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(54) Title: PROCESS TO ACCUMULATE THERMAL ENERGY USING A HEAT- CARRIER FLUID AND CORRESPONDING SYSTEM

(57) Abstract: A process and a corresponding system for the accumulation and use of thermal energy at medium or high temperatures, wherein a primary heat-carrier fluid is accumulated in a secondary accumulation section; it is subsequently fed to a heating section, where the primary fluid is heated and receives thermal energy; then, once heated, it is fed to a primary accumulation section, where the primary fluid is accumulated at the maximum temperature and from where it is collected for heat exchange with a secondary fluid, as part of a thermodynamic cycle for the production of electrical/mechanical energy; and wherein finally the primary fluid, after transferring heat to the secondary fluid and thereby cooling down, is fed and returns again to the secondary accumulation chamber, thus closing the cycle. Advantageously, the primary and secondary accumulation sections of the primary fluid, both epigeal and hypogeal, are of the tankless type, so that they do not involve the use of self- supporting tanks, or similar containers, and can be constructed in various ways, for example with a geological/artificial barrier, or in one or more natural cavities, such as those formed in a rock salt mine, or artificial cavities, provided or not with reinforcement and/or containment works. Moreover the primary heat-carrier fluid, used in this process to accumulate thermal energy, can be of the type including organic substances such as bitumen and/or the like.

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PROCESS TO ACCUMULATE THERMAL ENERGY USING A HEAT-CARRIER FLUID AND CORRESPONDING SYSTEM

Technical field

The present invention relates to a process to accumulate and collect thermal energy at a temperature preferably higher than 95°C, which uses one or more heat-carrier fluids intended to be accumulated in respective accumulation sections, and which is capable of considerably reducing the operative and management cost of the processes and in general of the technical solutions, at present known and adopted, for the accumulation of thermal energy, that are based on the use of heat-carrier fluids.

The present invention also relates to a system for the accumulation and collection of thermal energy which corresponds to and implements the aforementioned process.

Background art

Nowadays numerous projects are being developed in the art, aimed at optimising and reducing the financial impact of systems for accumulating and storing the thermal energy that is generated from discontinuous industrial sources or from solar radiation, in particular for the purpose of improving efficiency and reducing the running costs in plants for the production of mechanical/electrical energy, which use the thermal energy generated from these discontinuous industrial sources and/or from solar radiation.

In particular, in the field of electrical energy production plants that use appropriately concentrated solar radiation as energy source, also known as "Concentrating Solar Power" plants (CSP), the development of numerous processes and systems to accumulate heat at a medium or preferably high temperature can be seen, in order to compensate for the lack of solar radiation during the hours of darkness.

Included among these advanced systems are those based on the use of heat-carrier fluids, i.e. designed to transport heat, wherein these heat-carrier fluids are provided for accumulation in special accumulation sections, for the purpose of temporarily storing the heat transported by them, in view of a subsequent use of this heat to produce mechanical/electrical energy.

For example, these heat-carrier fluids, designed to be accumulated and then store thermal energy, include mineral oils or organic fluids which, depending on their constituent molecules, can be heated to approximately 400°C without being subject to excessive degradation.

Moreover, heat-carrier fluids comprising molten and eutectic salts can be used, and in particular the eutectic mixture comprising $NaNO_3$ at 60% and KNO_3 at 40%.

This mixture is advantageous compared with traditional fluids, it has low environmental impact given that its components are used as fertilisers, high melting temperature (220° C), low vapour pressure, high thermal stability (up to 570°C), and is not flammable.

However current systems for storing thermal energy used in industry, and those used in CSP installations, involve plant sections that are particularly onerous from a financial point of view, due to the cost of the heat-carrier fluid used and the intrinsic cost of the storage systems adopted for its accumulation.

Among these known plants, it is mentioned as example the Andasol 1 rated 50 MWe CSP plant, located in Guadix (Spain), which uses molten salts (approx. 30,000 t) in two separate metal tanks insulated with refractory material and operating at different temperatures, with a storage capacity equivalent to approximately 7 plant running hours in the absence of solar radiation.

Summary of the invention

Compared with the solutions, systems and installations at present known, this invention advantageously offers a new process for the accumulation and collection of thermal energy at medium and high temperatures, which is designed to reduce thermal energy storage and accumulation costs considerably, for example, but not only, in the context of a plant or more general system for the production of mechanical/electrical energy, and which at the same time involves a minor environmental impact and thereby an improved environmental sustainability.

In detail, the process to accumulate thermal energy, which is the object of this invention, comprises the following steps:

a) accumulation of a primary heat-carrier fluid in a secondary plant section at a mean temperature lower than the primary accumulation section, made up of one or more collection subsystems, containing or not material with high thermal inertia and/or heat exchangers;

b) collection of this primary fluid and its feeding to one or more subsections suitable for its heating and comprising one or more heat sources having temperatures higher than that of the primary fluid itself, wherein the thermal energy for heating the primary fluid comes, totally or partially, from discontinuous or variable sources and preferably from solar radiation;

c) heating of the primary fluid in one or more of these heating subsections;

d) subsequent feeding and accumulation of the primary fluid, at the maximum temperature, in the primary accumulation section;

e) collection from this primary accumulation section of the previously heated primary fluid and its feeding to a plant section where there is heat exchange between the primary fluid and a secondary fluid at a lower temperature, as part of a thermodynamic cycle aimed at generating mechanical/electrical energy, with resulting cooling of the primary fluid and simultaneous increase of the secondary fluid temperature to the required conditions of the thermodynamic cycle; and

f) collection of the primary fluid, once cooled in the heat exchange section, and cycle closure by feeding it to the secondary accumulation section.

As explained better further on, with the addition of further details, the process to accumulate thermal energy in accordance with the present invention involves the use of one or more primary heat-carrier fluids with a solidification point higher than or equal to the ambient temperature; it is suitable for application in relation to variable and/or discontinuous heat sources, preferably those in which the heat is provided by solar radiation, but not only, therefore also those in which the heat is provided by industrial plants; moreover, it also involves the accumulation of at least one primary heat-carrier fluid in a respective primary and secondary plant accumulation section, of the tankless type, that is not using metal vessels, or similar containers, mechanically resistant to operating temperatures and self-supporting, in order to contain tightly the primary fluid accumulated.

The tankless accumulation sections, or more concisely the tankless accumulations, used in the process of the invention, are characterised by less use/absence of metal or precious materials, the possibility of being able to be constructed by re-using and adapting decommissioned structures such as for instance tanks/cisterns, and by resistance to mechanical stress and seismic waves, due to the type of assembly and the self-sealing properties of the accumulated primary fluid which, being solid at ambient temperature, tends to solidify in the event of leakage from the surfaces bordering the accumulation sections.

A first type of tankless accumulation of the primary fluid, adopted in the process of the present invention, conveniently uses natural or artificial cavities with inflow/outflow wells/conduits of the primary fluid and situated in impermeable geological formations such as, for example, salt deposits, clays (for example ferralitic soil, red soil, laterite) or layers, banks and formations made up of impermeable and coherent rocks such as limestone, marl, fine sandstone, various lavas (for example tufas), and almost all crystalline schists of a siliceous nature, wherein any porous or draining material fractures/lenses are sealed by the nature of the primary fluid itself that has been used, which is solid at ambient temperature.

It should be noted that, even nowadays, geological formations such as clays and rock salt are used and commonly employed for the storage and accumulation of toxic materials.

A second type of tankless accumulation, adopted in the process for the accumulation of thermal energy in accordance with the present invention, requires the accumulation of a primary fluid in tankless primary and secondary sections, wherein the containment surfaces of these sections are formed by geological and/or artificial barriers, preferably containing material with high thermal inertia.

In particular, this material with high thermal inertia is characterised by a heat transfer coefficient, at the operating temperature, less than or equal to 25 W/mK, preferably less than 5 W/mK, and even more preferably less than 0.5 W/mK.

The use of such material with high thermal inertia is necessary when the nature of the containment material, the operating temperatures of the primary fluid and the ratio between the volume of the primary fluid itself and the surface bordering the accumulation section wherein it is stored do not permit a permanence of the bulk temperature, i.e. of the majority of the mass of the primary fluid, in the expected range and during the fixed time period.

This material with high thermal inertia is assembled so as to create a barrier suitable for containing the primary fluid and allows, due to the introduction of a thermal differential between the barrier exterior and interior, the cooling of the primary fluid and its attainment of solid state in the layers of the same barrier or in its vicinity, thus avoiding the dispersion of the primary fluid and simultaneously maintaining the mean temperature of the accumulation section in the expected range.

In particular, the attainment of the solid state of the primary fluid in the barrier or in its vicinity can occur between the contact surfaces, in the fractures or in the porosities of the barrier component materials.

The barrier can be made up of a single layer or successive layers created with different materials, having different porosity and thermal inertia.

These layers can be created from elements with high thermal inertia such as refractory bricks, insulating panels etc., or materials such as heat-insulating cements and mortar, or loose materials such as clays, pozzolans, perlites.

The primary heat-carrier fluids can be inorganic, for example water, low melt metal alloys, mineral oils or molten salts of K or Li or Na or Mg and their mixtures, in particular $LiNO_3$, $LiNO_3$-$NaNO_3$, KNO3-$LiNO_3$, KNO_3-$NaNO_2$-$NaNO_3$, $NaNO_2$, $NaNO_3$, KNO_3, KNO_3-$NaNO_3$ and especially mixtures of $NaNO_3$ at 60% and KNO_3 at 40% or organic substances such as thermoil and dowtherm fluids.

Especially significant from a technical/financial point of view is the use, as a primary heat-carrier fluid, of cheap cuts, high boiling derivatives from oil and with high thermal capacity, in particular greater than that of molten salts, and comprising for example fuel oils, charges for furnaces, pitch for cement factories, pyrolyzers or bitumens and/or their derivatives.

Bitumens and pitch are solid or semi-solid at ambient temperature and can be heated to temperatures equal to, or to the order of, 350°-380°C, without causing excessive formation of coke.

Before the development of the present invention, applications of these hydrocarbon cuts as heat-carrier fluids in systems for the storage of thermal energy from discontinuous and/or variable sources were not known.

Among the organic fluids mentioned previously, bitumens have unique peculiarities with respect to organic primary fluids that are used for the storage of thermal energy.

In particular bitumens are made up of asphaltene mixtures (polycondensed aromatics in the presence of nitrogen, sulphur and metals), polar aromatics (resins) and non-polar, saturated long-chain hydrocarbons.

Moreover, bitumens are considered as being materials with high environmental sustainability and low risk, and have negligible vapour pressure.

Moreover, bitumens do not have a specific melting, solidification or boiling point, they are solid at ambient temperature, have high molecular weight and a number of carbon atoms generally greater than 25, are insoluble in water, impermeable and generally hydrophobic, chemically inert, with a flash point higher than 230°C, and are characterised by auto-ignition temperatures higher than 300°C.

It should also be remembered that bitumens are not considered as hazardous according to EU regulations and, at ambient temperature, do not present significant risks to human health and the environment.

Finally bitumens, compared with molten salts, are characterised by greater thermal capacity and lower cost per tonne.

The use of hydrocarbon cuts in thermal energy accumulation systems is particularly advantageous when combined with organic Rankine cycles (ORC), for the purpose of generating electrical energy from primary fluids at medium or low enthalpy effectively.

The secondary fluids used in the process and system of the invention are usually made up of organic or inorganic molecules or molecule mixtures, and in general are suitable, after receiving heat in a heat exchange section from the primary heat-carrier fluid at a higher temperature, for undergoing physical transformations during a thermodynamic cycle that is typically intended for the production of mechanical/electrical energy, but which could also, more simply, have the function of improving the energy efficiency of a civil or industrial installation.

Therefore, it is clear that both the process and the corresponding system for the accumulation of thermal energy, conforming to the present invention and having the characteristics defined by the respective independent claims, 1 and 15, fully achieve the proposed objects.

Relevant features and further details of the process and system of the invention for the accumulation of thermal energy, specifically regarding the primary and secondary accumulation sections, both epigeal and hypogeal, which are provided and used in this process and system, are defined by independent claims 2 to 10.

Additional important and inventive features of the fluid or of the primary fluids used in the process and in the corresponding thermal energy accumulation system, in accordance with the present invention, are defined by dependent claims 11 to 14.

Brief description of the drawings

In addition to what stated previously, some preferred embodiments of this invention will now be described in detail, to be considered as non-exclusive examples, aimed at illustrating additional aspects, features and advantages of the same invention, with reference to the accompanying drawings, in which:

Fig. 1 is a partial schematic view of a geological/artificial barrier suitable for constructing a tankless section of accumulation of a primary heat-carrier fluid, wherein this accumulation section is used in the process and system to accumulate thermal energy according to the present invention;

Fig. 2 is a partial schematic view of a variation of the geological/artificial barrier in Fig. 1, for the tankless accumulation of thermal energy;

Fig. 3 is a partial schematic view of a further variation of the geological/artificial barrier in Fig. 1, for the tankless accumulation of thermal energy;

Fig. 4 schematically illustrates an element of material with high thermal inertia that is used in the construction of a containment barrier for a tankless accumulation section, used in the process and system to accumulate thermal energy according to the present invention;

Fig. 5 is a perspective schematic view that shows an example of tankless epigeal thermal storage, provided with containment banks in clay material;

Fig. 6 is a perspective schematic view of an example of tankless thermal storage, constructed in a quarry area;

Fig. 7 shows an example of tankless hypogeal thermal storage from artificial cavities formed, with the Frasch method, in deep geological salt layers;

Fig. 8 shows an example of tankless hypogeal multi-barrier thermal storage in artificial cavities formed in a rock salt mine and using a mixture of molten salts as primary heat-carrier fluid;

Fig. 9 shows an example of tankless semi-hypogeal thermal storage, with primary and secondary accumulation sections of a primary heat-carrier fluid situated in a covered multi-barrier vessel;

Fig. 10 illustrates an example of thermal energy accumulation and storage, wherein bitumen is used as the primary heat-carrier fluid; and

Fig. 11 illustrates an example of thermal energy accumulation and storage comprising a tankless epigeal multi-barrier primary accumulation section, and a traditional secondary accumulation section, wherein bitumen is used as the primary heat-carrier fluid.

Description of some examples and preferred embodiments of the invention

Referring to the drawings and in line with what is already stated, some examples and preferred embodiments of important parts, constructional and structural elements, in particular for the accumulation and storage of a primary heat-carrier fluid, which are provided and used, as described in detail herein below, in the process and in the corresponding thermal energy accumulation system in accordance with the present invention, will now be primarily described.

Moreover there will be described further examples where the thermal energy accumulation process and the corresponding system, according to the invention, distinguish themselves non only by the presence of the above relevant constructional and structural elements, but also by the use of some innovative types of primary fluids, as in particular bitumen.

Example 1

Fig. 1 schematically illustrates a geological/artificial barrier that is suitable for forming a tankless thermal energy accumulation section, i.e. one which does not include tanks, in particular metal, cisterns or similar containers, which are self-supporting, to store and tightly contain a fluid.

In detail, this geological/artificial barrier, hereinafter referred to more concisely as tankless accumulation or containment barrier, is made up of a bank and base in clay 1, onto which a plurality of layers of clay 2 are applied, appropriately pressed with a roller; a layer of anti-perforation geofabric, resistant to the maximum operating temperatures; a layer 3 of insulant of appropriate thickness; and a covering 4 with high density and low permeability.

Example 2

Fig. 2 again schematically illustrates a geological/artificial tankless accumulation barrier, which has the same configuration as the previous one, shown in Fig. 1, with the exception of an additional upper layer 5, made up of elements with high thermal inertia, such as for example refractory bricks which are superimposed dry in one or more layers for the purpose of constructing a more efficient multi-layered barrier, in terms of material and thermal dispersion.

Example 3

Fig. 3 in turn schematically illustrates another embodiment of a geological/artificial tankless accumulation barrier, which has the same composition as before, illustrated in Fig. 2, with the exception of an additional insulant layer 6 which is placed before the upper layer 5 constituted of elements with high thermal inertia, for the purpose of constructing a more efficient multi-layered barrier, in terms of material and thermal dispersion.

These geological/artificial tankless containment barriers can also be made up of alternating layers which are different to those stated previously, using materials with high thermal inertia in combination with materials of different porosity and density, loose or compact, to be selected on the basis of the type of primary fluid accumulated in the respective accumulation sections and on the basis of the maintenance time of this fluid in the range of design operating conditions.

Example 4

Fig. 4 schematically illustrates an element 1, of material with high thermal inertia, which is used to construct a containment barrier of a tankless thermal energy accumulation section, wherein this element 1 is placed between two electrically welded nets which are in turn made up of horizontal

2 and vertical 3 metal wires and arc interconnected with orthogonal metal wires 4 with a length equal to or greater than 20 mm.

More specifically, these nets have square meshes with diagonals equal to or less than 300 mm, whereas the vertical, horizontal and orthogonal metal wires that make up and interconnect the two nets have a thickness equal to or greater than 2 mm, with breaking point ftk equal to or greater than 200 N/mm^2 and preferably greater than 500 N/mm^2.

This element 1, placed between the electrically welded nets, is preferably assembled, in a structure of containment of the primary heat-carrier fluid, so that it is in contact with at least one layer 5 of a heat-resistant and/or low hydraulic permeability material, such as heat-insulating cement or mortar, for the purpose of constructing an effective barrier against the dispersion of heat and the loss of fluid.

Among the materials exhibiting high thermal inertia, element 1 is made of, and the parts it can be formed of, mention is made, for example, of expanded polystyrene known as EPS, preferably with high density, or glass or rock wool, or panels with vermiculite, perlite or similar filler.

Example 5

Fig. 5 schematically illustrates a phase of construction of a thermal energy storage, again of the tankless type, comprising a primary accumulation section 2 and a secondary accumulation section 3 of thermal energy, which are located in a quarry area, of rock salt for example, in the vicinity of the walls 1 of the quarry itself.

In this example, the primary 2 and secondary 3 thermal energy accumulation sections are bordered by respective side walls and a base, which in turn are constructed with bricks and/or in general with elements of refractory material, superimposed dry and in direct contact with the previously levelled rock salt ground and with the walls of the quarry.

Moreover, a covering 4 with high thermal inertia and density is applied to the internal surfaces of the accumulation sections, bordered by the elements of refractory material, such that this covering 4 constitutes, together with these elements of refractory material, a multi-layered barrier suitable for minimising both the dispersion of heat and the percolation of fluid towards the outside of the barrier.

Moreover, when constructing the accumulation sections the power shovels, normally used for the extraction of quarry material, can also be conveniently used to cover the accumulation sections with extracted rock salt, which is then suitably compacted with rollers for example.

In this way, once the thermal energy storage area has been finished it will be capable of confining the primary fluid inside the multi-layered barrier.

Depending on the dimensions of the quarry, the extraction of the rock salt can continue during and after the construction of the thermal energy storage area.

Example 6

Fig. 6 is a schematic perspective view of epigeal thermal energy storage, in other words one that extends above the ground, which again is tankless and provided with containment banks in clay material.

The primary and secondary accumulation sections of this epigeal thermal energy storage are bordered by sides and by a base which are constructed with geological substrate material and/or elements with high thermal inertia, for the purpose of constructing a geological/artificial barrier suitable for minimising/eliminating heat and fluid dispersion.

The substrate of the geological barrier, which forms the base 1 and the sides 2 of this thermal energy storage, consists of a natural geological formation with permeability and thickness at least equivalent to those defined and corresponding to the following requirements: hydraulic conductivity k ≤ 1 x 10-7 m/s with thickness ≥ 1 m, preferably hydraulic conductivity k ≤ 1 x 10-9 m/s with thickness ≥ 1 m, and more preferably hydraulic conductivity k ≤ 1 x 10-9 m/s with thickness ≥ 5 m.

If the geological barrier does not naturally meet the aforementioned requirements, it is completed artificially by means of a barrier or confinement system, such as to provide protection to the permeation of the primary fluid equivalent to that defined above, having a thickness not less than 0.05 m, preferably greater than 0.5 m.

The base and the walls are waterproofed with a covering of artificial material that is placed above the geological barrier, on a layer of compacted mineral material, in order to guarantee the tightness and maintain the temperature of the primary fluid for the entire time required.

This waterproof covering must have suitable features for resisting thermal, chemical and mechanical stress and is constructed, for example, with the assembly of elements 3 in material with high thermal inertia, which are placed inside the metal nets and covered with a heat-insulating cement mortar 5.

Covering 6 for the top of the thermal energy accumulation and storage sections can be constructed using a single-layer or multi-layered structure, preferably heat-insulating.

The base and sides of the epigeal storage are provided or not, depending on necessity, with geobarriers, geomesh, geotextiles, geogrids and drainage.

Example 7

Fig. 7 illustrates an example of thermal energy accumulation and storage, according to the present invention, which is again tankless but hypogeal, in other words it extends below the ground, wherein the respective primary and secondary thermal energy accumulation sections are constructed in artificial cavities which are formed using the Frasch method in deep geological salt layers.

In particular, in the operation of this example the stream of the primary heat-carrier fluid coming from a heating subsystem 14, of the solar radiation type, is fed, via an inflow well 1 traversing a geological layer 2, to a primary hypogeal cavity of accumulation 4, in turn formed in a layer containing a saline formation 3 and situated above another layer 9.

In this way the primary fluid is accumulated inside the primary hypogeal cavity 4, during the hours, when there is solar radiation, in which the primary fluid is heated, to a selected maximum temperature, in order to guarantee the required plant operation hours, when solar radiation is absent, during which the primary fluid cannot be heated.

In particular the quantity of primary fluid to be accumulated in the primary hypogeal cavity of accumulation 4, during the hours when there is solar radiation, is determined by considering the selected flow rate for feeding the primary fluid to the mechanical/electrical energy generation section placed downstream from the primary hypogeal cavity 4, and also considering the quantity of primary fluid that can be accumulated in the various lines and pipes of plant and in a secondary hypogeal cavity 11 of accumulation of the same primary fluid.

The primary fluid is drawn and collected from the primary hypogeal cavity of accumulation 4, via an extraction well 5, by a pumping and collection system 6 which sends it to a heat exchange system or subsystem 7, wherein the primary fluid yields heat, then cools down, to a secondary fluid, having a temperature lower than that of the primary fluid and suitable for generating mechanical/electrical energy as part of a thermodynamic cycle.

From this heat exchange subsystem 7 the stream of primary fluid is fed, via an inflow well 8, to the secondary hypogeal cavity of accumulation 11, located in the same saline formation, for example, at a different depth with respect to the primary hypogeal cavity of accumulation 4.

The capacity of this secondary hypogeal cavity of accumulation 11, wherein the primary fluid is accumulated at a temperature lower than that at which it is accumulated in the primary cavity of accumulation 4, is preferably equivalent to the capacity of the primary cavity 4.

Finally the primary fluid is collected from the secondary hypogeal cavity of accumulation 11, via an extraction well, by a pumping and collection system 12 which sends it to the solar radiation heating subsystem 14, from where the primary fluid is fed to the primary hypogeal cavity of accumulation 4, thus closing the cycle.

The flow rate of the salts in the circuit is regulated as a function of the intensity of the solar radiation such that a constant temperature of the primary fluid is maintained at the entrance in the hot primary cavity of accumulation.

Example 8

Fig. 8 illustrates an example of thermal energy accumulation and storage which is multi-barrier, hypogeal and again tankless and which is formed in a cavity, located under ground level, of a rock salt mine 1, and which uses a stream of primary heat-carrier fluid 2, having approximately a flow rate of 300 kg/s and comprising a mixture of salts made up of 60% $NaNO_3$ and 40% KNO_3.

In operation, the stream of primary heat-carrier fluid 2, coming from a heating subsystem 12 where the mixture of salts is heated by solar radiation, is fed at the selected maximum temperature, for example 550°C, to a primary accumulation section 3, located in the rock salt mine.

In this example too, the quantity of primary fluid to be accumulated in the primary accumulation section 3 at a higher temperature is equivalent to that, for example approximately 34,000 t, necessary for guaranteeing the required hours of operation for the section, placed downstream from the primary accumulation section, for the generation of electrical energy, while also considering the volume of fluid present in the lines of the plant in the calculation of this quantity to be accumulated.

The primary and secondary thermal energy accumulation sections are made up, for example, of a first wall made up of material 4 with high thermal inertia, such as refractory material and/or heat-insulating cement mortar, in which this wall is preferably covered, along the inner side, with a suitable material 5 with high density or with a metal laminate suitably shaped in order to compensate for thermal expansion.

The accumulation sections can be equipped with a manhole, placed on the cover over the top of these same sections, in order to allow their inspection.

In operation, the stream of primary fluid, fed by the primary fluid accumulated in the primary accumulation section 3, is drawn by a pumping and collection system 7 which sends it to a heat exchange and electrical energy generation subsystem 8, where the stream of primary fluid transfers heat that is used to produce approximately 50 MWe, via a superheated steam Rankine cycle, having efficiency equivalent to 42.2%.

Then, from the heat exchange and electrical energy generation subsystem 8, the stream of fluid is fed, via the inflow line 9, to a secondary accumulation section 10 at a lower temperature, for example 290°C, with respect to that of the primary accumulation section 3, and having capacity equivalent to the capacity of the primary section.

The two primary and secondary accumulation sections, respectively 3 and 10, are adjacent and separated by a bulkhead 6, made of material with low thermal conductivity and such that it guarantees the tightness of the fluid.

The secondary accumulation section, at a lower temperature, can be dimensioned for a primary fluid accumulation volume that is lower with respect to that of the primary accumulation section, given that the density of the primary fluid is greater when it is accumulated in the secondary accumulation chamber (approximately 1.9 kg/l against 1.7 kg/l), in the range of the expected temperatures.

Finally the stream of primary fluid, coming from the secondary hypogeal accumulation section, is fed, via the pumping and extraction subsystem 11, to the heating subsystem 12 operating by solar radiation, thus closing the cycle.

This thermal energy storage system is also equipped with one or more process control stations, suitable for monitoring and regulating operational parameters in the plant startup, running and shutdown phases, and is also equipped with systems of electrical interconnection with internal/external electrical loads to the same plant and/or to the external electricity system.

The pipes and solar radiation capture system are monitored continuously.

According to a variant of the thermal energy accumulation system with respect to that described previously, the primary and secondary accumulation sections can be conveniently formed in two different cavities situated in different locations of the rock salt mine.

For completeness of information, Table 1 below provides a series of details relating to this example of thermal energy storage, regarding in particular the operational and functional features of the primary fluid, such as for example its flow rate at the entrance and exit of the hypogeal accumulation sections and the features of the mass of salts, of which the primary fluid is formed, circulating in the plant.

Table 1 - Salt Mixture: $NaNO_3$-KNO_3 (60:40)

Features	Units		
Electrical power	[MWe]	50.0	
Thermal power	[MWth]	118.6	
Plant electrical efficiency	[%]	42.2	
Tankless hypogeal section		Primary	Secondary
Mean temperature	[°C]	550	290
Maximum inflow rate	[kg/s]	1008.8	300.0
Maximum outflow rate	[kg/s]	300.0	1008.8
Accumulation volume	[m^3]	20494.6	19559.6
Salts volume at mean temp.	[m^3]	19518.7	17781.4
Current salts mixture density	[kg/l]	1.7	1.9
Circulating molten salts mass	[t]	33962.5	33962.5
Mean salts mixture Cp	(kJ/kgk)	1.52	
Useful thermal gradient	[°C]	260	

Example 9

Figure 9 shows a further example of a thermal energy storage structure, again of the tankless type but semi-hypogeal, which comprises primary and secondary accumulation sections, respectively 2 and 3, for the accumulation of a primary heat-carrier fluid, which are placed in a covered multi-barrier vessel, wherein a stream 1 formed by the primary heat-carrier fluid and coming from a heating subsystem 12, where the primary fluid is heated by solar radiation, is fed, at the selected maximum temperature, to the primary accumulation section 2 of the primary fluid.

In particular this primary accumulation section 2 is constructed in a semi-hypogeal tank, such as for example a decommissioned quarry and/or other anthropical depression or not, which is situated in a geological layer 13 made up of cohesive material with homogeneous matrix, such as for example clay, tufa, rock salt.

The secondary accumulation section 3, at a temperature lower than that of the primary accumulation section 2, is separated from the latter by a multi-layered bulkhead that is suitable for preventing/reducing heat transfer between the two primary and secondary accumulation sections, and to this end uses a material 4 with high thermal inertia and low porosity, such as for example panels in EPS and/or glass wool reinforced with metal net and heat-insulating plaster, inserted between additional layers formed, for example, with refractory bricks 5.

The quantity of primary fluid that can be accumulated in the primary section at higher temperature is equivalent to the quantity necessary for guaranteeing the required hours of operation of the section downstream suitable for the generation of energy and incremented by the quantity of fluid present in the lines of the plant.

The pit, i.e. the hypogeal depression, is formed in a suitable geological surface layer and is bordered for example by a wall made up of panels, which is insulated, or rather does not have direct contact with the primary fluid, by means of a physical plaster that covers it and is suitable for the tightness for the primary fluid.

A cover 14 can be made from EPS panels, structured and covered with the same material with which the thermal energy storage structure was formed.

Still the structure can be equipped with inspection manholes or monitored with suitable sensors connected to a receiving station.

The stream 6 of primary fluid, fed from the primary fluid accumulated in the primary section 2, is activated by the pumping and collection system 7 which sends it to the energy generation and heat exchange subsystem 8, where the primary fluid transfers heat and thereby cools down.

Then the stream of primary fluid is sent from this electrical energy generation and heat exchange subsystem 8, via the inflow line 9, to the secondary accumulation section 3, at a lower temperature, adjacent to the primary accumulation section 2 and situated for example in a side area of the hypogeal depression.

Successively the stream of primary fluid, coming from the secondary accumulation section 3, is fed by the pumping and extraction subsystem 11 to the subsystem 12 of heating by solar radiation, thus closing the cycle.

Only when the pumping and collection systems 7 and 11 induce a same flow rate and also a same collection of primary fluid, respectively from the primary accumulation section 2 and from the secondary accumulation section 3, do the levels of primary heat-carrier fluid remain at a constant height with respect to the base, in the primary 2 and secondary 3 accumulation sections, whereas in the opposite case there will be different levels of primary fluid, which appropriate regulation systems will restore to equilibrium.

Example 10

Fig. 10 illustrates an example of thermal energy accumulation and storage, wherein the primary and secondary thermal energy accumulation sections are both epigeal and use bitumen as the primary fluid.

The type of thermal energy accumulation and storage, corresponding to this example, conveniently permits the planning and combination of different accumulation sections, primary and secondary, of the primary heat-carrier fluid used.

In operation, the stream 1 of the primary heat-carrier fluid, which is made up of an organic mixture rich in oxidised bitumens and having a flash point higher than 200°C, is fed, via corresponding feeding means such as pumps or similar apparatus, at the selected maximum temperature, for example 280°C, from the heating subsystem 12 where the stream 1 receives heat and is heated by solar radiation, to the primary epigeal accumulation section 3.

Also in this example, the quantity of primary fluid that is accumulated in the primary accumulation section 3 at higher temperature is determined and calculated such as to guarantee the approximately eight hours of operation required for the generation of mechanical/electrical energy in the absence of solar radiation, by also considering in this calculation the quantity of primary fluid that is present in the lines of the plant.

The stream 1 of primary fluid is then drawn from the primary accumulation section 3 by means of the pumping and collection system 7 which sends it to the energy generation and heat exchange subsystem 8, where the stream 1 of primary fluid yields heat to the secondary fluid.

Then from the heat exchange subsystem 8 the stream 1 is fed, via the inflow line 9, to the secondary accumulation section 10, at a lower temperature, for example 120°C, with respect to that of the primary accumulation section 3, and having an accumulation capacity equivalent to that of the primary section.

Finally the stream 1 of primary fluid is drawn and fed, via the pumping and extraction subsystem 11, from the secondary accumulation section 10 to the solar radiation heating subsystem 12, thus closing the cycle.

The primary and secondary accumulation sections can be equipped with suitable heat exchangers 2 and apparatus for blanketing with inert gas.

Moreover, the accumulation sections are constructed using a wall 5, of carbon steel, insulated from the exterior by means of a layer of rock wool 4, having thickness greater than 50 mm, or using another suitable material with high thermal inertia and appropriate thickness placed internally and/or externally, suitable for guaranteeing the maintenance of the mean temperatures of the fluid in the design temperature range for the prefixed time period.

The carbon steel walls are covered internally with aluminium or galvanised steel having a thickness greater than 0.7 mm.

Moreover, the two primary and secondary accumulation sections are equipped with inspection manholes and access ramps.

Example 11

Figure 11 illustrates another example of thermal energy storage that comprises a tankless epigeal multi-barrier primary accumulation section and a traditional secondary accumulation section, in which bitumen is used as the primary fluid.

This example of thermal energy storage can be advantageously implemented in order to transform a traditional bitumen storage cistern into a secondary accumulation section, thereby creating a really innovative primary accumulation section, in the context of a plant or system intended for producing mechanical/electrical energy from solar radiation.

In operation, a stream 1 of a primary heat-carrier fluid, which has an approximate flow rate of 136.2 kg/s and is made up of an organic mixture, rich in oxidised bitumens, having a flash point higher than 200°C, is fed at the maximum selected temperature, for example 280°C, by a heating subsystem 14, where the mixture has been suitably heated by solar radiation, to a tankless epigeal primary accumulation section 2.

The primary accumulation section 2 is constructed by assembling elements 3, with high thermal inertia, and is such that it constructs a multi-layered barrier suitable for the tight containment of the primary fluid and maintenance of the temperature over time.

These elements 3 are made up of panels with high thermal inertia placed between two electrically welded nets 4, which have in turn been constructed with horizontal and vertical metal wires and interconnected by galvanised or stainless steel orthogonal wires, having a length greater than 30 mm.

In particular the electrically welded nets, used in making these elements 3, have square meshes with diagonals less than 300 mm.

The vertical, horizontal and orthogonal wires forming and interconnecting these electrically welded nets have a thickness greater than 3 mm, with breaking point ftk equal to or greater than 500 N/mm^2.

The multi-layered barrier of the primary accumulation section 2 is formed by further covering the external side 5 and the internal side 6, exposed to the primary heat-carrier fluid, of these elements 3, with high thermal inertia, with a layer of heat-insulating cement mortar of suitable thickness and low hydraulic permeability.

Again, the external surface of this tankless primary accumulation section 2 can be usefully covered with suitable material, for example polymeric, with very low permeability and/or heat resistant.

As in the previous examples, the quantity of primary heat-carrier fluid accumulated in the primary accumulation section 2, at a higher temperature, corresponds to that necessary for guaranteeing eight hours of regular operation, despite the absence of solar radiation, of the heat exchange section where the primary fluid transfers its heat in order to generate mechanical/electrical energy, by also considering, when determining and calculating this quantity of primary fluid to be accumulated in the primary accumulation section 2, the quantity of primary fluid present in the lines of the plant.

In operation, the stream of primary fluid, fed from the primary fluid accumulated in the primary accumulation section 2, is activated by a pumping and collection system 7 which feeds it to a heat exchange subsystem 8, where the primary heat-carrier fluid yields its heat, and therefore cools down, in order to produce approximately 9.5 MWe, with efficiency equivalent to 21%, via an organic Rankine cycle.

From this heat exchange subsystem 8 the stream of primary fluid is fed, at a temperature equivalent to approximately 120°C, along an inflow line 9 and again under the action of the pumping and collection system 7 to a secondary accumulation section 10 having capacity equivalent to that of the primary accumulation section 2.

This epigeal secondary accumulation system 10, wherein the primary fluid has a lower temperature with respect to that of the epigeal primary accumulation chamber 2, is instead constructed traditionally and with traditional technology, and in particular is made up of a standard tank with containment walls 11 of carbon steel, wherein this tank is covered externally with a layer of rock wool 12 having a thickness greater than 50 mm, or with other appropriate heat-insulating material suitable for guaranteeing the maintaining of the temperature of the primary fluid, accumulated in the secondary accumulation section 10, during the fixed time period.

Moreover the internal walls of this secondary accumulation section 10 are covered with a sheet of aluminium or galvanised steel having a thickness greater than 0.7 mm.

Similarly to the previous examples, the stream of primary fluid is fed, via the pumping and extraction subsystem 13, from the secondary accumulation section 10 to the heating subsystem 14, where the primary heat-carrier fluid receives heat and then heats up due to the effect of solar radiation, thus closing the cycle.

The accumulation sections can be equipped with one or more heat exchangers, and also inert gas expansion vessels with the function of compensating for thermal expansions and contractions of the primary fluid contained and accumulated in the accumulation sections.

Here too, for completeness of information, Table 2 below provides a series of characteristic data of this last example of thermal energy accumulation and storage, using, as primary heat-carrier fluid, an organic bitumen mixture.

Table 2 (organic bitumen mixture)

Features	Units		
Electrical power	[MWe]	9.5	
Thermal power	[MWth]	45.5	
Plant electrical efficiency	[%]	21	
Epigeal accumulation section		Primary	Secondary
Mean temperature	[°C]	280	120
Maximum inflow rate	[kg/s]	457	136.2
Maximum outflow rate	[kg/s]	136.2	457
Accumulation volume	[m^3]	6050	6400
Fluid volume at mean temp.	[m^3]	5500	6090
Current mixture density	[kg/l]	0.89	0.805
Mixture accumulation mass	[t]	3930	3930
Mixture Cp	(kJ/kgk)	1.84	2.30
Useful thermal gradient	[°C]	160	

It also appears evident that further examples, variants, improvements, modifications and also different methods of application and use of the process and corresponding system for accumulating thermal energy, according to the present invention, can be implemented and developed further by persons skilled in the art, without departing from the scope and sphere of the invention itself, as defined by the respective claims.

CLAIMS

1. Process to accumulate thermal energy, for example in a mechanical/electrical energy production plant, comprising the following steps:

a) accumulation of at least one primary heat-carrier fluid, in a secondary accumulation section (11 - Fig. 7; 10 - Fig. 8; 3 - Fig. 9; 10 - Fig. 10; 10 - Fig. 11), of a plant, at a lower mean temperature with respect to that of a primary accumulation section (4 - Fig. 7; 3 - Fig. 8; 2 - Fig. 9; 3 - Fig. 10; 2 - Fig. 11), of the same plant, said primary and secondary accumulation sections of the plant being made up of one or more collection and accumulation subsystems of said primary fluid, constructed or not with material with high thermal inertia and including or not heat exchangers;

b) collection of said primary fluid from said secondary accumulation section and its feeding to one or more heating subsystems (14 - Fig. 7; 12 - Fig. 8; 12 - Fig. 9; 12 - Fig. 10; 14 - Fig. 11) associated with one or more heat sources and having a temperature higher than that of said primary fluid, wherein the thermal energy supplied to said primary fluid from said heating subsections has a discontinuous and/or variable course, as in particular when the heat source consists of solar radiation;

c) heating of said primary fluid in said one or more heating subsections (12 - Fig. 9);

d) feeding from one or more said heating subsections and accumulation of said primary fluid, at the selected temperature, in said primary accumulation section;

e) collection from said primary accumulation section (4 - Fig. 7; 3 - Fig. 8; 2 - Fig. 9; 3 - Fig. 10; 2 - Fig. 11) of said primary fluid, previously heated, and its feeding to a heat exchange section (7 - Fig. 7; 8 - Fig. 8; 8 - Fig. 9; 8 - Fig. 10; 8 - Fig. 11) suitable for carrying out heat exchange between said primary fluid and a secondary fluid at a temperature lower than that of said primary fluid, in particular as part of a thermodynamic cycle suitable for generating mechanical/electrical energy from the heat transferred through said heat exchange, with resulting cooling of said primary fluid and simultaneous increase of the temperature of said secondary fluid to the conditions required by said thermodynamic cycle; and

f) collection of said primary fluid, cooled, from said heat exchange section and its feeding to said secondary accumulation section (11 - Fig. 7; 10 - Fig. 8; 3 - Fig. 9; 10 - Fig. 10; 10 - Fig. 11), thus closing the cycle and therefore making said fluid available again, in said secondary accumulation section, to be fed to said one or more heating subsections and then heated again.

2. Process according to claim 1, wherein at least one of said one or more collection and accumulation subsystems, constituting the primary and secondary accumulation sections of said primary fluid, is hypogeal (4, 11 - Fig. 7; 3, 10 - Fig. 8) or partially hypogeal (2, 3 - Fig. 9), or is epigeal (3, 10 - Fig. 10; 2, 10 - Fig. 11).

3. Process according to claim 1 or 2, wherein at least one of said one or more collection and accumulation subsystems, constituting said primary and secondary accumulation sections, is of the tankless type (1,2,3,4 - Fig. 1; 1,2,3,4, 5 - Fig. 2; 1,2,3,4,5,6 - Fig. 3), that is it is constructed without the use of self-supporting metal tanks, mechanically resistant to operating temperatures and suitable for the tight containment of said primary fluid.

4. Process according to any of the previous claims, wherein said primary and secondary accumulation sections are constructed in natural or artificial cavities, are provided with inflow/outflow wells/conduits of the primary fluid and are situated in impermeable or mainly impermeable, or saline, geological formations.

5. Process according to claim 4, wherein the substrate of the base and of the sides of the accumulation sections of said collection and accumulation subsystems consists of a natural geological formation constituting a barrier that exhibits a permeability and thickness such as to meet the following requirements:

- hydraulic conductivity k ≤ 1 x 10-7m/s with thickness ≥ 1 m;
- preferably hydraulic conductivity k ≤ 1 x 10-9 m/s with thickness ≥ 1 m;
- more preferably, hydraulic conductivity k ≤ 1 x 10-9m/s with thickness ≥ 5 m;

wherein, if the barrier formed by the natural geological formation is not able to meet the aforementioned requirements, the base and sides of said accumulation sections are completed artificially so as to create a confinement barrier suitable for providing protection equivalent to or greater than that defined by the aforementioned requirements and having a thickness ≥ 0.05 m and preferably > 0.5 m.

6. Process according to claim 3, wherein the containment surfaces of the primary or secondary accumulation sections, of this collection and accumulation subsystem of the tankless type, are made up of geological and/or artificial barriers containing material with high thermal inertia.

7. Process according to claim 6, wherein said material with high thermal inertia is characterised by a heat transfer coefficient, at the operating temperature, less than or equal to 25 W/mK, preferably less than 5 W/mK, and more preferably less than 0.5 W/mK.

8. Process according to claim 6, wherein said material with high thermal inertia is placed between two electrically welded nets comprising horizontal and vertical metal wires.

9. Process according to claim 8, wherein said two electrically welded nets

are interconnected one in respect of the other with orthogonal metal wires having a length equal to or greater than 20 mm,

wherein the meshes of said two nets are square with diagonals equal to or less than 300 m, and

wherein said vertical, horizontal and orthogonal wires forming and interconnecting said electrically welded nets have a thickness equal to or greater than 2 mm, with breaking point ftk equal to or greater than 200 N/mm^2 and preferably greater than 500 N/mm^2.

10. Process according to any one of the previous claims, wherein said primary and secondary accumulation sections are equipped with geomeshes and/or geotextiles and/or geogrids and/or drainage.

11. Process according to one of the previous claims, wherein the primary fluid or primary fluids used are of the type containing liquid organic mixtures that include components with a number of carbon atoms equal to or greater than 7 and preferably greater than 9, and/or have an initial boiling temperature at atmospheric pressure equal to or higher than 98°C, and preferably higher than 150°C, these primary fluids being additivated or not.

12. Process according to any one of claims 1 to 10, wherein the primary fluid or primary fluids used have high contents of aromatic and/or cyclic hydrocarbons and preferably aromatic polycyclic and/or polynuclear, in particular belonging to the class of bitumens and their derivatives, oxidised or not, said primary fluid or said primary fluids being additivated or not.

13. Process according to any one of claims 1 to 10, wherein the fluid or primary fluids used are of the organic type containing molten salts and in particular molten salts constituting eutectics, and more particularly eutectic mixture comprising 60% sodium nitrate and 40% potassium nitrate.

14. Process according to any one of claims 1 to 10, wherein the fluid or primary fluids used are inorganic and contain low melting alloys or mineral

oils, or molten salts of K or Li or Na or Mg or their mixtures, and in particular $LiNO_3$, $LiNO_3$-$NaNO_3$, KNO3-$LiNO_3$, KNO_3-$NaNO_2$-$NaNO_3$, $NaNO_2$, $NaNO_3$, KNO_3, KNO_3-$NaNO_3$ and more particularly the mixture $NaNO_3$ at 60% and KNO_3 at 40%.

15. System for the accumulation of thermal energy of the type using at least one primary heat-carrier fluid suitable for exchanging heat with a secondary fluid to heat it, in particular as part of a thermodynamic cycle intended to generate mechanical/electrical energy, wherein said system implements the process according to any one of claims 1 to 14.

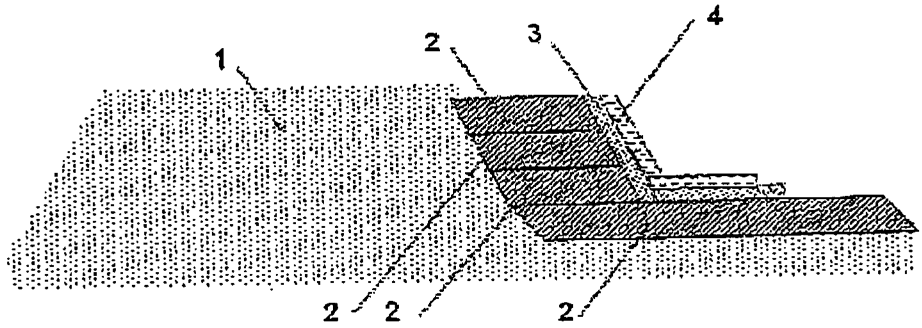

Fig. 1

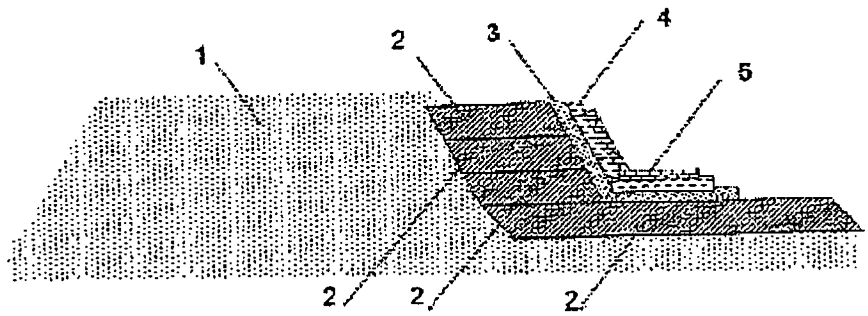

Fig. 2

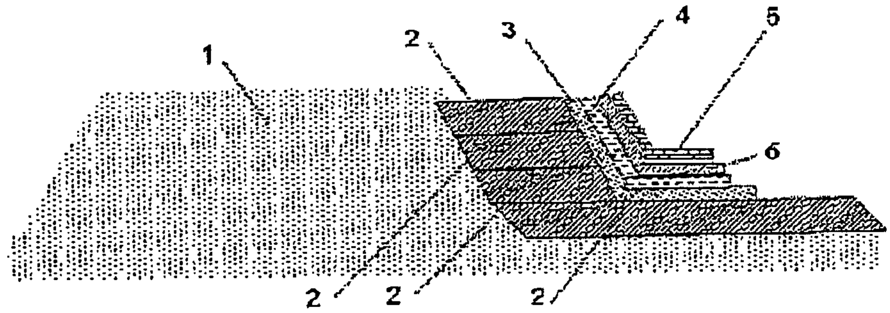

Fig. 3

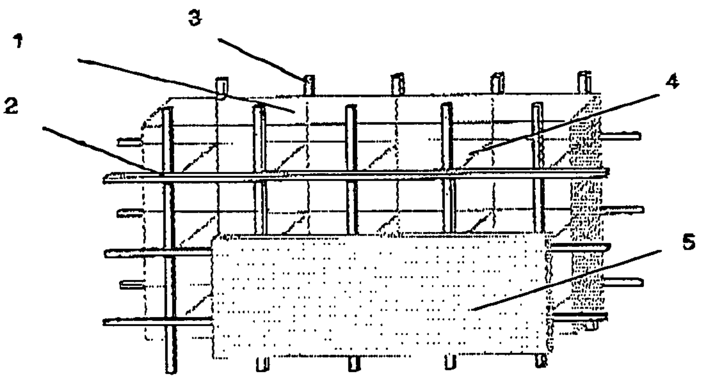

Fig. 4

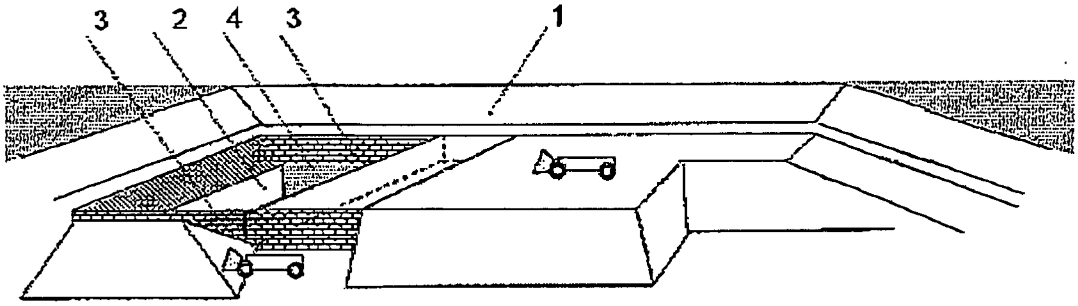

Fig. 5

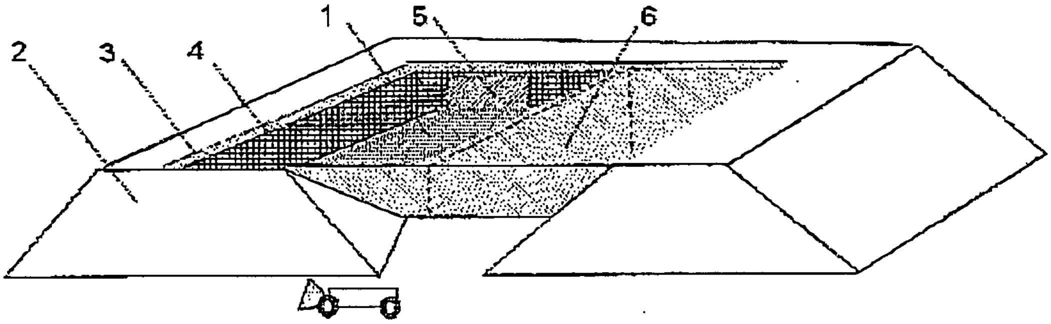

Fig. 6

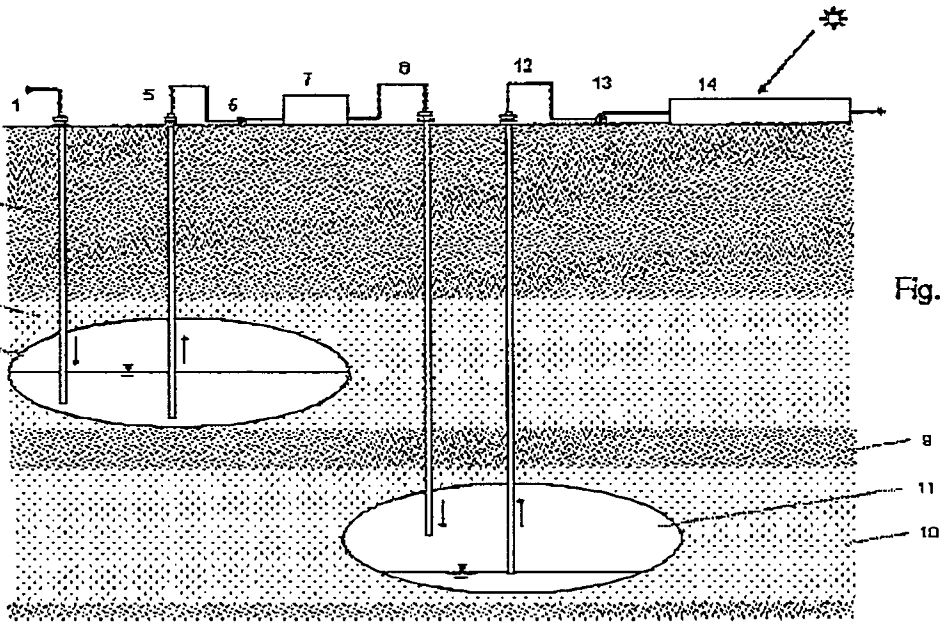

Fig. 7

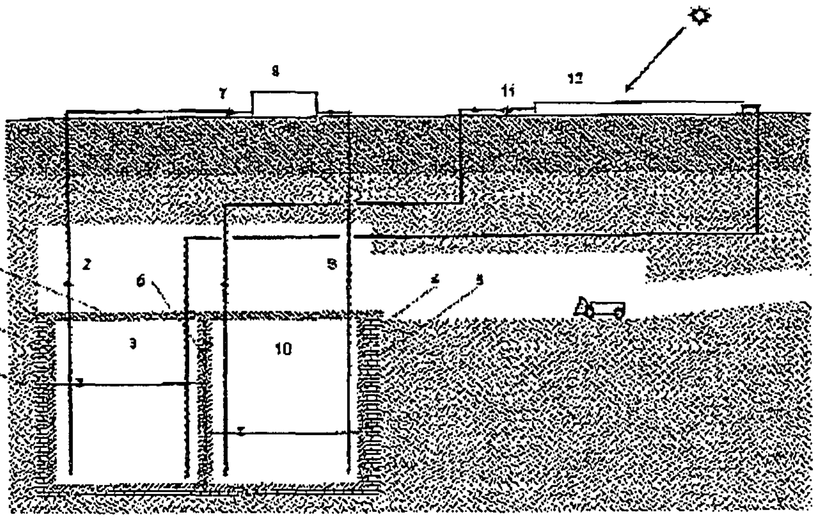

Fig. 8

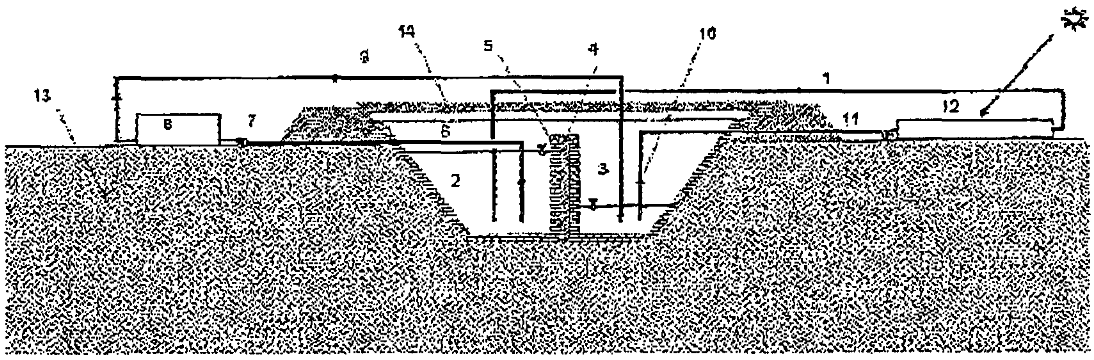

Fig. 9

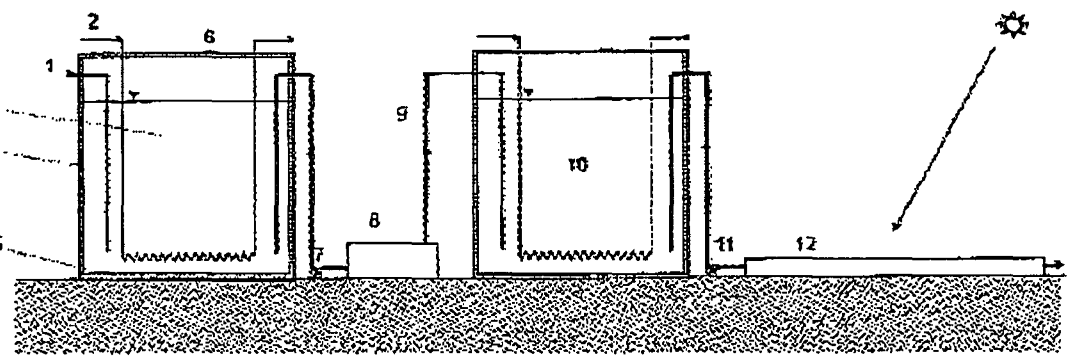

Fig. 10

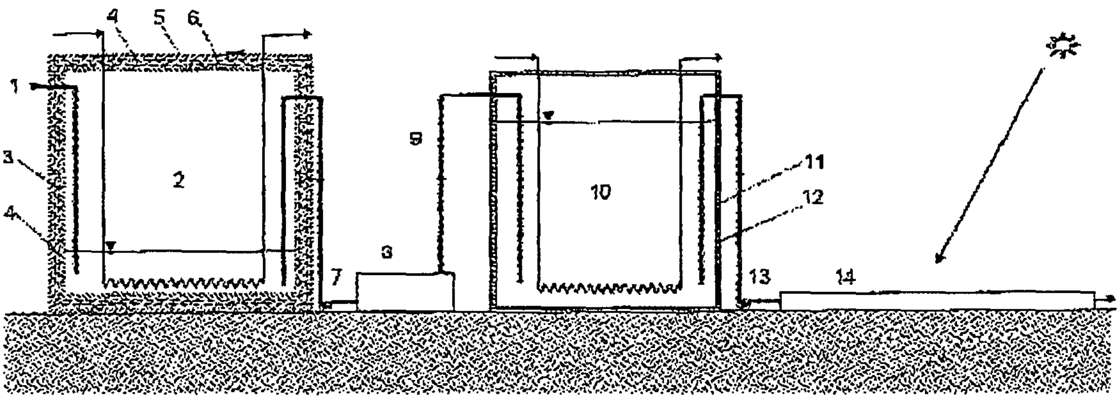

Fig. 11