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Evaluation the effects of Steam state equation, Spray and multi-cell subdivisions on Containment pressurization modeling in a LB-LOCA

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Abstract:

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Obj

Since the inception of nuclear power as a commercial energy source, safety has been recognized as a prime consideration in the design, construction, operation, maintenance and decommissioning of nuclear power plants. The release of radioactivity to the environment requires the failure of multiple safety systems and the breach of three physical barriers; fuel cladding, reactor cooling system and the containment. In this study nuclear reactor containment pressurization has been modeled in a Large Break Loss of Coolant Accident (LB-LOCA) and the effects of some main parameters on the modeling have been studied. First of all, containment has been considered as a control volume (single-cell model) and effects of steam state equation and spray (as a safety system in the containment accidents) have been studied on the model and results. In the second step, single-cell model has been developed to a multi-cell model to consider the effects of the nodalization and spatial location of cells in the containment pressurization in compared to single-cell model. Finally Bushehr Nuclear Power Plant (BNPP) containment has been considered as case study. Results of BNPP containment pressurization due to LB-LOCA have been compared between models and FSAR. Effects of Steam state equation, spray and multi-cell subdivisions have been considered in the results.

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Keywords: Containment pressurization; Single-cell model; Multi-cell model, Steam state equation; Spray effect.

PE: Poor English.

SC: Sentence(s) very confusing.

Nomenclature

A	*Area*	x	*Quality*
C_p	*Specific heat Capacity (Constant Pressure)*	Gr	*Grashof number*
C_V	*Specific heat Capacity (Constant Volume)*	Nu	*Nusselt number*
		Pr	*Prandtl number*
D	*Diameter*	Ra	*Rayleigh Number*
g	*Earth's gravity acceleration*	***Greek letters***	
G_v	*Water to steam conversion rate*	β	*Volumetric thermal expansion coefficient*
i,h	*Enthalpy*		
h_{conv}	*Convection heat transfer coefficient*	μ	*Dynamic viscosity*
H	*Average Enthalpy*	ρ	*Density*
k	*Thermal conductivity*	υ	*Kinematic viscosity*
l	*Characteristics length*	Φ	*Relative Humidity*
M	*Mass*	***Subscript***	
$\dot{M},G$	*Mass rate*	a	*Entrance mass rate*
P	*Pressure*	B	*Break*
q	*Heat Flux*	D	*Steam*
Q	*Heat source*	e	*Output mass rate*
r	*Radius*	f	*Saturated liquid*
R	*General gas constant*	fg	*Difference of saturated steam and liquid*
t	*Time*		
T	*Temperature*	g	*Saturated Steam*
u	*Internal energy per mass*	ij	*From i to j*
U	*Internal energy*	k	*Cell number*
v,υ	*Specific volume*	L	*Air*
V	*Volume*	sp	*Spray*
		Sc	*Spray condensation*
		W	*Water*
		Wc	*Wall Condensation*

1. Introduction

Nuclear safety has been one of the major issues to be studied since the inception of the nuclear industry. Nuclear reactor systems are sufficiently complex that dismissing the possibility of an accident followed by the release of radioactivity to the environment would be imprudent. Such a release would require the failure of multiple safety systems and barriers. Nuclear reactor containment is in fact the last of those barriers and so has one of the main roles in nuclear safety.

The consequence of sever reactor accidents depend greatly on containment safety features and containment performance in retaining radioactive material. The early failure of the containment structures at Chernobyl power plant contributed to the size of the environmental release of radioactive material in the accident. In contrast, the radiological consequences of the Three Mile Island Unit 2 accident were minor since the overall containment integrity was maintained and bypass was small [1].

During an accident in a water reactor nuclear power plant, the "Blowdown" phase refers to the initial discharge, with high mass flow rate of high-temperature pressurized coolant from the reactor cooling system into the containment. The intensity of the release is due to the high pressure difference between the cooling system and the containment atmosphere [2].

Given the importance of these, several studies have been done in recent years to evaluate the thermal-hydraulic behavior of the containment in the accident like LB-LOCA. In some cases a valid code (like CONTAIN, GOTHIC and etc) has been used for this simulation, while in the other a model has been developed for this purpose. Kljenak and Mavko have been simulated the thermal-hydraulic behavior of the containment in the Marviken blowdown 16 experiment with ASTEC and CONTAIN code [2]. GOTHIC and RELAP5 codes have been used by Papini et al. to analyze IRIS containment in a small break (SB) LOCA [3]. Also GOTHIC code has been used to simulate SB-LOCA in refurbished Wolsong-1 Nuclear power

? (def. was on abstract!)

PE

SC/PE

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plant by Kim and Park [4]. The GOTHIC code is a general purpose thermal-hydraulic code used to model multi component and multi phase flow systems. This code is suitable for safety analysis of nuclear power plant containment buildings [5]. Some other works have been used this code to simulate reactor containments [6, 7]. In this study, in first step a single-cell model (total volume of containment has been considered as a control volume) has been developed to simulate containment pressurization. Effects of Steam state equation and spray have been studied on this model. In the second step, the model has been developed to multi-cell model and the effects of nodalization and spatial location of cells have been considered on the results. Finally Results have been compared with BNPP FSAR results.

? SC/PE

PE

2. Single-Cell Model

Single-cell model has been developed according to [5] by adding spray model, wall condensation and considering different steam state equations. Total volume of containment has been considered as a control volume. Mass and energy balance equations have been applied for this control volume. Some assumptions that have been applied in this model are listed below:

- Total volume of containment has been considered as a control volume.
- Containment includes three layers; Steel containment, Gap and concrete containment.
- It is supposed that water from the break flashes to containment volume.
- Condensation layer has been considered in the containment inner.

Figure 1 shows the mass, energy and heat transfer processes in single-cell model in the containment.

Location of Figure 1 * See notes in the figure.

2.1. Heat Transfer (Section should be rewritten!)

RE Heat transfers from three layers according to below equations and prevents containment pressure to increase beyond its design pressure.

Containment Inner

$$q_{Heat\ Flux} = h_{conv}(\Delta T) \quad (Convection) \tag{1}$$

Where

$$h_{conv} = \left\{ 0.825 \left(\frac{9.8 \frac{1}{v_f} (\frac{1}{v_f} - \frac{1}{v_g}) k_f^3 i_{fg1}}{\mu_f (T_{Cont} - T_{steel\ inner}) l} \right)^{0.25} \right\} \tag{2}$$

And

$$i_{fg1} = i_{fg} + 0.68 C_{pf} (T_{Cont} - T_{steel\ inner}) \tag{3}$$

~~The~~ the h_{conv} is convective heat transfer coefficient in the containment in the presence of condensation layer [8]. ~~Read if there is not any condensation layer?~~

Steel and concrete layers

Heat ~~transfers~~ transfer in steel and concrete layers according to conduction heat transfer resistance equation:

$$q_{Heat\ Flux} = \frac{\Delta T}{R} \tag{4}$$

Where for the spherical shape, R should be as:

$$R = \frac{r_{outer} - r_{inner}}{4\pi r_{inner} r_{outer} k} \tag{5}$$

Eqns 1-3: (4)→(5)
Eqns 4-5: (2), (4)
Eqns 6-8: (4)↔(3)↔(2)
(2)→(1)

Gap and Containment outer

Heat transfer phenomena in the gap ~~and~~ (between containment) and to the environment are natural convection processes. Convective heat transfer coefficient of natural convection can be calculated according to below equations [8]:

$$Nu = \frac{h_{conv} D}{k} = 2 + \frac{0.589 Ra^{1/4}}{[1 + (0.469/Pr)^{9/16}]^{4/9}} \tag{6}$$

(5) (4) (3) (2) (1)

(1) ENVIRONMENT
(2) CONCRETE
(3) GAP
(4) STEEL
(5) INNER SYSTEM

Shouldn't the eqn be:

$$\int_t^{t+\Delta t} (\dot{M}_{DB} \cancel{dt} - \dot{M}_{Sc} - \dot{M}_{Wc})dt + M_D(t) \; ?$$

Where

$$Ra = Gr \times \Pr \qquad (7) \qquad Gr = \frac{D^3 g\, \Delta T\, \beta}{\upsilon^2} \quad , \; Pr = \frac{\mu C_p}{k} \qquad (8)$$

2.2. Mass balance

? WHAT DO YOU MEAN HERE? ? WATER/STEAM UNDERTOOK AN ISOTHERMAL FLASH? OR DO THEY FLOW TO THE CONTAINMENT VOLUME?

During the accident steam and water flash to containment volume. Water and steam mass balances can be calculated from below equation:

$$M_D(t + \Delta t) = \int_t^{t+\Delta t} \dot{M}_{DB}(t)dt - \dot{M}_{Sc}dt - \dot{M}_{Wc}dt + M_D(t) \qquad (9)$$

Where M_D, $\dot{M}_{DB}$, $\dot{M}_{Sc}$ and $\dot{M}_{Wc}$ are Steam mass, Steam mass rate from break, spray condensation rate and wall condensation rate respectively. Initial steam mass ($M_{D(t=0)}$) can be calculated from initial relative humidity in the containment, for water:

$$M_W(t + \Delta t) = \int_t^{t+\Delta t} \dot{M}_{WB}(t)dt + M_W(t) \qquad (10)$$

Where M_W and $\dot{M}_{WB}$ are water mass and water mass rate from break. It should be considered that spray water and the mass of produced water (condensate steam) from wall condensation and spray condensation are collected in the reactor sump, cooled in a heat exchanger and recycled as new feed water for spray, so should be neglected in the water mass balance. Also it is supposed that water and steam have flashed to containment volume, so:

$$M_{D(t+\Delta t)} + M_{W(t+\Delta t)} = \frac{V_{Containment}}{(1-x)\mathrm{v}_{f\,(T_{Cont(t+\Delta t)})} + x\,\mathrm{v}_{g(T_{Cont(t+\Delta t)})}} \qquad (11)$$

2.2.1. Spray condensation

The spray system provides a uniformly divided water spray to the containment atmosphere. Heat and mass transfer to the droplets provide a rapid reduction in temperature, pressure and fission product concentration. Spray droplets enter the containment vapor and condensate

$P_{MAX} \backslash P_{MIN}$: ? HOW IS THESE CALCULATED / OBTAINED?

?

WHAT DO YOU MEAN?

vapor around themselves. Spray flow rate depends on containment pressure as second order function:

$$\dot{M}_{spray} = \dot{M}_{spray}^{max} \frac{P_{cont} - P_{max}}{P_{max} - P_{min}} \qquad (12)$$

Spray condensation rate depends on thermodynamic state of steam; for saturate(d) and superheated steam, spray condensation rates will be calculated by equation (13) and (14) respectively.

$\dot{M}_{sp} = \dot{M}_{spray}$

you should keep the same subscript.

$$\dot{M}_{Sc} = \dot{M}_{sp} \left(\frac{i_f - i_{sp}}{i_{fg}} \right) \qquad (13)$$

$$\dot{M}_{Sc} = \dot{M}_{sp} \left(\frac{(i_f - i_{sp}) - (i_{suprheat} - i_g)}{i_{fg}} \right) \qquad (14)$$

SUPERHEAT

2.2.2. Wall condensation

PE

Heat transfer from containment inside to the environment can condense some of the steam on the steel containment inner layer. It is assumed that the latent heat of condensation that is released the condensate is transferred by conduction completely to the containment wall. The wall condensation rate for saturate steam state can be calculated by:

$$\dot{M}_{Wc} = \frac{q_{Heat\ Flux} \times A_{Steel\ containment}}{h_{fg}} \qquad (15)$$

And for superheated steam state can be calculated by equation (16).

$$\dot{M}_{Wc} = \frac{q_{Heat\ Flux} \times A_{Steel\ containment}}{[(h_{superheat} - h_g) + h_{fg}]} \qquad (16)$$

2.3. Energy Balance

As shown in figure 1, energy balance equation in the control volume can be written as:

$$q_{Break}(t + \Delta t) - q_{Heat\ Transfer}(t + \Delta t) = U(t + \Delta t) - U(t) \qquad (17)$$

specific

Where U is internal energy and can be written according to water enthalpy (i_W) and steam

specific

enthalpy (i_D) as:

$$q_{Break}\,(t+\Delta t) = \left[i_W\,(t+\Delta t)\dot{M}_W\,(t+\Delta t) + i_D\,(t+\Delta t)\dot{M}_D(t+\Delta t)\right] \times \Delta t \qquad (18)$$

Also $U(t+\Delta t)$ can be written as fallowed:

$$\begin{aligned} U(t+\Delta t) - U(t) &= [\,U(t+\Delta t) - U(t)]_L + [U(t+\Delta t) - U(t)]_W \\ &+ [U(t+\Delta t) - U(t)]_D \qquad (19) \end{aligned}$$

Where subscript L, W and D indicate air, water and steam component respectively. Internal energy of air can be written as:

$$[U(t+\Delta t) - U(t)]_L = M_L C_{VL}(T(t+\Delta t)_{Cont} - T_{cont}(t)) \qquad (20)$$

And also

$$\begin{aligned} U_W\,(t+\Delta t) + U_D\,(t+\Delta t) &= [M_D\,(t+\Delta t) + M_W\,(t+\Delta t)] \\ &\times \left[(1-x)u_{f\,(T_{Cont(t+\Delta t)})} + x u_{g(T_{Cont(t+\Delta t)})}\right] \quad (21) \end{aligned}$$

x can be calculated from combination of equations 17 to 21. Figure 2 shows the solution algorithm for containment temperature (T_{cont}). Containment pressure can be calculated from below equation:

$$P_{cont}\,(t+\Delta t) = P_L\,(t+\Delta t) + P_D\,(t+\Delta t) \qquad (22)$$

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Where P_L calculates ~~by~~ ideal gas law in T_{Cont} and P_D calculate ~~by~~ steam state equation that will be described.

Location of Figure 2 * SEE COMMENTS IN THE FIG.

2.3.1. Steam State Equation

PG

Steam thermodynamic state can be supposed after calculation of x from solution algorithm (figure 2). Three states have been considered for steam in calculations:

1- Ideal gas low

QUALITY : $\frac{i_x - i_f}{i_g - i_f}$

FLUID IS SUPERHEATED STATE ?

$0 \leq x \leq 1$

2- $P_D = f(T_{cont}, v)$ *if* $x > 1$

3- Saturation Steam Table *if* $x < 1$

In the first option, Steam pressure calculates from Ideal gas low in T_{cont}. Second option calculates steam pressure as a function of containment temperature and specific volume. Note that although quality (x) should be in the range of 0 to 1 but $x>1$ shows the superheated steam state. Finally steam pressure IS calculate~~s~~D from saturation steam table in T_{cont} in third option.

3. Multi-cell Model

In the multi-cell model total volume of containment subdivides to some cells (control volumes). Balance equations of mass and energy and mass and heat transfer equations between connected cells will be written. Finally all of the respective equations have been solved simultaneously for all cells to obtain thermal-hydraulic parameter of containment in order to time and location in the containment. Figure 3 shows multi-cell model and its processes. Some assumptions have been used in multi-cell model as listed below;

- The cell IN WHICH ~~that~~ break has ~~been~~ occurred ~~in~~, will be named Cell 1. The respective equations of this cell are different from others.
- Because of break flashes to cell 1, thermodynamic properties of this cell considered as saturation state in all time steps (excluded initial time).
- Three components include water (W), Steam (D) and air (L) have been considered in all of cells.
- It is supposed that water mass can't transfer between cells and only steam and air mass transfers are allowed.
- Symbols (') and (·) show the thermal derivation (derivation to temperature) and time derivation of that parameter respectively.

Location of Figure 3

WHY ARE DIFFERENT SYMBOLS ASSIGNED TO THE SAME QUANTITIES? E.G: ENTHALPY (i, h), MASS FLOW RATE ($\dot{M}$, G)? IT MAKES THE READING VERY CONFUSING!

3.1. Equations of Cell 1

Equations of cell 1 have been developed according to [9]. As break has been considered in cell 1, mass and energy of break have been entered in these equations:

$$\dot{M}_{D1} = G_{DB} - \sum_{j=1}^{n} G_{D1j} + G_{V1} \qquad (23)$$

$$\dot{M}_{W1} = G_{WB} - \sum_{j=1}^{n} G_{W1j} - G_{V1} \qquad (24)$$

$$\dot{M}_{L1} = - \sum_{j=1}^{n} G_{L1j} \qquad (25)$$

Where G_{D1j}, G_{W1j}, G_{L1j} are steam, water and air mass transfer rate from cell 1 to j respectively and G_{V1} is water to steam conversion rate in cell 1. Energy balance equation for cell 1 should be as:

$$\frac{\partial (M_{01} h_{01})}{\partial t}$$

$$(G_{DB} + G_{WB})h_B - \sum_{j=1}^{n}(G_{D1j}h_{D1j} + G_{W1j}h_{W1j} + G_{L1j}h_{L1j}) + Q_1 \qquad (26)$$
$$= \dot{\overline{M_{D1}h_{D1}}} + \dot{\overline{M_{W1}h_{W1}}} + \dot{\overline{M_{L1}h_{L1}}} - V_1 \dot{P}_1$$

WHY? ASSUMED INCOMPRESSIBLE? EXPLAIN!

Where h_B, h_{D1j}, h_{W1j} and h_{L1j} are break enthalpy, enthalpy of steam that transfer from cell 1 to j, enthalpy of water that transfer from cell 1 to j and enthalpy of air that transfer from cell 1 to j respectively. Equation (27) shows the volume constraint equation:

~~WHY ASSUMED INCOMPRE~~

$$\dot{\overline{M_{D1}\upsilon_{D1}}} + \dot{\overline{M_{W1}\upsilon_{W1}}} + \dot{\overline{M_{L1}\upsilon_{L1}}} = 0 \qquad (27)$$

$$\sum \frac{\partial}{\partial t}(M_k v_k) = 0$$

Total pressure in cell 1 is the summation of steam and air partial pressure, so:

$$P_1 = P_{L1} + P_{D1} \qquad (28)$$

$$\dot{P}_1 = \dot{P}_{L1} + \dot{P}_{D1} \qquad (29)$$

$$\frac{\partial P_1}{\partial t} = \frac{\partial P_{L1}}{\partial t} + \frac{\partial P_{D1}}{\partial t}$$

$$P_{L1} = \frac{R_L T_1}{\upsilon_{L1}} = \frac{M_{L1} R_L T_1}{V_1} \qquad (30)$$

$$\dot{P}_{L1} = \frac{R_L}{V_1}(T_1 \dot{M}_{L1} + M_{L1} \dot{T}_1) \qquad (31)$$

$$P_{D1} = f\,(T_1) \tag{32}$$

$$\overset{\bullet}{P}_{D1} = \frac{df(T_1)}{dt} = \frac{df(T_1)}{dT_1}\,\frac{dT_1}{dt} = \frac{df(T_1)}{dT_1}\,\overset{\bullet}{T}_1 = \frac{dP_{D1}}{dT_1}\,\overset{\bullet}{T}_1 \tag{33}$$

$$\overset{\bullet}{P}_1 = \frac{R_L}{V_1}\,(\,T_1\,\overset{\bullet}{M}_{L1} + M_{L1}\,\overset{\bullet}{T}_1\,) + \frac{dP_{D1}}{dT_1}\,\overset{\bullet}{T}_1 \tag{34}$$

Equation (34) shows the pressure changes in order to time in cell 1. By combining equation (23), (24), (25) and (34):

$$\begin{aligned} G_{V1} = {} & \frac{G_{DB}(h_{DB} - h_{D1}) + G_{WB}(h_{WB} - h_{W1}) - F_1 + Q_1 + R_L T_1 \overset{\bullet}{M}_{L1}}{h_{D1} - h_{W1}} \\ & -\left(\frac{M_{D1}h'_{D1} + M_{W1}h'_{W1} + M_{L1}(Cp_{L1} - R_L) - V_1\,\dfrac{dP_{D1}}{dT_1}}{h_{D1} - h_{W1}}\right)\overset{\bullet}{T}_1 \end{aligned} \tag{35}$$

H ?

Where

$$F_1 = \sum_{j=1}^{n}\,[\,G_{D1j}\,(H_{D1j} - h_{D1}) + G_{W1j}\,(H_{W1j} - h_{W1}) + G_{L1j}\,(H_{L1j} - h_{L1})\,] \tag{36}$$

Also by combining equations (23), (24), (25) and volume constraint equation, another equation of G_{V1} will be:

$$\begin{aligned} G_{V1} = {} & -\left(\frac{(G_{DB} - \sum_{j=1}^{n} G_{D1j})\,\upsilon_{D1} + (G_{WB} - \sum_{j=1}^{n} G_{W1j})\,\upsilon_{W1} - (\sum_{j=1}^{n} G_{L1j})\,\upsilon_{L1}}{\upsilon_{D1} - \upsilon_{W1}}\right) \\ & + \overset{\bullet}{T}_1\,\frac{(M_{D1}\upsilon'_{D1} + M_{W1}\upsilon'_{W1} + M_{L1}\upsilon'_{L1})}{\upsilon_{D1} - \upsilon_{W1}} \end{aligned} \tag{37}$$

By combining equations (35) and (37), the rate of changes in temperature of cell 1 is:

$$\overset{\bullet}{T}_1 = \frac{G_{DB}(h_{DB} - h_{D1}) + G_{WB}(h_{WB} - h_{W1}) + Q_1 + R_L T_1 \overset{\bullet}{M}_{L1} + B_1 - F_1}{C_1} \tag{38}$$

Where

$$B_1 = \left(\frac{h_{D1} - h_{W1}}{\upsilon_{D1} - \upsilon_{W1}}\right)\left[\,(G_{DB} - \sum_{j=1}^{n} G_{D1j})\,\upsilon_{D1} + (G_{WB} - \sum_{j=1}^{n} G_{W1j})\,\upsilon_{W1} - (\sum_{j=1}^{n} G_{L1j})\,\upsilon_{L1}\right] \tag{39}$$

and

$$C_1 = M_{D1}h'_{D1} + M_{W1}h'_{W1} + M_{L1}(Cp_{L1} - R_L) - V_1\frac{dP_{D1}}{dT_1} - \left(\frac{h_{D1} - h_{W1}}{\upsilon_{D1} - \upsilon_{W1}}\right)(M_{D1}\upsilon'_{D1} + M_{W1}\upsilon'_{W1} + M_{L1}\upsilon'_{L1}) \tag{40}$$

3.2. Mass transfer

One of the most important parameters in multi-cell modeling is mass transfer rate between different cells. Mass transfer rate has some effects on pressure-time history in short time. ? Orfice-flow [10] model has been considered as mass transfer equation between cells. This model is based on theoretical and experimental facts. Figure 4 shows the model. Mass-flow function can be calculated from equation (41) between cell i and j:

→ κ?

$$Mass - Flow\ Function = \frac{\dot{m}}{A}\frac{\sqrt{RT_k}}{P_k} = \sqrt{\frac{2\kappa}{\kappa - 1}\left(\frac{P_j}{P_k}\right)^{2/\kappa}\left[1 - \left(\frac{P_j}{P_k}\right)^{(\kappa-1)/\kappa}\right]} \tag{41}$$

?

Location of Figure 4 * SEE COMMENTS IN THE FIGURE!

And so the mass transfer rate is:

$$\dot{m} = (Mass - Flow\ Function)\frac{AP_k}{\sqrt{RT_k}} \tag{42}$$

Component here (K) refers to cell, doesn't it?

According to equation (42), mass transfer rate of each component is:

P_{DK} → ?

$$G_{Dkj} = (G_{Dkj} + G_{Lkj})\frac{P_{DK}}{(P_{DK} + P_{LK})} = \dot{m}\frac{P_{DK}}{(P_{DK} + P_{LK})} = \dot{m}\frac{P_{DK}}{P_k} \tag{43}$$

→ LK?

$$G_{Lkj} = (G_{Dkj} + G_{Lkj})\frac{P_{LK}}{(P_{DK} + P_{LK})} = \dot{m}\frac{P_{LK}}{(P_{DK} + P_{LK})} = \dot{m}\frac{P_{LK}}{P_k} \tag{44}$$

And according to model assumptions; $G_{Wkj}=0$.

3.3. Equation of other cells

Mass balance equations for other cells(all the cells excluded cell 1) can be written as:

• NOTATION: TRY TO KEEP IT CONSISTENT e.g., K & K

$$\overset{\bullet}{M}_{DK} = \sum_{1}^{e} G_{DKe} - \sum_{1}^{a} G_{DKe} + G_{VK} \qquad (45)$$

$$\overset{\bullet}{M}_{WK} = \sum_{1}^{e} G_{WKe} - \sum_{1}^{a} G_{WKe} - G_{VK} \qquad (46)$$

Are "e" & "a" reference cell numbers for in/out mass flow?

$$\overset{\bullet}{M}_{LK} = \sum_{1}^{e} G_{LKe} - \sum_{1}^{a} G_{LKe} \qquad (47)$$

→ IT IS NOT CLEAR

Where in this equations, symbol (e) represent the 'entrance mass rate' to respective cell and symbol (a) shows 'output mass rate' from respective cell. Also Temperature changes rate should be calculated by:

WHAT DOES THE SUBSCRIPT "C" STAND FOR?

$$\overset{\bullet}{T}_{K} = \frac{F_{eK} - F_{aK} + Q_{K} + R_{L} T_{K} \overset{\bullet}{M}_{LK} + B_{K} + G_{CWK}(h_{CW} - h_{WK})}{C_{K}} \qquad (48)$$

ok

Where

$$F_{eK} = \sum_{1}^{e} [G_{DKe}(H_{De} - h_{DK}) + G_{WKe}(H_{We} - h_{WK}) + G_{LKe}(H_{Le} - h_{LK})] \qquad (49)$$

$$F_{aK} = \sum_{1}^{a} [G_{DKa}(H_{Da} - h_{DK}) + G_{WKa}(H_{Wa} - h_{WK}) + G_{LKa}(H_{La} - h_{LK})] \qquad (50)$$

F_{ek} and F_{ak} represent input and output energy to and from a cell. H shows the enthalpy in average temperature and pressure between two connected cells.also

$$B_{K} = \left(\frac{h_{DK} - h_{WK}}{\upsilon_{DK} - \upsilon_{WK}}\right)\left[\left(\sum_{1}^{e} G_{Ke} - \sum_{1}^{a} G_{Ka}\right)\upsilon_{DK} + \left(\sum_{1}^{e} G_{WKe} - \sum_{1}^{a} G_{WKa}\right)\upsilon_{WK}\right] \qquad (51)$$

$$C_{K} = M_{DK} h'_{DK} + M_{WK} h'_{WK} + M_{LK}(Cp_{LK} - R_{L}) - V_{K}\frac{dP_{DK}}{dT_{K}} - \left(\frac{h_{DK} - h_{WK}}{\upsilon_{DK} - \upsilon_{WK}}\right)(M_{DK}\upsilon'_{DK} + M_{WK}\upsilon'_{WK}) \qquad (52)$$

Water to steam conversion rate can be calculated from equation (53) for other cells:

Cp

SUBSCRIPT

$$G_{VK} = \frac{F_{eK} - F_{aK} + Q_K + R_L T_K \dot{M}_{LK} + G_{CWK}(h_{CW} - h_{WK})}{h_{DK} - h_{WK}} - \left(\frac{M_{DK} h'_{DK} + M_{WK} h'_{WK} + M_{LK}(Cp_{LK} - R_L) - V_K \frac{dP_{DK}}{dT_K}}{h_{DK} - h_{WK}}\right)\dot{T}_K \tag{53}$$

By assuming ideal gas equation in other cells, pressure equation can be written as

$$P_K = P_{LK} + P_{DK} \tag{54}$$

$$\dot{P}_K = \dot{P}_{LK} + \dot{P}_{DK} \tag{55}$$

$$P_{LK} = \frac{R_L T_K}{\upsilon_{LK}} = \frac{M_{LK} R_L T_K}{V_K} \tag{56}$$

$$\dot{P}_{LK} = \frac{R_L}{V_K}(T_K \dot{M}_{LK} + M_{LK} \dot{T}_K) \tag{57}$$

$$P_{DK} = \frac{R_D T_K}{\upsilon_{DK}} = \frac{M_{DK} R_D T_K}{V_K} \tag{58}$$

$$\dot{P}_{DK} = \frac{R_D}{V_K}(T_K \dot{M}_{DK} + M_{DK} \dot{T}_K) \tag{59}$$

$$\dot{P}_K = \frac{1}{V_K}\left[\dot{T}_K (M_{DK} R_D + M_{LK} R_L) + T_K(\dot{M}_{DK} R_D + \dot{M}_{LK} R_L)\right] \tag{60}$$

According to assumption that water mass cannot transfer between cells:

$$\sum_1^e G_{WKe} \sim 0 \tag{61}$$

$$\sum_1^a G_{WKa} \sim 0 \tag{62}$$

By using equations (61) and (62), some equations of other cells can be ~~rewrited simpler~~. "REWRITTEN IN A SIMPLER FORMAT."

Figure 5 shows the overall solution algorithm for multi-cell model.

Location of Figure 5 * SEE COMMENTS IN THE FIG.

4. BNPP Containment

In the design of BNPP, the reactor plant is used with WWER-1000 type reactor (model V-446) upgraded on the basis of operation experience of V-320 series plants. This type of reactor is four-loop reactor plant with water-cooled water-moderated reactor (WWER). The reactor core has a hexagonal configuration and 1/6 symmetric shape. It consists of 163 hexagonal fuel assemblies of the same geometry and produces 3000 MWth at full power.

The design envisages double emergency preventive containment of the reactor building, consisting of the inner steel containment and outer reinforced concrete containment. Inner steel containment limits the hermetic volume and presents a sphere with a diameter of 56 m, supported by reinforced concrete bed. The inner containment is intended for restricting radioactive substances release due to accidents and for isolating those systems and components which are necessary to perform their intended functions in order to mitigate consequences of the accident. The outer reinforced concrete containment presents a cylinder with an external diameter of 62.8 m, covered by semi-spherical dome. Figure 6 shows a 3D structure of BNPP containment and its components layout. Some specifications of containment have been presented in Table 1.

Location of Figure 6

Table 1
BNPP containment specifications.

5. Results

5.1. Accident scenario

could you explain this type of accident scenario?

One of the most dangerous accidents in the NPP is Double Ended Cold Leg (DECL) that is the specific type of Large Break LOCA. DECL means a total guillotine type of break in cold leg pipe. This accident has been selected in BNPP for bench marking the model results. Figure 7 and 8 show the data of break mass and break energy of DECL respectively [11] that have been used as input data for single-cell and multi-cell models. Results have been compared with FSAR results. FSAR has divided total volume of the containment to 23 cells (Figure 13) and simulate the accident in the containment by ANGAR [11] code.

Location of Figure 7

Location of Figure 8

BNPP Containment spray system (TJ) is designed for operation under emergency conditions arising from leakage of the primary coolant system and leakage of the secondary side inside the containment. Under normal operating conditions the system does not operate and is in the standby mode. During emergency conditions the system performs the reduction function of pressure, temperature and radioactive iodine isotope concentration inside the steel containment. The spray headers are arranged in the upper part of the containment.When the signal appears indicating that the pressure under the containment is higher than 0.03 MPa (gage), a command is generated to automatically open them in order to make the system more reliable. Boric acid solution in the amount of 83.3 kg/s (300 t/h) per one channel is supplied to the spray injector orifices using pumps of residual heat removal system.

5.2. Single-cell results

Results of temperature and pressure in the DECL accident without spray actuation have been shown in figure 9 and 10 respectively. Cumulative break mass (kg) curve also attached to each figures for evaluation of curve trends. Also in figure 10 the effects of steam state equations on the containment pressurization have been considered.

Location of Figure 9

Location of Figure 10

Why ~~do~~ are FSAR results (w spray) so similar to Pressure calc assuming IDEAL GAS BEHAVIOUR?

Figure 11 and 12 show the effect of spray on temperature and pressure profiles in DECL accident. As can be seen in these figures, spray as an engineering safety feature has clear effects on containment depressurization.

Location of Figure 11

Location of Figure 12

The differences between steam state equations on containment pressurization model can be seen in figure 10. As can be seen in this figure, it seems that ideal gas can predict best results (relative to FSAR), but by applying spray model on containment pressurization model (Figure 12), the superheated steam will be the better result relative to FSAR results. Containment temperature profiles have been show in figure 9 and 11 without spray and with spray models.

WHY?

5.3. Multi-cell results

In the multi-cell modelling total volume of containment has been considered as 4 cells. Figure 13 shows the cells and specifications of the cells have been listed in Table 2. As can be seen in figure 13, 23 cells that have been considered in the FSAR analysis with ANGAR code, have been compressed into 4 cells. In Table 2 effective connection surface of cells with each other have been listed. This factor represents some parts such as doors, windows, corridors or open surfaces that air and steam can exchange through them between cells. Figure 14 shows the average pressure in the containment. Temperature profiles of cell 1 to 4 have been shown in figure 15 to 18 respectively.

Location of Figure 13

Table 2

Specifications of cells

Location of Figure 14

Location of Figure 15

Location of Figure 16

Location of Figure 17

Location of Figure 18

As can be seen in figure 14, multi-cell model can predict average pressure in the containment. Because of almost similar pressure profiles in cell 1 to 4, only average pressure profile has been shown in the article (and also in FSAR). In the temperature profiles (figure 15 to 18) as can be seen, the cell that break occurs in it (Cell 1) has reached to its maximum temperature in shorter time than other cells. The amount of maximum temperature depends on cell volume, cell location and effective connection surface of cell with other cells and especially with cell 1.

6. Conclusion

During a LB-LOCA accident, a large amount of water-steam mixture can be flashed into the containment and the aim of the containment system is to avoid or limit the release of these to the environment by maintaining its integrity. In this study the effects of spray, steam state equation and dividing containment to some cells (multi-cell model) have been considered on containment pressurization. As can be seen in figure 9 to 12 it seems that superheated steam state equation can predict containment pressurization model with the better results than others. Also the safety effects of containment spray system -as an engineering safety feature- in reducing containment pressure and temperature in Break accidents can be seen by comparison between figure 9 and 11 and also figure 10 and 12. The effects of multi-cell subdivisions can be seen in figure 14 and figures 15 to 18. It seems that using multi-cell subdivisions can improve the results. Multi-cell model have the advantages of predicting pressure and temperature as a function of time and coordinate. This feature can help the designer to locate safety systems such as HVAC systems and hydrogen recombiners in their best location in containment layout.

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Figure Captions:

Figure 1. Single-cell Model processes.

Figure 2. Single-cell Model solution algorithm.

Figure 3. Multi-cell Model processes.

Figure 4. Orfice-flow mass transfer model.

Figure 5. Overall solution algorithm for multi-cell model.

Figure 6. 3D structure of BNPP Containment.

Figure 7. Break mass of DECL

Figure 8. Break Energy of DECL

Figure 9. Temperature profile of DECL without spray.

Figure 10. Pressure profile of DECL without spray.

Figure 11. Effects of spray on temperature profile.

Figure 12. Effects of spray on pressure profile.

Figure 13. Layout of cells in the BNPP containment.

Figure 14. Average pressure profile of the containment.

Figure 15. Temperature profile of cell 1.

Figure 16. Temperature profile of cell 2.

Figure 17. Temperature profile of cell 3.

Figure 18. Temperature profile of cell 4.

YOU SHOULD CONSIDER ADDING
* MORE DESCRIPTIVE
(AND SELF-CONTAINED) ~~CAPTION~~ FIGURE
CAPTIONS!

Figure1

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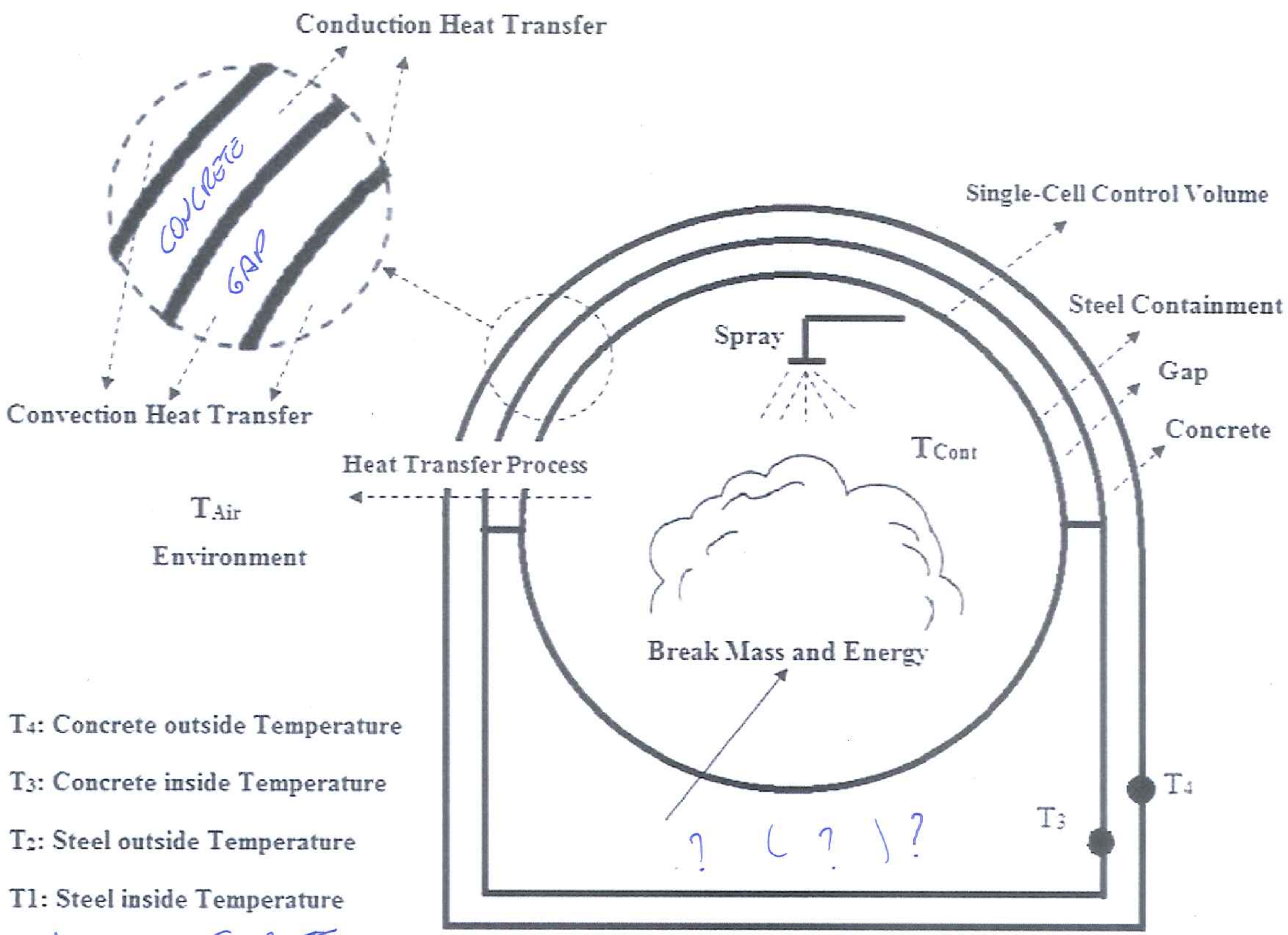

Where are T_1 & T_2 in this diagram?

Figure2
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POOR QUALITY!

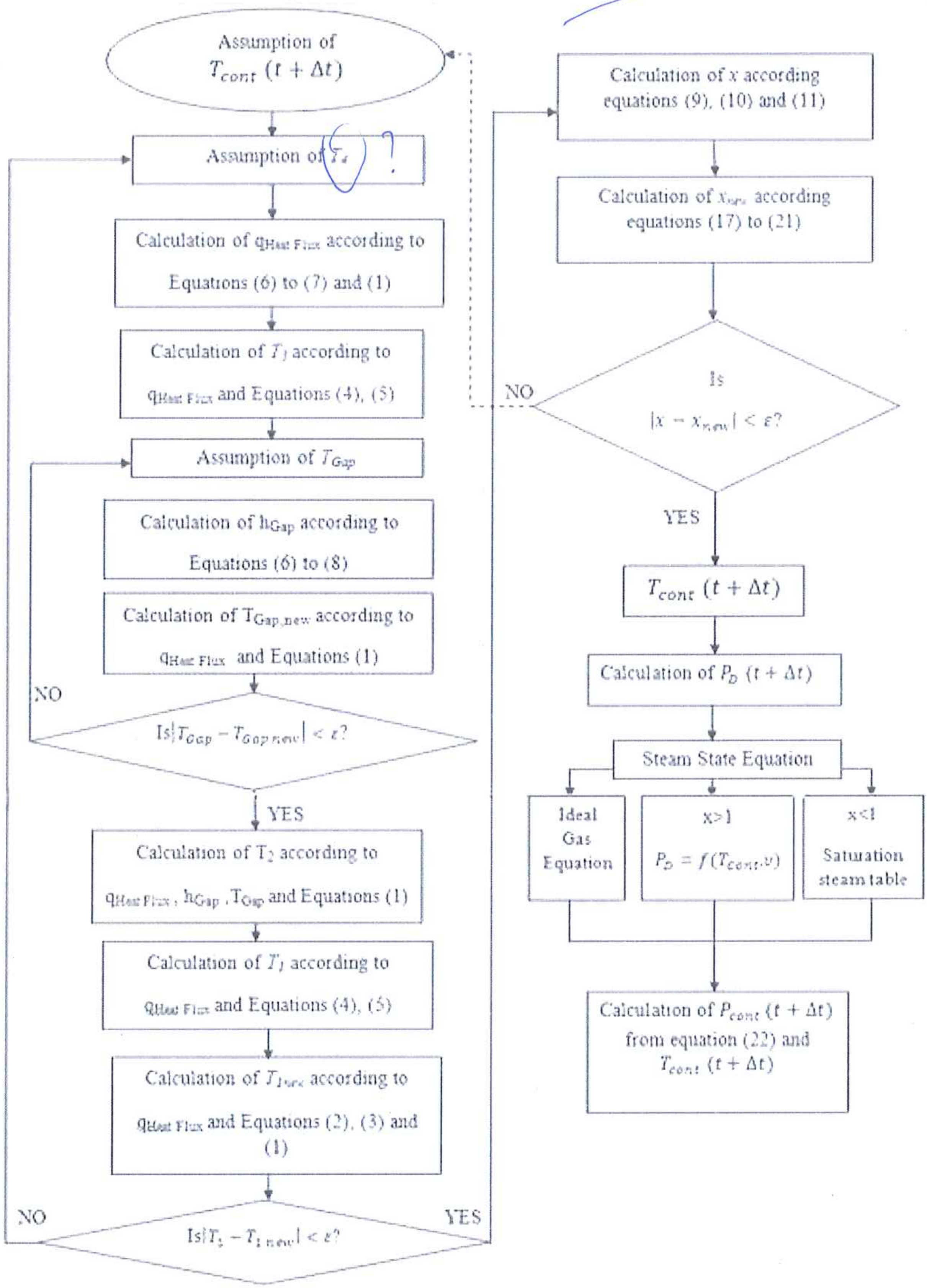

Figure3
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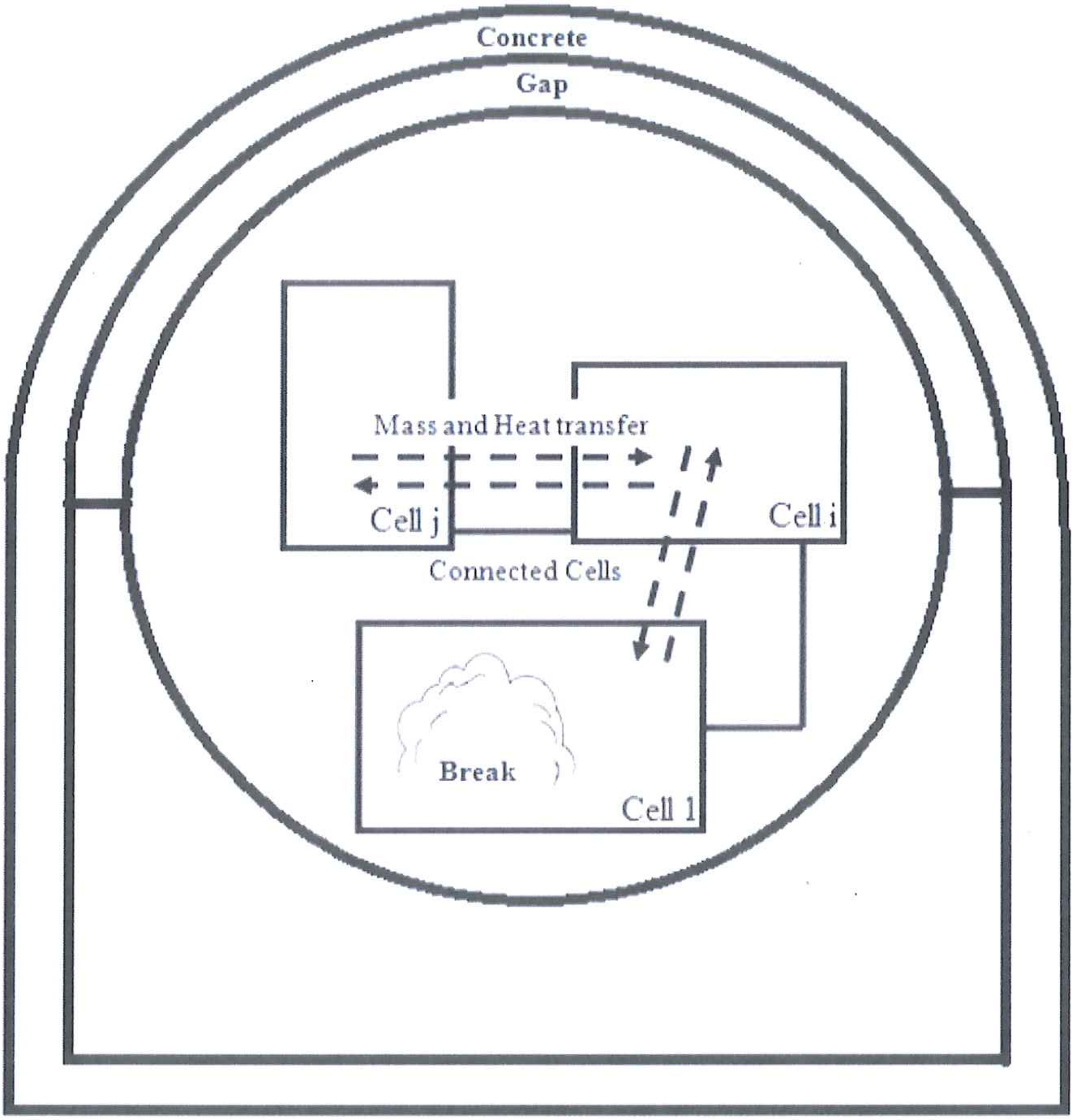

Figure4

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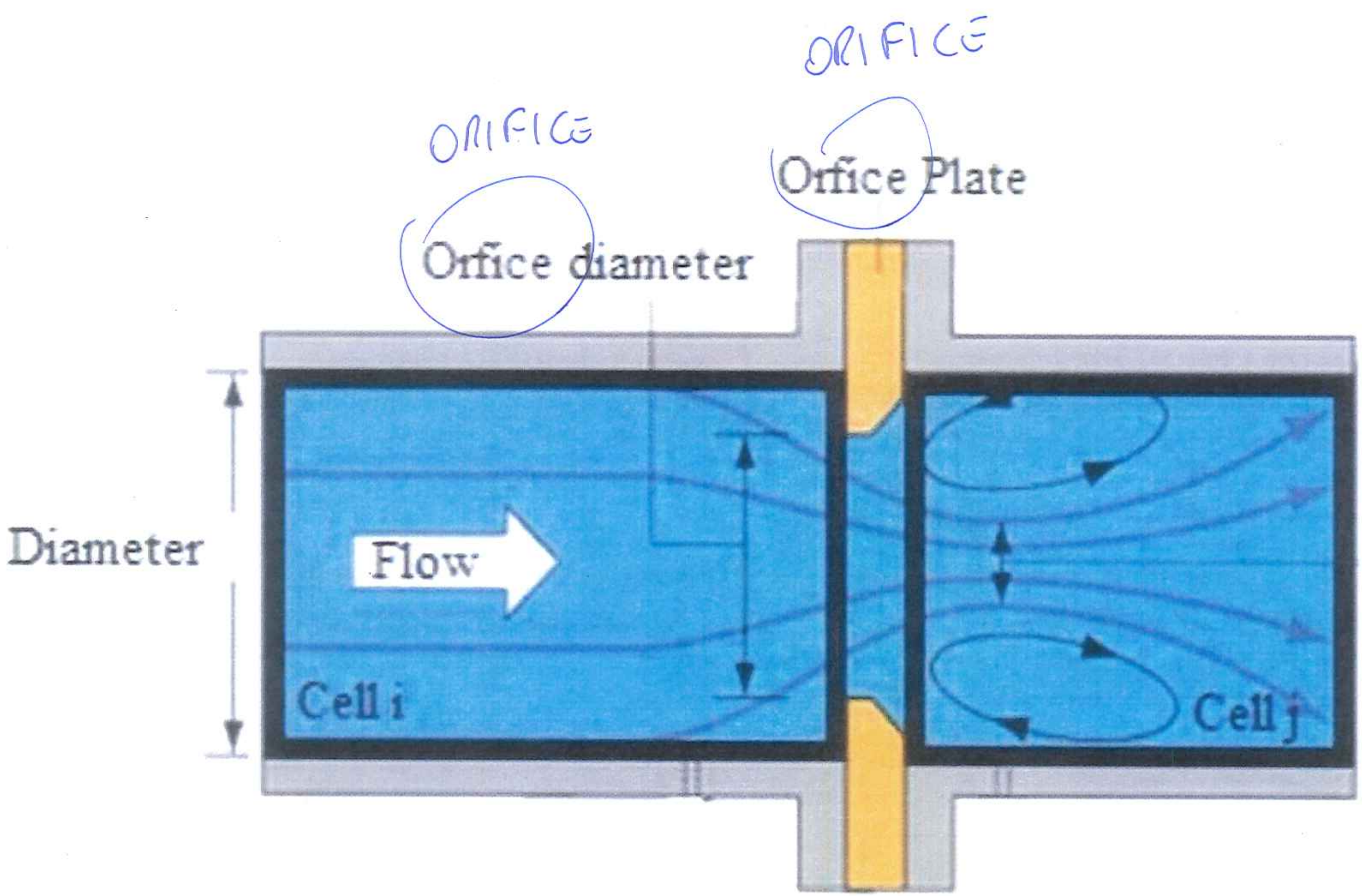
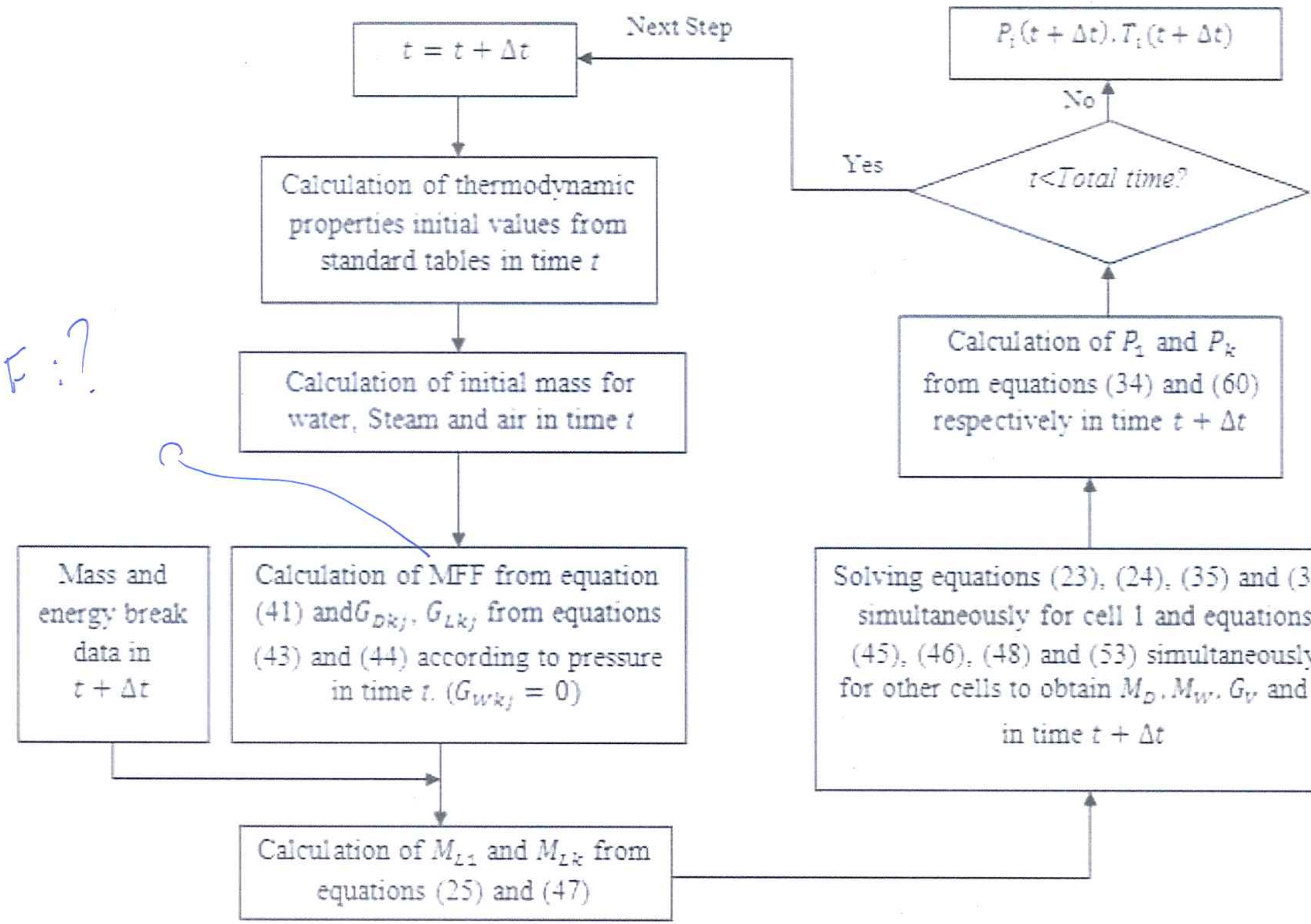


Figure5



$t = t + \Delta t$
Next Step
$P_i(t + \Delta t), T_i(t + \Delta t)$
No
Yes
t<Total time?
Calculation of thermodynamic properties initial values from standard tables in time t
Calculation of initial mass for water, Steam and air in time t
Calculation of P_1 and P_k from equations (34) and (60) respectively in time $t + \Delta t$
MFF :?
Mass and energy break data in $t + \Delta t$
Calculation of MFF from equation (41) and G_{Dkj}, G_{Lkj} from equations (43) and (44) according to pressure in time t. ($G_{Wkj} = 0$)
Solving equations (23), (24), (35) and (38) simultaneously for cell 1 and equations (45), (46), (48) and (53) simultaneously for other cells to obtain M_D, M_W, G_V and T in time $t + \Delta t$
Calculation of M_{L1} and M_{Lk} from equations (25) and (47)

Figure6
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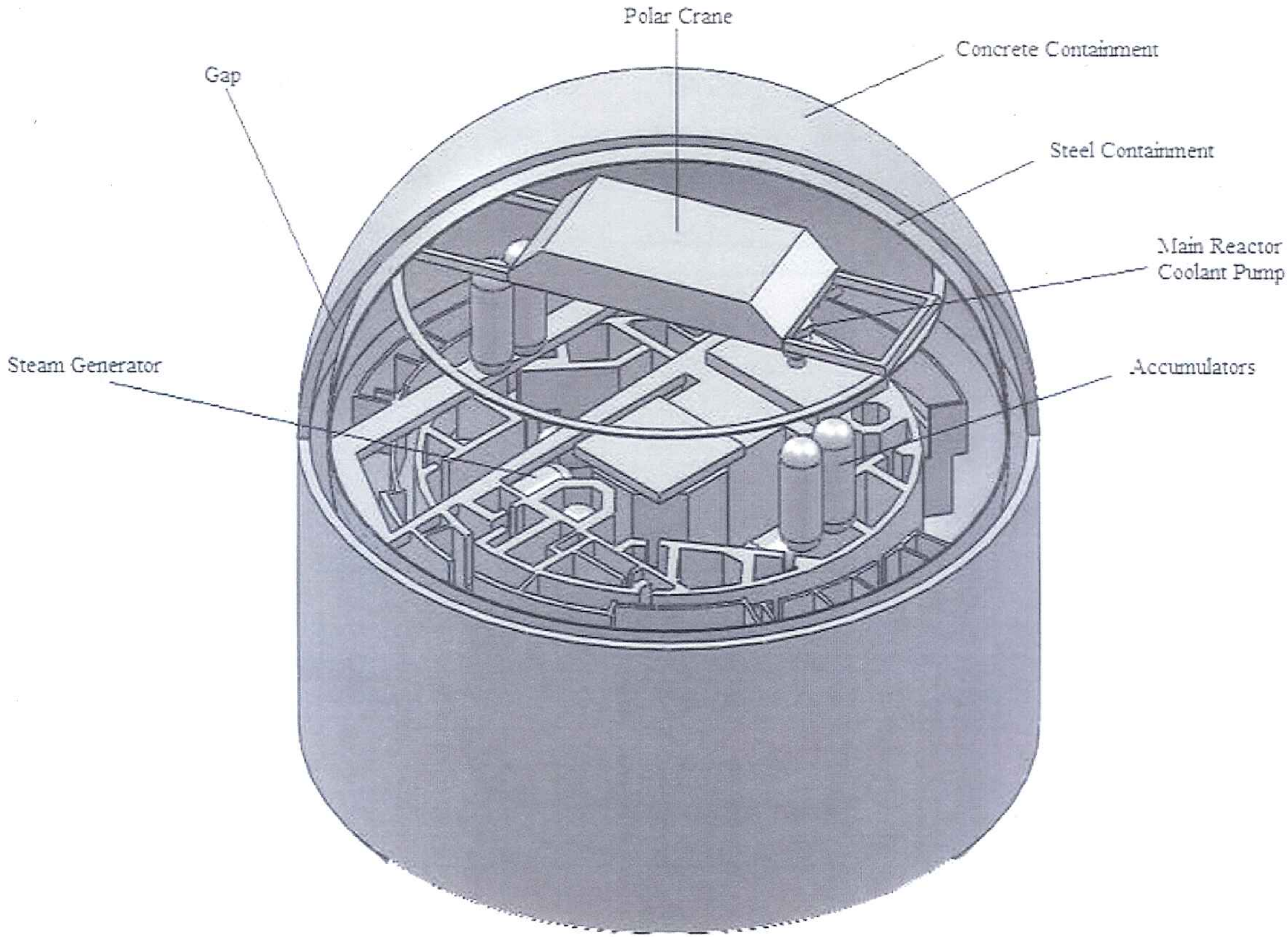

Figure7

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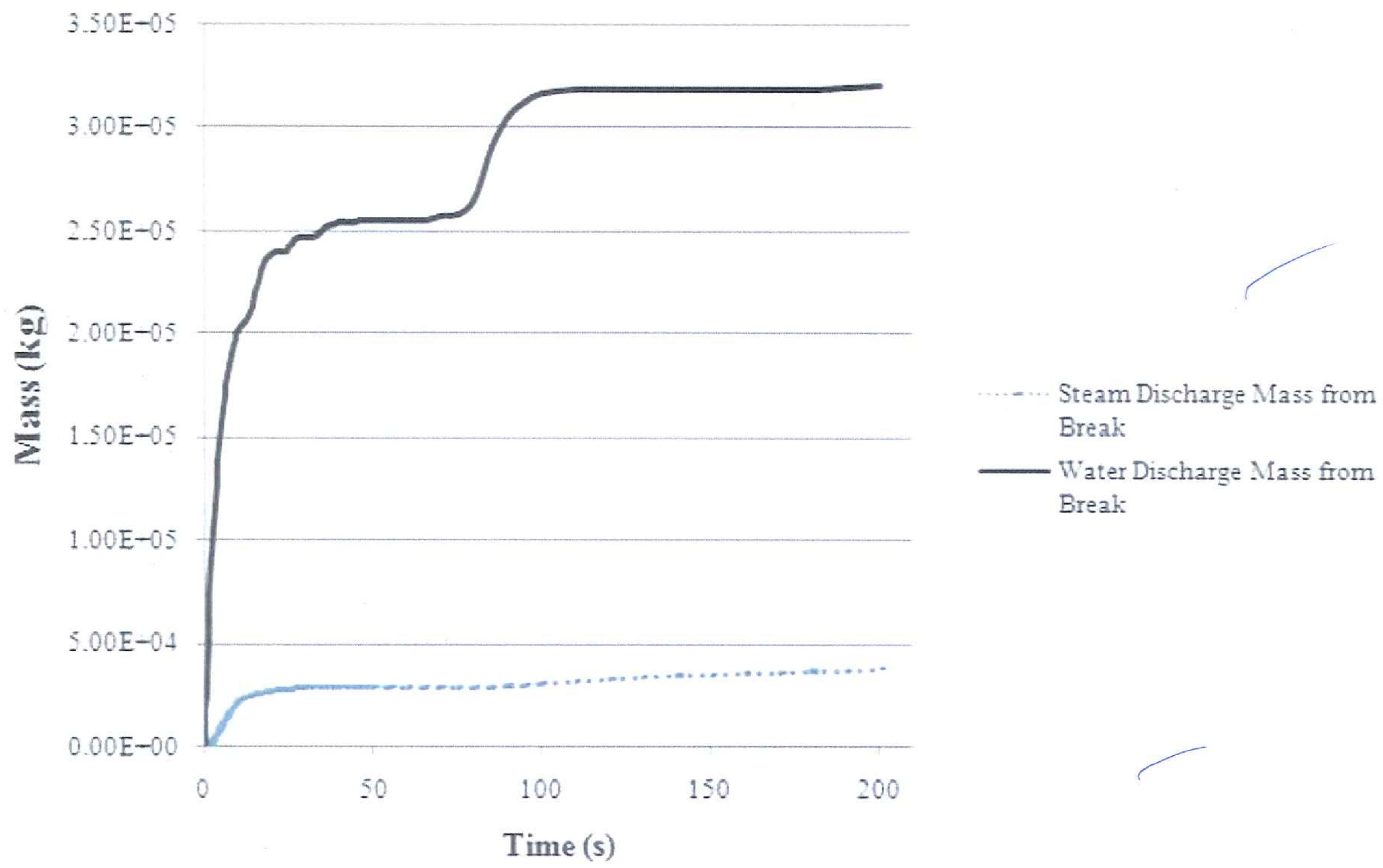

Figure8

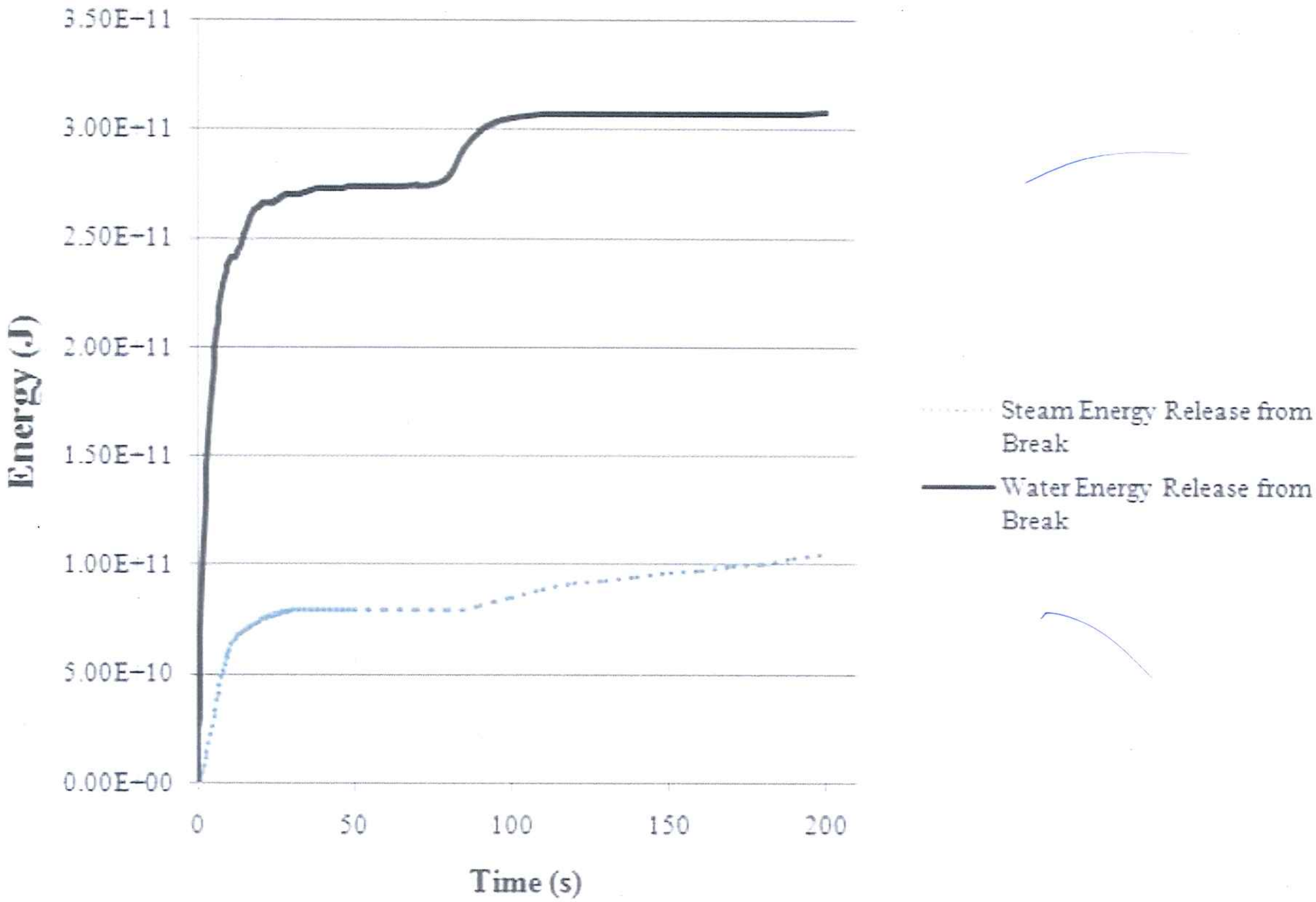
3.50E−11
3.00E−11
2.50E−11
2.00E−11
1.50E−11
1.00E−11
5.00E−10
0.00E−00
Energy (J)
0
50
100
150
200
Time (s)
Steam Energy Release from Break
Water Energy Release from Break

Figure9
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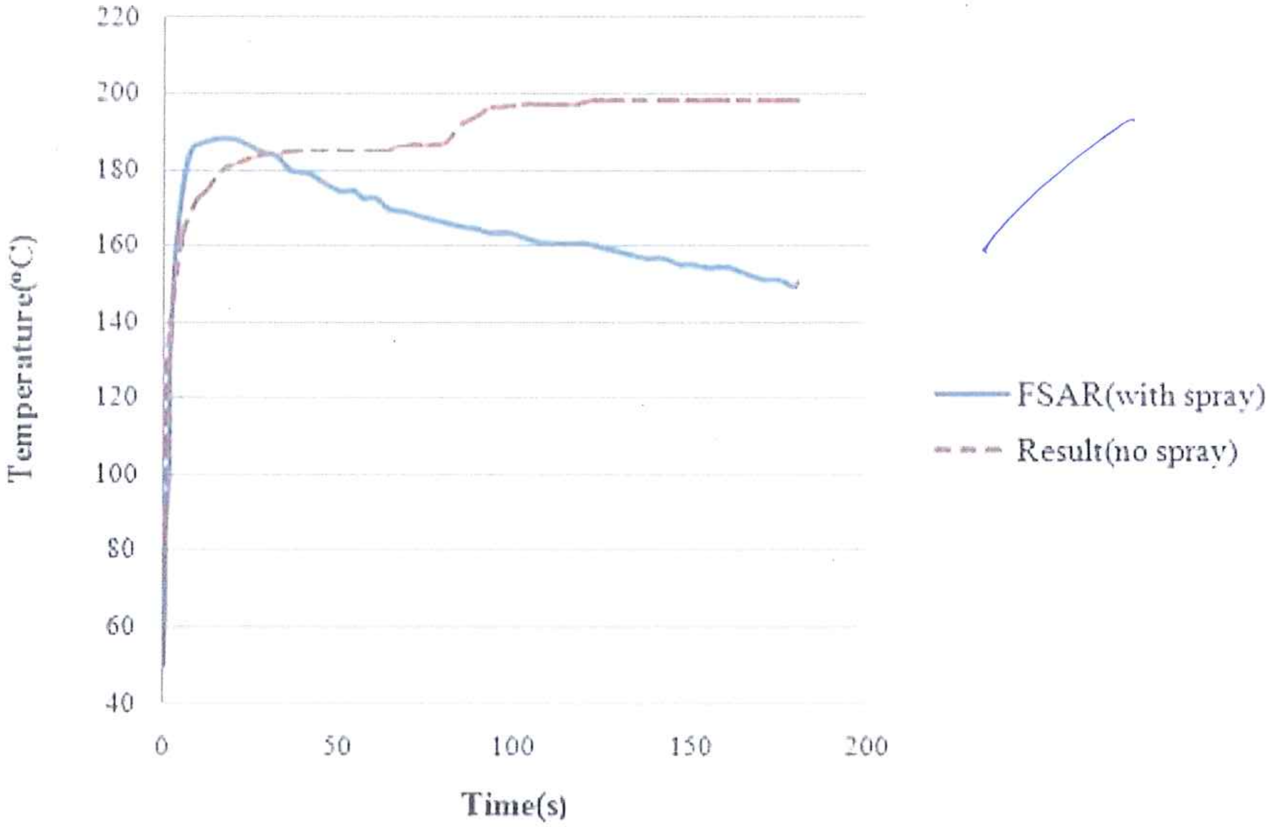

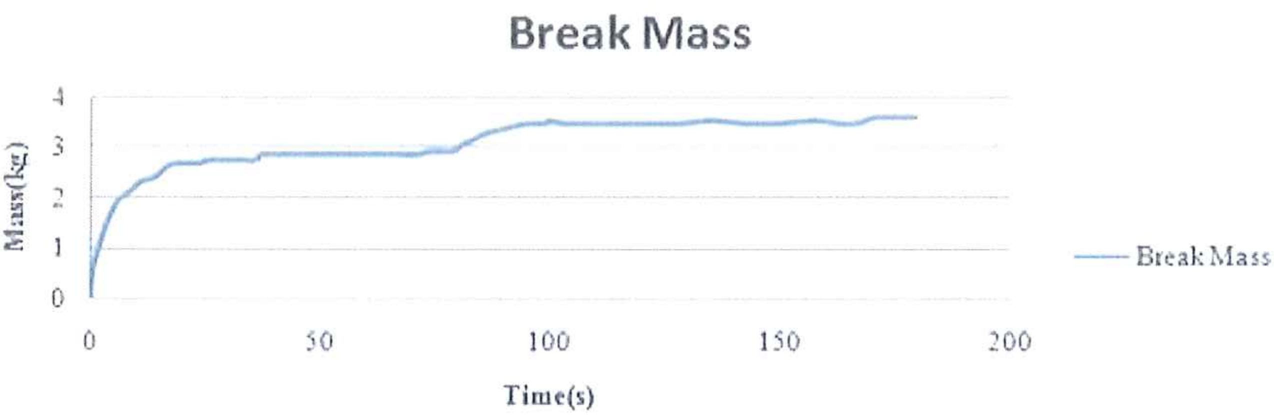

Figure10

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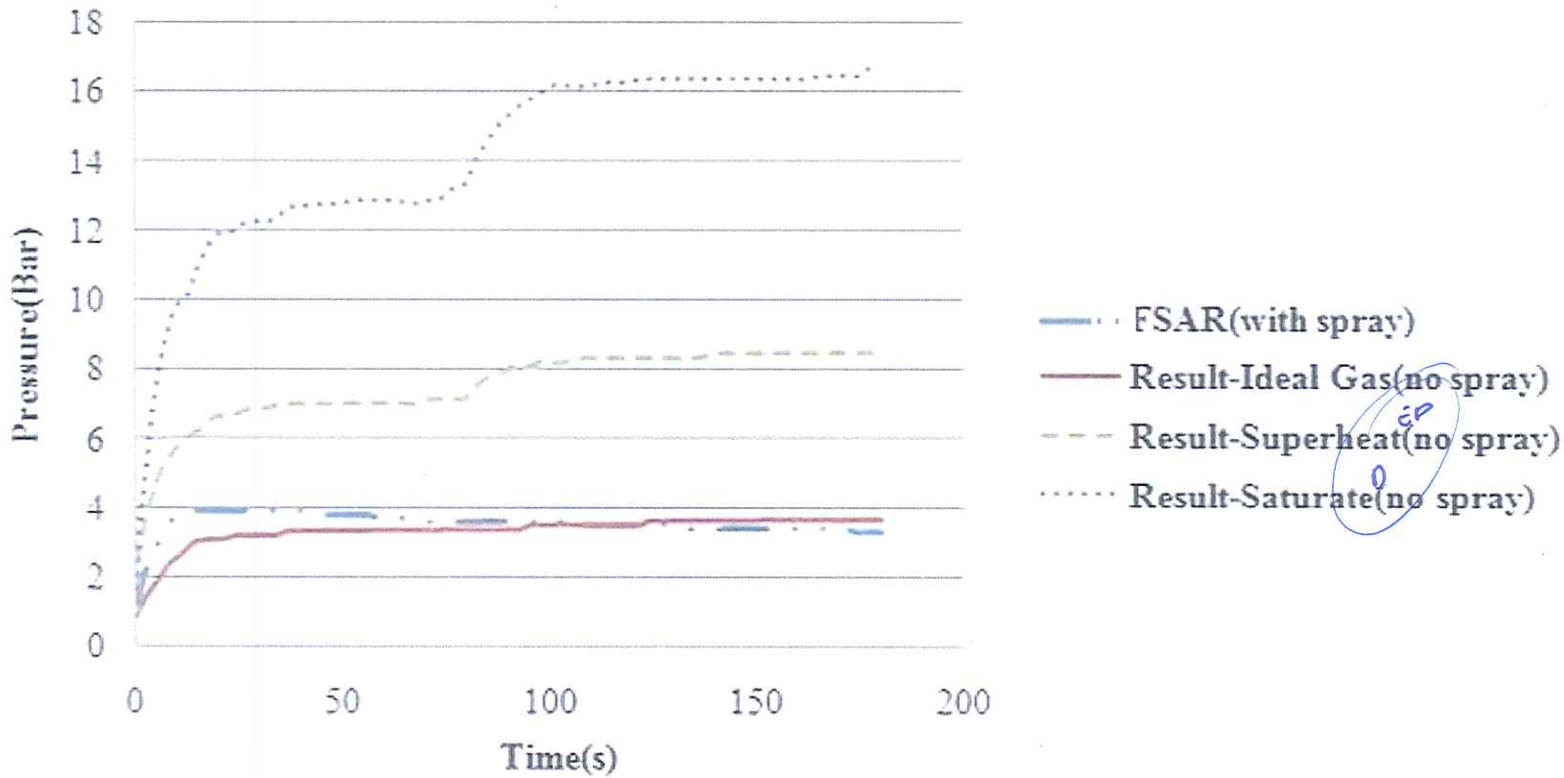

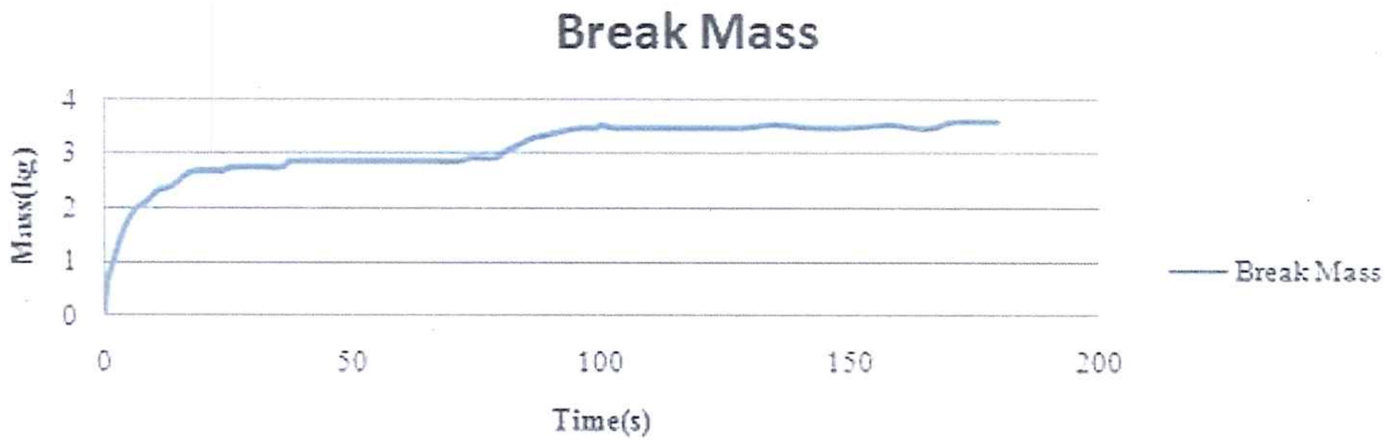

Figure11

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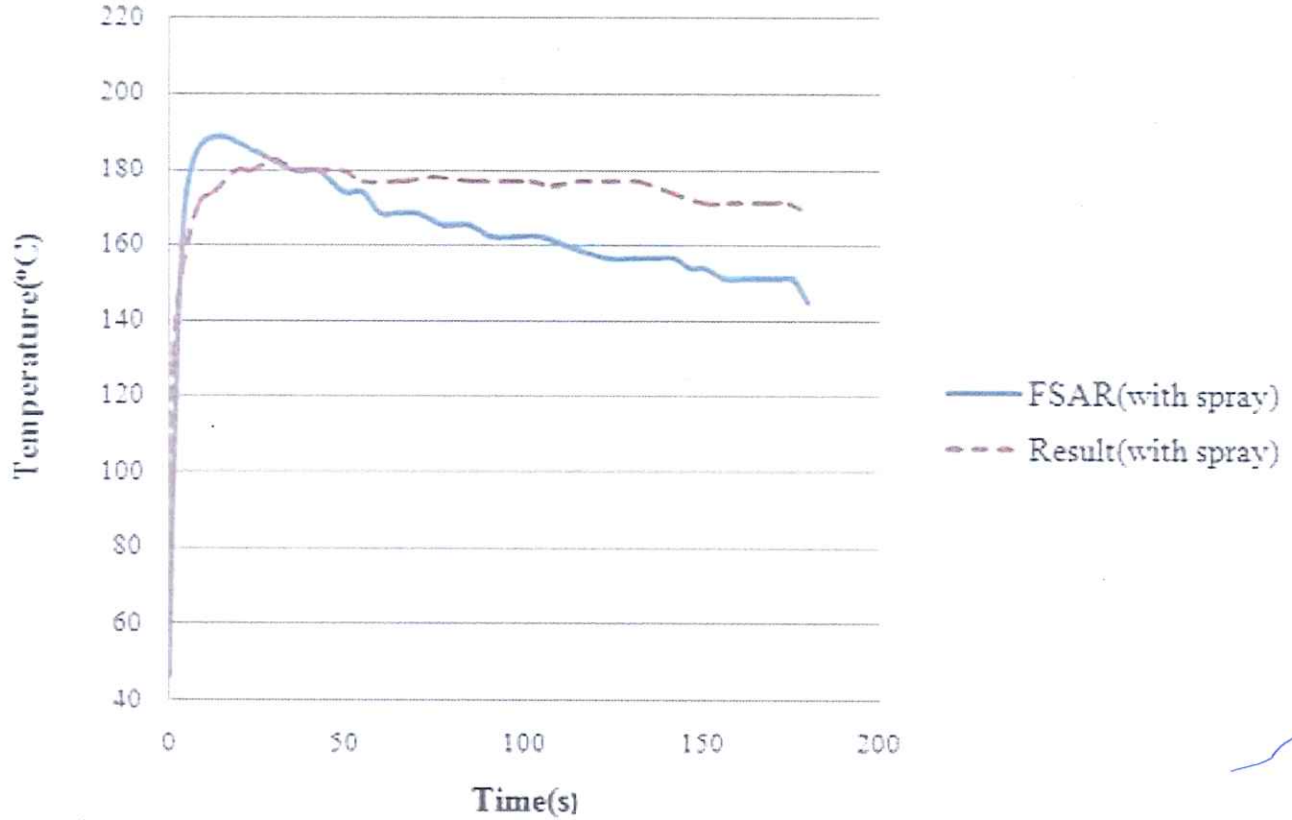

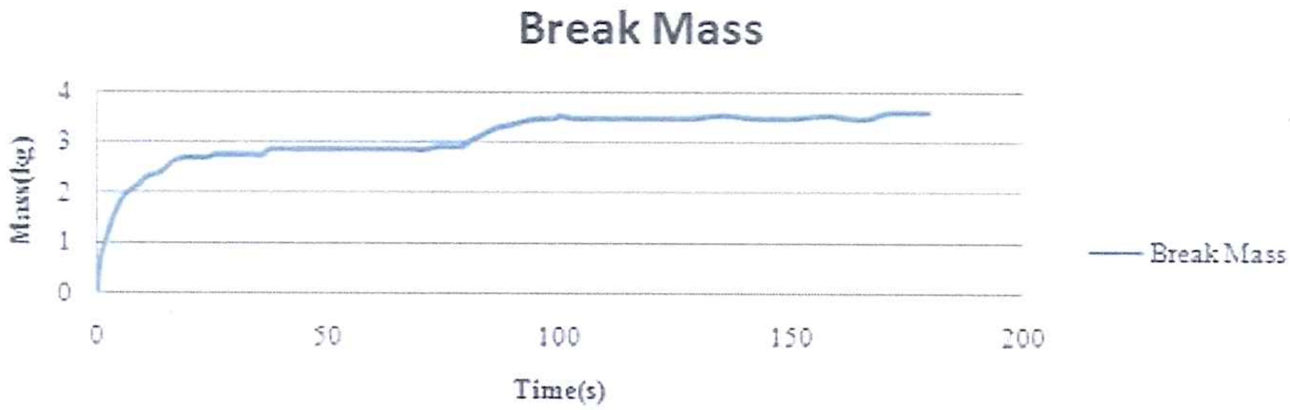

Figure12

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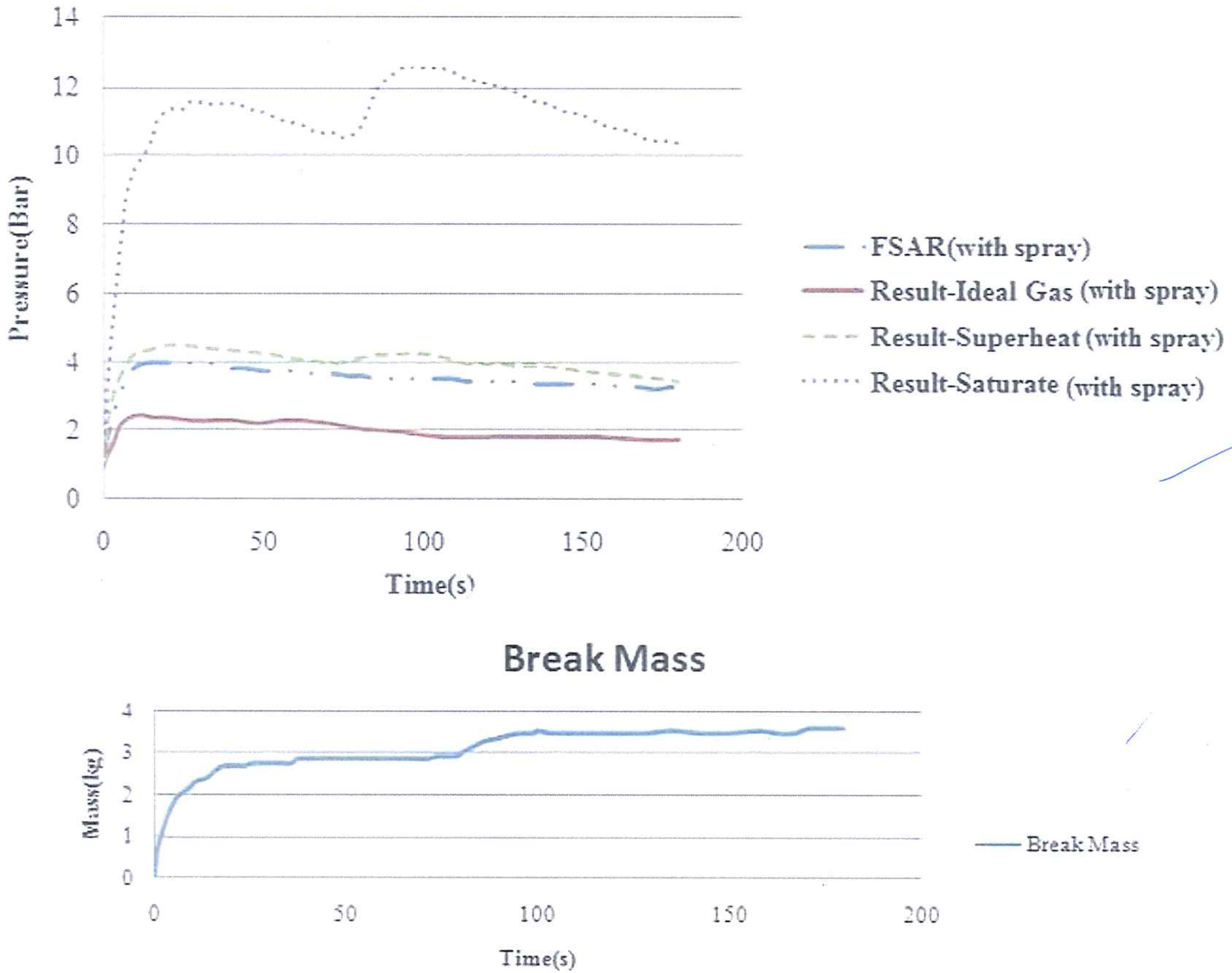
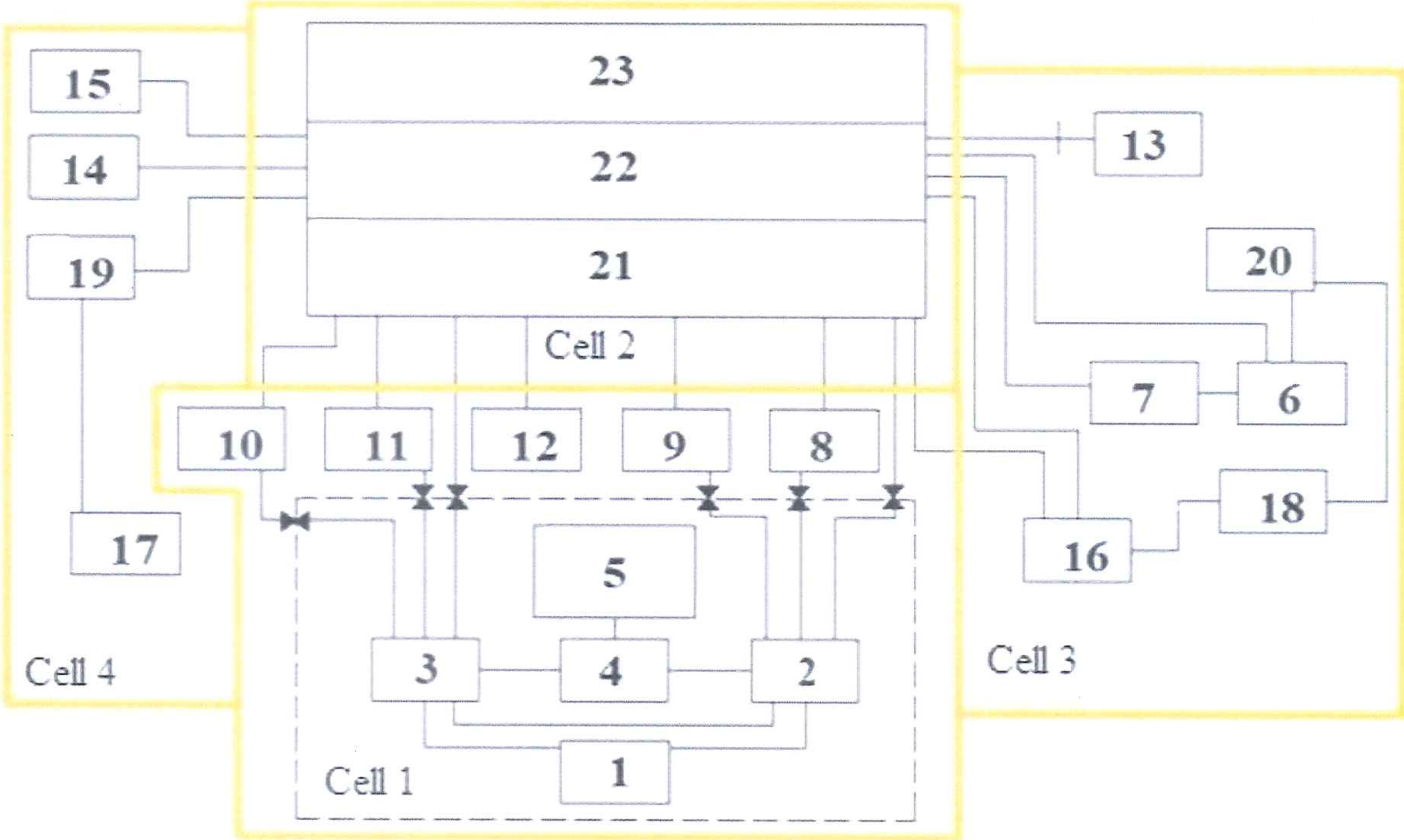


Figure13



23
22
21
15
14
19
17
13
20
7
6
18
16
10
11
12
9
8
5
3
4
2
1
Cell 1
Cell 2
Cell 3
Cell 4

Figure14
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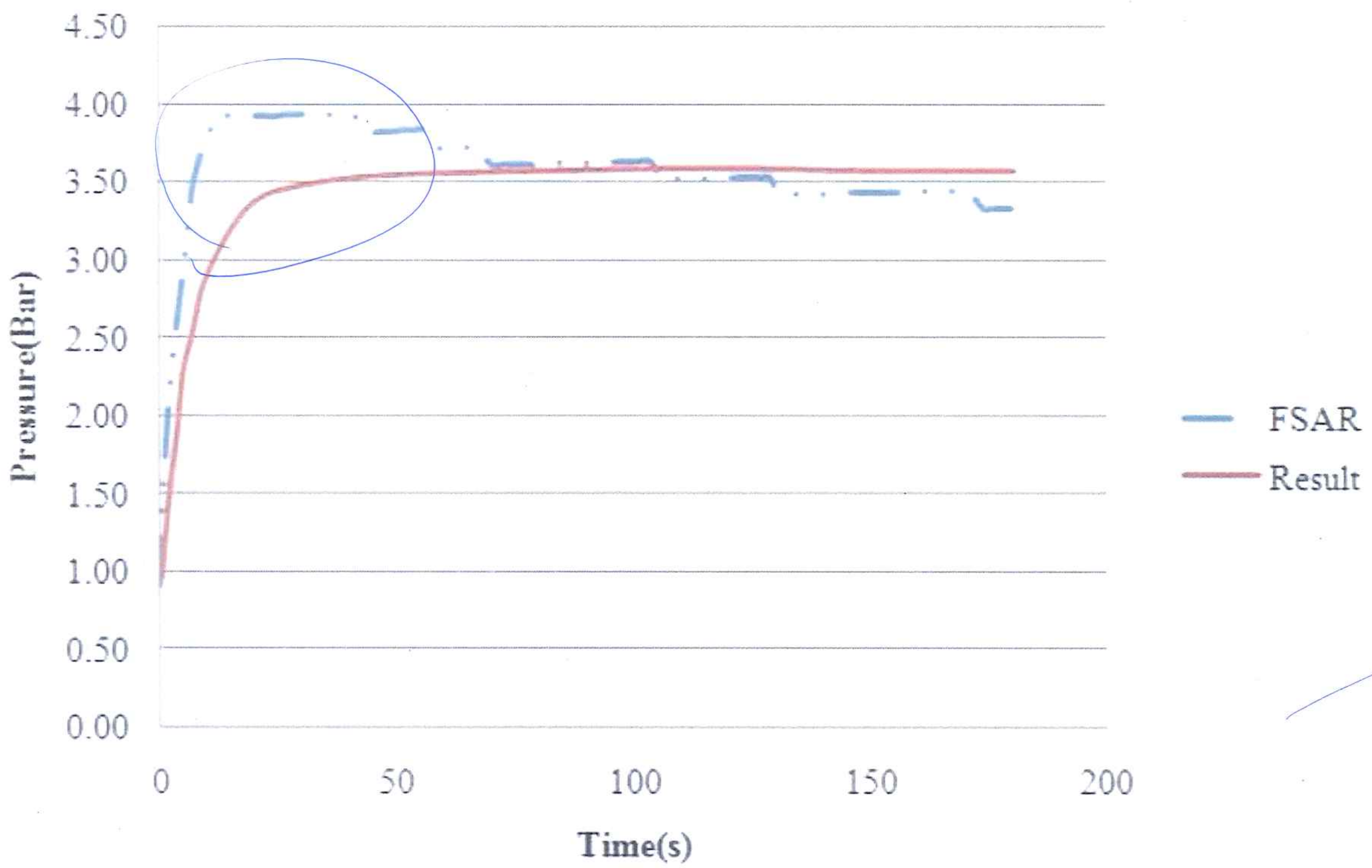

Figure15

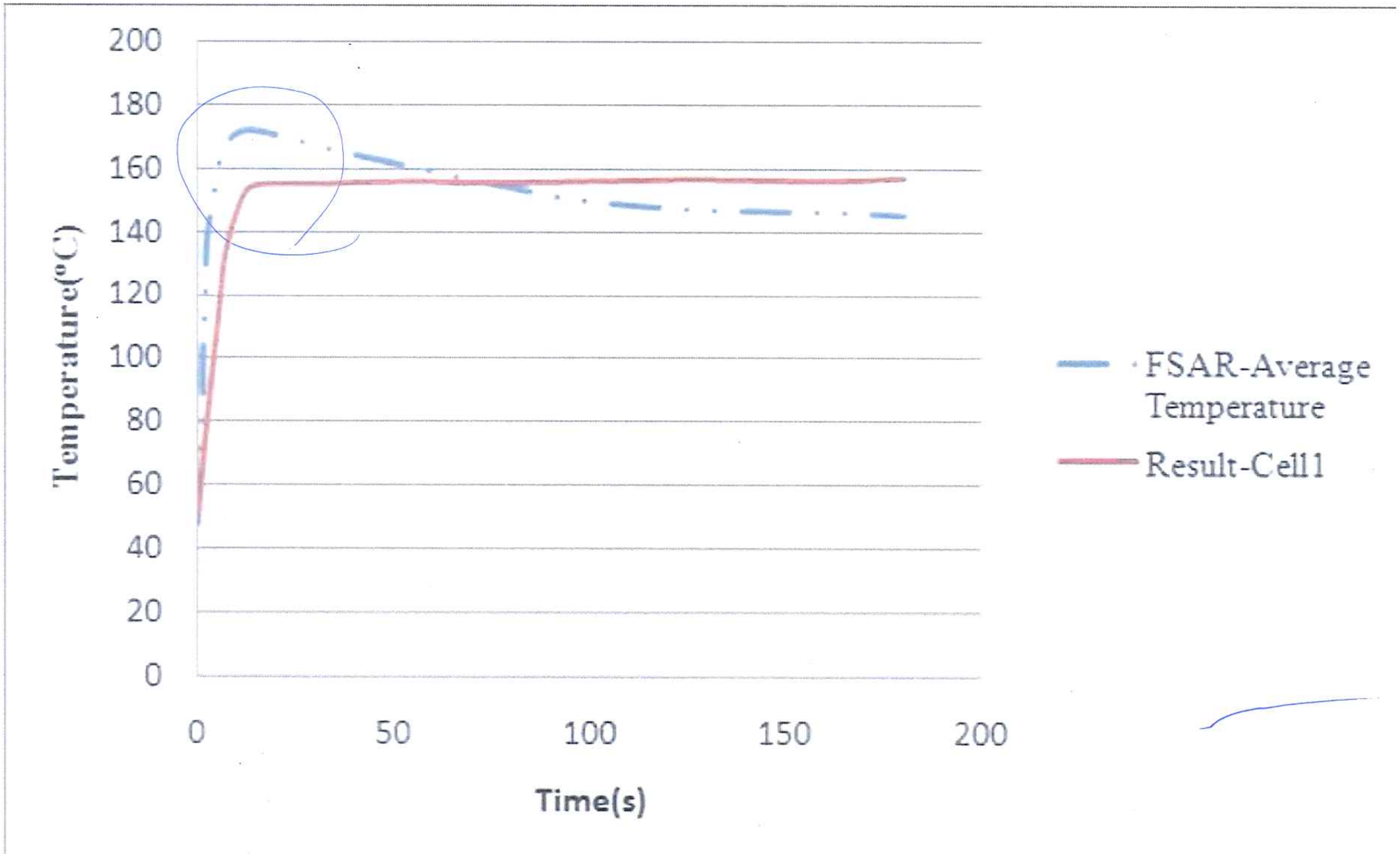
Temperature(°C)
200
180
160
140
120
100
80
60
40
20
0
0
50
100
150
200
Time(s)
FSAR-Average Temperature
Result-Cell1

Figure16

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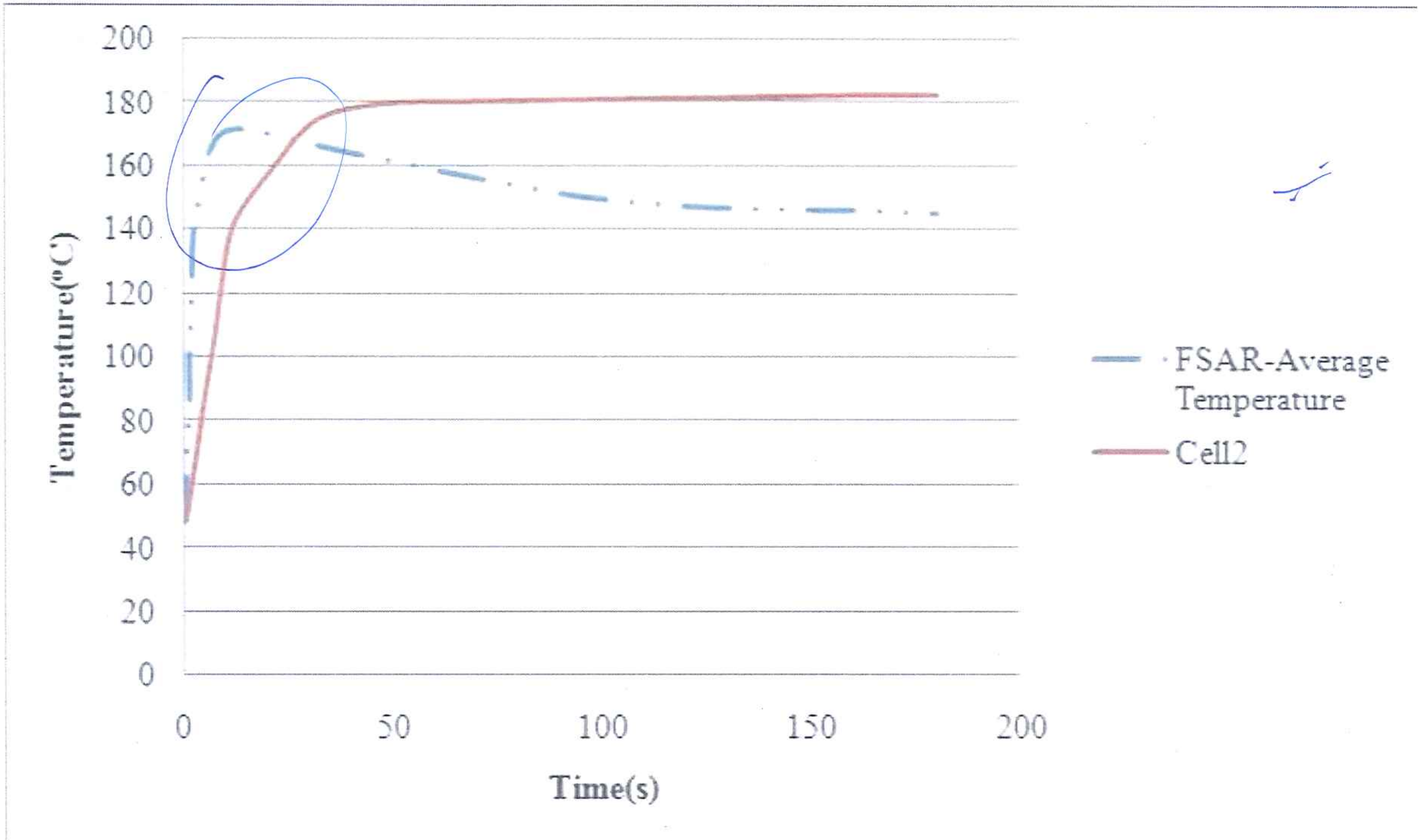

Figure17
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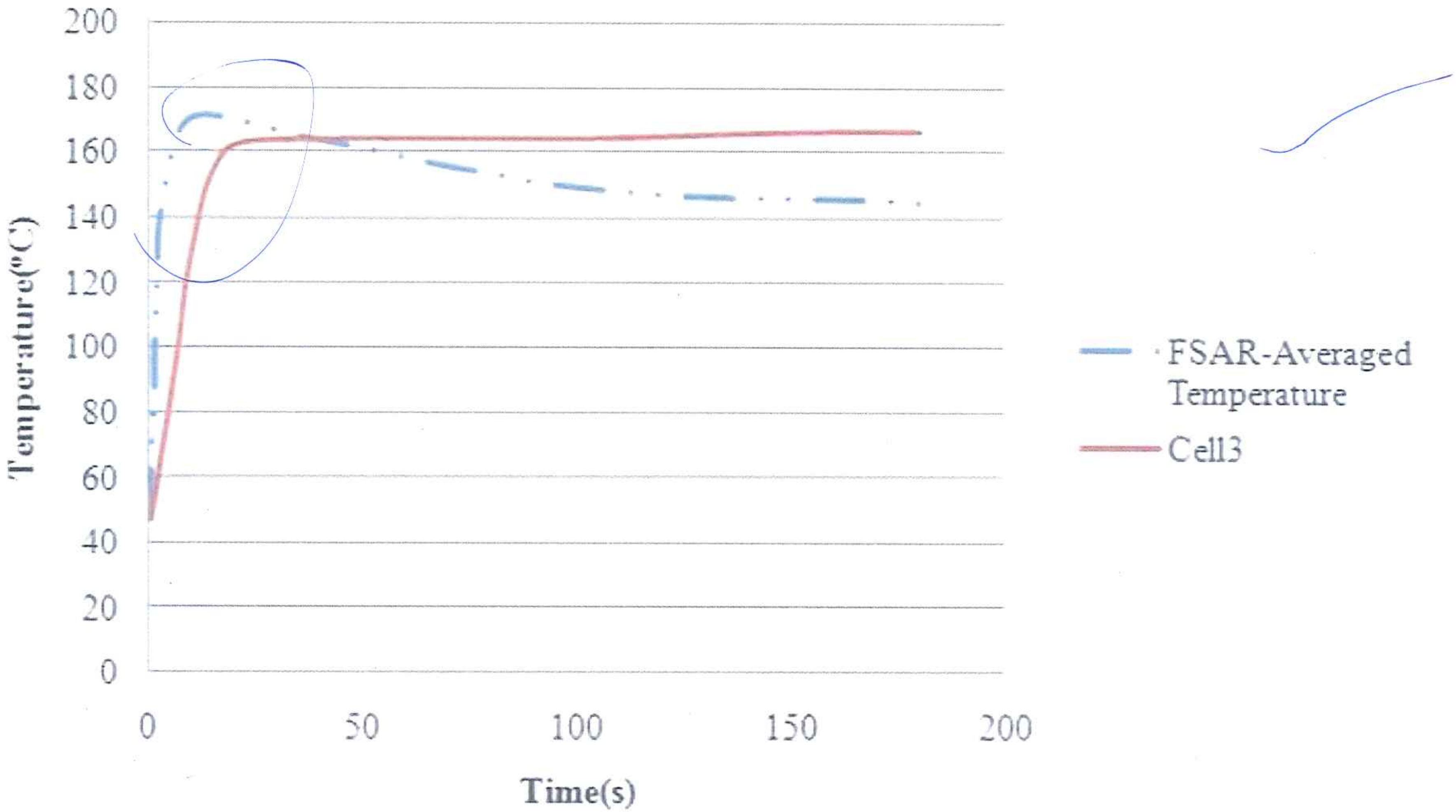

Figure18
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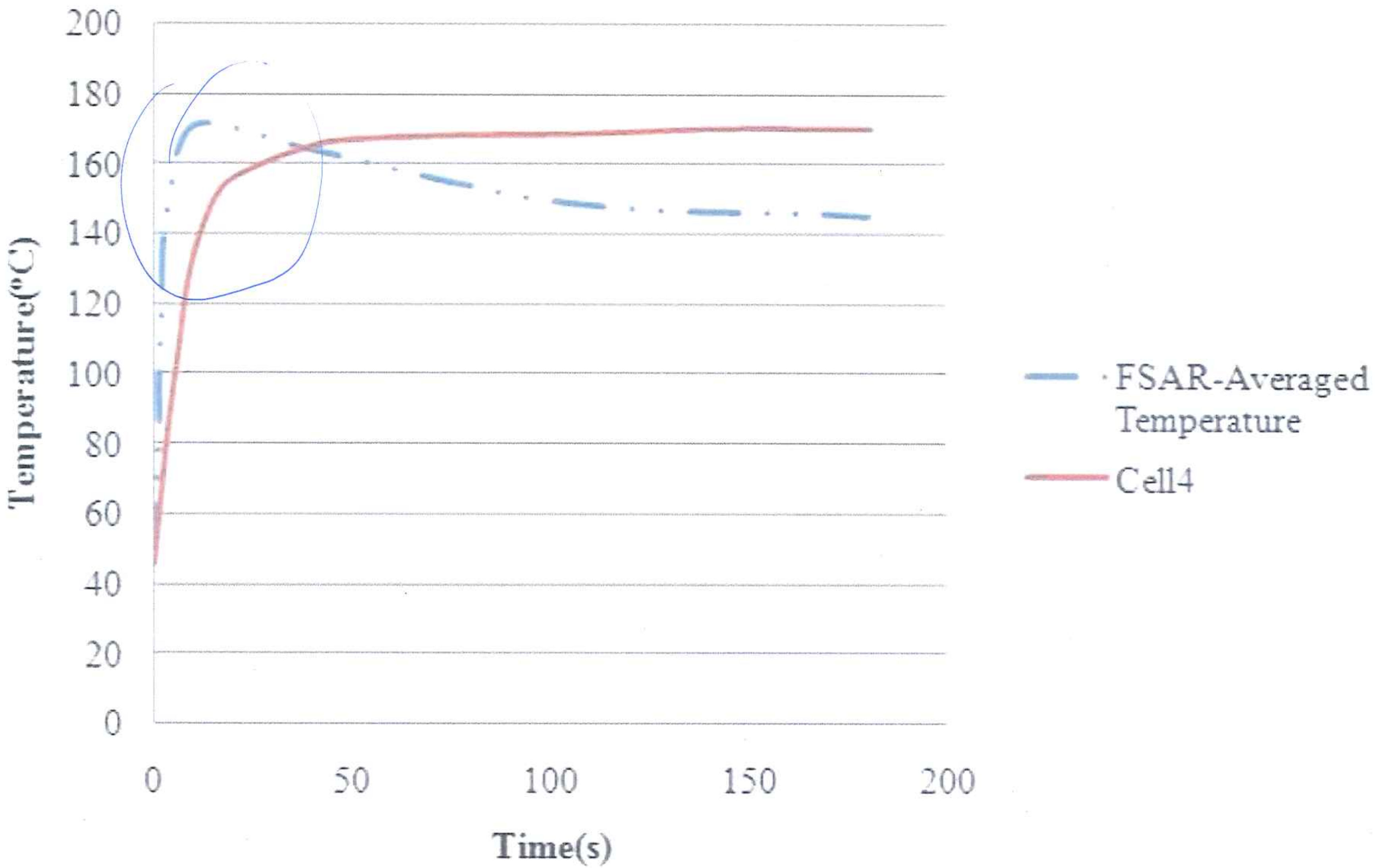

Table1

Table 1

BNPP containment specifications

Parameter	Value
Structural Parameters:	
Inner steel Diameter (mm)	28000
Inner steel thickness (mm)	1650
outer cast-in-situ reinforced concrete thickness (mm)	1750
Containment free Volume (m^3)	71040
Design parameters:	
Maximum internal pressure at 150 °C (MPa)	0.46
Maximum pneumatic test pressure at a temperature of up to 60 °C (MPa)	0.51
Peak temperature (in separate compartment) (°C)	Up to 206 °C during up to 5 minutes
Maximum (averaged over the volume) temperature (°C)	150
The main heat sinks inside the containment	
The total area of all the concrete walls (m^2)	18860
The surface area of the steel containment, the effective area of the metal structures and the equipment without heat insulation (m^2)	17712

Table 2

Specification of cells

Cell Number	Volume(m^3)	Effective connection surface (m^2)			
		1	2	3	4
1	10809	---	536.24	---	---
2	51580	536.24	---	389.49	247.4
3	1740	---	389.49	---	---
4	3570	---	247.4	---	---

*Abstract

Abstract:

Since the inception of nuclear power as a commercial energy source, safety has been recognized as a prime consideration in the design, construction, operation, maintenance and decommissioning of nuclear power plants. The release of radioactivity to the environment requires the failure of multiple safety systems and the breach of three physical barriers; fuel cladding, reactor cooling system and the containment. In this study nuclear reactor containment pressurization has been modeled in a Large Break Loss of Coolant Accident (LB-LOCA) and the effects of some main parameters on the modeling have been studied. First of all, containment has been considered as a control volume (single-cell model) and effects of steam state equation and spray (as a safety system in the containment accidents) have been studied on the model and results. In the second step, single-cell model has been developed to a multi-cell model to consider the effects of the nodalization and spatial location of cells in the containment pressurization in compared to single-cell model. Finally Bushehr Nuclear Power Plant (BNPP) containment has been considered as case study. Results of BNPP containment pressurization due to LB-LOCA have been compared between models and FSAR. Effects of Steam state equation, spray and multi-cell subdivisions have been considered in the results.

Keywords: Containment pressurization; Single-cell model; Multi-cell model, Steam state equation; Spray effect.