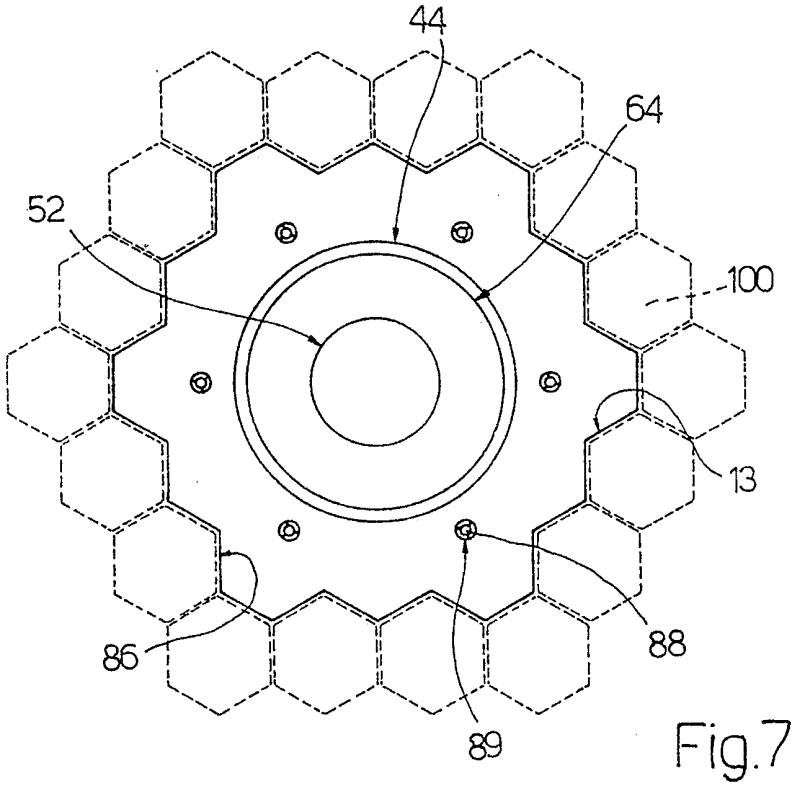


Fig.7

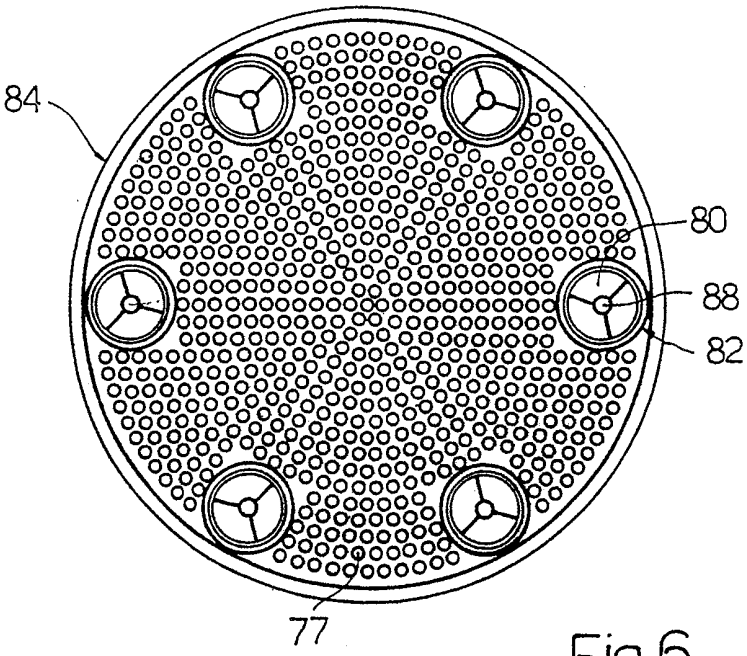


Fig.6

INTERNATIONAL SEARCH REPORT

Inte ional Application No
PCT/IT 99/00131

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G21C1/30 G21C7/34

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 6 G21C

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

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

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 349 001 A (STANTON) 24 October 1967 (1967-10-24) column 1, line 44 - column 2, line 2 column 2, line 49 - column 3, line 18 column 4, line 19-25; figures 1-3	1,17,18
P,X	WO 99 08286 A (CINOTTI LUCIANO ;FINMECCANICA SPA (IT)) 18 February 1999 (1999-02-18)	1-4, 17-22
A	page 7, line 9 - page 18, line 21; figures 1-3	5,6
A	US 5 160 696 A (BOWMAN CHARLES D) 3 November 1992 (1992-11-03) abstract column 10, line 61 - column 11, line 28; figure 4	1,18,19, 21

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 August 1999	06/09/1999

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Jandl, F

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INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte ional Application No
PCT/IT 99/00131

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 3349001 A	24-10-1967	NONE	
WO 9908286 A	18-02-1999	IT T0970715 A AU 8646698 A	05-02-1999 01-03-1999
US 5160696 A	03-11-1992	NONE	