Recent Investigation (2)

Estimation of Erosion Line of Refractrory Brick in Blast Furnace Hearth Using BEM and Cellular Automata

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Background

For a safe and longer service of **blast furnaces**, it is important to watch the current conditions of refractory brick inside the furnace.

The temperature or heat flux on the outer surface of the furnace can be measured at some selected points, but **measurement of the interface** between molten metal and the refractory brick is **impossible**.

It is required to **develop a computational approach to estimate the so-called erosion line of the refractory brick**, using the measured temperatures on the outer surface.

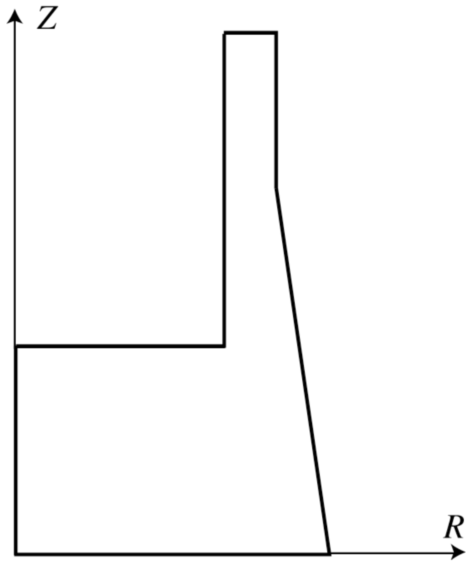
Background

Basic Assumptions

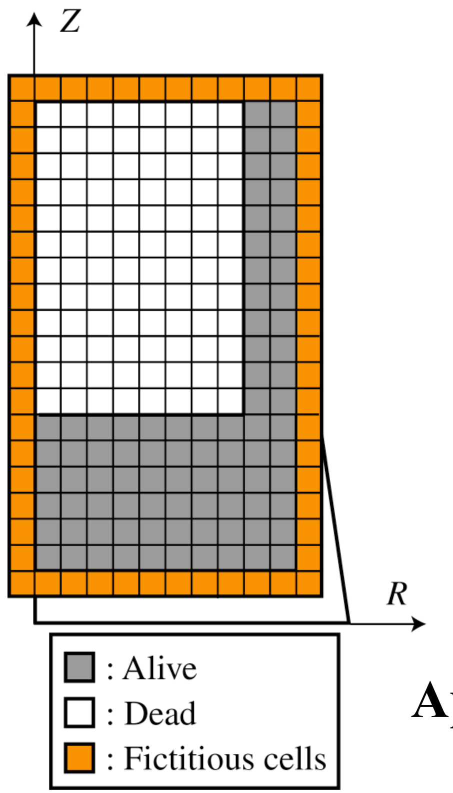
1. The blast furnace can be modeled into a rotationally symmetric body.
2. It is in a steady-state heat conduction.
3. The temperature is measured at selected points on the outer surface of the furnace.
4. The interface between molten metal and the refractory brick is subject to the Dirichlet boundary condition, that is, the temperature is equal to solidification of molten metal.

Background

1. **BEM software is applied to compute the temperature field of the blast furnace.**
2. **Cellular automata (CA) is employed to estimate the interface of molten metal and refractory brick.**

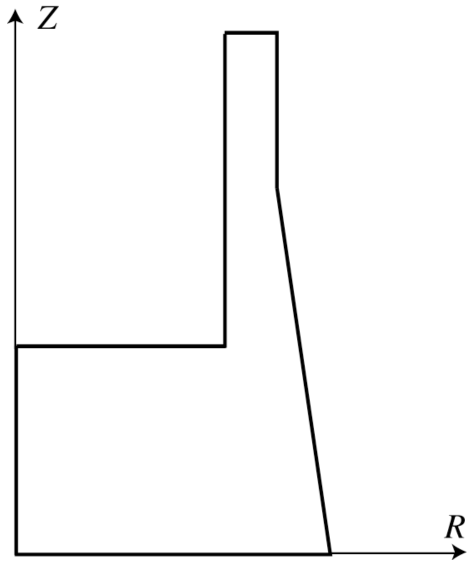


Blast furnace hearth



Application of CA

BEM



Blast furnace hearth

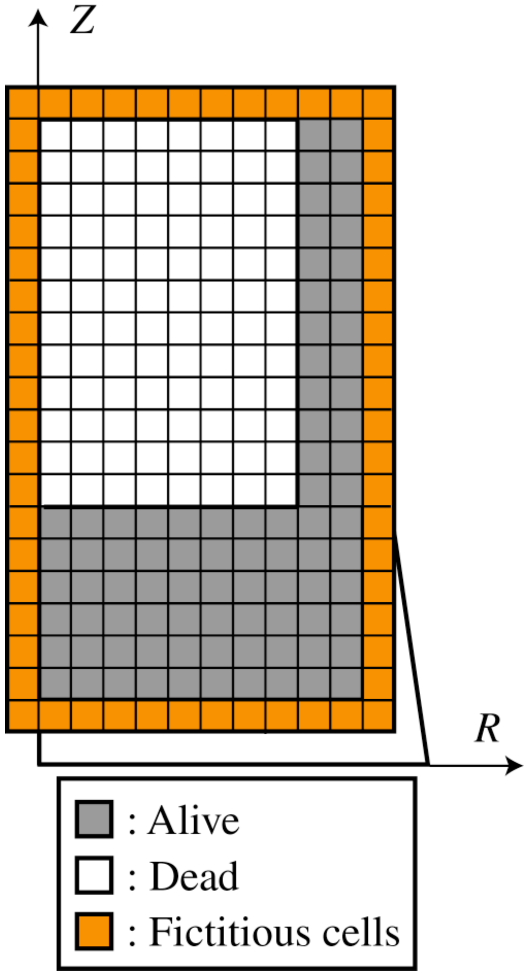
Governing differential equation: $\nabla^2 u(x) = 0$

Boundary integral equation:

$$c(y)u(y) + \int_{\bar{\Gamma}} \bar{Q}^*(x,y)u(x)d\bar{\Gamma} = \int_{\bar{\Gamma}} \bar{U}^*(x,y)q(x)d\bar{\Gamma}$$

The asterisked functions with superimposed bar denote the fundamental solution of axisymmetric body.

Cellular Automata

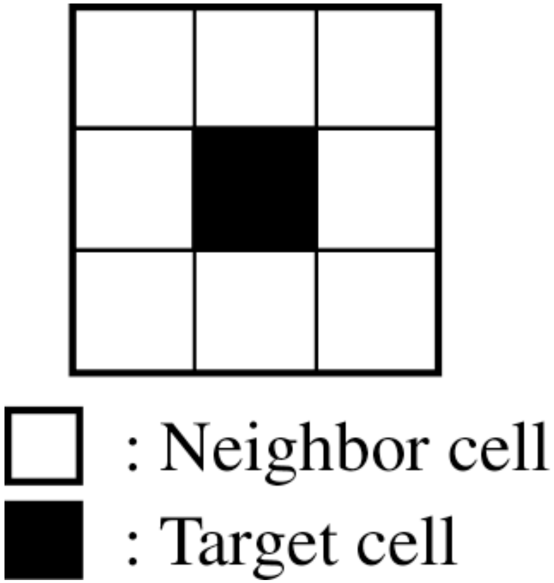


The region of interest is uniformly divided into equal cells.

A state-quantity is assumed for each cell.

The whole behavior of the cells is searched by changing the state quantities due to local and transition rules.

Cellular Automata

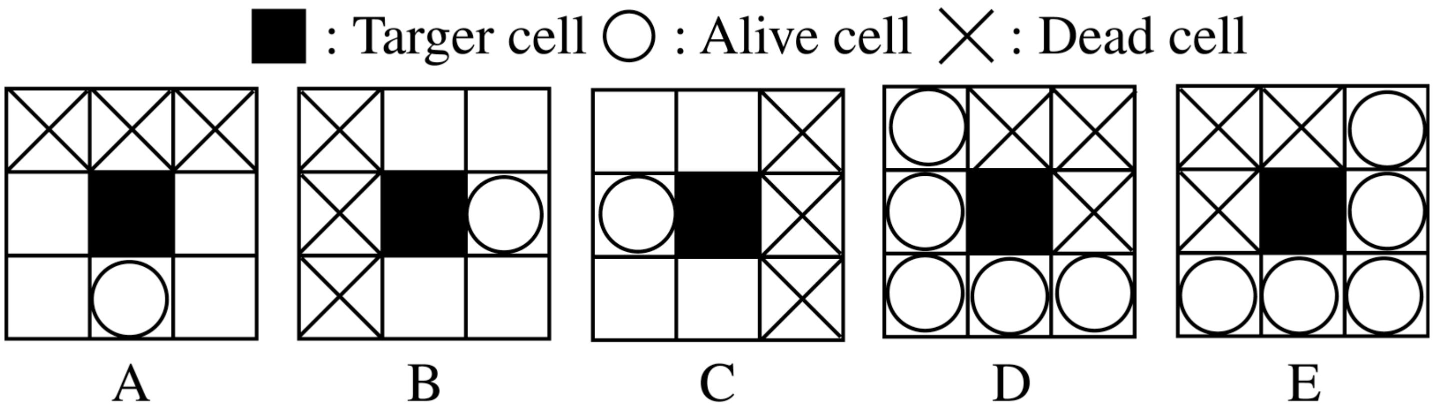


Moore neighbor:
8 neighbor cells surrounding the target cell

States of a cell:
Alive(exist), Dead(not exist)
Remaining(always exist)

Local rule:
Next state of the cell is determined by a local rule related to the current state of the cell and the surrounding cells in Moore neighbor.

Local Rule 1:

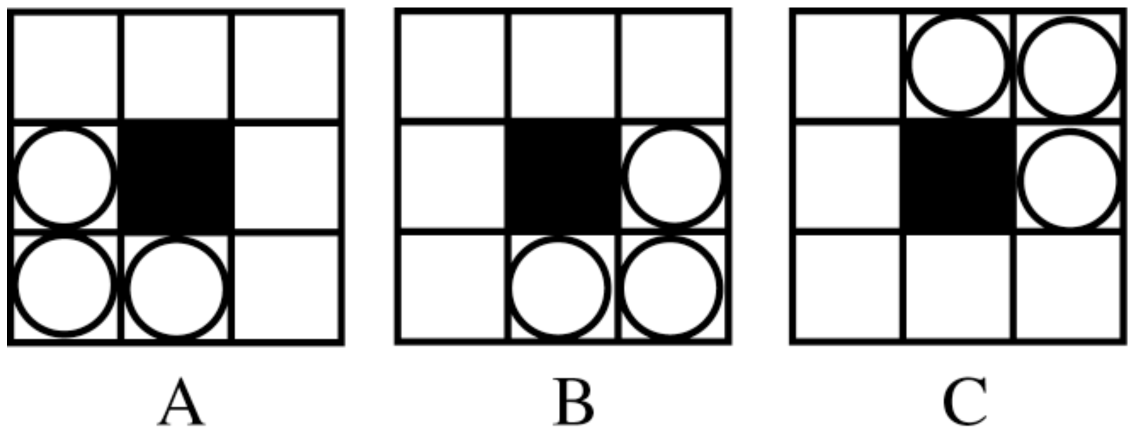


If the target cell is "Alive", "Not-Remaining" and the Moore neighbor cells hold for the above patterns, then the target cell is changed from "Alive" to "Dead".

Pattern A is not used along the upper side.
Pattern B is not used along the left side.

Cellular Automata

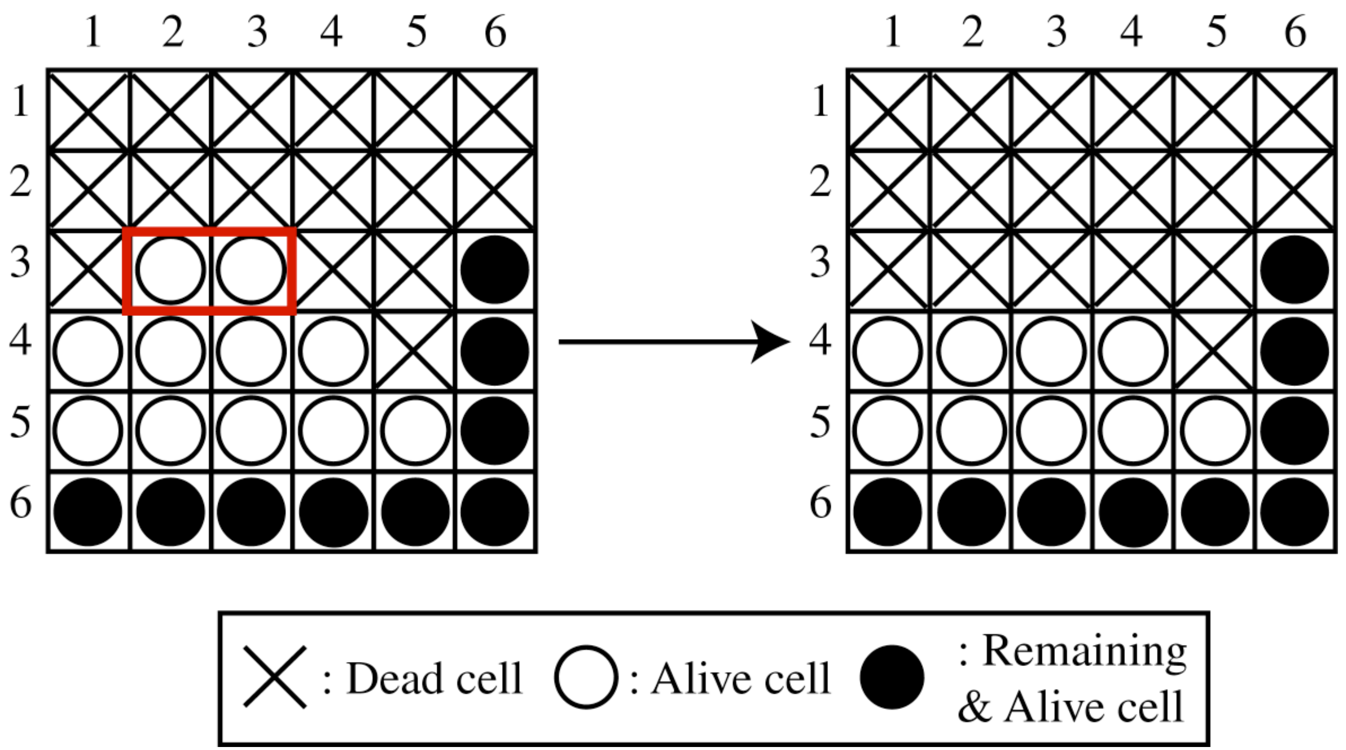
Local Rule 2:



If the target cell is "Dead", "Not-Remaining" and the Moore neighbor cells hold for the above patterns, then the target cell is changed from "Dead" to "Alive".

Cellular Automata

Empirical Rule:



If a few "Alive" cells in one row or column are surrounded by the "Dead" cells as shown above, such cells are changed from "Alive" to "Dead".

Cellular Automata

Cost Function:

$$W = \sum_{i=1}^{N} \left(\frac{u_i - \hat{u}_i}{\hat{u}_i} \right)^2$$

u_i : Computed temperature by BEM at point *i*

$\hat{u}_i$: Measured temperature at point *i*

N : Number of points measuring temperature

Transition Rule

Step 1: Carry out BEM analysis under the initial shape of erosion surface
and save the value of the cost function.

Step 2: Apply the **empirical rule** to all the rows and columns of the cells.

Step 3: Apply the **local rule 1**, and compute the cost function if the shape is changed. Repeat this process for all the cells. Save the lowest cost function and its shape.

Step 4: Apply the **local rule 2**, and compute the cost function if the shape is changed. Repeat this process for all the cells. Save the lowest cost function and its shape.

Step 5: Repeat steps 2 to 4 until the cost function is unaltered.

Computational Results

Analysis model

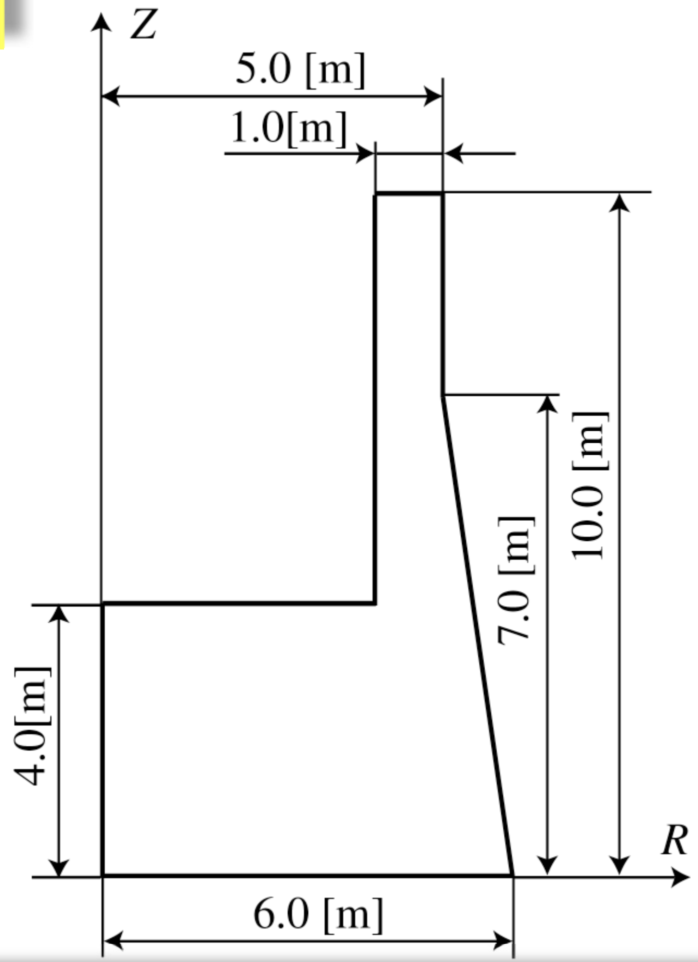
耐火物
$\lambda = 13.0$ [W/mK]

内壁
$u = 1150$ [℃]

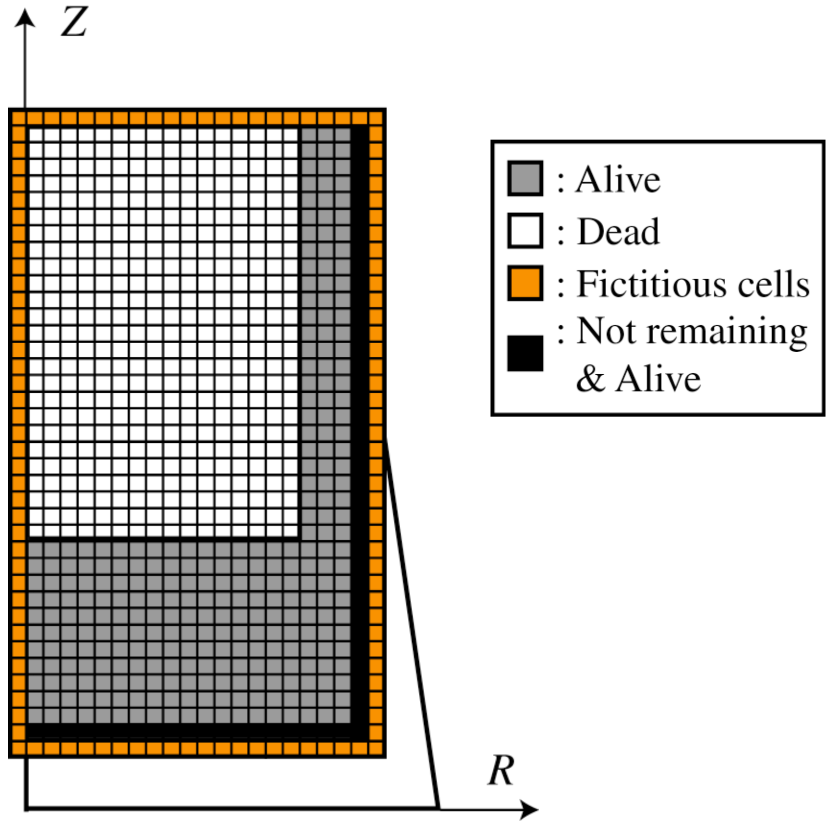
溶鉱炉上部
$q = 0$ [W/m^2]

外壁
$h = 70$ [W/m^{2}K]
$u_a = 30$ [℃]

溶鉱炉下面
$h = 35$ [W/m^{2}K]
$u_a = 30$ [℃]



Cell division

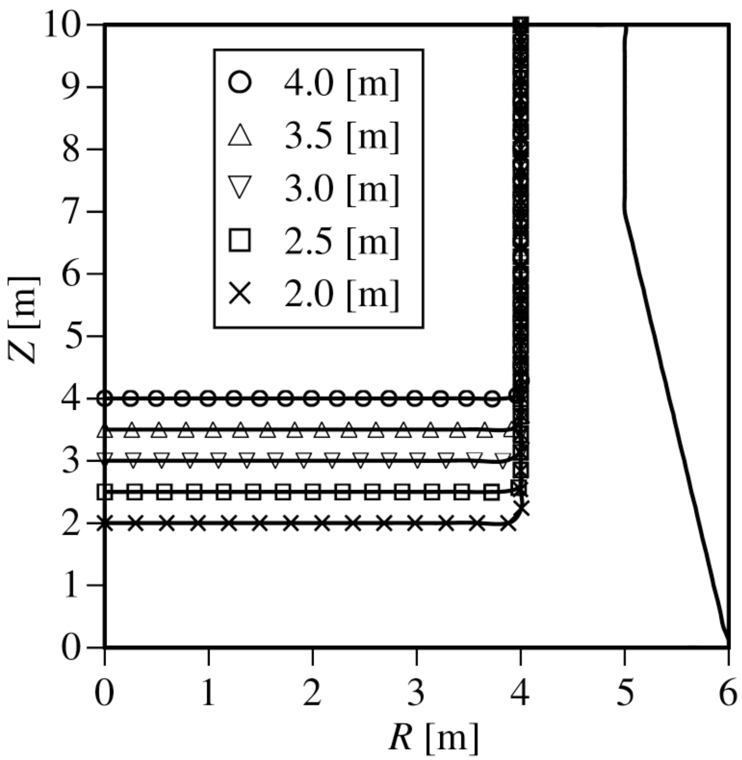


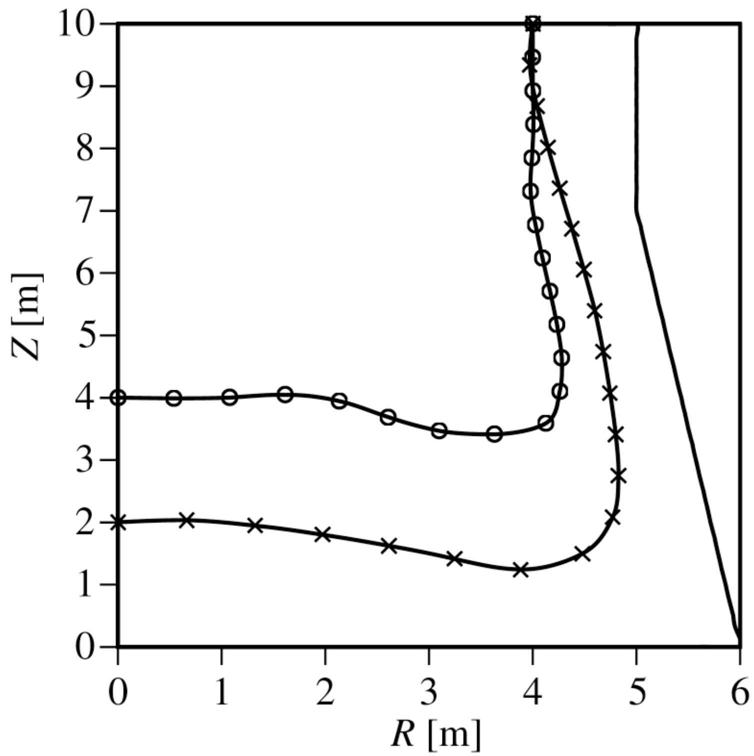
The rectangular region 5.0 [m]×9.0 [m] is uniformly divided into square cells with size of 0.25 [m]×0.25 [m].

Computational Results

Five initial surfaces are assumed with different bottom heights

The target shape is assumed between the two curves shown below.

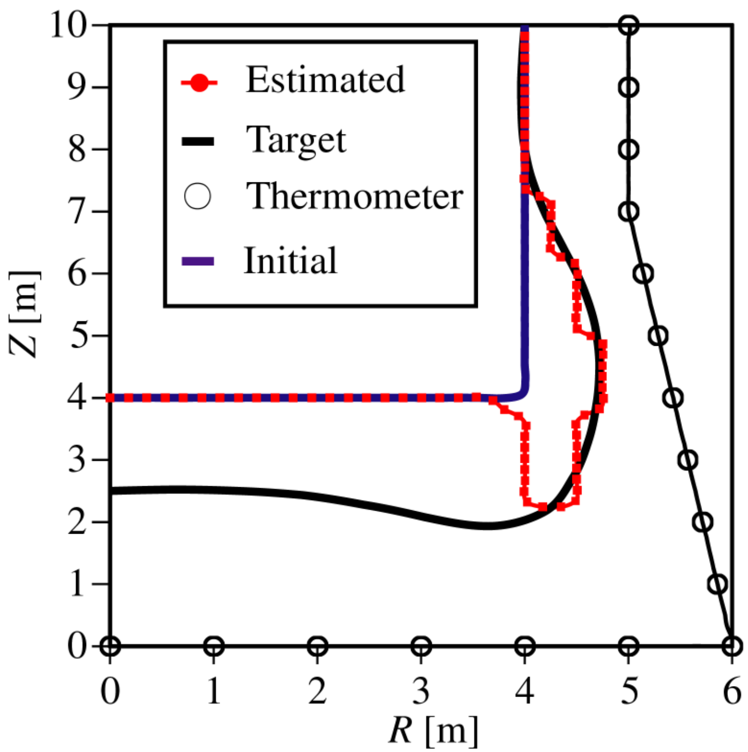




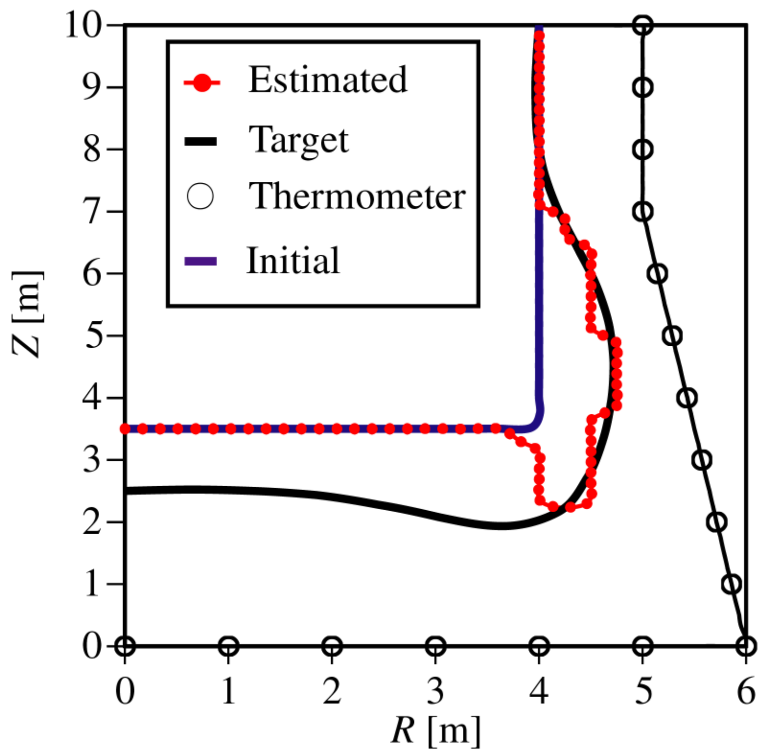
Case (1)

It is assumed that the temperature is measured at 17 points on the outer surface of furnace.

Initial shape with bottom height 4.0 m



Initial shape with bottom height 3.5 m



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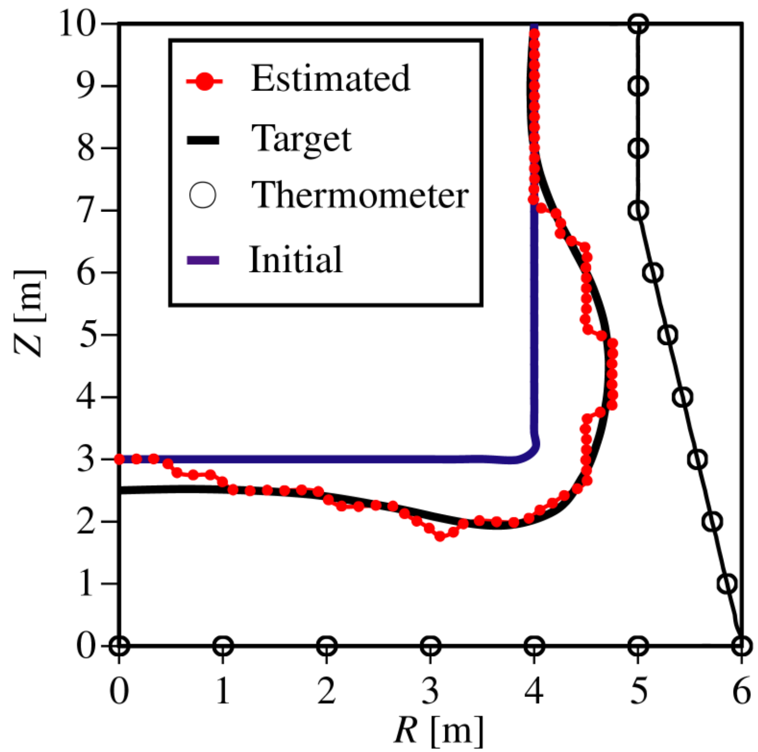
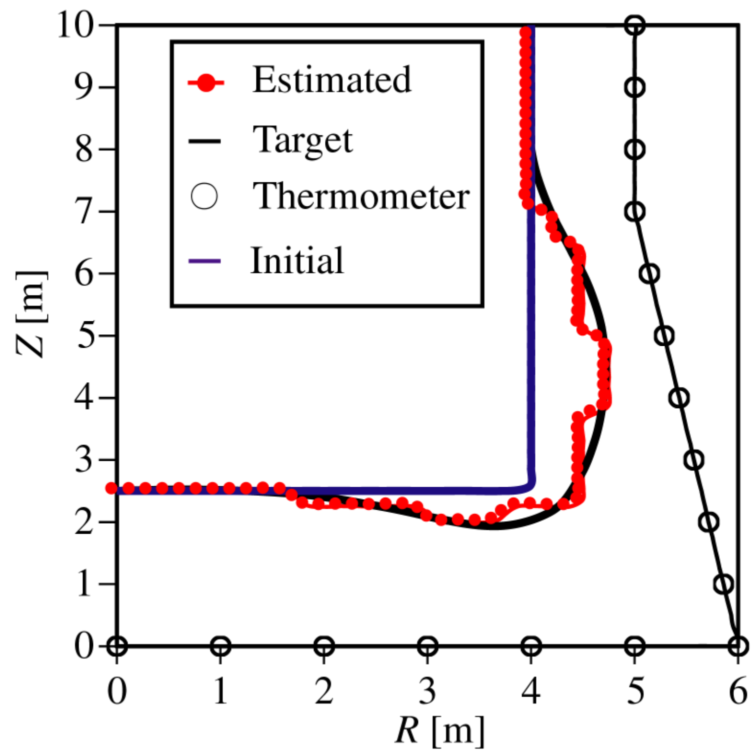


Initial shape with bottom height 2.5 m



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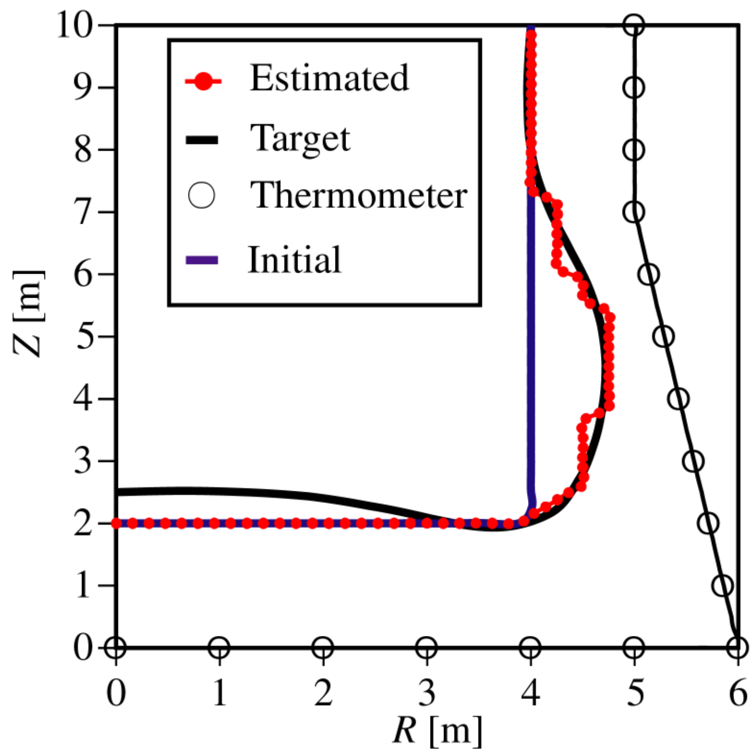

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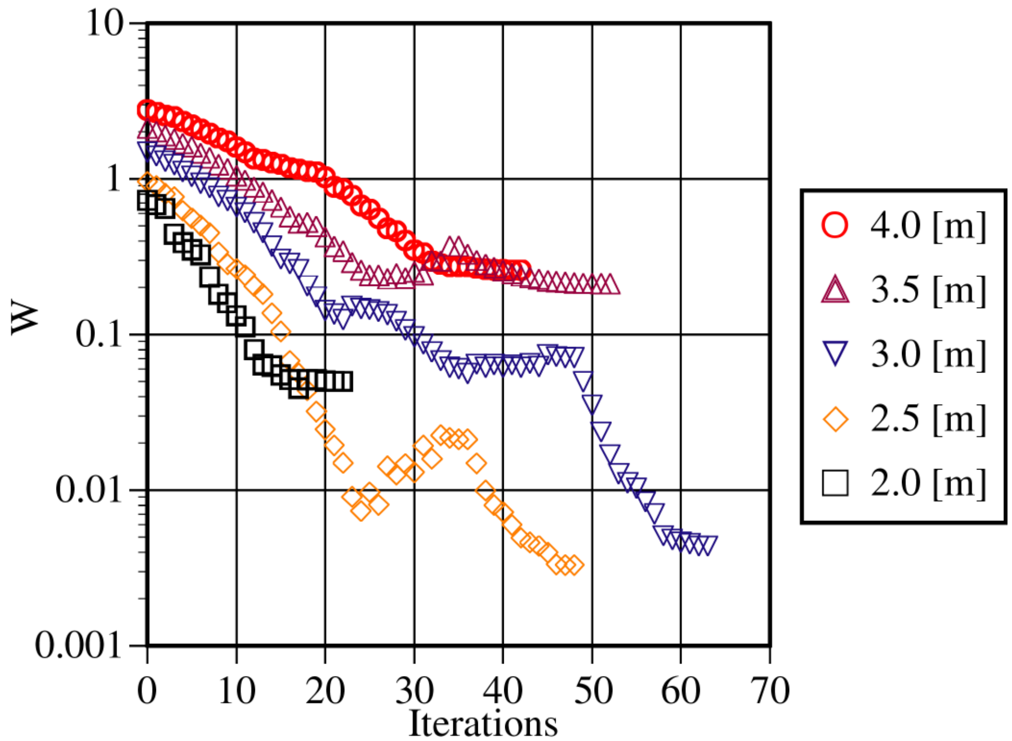
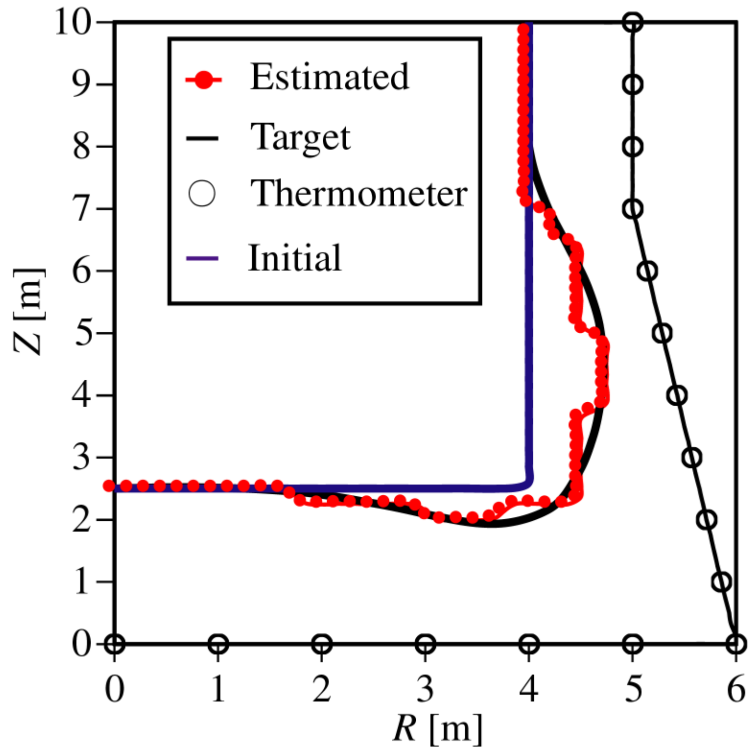
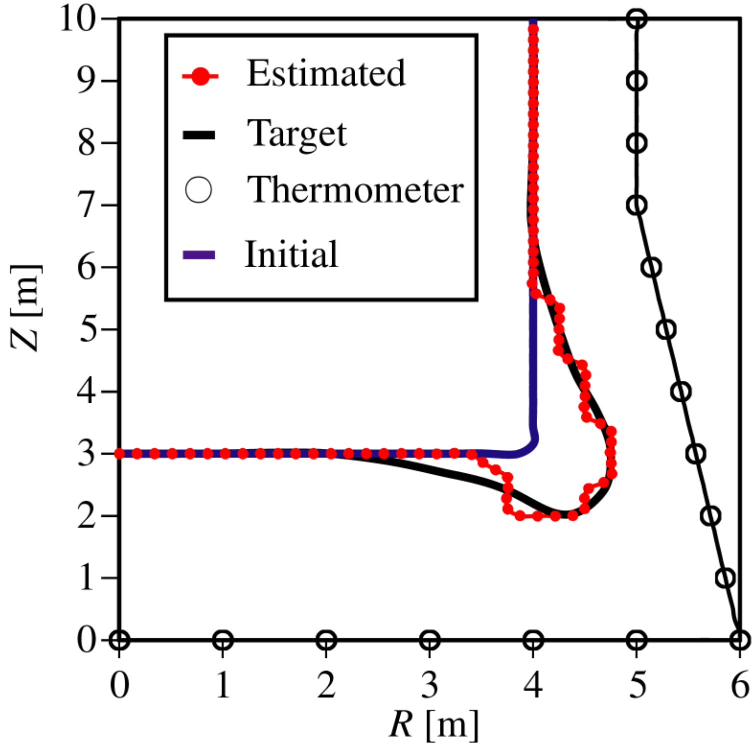
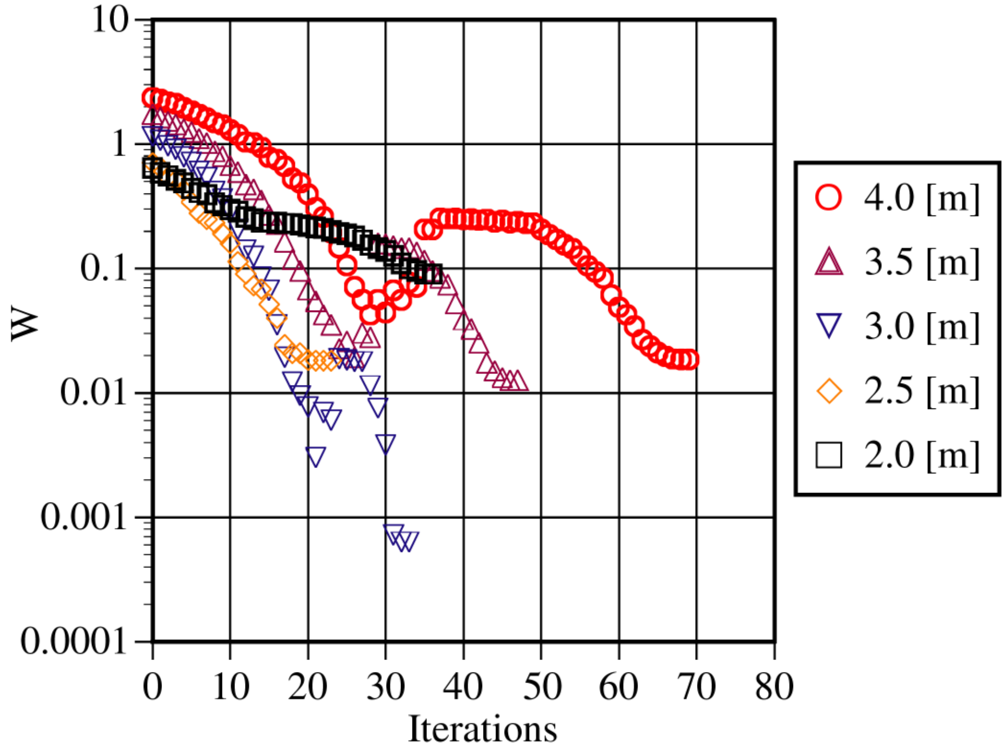




The initial shape with bottom height 2.5 m gives the minimum value of the cost function,which leads to the most plausible erosion line of the refractory brick.

Case (2)





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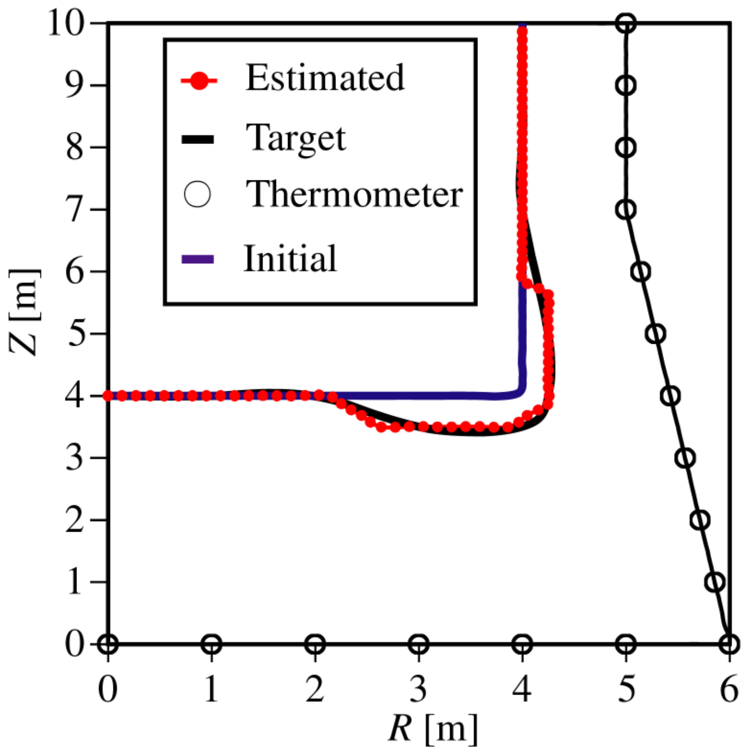
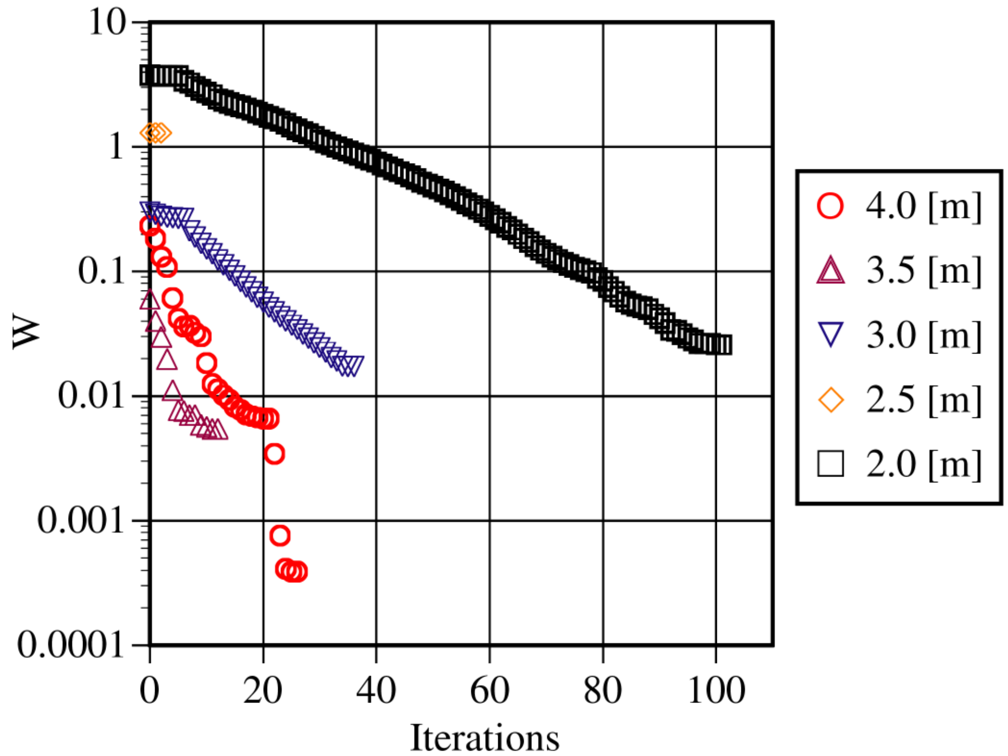
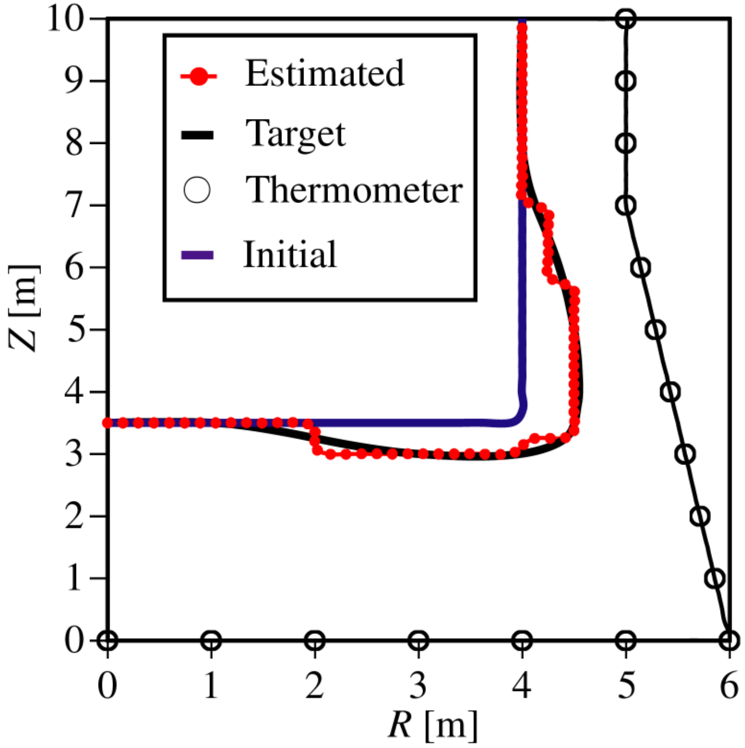
Case (3)

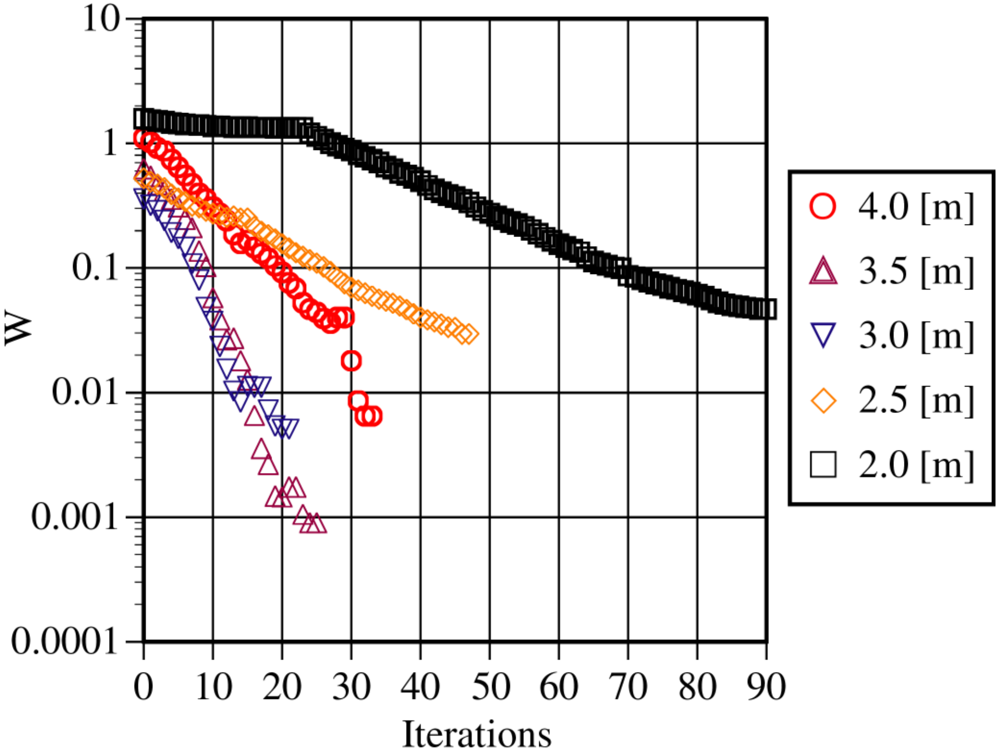




The initial shape with bottom height 4.0 m gives the minimum value of the cost function,which leads to the most plausible erosion line of the refractory brick.

Case (4)





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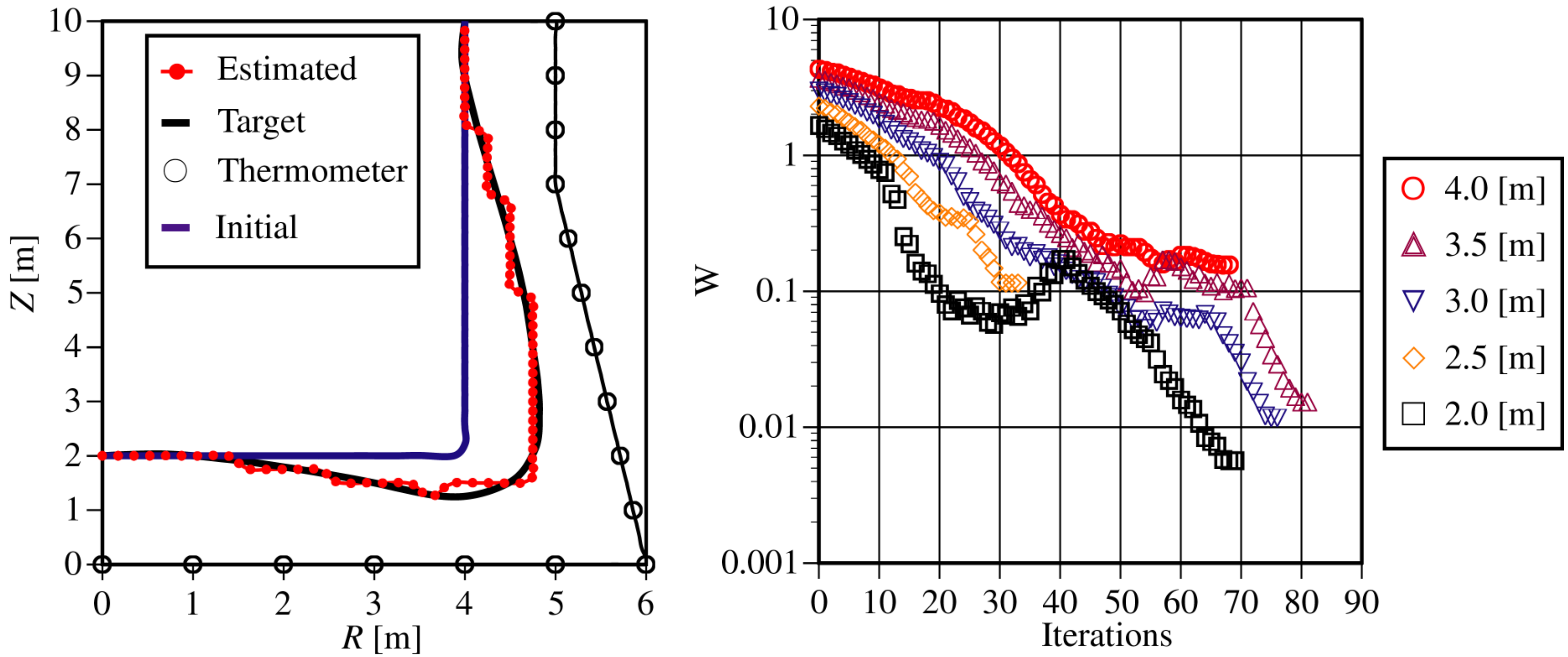
Case (5)



The initial shape with bottom height 2.0 m gives the minimum value of the cost function,which leads to the most plausible erosion line of the refractory brick.

Concluding Remarks

- **BEM and cellular automata were combined to estimate the erosion surface of refractory brick in blast furnace hearth.**
- **If *a priori* information is taken into account appropriately, successful estimation can be made through the present BEM-cellular inverse analysis.**
- **It is recommend to apply a sensitivity-based inverse analysis, such as the extended Kalman-filter, if a more accurate solution is required from the rough estimation via cellular automata.**
- **As future work, the present inverse analysis will be incorporated into an on-line monitoring system of the health conditions in a blast furnace.**

Thank you for your kind attention!