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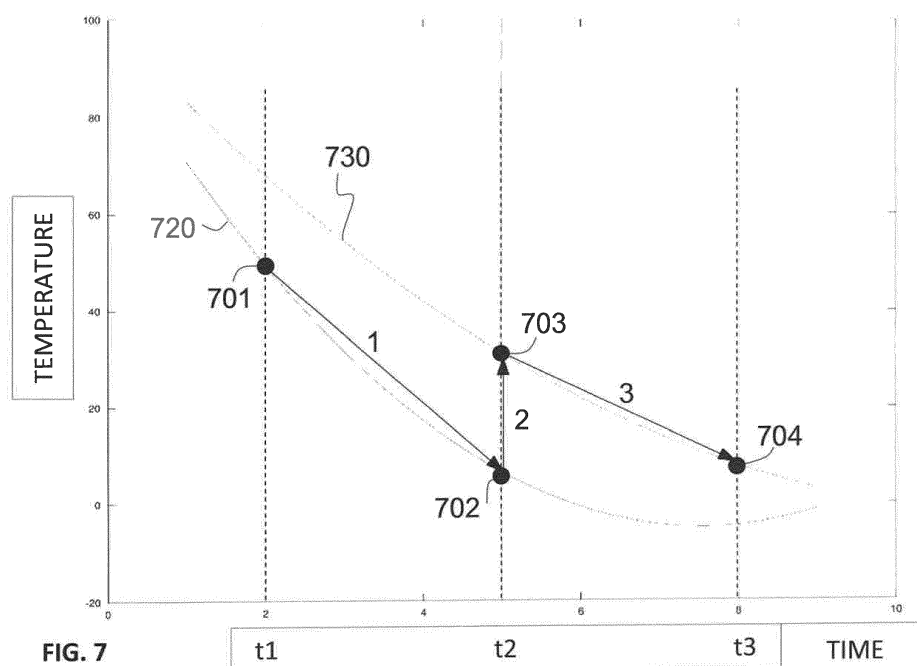
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(54) **Real-time method for automated prediction of internal layer temperature of paving material during paving operations**

(57) Method for determining internal temperature of a paving material. When a mat of a paving material is distributed over the road, internal temperature of the material at any particular spot on the mat is determined based on surface temperature measured at that spot and on the dependency between internal and surface temperatures of the material derived from temperature measurements taken at the at least one other, representative,

spot on the mat. The dependency is derived from substantially simultaneous measurements of internal and surface temperatures of the material taken at the representative spots on the mat over a period of time. In this manner, cooling behavior of the particular paving material being used at the paving site, for particular ambient conditions present at that time, may be determined for the representative spots and then used to predict cooling behavior for other spots on that mat.

**FIG. 7****EP 2 666 908 A1**

Description

FIELD OF THE INVENTION

[0001] Generally, the invention relates to systems and methods used in paving. More specifically, the invention relates to systems and methods for determining internal temperature of a paving material during paving operations.

BACKGROUND OF THE INVENTION

[0002] During construction of new roads, a paving machine (referred to herein as a "paver") distributes hot paving material. For example, a paver would typically distribute hot-mix asphalt mixtures (HMA's), at temperatures between approximately 110 and 150 degrees Celsius, depending on the mixture characteristics, layer thickness and ambient conditions. The paver is followed by a compaction machine (referred to herein as a "compactor") that compacts the paving material while the material is still warm.

[0003] Compaction is the final and crucial step for the road's lifetime. The temperature of the paving material has a direct impact on the elastic and plastic characteristics of the material and, therefore, on the compaction behaviour of the material. As a result, it is important to perform compaction while the paving material is within a certain temperature window.

[0004] Currently, various methods for attempting to predict the temperature of the paving material are used on construction sites. These methods range from construction workers using their practical experience to simply make a guess about the cooling process of the paving material to employing different software packages designed to predict the temperature based on a number of input parameters. The input parameters typically relate to the type of the paving material used, such as e.g. a particular type of HMA, and to the ambient weather conditions at the construction site, such as e.g. wind, air temperature, humidity and solar radiation. Sometimes the surface temperature of a mat of a paving material distributed over a road, measured with an infrared (IR) camera, is also used as an input parameter. The software packages then use different types of theoretical physical modelling, assuming different theoretical cooling rate models, to predict the temperature of the paving material at some future points in time.

[0005] One problem with such methods is that variations in the chemical composition of the paving material that is actually being used at a particular construction site and variations in the ambient weather conditions from what is assumed by the theoretical models may lead to inaccurate predictions. Another problem is that a number of parameters need to be measured and manually entered by the personnel at the site, which both leaves room for making errors and takes up personnel's time. In addition, the underlying physical models used might be in-

accurate in predicting real-world cooling behaviour.

[0006] As the foregoing illustrates, there is a need to provide means for assessing whether and when a paving material distributed over the road may be in the condition that is optimum for the compaction in a manner that eliminates at least some of the drawbacks described above.

SUMMARY OF THE INVENTION

[0007] It is an object of the invention to provide a method and a system for determining optimum temperature for the compaction of a paving material.

[0008] One aspect of the invention discloses a computer-implemented method for determining internal temperature of a paving material. The method includes steps of obtaining a dependency between an internal temperature (T_{in}) and a surface temperature (T_{surf}) of the paving material based on a plurality of measurements of the internal temperature and the surface temperature of the paving material taken at one or more first spots over a period of time, obtaining a surface temperature of the paving material at one or more second spots, and determining an internal temperature of the paving material at the one or more second spots based on the obtained dependency and the obtained surface temperature at the one or more second spots, where the one or more second spots are distinct from the one or more first spots.

[0009] In the following description, the one or more first spots will be referred to as "representative spots" while the one or more second spots will be referred to as "target spots."

[0010] As used herein, the term "internal temperature" refers to the temperature of a paving material at some depth below the upper surface of a paved mat, while the term "surface temperature" refers to the temperature on the upper surface of the mat.

[0011] As used herein, the term "spot" in context of a "spot of the paved mat" refers to a particular location on the mat, such as a location determined by Global Positioning System (GPS). In one embodiment, the representative spots and the target spots could be different spots on a single mat of paving material distributed over the road. In other embodiments, one or more of the representative spots could be in one mat of the paving material while one or more of the target spots could be in another mat of that material, as long as the representative spots could be considered to be representative of the target spots in terms of cooling and compaction behavior of the paving material.

[0012] The invention is based on the recognition that, when a mat of a paving material is distributed over a portion of the road, internal temperature of the material at any particular spot on the mat can be determined based on surface temperature measured at that spot and on the dependency between internal and surface temperatures of the material derived from temperature measurements taken at the at least one other, representative, spot on the mat. The dependency is derived from sub-

stantially simultaneous measurements of internal and surface temperatures of the material taken at the representative spots on the mat over a period of time. In this manner, cooling behavior of the particular paving material being used at the paving site, for particular ambient conditions present at that time, may be determined for the representative spots and then used to predict cooling behavior for other spots on that mat. Predicting the cooling behavior of the paving material based on temperature measurements obtained directly at the paving site (i.e., based on the empirical data), as opposed to predicting based on theoretical models using a number of input parameters allows better accounting for the real-life conditions at the particular paving site as well as for the variations in the chemical composition of the paving material, which leads to more accurate predictions for practical cases. In addition, establishing the dependency between the relatively easy-to-measure surface temperature and the more-difficult-to-measure internal temperature at one or more representative spots on the mat allows estimating internal temperature at other spots of the mat based on the measured surface temperature at those spots. In turn, being able to assess the internal, as opposed to only the surface temperature of the paving material, allows performing compaction of the mat at more optimal conditions.

[0013] In an embodiment, the obtained surface temperature of the paving material at the one or more target spots could be a surface temperature measured at time t_1 , while the internal temperature of the paving material to be determined could be an internal temperature determined for time t_3 , t_3 being later than t_1 . For example, the obtained surface temperature of the paving material at the one or more target spots could be surface temperature measured upon distribution of the paving material in a mat, obtained e.g. by means of an IR line scanner. In various further embodiments, the method may further include the steps of obtaining a cooling rate function $T_{surf}(t)$ for the surface temperature and/or a cooling rate function $T_{in}(t)$ for the internal temperature based on the plurality of measurements of the internal temperature of the paving material taken at the one or more representative spots and using one or both of these cooling rate functions in determining the internal temperature of the paving material at the one or more target spots at time t_3 .

[0014] In an embodiment, the dependency between the surface and internal temperature could be a dependency derived as a differential function, $\Delta T(t)$, between the internal temperature and the surface temperature of the paving material based on the established cooling rate function for the internal temperature and the established cooling rate function for the surface temperature.

[0015] In an embodiment, the cooling rate functions for the surface temperature and for the internal temperature could be established not only by determining respective cooling rates based on the measurements taken during the first time period, but also by predicting the cooling rates for the points in time beyond the first time period.

[0016] In an embodiment, the method may further comprise the steps of obtaining a range of optimum compaction temperatures of the paving material, the range comprising the lowest boundary and the highest boundary, and, based on the obtained dependency and the obtained surface temperature at the one or more target spots, determining, for at least some of the one or more target spots, a point in time when the internal temperature of the paving material at the spot is at the lowest boundary of the range and/or a point in time when internal temperature of the paving material at the spot is at the highest boundary of the range. The method may then further include the step of generating a contour plot illustrating, for at least some of the target spots, the determined points in time when the internal temperature of the paving material at the spot is at the lowest boundary of the range and/or at the highest boundary of the range.

[0017] In an embodiment, the method could further include the step of generating a plot illustrating the determined internal temperature of the paving material at the one or more target spots.

[0018] In an embodiment, the method could further include the step of generating one or more instructions regarding how compaction process of the paving material is to be carried out based on the determined internal temperature of the paving material at the one or more target spots.

[0019] In another aspect of the invention, a system for determining internal temperature of a paving material is provided. The system includes at least a processor comprising means configured for performing the steps of the methods described above.

[0020] In an embodiment, the system could further include one or more first devices configured for measuring the surface temperature of the paving material at the one or more representative spots at different times over the first period of time, one or more second devices configured for measuring the internal temperature of the paving material at the one or more representative spots at the different times over the first period of time, and one or more third devices configured for measuring the surface temperature of the paving material at the one or more target spots. In such a system, the processor would be configured to receive measurement data from the one or more first devices, the one or more second devices, and the one or more third devices. In an embodiment, at least some of the first devices could comprise infrared cameras, at least some of the second devices could comprise thermocouples, and the third devices could comprise infrared cameras and/or infrared line scanners.

[0021] Such systems could further include a display unit for displaying at least one of the following: the internal temperature and the surface temperature of the paving material taken at the representative spots over the first period of time, the obtained surface temperature of the paving material at the target spots, the determined internal temperature of the paving material at the target spots, and the expected cooling rate in relation to the time before

internal and/or surface temperature reaches a certain value.

[0022] Still other aspects of the invention relate to a computer program and a, preferably non-transitory, computer-readable storage medium storing a computer program for carrying out steps of one or more of the methods described herein.

[0023] Hereinafter, embodiments of the invention will be described in further detail. It should be appreciated, however, that these embodiments may not be construed as limiting the scope of protection for the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] In the drawings:

FIG. 1 provides a schematic illustration of a system operable to implement one or more aspects of the present invention;

FIG. 2 provides a flow diagram of method steps for determining internal temperature of a paving material, according to one embodiment of the present invention;

FIG. 3 provides an exemplary contour plot for surface temperatures measured in step 210 of the method of FIG. 2 obtained via an IR line scanner, according to one embodiment of the present invention;

FIG. 4 provides an exemplary display for surface temperatures and internal temperatures measured in step 230 of the method of FIG. 2 and curve fitting for the internal temperatures, according to one embodiment of the present invention;

FIG. 5 illustrates a cooling rate function $T_{\text{surf}}(t)$ for the surface temperature and a cooling rate function $T_{\text{in}}(t)$ for the internal temperature, according to one embodiment of the present invention;

FIG. 6 illustrates a differential function $\Delta T(t)$, according to one embodiment of the present invention;

FIG. 7 illustrates a three-step determination of internal temperature, according to one embodiment of the present invention;

FIG. 8 illustrates a two-step determination of the internal temperature, according to one embodiment of the present invention;

FIG. 9 illustrates a two-step determination of the internal temperature, according to another embodiment of the present invention;

FIG. 10 illustrates a one-step determination of the internal temperature, according to one embodiment of the present invention; and

FIG. 11 illustrates optimum compaction windows with respect to cooling of asphalt as a function of time.

DETAILED DESCRIPTION OF THE DRAWINGS

[0025] FIG. 1 provides a schematic illustration of a sys-

tem 100 operable to implement one or more aspects of the present invention. As shown, the system 100 includes an automated temperature unit (ATU) 110 comprising an IR camera 120 for measuring surface temperature of a paving material and a thermocouple 130 for measuring internal temperature of the material, over a period of time, both types of measurements to be taken at the same representative spot on the asphalt mat. Optionally, the ATU 110 also includes a processor 140 for processing measurement data measured by the IR camera 120 and the thermocouple 130. In an embodiment, both the IR camera 120 and the thermocouple 130 may comprise so-called "smart sensors" that are capable of obtaining analog signals as inputs, then processing and transmitting measurement data in digital form.

[0026] The measurement data obtained by the IR camera 120 and the thermocouple 130 may be stored in a memory 150, preferably in a form of a database, and, using e.g. a wireless network at the construction site, accessible to the construction team on site and managers via Internet. While FIG. 1 illustrates only one ATU 110 and the following description is provided for measurements taken at a single representative spot on the asphalt mat, in other embodiments the system 100 may include more than one ATUs 110 so that measurements from multiple representative spots could be taken and analyzed.

[0027] The system 100 further includes at least one other camera for measuring surface temperature of the asphalt mat, shown in FIG. 1 as an IR camera 160, a processor 170, and a display 180 coupled to the processor 170. As described in greater detail in association with FIG. 2, the processor 170 is configured to at least obtain a dependency between internal and surface temperature of the asphalt based on measurement data obtained for a representative spot via the ATU 110 and obtain surface temperature of the asphalt at one or more target spots for which internal temperature should be determined. The processor 170 is further configured to use the obtained dependency between internal and surface temperatures and the obtained surface temperature at the target spots to determine internal temperature of the asphalt at those spots.

[0028] The memory 150 may be operable to store instructions that, when executed by the processor 170 and, optionally, the processor 140, perform any of the methods described herein. The display 180 is configured to visualize at least some of the results of the method steps performed by the processors 170 and/or 140. The system 100 may further optionally include an interface (not shown in FIG. 1) configured to receive user input from one or more user input devices, such as e.g., keyboard or a mouse (also not shown in FIG. 1) and forward the user input to the processors 170 and/or 140.

[0029] Connections between different components in FIG. 1 may use different protocols, as known in the art. It will be appreciated that the system shown herein is illustrative and that variations and modifications are pos-

sible.

[0030] FIG. 2 provides a flow diagram 200 of method steps for determining internal temperature at one or more target spots of the asphalt mat, according to one embodiment of the present invention. While the method steps are described in conjunction with FIG. 1, persons skilled in the art will recognize that any system configured to perform the method steps, in any order, is within the scope of the present invention.

[0031] The method begins with the paver distributing a layer of asphalt over the road. In step 210, surface temperature at one or more target spots is measured with the IR camera 160. Each of the surface temperature measurements of step 210 is associated at least with information identifying the particular spot where the measurement was taken. Such information could comprise, for example, the GPS coordinates of the spot. In this manner, different target spots on the asphalt mat can later be distinguished between one another. Optionally, the surface temperature measurements of step 210 can also be associated with a time stamp indicating the time when the measurement was taken. The time stamps could either comprise absolute time values or relative times, such as e.g. times relative with respect to the beginning of the asphalt paving operation. Thus, temperature measurements of step 210 could result in a data stream as shown in Table 1 below.

TABLE 1: SURFACE TEMPERATURE MEASUREMENTS OBTAINED FOR THE TARGET SPOTS AT STEP 210 OF METHOD 200

$T_{surf,i}$	GPS_i	t_i
$T_{surf,1}$	GPS_1	t_1
$T_{surf,2}$	GPS_2	t_2
$T_{surf,3}$	GPS_3	t_3
$T_{surf,4}$	GPS_4	t_4
$T_{surf,5}$	GPS_5	t_5
...	...	...
$T_{surf,n}$	GPS_n	t_n

[0032] In Table 1, subscript "i", refers to different target spots, "n" is an integer indicating the total number of different target spots where surface temperature measurements were taken, " T_{surf} " refers to surface temperatures of the different target spots measured with the IR camera 160, "GPS" refers to GPS coordinates of the different target spots and "t" refers to the time of measurements.

[0033] While, as will be shown below, it is important to know at what time the surface temperature measurements of step 210 were taken, the time stamps associated with each of the data points in Table 1 are optional because, in various embodiments, it may be possible to obtain or to estimate the times in other manners. For example, measurements of step 210 could always be

done immediately as the paver is distributing the asphalt layer or at some other predetermined, known, points in time. Further, the measurements of step 210 taken at different target spots on the asphalt mat could be assumed to be taken at the same time. This assumption may be made either because multiple IR cameras 160 are used substantially simultaneously (e.g. one IR camera 160 per each target spot) or because the time difference between the measurements may be neglected and, therefore, the measurements may be assumed to be taken at the same time (e.g. when an IR line scanner is used as the IR camera 160 to take continuous measurements for the entire asphalt mat or a portion thereof).

[0034] In one embodiment, the measurements of step 210 may be taken as the paver is distributing the asphalt layer by e.g. installing the IR camera 160 in the form of an IR line scanner at the back of the paver. Such a line scanner can then obtain initial surface temperature substantially continuously for each spot on the road where asphalt was distributed.

[0035] In another embodiment, the measurements of step 210 may be taken at some later point in time, e.g. right before the internal temperature at those spots need to be determined.

[0036] In one embodiment, measurement data obtained in step 210 may first be stored in a database in the memory 150 and later obtained by the processor 170. In another embodiment, the measurement data may be provided to the processor 170 (streamed) for immediate processing, without storage in the memory 150.

[0037] In an optional step 220, the processor 170 may be configured to instruct display of some kind of representation of the measurement data of step 210 on the display 180. For example, the processor 170 may instruct display of a contour plot illustrating measured surface temperatures for each of the target spots of the asphalt mat. Such an exemplary contour plot for surface temperatures of step 210 obtained via an IR line scanner installed at the back of a paver is illustrated in FIG. 3.

[0038] In step 230, one or more ATUs 110 are used to measure surface and internal temperature of the asphalt at one or more representative spots on the distributed asphalt mat. Each ATU 110 is configured to measure surface and internal temperatures, simultaneously, at a particular representative spot in the asphalt mat over a period of time. While the ATU 110 may be used to obtain measurements at any spot after the paver has laid down an asphalt mat, preferably, the measurement spot should be chosen such that it can be considered to be representative, in terms of cooling behaviour, for at least some other portion of the mat. To that end, one ATU 110 could perform surface and internal temperature measurements at a spot at the beginning of the asphalt mat, another ATU 110 - at a spot in the middle of the mat, while a third ATU 110 - at a spot at the end of the mat. For easy access by the construction site workers, the ATUs 110 could be placed close to the edge of the asphalt mat.

[0039] Each ATU 110 may be used to obtain measure-

ments as follows. After a paver (not shown in the figures) passes a proposed representative spot, the thermocouple 130 is injected into the asphalt layer at that spot and the IR camera 120 is aimed at the spot where the thermocouple 130 is injected. The IR camera 120 may be configured to automatically adjust level and span of the IR images taken, indicating lowest and highest temperature within the scope of the images. It can be assumed that such averaged information of the temperature distribution on a relatively small area provides adequate information about the surface temperature of asphalt. Once the IR camera 120 and the thermocouple 130 are in place, continuous readings of the surface and internal temperature are obtained over a period of time. Such temperature measurements taken at a particular representative spot result in a data stream as shown in Table 2.

TABLE 2: SURFACE AND INTERNAL TEMPERATURE MEASUREMENTS OBTAINED FOR THE REPRESENTATIVE SPOTS AT STEP 230 OF METHOD 200

t_k	$T_{surf,k}$	$T_{in,k}$
t_1	$T_{surf,1}$	$T_{in,1}$
t_2	$T_{surf,2}$	$T_{in,2}$
t_3	$T_{surf,3}$	$T_{in,3}$
t_4	$T_{surf,4}$	$T_{in,4}$
t_5	$T_{surf,5}$	$T_{in,5}$
...	...	...
t_m	$T_{surf,m}$	$T_{in,m}$

[0040] In Table 2, subscript "k" refers to different points in time over the time period of taking measurements at that representative spot, "m" is an integer indicating the total number of measurements taken at the representative spot over the time period of taking measurements, " T_{surf} " refers to surface temperature of the representative spot measured with the IR camera 120, and " T_{in} " refers to internal temperature of the representative spot measured with the thermocouple 130.

[0041] In an embodiment, the thermocouple 130 could be a measurement device capable of obtaining and storing readings from multiple thermocouple probes. For example, the thermocouple 130 could include four probes. Such a device would be able to obtain reliable measurements even if some of the probes would be damaged, which could happen e.g. if the thermocouple 130 is driven over by a compactor. Continuous nature of data collection over a period of time and multiple inputs from the multiple available probes of the thermocouple 130 may then require a data fusion solution. Such a solution could be implemented by fusion across the different probes of the thermocouple 130, when a plurality of probes nominally measure the same property, T_{in} . For example, fusion across four thermocouple probes of the thermocou-

ple 130 may be implemented by selecting maximum temperature from the four available measurements. Alternatively, fusion across multiple probes may be implemented by averaging the temperature readings obtained by the multiple probes of the thermocouple 130. Thus, the values in the column T_{in} in Table 2 could be values that have been in some manner fused across the different probes of the thermocouple 130.

[0042] To save the measured temperature information for future reference, IR images may be stored in the memory of the IR camera 120 at the moment of measurements, while readings from the thermocouple 130 may be continuously stored in the inner memory of the thermocouple 130 (these memory units are not shown in FIG. 1). The temperature measurement data obtained by the IR camera 120 and the thermocouple 130 is eventually provided to the processor 170, possibly after first being stored in the memory 150 and/or processed by the processor 140.

[0043] It should be noted that measurements of step 210 and step 230 do not necessarily occur in the order illustrated in FIG. 2. In other embodiments, these measurements could be taking place simultaneously, during overlapping time periods, or in the reverse order (i.e., first, the measurements of step 230 are performed and the measurements of step 210 are performed at some later point in time). In the following, various embodiments dealing with the processing of the data obtained in steps 210 and 230 are discussed. While, in these embodiments, the processing is described with reference to the processor 170, person skilled in the art will recognize that some or all of the processing can also be performed by the processor 140.

[0044] After the processor 170 has received measurement data from steps 210 and 230, the method may proceed to the optional step 240 where the processor 170 would use the internal temperature values measured by the thermocouple 130 for a particular representative spot over a period of time [1:m] to derive a cooling rate function of internal temperature. Similarly, in the optional step 250, which could also take place before, overlapping, or simultaneously with step 240, the processor 170 would use the surface temperature values measured by the IR camera 120 for the same representative spot over the period of time [1:m] to derive a cooling rate function of surface temperature. To that end, in one embodiment, the Matlab software with its Curve Fitting Toolbox could be used to find suitable fitting functions for the surface and internal temperature data points. In one embodiment, the processor 170 could find the suitable fitting functions for the internal and surface temperature only in the time range of measurements, i.e. in the time period [1:m]. In other embodiments, the processor 170 could also use the measured surface and temperature data for the representative spot to predict these temperatures for the points in time beyond the time period [1:m].

[0045] The processor 170 may also be configured to instruct display of some kind of representation of the

measurement data of step 230 and/or of the curve fitting results of steps 240 and/or 250 and/or any overlay representation of these measurements on the display 180. FIG. 4 illustrates an exemplary screen shot that could be displayed on the display 180 illustrating data points measured by the IR camera 120 in step 230 (line 420), data points measured by the thermocouple 130 in step 230 (line 430), and a fitted curve 435 representing a cooling rate function derived for the internal temperature based on the data points of line 430. The screen shot of FIG. 4 also illustrates the latest value of temperature measured at the representative spot by the IR camera 120 (value 422 in FIG. 4) and the latest value of temperature measured at the representative spot by the thermocouple 130 (value 432 in FIG. 4).

[0046] FIG. 4 illustrates an embodiment where measurements of step 230 began immediately after the asphalt was distributed on the road, as can be seen from the fact that internal temperature and surface temperature start at time zero from the same value. In other embodiments, however, the measurements of step 230 could start some time later, when already from the very beginning there would be a small, but nevertheless noticeable difference between internal and surface temperatures measured at the representative spot. This situation is shown in FIG. 5 illustrating a line 520 representing a cooling rate function, $T_{\text{surf}}(t)$, derived for the surface temperature based on the data measured by the IR camera 120 and a line 530 representing a cooling rate function, $T_{\text{in}}(t)$, derived for the internal temperature based on the data measured by the thermocouple 130.

[0047] Based on the measurements obtained by the ATU 110 at step 230 for the representative spot, in step 260, the processor 170 would derive a dependency between internal and surface temperature that allows determination of internal temperature at any target spot based on the value of surface temperature measured at that spot, in step 270 of the method 200.

[0048] Such a dependency could take various forms, all of which are within the scope of the present invention, as long as the derived dependency between internal and surface temperature taken at a representative spot allows the processor 170 to determine internal temperature at the at least one target spot, in step 270 of FIG. 2.

[0049] In one embodiment, the dependency could be expressed in a form of a look-up table where, for a particular initial temperature of the asphalt mixture (i.e., temperature at which the mixture was distributed on the road or the initial temperature at time 0), internal and surface temperatures measured at the representative spot are given for different points in time after time 0. The processor 170 could then utilize such a dependency, in step 270, by taking the surface temperature measured for a particular target spot and referring to the look-up table to determine what internal temperature corresponds to that surface temperature. This embodiment assumes that the initial temperature of the asphalt at the target spot is substantially the same as the initial temperature of the as-

phalt at the representative spot.

[0050] In another embodiment, the dependency could be expressed as a difference between the internal temperature and surface temperature for the different points in time. Line 600 in FIG. 6 illustrates such a differential function ΔT , obtained as a result of subtraction of the cooling rate function for the surface temperature (such as the one illustrated with the line 520 in FIG. 5) from the cooling rate function for the internal temperature (such as the one illustrated with the line 530 in FIG. 5), as follows:

$$\Delta T(t) = T_{\text{in}}(t) - T_{\text{surf}}(t)$$

[0051] The differential function $\Delta T(t)$ may then be used in different manners to determine internal temperature at the target spot irrespective of what the initial temperature of the asphalt was at that spot, as illustrated with four embodiments described below and illustrated in FIGs 7-10. As will be shown, the differential function $\Delta T(t)$ allows obtaining internal temperature at a target spot even when the initial temperature of asphalt at the target spot was not the same as the initial temperature at the representative spot.

[0052] The first manner is illustrated in FIG. 7 showing a three-step determination of internal temperature, according to one embodiment of the present invention. Lines 720 and 730 in FIG. 7 are analogous to lines 520 and 530 of FIG. 5, illustrating, respectively, a cooling rate function $T_{\text{surf}}(t)$ derived for the surface temperature based on the data measured by the IR camera 120 and a cooling rate function $T_{\text{in}}(t)$ derived for the internal temperature based on the data measured by the thermocouple 130. The lines 720 and 730 are derived based on the surface and internal temperature measurements taken at a representative spot in step 230 of FIG. 2. In various embodiments, either the measurement data of step 230 is provided to the processor 170 which then derives the cooling rate functions $T_{\text{surf}}(t)$ and $T_{\text{in}}(t)$ or the processor 140 derives these functions and provides them to the processor 170 for further processing.

[0053] In FIG. 7, point 701 at the intersection of $T_{\text{surf}}(t)$ 720 and a vertical dashed line from time t_1 indicates the surface temperature measured at a particular target spot by the IR camera 160 in step 210 of FIG. 2. Point 704 at the intersection of $T_{\text{in}}(t)$ 730 and a vertical dashed line from time t_3 indicates internal temperature, at the target spot, that is to be determined in step 270 of FIG. 2. To that end, the processor 170 is configured to, first, determine surface temperature at point t_2 in time, shown in FIG. 7 with point 702, by using the cooling rate function $T_{\text{surf}}(t)$ 720. This is shown in FIG. 7 as step 1 with an arrow from point 701 to point 702. After that, the processor 170 is configured to use the differential function $\Delta T(t)$ derived for the curves 720 and 730, such as the function shown in FIG. 6 to determine internal temperature

at time t2. This is done by identifying the value of ΔT (t2) on the differential function (in FIG. 6, this is the point 602 at the crossing of line 600 and the dashed vertical line at time t2). Knowing ΔT (t2) (point 602 in FIG. 6) and T_{surf} (t2) (point 702 in FIG. 7), the processor 170 can determine the internal temperature at time t2 (point 703 and the second step shown with an arrow 2 in FIG. 7) as follows:

$$T_{\text{in}}(t2) = T_{\text{surf}}(t2) + \Delta T(t2).$$

[0054] Finally, the processor 170 is configured to use the cooling rate function $T_{\text{in}}(t)$ 730 to determine internal temperature at time t3 (i.e., point 704). This is shown in FIG. 7 as step 3 with an arrow from point 703 to point 704.

[0055] This manner of determining the internal temperature at the target spot may be particularly advantageous e.g. in a case when a number of temperature readings T_{surf} is more than T_{in} readings.

[0056] The second manner for using the differential function $\Delta T(t)$ to determine internal temperature at the target spot is illustrated in FIG. 8 showing a two-step determination of internal temperature, according to one embodiment of the present invention. FIG. 8 shows lines 720 and 730 and points 701 and 704 indicating that those are the same lines and points illustrated and described in association with FIG. 7. Therefore, in the interests of brevity, description of these lines and points is not repeated here. FIG. 8 further shows a point 803 at the intersection of $T_{\text{in}}(t)$ 730 and a vertical dashed line from time t1, representing internal temperature at time t1.

[0057] According to the embodiment illustrated in FIG. 8, in order to determine the internal temperature at the target spot at time t3, the processor 170 is configured to, first, determine internal temperature at time t1 (point 803). To that end, the processor 170 is configured to use the differential function $\Delta T(t)$ derived for the curves 720 and 730. This is done by identifying the value of ΔT (t1) on the differential function (in FIG. 6, this is the point 601 at the crossing of line 600 and the dashed vertical line at time t1). Knowing ΔT (t1) (point 601 in FIG. 6) and T_{surf} (t1) (point 701 in FIG. 8), the processor 170 can determine the internal temperature at time t1 (point 803 and the first step shown with an arrow 1 in FIG. 8) as follows:

$$T_{\text{in}}(t1) = T_{\text{surf}}(t1) + \Delta T(t1).$$

[0058] After that, the processor 170 can determine internal temperature at time t3 (point 704 in FIG. 8) by using the cooling rate function $T_{\text{in}}(t)$ 730. This is shown in FIG. 8 as step 2 with an arrow from point 803 to point 704.

[0059] This manner of determining the internal temperature at the target spot may be particularly advantageous in case of quickly changing weather conditions, which cause the rapid changes of surface cooling rate.

[0060] Note that a particular embodiment of the scenario of FIG. 8 includes measurement of the surface temperature at a target spot at the time of laying down the asphalt layer (i.e. t1 = 0). At such a time, the internal temperature at the target spot is equal or may be reasonably assumed to be equal to the surface temperature at the spot. Thus, for such a particular embodiment, point 701 coincides with point 803 and the processor 170 would use the differential function $\Delta T(t)$ derived for the curves 720 and 730 by identifying the value of ΔT at time zero (i.e., $\Delta T=0$). The processor 170 would then follow the cooling rate function 730 for the internal temperature to determine the internal temperature at the target spot at time t3.

[0061] The third manner for using the differential function $\Delta T(t)$ to determine internal temperature at the target spot is illustrated in FIG. 9 showing a two-step determination of internal temperature, according to another embodiment of the present invention. FIG. 9 shows lines 720 and 730 and points 701 and 704 indicating that those are the same lines and points illustrated and described in association with FIG. 7. Therefore, in the interests of brevity, description of these lines and points is not repeated here. FIG. 9 further shows a point 902 at the intersection of $T_{\text{surf}}(t)$ 720 and a vertical dashed line from time t3, representing surface temperature at time t3.

[0062] According to the embodiment illustrated in FIG. 9, in order to determine the internal temperature at the target spot at time t3, the processor 170 is configured to, first, determine surface temperature at time t3 (point 902 in FIG. 9) by using the cooling rate function $T_{\text{surf}}(t)$ 730. This is shown in FIG. 9 as step 1 with an arrow from point 701 to point 902. After that, the processor 170 can determine internal temperature at time t3 (point 704). To that end, the processor 170 is configured to use the differential function $\Delta T(t)$ derived for the curves 720 and 730 by identifying the value of ΔT (t3) on the differential function (in FIG. 6, this is the point 603 at the crossing of line 600 and the dashed vertical line at time t3). Knowing ΔT (t3) (point 603 in FIG. 6) and T_{surf} (t3) (point 902 in FIG. 9), the processor 170 can determine the internal temperature at time t3 (point 704 and the second step shown with an arrow 2 in FIG. 9) as follows:

$$T_{\text{in}}(t3) = T_{\text{surf}}(t3) + \Delta T(t3).$$

[0063] The three manners described above illustrate embodiments where the surface temperature at the target spot is taken at a time that is earlier than the time for which the internal temperature at that spot should be determined, i.e. t1 < t3. These embodiments are useful when e.g. the surface temperature is measured, in step 210, either upon distributing of asphalt layer (using e.g. IR line scanner) or relatively soon after. Of course, these embodiments are also applicable for any time of measurement of step 210 as long as that time is before the

time for which the internal temperature at the target spot should be determined. Yet another embodiment can be envisioned where it would be desirable to measure the surface temperature at a particular target spot at a particular time and then determine the internal temperature at that spot at that time. This embodiment is illustrated in FIG. 10.

[0064] FIG. 10 showing a one-step determination of internal temperature provides the fourth manner for using the differential function $\Delta T(t)$ to determine internal temperature at the target spot, according to one embodiment of the present invention. FIG. 10 shows lines 720 and 730 and point 704 indicating that those are the same lines and the same point illustrated and described in association with FIG. 7. Therefore, in the interests of brevity, description of these lines and this point is not repeated here. FIG. 10 further shows a point 1002 at the intersection of $T_{surf}(t)$ 720 and a vertical dashed line from time t_3 , representing surface temperature at the target spot at time t_3 that was measured by the IR camera 160 in step 210 of FIG. 2.

[0065] According to the embodiment illustrated in FIG. 10, in order to determine the internal temperature at the target spot at time t_3 , the processor 170 is configured to use the differential function $\Delta T(t)$ derived for the curves 720 and 730 by identifying the value of $\Delta T(t_3)$ on the differential function (in FIG. 6, this is the point 603 at the crossing of line 600 and the dashed vertical line at time t_3). Knowing $\Delta T(t_3)$ (point 603 in FIG. 6) and $T_{surf}(t_3)$ (point 1002 in FIG. 10), the processor 170 can determine the internal temperature at time t_3 (point 704 and the only step shown with an arrow 1 in FIG. 10) as follows:

$$T_{in}(t_3) = T_{surf}(t_3) + \Delta T(t_3).$$

[0066] The foregoing descriptions illustrate how dependency between the surface temperature and the internal temperature established based on empirical data obtained at a representative spot on the asphalt mat can be used to determine internal temperature at a target spot on the mat once the surface temperature at the target spot is known. In some embodiments, cooling rate functions derived for the surface and internal temperatures from the empirical data obtained at the representative spot on the asphalt mat are also employed. A person skilled in the art will easily recognize how these teachings could be applied to determine and visualize various other values that may be useful in paving operations.

[0067] For example, instead, or in addition to, determining one particular value for internal temperature at a target spot, it may be useful to determine internal temperatures at that spot for different surface temperatures and/or at different times so that asphalt compaction could be carried out at the most optimal conditions.

[0068] As is well-known, asphalt compaction should be completed in specific temperature ranges (e.g. 90 to

120°C), have specified maximum temperature for compaction (e.g. approximately 130°C), or have specified minimum temperatures (e.g. between 70 and 80°C). There is general agreement that minimum compaction temperature, where the mixture is stiff enough to prevent further reduction of air, varies depending on the mix properties, layer thickness and environmental conditions. If the material temperature is too low during compaction, the functional properties of the resulting road surface, such as e.g. the texture of the surface, may decrease. The same holds for the maximum temperature: when the binder is too fluid, compactors will simply displace or "shove" the paving material rather than compact it. As a result, cracks behind the rolls may appear, the mixture may stick to the rolls, and the rolls may sink into the mixture. These minimum and maximum temperatures may be viewed as understressed and overstressed situations, where the time in between would be the optimal compaction window, where, for different paving material mixtures and different ambient conditions, the ideal compaction window shifts along the timeline. FIG. 11 illustrates such optimum compaction windows with respect to cooling of asphalt as a function of time.

[0069] When optimum compaction temperature window, such as the one shown in FIG. 11, is known and when surface temperature at a target spot is measured in step 210 of FIG. 2, the approaches described above may be used to determine a time range when internal temperature of the asphalt at the target spot is within the optimum compaction window. To that end, the processor 170 may be configured to obtain a range of optimum compaction temperatures of the asphalt mixture, which range includes the lowest and the highest boundary. The processor 170 would then use the dependency between surface and internal temperatures derived based on the measurements of step 230, as well as the surface temperature at a target spot measured in step 210 to determine a point in time when the internal temperature of the asphalt at that target spot is at the lowest boundary of the range and a point in time when internal temperature of the asphalt at that target spot is at the highest boundary of the range. The processor 170 may then instruct the display 180 to display the determined points in time when the internal temperature of the asphalt at the target spot is at the lowest boundary of the range and at the highest boundary of the range. If, in step 210 of FIG. 2, the surface temperature was determined for more than one target spot (e.g. if the surface temperature was measured for the entire asphalt mat using the IR line scanner installed at the back of the paver), then the processor 170 can determine such range of suitable times for each spot on the mat. The processor 170 could then generate and instruct the display 180 to display a contour plot illustrating these time ranges for each of the GPS coordinates on the asphalt mat. Such calculations and visualizations could help compactor operators to make better informed decisions about which parts of the newly paved asphalt mat will be within the required temperature window in the

near future (e.g., 5 minutes, 10 minutes, or 15 minutes).

[0070] In an embodiment, based on the internal temperatures at one or more target spots determined in one of the manners described above, the processor 170 could also be configured to generate instructions for construction site workers regarding how compaction process of the asphalt is to be carried out. In this manner, the techniques disclosed herein can support operational choices of construction machine operators by providing real-time information of the surface and internal temperatures and predicting cooling rates based on the measurements. The processor 170 could then provide an indication to the workers as to the estimated time before asphalt layer cools down to a certain temperature, when additional rolling is useless or even hazardous. Displaying various parameters on the display 180, such as e.g. current temperature readings and expected cooling curves, is expected to assist compactor operators on site in making well-founded operational decisions.

[0071] While most of the descriptions provided herein used asphalt as a paving material, these descriptions can also be applied for other paving materials. Further, while temperature measurements of step 230 of FIG. 2 were described mainly with reference to a single representative spot, in other embodiments multiple representative spots could be used to obtain more accurate predictions for the target spots. For example, the curve such as the one illustrated in FIG. 6 may be obtained and used for different initial temperatures of the paving material at different representative spots. Still further, by using multiple thermocouples 130 injected at different depths at each representative spot during the measurements of step 230 of FIG. 2, internal temperatures at different depths at the target spots can be determined.

[0072] While the system 100 was described with respect to the IR cameras 120 and 160, a person skilled in the art will recognize that employing any device capable of measuring surface temperature of a paving material instead of the IR cameras 120 and 160 is within the scope of the present invention. Similarly, while the system 100 was described with respect to the thermocouple 130, a person skilled in the art will recognize that employing any device capable of measuring internal temperature of a paving material instead of the thermocouple 130 is within the scope of the present invention. Further, while measurements of step 210 were described in association with GPS coordinates identifying each of the target spots, in other embodiments, any other means for identifying and/or differentiating between the target spots could be used.

[0073] Further, while step 210 of FIG. 2 was described with respect to measuring the surface temperature at the target spots, in other embodiments, the surface temperature obtained in that step could also be predicted. For example, the surface temperature at the target spots at particular times could be predicted based on the cooling rate function for the surface temperature derived from surface temperature measurements taken at a repre-

sentative spot, assuming the initial temperature of the asphalt at lay down at the representative and the target spot is the same. Alternatively, the surface temperature at the target spots at particular times could be predicted based on one of the well-known theoretical models and a number of input parameters regarding e.g. initial temperature, type of the paving material mixture being used, and ambient weather conditions.

[0074] Various embodiments of the present invention may be implemented in the form of software tools using an appropriate programming language, such as e.g. MATLAB™, C#/C++/C or Java.

[0075] One embodiment of the invention may be implemented as a program product for use with a computer system. The program(s) of the program product define functions of the embodiments (including the methods described herein) and can be contained on a variety of, preferably non-transitory, computer-readable storage media. Illustrative computer-readable storage media include, but are not limited to: (i) non-writable storage media (e.g., read-only memory devices within a computer such as CD-ROM disks readable by a CD-ROM drive, flash memory, ROM chips or any type of solid-state non-volatile semiconductor memory) on which information is permanently stored; and (ii) writable storage media (e.g., floppy disks within a diskette drive or hard-disk drive or any type of solid-state random-access semiconductor memory) on which alterable information is stored. The computer program, or parts thereof, may be run on the processors 170 and/or 140.

Claims

1. A method for determining internal temperature of a paving material, the method comprising:
 - obtaining a dependency between an internal temperature (T_{in}) and a surface temperature (T_{surf}) of a paving material based on a plurality of measurements of the internal temperature and the surface temperature of the paving material taken at one or more first spots over a first period of time;
 - obtaining a surface temperature of the paving material at one or more second spots; and
 - determining an internal temperature of the paving material at the one or more second spots based on the obtained dependency and the obtained surface temperature at the one or more second spots, wherein the one or more second spots are distinct from the one or more first spots.
2. The method according to claim 1, wherein the obtained surface temperature of the paving material at the one or more second spots comprises surface temperature measured at a first time (t_1) and wherein

the determined internal temperature of the paving material at the one or more second spots comprises internal temperature determined for a third time (t3), the third time being later than the first time, the method further comprising:

obtaining a cooling rate function ($T_{\text{surf}}(t)$) for the surface temperature based on the plurality of measurements of the internal temperature of the paving material taken at the one or more first spots,
 obtaining a cooling rate function ($T_{\text{in}}(t)$) for the internal temperature based on the plurality of measurements of the internal temperature of the paving material taken at the one or more first spots,
 determining intermediate surface temperature at the one or more second spots at a second time (t2) based on the obtained surface temperature at the one or more second spots and the obtained cooling rate function ($T_{\text{surf}}(t)$) for the surface temperature,
 determining intermediate internal temperature at the one or more second spots at the second time (t2) based on the determined intermediate surface temperature at the one or more second spots at the second time (t2) and the obtained dependency, and
 determining the internal temperature at the one or more second spots at the third time (t3) based on the determined intermediate internal temperature at the one or more second spots at the second time (t2) and the obtained cooling rate function ($T_{\text{in}}(t)$) for the internal temperature.

3. The method according to claim 1, wherein the obtained surface temperature of the paving material at the one or more second spots comprises surface temperature measured at a first time (t1) and wherein the determined internal temperature of the paving material at the one or more second spots comprises internal temperature determined for a second time (t3), the second time being later than the first time, the method further comprising:

obtaining a cooling rate function ($T_{\text{in}}(t)$) for the internal temperature based on the plurality of measurements of the internal temperature of the paving material taken at the one or more first spots,
 determining intermediate internal temperature at the one or more second spots at the first time (t1) based on the obtained dependency and the obtained surface temperature at the one or more second spots, and
 determining the internal temperature at the one or more second spots at the second time (t3) based on the determined intermediate internal

temperature at the one or more second spots at the first time (t1) and the obtained cooling rate function ($T_{\text{in}}(t)$) for the internal temperature.

4. The method according to claim 1, wherein the obtained surface temperature of the paving material at the one or more second spots comprises surface temperature measured at a first time (t1) and wherein the determined internal temperature of the paving material at the one or more second spots comprises internal temperature determined for a second time (t3), the second time being later than the first time, the method further comprising:

obtaining a cooling rate function ($T_{\text{surf}}(t)$) for the surface temperature based on the plurality of measurements of the internal temperature of the paving material taken at the one or more first spots,
 determining intermediate surface temperature at the one or more second spots at the second time (t3) based on the obtained surface temperature at the one or more second spots and the obtained cooling rate function ($T_{\text{surf}}(t)$) for the surface temperature, and
 determining the internal temperature at the one or more second spots at the second time (t3) based on the determined intermediate surface temperature at the one or more second spots at the second time (t3) and the obtained dependency.

5. The method according to any one of the preceding claims, wherein the obtained dependency is derived by:

- establishing a cooling rate function ($T_{\text{in}}(t)$) for the internal temperature based on the plurality of measurements of the internal temperature of the paving material taken at the one or more first spots;
 - establishing a cooling rate function ($T_{\text{surf}}(t)$) for the surface temperature based on the plurality of measurements of the surface temperature of the paving material taken at the one or more first spots; and
 - deriving the dependency as a differential function ($\Delta T(t)$) between the internal temperature and the surface temperature of the paving material based on the established cooling rate function for the internal temperature and the established cooling rate function for the surface temperature.

6. The method according to any one of the preceding claims, further comprising:

- obtaining a range of optimum compaction tem-

- peratures of the paving material, the range comprising the lowest boundary and the highest boundary;
- based on the obtained dependency and the obtained surface temperature at the one or more second spots, determining, for at least some of the one or more second spots, a point in time when the internal temperature of the paving material at the spot is at the lowest boundary of the range and/or a point in time when internal temperature of the paving material at the spot is at the highest boundary of the range.
7. The method according to claim 6, further comprising generating a contour plot illustrating, for the at least some of the one or more second spots, the determined point in time when the internal temperature of the paving material at the spot is at the lowest boundary of the range and/or the determined point in time when internal temperature of the paving material at the spot is at the highest boundary of the range.
 8. The method according to any one of the preceding claims, wherein the obtained surface temperature of the paving material at the one or more second spots comprises surface temperature measured upon distribution of the paving material in a mat.
 9. The method according to claim 8, wherein the initial surface temperature for the one or more second spots is measured using an infrared line scanner.
 10. The method according to any one of the preceding claims, further comprising generating one or more instructions regarding how compaction process of the paving material is to be carried out based on the determined internal temperature of the paving material at the one or more second spots.
 11. A computer program comprising software code portions configured for, when executed by a processor, performing the steps of the method as defined in any one of claims 1-10.
 12. A system for determining internal temperature of a paving material, the system comprising at least a processor comprising means configured for performing the steps of the method as defined in any one of claims 1-10.
 13. The system of claim 12, further comprising:
 - one or more first devices configured for measuring the surface temperature of the paving material at the one or more first spots at different times over the first period of time;
 - one or more second devices configured for measuring the internal temperature of the paving

ing material at the one or more first spots at the different times over the first period of time;

- one or more third devices configured for measuring the surface temperature of the paving material at the one or more second spots, wherein the processor is configured to receive measurement data from the one or more first devices, the one or more second devices, and the one or more third devices.

14. The system of claim 13, wherein the first devices comprise infrared cameras, the second devices comprise thermocouples, and the third device comprises infrared cameras and/or infrared line scanners.
15. The system of any one of claims 12-14, further comprising a display unit for displaying at least one of:

the internal temperature and the surface temperature of the paving material taken at the one or more first spots over the first period of time; the obtained surface temperature of the paving material at the one or more second spots; and the determined internal temperature of the paving material at the one or more second spots.

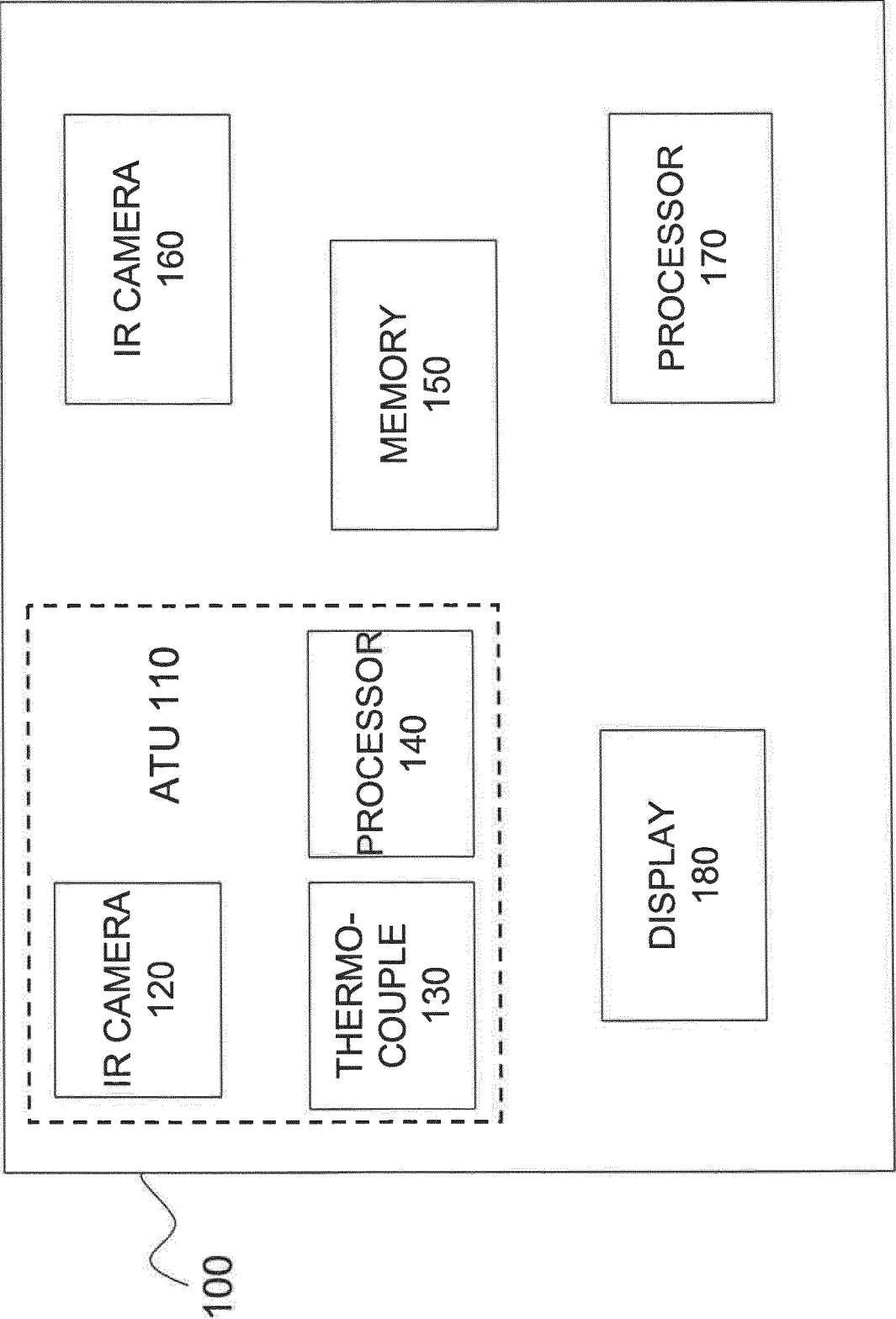


FIG. 1

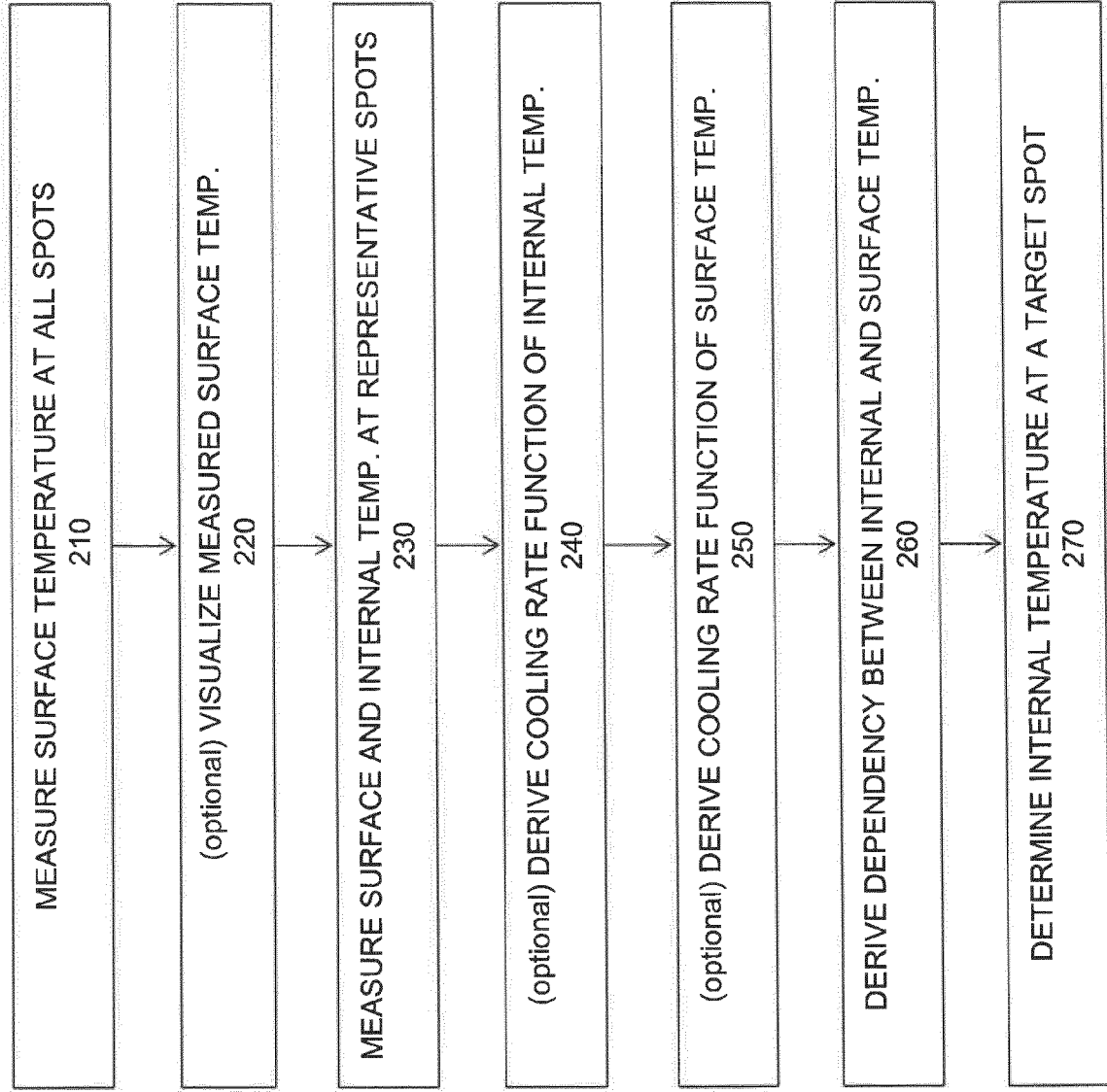


FIG. 2

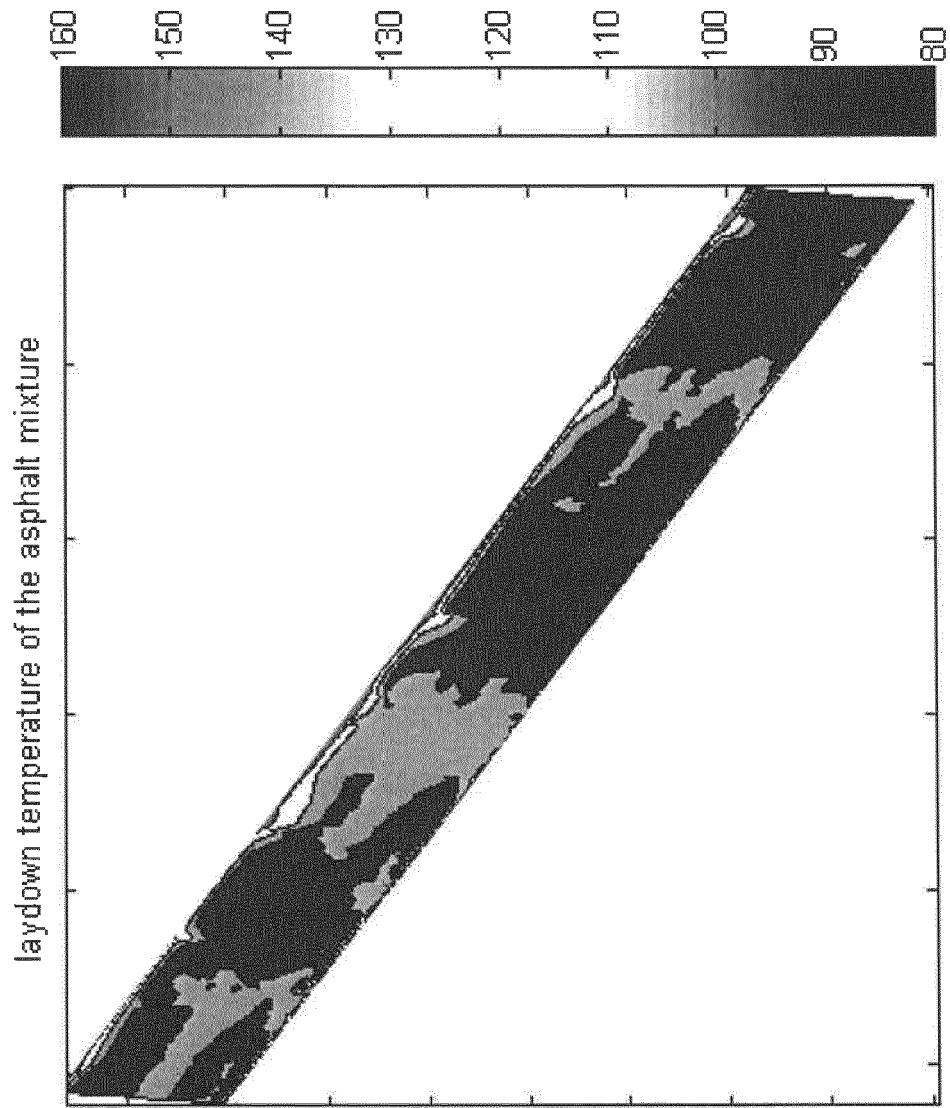


FIG. 3

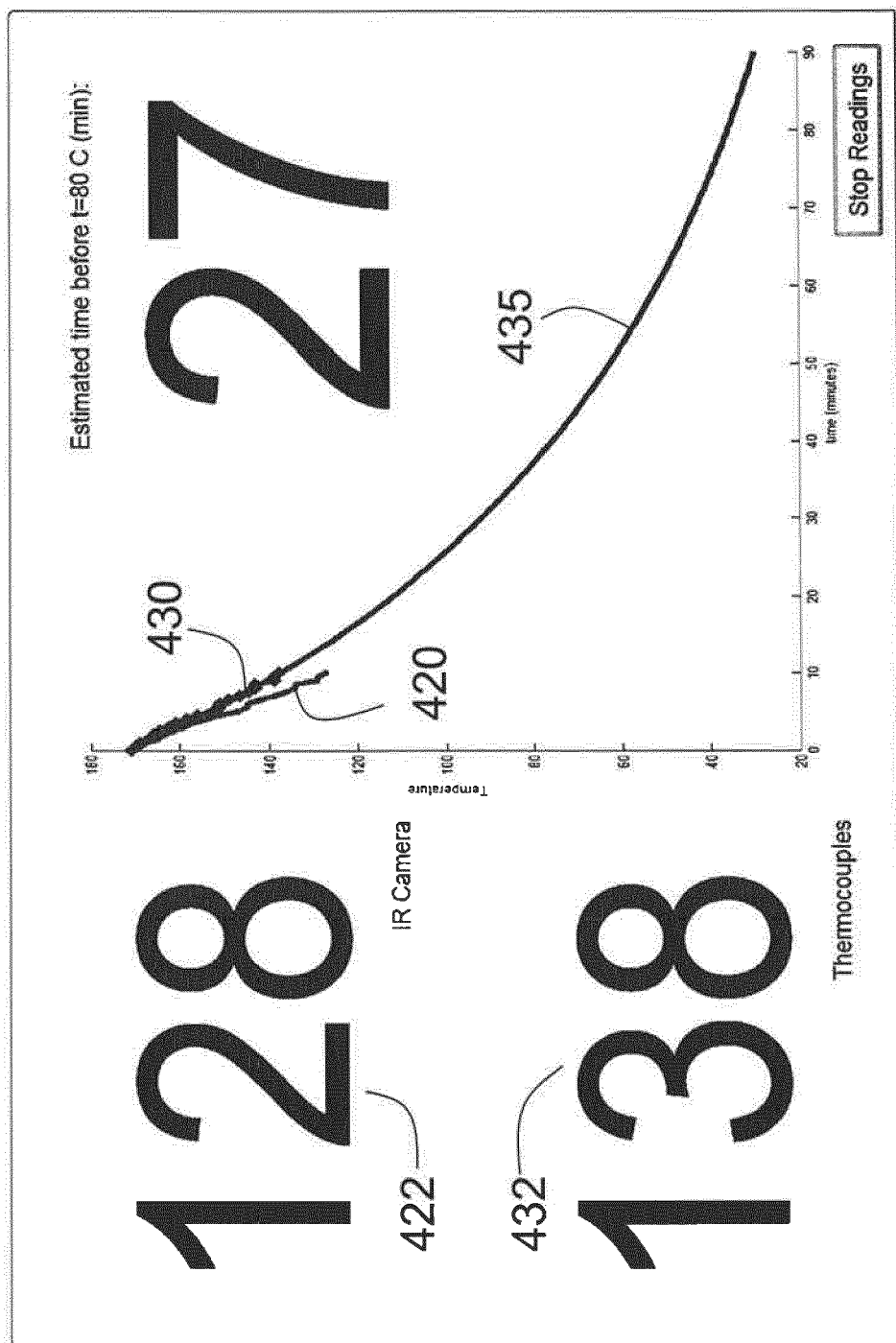


FIG. 4

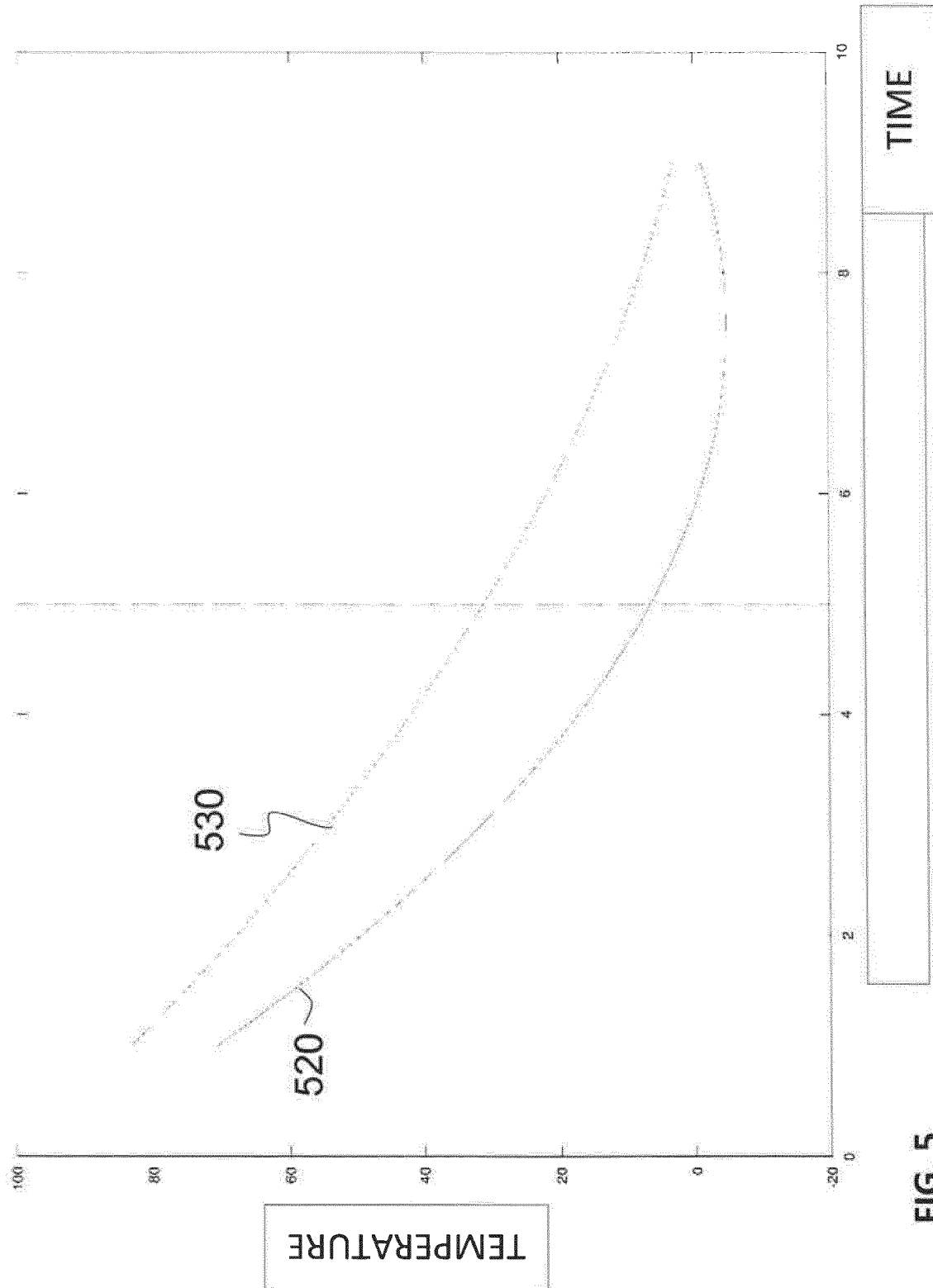


FIG. 5

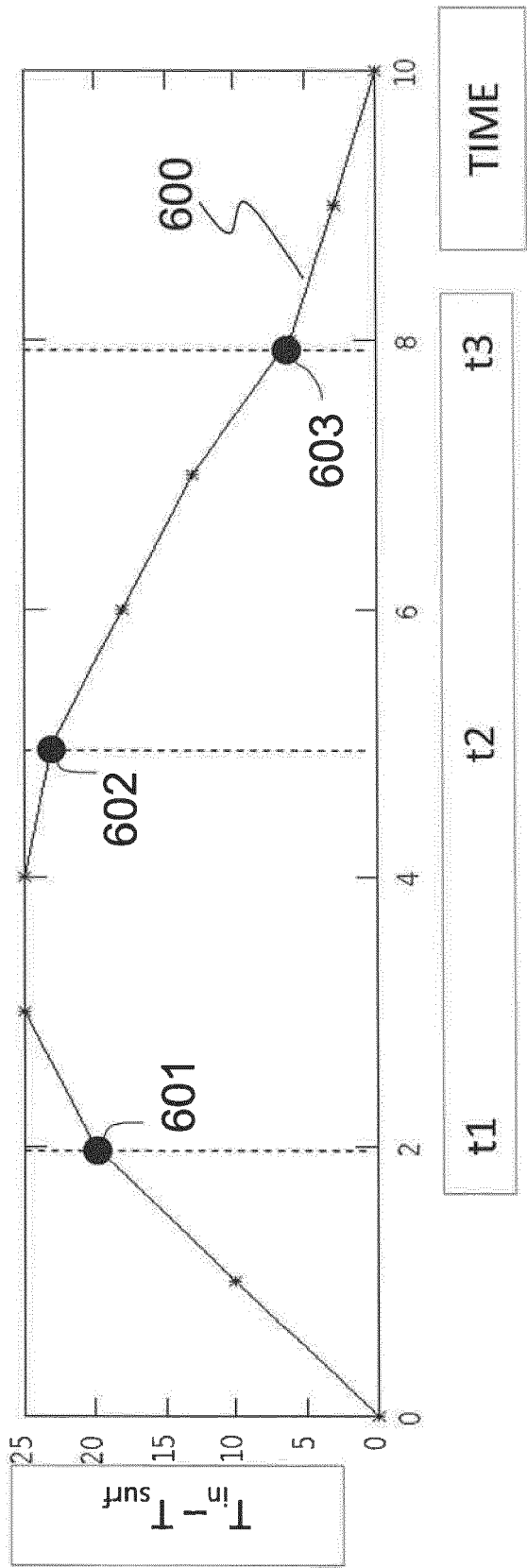
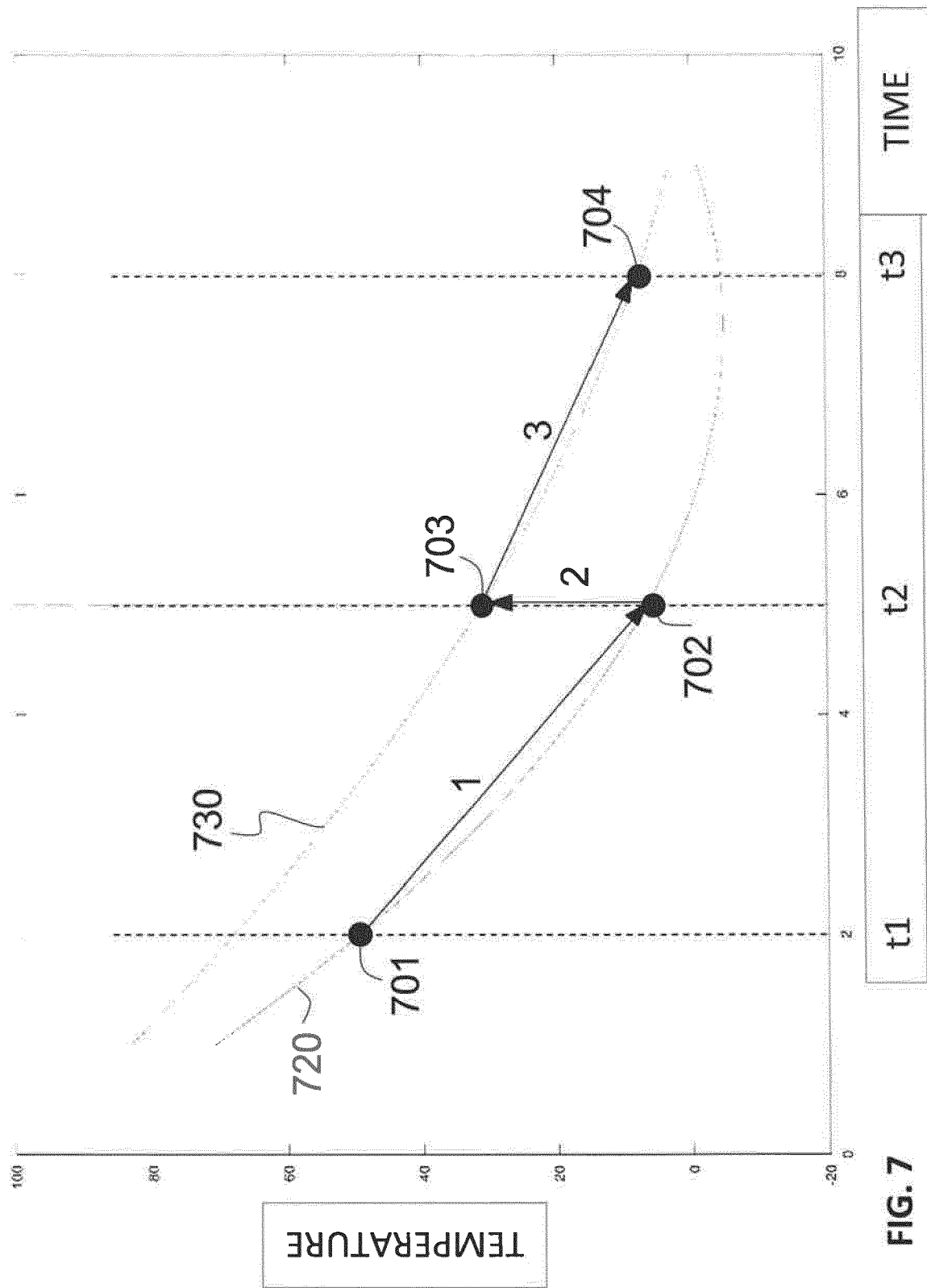


FIG. 6



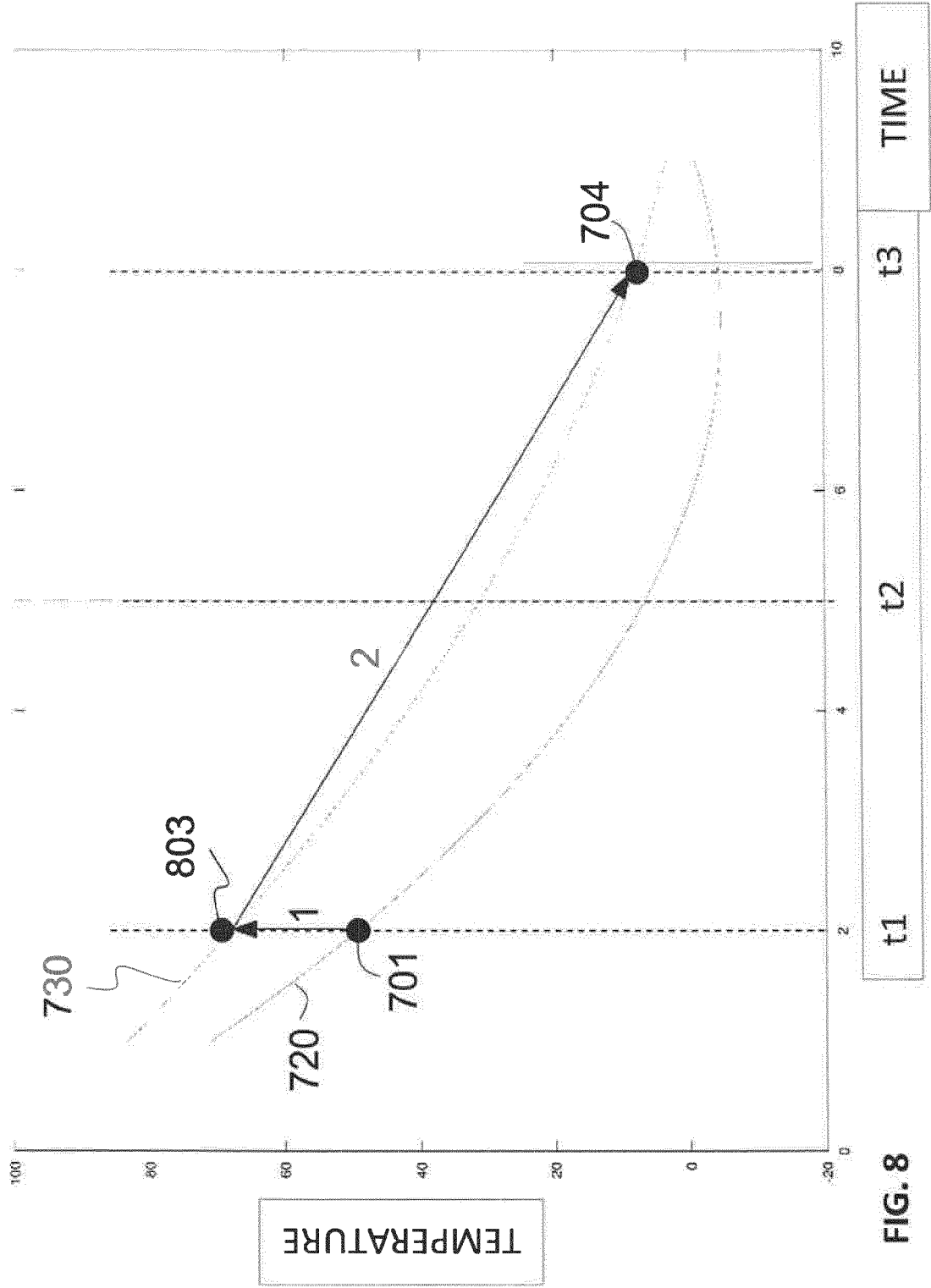


FIG. 8

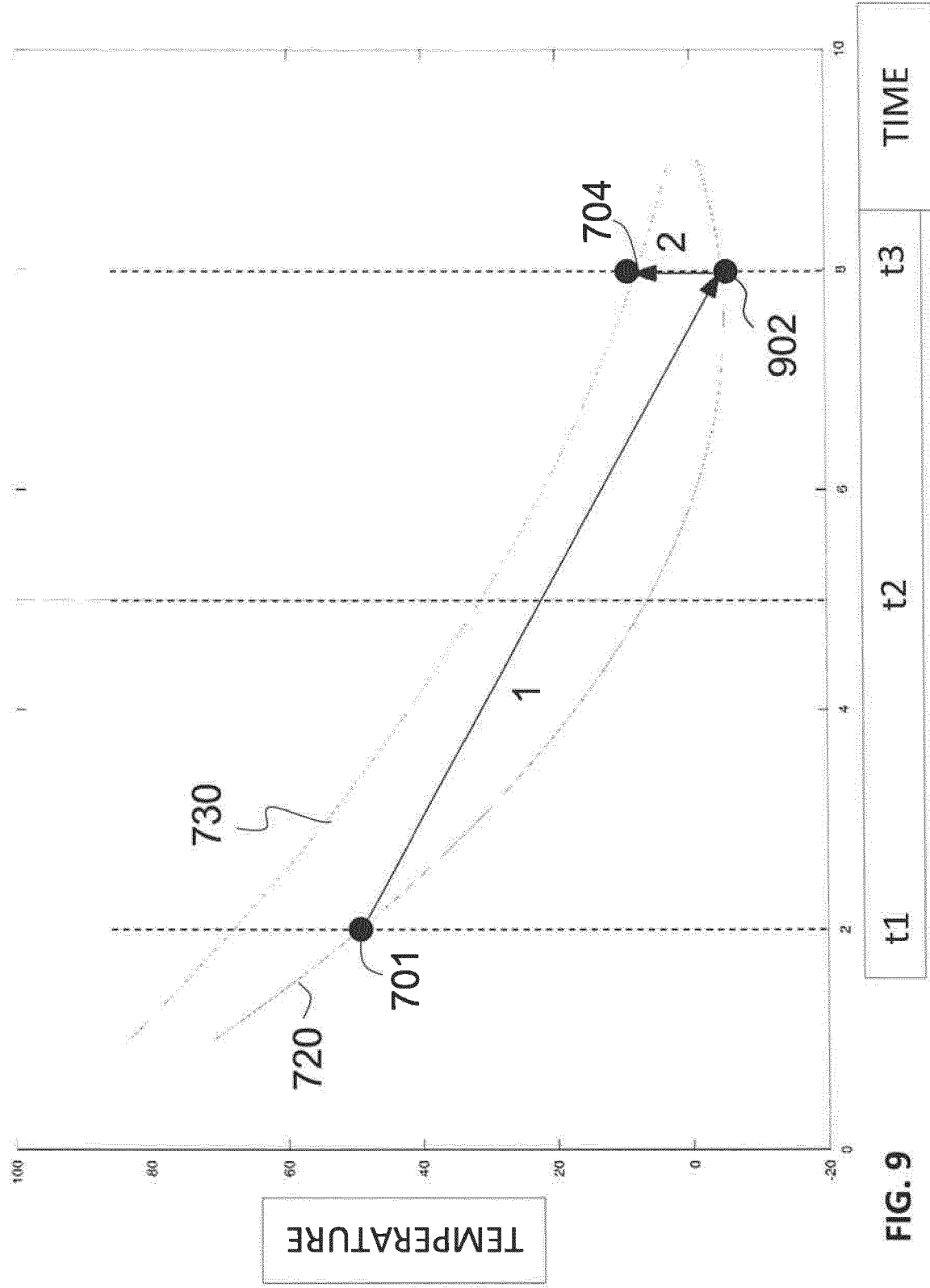


FIG. 9

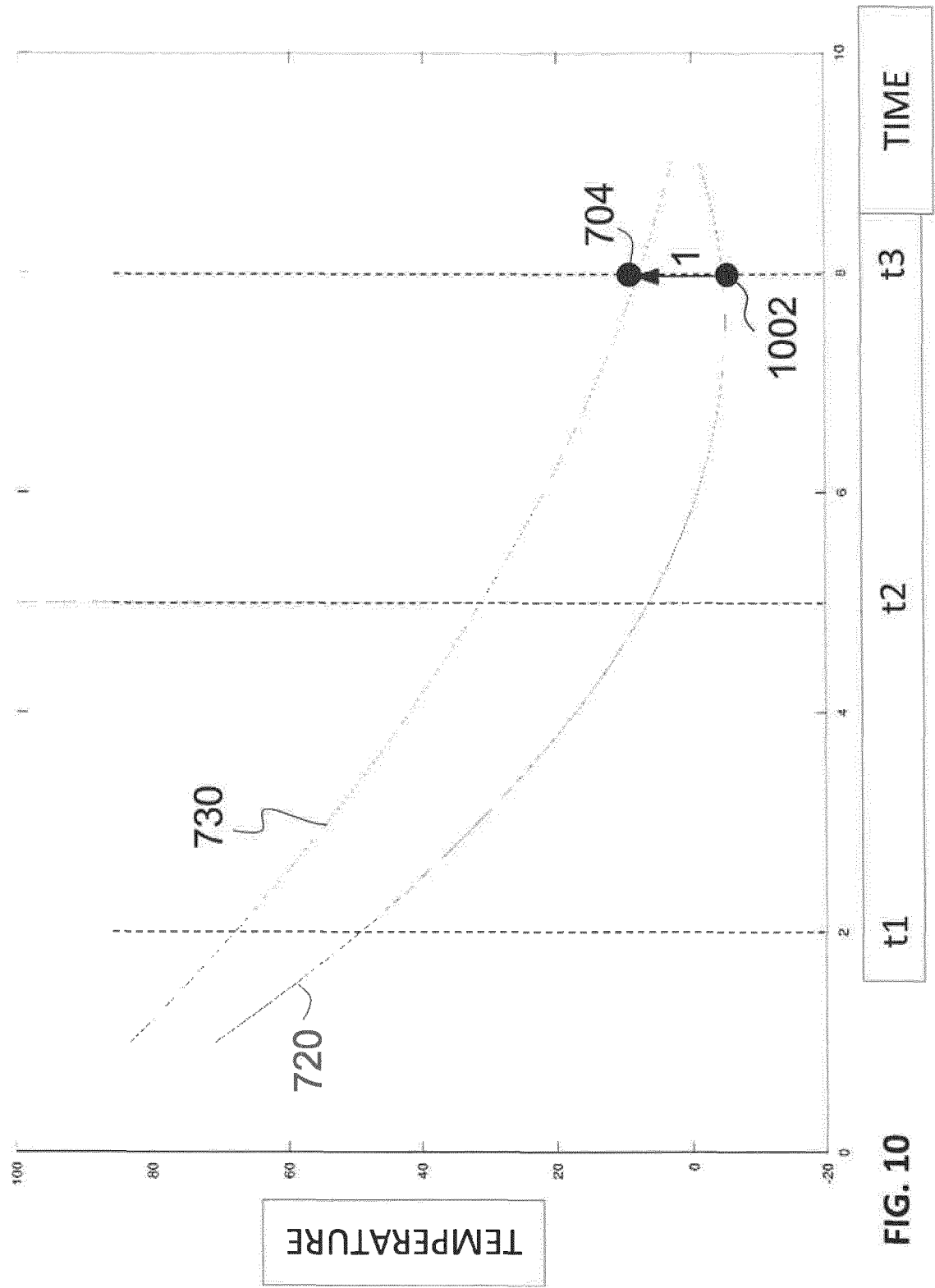


FIG. 10

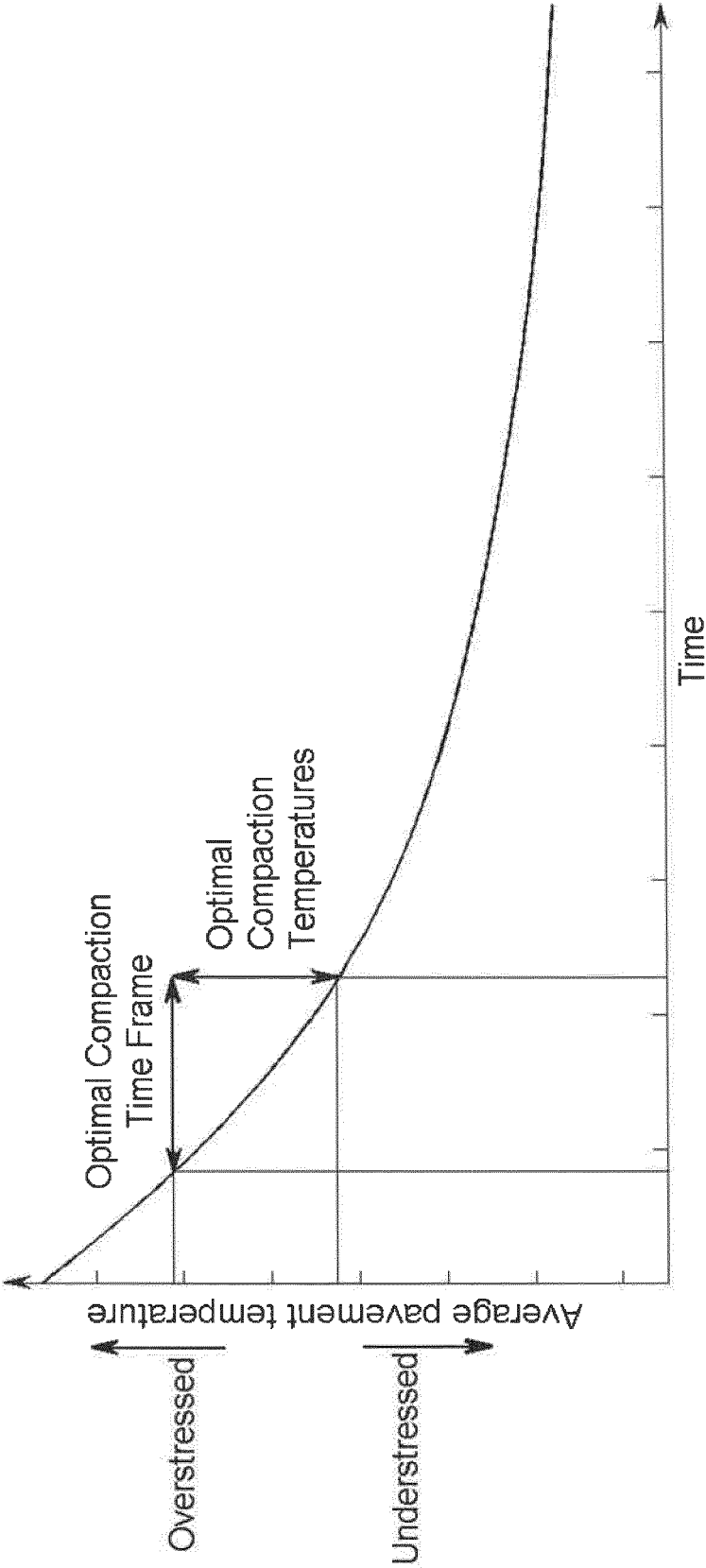


FIG. 11



EUROPEAN SEARCH REPORT

Application Number
EP 12 16 9276

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The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 9 November 2012	Examiner Beucher, Stefan
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

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EUROPEAN SEARCH REPORT

Application Number
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			TECHNICAL FIELDS SEARCHED (IPC)
The present search report has been drawn up for all claims			
Place of search Munich		Date of completion of the search 9 November 2012	Examiner Beucher, Stefan
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			

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**ANNEX TO THE EUROPEAN SEARCH REPORT
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EP 12 16 9276

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
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