

# COMPUTATIONAL MODELING OF BLAST FURNACE COOLING STAVE BASED ON HEAT TRANSFER ANALYSIS

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**Abstract.** The three dimensional heat transfer and thermal stresses of a steel cooling stave in a blast furnace are modeled and analyzed. The temperature in a thermal stress field of cooling stave is calculated by using the finite element method software ANSYS. The radiation heat transmitted from solid materials (coke, ore, and flux) to inner surface of the cooling stave is neglected in the computational analysis. In this analysis two different types of lining materials are taken. These are the silicon carbide brick and high alumina brick. These lining materials are used at different loads, i.e., gas temperature from 773 K to 1573 K, as well as stave with skull is used at this gas temperature. Different assumptions and boundary conditions are taken in modeling as well as in analysis. Kinds of parameters are taken for the heat transfer analysis of cast steel cooling stave in a blast furnace. The water temperature is chosen as 303 K. The results indicate that the maximum temperature and thermal stress of hot face are highest in silicon carbide brick and lowest in high alumina brick. The peel stress and von Mises stress are calculated. The result indicates that the silicon carbide brick is better, so that it can withstand various circumstances which affect the life of the cooling stave and the blast furnace. Therefore the suitable lining for the stave is the silicon carbide brick.

## 1. Introduction

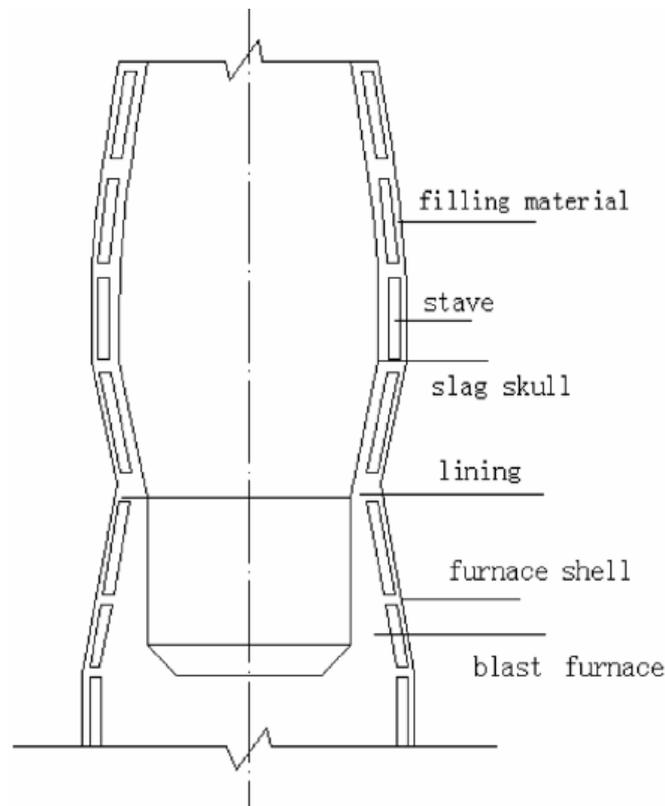
The blast furnace is a fundamentally vertical shaft varying in height from 24 to 33 meters with the diameter at the hearth of about 8.5 m. It is the most widely used iron making process. The total volume is more than 1400 cubic meters. The blast furnace has charging arrangements at the top and means of running off the pig iron and slag at the bottom. Air is blown near the bottom of the furnace, and this increases the speed of combustion and maintains the necessary higher temperature.

Damaged cooling staves are one of the main significant reasons that lead to a major overhaul or medium maintenance of a blast furnace. Therefore, cooling stave life is the key parameter for extending life of a blast furnace [1–9]. As ductile cast iron cooling staves cannot meet up the necessity of the stave life well, and the capital cost associated with a copper stave is also very higher than the cast iron one, there has been a bigger consideration for steel cooling stave with high specific elongation, tensile strength, melting temperature and thermal conductivity. There are many mathematical models describing the heat transfer

process of the cooling stave. Steiger [1] developed the heat transfer model to predict the temperature field of copper cooling plate and lining. Wang et al. [2] simulated the three-dimensional heat transfer model to describe the temperature field in the wall of the lower stack region of a blast furnace. Some researchers [3–11] in China have done some numerical simulations to calculate the temperature field of the cooling stave. However, these models apply only to copper or cast iron cooling staves, not to other cooling staves. Besides, only the temperature field has been considered in these models while the thermal stress field is not calculated. Therefore, these calculation results are unlikely to satisfactorily describe the damage of cooling stave which is mainly caused by thermal stresses changes within the cooling stave.

This paper describes a three-dimensional mathematical model of temperature and thermal stress fields for blast furnace steel cooling stave and lining. The effect of the different kinds of parameters on maximum temperature and thermal stresses of the stave hot surface has been considered.

The blast furnace is the equipment which produces molten iron. The blast furnace is shown in Fig. 1 schematically.



**Fig. 1.** Schematic view of blast furnace.

**1.1. Schematic diagram of the blast furnace.** This invention relates to a cooling installation for metallurgical units, the walls of which are subjected to thermic fluxes of elevated temperature and, more particularly, to the cooling of blast furnaces by means of stave coolers. Modern blast furnaces are increasingly utilized at such velocities and pressure levels that it is important to control the heat fluxes and their transfer, particularly in the zones of the bosh, the body, and the lower, mid, and upper shaft. In particular, in the case of self

supporting units, it is indispensable that the shell is not be affected by the temperature level and it is not be subjected to the variations in temperature which could lower the shell's resistance to the strains to which it is subjected.

The heat flux emitted in the different zones of the blast furnace must be collected by the heterogeneous system consisting of the lining, the cooling element, that is, the stave cooler, and the shell, such that the cooling element serves the double function of effective cooling of the lining and screening the passage of the flux towards the shell.

**1.2. Model of a cooling stave.** Cooling staves arranged against the internal face of the shell between this latter and the refractory coating fulfill a double function. The staves are made of cast iron, steel, copper elements having a network of tubes in which the cooling fluid circulates. The cooling fluid, in the prior art, is a water, and it is subjected to a vaporization upon contact with the heat flux which the stave cooler is to be absorb.

**Computational modeling of the blast furnace cooling stave.** The main aim of the study is to analyze the behavior of lining material at different loads through heat transfer analysis by finite element method software called ANSYS [12].

In this study two different types of bricks like silicon carbide brick and high alumina bricks are taken for the lining material of the blast furnace cooling stave as well as two different types of skull are considered, in which first has negligible (without) thickness and the other one has certain thickness in mm. So with these two skulls, the heat transfer analysis is made at different temperatures (loads) from 773 K to 1573 K to compare which lining gives the better result than the other.

Some assumptions are taken in the modeling as well as in analysis part. In modeling, the upper edge and lower edge of the stave are fixed; and in analysis the assumptions like steady state conductive heat transfer process, no heat transfer between linings, stave, filling material, and furnace shell are used.

Pro-E is used for the modeling [13] and ANSYS is used for simulation. The results in the form of temperature plots are taken for different sections of the model. On the base of the temperature values from the temperature contour plots, coupled field analysis is done for thermal structural calculations to check the bulging (expansion) in the model as well as to check the failure of the model at higher temperatures (loads). The peel stress, shear stress, von Mises stress are calculated. By considering all values of stresses, temperatures, temperature-structural analysis comparison is done in both the linings.

## 2. Modeling and analysis

The biggest heat load (thermal zone) of the blast furnace is concentrated within the lower stave region of the blast furnace with intensified smelting. Cooling stave is one of the most important reasons that bring in major repair and maintenance of a blast furnace. Therefore, cooling stave life is a key parameter for the life of the blast furnace. Figure 2 demonstrates the smelting process as well as the arrows showing process after smelting. The body of the blast furnace is of steel. For the cooling stave we took cast steel. Cast steel is used because life of a cast iron cooling stave is too short and copper cooling staves capital cost is too high.

Some positives of using cast steel are like high specific elongation, tensile strength, melting temperature, thermal conductivity.

Now, coming to the process inside the blast furnace. Initially the huge blast of fuel gases comes from the tuyere. PCI is injected through the lance of the tuyere and air is blow through the bustle pipe. The combustion takes place in the raceway region of the blast furnace as shown in the Fig. 2. After that, the huge blast goes to the bosh region where the coke, flux, and ore come from the top (bell valve region). Smelting takes place in the bosh region (smelting region). After the smelting process, molten iron goes to the hearth portion and the combustion gases attack the wall of the blast furnace. Because slag has low density it comes

over the hearth portion and settles down or forms a layer over the surface of the wall of the blast furnace.

Cooling staves are placed along the periphery of the blast furnace wall. Each cooling stave faces with different loads like near to the bell valve (top). Cooling stave faces with low temperature as compare to the stave which is placed near to the smelting region. So each stave is considered separately because the biggest heat load of a blast furnace is concentrated within the lower stave region because of the smelting process.

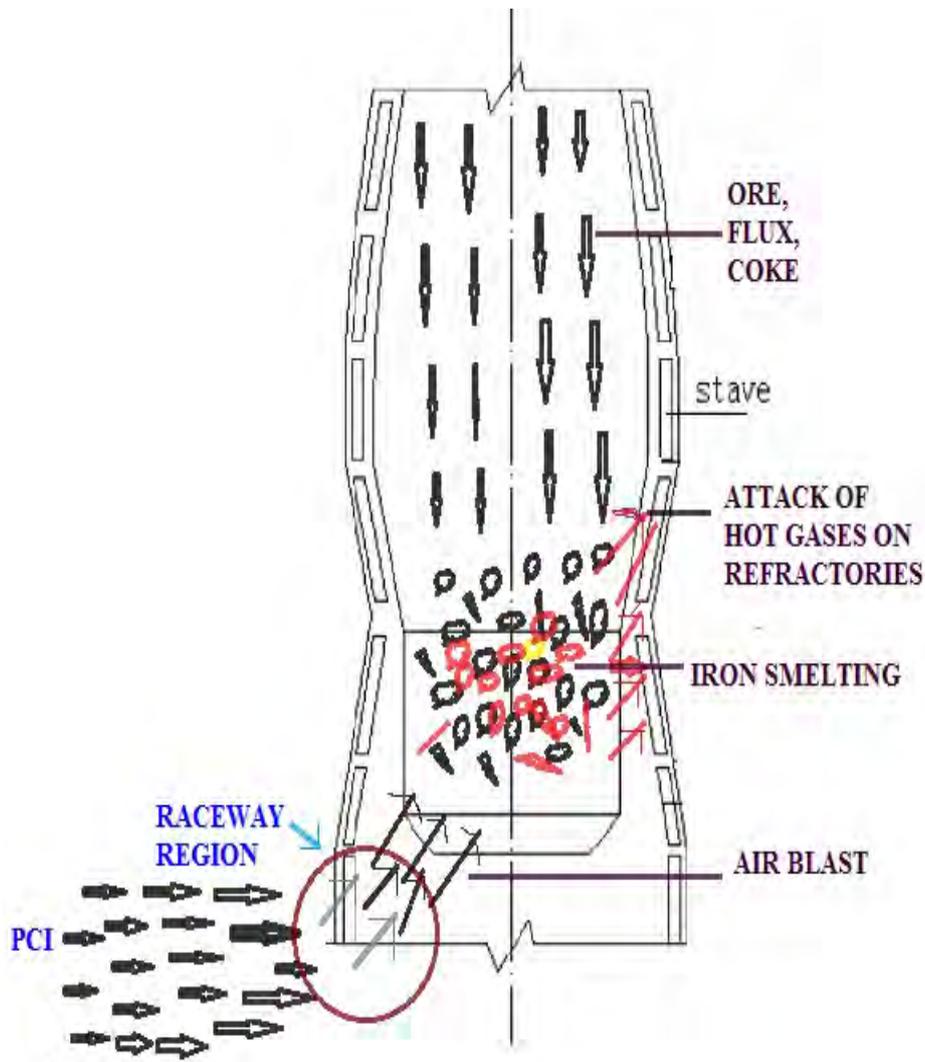
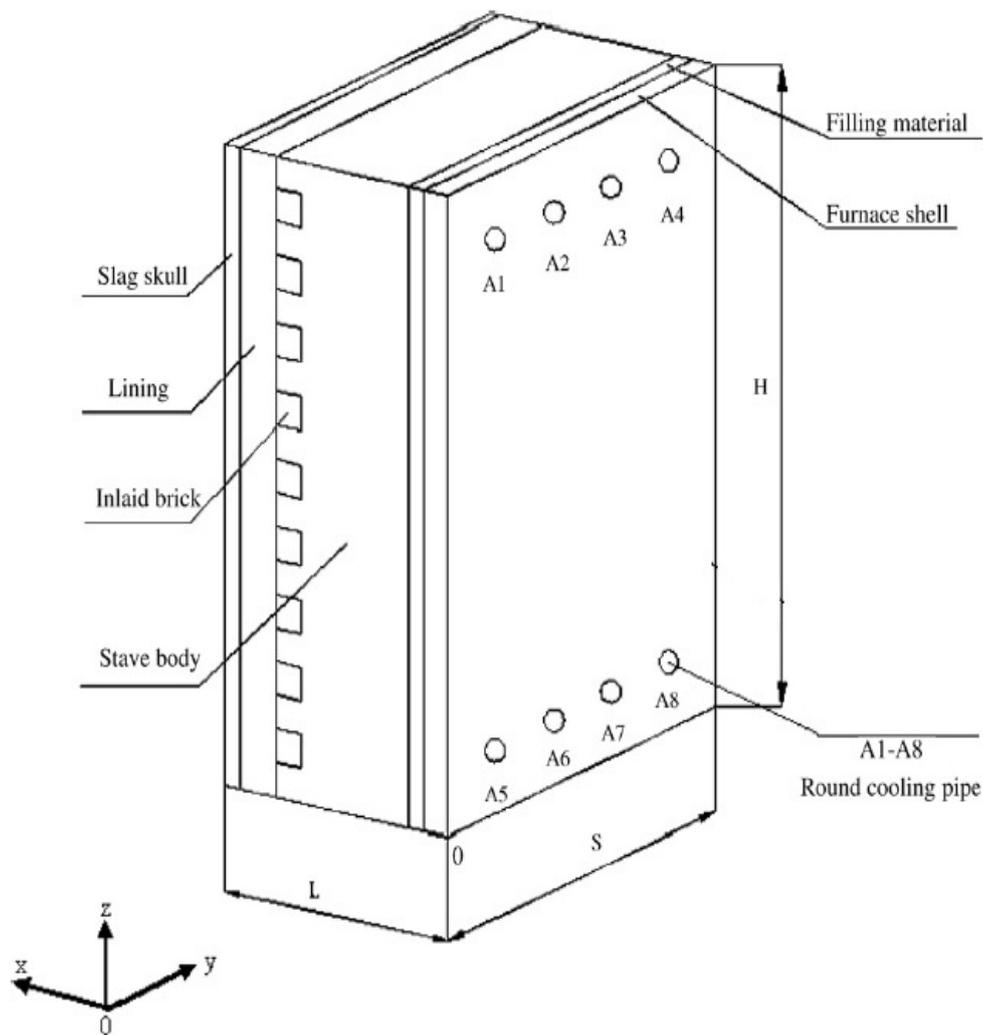


Fig. 2. Introduction to the problem.

Now, in this study of cooling stave 5 different loads are considered from 773 K to 1573 K. The water temperature is taken as 303 K, and the parameters related to the modeling and the analysis will be discussed in the below section.

**2.1. Modeling of the blast furnace cooling stave.** In the above Fig. 3 along with the cooling stave, some linings are presented like refractory lining which faces with the hot gases, 9 inlaid bricks, filling material, and furnace shell. Few holes are shown. These holes represent the cooling pipes, so 4 cooling pipes are connected. Design parameters of the blast furnace cooling stave are shown in Table 1.



**Fig. 3.** Cooling stave with linings.

Table 1. Design parameters.

<b>Part</b>	<b>Length</b>	<b>Width</b>	<b>Height</b>
Furnace shell	10	718	1400
Filling material	8	718	1400
Stave body	180	718	1400
Inlaid bricks	70	718	70
Lining	100	718	1400
Slag skull	42	718	1400
<b>Part</b>	<b>Diameter, mm</b>	<b>Length, mm</b>	<b>Numbers used</b>
Cooling channel ( pipe)	50	200	4
<b>Part</b>	<b>Volume, mm x mm x mm</b>		<b>Numbers used</b>
Inlaid bricks	70 x 718 x 70		9
<b>Part</b>	<b>Volume, mm x mm x mm</b>		
Blast furnace cooling stave	340 x 718 x 1400		

**2.2. Analysis.** In analysis of cooling stove the various conditions were considered.

Table 2. Materials selection.

Part	Material
Lining	Case 1: high alumina bricks Case 2: silicon carbide bricks
Stave body	Cast steel
Inlaid bricks	Silicon carbide

Table 3. Materials properties [6].

Properties Part	Density, kg/m <sup>3</sup>	Ther. cond., W/(m °C)	C <sub>p</sub> , J/(kg °C)	Young's modulus, Pa	Poisson ratio	Coeff. of lin. exp., 1/°C
Furnace shell	7840	52.2-.25t	465	1.7x10 <sup>11</sup>	0.3	1.06x10 <sup>-5</sup>
Filling material	330	.35	876	2.1x10 <sup>10</sup>	0.1	4.7 x 10 <sup>-6</sup>
Stave body	7800	52.2-.25t	500	1.7x10 <sup>11</sup>	0.3	1.06x10 <sup>-5</sup>
Inlaid bricks	2400	21-.009t	963+.147t	2.1x10 <sup>10</sup>	0.1	4.7 x 10 <sup>-6</sup>
Slag skull	2000	1.2	983	2.1x10 <sup>10</sup>	0.1	4.7 x 10 <sup>-6</sup>
Lining material (alumina)	2750	2.09+.002t	1310.4	1.65	0.25	7.8x10 <sup>-6</sup>
Lining material (SiC)	2400	21-.009t	963+.147t	2.1x10 <sup>10</sup>	0.1	4.7 x 10 <sup>-6</sup>

**Assumptions:**

- Formation of skull is considered.
- Steady state conductive heat transfer process.
- Heat transfer between lining, stave, filling material, furnace shell are not considered.
- Heat radiation heat transmitted from solid materials (coke and ore) to inner surface of the stave is neglected.

**Loads and boundary conditions for thermal and structural calculations:**

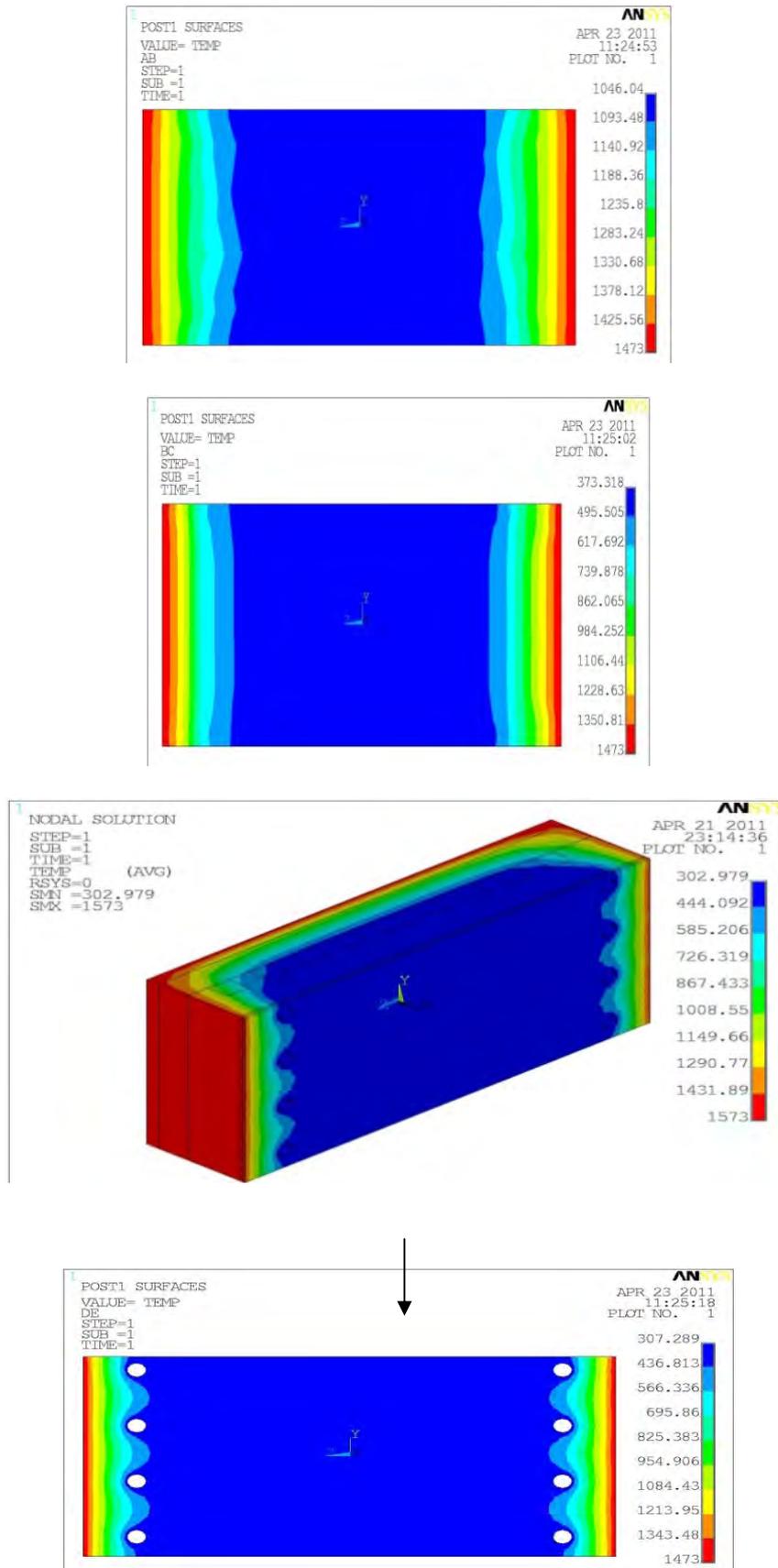
- Air temperature is 323 K, water temperature is 303 K.
- Heat convection coefficients: between furnace shell and atmosphere - 12 W/(m<sup>2</sup> K), between water and inner sides of the furnace shell - 8000 W/(m<sup>2</sup> K),

Table 4.

Temperature, K	Heat convection coefficient (h), W/(m <sup>2</sup> K)
1273	232
1473	240
1673	250
1873	260

- Different loads applied on the hot face of cooling stove: 773 K, 973 K, 1173 K, 1373 K, 1573 K.

Few thermal results for *with skull model* at the load 1573 K are shown in Figs. 4, 5.



**Fig. 4.** Contour profile for *with skull model* at 1573 K.

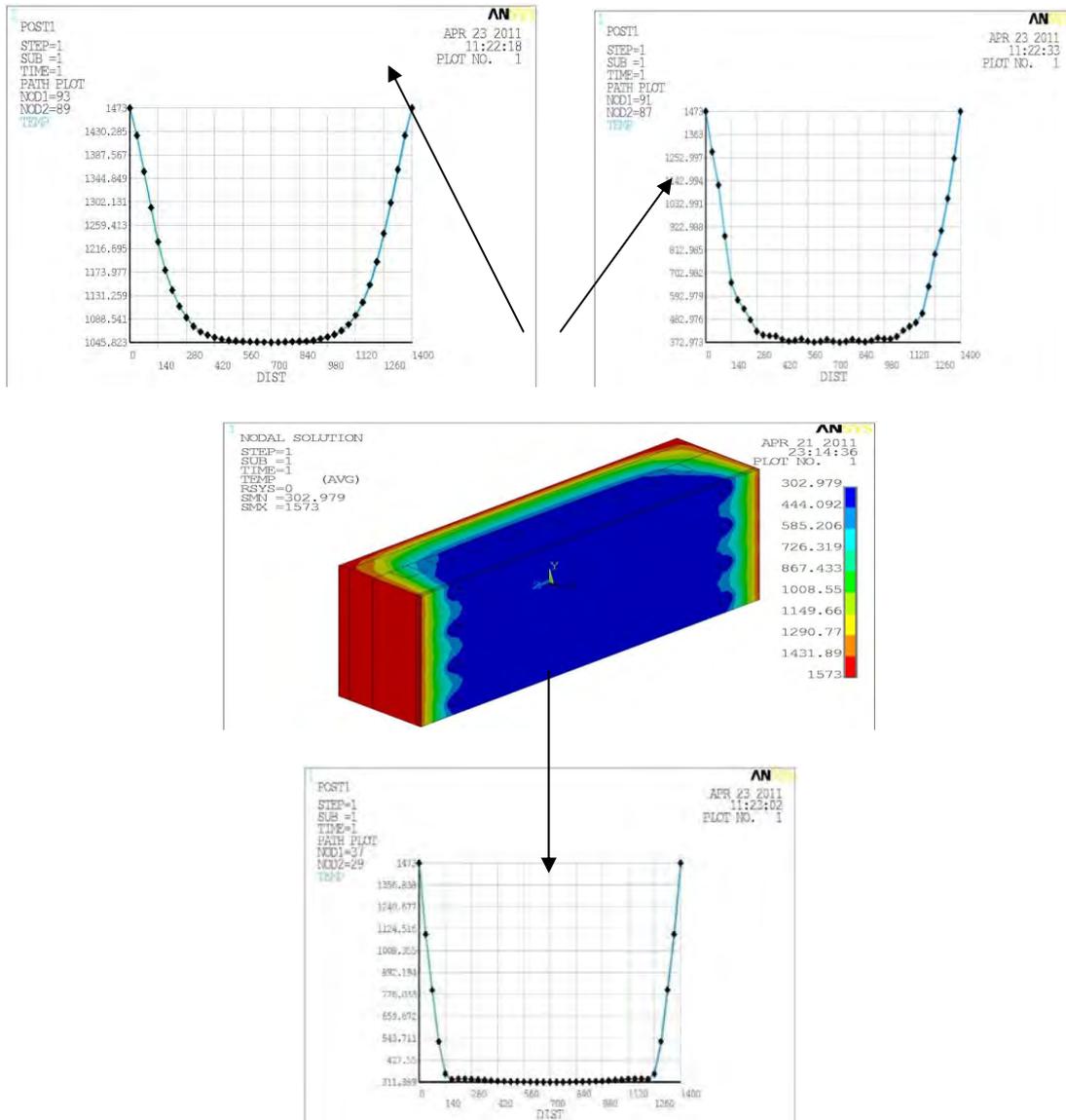


Fig. 5. Graphical plot for with skull model at 1573 K.

**Thermal structural analysis.** Basically, thermal structural analysis is an indirect process; in this the values are taken from the thermal calculations directly. The next diagram in Fig. 6 shows the thermal structural analysis.

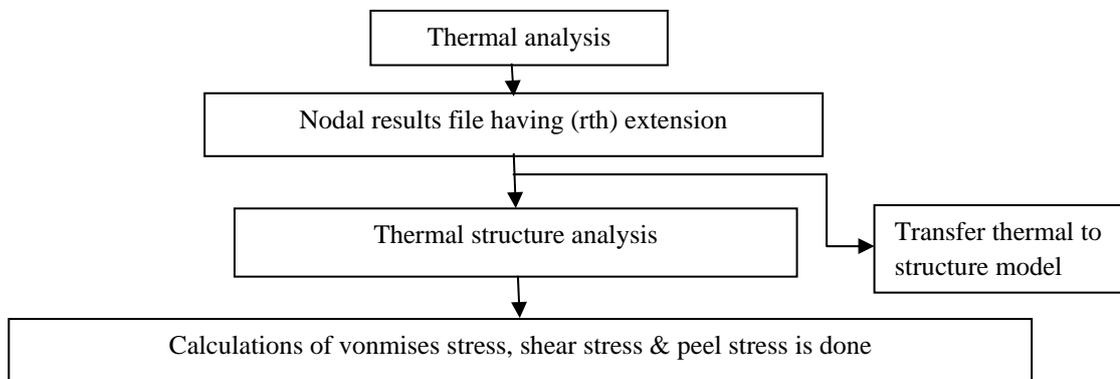


Fig. 6. Flow chart of thermal structural analysis.

After taking the temperature values, the first thing is to define boundary conditions for the structural analysis. The node point is to be defined. After defining the nodal values, temperature is applied on this nodal points as well as load is applied on that particular face. After that final process is to obtain the result from post processing. The results are in the form of contours and graphs of peel stress, von Mises stress, and shear stress.

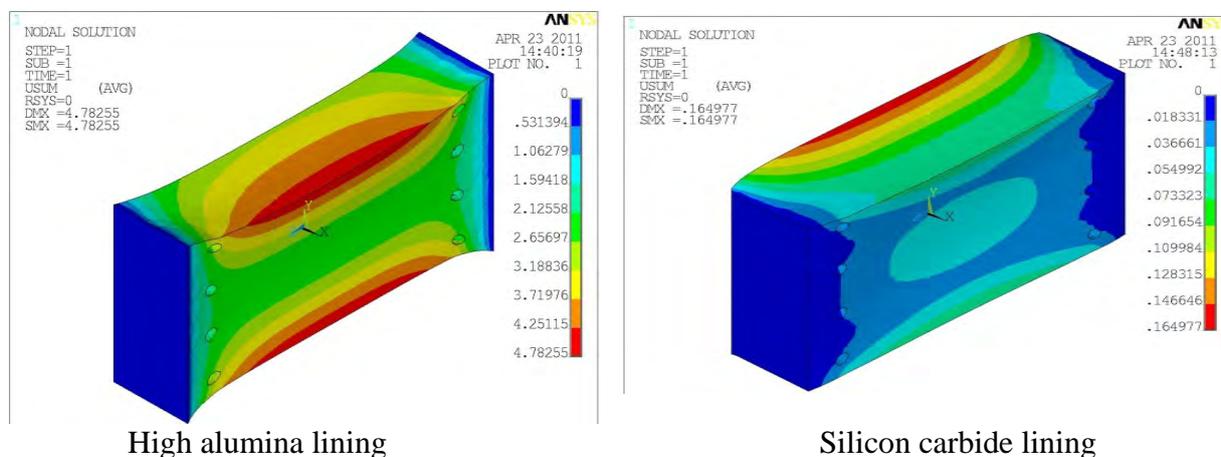
In an elastic body that is subject to a system of loads in 3 dimensions, a complex 3 dimensional system of stresses is developed. That is, at any point within the body there are stresses acting in different directions, and the direction and magnitude of stresses change from point to point.

There are three "principal stresses" that can be calculated at any point, acting in the x, y, and z directions. (The x, y, and z directions are the "principal axes" for the point and their orientation changes from point to point, but that is a technical issue.)

Von Mises found that, even though none of the principal stresses exceeds the yield stress of the material, it is possible for yielding from the combination of stresses.

Von Mises criterion is the formula for combining these 3 stresses into an equivalent stress, which is then compared to the yield stress of the material. The yield stress is well known property of the material, and it is usually considered as the failure stress.

The equivalent stress is often called the "von Mises stress" as a shorthand description. If the "von Mises stress" exceeds the yield stress, then the material is considered to be at the failure condition.



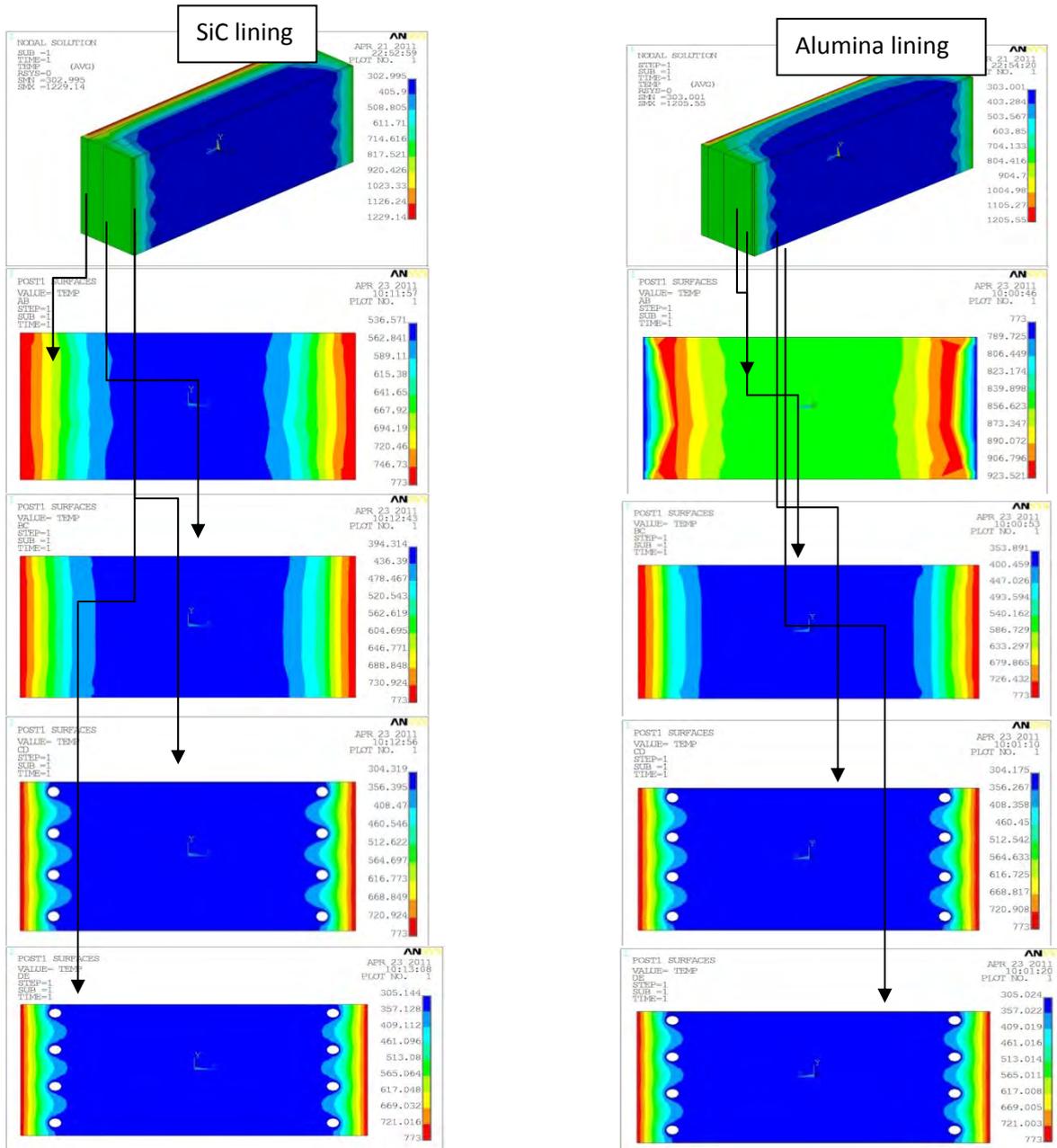
**Fig. 7.** Displacement contours of high alumina and SiC linings at 1573 K.

### 3. Results and discussion

Results deals with the various graphical and contour plots of thermal analysis made for the cooling stove. Various contour plots and graphical plots related to displacements, von Mises stress, peel stress, shear stress in the hot face of the stove are determined across all the four planes, i.e., linings. These contour plots are analyzed and discussed.

Below figures shows the contour and graphical plots of thermal analysis for *with skull model* and *without skull model* of alumina and silicon carbide lining at different loads. In Fig. 8 thermal contours for *with skull model* at 773 K are shown. All four planes have separate

profiles and the temperature variations at each profile are different. As it is displayed in Fig. 8 at 773 K load the high temperature achieves 923 K in the alumina lining and the temperature is nearly to 750 K in SiC. At 1173 load (Fig. 9), in SiC lining most of the region has temperature from 842 to 859 K, but in alumina the temperature is around 539 K. When we approach the high load (Fig. 10), i.e., 1573 K, the SiC lining temperature in the corner is between 1458 K and 1573 K, and in aluminum, it is about 1428-1473 K.



**Fig. 8.** Thermal contour plots of SiC and alumina linings at 773 K.

Figure 11 shows the thermal contours of *without skull model* at lower load condition. In SiC lining the temperature range is 440 - 484 K and in alumina lining the temperature range is 334-350 K. At higher load condition, i.e., at 1573 K (Fig. 12), the range of alumina lining is 386-422 K but in SiC it is quite high and it is in the range 1487-1508 K.

Figures 13–18 are the graphical plots.

At load 1173 K in alumina lining the curve decreases gradually w.r.t. distance and in the second plane the fluctuation is quite high, the most temperature range is between 353-365 K, but the SiC graph is stable, i.e., the curve is smooth.

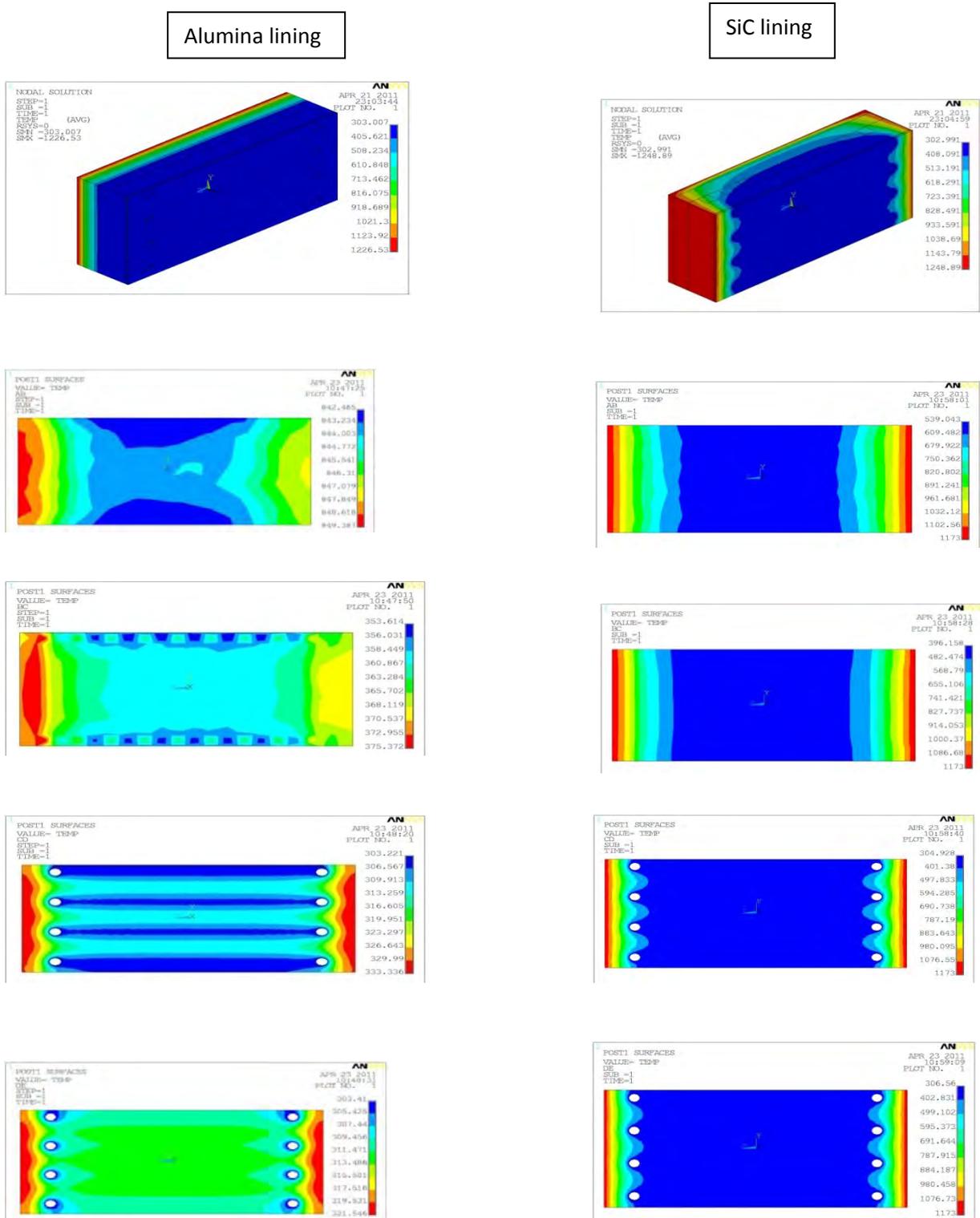


Fig. 9. Thermal contours at 1173 K.

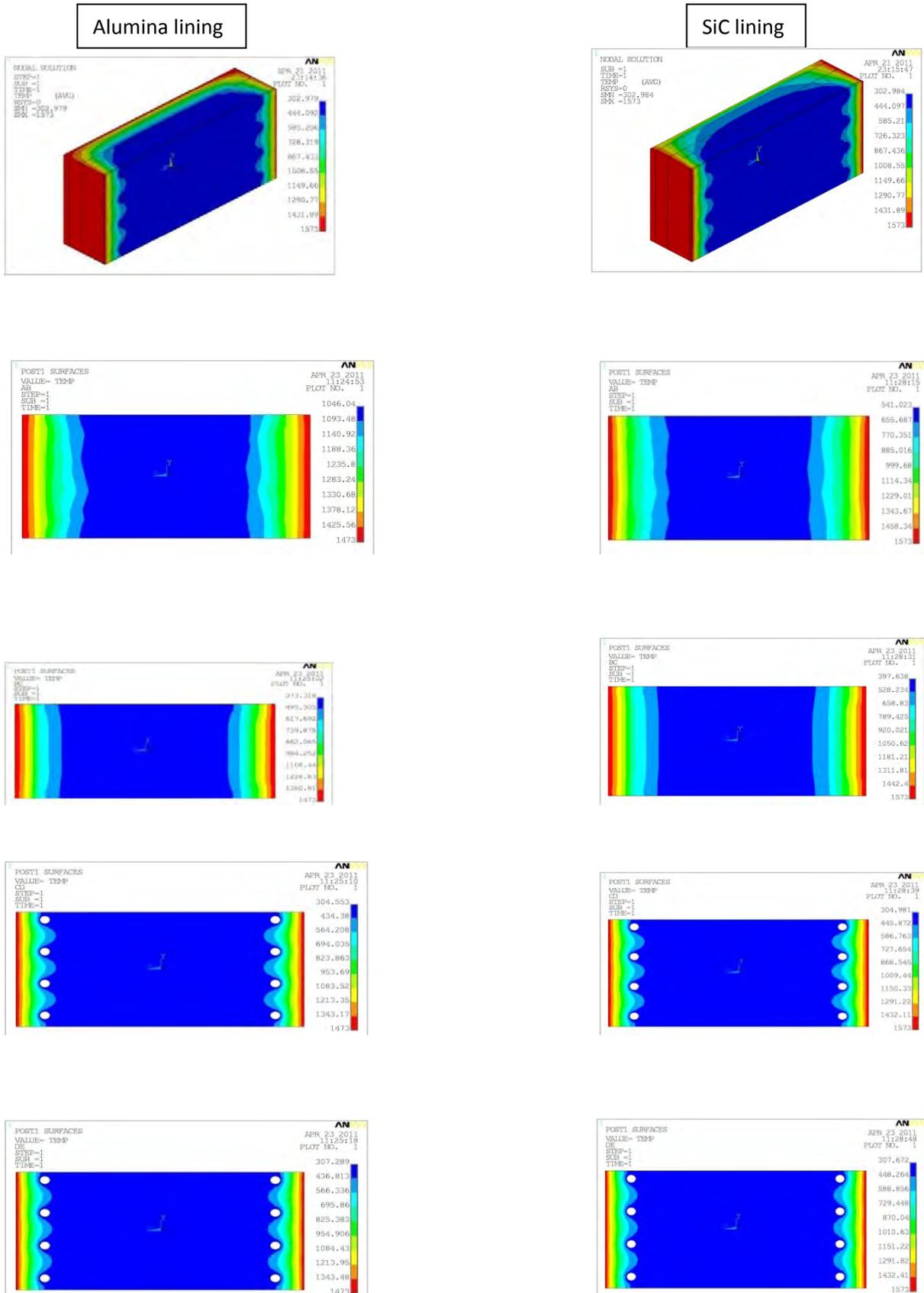


Fig. 10. Thermal contours at 1573 K.

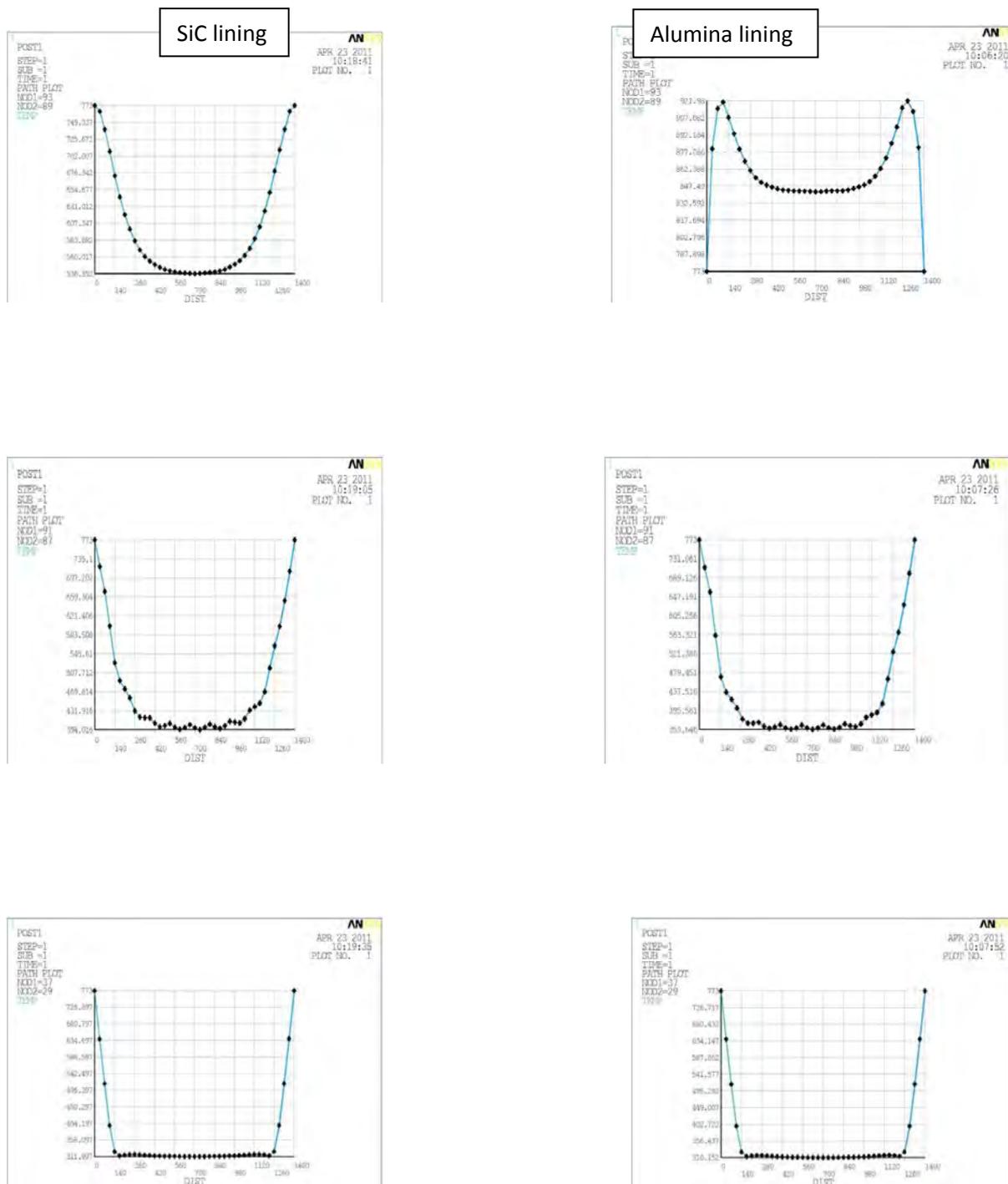


Fig. 11. Graphical plots for *with skull model* at 773 K.

Alumina lining

SiC lining

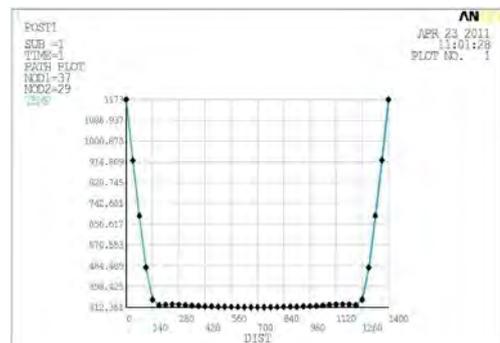
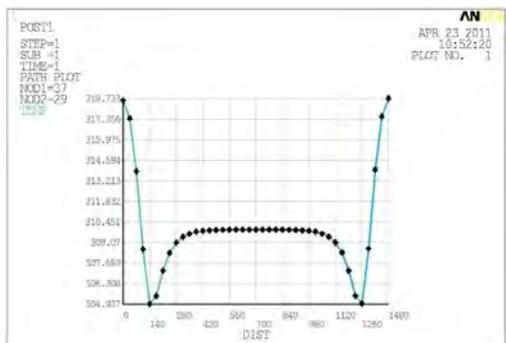
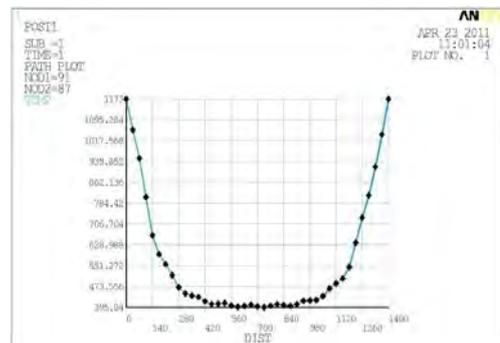
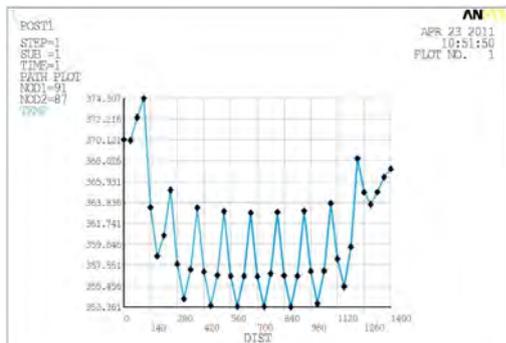
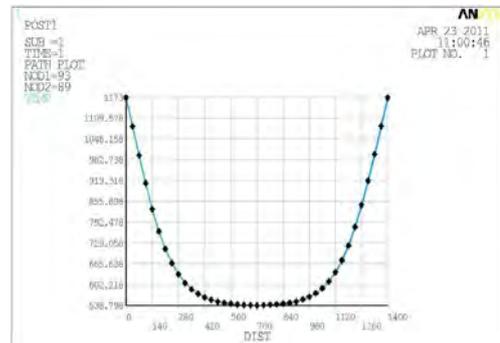
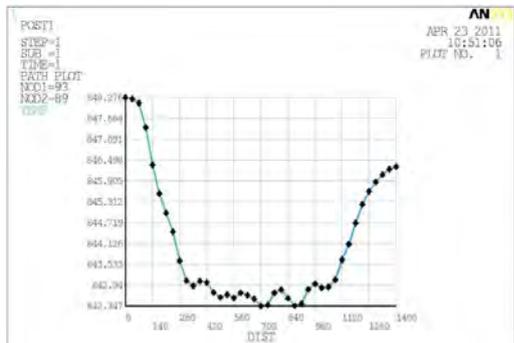


Fig. 12. Graphical plots for with skull model at 1173 K.

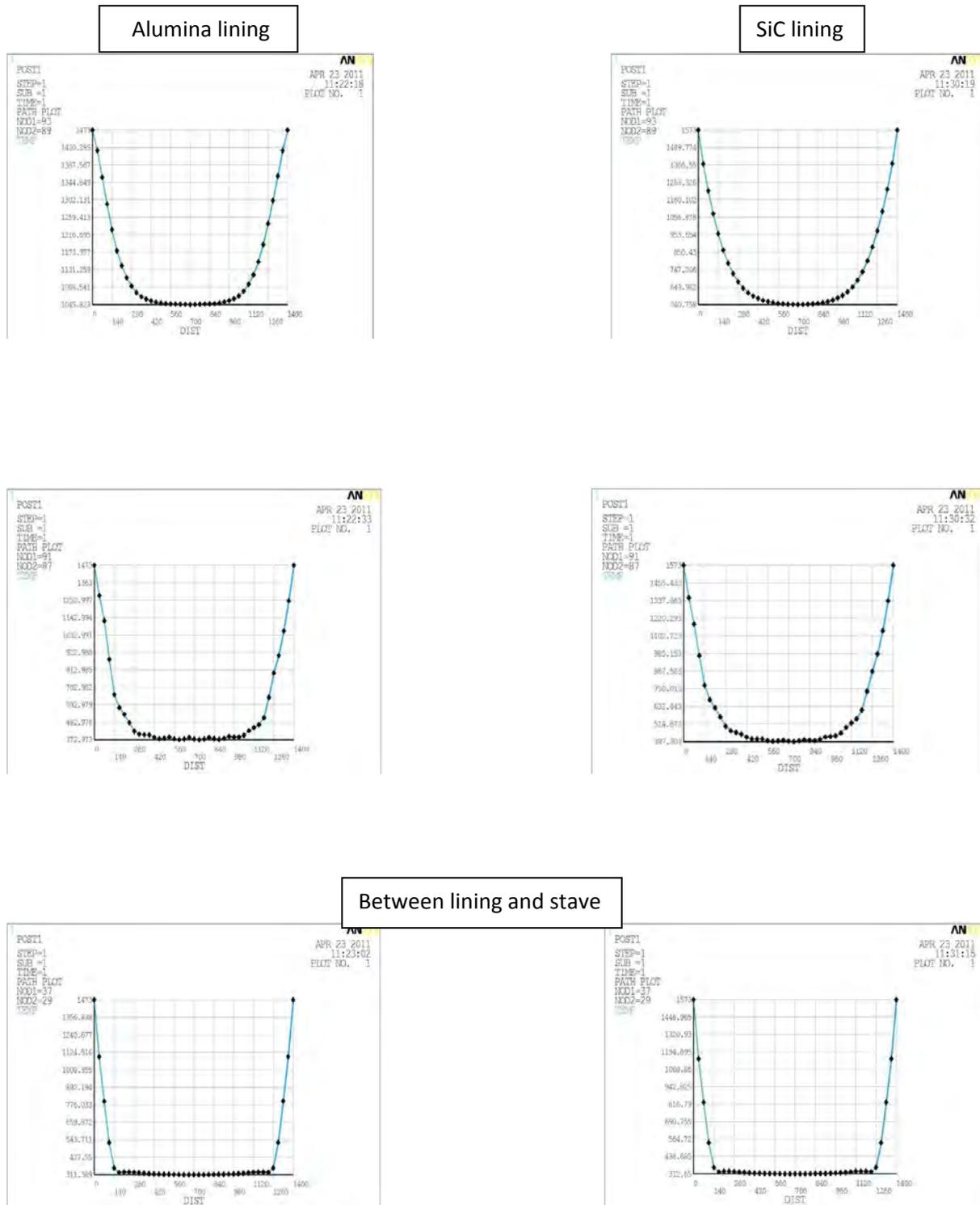


Fig. 13. Graphical plots for *with skull model* at 1573 K.

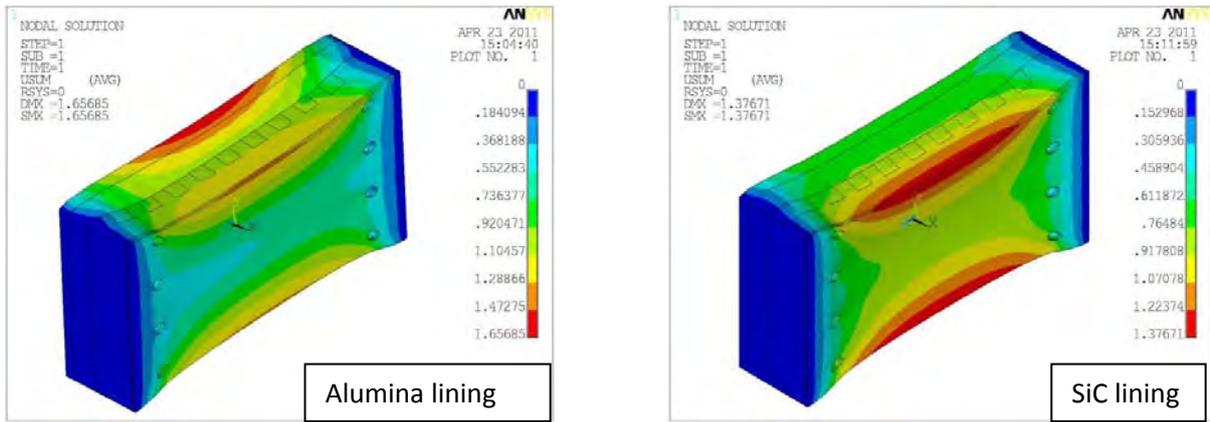


Fig. 14. Contour plots of displacements for with skull model at 773 K.

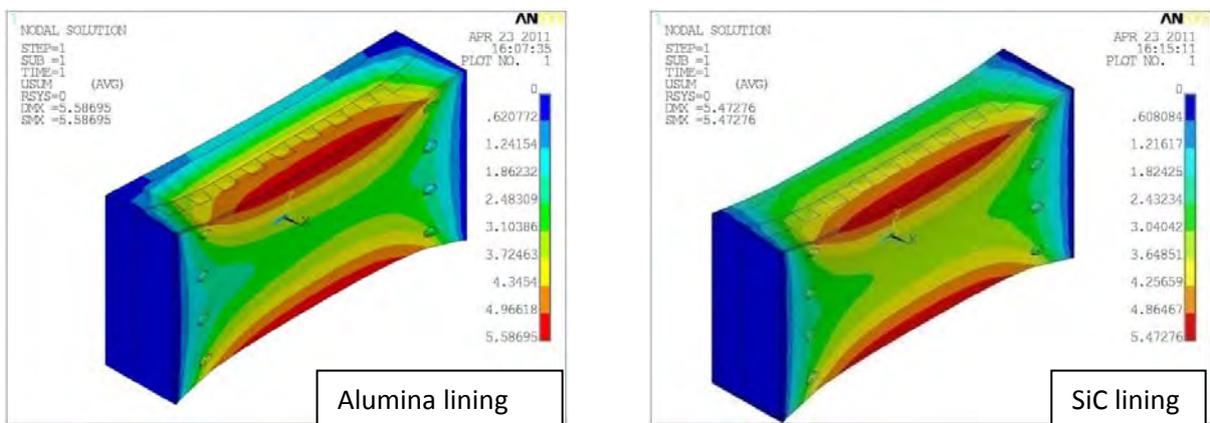


Fig. 15. Contour plots of displacements for with skull model at 1573 K.

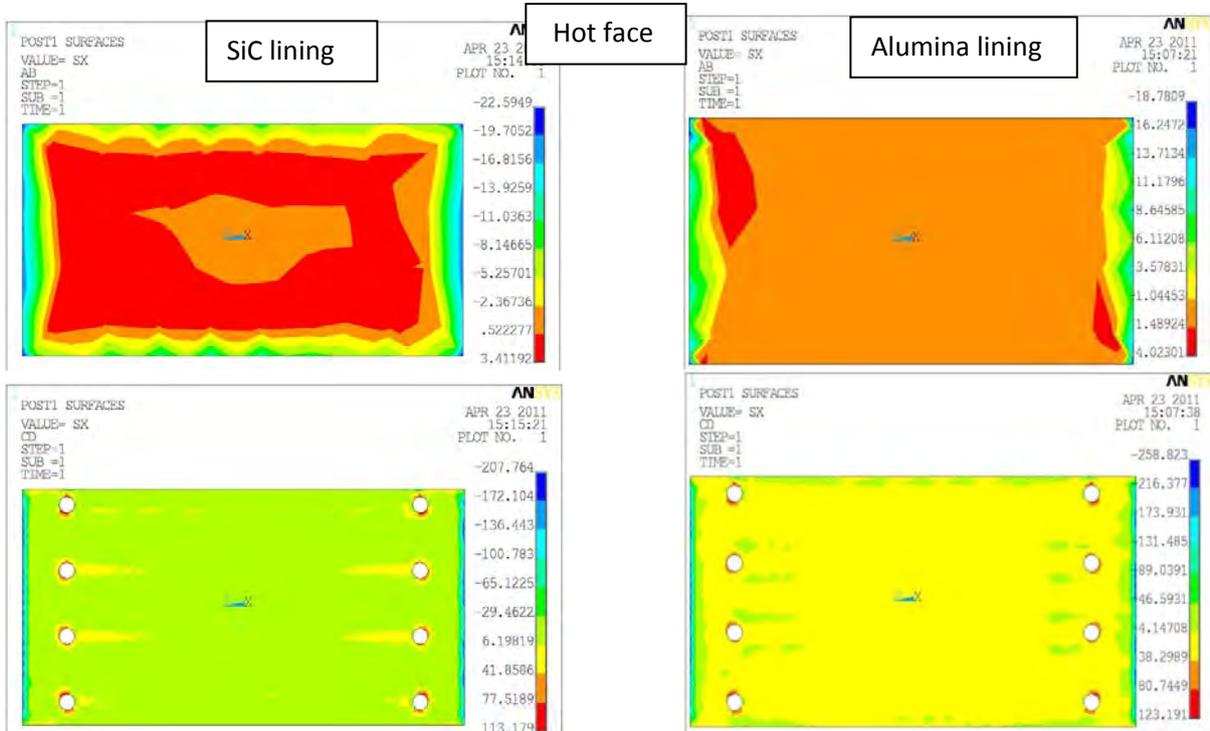


Fig. 16. Contour plots of peel stress for with skull model at 773 K.

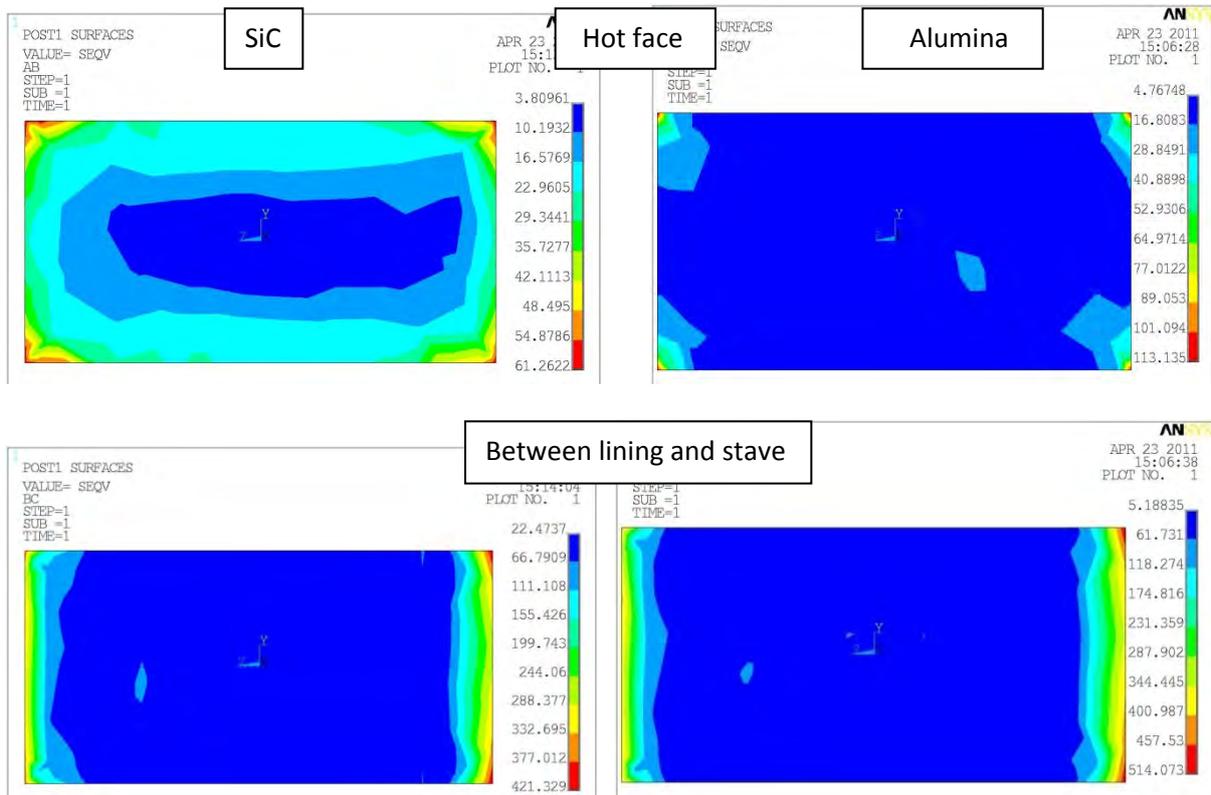


Fig. 17. Contour plots of von Mises stress for with skull model at 773 K.

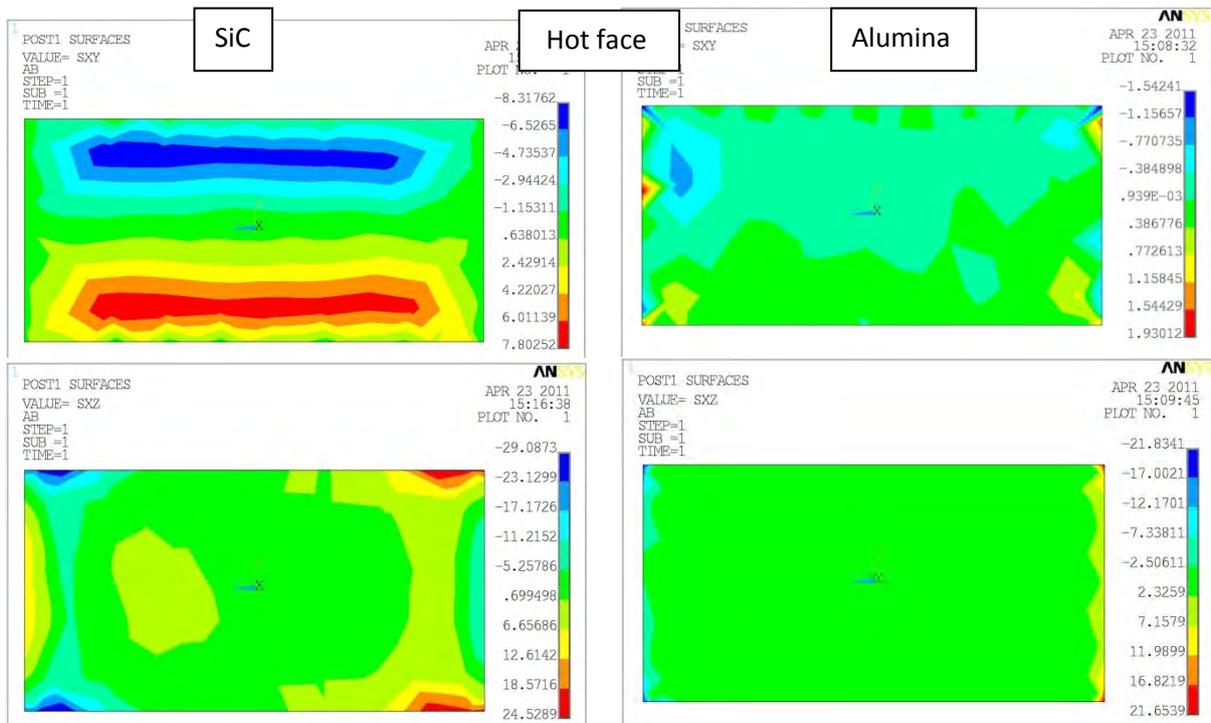


Fig. 18. Contour plots of shear stress for with skull model at 773 K.

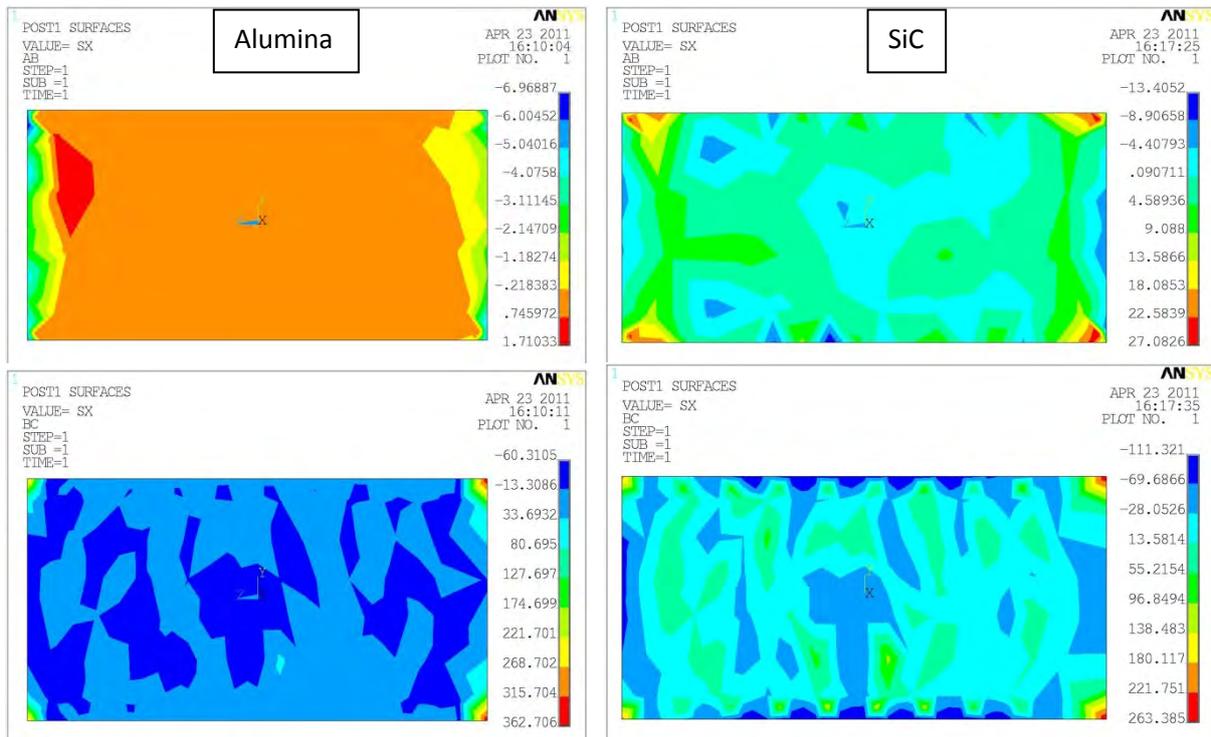


Fig. 19. Contour plots of peel stress for *with skull model* at 1573 K.

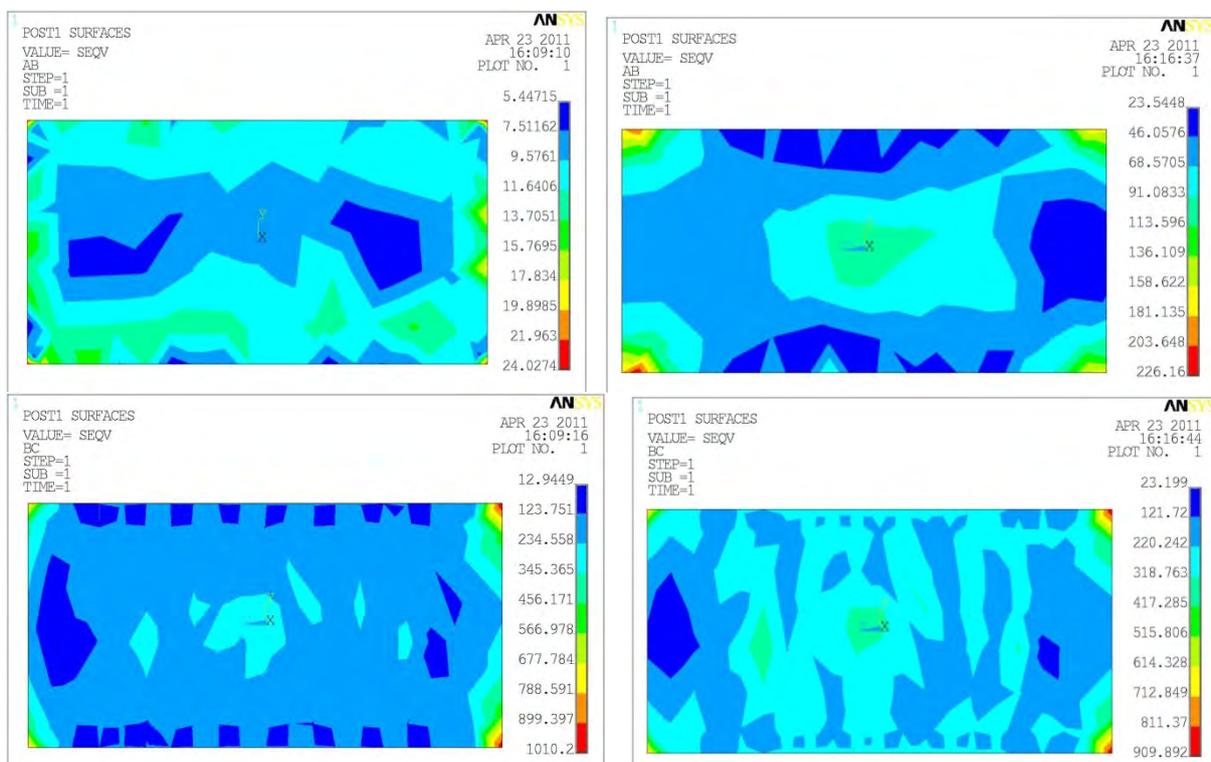


Fig. 20. Contour plots of Von Mises stress for *with skull model* at 1573 K.

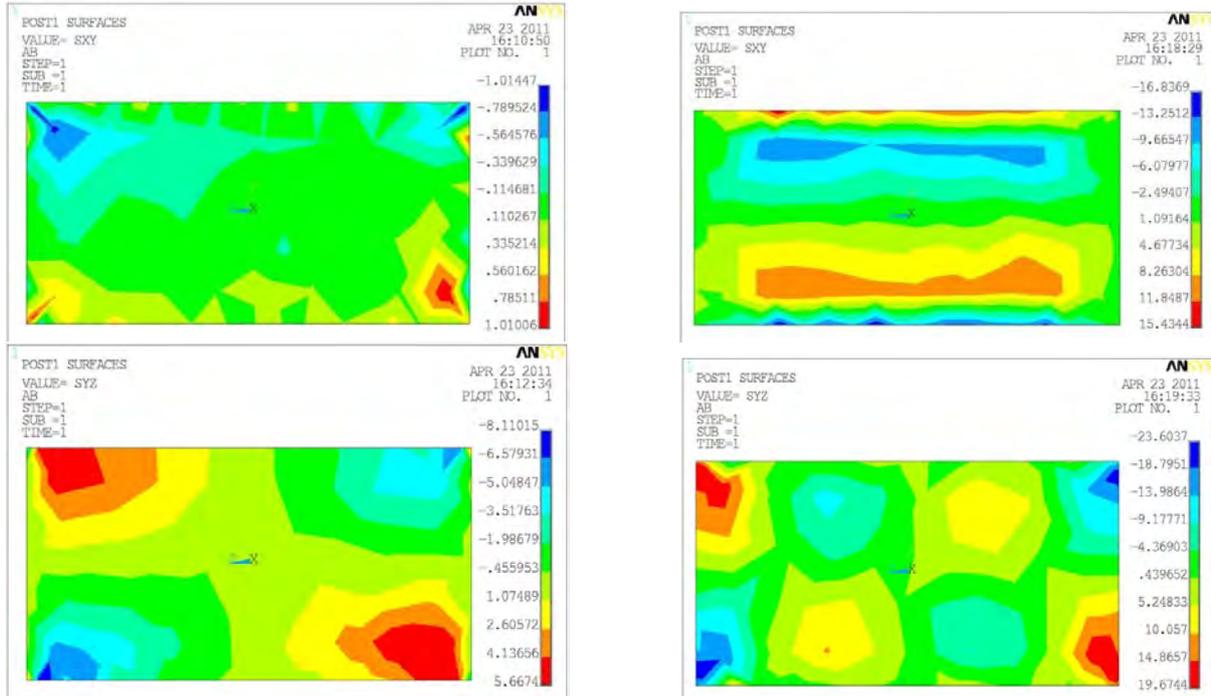


Fig. 21. Contour plots of shear stress for with skull model at 1573 K.

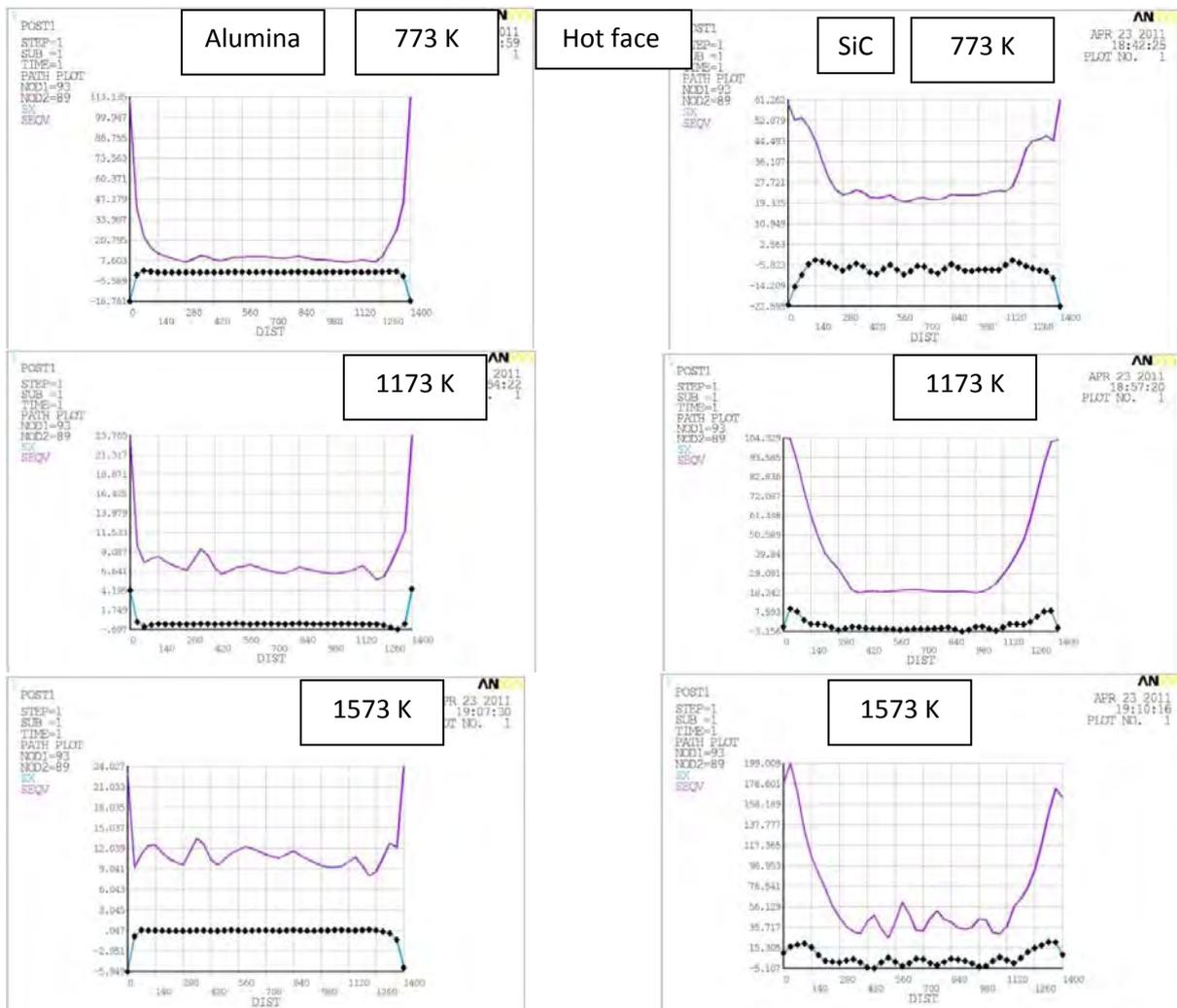


Fig. 22. Graphical plots of peel and von Mises stresses for with skull model.

#### 4. Conclusions

In this simulation process, few conclusions have been made.

In case of *with skull model*:

1. At higher loads, i.e., at 1573 K, maximum temperature achieved in alumina is 1473 K and the temperature range in output is between 1046 K and 1473 K, whereas in case of SiC maximum temperature is close to 1570 K and the temperature range in output is between 541 K and 1573 K.

Hence the maximum temperature in the hot face of SiC lining is higher than in alumina lining.

Some advantages are following:

- Melting of slag and iron is high in SiC lining.
  - Impact of blast furnace charge is high in SiC lining.
2. At 773 K maximum displacements are 1.65 mm in alumina and 1.35 mm in SiC. At 1573 K maximum displacements are 5.58 mm in alumina and 5.4 mm in SiC.
  3. It shows that, the expansion rate in the alumina lining is more than in SiC lining.
  4. At 1573 K, von Mises stress in alumina lining is in the range of 23 MPa - 230 MPa and in SiC it is 24 MPa.

From these observations we can conclude that at higher load the stress value of alumina lining crosses the value of steel ultimate strength value. So, failure takes place at higher load condition.

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