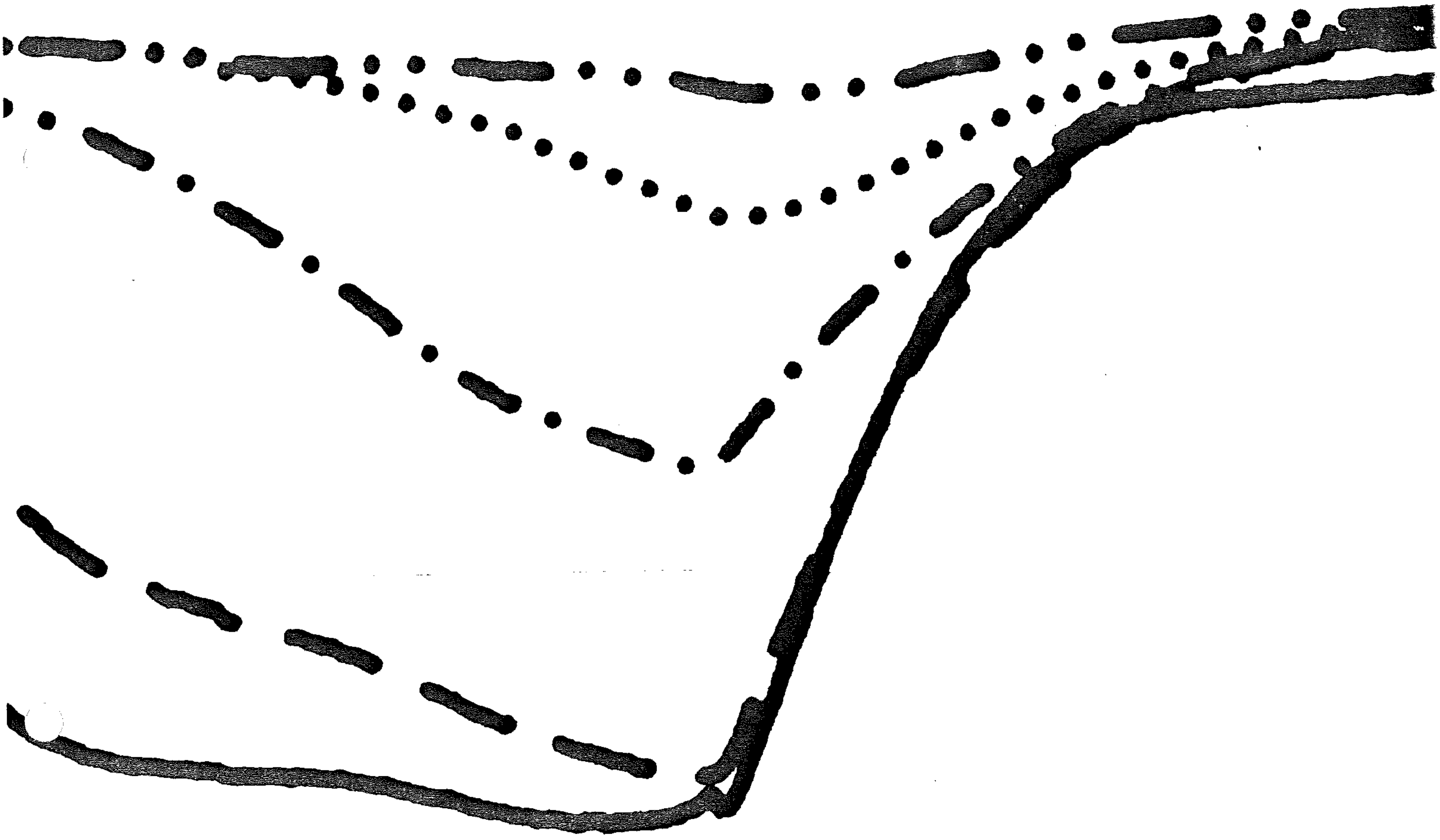
Cascade
Temperature Controller



Functional Description of the Cascade Controller

The cascade controller has been designed to control the high temperature heating elements of the ASM DFS250 furnace. Since the specifications of a temperature controller are always limited by the thermal specifications of the furnace it is regulating, a short description of this furnace, the DFS250, will be given.

Figure 1 is a diagram of the DFS250.

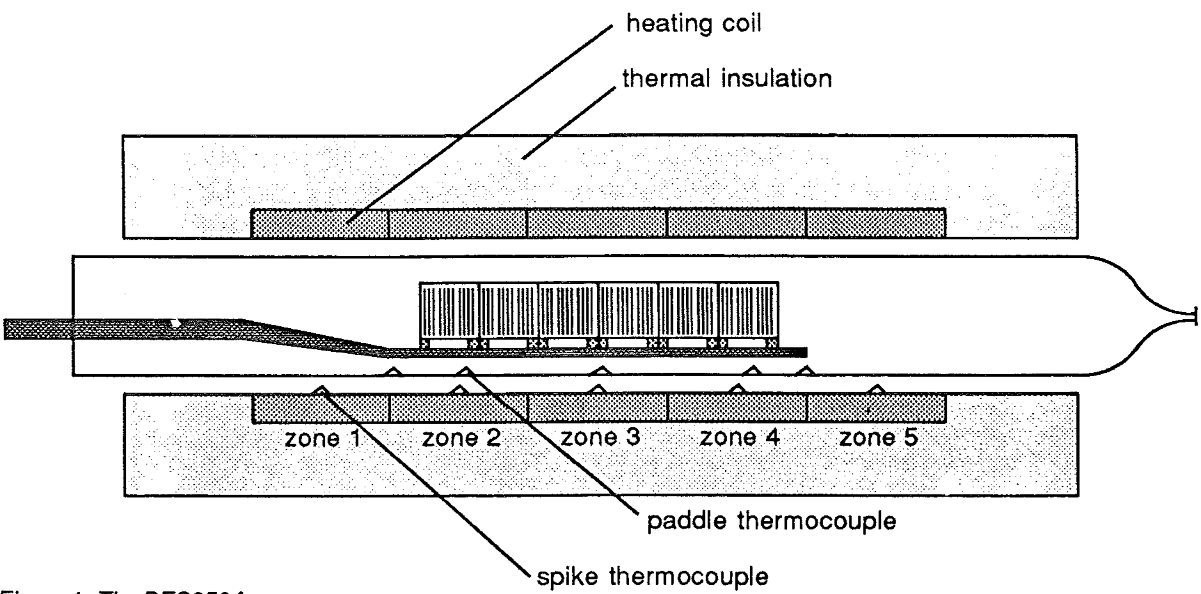


Figure 1 The DFS250 furnace

The furnace heating wire is spirally wound and divided into 5 individually controlled heating zones. Five spike thermocouples, one at the centre of each zone, are located between the process tube and the heating coil. Five paddle (or calibration) thermocouples are located inside the tube: they are inserted into the tube under the source-gas balljoint, which means that they are lying on the bottom of the process tube. The distance between the first and the last paddle thermocouple is 1000 mm: this ensures that a flatzone of the same length (extending over all three centre zones) can be established even when the closing properties of the furnace have to be accounted for.

The DFS250 high temperature heating element has a maximum installed power of 35 kW: each end zone has 8.5 kW installed power, and each of the three centre zones has 6.0 kW installed power.

The maximum attainable heat-up and cool-down rates listed in table 1 were derived using these maximum power figures, together with the insulation characteristics of the heating element and the waferload in the furnace.

THERMAL SPECIFICATIONS DFS250
High Temperature

Number of zones	5
Temperature range	450°C - 1300°C
Flatzone 450°C - 1300°C	±0.5°C over 1000 mm
Heat-up rates	
500°C	37°C/min
750°C	32°C/min
1000°C	18°C/min
1250°C	15°C/min
Cool-down rates	
500°C	2.0°C/min
750°C	4.0°C/min
1000°C	6.5°C/min
1250°C	7.0°C/min
Maximum power consumption per element	35.0 kW
Steady state power consumption	
500°C	2.4 kW
750°C	4.7 kW
1000°C	9.0 kW
1250°C	17.0 kW

Furnace with 150/300 wafers (150 mm) and an N_2 flow of 15 slm

Table 1

The furnace as a system requires a power input which results in an energy content that can be expressed as a temperature. One zone of the furnace "system" is shown in model form in figure 2.

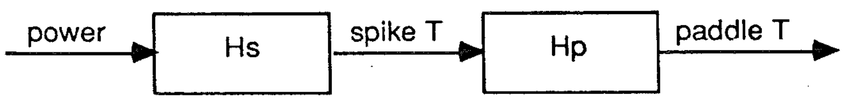


Figure 2 Model of a one-zone furnace system

where Hs = spike transfer function (power to spike temperature)
Hp = paddle transfer function (spike temperature to paddle temperature)

The transfer functions can be described in terms of process gain factors and time constants, both of which are temperature dependent. If the simple model in figure 2 is applied to a 5-zone furnace, additional interactions become important and must be accounted for in the new model. This results in a much more complex structure, as shown in figure 3.

Cascade Controller specifications for low temperature element DFS250

The specifications apply to the following process conditions:

- DFS250, 5-zone low temperature heating element (temperature control range 250°C - 900°C)
- quartz or silicon carbide process tube 230 mm ID, 245 mm OD
- maximum waferload of 150 wafers (150 mm) distributed over 6 quartz cassettes
- 15 slm nitrogen flow
- 400°C - 800°C loading temperature
- 100 mm/min - 250 mm/min loading speed

A typical setpoint wave-form is shown in figure 1.

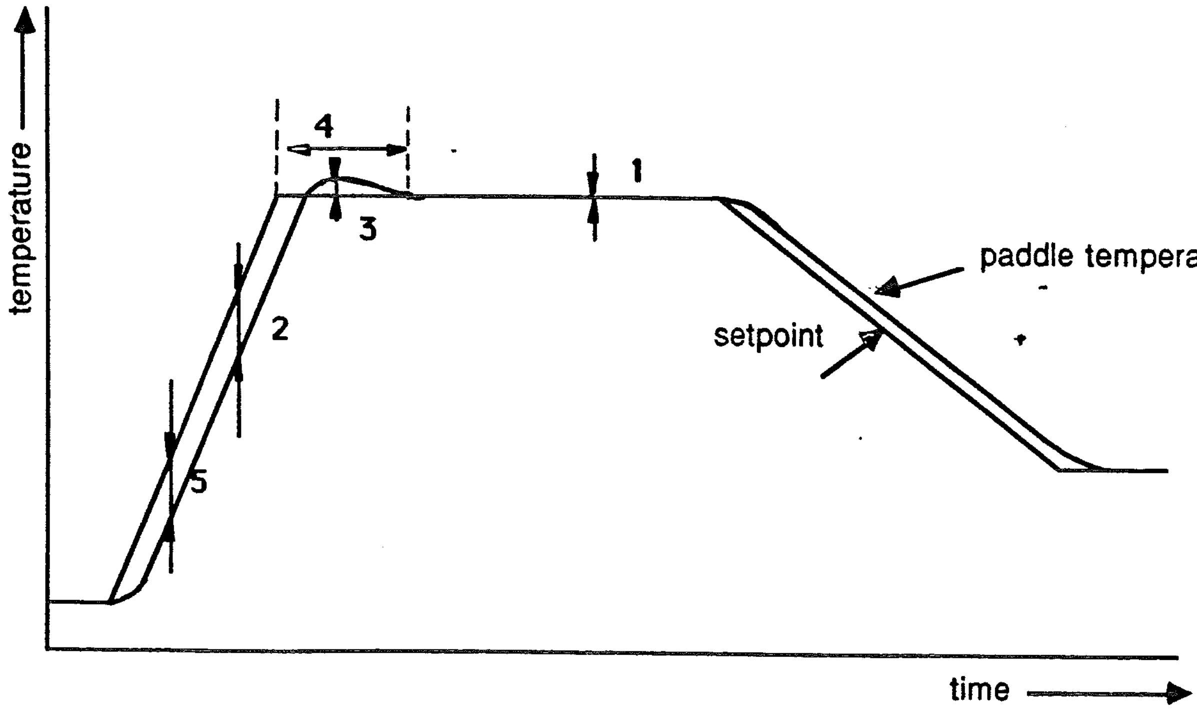


Figure 1 Setpoint wave-form

Figure 1 shows the temperature after loading, during a ramp-up to process temperature and during a ramp-down.

The following specifications are derived from the setpoint wave-form: (DFS - 250)

1. The flatzone is at least 1000 mm in length. In this area the paddle temperatures are within ±0.5°C of the setpoint.

2. The degradation of the flatzone during ramp-up and ramp-down does not exceed 5.0°C.

   The maximum **ramp-up rate (in °C/min)** with this maximum flatzone degradation is shown in the following table:

Tube material	Temperature (°C) 300	450	600	750
Quartz	5.0	6.0	7.0	8.0
Silicon carbide	3.5	4.0	4.5	5.0

   The maximum **ramp-down rate (in °C/min)** with this maximum flatzone degradation is shown in the following table:

Tube material	Temperature (°C) 300	450	600	750
Quartz	1.0	2.0	3.0	4.0
Silicon carbide	1.0	1.5	2.5	3.0

   NOTE: The degradation of the flatzone is defined as the maximum temperature difference between the fastest and the slowest responding paddle thermocouple.

3. Overshoot after a ramp-up and undershoot after a ramp-down, with the maximum ramp rates given in the tables above does not exceed 0.5°C. This means effectively no overshoot because the overshoot is limited to within the the flatzone region. When the maximum ramp rates are exceeded (e.g. a step to setpoint) the overshoot/undershoot will be less than 3.0°C.

4. The recovery time after ramping (i.e. the time needed to re-establish the flatzone) does not exceed 4 minutes plus the lag time. The lag time is defined as the time the temperature lags behind the setpoint. The lag time can also be derived from the deviation in temperature from the setpoint, divided by the ramp rate.

5. The maximum deviation between setpoint and temperature during ramping (with maximum ramp rates) does not exceed 15°C.

6. The recovery time after loading (i.e. the time needed to re-establish the flatzone), with a loading temperature of between 400°C and 800°C and a loading speed of between 100 mm/min and 250 mm/min, is less than 25 minutes.

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Cascade Controller Specifications for DFS210

These specifications apply to the following process conditions:

- DFS210, 3-zone high temperature heating element (temperature control range 500°C - 1250°C)
- DFS210, 3-zone low temperature heating element (temperature control range 250°C - 900°C)
- quartz or silicon carbide process tube 200 mm ID, 210 mm OD
- maximum waferload of 150 wafers (125 mm) distributed over 6 quartz cassettes
- 15 slm nitrogen flow
- 600°C - 800°C loading temperature (high temperature element)
  400°C - 800°C loading temperature (low temperature element)
- 100 mm/min - 250 mm/min loading speed

A typical setpoint wave-form is shown in figure 1.

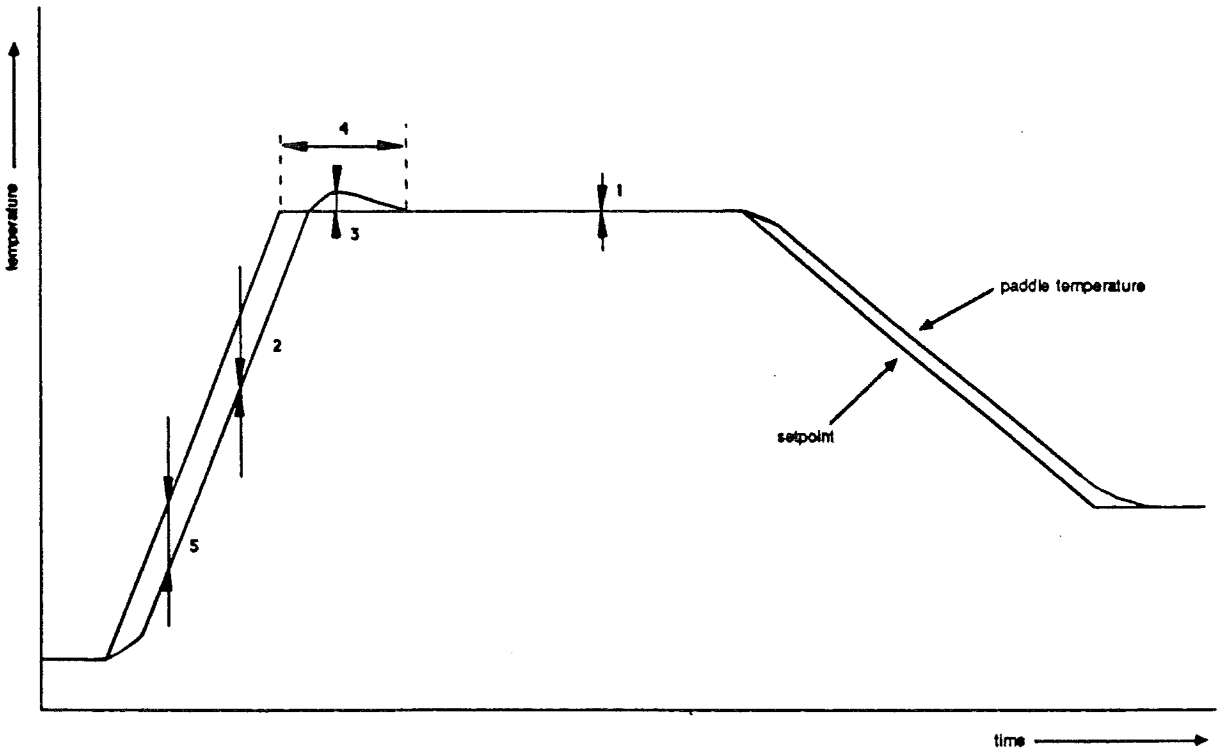

Figure 1 Setpoint wave-form

Figure 1 shows the temperature after loading, during a ramp-up to process temperature and during a ramp-down.

The following specifications are derived from this wave-form:

1. The flatzone is at least 900 mm in length. In this area the paddle temperatures are within ±0.5°C of the setpoint.
2. The degradation of the flatzone during ramp-up and ramp-down does not exceed 6.0°C (high temperature element) or 3.0°C (low temperature element).

The maximum **ramp-up rate** (in °C/min) with this maximum flatzone degradation is shown below. (DFS-210)

LOW TEMPERATURE ELEMENT:

Tube material	Temperature (°C) 300	450	600	750
Quartz	5.0	6.0	7.0	8.0
Silicon carbide	3.5	4.0	4.5	5.0

HIGH TEMPERATURE ELEMENT:

Tube material	Temperature (°C) 500	750	1000	1250
Quartz	10.0	15.0	15.0	10.0
Silicon carbide	7.0	10.0	10.0	7.0

The maximum **ramp-down rate** (in °C/min) with this maximum flatzone degradation is shown below.

LOW TEMPERATURE ELEMENT:

Tube material	Temperature (°C) 300	450	600	750
Quartz	1.0	2.0	3.0	4.0
Silicon carbide	1.0	1.5	2.5	3.0

HIGH TEMPERATURE ELEMENT:

Tube material	Temperature (°C) 500	750	1000	1250
Quartz	1.0	2.5	4.0	5.5
Silicon carbide	1.0	2.0	3.0	4.5

NOTE: The degradation of the flatzone is defined as the maximum temperature difference between the fastest and the slowest responding paddle thermocouple.

3. Overshoot after a ramp-up and undershoot after a ramp-down, with the maximum ramp rates given in the tables above does not exceed 1.0°C. When the maximum ramp rates are exceeded (e.g. a step to setpoint) the overshoot/undershoot will be less than 5.0°C.

4. The recovery time after ramping (i.e. the time needed to re-establish the flatzone) does not exceed 6 minutes (high temperature element) or 4 minutes (low temperature element) plus the lag time. The lag time is defined as the time the temperature lags behind the setpoint. The lag time can also be derived from the deviation in temperature from the setpoint, divided by the ramp rate.

5. The maximum deviation between setpoint and temperature during ramping (with maximum ramp rates) does not exceed 15°C.

6. The recovery time after loading (i.e. the time needed to re-establish the flatzone)

   - with a loading temperature of between 600°C and 800°C and a loading speed of between 100 mm/min and 250 mm/min, is less than 35 minutes (high temperature element).

   - with a loading temperature of between 400°C and 800°C and a loading speed of between 100 mm/min and 250 mm/min, is less than 45 minutes (low temperature element).

<u>NOTES</u>

i) Recovery time after ramping can be decreased by choosing a lower ramp rate than the maximum allowable ramp rate. The degradation of the flatzone, overshoot and undershoot will also be less than specified in this case.

ii) If a ramp-up is started after the furnace is loaded (as soon as the door is closed) the flatzone can recover during this ramp-up. The new temperature setpoint will, however, have to be at least 100°C higher than the loading temperature.

The profiling table gives the static difference (spike correction) between spike temperature and paddle temperature, which is used by the PID (Proportional, Integral, Derivative) algorithm; this is the conventional method of temperature control.

A more accurate and quicker method for controlling the system is to regulate the paddle thermocouples inside the process tube. One may think that the simplest implementation of this method would be to loop the paddle temperatures back to the PID controller; this, however, is not possible because of the large time constants involved, which give oscillations after small disturbances (e.g. setpoint changes) and cause inaccuracy. An extra outer loop, controlled by a PI algorithm has therefore to be established for the paddle temperatures - this is called cascade control and is shown for one zone in figure 5.

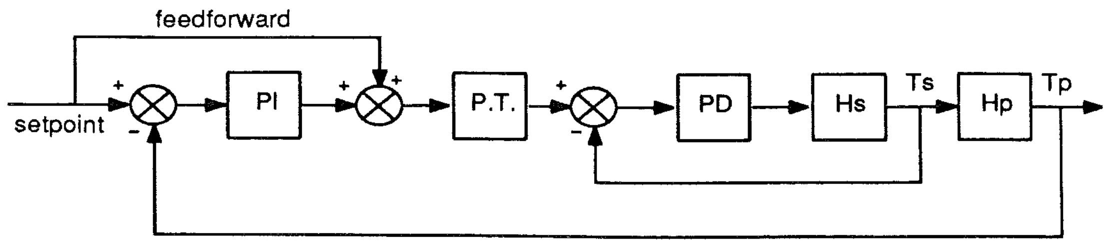

Figure 5 The inner and outer loop of the cascade controller

Figure 5 shows the cascade controller structure for one zone. When this model is applied to all five zones, then further additions can be made to compensate for interactions between zones.

Even if the cascade controller is present, the furnace can still be regulated in the spike control mode; the PD algorithm for controlling the spike temperature, as shown in figure 5, is then replaced by a PID controller.

Since the thermal response of the furnace is temperature-dependent, so too are the control parameters used by the algorithm. The gain-scheduling technique is used to calculate the required control parameters as a function of furnace temperature.

Special attention has been paid to minimizing the overshoot/undershoot of the paddle temperatures after ramp-up/ramp-down. This is accomplished by a special setpoint generation. This setpoint generation will not be explained in detail here - essentially, the setpoints for the spike temperatures are gradually adjusted when the paddle temperatures reach their final setpoint; this effectively avoids overshoot and undershoot.

In order to maintain the flatzone during temperature ramping, a flatzone controller has been designed as an integral part of the cascade controller. This flatzone controller acts on the temperature differences between the paddle thermocouples during ramp-up and ramp-down. In this way, the degradation of the flatzone during dynamic behaviour is limited.

Cascade Controller Specifications

To determine accurate and market-oriented specifications for the cascade controller, a questionnaire was sent to a selection of the major semiconductor manufacturers in Europe. The results of the questionnaire enabled us to formulate preliminary specifications from which the final design specifications were derived. The cascade controller can control the paddle temperatures (cascade control mode) or the spike temperatures (spike control mode). All dynamic specifications are therefore valid for either the paddle temperatures (cascade control) or the spike temperatures (spike control).

General specifications

These specifications apply to the following process conditions:

- DFS250, 5-zone high temperature heating element (temperature control range 500°C -1250°C)
- quartz or silicon carbide process tube 230 mm ID, 245 mm OD
- maximum waferload of 150 wafers (150 mm) distributed over 6 quartz cassettes
- 15 slm nitrogen flow
- 600°C - 800°C loading temperature
- 100 mm/min - 250 mm/min loading speed

A typical setpoint wave-form is shown in figure 6.

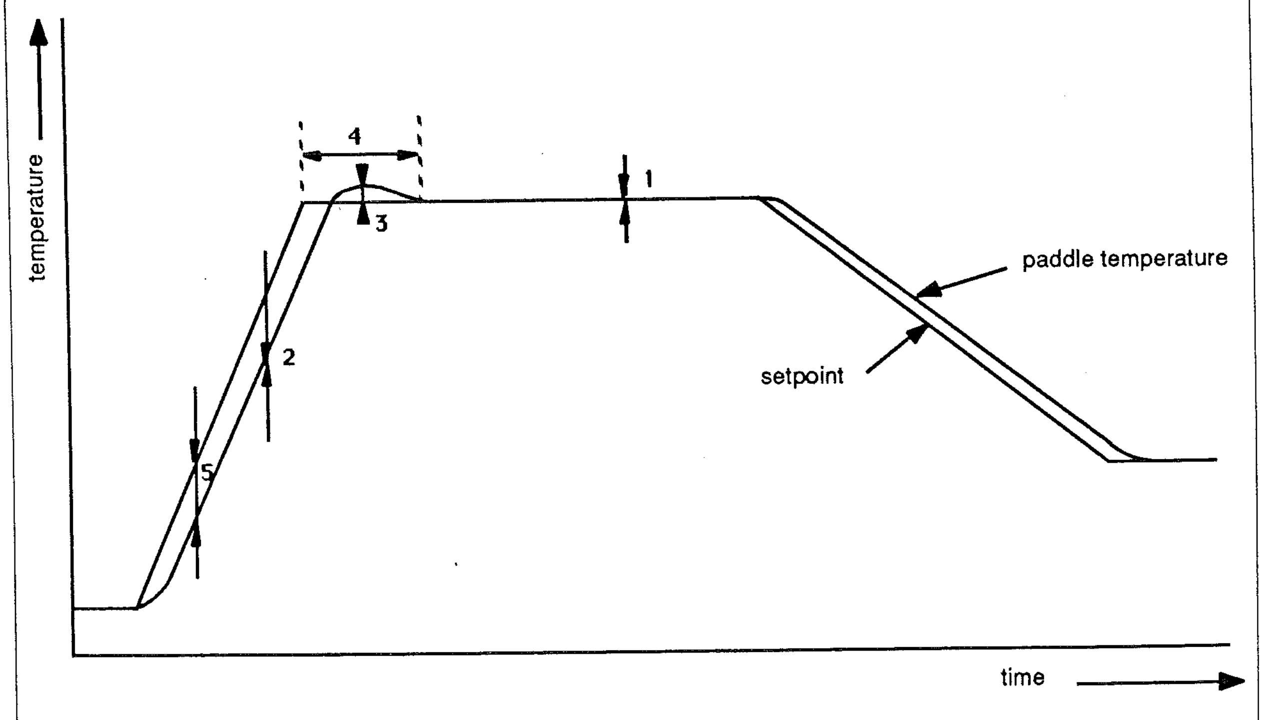

Figure 6 Setpoint wave-form

Figure 6 shows the temperature during a ramp-up to process temperature and during a ramp-down.

The specifications below are derived from the wave-form on figure 6:

1. The flatzone is at least 1000 mm in length. In this area the paddle temperatures are within ±0.5°C of the setpoint.

2. The degradation of the flatzone during ramp-up and ramp-down does not exceed 3.0°C.

   The maximum **ramp-up rate (in °C/min)** with this maximum flatzone degradation is shown in the following table:

Tube material	Temperature (°C) 500	750	1000	1250
Quartz	10	15	15	10
Silicon carbide	7	10	10	7

   The maximum **ramp-down rate (in °C/min)** with this maximum flatzone degradation is shown in the following table:

Tube material	Temperature (°C) 500	750	1000	1250
Quartz	1.0	2.5	4.0	5.5
Silicon carbide	1.0	2.0	3.0	4.5

   NOTE: The degradation of the flatzone is defined as the maximum temperature difference between the fastest and the slowest responding paddle thermocouple.

3. Overshoot after a ramp-up and undershoot after a ramp-down, with the maximum ramp rates given in the tables above does not exceed 0.5°C. This means effectively no overshoot because the overshoot is limited to within the flatzone region. When the maximum ramp rates are exceeded (e.g. a step to setpoint) the overshoot/undershoot will be less then 3.0°C.

4. The recovery time after ramping (i.e. the time needed to re-establish the flatzone) does not exceed 2 minutes plus the lag time. The lag time is defined as the time the temperature lags behind the setpoint. The lag time can also be derived from the deviation in temperature from the setpoint, divided by the ramp rate.

5. The maximum deviation between setpoint and temperature during ramping (with maximum ramp rates) does not exceed 15°C.

6. The recovery time after loading (i.e. the time needed to re-establish the flatzone), with a loading temperature of between 600°C and 800°C and a loading speed of between 100 mm/min and 250 mm/min, is less than 15 minutes.

NOTES

i) Recovery time after ramping can be decreased by choosing a lower ramp rate than the maximum allowable ramp rate. The degradation of the flatzone will in this case also be less than specified.

ii) If a ramp-up is started after the furnace is loaded (as soon as the door is closed) the flatzone can recover during this ramp-up. The new temperature setpoint will, however, have to be at least 100°C higher than the loading temperature.

Cascade controller safety mechanisms

If a thermocouple fails, the cascade controller must continue to function accurately for the remainder of the process time. Three possible failure scenarios must be considered:

1. Cascade control, paddle thermocouple failure

   The cascade controller will switch to the spike PID control mode for the affected zone(s), and the flatzone controller will be switched off.

2. Cascade control, spike thermocouple failure

   If the failure occurs in one of the zones with a backup thermocouple (zones 1, 3 and 5), control will switch to the appropriate backup thermocouple. If a zone 2 or 4 thermocouple fails, then the controller will operate as a 3-zone cascade controller, using zones 2, 3 and 4 as the centre zone. In the latter case, the flatzone controller will be switched off.

3. Spike control, spike thermocouple failure

   For this failure situation, the same action will be taken as detailed in point 2; however, a 3-zone spike control mode will be used.

Automatic profiling sequence

The profiling procedure is used to determine the difference between spike and paddle temperature readings in the steady state. These values (spike corrections) are stored in the profiling table, and are used by the cascade controller.

Normal operation of the furnace eventually results in ageing of the thermocouples, which affects the spike correction values. Re-profiling of the furnace must therefore be done on a regular basis to compensate for this ageing. If the conventional spike PID control algorithm is used, this procedure must be carried out as a separate task. The cascade controller, however, allows the user to profile during processing. In fact, profiling is being carried out during every process run, and the process engineer can choose whether or not to update the profiling table with the new results at the end of each run. In this way, the profiling table always represents the current characteristics of the thermocouples with which the controller is working.

Control parameter tuning

A tuning feature allows the process engineer to change the control settings within safe limits. The controller behaviour can be accelerated, giving a faster furnace temperature response (but considerable overshoot) or can be slowed down, resulting in a more sluggish furnace response.

Control modes

The controller has two modes of control:

- cascade control with flatzone controller;
- spike control.

If the control mode is changed, a short stablization period must be allowed for.

Cascade Controller Performance

The best way to illustrate the cascade controller performance is to compare it with the conventional spike control algorithm. This comparison is made in three situations:

- ramp-up from 750°C to 850°C at 11.5°C/min
- ramp-down from 850°C to 750°C at 2.0°C/min
- loading at 700°C, loading speed 100 mm/min

Ramp-up from 750°C to 850°C at 11.5°C/min

The furnace response to ramp-up under cascade control is shown in figure 7.

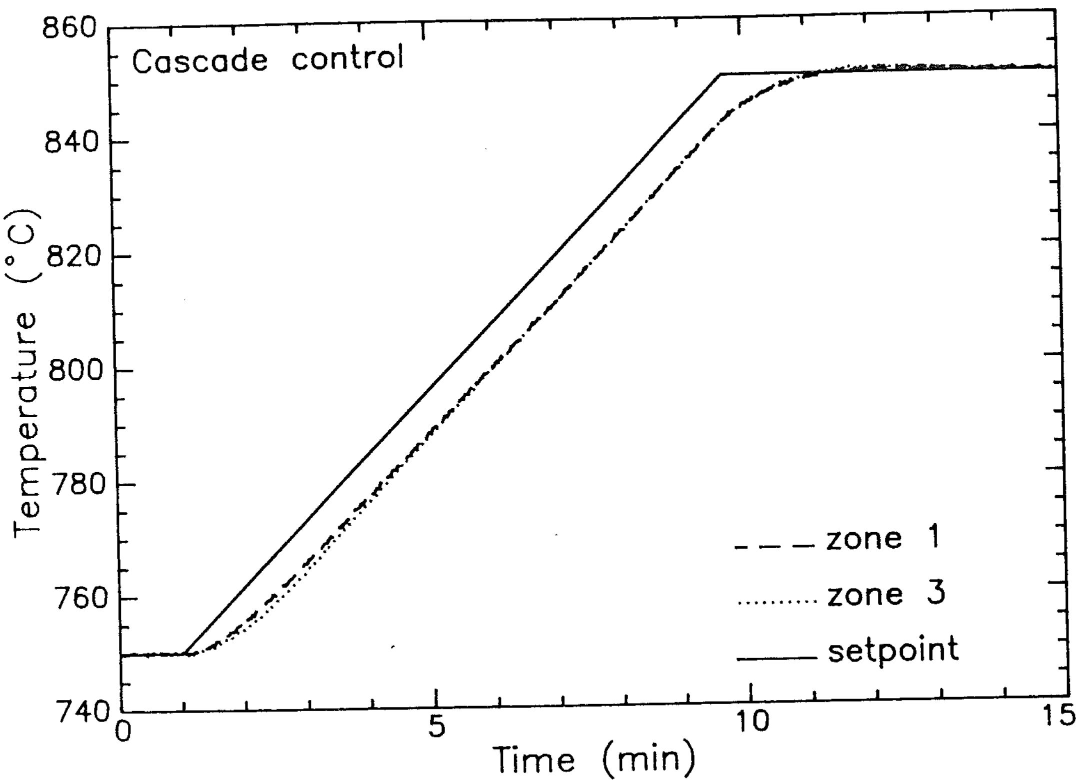

Figure 7 Ramp-up at 11.5°C/min, 750°C - 850°C, cascade control

The figure shows a stable furnace at 750°C. The setpoint is then ramped to 850°C, and the furnace recovers. Only the fastest responding thermocouple (zone 1) and the slowest responding thermocouple (zone 3) are shown on the figure. For this setpoint wave-form under cascade control, the results are as follows:

- flatzone degradation: < 1.5°C
- recovery time after ramp-up: 2 min
- greatest deviation between setpoint and temperature: 10°C

Figure 8 shows the furnace response under spike control, with exactly the same conditions:

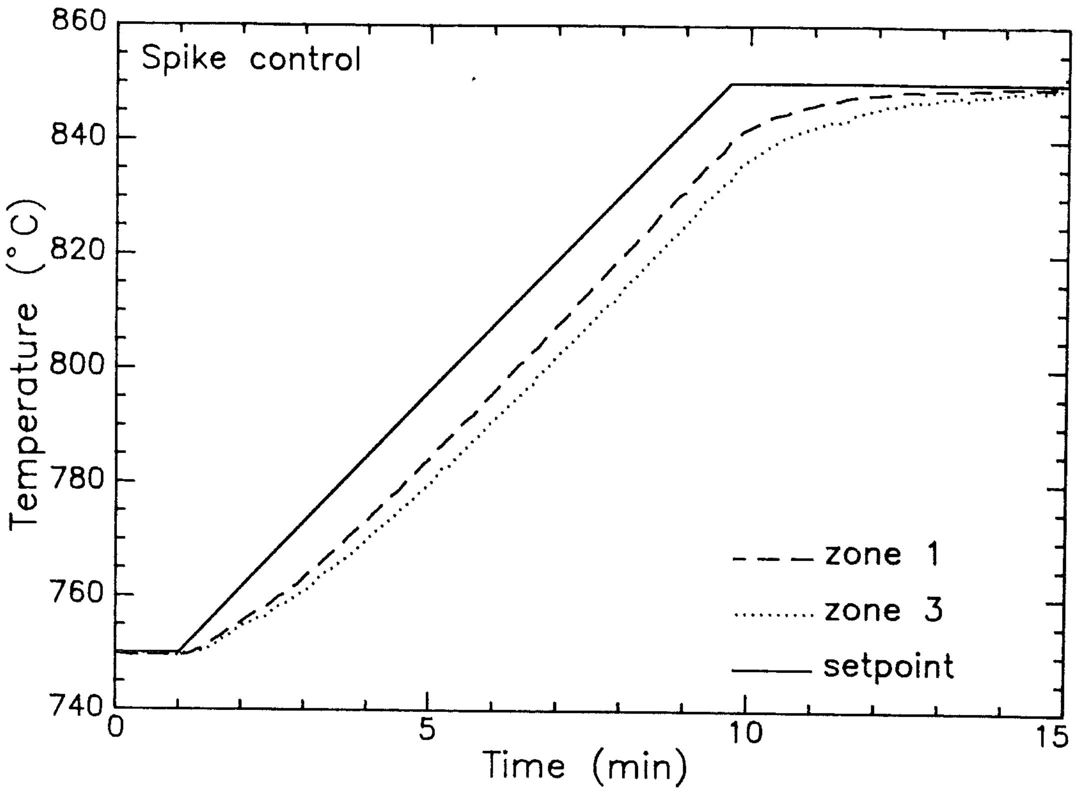

Figure 8 Ramp-up at 11.5°C/min, 750°C-850°C, spike control

For spike control, the results are as follows:

- flatzone degradation: <6.0°C
- recovery time after ramp-up: 6 min
- greatest deviation between setpoint and temperature: 20°C

The most important results for the two types of controller - flatzone degradation and recovery time are detailed in figures 9 and 10. Both figures clearly show the superior thermal response achieved with cascade control.

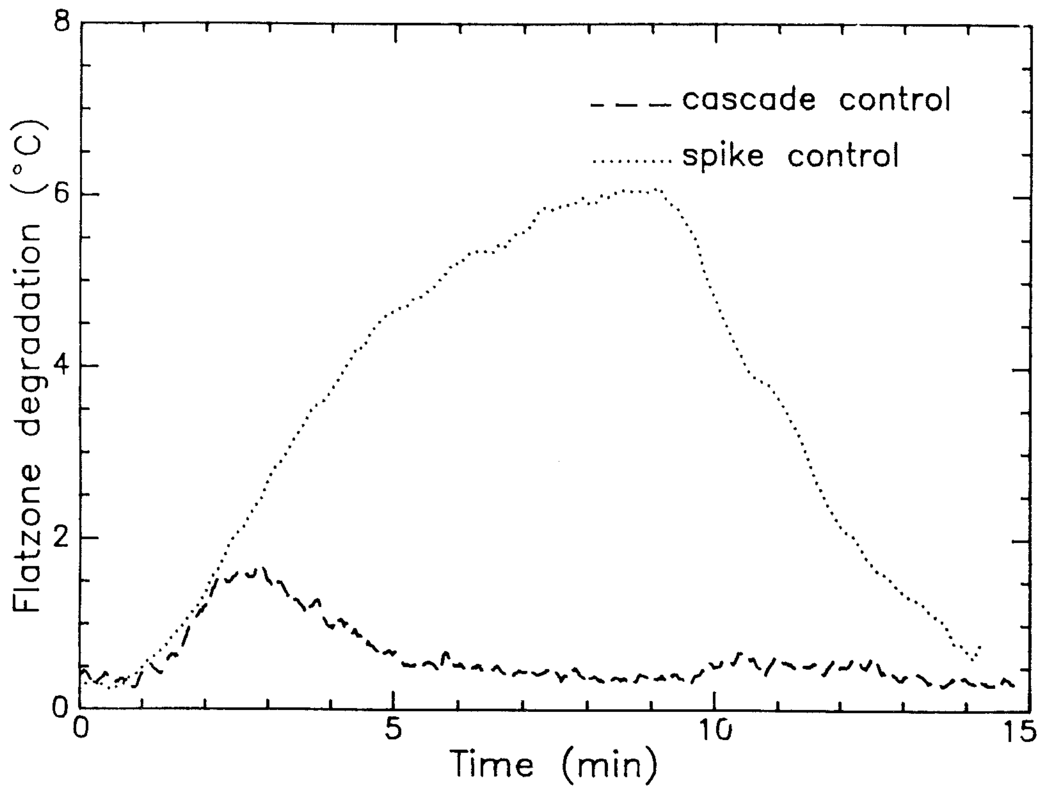

Figure 9 The flatzone degradation during ramp-up (750°C-850°C at 11.5°C/min) for both controllers

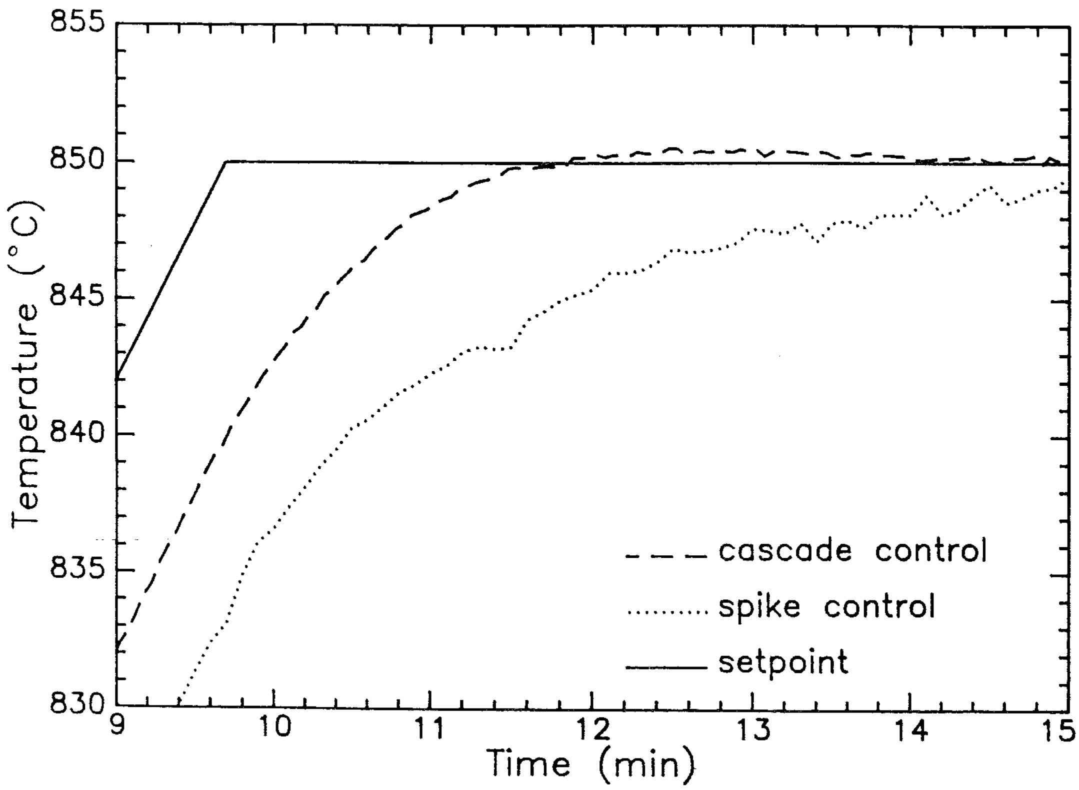

Figure 10 The recovery time after ramp-up (750°C-850°C at 11.5°C/min) for both controllers

Ramp-down from 850°C to 750°C at 2.0°C/min

The furnace response to a ramp-down under cascade control is shown in figure 11.

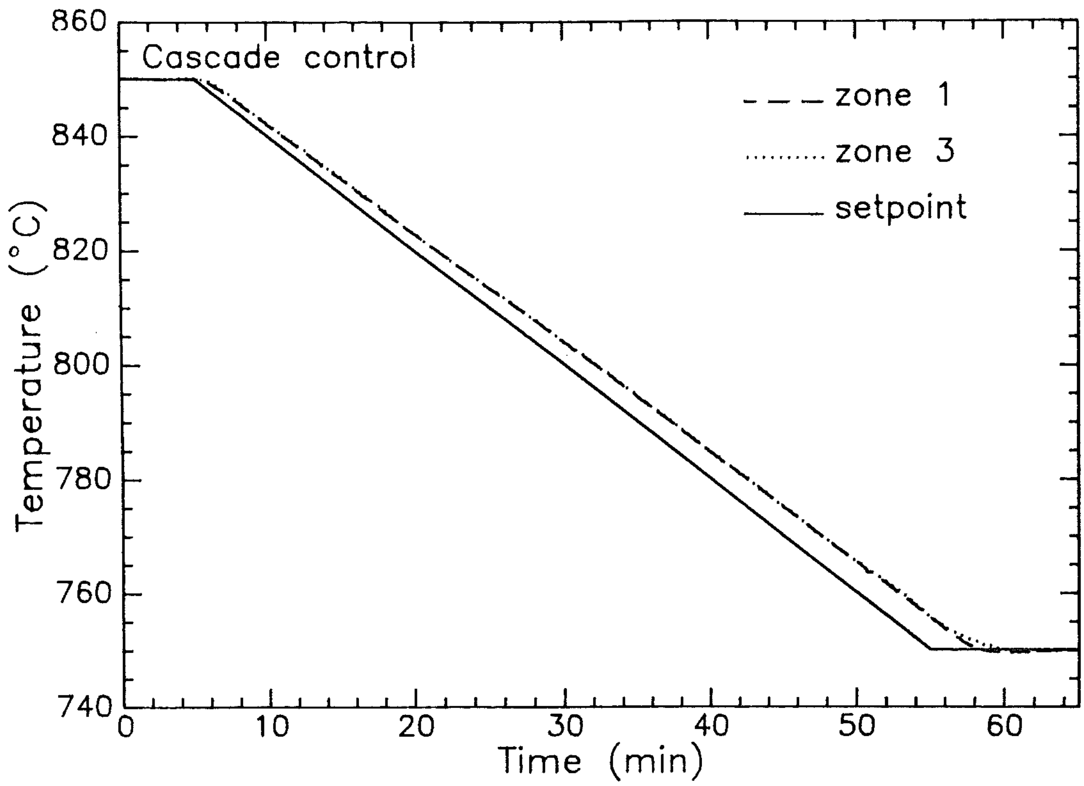

Figure 11 Ramp-down at 2.0°C/min, 850°C-750°C, cascade control

The flatzone is maintained perfectly during this ramp-down:

- flatzone degradation: <1.0°C
- recovery time after ramp-down: 4 min
- greatest deviation between setpoint and temperature: 5°C

If the same ramp-down is performed under the same conditions but using spike control, the results are as follows:

- flatzone degradation: <1.6°C
- recovery time after ramp-down: 7 min
- greatest deviation between setpoint and temperature: 15°C

The most important results for the two types of controller - flatzone degradation and recovery time are detailed in figures 12 and 13. Once again, the results show clearly the superior response of cascade control.

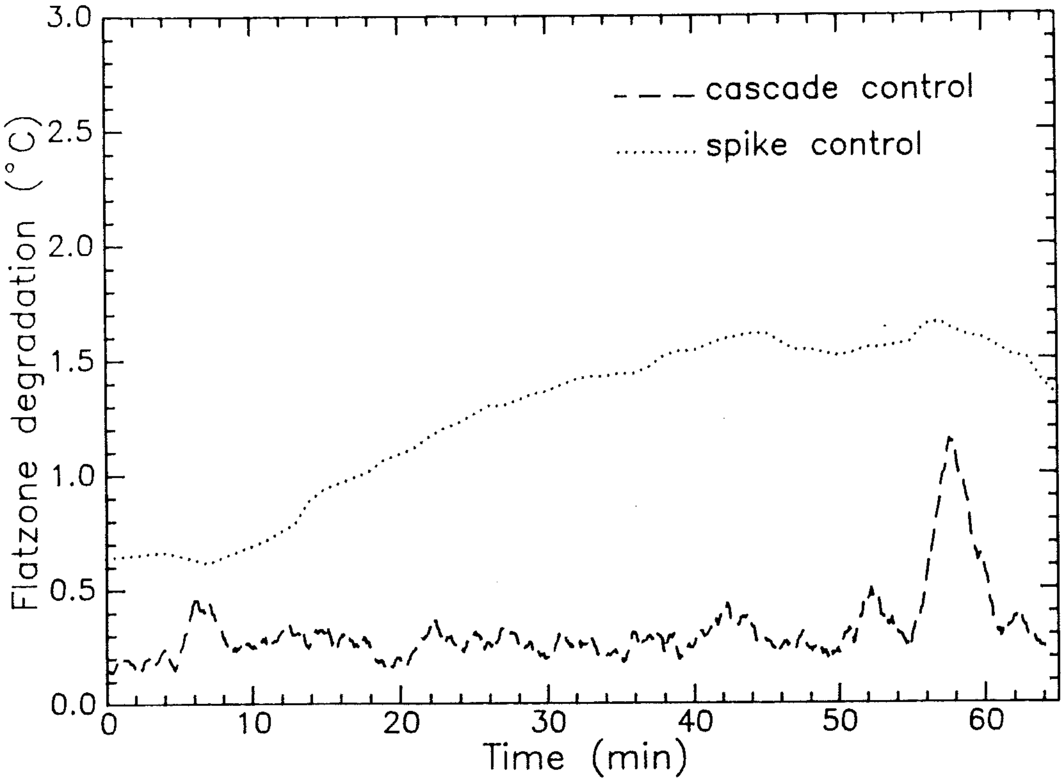

Figure 12 The flatzone degradation during ramp-down (850°C -750°C at 2.0°C/min) for both controllers

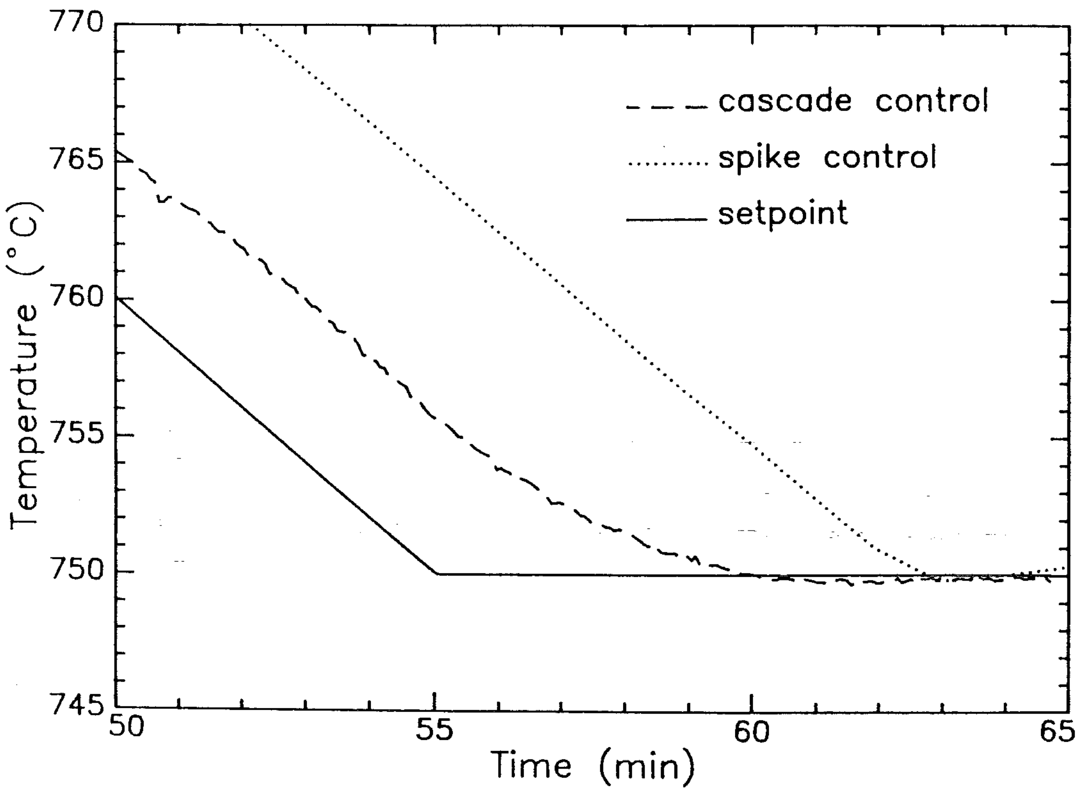

Figure 13 The recovery time after ramp-down (850°C-750°C at 2.0°C/min) for both controllers

Loading

The furnace was loaded under the following conditions:

- 150 wafers (150 mm) placed in 6 cassettes
- silicon carbide paddle (cantilever loading)
- loading speed: 100 mm/min
- loading temperature: 700°C

The temperature response to the loading sequence under cascade control is shown in figure 14.

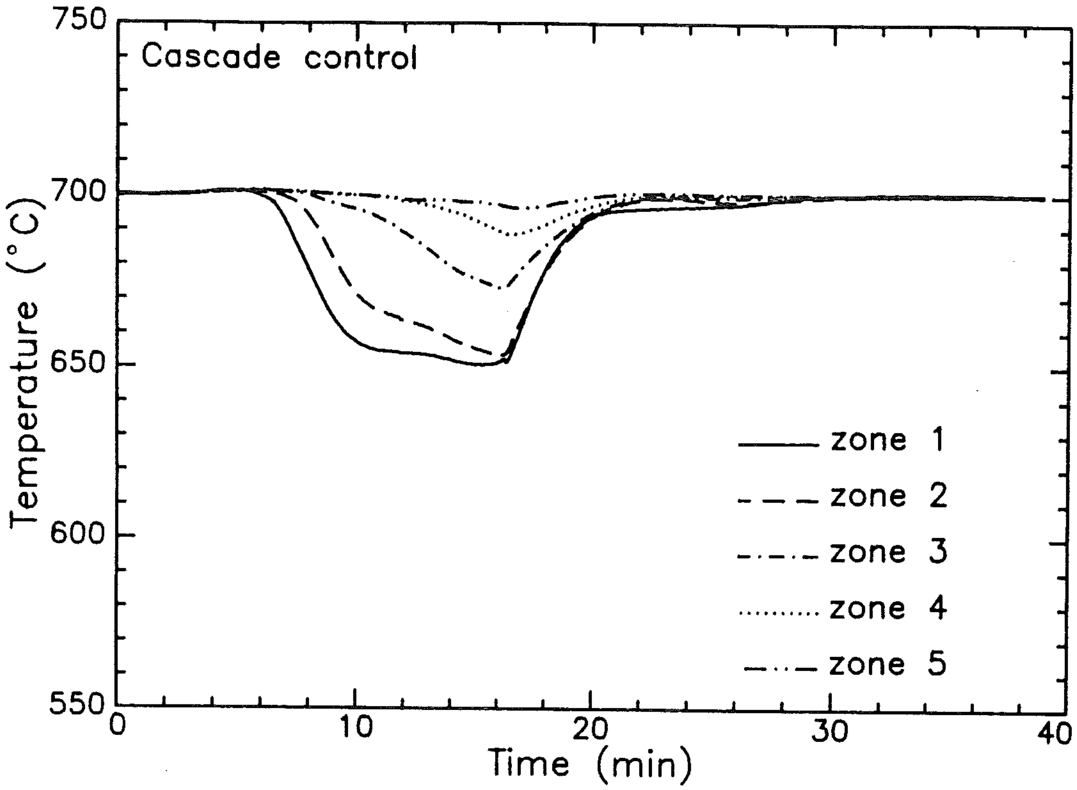

Figure 14 Loading the furnace, cascade control

The loader starts to move at t=3 minutes; until that time the wafers are out of the (open) furnace. As is shown in the figure, the cascade controller establishes a flatzone even when the door of the furnace is open. This clearly demonstrates the robustness of the cascade controller. For two extreme cases - waferload in the furnace with the door closed, empty furnace with the door open - the cascade controller maintains a flatzone. At t=16 minutes the door is closed. The recovery time after loading, defined as the time needed to re-establish the flatzone after the door is closed, is 12.5 minutes. Note that there is a temperature distortion of 50°C in the load zone (zone 1).

The same loading sequence under spike control is shown in figure 15:

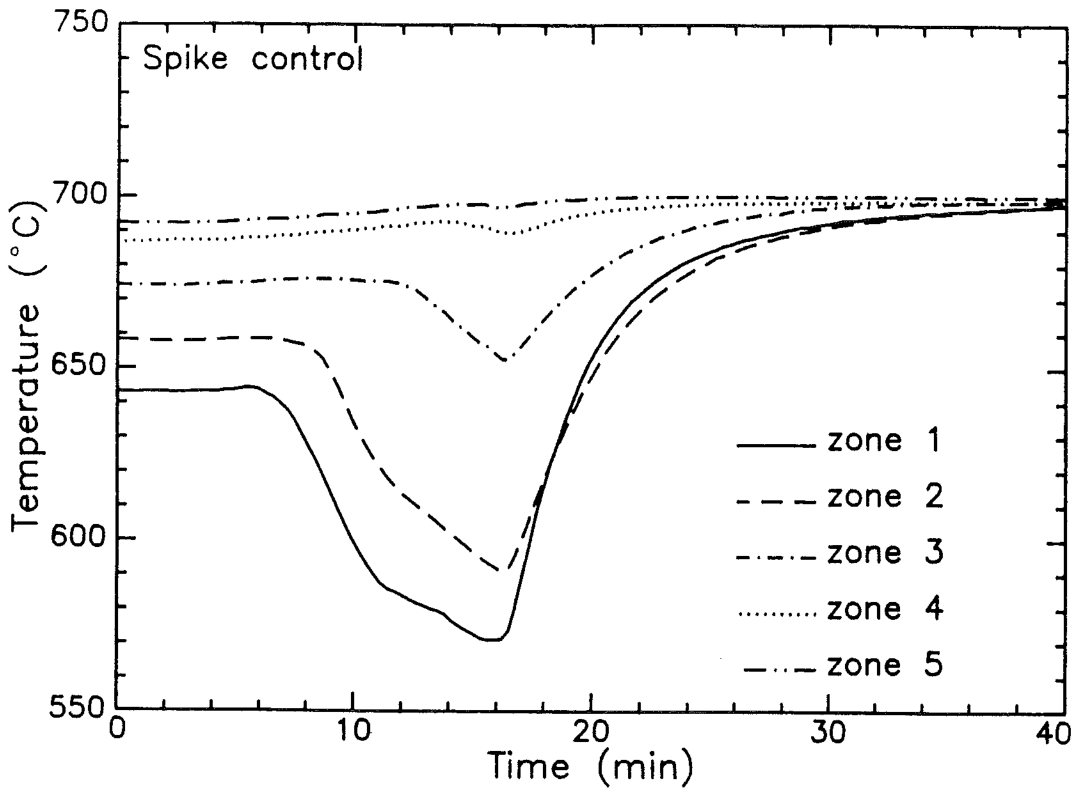

Figure 15 Loading the furnace, spike control

Because the furnace is not profiled in an open door situation, the paddle thermocouple temperatures are not equal and the load zone temperature decreases by 75°C during loading. At t=16 minutes, the furnace door is closed, and the furnace takes 33.5 minutes to recover: 21 minutes more than under cascade control.

Operational constraints

One operational factor must be pointed out. Due to the design and operation of the cascade controller, the thermocouple assembly which houses the five paddle thermocouples must remain in the tube at all times. This, as far as thermocouple lifetime is concerned, gives advantages; it is well known that accuracy and lifetime of a thermocouple is enhanced if it is not subjected to frequent and drastic changes in temperature. The thermocouple assembly is therefore permanently housed inside the process tube (it has to be inserted into the furnace via an inlet at the source side of the furnace under the source-gas balljoint); it cannot be attached to the cantilever paddle itself, for obvious reasons.

When process requirements do not allow a thermocouple assembly in the tube, the cascade controller still offers a big advantage: a fast profiling run can be made before the thermocouples are removed, and then control can be switched back to the spike thermocouples.

Conclusions

In the previous sections we have described the cascade controller, and provided specifications. The main differences between the cascade controller and the conventional spike PID controller under typical process conditions have also been illustrated. The major conclusion which can be drawn is that the cascade controller gives superior results - especially where stringent temperature control is required. Furthermore, the additional operational advantages offered by the cascade controller (including automatic profiling during processing and the absence of tune-in) result in a convincing increase in throughput for any furnace operating under cascade temperature control.

A (final) word about the ASM cascade controller

Various manufacturers of wafer processing equipment use the term "cascade control" to describe many and varied temperature control concepts. In the majority of cases, these modes of control are nothing more than simple master/slave control structures, where the master controller is used to adjust/trim the setpoint of the slave controller. These types of control normally only function under steady state conditions, and therefore can only be used during furnace profiling. In addition, because of their design, these controllers are renowned for their sluggish performance.

The cascade controller which we have described in this booklet bears no resemblance to these master/slave controllers whatsoever: our cascade controller functions superbly under static and dynamic conditions (setpoint changes, loading/unloading, disturbances). A true comparison between our cascade controller and other cascade-like controllers can only be made by checking the performance of both the control algorithm and the furnace itself, under all operating conditions.