

MIT Pressurizer Insurge Test ST4 – Exercise Problem

OBJECTIVES

- Practice using the analysis techniques outlined in the presentation.
- Learn to use the cause and effect diagram to systematically examine the system behavior and identify problems.



Note that it is not expected that you will get an excellent match with the MIT pressurizer data after addressing the issues you identify for this exercise. At least one of the model issues requires a deeper analysis than can practically be addressed in the time allotted for this exercise. We will be discussing the errors in the model following the exercise and will identify any issues you have not addressed in the model.

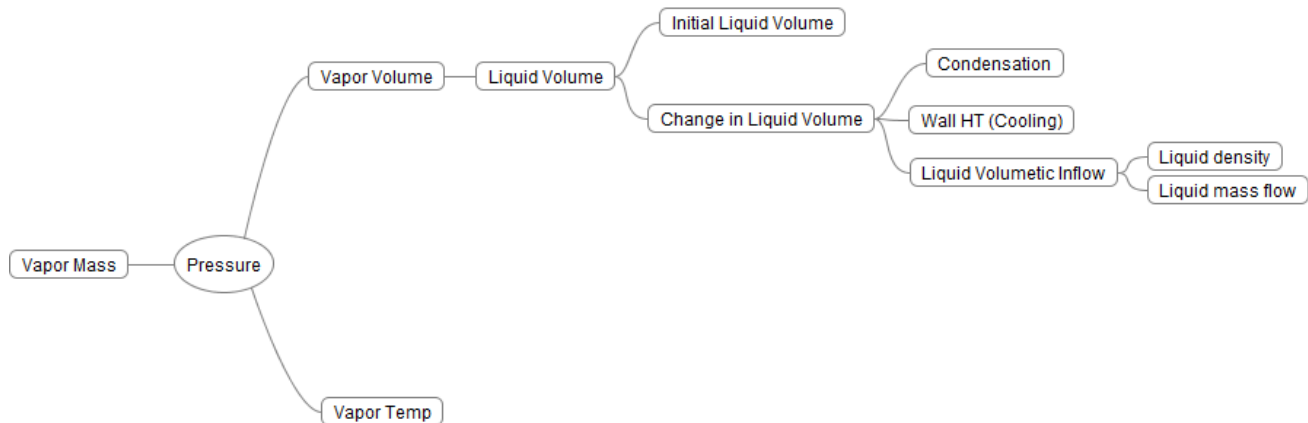
REFERENCES

1. H. R. Saedi, "Insurge Pressure Response and Heat Transfer for PWR Pressurizer", MIT Thesis 1982, <https://dspace.mit.edu/handle/1721.1/15523>
2. Sang-Nyung Kim, "An Experimental and Analytical Model of a PWR Pressurizer During Transients", MIT Dissertation 1984, <https://dspace.mit.edu/handle/1721.1/15611>

Page numbers from the reference will refer to PDF page numbers and not the page numbers depicted in the report. Note that MIT pressurizer test ST4 test, upon which this exercise is based, is included in Reference 1 along with a few other tests. Reference 2 contains tests that were performed later.

CAUSE AND EFFECT (C&E) DIAGRAM

The initial cause and effect diagram is shown below.



We would like to explore the branches in the order they are expected to have an impact on the pressure response as far as this can be determined. Which factors are expected to play the largest role in the MIT pressurizer insurge test ST4?

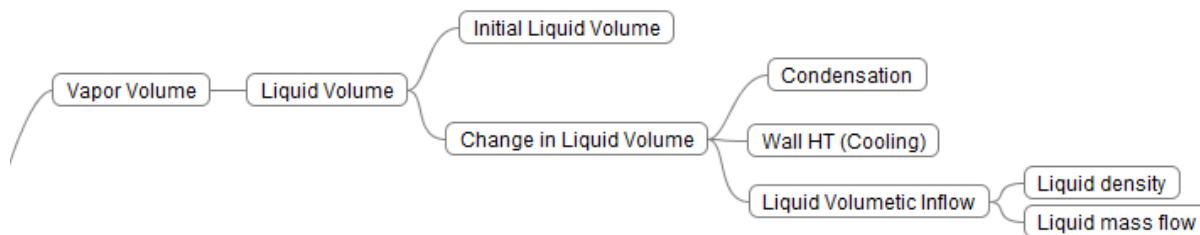
In this case a qualitative assessment can get us started. The response of the system is driven by the mass influx, so the vapor/liquid volume is of primary importance and will be our starting point.

Is there a simple way to quantify these effects?

- Vapor/Liquid Volume – the potential impact on pressure can be calculated via V_i^{vap}/V_f^{vap} (i.e., initial vapor volume divided by the final vapor volume). Since the test apparatus is basically a cylinder, the volume is $V=A \cdot L$ where A is the cross sectional area and L is the length (or level). The cross sectional area for a cylinder is constant, thus the change in liquid level can be used to indicate the change in volume, and the formula L_i^{vap}/L_f^{vap} characterizes the impact of change in vapor volume on the level.
- How might you quantify the impact of the change in temperature based on the available data? Think on this. We will consider it later in the exercise.
- Can you think of a method to estimate the amount of condensation and the impact on pressure? This will also be examined later in the exercise.

EXAMINE THE C&E VAPOR VOLUME BRANCH

The vapor volume branch will be used to illustrate how the C&E diagram can be used to guide technical analysis efforts. For the other two branches, less guidance will be provided for reviewing the model to give you an opportunity to practice this technique with more independence.



As discussed in the presentation, some of the factors in the vapor volume branch are significant and others are small and can be neglected.

- Initial Liquid Volume – Reference 1 indicates an initial level of 17 inches (0.43 m) on page 101. The apparatus height is 45 inches (1.134 m), so this is not negligible.
- Three factors potentially contribute to the change in liquid volume.

1. Condensation (SMALL) – steam is much less dense than water, so it seems relatively obvious that this is an unimportant factor for liquid volume. Is there a quick estimate to quantify this? One method is to assume all the steam condenses. This is a bounding case. How much would that impact the level?

- Calculate the saturated steam density from a pressure of 71.5 psia (0.49 MPa). While you are at it get the saturated liquid density as well.

Vapor Density =

Liquid Density =

- Calculate the initial vapor volume from the apparatus height of 1.134 m, the initial liquid level of 0.43 m, and the pipe diameter of 0.203 m.

Vapor Volume =

- Calculate the vapor mass from the volume and density

Vapor mass =

- Calculate the condensed vapor volume from the vapor mass and saturated liquid density

Condensed Volume =

- Calculate the change in level impact by dividing the volume by the pipe cross sectional area

Max change in level from condensation =

2. Wall Heat Transfer (SMALL) – This is a relatively short test, and the walls of the test apparatus are insulated, so this can be discounted. If you did want to estimate the impact of heat loss from the liquid on level (or liquid volume) how might you do this?
3. Liquid Volumetric Flow (BIG) – Reference 1 pages 101 indicates that the change in liquid level over the test is 18 inches (an estimate). Given that the initial liquid level was specified as 17 inches and the length of the test apparatus is 45 inches, this is a significant effect. From this information, the initial vapor length $L_i^{vap} = 45 \text{ in} - 17 \text{ in} = 28 \text{ in}$. The final vapor length is $L_f^{vap} = 28 \text{ in} - 18 \text{ in} = 10 \text{ in}$. Liquid level and liquid velocity are directly related to the Liquid Volumetric Inflow. We would like to examine these in more detail, so in accordance with the rules of the game, add them to the C&E diagram where you feel they best fit.
4. If change in vapor volume were the only factor impacting pressure, estimate the relative change in pressure via:

$$L_i^{vap} / L_f^{vap} =$$

The percent change is calculated by subtracting 1 then multiplying by 100. What is the percent change?

% change =

For this experiment, the liquid level characterizes the change in liquid/vapor volume. Since it is relatively easy to get this in TRACE, **liquid level will be used as a key analysis parameter**. We will calculate the change in level from the mass influx data next so that it is available for comparison with the simulation response.

CALCULATE LIQUID LEVEL FROM THE EXPERIMENTAL DATA

In this step, we practice the **Derived Data** quantitative analysis technique. The derived data will help us verify that we are accurately predicting the liquid level in the simulation, which is our first key analysis parameter.



Page 101 of reference 1 indicates an initial level of 17 inches and level rise was 18 inches. Both appear to be estimates. Figures A.4.3 through A.4.11 on pages 104-112 indicate the liquid level at different time snapshots. Careful measurement of the level indicated on page 104 indicates a starting level of 17.4 inches (Ref. 1 page 18). In this exercise we will assume 17 inches is correct, but you might consider adjusting this after the exercise to determine the impact on results.

The mass flux into the test apparatus was specified in the MIT pressurizer report (Reference 1 Figure A.4.2 on page 103). The volumetric flow would allow us to calculate a change in level, so density is needed to convert the mass flow to volumetric flow. To get the density we need temperature and pressure.

The initial pressure of 71.5 psia (0.49 MPa) can be taken from Figure A.4.1 on page 102 of reference 1. Page 31 of the reference indicates that the inflow temperature is 70 F (294 K). Do the following:

1. Open the excel workbook from exercise 1 (MIT-PZR-Data.xlsm).
2. Go to the tab Inflow BC.



Note that for convenience the water temperature and the pressure are included for you in the excel workbook. The test apparatus diameter (Pipe Diam) is also included along with the test apparatus height, initial water level and a conversion factor to convert lbm to kg.

3. Use the available information to convert the flow from lbm/s to kg/s in excel. If you are inexperienced with excel, consider getting some tips from the instructors as to how to do this calculation with minimal effort.



This excel workbook includes macros for calculating thermodynamic properties. Click on the tab **Functions**. This tab lists all of the thermodynamic values that can be calculated via excel macros. The macro names are listed in column I. The macros each take either 1 or 2 inputs. An example of the type of inputs expected are shown in columns B and C for input 1 and D and E for input 2 (if present). Column F show an example of each type of calculation. If you click on the cell, you will see the example calculation in the formula field. Column H provides a description of the value that is calculated.

4. Calculate the volumetric flow in m^3/s from the mass flow and the density. The density can be calculated using the macro `rho_pT`, where the `pT` indicates that this function takes pressure (`p`) and temperature (`T`) as inputs (in that order).



Note that the thermodynamic properties macros take pressure in units of Pa and not MPa.

5. Calculate the liquid influx velocity in m/s based on the volumetric flow and the cross sectional area of the test apparatus. The pipe diameter is included in the worksheet for convenience. The excel macro `PI ()` returns the value of π .
6. Integrate the liquid velocity over time to calculate the liquid level. The first value in this column can simply be set to the initial liquid level. The rest of the level

values can be calculated a $L_i + v * \Delta t$ where L_i is the previous level that was calculated. For more accuracy, you can use an average velocity over the timestep for v when calculating the new level. Again, if you are unfamiliar with how to do numerical integrals in excel, just ask one of the instructors for assistance.



The level should start at 0.43 m and stop at about 0.833 m. If you are not getting this result, review over you calculations or seek the help of an instructor.

7. Optionally add a plot of Liquid Level vs. Time to the excel worksheet.

This is an example, where a little bit of calculation provides you with useful information for better assessing your model.

ADD THE LIQUID LEVEL (KEY ANALYSIS PARAMETER) TO THE MODEL

Now that we calculate the liquid level vs. time, let's add a control system that plots the level vs. time for comparison (similar to the pressure vs. time control added earlier).

1. Open the MIT pressurizer SNAP model if not already open.
2. In the Default View tab of the **View Window**, add another **Function** control block (Dropdown menu → Control Systems → Control Blocks) and number is at **-110**. Remember that you need to unlock the view if it is currently locked to edit the controls.
3. Connect the existing time signal variable 10 to the new function block -110.
4. Select control block -110. Expand the Function Table and copy the time vs. liquid values from excel to the table.

We also need the simulation liquid level. The simplest way to get this is a collapsed liquid level signal variable. This assumes that all steam is converted to liquid, which is a source of error. Our previous calculation of the change in level due to the vapor gives us a way to estimate how much error this causes.



1. Select Dropdown menu → Control Systems → Signal Variables and select **Collapsed Water Level** from the list. Set the signal

number to **110**

2. In the **Properties Window** expand the Signal table and set the Hydraulic source to **Pipe 333** and have it sum cells **1** through **20**.
3. Lock the model and run the simulation.

ADD A LEVEL PLOT TO THE ANIMATION MODEL

Now the simulation liquid level and the derived liquid level are available, lets add a plot that helps us assess how well we model the liquid level.

1. In SNAP, select the animation model from the **Navigator Window**. If the animation model that you created was closed, open it again.
2. Select the connect icon  to connect to the simulation that was just run.
3. Add a new strip plot to the animation view (Drowdown menu → Indicators → Strip Plot).
4. Select the strip plot and expand the Plot Data table.
5. Add another data channel so that there are 2 channels. Connect both to the **Master** data source and set the Data Channels to **cb110** and **sv110**.
6. Press play  to see the simulation results. How do things look?

From the results, there is clearly a problem with how the mass inflow is set up.

EXAMINE THE FILL COMPONENT

According to the rules of the C&E game, we can look at things we have identified on our C&E diagram. One of the things that was added was the liquid velocity. This is configured in the fill component.

1. Select the MIT-PRZ-Model in **Navigator Window** in SNAP. Select Fill component 330 and expand the Fill Table in the **Properties Window**.
2. Compare the velocities in the Fill Table with the velocities that you calculated in

the excel workbook. How do the values compare?

3. The velocities don't match, so copy the table values from excel into the fill component.
4. Rerun the simulation.
5. Return to the animation model and examine the results. How do things look?

SEARCH FOR ANOTHER FILL ISSUE

Hmmm. Things still don't look right. What else might be the problem. Lets go back to the C&E diagram. We added liquid velocity as a factor that is directly related to volumetric flow. However liquid velocity isn't sufficient to determine the volumetric flow. A flow area is also needed. We want to examine the flow area, so add this to the C&E diagram and look at the model again.

1. Return to the MIT pressurizer model in SNAP.
2. The Fill doesn't have its own flow area, so select the Pipe that the fill is connected to.
3. In the [Properties Window](#), expand the **Component Geometry** table. Check that the 'Vol. Avg. Flow Areas' for the cell are correct. Fix if needed.
4. Select the **Edges** tab and check the junction areas. Note that it is the area of the first junction that really impacts the volumetric flow since this is the only area that directly interacts with the Fill component. Note that this is incorrect. Correct the flow area.
5. Run the model again and open the animation model and review the results. How does the level look now?

With these changes, our key analysis parameter (liquid level) is looking good. While the level looks OK now, the pressure response is not good. However, because we have focused our attention on the Vapor Volume branch first and have identified a key analysis parameter that helps verify that vapor volume is modeled correctly, we can focus our attention on the other primary factors that impact pressure.



One advantage of the C&E diagram is that it can help structure our analysis efforts. It can also help us determine when we have adequately looked down a particular path to describe a trend or find an error.

A question to consider. Suppose that there had been an error in the cell volume area in the vapor space region. How would that have been represented in the C&E diagram?

QUICK ASSESSMENT OF THE C&E TEMPERATURE AND MASS BRANCHES

ESTIMATE THE POTENTIAL CHANGE IN PRESSURE DUE TO CHANGE IN TEMPERATURE

Next we need to decide whether to examine the C&E branch associated with change in vapor temperature or change in vapor mass. Earlier in the exercise you were asked how you might quantify the impact of the change in temperature based on the available data (we know mass influx and pressure)?

Here is one way to estimate the change in pressure due to change in temperature from the data. We know the system pressure. Also note that the steam is at the saturation temperature. As the pressure increases, the steam should remain at saturation temperature. Thus we can calculate the saturation temperature at the initial and peak pressure for the transient and use this to assess the effect on pressure via T_f/T_i .



Note that the temperature must be referenced from absolute zero for this equation to be valid. Thus Kelvin or Rankine are appropriate for calculating the temperature ratio, but not Celcius or Fahrenheit.

To do a quick assessment of the relative importance of the temperature do the following:

1. Open the excel workbook and go to the Pressure Response tab.
2. For the given table of pressures, calculate the saturation temperatures using the Tsat_p macro (where the p at the end of the name indicates that this is a function of pressure alone). On the Functions tab you can see that this returns values in units of Kelvin.
3. Take the minimum and maximum saturation temperature from this table and calculate the value for:

$$T_f/T_i =$$

$$\% \text{ change} =$$

This should indicate less than 2% change in pressure due to the change in temperature.

Given that the mass influx potentially changes the pressure by about 200%, this is negligible.

ESTIMATE THE CHANGE IN PRESSURE DUE TO CHANGE IN VAPOR MASS

At this point we can use the following method to estimate how big the relative change in vapor mass m_f/m_i is compared to the T_f/T_i and V_i/V_f . Recall that we can estimate the change in pressure due to change in volume, mass, and temperature via the formula.

$$\frac{P_f}{P_i} = \frac{V_i}{V_f} \cdot \frac{m_f}{m_i} \cdot \frac{T_f}{T_i} \quad (1)$$

We have already calculated the volume ratio and the temperature ratio. The pressure ratio can be calculated from the pressure response for test ST4. How much did the actual pressure change by over the experiment? To calculate this:

1. In the excel workbook on the **Pressure Response** tab, calculate the ratio of the largest pressure to the smallest pressure.

$$P_f/P_i = \quad \quad \quad \% \text{ change} =$$

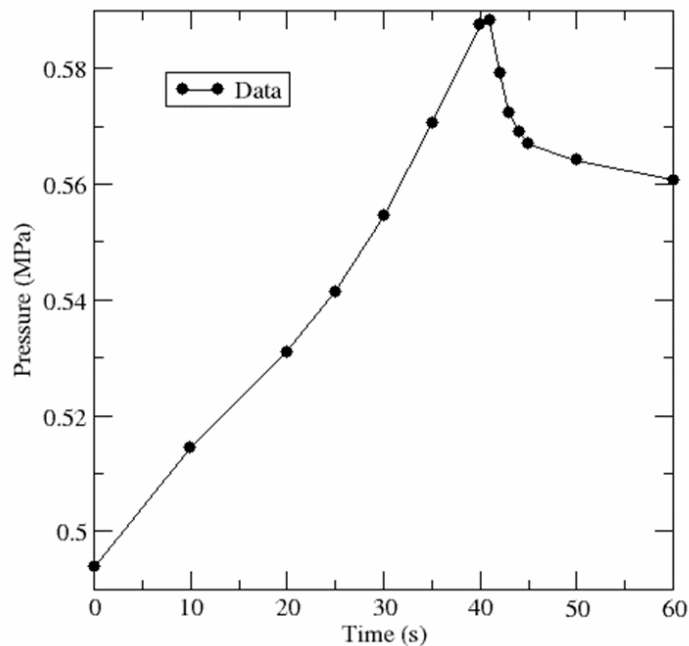
2. Solve equation (1) for m_f/m_i , substitute in the other values and solve to get the relative change in the vapor mass.

$$m_f/m_i = \frac{P_f}{P_i} \cdot \frac{V_f}{V_i} \cdot \frac{T_i}{T_f} =$$

This should show that the relative mass changes significantly – much more than the relative temperature. Thus we will explore the C&E mass change branch in more detail, but will not examine the C&E temperature change branch further.

C&E MASS BRANCH - DERIVED QUANTITIES

Let's consider the pressure response diagram again, and see if we can gain some insight from the response.



Lets describe what is happening:

1. At time 0 liquid is injected into the test apparatus and the pressure starts to increase. The volume decreases at a much faster rate than the pressure increases due to the fact that condensation is occurring as the pressure (and saturation temperature) increases.
2. Just after 40 seconds, the flow stops and the change in vapor volume essentially stops. The pressure continues to decrease due to wall HT / condensation.
3. After flow stops, the pressure decreases rapidly for a few seconds and then much more gradually. This indicates two different condensation rates, one associated with heating of the walls (stored energy) and the second more gradual, the heat flux to the environment after the walls reach the saturation temperature. We don't have a value for heat loss to the environment, so we would like to derive this if possible from the tail end pressure response.

CONDENSATION DERIVED DATA

The ideal gas law is useful for identifying the factors that impact pressure, and for performing a quick assessment of the importance of different parameters on the pressure response. However, steam tables are useful for a more careful and accurate analysis. Let's consider what information we can extract based on the data that we have.

The experimental data that is available is:

1. The system pressure response
2. The mass flux into the test apparatus
3. Geometry information for the test apparatus and walls
4. Material types (stainless steel walls, water entering the apparatus)
5. Water and vapor initial conditions (water and steam at saturation)
6. Temperature of the liquid entering the apparatus

We have already used this information to derive the following:

1. Liquid volumetric flow
2. Liquid velocity into the apparatus
3. Liquid level
4. Saturation temperature based on the pressure

What other useful information can we derive from this data:

1. Other saturation properties are available.
2. Vapor mass: $m_{vap} = \rho_{vap} V_{vap}$, V_{vap} = Volume of the vapor space
3. Volume of the vapor space:

$$V_{vap} = L_{vap} \pi D/4$$

4. Condensation rate: dm_{vap}/dt

5. Heat loss rate due to condensation: $Q_{cond} = h_{fg} \frac{dm_{vap}}{dt}$

6. Heat flux out the walls: Q_{cond}/A_{wall} , A_{wall} = Area of wall in the vapor space
7. Approximate area of the wall in the vapor space: $A_{wall} = \pi D L_{vap}$

The heat flux out the wall over the last few seconds allows us to predict an outer wall heat flux for the model. To calculate the above values:

1. Open the excel workbook.
2. One of the first values that we need is the vertical length of the vapor space. Select the **Inflow BC** tab. The vapor length is the test apparatus height minus the liquid level. The test apparatus height (Pipe Height) is provided on this tab. Calculate the vapor space length as a function of time using the liquid level and the test apparatus height.
3. Select the **Pressure Response** tab. We now need the vapor space length for the set of time points in the pressure response table. Use the **Interpolate** macro that is included in this workbook to get the level values at each of the times in the pressure response table. The **Interpolate** macro is described with an example on the **Interpolate** tab.



Calculating the level manually from the points in Inflow BC would be cumbersome. The **Interpolate** makes the job a lot easier. The interpolate function takes an x value, followed by a table of x values and a table of y values. It returns an interpolated y value for the x value that was passed in.

4. Calculate the volume of the vapor space by multiplying the vapor space level by $\pi D^2/4$, where the Pipe Diameter is provided on the worksheet for convenience.
5. Calculate the mass of the vapor by multiplying the vapor space volume by the vapor density calculated using the **rhoV_p** macro, which returns units of kg/m^3 .
6. Calculate the condensation rate dm_{vap}/dt by dividing the change in mass between two subsequent time points by the change in time.
7. Calculate the heat loss rate due to condensation by multiplying the condensation rate dm_{vap}/dt by the heat of vaporization / condensation macro **hLV_p**, which

returns units of J/kg .

8. Estimate the exposed surface area of the wall in the vapor space via $\pi D L_{vap}$, where L_{vap} is the length of the vapor space calculated in step 3, and the test apparatus diameter D is specified on the worksheet.
9. Calculate the wall heat flux by dividing the condensation rate by the vapor space wall surface area.
10. Update the wall heat flux in the model using a value consistent with the tail end heat flux (last two calculated values). You can change this for each cell in the heat structure. However for convenience, a heat flux numerics variable was defined that can be used to set the heat flux for all of the cells. The variable is named 'Losses'. You can check the heat structure to see where this is used to set the boundary condition on each cell.

Compare the magnitude of the wall heat flux at the tail end of the simulation (steady state heat losses) with the heat flux during liquid inflow (adding stored energy to the walls plus steady state heat flux). Proportionally, how big is the wall stored energy phenomenon vs. wall heat flux? This suggests that getting the metal mass correct for this model makes a significant difference.

C&E VAPOR MASS BRANCH

Expand the C&E vapor mass branch or use a previously expanded diagram. You can use MindMap if you like.

Vapor Mass —

EXPLORING THE C&E MASS BRANCH

Now you can use the techniques we have discussed to explore the mass branch of the Cause and Effect diagram and try to improve the MIT pressurizer prediction. Remember the rules of the game for this exercise. You can look at any parameter you like, but first represent it in the C&E diagram (i.e., determine the physics that is happening and how it ties back to change in vapor mass). You can use AptPlot to explore the system response.

Note that there are six issues we have identified in this model:

- There are four input errors in this model, two of which have already been identified in the C&E level branch.
- There is one refinement of the model that can impact results.
- There is one subtle issue that might be considered a modeling error that has a significant impact on results. It may be difficult to identify in the time allotted.

The next page includes a table where you can list any items you identify as issues and indicate how the issue impacts the pressure prediction. A couple of extra rows have been added in case you identify items we did not consider for this exercise.

When you identify an issue, see if you can correct it. Then run the simulation and check the results in the animation.

Issue	How does this negatively impact prediction of the pressure?
1. Incorrect Liquid Velocity	
2. Incorrect pipe junction area	
3.	
4.	
5.	
6.	