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(71) Applicant
United Kingdom Atomic Energy Authority
11 Charles II Street
London SW1Y 4QP
(72) Inventors
Gordon Thatcher
Alan John Mitchell
(74) Agents
L A Dunnill
Patents Branch
United Kingdom Atomic Energy Authority
11 Charles II Street
London SW1Y 4QP

(54) Liquid metal cooled fast breeder nuclear reactors

(57) A liquid metal cooled fast breeder nuclear reactor wherein the breeder sub-assemblies each incorporate a *fluidic flow control valve* 31 for regulating the rate of flow through the sub-assembly. A governing component for the valve is derived from a minor fraction flow driven by an electromagnetic flow coupler 30 associated with the main flow. The minor fraction flow is influenced by a temperature sensitive electro-magnetic braking device 24 to generate a back pressure which controls valve 31. Alternatively, the flow coupler is itself temperature sensitive and the pressure generated thereby in the minor fraction flow acts as the control pressure for the control valve.

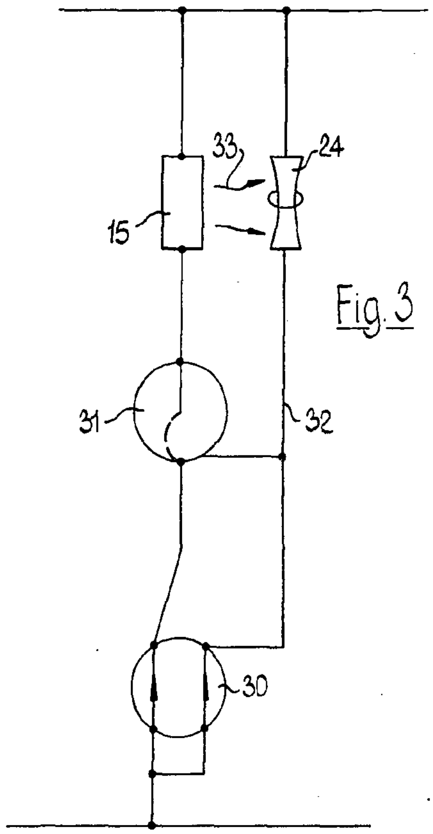

Fig.3

GB 2 056 749 A

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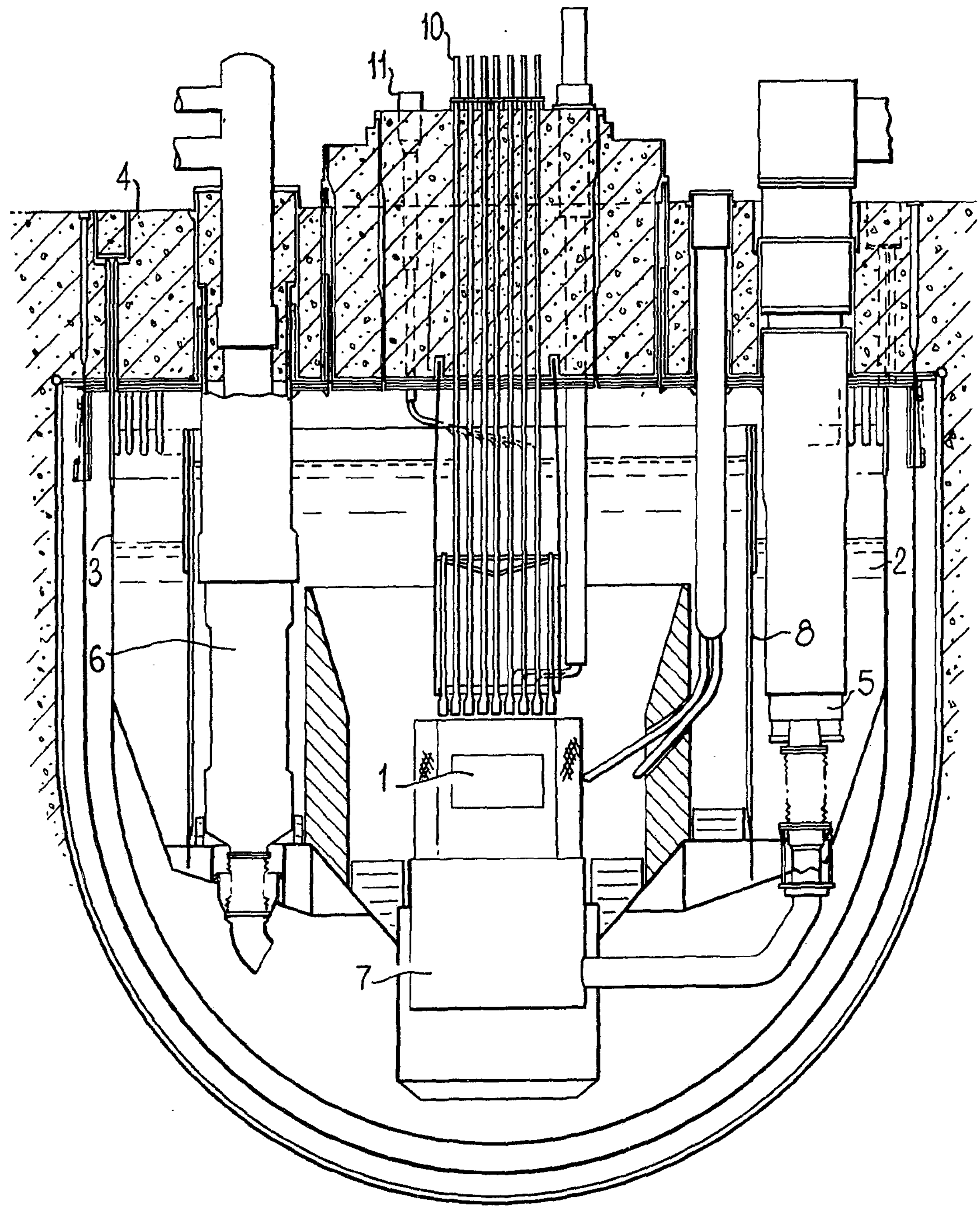
Fig. 1



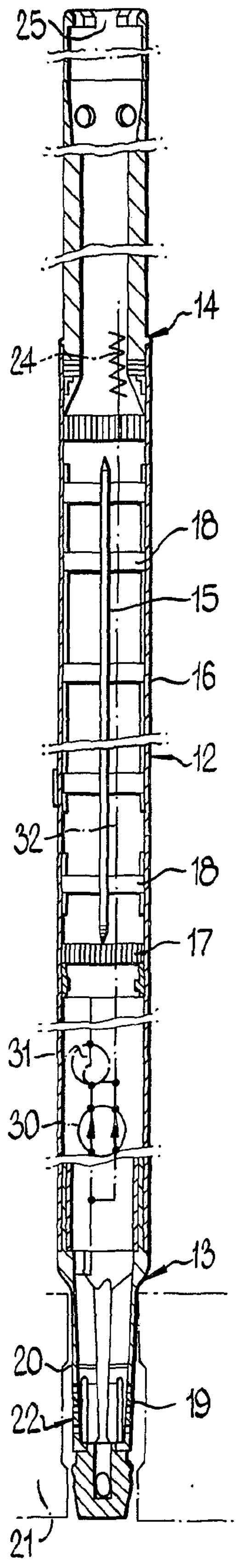


Fig. 2

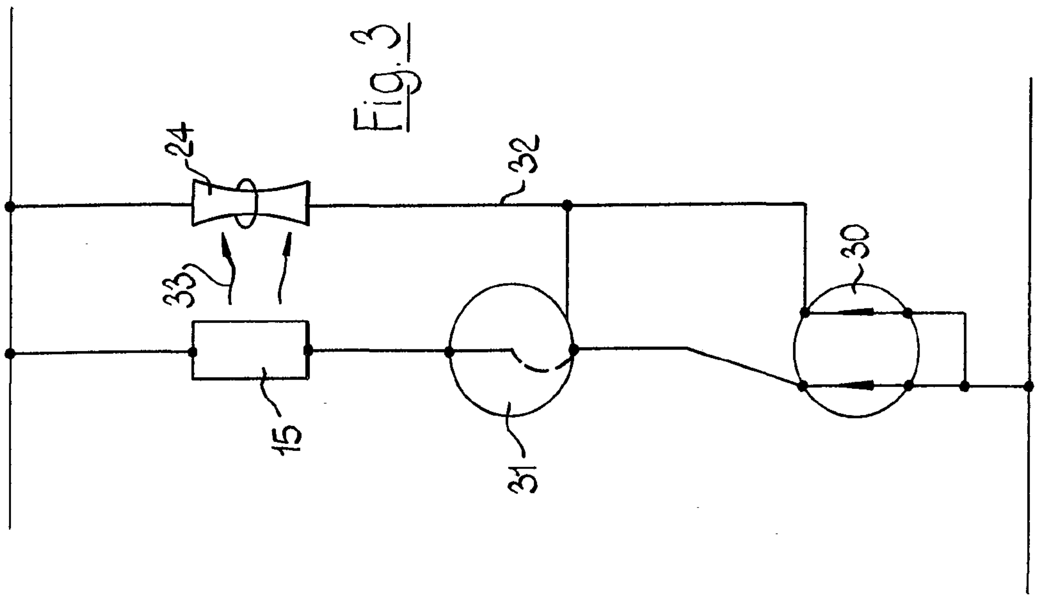


Fig. 3

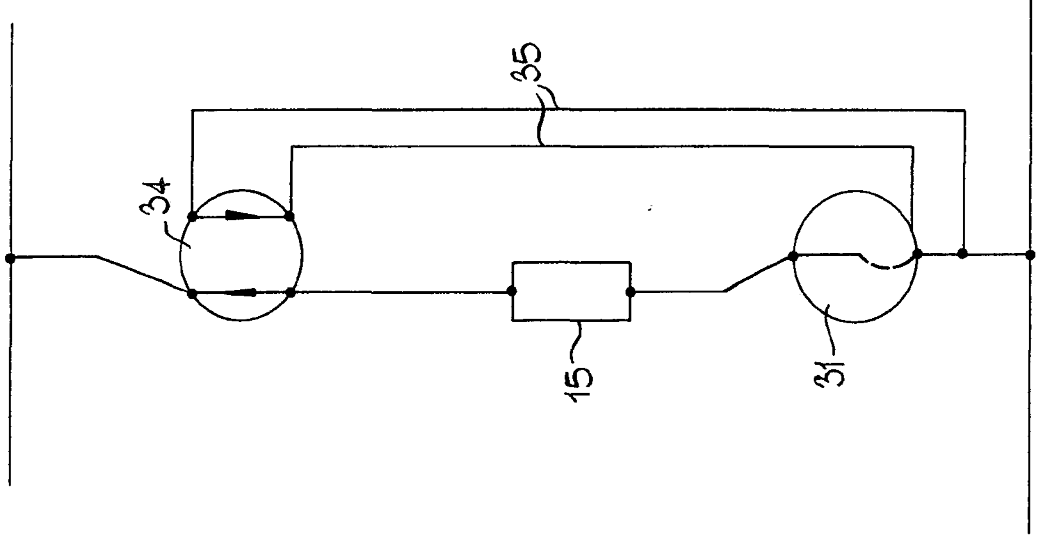


Fig. 5

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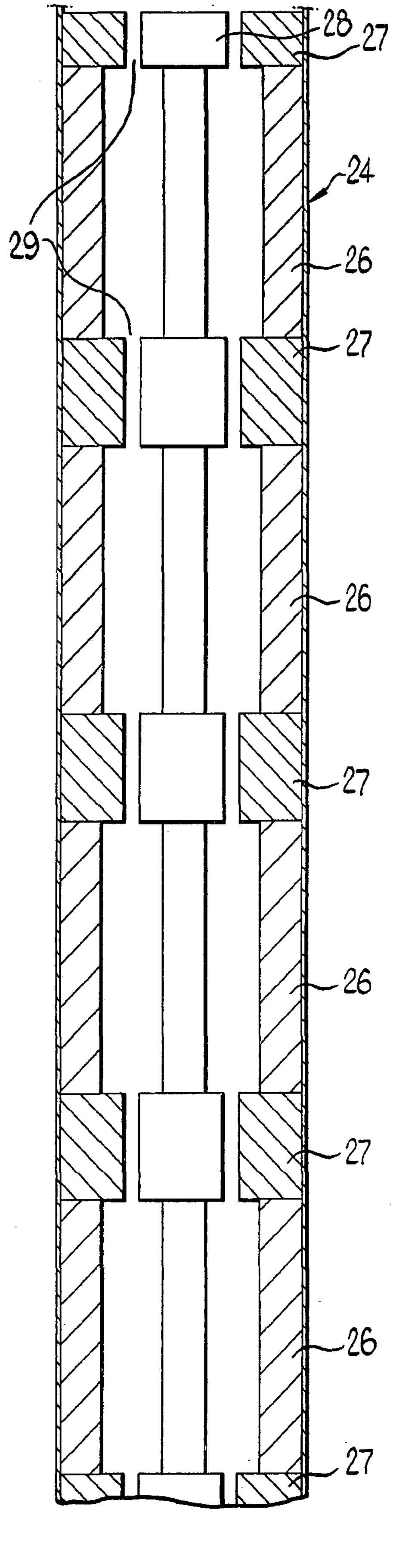

Fig.4

SPECIFICATION

Liquid metal cooled fast breeder nuclear reactors

This invention relates to liquid metal cooled fast breeder nuclear reactors.

In a liquid metal-cooled fast breeder nuclear reactor the fuel assembly comprises a multiplicity of slender fuel elements or pins over which liquid metal coolant such as sodium is flowed. For convenience, the fuel assembly is divided into a plurality of interchangeable sub-assemblies each comprising a plurality of fuel pins enclosed by a wrapper and having a lifting head. The sub-assemblies are positioned in side-by-side array and each one is located in cantilever manner by a lower end spike which is plugged into a fuel assembly supporting diagrid. The sub-assemblies in the central region of the fuel assembly mainly comprise fissile material whilst the sub-assemblies in the surrounding outer region comprise breeder material. During operation of the nuclear reactor the breeder material captures neutrons emitted by fission in the fissile material to produce further fissile material. As irradiation of the fuel assembly progresses and the fissile content of the breeder material increases, fission of some of the newly formed fissile material takes place so that the power output and therefore the coolant temperature from the breeder sub-assemblies progressively increases. Increased and varying temperatures of coolant streams flowing from the fuel assembly gives rise to a condition known in the fast reactor art as thermal striping, a condition which, because of rapid temperature fluctuations, gives rise to cracking in reactor structure material. In co-pending application numbers 51635/77 and 904/78 by the United Kingdom Atomic Energy Authority there is disclosed a liquid metal cooled fast breeder nuclear reactor wherein each of at least some of the breeder sub-assemblies has an electro-magnetic device for regulating the flow of coolant through the sub-assembly, the magnetic field of the electro-magnetic device being temperature sensitive. The electro-magnetic device applies a braking effort or restriction to the flow of coolant through the breeder sub-assemblies the restriction being temperature dependent and reducing with increased temperature so that, with increased power output, coolant flow is increased thereby maintaining the outlet temperature of the coolant substantially constant. The reduced restriction is caused by reduced magnetic flux permeability of the magnetic materials caused by increased temperature. By utilising pole pieces of ferromagnetic alloy having a Curie point approximately equal to the desired coolant outlet temperature of the breeder sub-assemblies the electro-magnetic devices serve as thermostatic controls. Two disadvantages are envisaged with the construction described in application nos. 51635/77 and 904/78, firstly, when the restriction to flow due to the electro-magnetic brake is high, coolant pressure in the sub-assembly wrapper is high causing dilation of the wrapper under irradiation creep, and secondly, an electro-magnetic brake of sufficient capacity is of relatively large proportions and therefore difficult to accommodate in the fuel sub-assembly structure.

An object of the present invention is to provide a liquid metal-cooled fast breeder nuclear reactor having fuel sub-assemblies with electro-magnetic means of relatively small proportions and which seek to maintain the outlet coolant temperature of at least some of the breeder sub-assemblies substantially constant throughout the life of the fuel assembly without severely pressurising the sub-assembly.

According to the present invention in a liquid metal cooled fast breeder nuclear reactor wherein each of at least some of the breeder sub-assemblies has an electro-magnetic device for regulating the flow of coolant through the sub-assembly, the magnetic fields of the electro-magnetic devices being temperature sensitive, the rate of coolant flow through the sub-assembly is controlled by a fluidic flow control valve for which a governing component is derived from the electro-magnetic device, a minor fraction of coolant flow associated with the electro-magnetic device being driven by electro-magnetic interaction with a major fraction of coolant flow through the sub-assembly. From another aspect the flow through a sub-assembly is divided into major and minor fractions, the minor fraction being driven by a magnetohydrodynamic device hereinafter termed an electro-magnetic flow coupler associated with the major fraction, the minor fraction flow being influenced by an electro-magnetic braking device to generate a back pressure for governing a fluidic flow control valve hereinafter termed a vortex amplifier controlling the major fraction flow over the fuel pins of the sub-assembly. The electro-magnetic device for regulating the flow of coolant through the sub-assembly may also drive the minor fraction of coolant flow by electro-magnetic interaction, that is, the electro-magnetic device may be a flow coupler having a temperature sensitive magnetic field.

The electro-magnetic braking devices of the sub-assemblies are arranged progressively to decrease the resistance of the fluidic flow control valves to coolant flow and thereby increase the rate of coolant flow through the sub-assemblies as the breeder power output rises during continued irradiation of the reactor fuel assembly so that the outlet coolant temperatures of the breeder sub-assemblies which include electro-magnetic devices are maintained substantially constant.

A liquid metal-cooled fast breeder nuclear reactor embodying the invention is described by way of example with reference to the accompanying drawings wherein:

Figure 1 is a diagrammatic cross-sectional view,

Figure 2 is a diagrammatic cross-sectional view of a breeder fuel sub-assembly,

Figure 3 is a line diagram of coolant flow through the breeder fuel sub-assembly

Figure 4 is a sectional view of an electro-magnetic braking device, and

Figure 5 is a line diagram of coolant flow through an alternative construction of breeder fuel sub-assembly.

Fig. 1 illustrates a liquid metal-cooled fast breeder nuclear reactor having a fuel assembly 1 submerged in a pool 2 of liquid sodium coolant in a primary vessel 3. The primary vessel is suspended from the roof of a containment vault 4 and there is provided a plurality of coolant pumps 5 and heat exchangers 6 only one of each of pump and heat exchangers being shown. The fuel assembly 1 mounted on a diagrid 7 is housed with the heat exchangers in a core tank 8 whilst the pumps 5, which deliver coolant to the diagrid, are disposed outside of the core tank. The core or fuel assembly 1 comprises a plurality of interchangeable sub-assemblies 9 which upstand from the diagrid in closely spaced side-by-side array. Control rods 10 and instrumentation 11 penetrate the roof of the vault. The fuel assembly 1 comprises a central region having sub-assemblies 9 containing fissile or driver material and an outer annular region having sub-assemblies containing fertile or breeder material. Each of the breeder sub-assemblies has an electro-magnetic device, to be described hereafter, for regulating the flow of coolant through the breeder sub-assemblies by way of a fluidic flow control valve. The magnetic fields of the electro-magnetic devices are temperature sensitive so that the coolant flow is increased as breeder power output increases during continued irradiation of the fuel assembly. The rate of coolant flow through the sub-assemblies is thereby progressively increased to maintain the coolant outlet temperature substantially constant.

The sub-assemblies 9, as shown in Fig. 2, each comprise a central fuel section 12, a lower end locating section 13 and a tubular upper end section 14. The fuel section comprises a bundle of elongate fuel pins 15 enclosed within a tubular wrapper 16 of hexagonal cross-section, the pins being supported within the wrapper at their lower ends by a grid 17 and braced intermediate their lengths by cellular grids 18 of honeycomb form. The lower end locating section 13 comprises a spike 19 for engaging sockets 20 in a fuel assembly support structure 21 and has apertures 22 through which coolant can flow from within the structure. The tubular upper section 14 which defines an outlet for coolant flow has a lifting head 25.

The pins of the fuel sub-assemblies 9 in the central section of the fuel assembly contain fissile material, for example, mixed oxides of Pu239 and U235 although at each end of the pins there is a quantity of fertile material, for example, oxide of U238. The pins of the fuel sub-assemblies in the outer region surrounding the central region of the fuel assembly contain fertile or breeder material, for example, oxide of U238.

Each of the breeder fuel sub-assemblies has (as shown diagrammatically in Figs. 2 and 3) an electro-magnetic flow coupler 30, an electro-magnetic braking device 24 and a vortex amplifier 31.

The flow coupler 30 is an electro-magnetic liquid metal pump comprising a pair of electrically connected parallel ducts for liquid metal. A magnetic field applied transversely to cross the ducts in series is arranged so that liquid metal flowing through a first one of the ducts and the magnetic flux induces an electric current in the duct and the interaction of the current with the magnetic flux creates a force in opposition to flow. The current will circulate by way of connectors from the first duct through the second duct the direction of current flow in the second duct being of opposite sense to that in the first and its interaction with the magnetic field (which remains in the same directional sense across each duct) will generate a driving force on the liquid metal in the second duct thereby to effect a driven flow in the same direction as the driving flow.

The electro-magnetic braking device 24 comprises a liquid metal flow duct directed through a transverse magnetic field so that, as in the flow coupler, when liquid metal flows through the duct and magnetic flux a retarding force in opposition to the fluid flow is set up by electromagnetic interaction.

The vortex amplifier 31 comprises a generally flat cylindrical casing having an inlet port for fluid flow radial to the circular chamber, an outlet port arranged along the axis of the chamber and a governing port for fluid flow arranged tangentially to the circular surface of the chamber so as to cause the main flow in the chamber to become a circulating vortex when flow is injected through the tangential port.

In operation of the nuclear reactor and with respect to each breeder fuel sub-assembly a major fraction of the coolant flows upwardly from the lower end spike 19 by way of the electro-magnetic flow coupler 30, through the vortex amplifier 31 and thence to flow in heat exchange with the fuel pins 15. A minor fraction of coolant flows from a point preceding the electro-magnetic flow coupler 30 through the driven side of the flow coupler and through the electro-magnetic braking device 24 disposed in the upper section of the sub-assembly by way of a duct 32. The duct 32 occupies a position normally occupied in a conventional fuel sub-assembly by one of the fuel pins. In Fig. 3 the bundle of fuel pins is designated 15 and there is a temperature coupling 33 between the major flow of coolant and the electro-magnetic braking device.

The electro-magnetic braking device 24 is generally as described in co-pending application no. 00904/78 and as shown in Fig. 4 comprises a series of annular permanent magnets 26, a series of annular pole pieces 27 alternating with the magnets and a co-axial armature 28. An annular gap 29 bounded by the pole pieces and the armature defines a flow path for the minor fraction of liquid metal coolant flowing upwardly through the sub-assembly. The pole pieces 27 and armature 28 are of ferromagnetic material. The braking pressure of the device is dependent on the intensity of the magnetic flux conducted across the gap and the rate of flow of the coolant whereby circulatory currents are set up in the liquid metal in a plane normal to the direction of coolant flow. The circulatory currents induce an opposing force to the flow of coolant.

In operation of the nuclear reactor, liquid metal coolant drawn from the outer region of the pool is passed upwardly through the fuel sub-assemblies in heat exchange with the fuel pins 15 thence from the upper ends by way of the electro-magnetic braking devices 24. During operation of the reactor neutrons emitted by fissions in the fissile region of the fuel assembly are captured by the fertile material thereby creating within it a fissile content which progressively increases as irradiation progresses. Some of the newly created fissile material in the breeder sub-assemblies will also undergo fission, the rate of fission increasing as the fissile content increases with the result that the power output of the breeder sub-assemblies progressively increases. With respect to the breeder fuel sub-assemblies flow of the major fraction of liquid metal coolant through the flow coupler 30 generates a driving force to urge the minor flow through electro-magnetic braking device 24 and the resistance to flow afforded by the braking device creates a back pressure which serves as a control component for the vortex amplifier 29 thereby restricting flow of the major fraction through the breeder sub-assemblies. The restriction to the minor flow is temperature dependent and reduces with increased temperature of the major fraction flow outlet so that, with increased power output, total coolant flow through the sub-assembly is increased thereby maintaining the outlet temperature of the coolant substantially constant. As the temperature of the coolant leaving the fuel pins approaches the Curie point of the magnetic materials the effectiveness of the electro-magnetic braking device decreases lowering the control pressure and thereby increases rate of flow of the major fraction. The device thereby serves as a thermostat to control the sub-assembly outlet temperature.

In an alternative construction of fuel sub-assembly shown diagrammatically in Fig. 5 an electro-magnetic flow coupler 34 having a temperature sensitive magnetic field provides a control flow to the vortex amplifier. Coolant flow entering the sub-assembly by way of the spike divides into major and minor fractions the major fraction flowing through the bundle of fuel pins by way of a vortex amplifier 31. The minor fraction flow passes through the electro-magnetic device 34 disposed in the upper regions of the fuel sub-assembly then to the control port of the vortex amplifier by way of ducts 35 which occupy positions in the sub-assembly normally occupied by fuel pins. Pressure for controlling the vortex amplifier is generated by electro-magnetic interaction of the minor fraction flow with the major fraction flow that pressure varying with the magnetic flux permeability of the magnetic materials so that as the Curie point of the magnetic material is approached the control pressure for the vortex amplifier reduces allowing a greater flow of coolant through the sub-assembly. In the electro-magnetic device 34 the liquid metal carrying ducts are arranged side by side so that the magnetic flux passes through them in parallel, the current then generated by the major flow passes through the minor flow duct in the same directional sense so that the resultant fluid flow of the minor fraction is opposite to that of the major flow. In use the wrappers of the described sub-assemblies are not severely pressurised because in each sub-assembly the restriction to flow of the major fraction of coolant flow occurs in the vortex amplifier which is disposed upstream of the fuel pins so that dilation of the wrapper under irradiation creep is largely avoided. Furthermore, because the electro-magnetic brake is required to control only the minor fraction of coolant flow, a relatively small fraction, a brake of sufficient capacity can be of relatively small proportions thereby facilitating its accommodation in the sub-assembly. Use of smaller permanent magnets also has the advantageous effect of reducing the amount of cobalt in the system.

CLAIMS

1. A liquid metal cooled fast breeder nuclear reactor wherein each of at least some of the breeder sub-assemblies has an electro-magnetic device for regulating the flow of coolant through the sub-assembly, the magnetic field of the electro-magnetic device being temperature sensitive, and wherein the rate of coolant flow through the sub-assembly is regulated by a fluidic flow control valve for which a governing component is derived from

the electro-magnetic device, a minor fraction of coolant flow associated with the electro-magnetic device being driven by electro-magnetic interaction with a major fraction of coolant flow through the sub-assembly to provide the governing component.

2. A liquid metal cooled fast breeder nuclear reactor wherein the coolant flow through a breeder sub-assembly is divided into major and minor fractions, the minor fraction being driven by a magnetohydrodynamic device associated with the major fraction, the minor fraction flow being influenced by an electro-magnetic braking device to generate a back pressure for governing a fluidic flow control valve regulating the major fraction flow over the fuel pins of the sub-assembly.

3. A liquid metal cooled fast breeder nuclear reactor according to Claim 1 wherein the electro-magnetic device is a flow coupler for driving the minor fraction of coolant flow by electromagnetic interaction, the device having a temperature sensitive magnetic field.

4. A liquid metal cooled fast breeder nuclear reactor substantially as hereinbefore described with reference to Figs. 1, 2, 3 and 4 of the accompanying drawings.

5. A liquid metal cooled fast breeder nuclear reactor substantially as hereinbefore described with reference to Figs. 1, 2, 3 and 5 of the accompanying drawings.

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