SOLAR ENERGY COLLECTION APPARATUS AND METHOD

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ABSTRACT

An apparatus for collecting heat from a solar concentrator has an isothermal body defining an elongated cavity with a circular opening having a diameter equal to a diameter of a focus of the solar concentrator. The cavity has reflective walls such that solar rays contacting the walls are substantially reflected. The circular opening is located at the focus of the solar concentrator and perpendicular to a principal axis of the solar concentrator, and the axis of the cavity is aligned with the principal axis of the solar concentrator. The heat generated in the isothermal body is absorbed by the heat sink. The length of the cavity is sufficient to absorb a desired proportion of the energy in the solar rays entering the cavity and is about 5 to 9 times the diameter of the opening of the cavity. Depending on material used, the isothermal body can be enclosed in a reducing atmosphere to maintain reflectivity of the cavity walls.
- target dia in = 6  
  suns = 5482.014559

- target dia in = 15  
  suns = 877.1223295

Fig 5
SOLAR ENERGY COLLECTION APPARATUS AND METHOD

This invention is in the solar energy field and in particular the collection of concentrated solar radiation for the purpose of driving a thermo-chemical, thermo-mechanical or other thermal process.

BACKGROUND

There exists today considerable interest in harnessing renewable solar thermal energy for a multitude of heat driven processes. These may include thermo-mechanical as in sterling engine or steam turbine power generation systems, thermo-chemical reforming, thermal-cracking, process heating, general heating, materials processing etc. Solar collection systems are usually placed in locations where sunlight is readily available. In a typical system mirrors either flat-segmented, or curved, are arranged in a parabolic or trough configuration to concentrate incident solar radiation on a predefined target. Tracking control systems or preprogrammed algorithms maintain the required optical geometry by moving the mirror as the sun transverses the sky.

The target is usually some form of cavity or shallow dish into which the concentrated light cone is directed. The cavity is commonly disposed with a plurality of tubes into which a coolant is flowed to convey absorbed heat to the working process. Some cavity designs as in U.S. Pat. No. 5,113,659 incorporate a series of hot shoes inside a cavity to conduct thermal energy to a plurality of free piston sterling generators. In some solar thermo-chemical processing the image fireball is employed to directly heat catalyst beds in transparent process tubes often resulting in hotspots, causing catalyst sintering and poor process temperature control.

In all these collection schemes, the spot size and shape must be tailored for the heat exchange and cavity parameters. To avoid local overheating effects the fireball is often defocused or multiple fireballs are skewed to provide a homogenous heat zone into which the process heat exchange tubes are displaced. This results in a less than optimal focus of the solar fireball on the target and an increase in radiation losses due to the enlarged solar image size with the accompanying increased area of hot radiating surfaces.

Scaling and the costs of solar collection technology will be dictated to a large part by overall product conversion efficiency, therefore the goal of any solar collection system is the maximum product production for the smallest possible solar collection area. A key factor in achieving this goal is the minimization of parasitic losses due to target re-radiation.

The required process temperatures dictate the collection means, be it trough reflectors for low-grade heat applications or parabolic concentrators for higher temperatures. Steam systems may be operated at moderate temperatures of less than 800 K, whereas thermo-chemistry in an effort to obtain high equilibrium constants in some exothermic reactions may require substantially higher temperatures. Unfortunately as process temperatures increase, parasitic radiation loss follows Stefan’s law (P = σεAT^4) such that losses due to thermal radiation increase sixteen fold for each doubling of the absolute temperature of the target, which is at the process temperature. It follows that minimum radiation loss can be realized by utilizing the smallest possible fireball image or the highest solar concentration in conjunction with an optimized cavity receiver configuration in which the blackbody area equals the focused solar image.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a solar heat collecting apparatus and method that overcomes problems in the prior art.

In a first embodiment the invention provides an apparatus for collecting heat from a solar concentrator and for transferring the collected heat to a heat sink. The apparatus comprises an isothermal body defining an elongated cavity with a substantially circular opening having a diameter substantially equal to a diameter of a focus of the solar collector, the cavity having reflective walls such that solar rays contacting the walls are substantially reflected. The isothermal body is adapted to be oriented such that the circular opening is located substantially at the focus of the solar collector and substantially perpendicular to a principal axis of the solar concentrator, and such that an axis of the cavity is substantially aligned with the principal axis of the solar concentrator. The isothermal body is adapted for thermal connection to the heat sink such that heat generated in the isothermal body is absorbed by the heat sink. The length of the cavity is sufficient to absorb a desired proportion of the energy in the solar rays entering the cavity.

In a second embodiment the invention provides an apparatus for collecting heat from the sun and for transferring the collected heat to a heat sink. The apparatus comprises a solar concentrator, and an isothermal body defining an elongated substantially cylindrical cavity with a substantially circular opening having a diameter substantially equal to a diameter of a focus of the solar collector, the cavity having reflective walls such that solar rays contacting the walls are substantially reflected. The isothermal body is oriented such that the circular opening is located substantially at the focus of the solar collector and substantially perpendicular to a principal axis of the solar concentrator, and such that an axis of the cavity is substantially aligned with the principal axis of the solar concentrator. The isothermal body is adapted for thermal connection to the heat sink such that heat generated in the isothermal body is absorbed by the heat sink and a length of the cavity is about 5 to 9 times the diameter of the circular opening.

In a third embodiment the invention provides a method for collecting heat from a solar concentrator for transfer to a heat sink. The method comprises providing an isothermal body defining an elongated cavity with a substantially circular opening having a diameter substantially equal to a diameter of a focus of the solar collector, the cavity having reflective walls such that solar rays contacting the walls are substantially reflected; orienting the isothermal body such that the circular opening is located substantially at a focus of the solar collector and substantially perpendicular to a principal axis of the solar concentrator, and such that an axis of the cavity is substantially aligned with the principal axis of the solar concentrator; reflecting each solar ray that contacts a reflective wall from a first contact point on the reflective wall to a second point on a reflective wall and to a plurality of subsequent contact points on the reflective walls wherein a portion of the energy contained in each solar ray is absorbed by a reflective wall at each contact point until a desired proportion of the energy contained in the solar ray is absorbed by the reflective walls; thermally connecting the
heat sink to the isothermal body such that heat generated in the isothermal body by the absorbed energy of the solar rays is absorbed by the heat sink.

[0011] The solar radiation is converted to heat by multiple internal reflections within the reflective cavity disposed in the isothermal body, and this cavity receiver assembly is thermally coupled to the required heat process or heat sink. The isothermal body has significant mass to integrate thermal fluctuations and provide the coupled process with a substantially consistent temperature regardless of minor insulation or fireball image deviations.

[0012] The cavity opening is positioned at the focus of a parabolic solar concentrator on the principal optical axis such that the light cone is at its minimum diameter at the cavity entrance.

[0013] The mechanical configuration resembles a thick walled hollow cylinder clad with or constructed wholly of a chemically reducible material such as, but not limited to, copper. The isothermal cavity is thermally coupled to a heat process while the open end of the cavity intercepts the light cone at the focus of a solar concentrator. Solar flux enters the cavity and undergoes multiple internal reflections while evenly dispersing and gradually reducing the radiation to heat which is absorbed by the isothermal body of the receiver and conducted to the process. Reflectivity of the cavity walls is maintained by an inert or reducing local atmosphere.

DESCRIPTION OF THE DRAWINGS

[0014] The aforementioned objects and advantages of the present invention as well as additional objects and advantages thereof will be more fully understood herein as a result of a detailed description of preferred embodiments of the invention when taken in conjunction with the following drawings where like components in the drawings are assigned like designators and where:

[0015] FIGS. 1 and 2 are schematic views of a prior art solar heat collection system configured to drive a Sterling to electrical converter.

[0016] FIG. 3 depicts the target irradiance profile of a radially skewed solar collector used in the prior art to reduce solar concentration to an acceptable level.

[0017] FIG. 4 is a graph of the radial flux distribution of the prior art and the current invention.

[0018] FIG. 5 is a graphical representation of blackbody thermal radiation loss in relation to target temperature and area.

[0019] FIG. 6 is a schematic sectional side view of an embodiment of the present invention employed in a Sterling engine driven generator system.

[0020] FIG. 7 is a schematic sectional side view of an alternate embodiment of the invention in a superheating application.

[0021] FIGS. 8 and 9 are schematic sectional side views of an embodiment of the present invention employed in a thermo-chemical reactor system.

[0022] FIG. 10 is a schematic isometric view of an isothermal body of the invention defining a co-axial cavity and illustrating a single ray path and the basic principals of the cavity operation.

[0023] FIG. 11 is an end view of the thermally conductive body of FIG. 10 illustrating the internal ray path.

DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

[0024] FIGS. 1 and 2 schematically illustrate a prior art system of solar heat collection driving a heat engine and electric generator combination. Solar heat collection systems are used to provide heat for a wide variety of purposes in which the collected heat is transferred to a heat sink, such as the illustrated heat engine, that essentially consumes the heat. The operating temperature will vary depending on the purpose, and the system will be designed such that all the collected heat will be drawn away by the heat sink once the operating temperature is at the desired temperature which can vary from about 100°F C. to 1400°F C. or more.

[0025] In this example solar radiation 1 is reflected by the solar concentrator 2 in solar rays 7 of a solar beam and focused on a target 8 positioned in a cavity 11 at the focus of a parabolic concentrator 2. The target 8 consists of a plurality of metal tubes 3 arranged symmetrically about the principal axis 9 of the parabolic solar concentrator 2 to intercept the light cone. To reduce thermal convection losses a quartz window 5 covers the target 8. A coolant flows through the tubes 3 to remove heat generated by the absorption of radiation on the tubes 3 and transfer this heat to the heat engine 4 by conduction.

[0026] The mechanical energy converted by the heat engine in this example is communicated by a shaft 10 to a generator 6, which converts the mechanical energy to electrical energy. In this example, the flux distribution directed at target 8 conforms to an annular ring as shown in FIG. 3 by skewing multiple fireball images on the tubular heat exchange structure in an effort to reduce solar flux intensity levels to the heat exchange design limits. In FIG. 4, curves W graphically illustrate the resulting radial flux distribution at the target 8 caused by the superimposed and skewed fireball images of FIG. 3. As seen in FIG. 3, an approximately circular portion in the middle of the target is substantially not exposed to the solar rays 7. The concentration of the solar beam 7 on the target 8 is thus reduced by increasing the radiated target area.

[0027] Solar concentration is typically measured in units of “suns”. One sun represents the energy incident upon a unit area normal to the sun, which is about 1000 watts per square meter (W/m²). Further for example, while the solar concentration possible at the focus might be about 5500 suns, the heat exchange tubing 3 will not withstand the heat developed at that concentration. Given the heat capacity and mass flow of the coolant, along with thermal transfer parameters of the heat exchange, the maximum safe solar concentration in this example is limited to about 877 suns or 877000 W/m². To reduce the solar concentration the mechanism is arranged, by skewing the parabolic concentrator 2 for example, so that a larger area is radiated, and the solar concentration is thus reduced, to effect the required thermal transfer while maintaining the temperature of the exchanger within design limits.

[0028] Increasing the target size however also increases the radiation losses at a given temperature and reduces the efficiency of the solar collector. As shown in FIG. 5, the magnitude of energy loss at an emissivity of 1.0 due to target re-radiation is substantially affected by the process temperature and the radiant area of the target. In the example above in FIGS. 1 and 2, the diameter of the target 8 would be about 15 inches and the solar concentration is 877 suns on a target area...
of about 177 square inches (including the circular portion in the middle of the target that is substantially not exposed to the solar rays 7). By rearranging the parabolic solar concentrator 2 to concentrate a single fireball at the focus, the target can have a diameter of about 6 inches so that the solar concentration is 5500 suns on a target area of about 28 square inches at the focus. Thus the target area is reduced by a factor of about 6.25 and the concentration correspondingly increases by a factor of 6.25.

[0029] As seen in FIG. 5, by decreasing the target size to six inches from 15 inches, the radiation loss can be reduced from 13% to 2% where the process operating temperature is 850°C. As seen in FIG. 5, the radiation losses for the larger target increase dramatically as the operating temperature rises, while the radiation losses for the smaller target increase much less. These data are thermodynamic realities consistent with any blackbody solar receiver design at the indicated temperatures. The much higher solar concentration however is problematic when actually building a collector of such a small diameter.

[0030] FIG. 6 illustrates an embodiment of an apparatus of the invention for collecting heat from a solar concentrator and for transferring the collected heat to a heat sink. The heat sink in the illustrated embodiment is a Sterling engine-generator similar in design to that of FIGS. 1 and 2 with a collection apparatus of the present invention. Here, instead of skewing the concentrator, solar radiation 1 concentrated by a parabolic solar concentrator 2 is sharply focused to a single fireball image at the entrance opening of elongated cavity 13. Here the solar concentration is greatest, and the diameter of the target, the entrance opening of the cavity 13, is smallest. In FIG. 4, curve S graphically illustrates the resulting radial flux distribution at the target 8 with a single fireball image.

[0031] The opening of the cavity 13 is circular having a diameter substantially equal to the diameter of the focus of the solar collector 2. The cavity 13 is oriented such that the circular opening is located at the focus of the solar collector 2 and substantially perpendicular to a principal axis 9 of the solar concentrator 2, and such that an axis of the cavity 13 is substantially aligned with the principal axis 9.

[0032] The cavity 13 is defined in an isothermal body 12 made from stainless steel, or the like. The cavity 13 is lined with a metal liner 32 such as copper exhibiting good reflectivity in a chemically reduced state and excellent thermal conductivity. Alternatively, the isothermal body 12 may be constructed wholly of a chemically reducible and thermally conductive material such as but not limited to copper. In any event the cavity 13 has reflective walls such that solar rays 7 contacting the walls are substantially reflected. Multiple reflections of the light beam within the cavity 13 transform the energy from the solar rays to heat in the walls of the cavity 13 that is transferred by conduction to the isothermal body 12 increasing its temperature and making this heat energy available to the heat sink process.

[0033] By reflecting solar rays 7 that contact a reflective wall from a first contact point on the reflective wall to a second point on a reflective wall and to a large plurality of subsequent contact points on the reflective walls the effective area of the receiver is increased from the area of the opening of the cavity to the area of the walls of the cavity. Since the cavity is elongated compared to the opening of the cavity, the proportion of solar rays that reflect from wall to wall and then out through the opening before being absorbed is small.

[0034] The proportion of solar energy absorbed can be increased by increasing the length of the cavity. Total absorption of the beam is unrealistic, however if the length of the reflective cavity 13 is about 5-9 times the diameter of the cavity entrance opening the length of the cavity will generally be sufficient to absorb a desired significant proportion of the solar rays entering the cavity. Tests have shown a very good approximation of a blackbody absorber is realized with minimal blackbody area where the length of the reflective cavity 13 is about 7 times the diameter of the cavity entrance opening. With such a configuration about 95% of the solar energy is absorbed.

[0035] Increasing the length of the cavity 13 will increase the proportion of solar rays absorbed, however the length of the isothermal body 12 is also increased. As the size of the isothermal body 12 increases, conductive heat losses from the isothermal body increase as well and gains in radiation reduction are offset by conduction losses through the enlarged surface area of the isothermal body 12. Decreasing the length of the cavity 13 will result in a reduced proportion of the energy in the solar rays 7 being absorbed, as a greater proportion of the rays will be reflected out of the cavity 13 and lost.

[0036] The cavity 13 is maintained in a reducing local atmosphere for the chemical reduction of exposed metallic components whose reflectivity would decrease if oxidized and thus reduce the effectiveness of the apparatus.

[0037] FIGS. 10 and 11 illustrate the isothermal body 12 and cavity 13 of the present invention excluding any heat extraction means where a single ray path of the solar beam 7 is traced through the entrance 20 of the cavity 13 and encounters the reflective wall of the cavity 13. The solar ray 7 or photon in this example undergoes many reflections before finally being absorbed by the cavity wall where its energy is transferred to the isothermal body 12 thus increasing its internal energy or temperature. The path followed by the photon in FIGS. 10 and 11 is but one of a myriad of paths possible, depicted for illustrative purposes only. Focused light energy with a Gaussian beam profile directed at the cavity entrance would follow every possible path within the cavity evenly distributing the heat therein.

[0038] As the temperature of the isothermal body 12 increases, the exposed face 14, depending on its emissivity and area, will radiate energy contributing to the total parasitic loss. It is advantageous therefore to construct a shield 30 of a similar reducible material such as copper, as illustrated in FIGS. 6-9, to cover this or any exposed face of the isothermal body 12 between the opening of the cavity and the outer edges of the isothermal body in an effort to reduce the thermal radiation loss by reducing surface emissivity. Chemically reducible and similar shields can be used to cover any exposed components at the process temperature.

[0039] FIG. 7 shows a superheating arrangement used for steam or working fluids of a heat process. Solar energy as described in the aforementioned is absorbed by the mechanism of multiple internal cavity reflections and absorption, which heat the isothermal body 12 to the process temperature required. The working fluid enters the receiver at 18 and is circulated cyclically through passages 17, symmetrically located in the isothermal body 12, absorbing energy from the body and exiting to the required process at 19.

[0040] In the embodiments of FIGS. 6 to 9, a sealed enclosure 16 is provided which serves to contain a reducing atmosphere 15 as well as any required insulation. A window 5
allows entry of solar radiation to the reflective cavity 13 and also provides a gas seal for the enclosure 16. The enclosure 16 is filled with a reducing atmosphere, such as 5% hydrogen and the balance a filler gas that is inert at the operating temperature. Nitrogen is a good choice since it is cheap and inert at higher operating temperatures. Other inert gases such as argon, etc., could be used as well. The reducing atmosphere maintains the reducible metals, for example oxygen-free high conductivity (OFHC) copper or other like metallic compounds, in their required metallic form. In this state, the reflective surfaces of the liner 32 of reflective cavity 13 and shield 30 maintain a low emissivity thereby fulfilling their function in this invention.

To reduce heat loss the enclosure 16 containing the reducing gas is insulated.

In FIGS. 6-9, as solar radiation heats the cavity 13, thermal expansion of the metal cavity liner 32 forms the metallic walls of the cavity 13 causes high compression forces against the interior walls of the isothermal body 12. Intimate contact between these components decreases the thermal resistance of the metallic boundary between the liner 32 and the isothermal body 12 enhancing thermal transfer to the heat receiving isothermal body 12, increasing the maximum rated flux density of the cavity by making the cavity liner and receiver assembly substantially isothermal.

FIGS. 8 and 9 illustrate a thermo-chemical solar reactor where concentrated solar beam 7 enters a gas sealed enclosure 16 through a quartz window 5 where, through multiple cavity reflections, the energy of the solar beam 7 is absorbed by the isothermal body 12 and converted to heat. Reactant gas is admitted to the feed line 22 and preheat channel 24. The hot reactant, on exiting the preheater channels 24, enters the reaction beds 25 within the isothermal body where a catalyzed endothermic reaction occurs. The products in these examples exit the isothermal body at tubes 23.

Other embodiments of the examples depicted in FIGS. 6 through 9 would include a solid isothermal body constructed of a reducible metal or ceramic whereby eliminating the need for a reflective cavity liner or shield. Other means of inhibiting oxidation of these key components such as other reducing gasses or varying concentrations of the prescribed gasses are contemplated within the scope of this invention.

The apparatus of the present invention is suitable for use with higher operating temperatures where radiation losses represent a significant portion of collected solar energy. At lower operating temperatures, the radiation losses are less significant and use of the apparatus will not typically provide significant benefits.

Thus the foregoing is considered illustrative only of the principles of the invention. Further, since numerous changes and modifications will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and operation shown and described, and accordingly, all such suitable changes or modifications in structure or operation which may be resorted to are intended to fall within the scope of the claimed invention.

1. An apparatus for collecting heat from a solar concentrator and for transferring the collected heat to a heat sink, the apparatus comprising:

an isothermal body defining an elongated cavity with a substantially circular opening having a diameter substantially equal to a diameter of a focus of the solar collector, the cavity having reflective walls such that solar rays contacting the walls are substantially reflected;

wherein the isothermal body is adapted to be oriented such that the circular opening is located substantially at the focus of the solar collector and substantially perpendicular to a principal axis of the solar concentrator, and such that an axis of the cavity is substantially aligned with the principal axis of the solar concentrator;

wherein the isothermal body is adapted for thermal connection to the heat sink such that heat generated in the isothermal body is absorbed by the heat sink; and

wherein a length of the cavity is sufficient to absorb a desired proportion of the energy in the solar rays entering the cavity.

2. The apparatus of claim 1 wherein the proportion of the energy in the solar rays entering the cavity that is absorbed increases as the length of the cavity increases.

3. The apparatus of claim 1 wherein the length of the cavity is about 5 to 9 times the diameter of the circular opening.

4. The apparatus of claim 3 wherein the length of the cavity is between 6.5 to 7.5 times the diameter of the circular opening.

5. The apparatus of claim 1 wherein the cavity is substantially cylindrical.

6. The apparatus of claim 1 wherein the isothermal body is made from a reflective material such that the walls of the cavity are reflective.

7. The apparatus of claim 1 comprising a liner made of reflective material between the isothermal body and the cavity and operative to provide the reflective walls of the cavity.

8. The apparatus of claim 7 further comprising a low-emissivity shield covering an end of the isothermal body between the opening of the cavity and outer edges of the isothermal body.

9. The apparatus of claim 1 further comprising an enclosure enclosing the isothermal body, and a reducing atmosphere inside the enclosure operative to substantially prevent oxidation of the reflective walls of the cavity and thereby maintain reflectivity of the reflective walls.

10. The apparatus of claim 9 wherein the reflective walls comprise OFHC copper and wherein the reducing atmosphere contains hydrogen and a filler gas.

11. The apparatus of claim 9 further comprising insulation in walls of the enclosure.

12. An apparatus for collecting heat from the sun and for transferring the collected heat to a heat sink, the apparatus comprising:

a solar concentrator;

an isothermal body defining an elongated substantially cylindrical cavity with a substantially circular opening having a diameter substantially equal to a diameter of a focus of the solar collector, the cavity having reflective walls such that solar rays contacting the walls are substantially reflected;

wherein the isothermal body is oriented such that the circular opening is located substantially at the focus of the solar collector and substantially perpendicular to a principal axis of the solar concentrator, and such that an axis of the cavity is substantially aligned with the principal axis of the solar concentrator;

wherein the isothermal body is adapted for thermal connection to the heat sink such that heat generated in the isothermal body is absorbed by the heat sink; and
wherein a length of the cavity is about 5 to 9 times the diameter of the circular opening.

13. The apparatus of claim 12 further comprising a low-emissivity shield covering an end of the isothermal body between the opening of the cavity and outer edges of the isothermal body.

14. The apparatus of claim 12 further comprising an enclosure enclosing the isothermal body, and a reducing atmosphere inside the enclosure operative to substantially prevent oxidation of the reflective walls of the cavity and thereby maintain reflectivity of the reflective walls.

15. The apparatus of claim 14 wherein the reflective walls comprise OFHC copper and wherein the reducing atmosphere contains hydrogen and a filler gas.

16. A method for collecting heat from a solar concentrator for transfer to a heat sink, the method comprising:

providing an isothermal body defining an elongated cavity with a substantially circular opening having a diameter substantially equal to a diameter of a focus of the solar collector, the cavity having reflective walls such that solar rays contacting the walls are substantially reflected;

orienting the isothermal body such that the circular opening is located substantially at a focus of the solar collector and substantially perpendicular to a principal axis of the solar concentrator, and such that an axis of the cavity is substantially aligned with the principal axis of the solar concentrator;

reflecting solar rays that contact a reflective wall from a first contact point on the reflective wall to a second point on a reflective wall and to a plurality of subsequent contact points on the reflective walls until a desired proportion of the energy contained in the solar rays is absorbed by the reflective walls;

thermally connecting the heat sink to the isothermal body such that heat generated in the isothermal body by the absorbed energy of the solar rays is absorbed by the heat sink.

17. The method of claim 16 wherein the proportion of the energy in the solar rays entering the cavity that is absorbed increases as the length of the cavity increases.

18. The method of claim 16 wherein the cavity is substantially cylindrical and the length of the cavity is about 5 to 9 times the diameter of the opening of the cavity.

19. The method of claim 16 comprising enclosing the isothermal body in an enclosure and providing a reducing atmosphere inside the enclosure operative to substantially prevent oxidation of the reflective walls of the cavity and thereby maintain reflectivity of the reflective walls.

20. The method of claim 19 wherein the reflective walls comprise OFHC copper and wherein the reducing atmosphere contains hydrogen and a filler gas.

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