Brayton Cycle (Gas Turbine Power Cycle)

Objective

The objective of this lab exercise is to gain practical knowledge of the Brayton cycle. The Brayton cycle illustrates the cold-air-standard assumption (constant specific heats at room temperature) model of a gas turbine power cycle. A portable propulsion laboratory[1] containing a Model SR-30 turbojet is used in this exercise. The student shall apply the basic equations for Brayton cycle analysis by using empirical measurements at different points in the Brayton cycle.

Figure 1: TTL Mini-Lab manufactured by Turbine Technologies Ltd. (TTL)

Background

A simple gas turbine engine has three main components: a **compressor** section, **a combustion chamber** and a **turbine** section. Basic operation entails drawing atmospheric air into the compressor where it is heated through compression. The compressed and heated air is mixed with fuel in the combustion chamber. The air/fuel mixture burns at constant pressure in the combustion chamber. The resulting hot gas is directed to the turbine section where it expands. As the gas expands it produces a thrust reaction and performs work by turning the turbine. The turbine is connected to the compressor by a shaft. The resulting shaft work is used to drive the compressor and auxiliary power supplies.

The gas turbine has wide spread application. Most notably, it is used to power and propel aircraft and large ships. In some cases only the thrust resulting from the expanding gas exiting the turbine is used for propulsion and the shaft work is used to drive the compressor and power electrical systems. In turbo-fan engines some of the shaft work is used to drive a large fan that aids in propulsion. In other applications, such as helicopters and ships, propulsion is achieved through the shaft work, which is used to drive transmission/gear boxes that are connected to the rotor blades or propeller, respectively. Gas turbines are also commonly used to drive large electrical generators in power plant applications.

Theory

The Brayton cycle consists of four basic processes (see Figure3 & 4). Low-pressure air is drawn into the compressor section and undergoes **isentropic compression**. Next, the heated and compressed air is combined with fuel in the combustion chamber. The air/fuel mixture

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[1] Manufactured by Turbine Technologies Ltd. Called TTL Mini-Lab

experiences reversible constant pressure heat addition. The resulting hot gas enters the turbine section where it **undergoes isentropic expansion**. To complete the cycle (the exhaust and intake in the open cycle) the gas experiences **reversible constant pressure** heat rejection. Thermodynamics and the First Law of Thermodynamics determine the overall energy transfer. The following assumptions are used when analyzing the gas turbine cycles:

1. The working fluid (air) is an ideal gas throughout the cycle.
2. The combustion process is constant-pressure heat addition.
3. The exhaust process is constant-pressure heat rejection.
4. The specific heat is constant at the lowest temperature in the cycle.

To perform the thermodynamic analysis on the cycle each component is modeled as a control volume. All processes are executed in steady-flow sections and can be analyzed as a steady-flow process, expressed on a basis of unit mass as $q - w = h_{exit} - h_{inlet}$.

The thermal efficiency of the ideal Brayton cycle is:

$$\eta_{thBrayton} = w_{net} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)} = 1 - \frac{T_1\left(\frac{T_4}{T_1 - 1}\right)}{T_2\left(\frac{T_3}{T_2 - 1}\right)}$$

Processes 1 –2 and 3 – 4 are isentropic, and $P_2 = P_3$ and $P_1 = P_4$ therefore:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

Using these relationships the thermal efficiency simplifies to:

$$\eta_{th,Brayton} = 1 - \frac{1}{r_P^{(k-1)/k}}$$

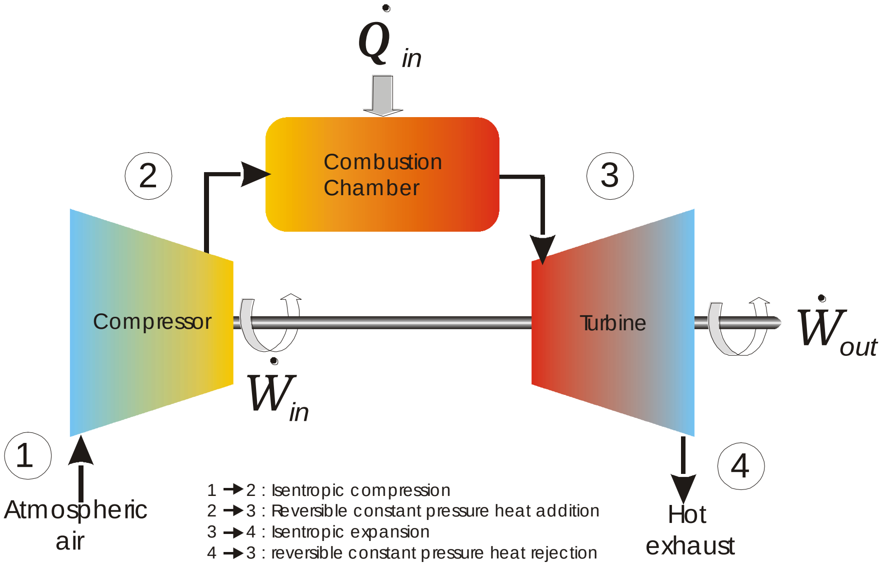
Where r_P is the pressure ratio = P_2/P_1 and k is specific heat ratio, which is 1.4 for air at room temperature.

The back work ratio is defined as the ratio of compressor work to turbine work and is given as:

$$r_{bw} = w_{COMP,in}/w_{TURB,out}$$

Figure 2: SR-30 Engine.

Figure 3: Basic Brayton cycle.



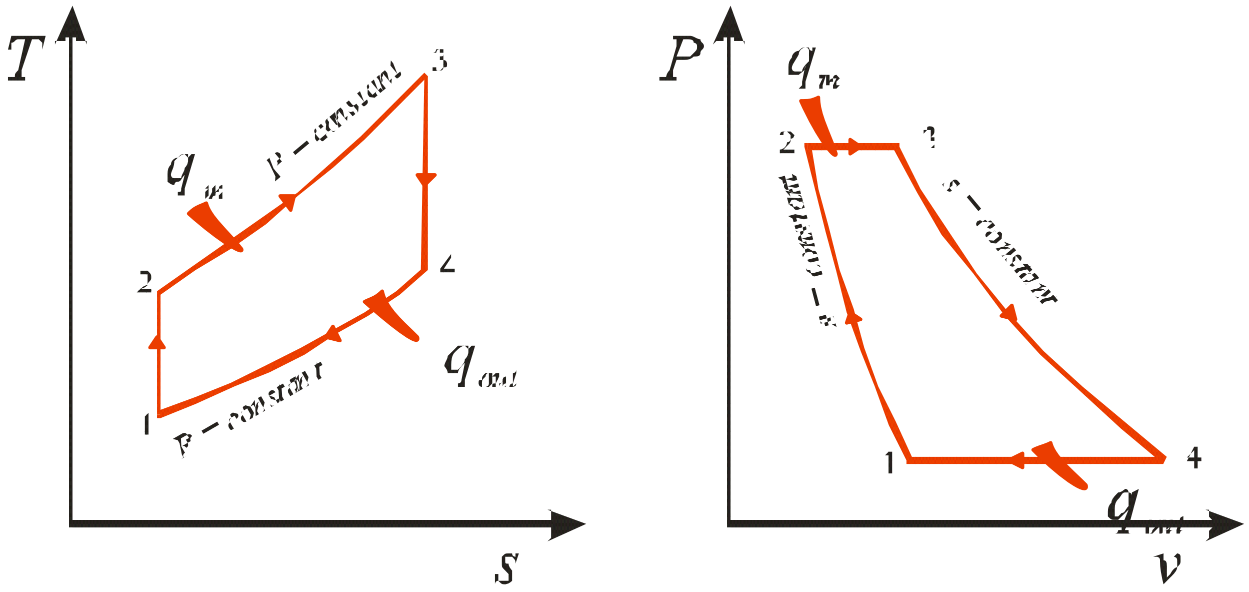


Figure 4: $T - s$ and $P - v$ diagrams for the ideal Brayton cycle.

a) Compressor Section

Ideally there is no heat transfer from the control volume to the surroundings. Under steady-state conditions (and neglecting potential and kinetic energy effects) the First Law for the control volume is:

$$\dot{\boldsymbol{H}}_{\boldsymbol{in}} - \dot{\boldsymbol{W}}_{\boldsymbol{in}} = \dot{\boldsymbol{H}}_{\boldsymbol{in}}$$

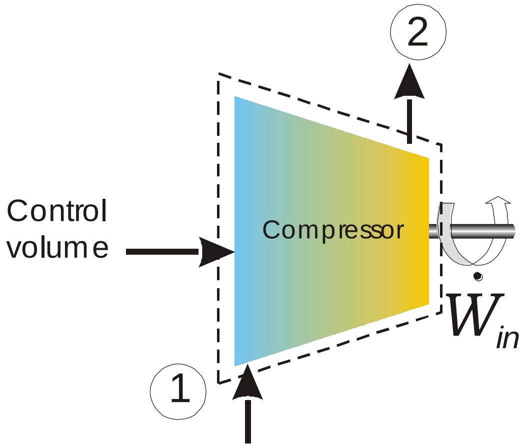


Figure 5: Compressor, control volume model.

This can be rewritten in a more specific form of the First Law considering there is one flow into and one flow out of the control volume:

$$\dot{m}h_{in} - \dot{m}w_c = \dot{m}h_{out}$$

The terms are rearranged and the enthalpy is rewritten using the equation of state: $dh = c_p dT$, which assumes the working fluid is an ideal gas and constant specific heat.

$$-w_c = h_{out} - h_{in} = c_{p,c}(T_{C,out} - T_{C,in})$$

For accurate analysis of the compressor the specific heat of the fluid should be evaluated at the linear average between the inlet temperature and the outlet temperature: $(T_{in} - T_{out})/2$.

The irreversibility present in the real process can be modeled by calculating the efficiency (η) of the compressor:

$$\eta_C = \frac{w_{c,s}}{w_{c,a}} = \frac{h_{out,s} - h_{in}}{h_{out,as} - h_{in}} = \frac{T_{out,s} - T_{in}}{T_{out,a} - T_{in}}$$

Where the subscript "*s*" refers to the ideal or isentropic process and the subscript "*a*" refers to the real or actual process. For a perfect gas the above equation is reduced to:

$$\eta_C = \frac{T_{out,s} - T_{in}}{T_{out,a} - T_{in}}$$

b) Combustion Section

In the ideal combustion section no work is transferred to the surroundings from the control volume. Under steady-state conditions, and neglecting kinetic and potential energy effects, the first law application is:

$$\dot{H}_{in} - \dot{Q}_{in} = \dot{H}_{out}$$

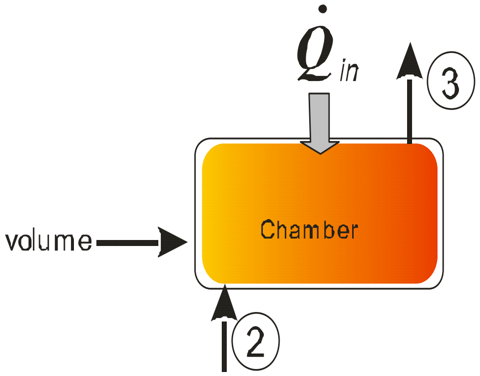


Figure 6: Combustion chamber, constant pressure model.

Considering that we have one flow in and one flow out of the control volume, we can use a more specific form of the first law.

$$\dot{m}h_{in} - \dot{m}q_B - \dot{m}h_{out}$$

Or, rearrange by grouping the terms associated with each stream: $q_B = h_{out} - h_{in}$. Assuming ideal gasses and constant specific heats, enthalpy differences are readily expressed as the temperature differences as:

$$q_B = C_{p,B}\,(T_{B,out} - T_{B,in})$$

Again, to be more accurate, the specific heat of each fluid should be evaluated at the linear average between its inlet and outlet temperature.

C) Turbine Section

No heat is transferred to the surroundings in the ideal conditions for a control volume turbine section. Under steady-state conditions, and neglecting kinetic energy and potential energy effects, the first law for this control volume is then written:

$$\dot{m}h_{in} - \dot{m}w_T - \dot{m}h_{out}$$

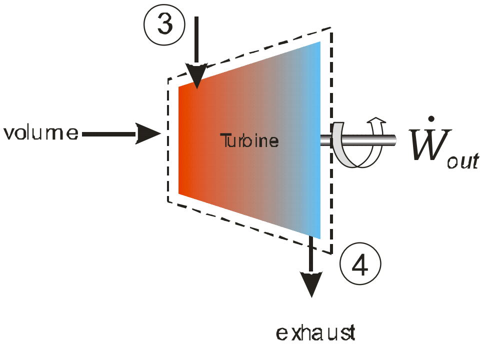


Figure 7: Turbine, control volume model

Rearranging the terms associated with each stream gives: $- w_T = h_{out} - h_{in}$. Assuming ideal gasses and constant specific heats, enthalpy differences are readily expressed as the temperature differences as:

$$- w_T = C_{p,T}\,(T_{T,out} - T_{T,in})$$

To be more accurate, the specific heat of each fluid should be evaluated at the linear average between its inlet and outlet temperature.

The irreversibility present in the real process can be modeled by calculating the efficiency (η) of the compressor:

$$\eta_T = \frac{w_{c,a}}{w_{c,s}} = \frac{h_{out,a} - h_{in}}{h_{out,s} - h_{in}} = \frac{T_{out,a} - T_{in}}{T_{out,s} - T_{in}}$$

Where the subscript "*s*" refers to the ideal or isentropic process and the subscript "*a*" refers to the real or actual process. For a perfect gas the above equation is reduced to:

$$\eta_T = \frac{T_{out,a} - T_{in}}{T_{out,s} - T_{in}}$$

EXPERIMENT PROCEDURES

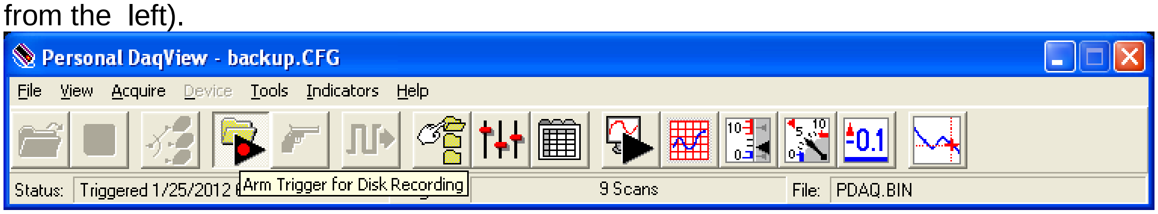
WARNING

Before starting the experiment, make sure you read the following.

1. Make sure that neither you nor any of your belongings are placed in front of the intake or the exhaust sections of the SR-30 engine while it is operating.
2. Ear protection must be worn while the SR-30 engine is operating.
3. The SR-30 engine rotates at very fast speeds. Therefore, stay far away from the test bench to avoid injury if the engine malfunctions.
4. Make sure the engine low-oil-pressure light extinguishes immediately after engine start-up. If the light stays illuminated or lights at any time during engine operation turn off the fuel flow to the SR-30 engine immediately.
5. If at any time you suspect the SR-30 engine is not operating properly immediately turn off the fuel flow and shut down the engine.

Experiment Procedures

1. The Professor will walk you through the inspection procedure.
2. Inspect for free rotation of the compressor/turbine.
3. Ensure there are no obstructions in front of the intake or exhaust of the SR-30 engine.
4. Check fuel and oil levels.
5. Connect the air hose from the portable compressor or compressed air supply from Facilities to the TTL Mini-Lab.
6. Turn on compressed air to build-up pressure.
7. Connect USB to the computer and the engine
8. Turn on power to the computer and launch **pDAQVIEW** program using the icon on the desktop.
9. Prior to operating the engine ensure you know how to read and retrieve data from the pDAQVIEW program.
10. On the Main Control Window (data acquisition tool bar), select **File – Open.**
11. Double Click on **backup.CFG**
12. On the data acquisition tool bar **click** on the arm trigger for disk recording icon (fourth icon from the left).

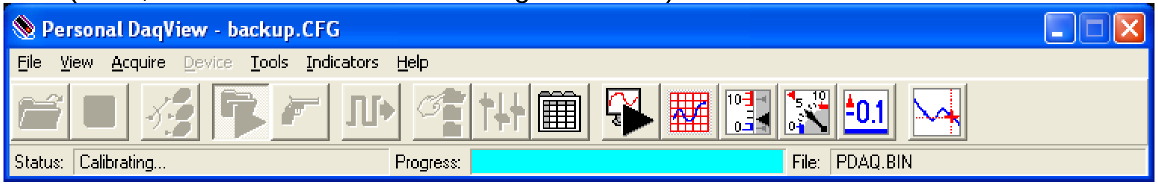


Status: Triggered 1/25/2012

9 Scans

File: PDAQ.BIN

13. When the program asks to overwrite data, answer '**yes**'. The progress bar should turn blue (if not, there is an error in the configuration file).



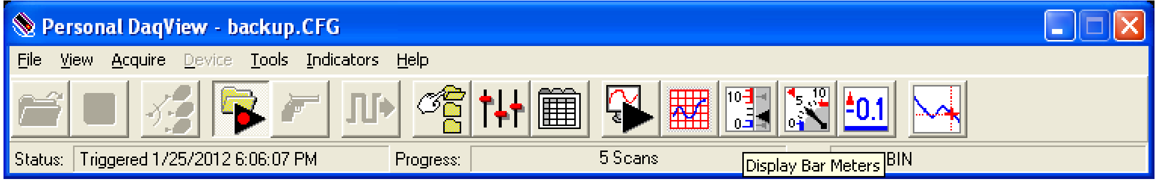
Status: Calibrating...

Progress:

File: PDAQ.BIN

14. Turn the key on the jet engine to the '**on'** setting

15. In the PDaqView software, open the '**Bar Graph Meter'**



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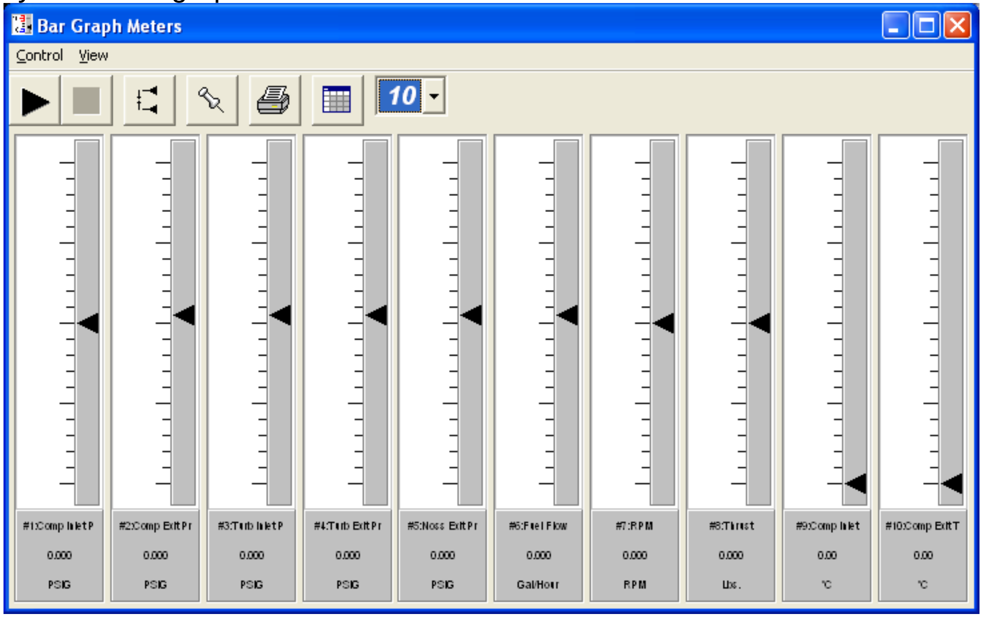
Progress:

5 Scans

BIN

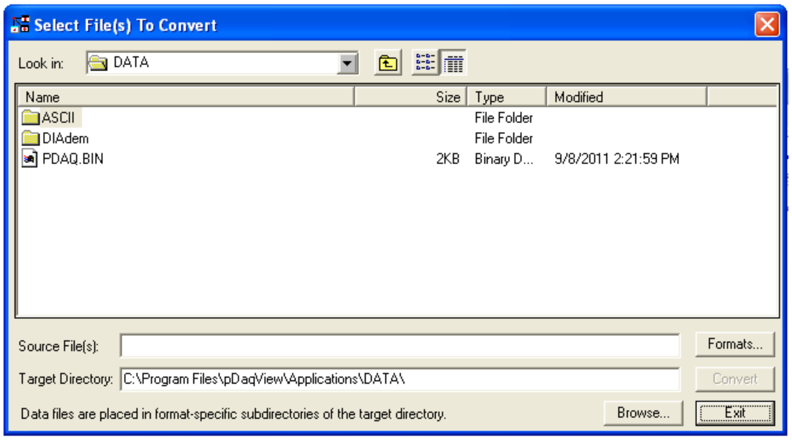
16. Click Play in the bar graph meter window



#1:Comp InletP	#2:Comp ExitPr	#3:Turb InletP	#4:Turb ExitPr	#5:Noss ExitPr	#6:Fuel Flow	#7:RPM	#8:Thrust	#9:Comp Inlet	#10:Comp ExitT
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.00	0.00
PSIG	PSIG	PSIG	PSIG	PSIG	Gal/Hour	RPM	Lbs.	°C	°C

<u>AT THIS POINT THE PROGRAM IS SET UP AND ID RECORDING DATA</u>

17. Have one team member ready to obtain exit gas temperature with laser gun.
18. Press the green (**'Start'**) button on the jet engine. The jet engine will start up.
19. After RPM stabilizes (about 15-20 seconds), slowly increase RPM with lever to the desired RPM (Exit gas temperature should not exceed 550 degrees C).
20. Collect Exit Gas Temperature (EGT) readings from laser gun every 5 seconds.
21. Run the engine for 45-60 seconds
22. Press Red button to stop engine
23. Click stop button on screen to stop data logging
24. Click arm trigger for disk recording icon
25. The program will ask if you would like to overwrite the existing file. Answer 'yes to all'
26. Go to tools→convert binary data→



Look in: DATA

Name	Size	Type	Modified
ASCII		File Folder	
DIAdem		File Folder	
PDAQ.BIN	2KB	Binary D...	9/8/2011 2:21:59 PM

Source File(s):

Target Directory: C:\Program Files\pDaqView\Applications\DATA\

Data files are placed in format-specific subdirectories of the target directory.

- i. Choose PDAQ.bin file and click 'convert'
- ii. Answer 'yes to all' to overwrite existing file
- iii. Close the window 'Select Files' window

27. Open ‘Shortcut to ASCII’ file on desktop and ensure that your data was properly recorded.
    i. Open PDAQ.txt in excel format
    ii. Save file as an excel spreadsheet onto your USB portable drive as: GroupName_StudentName_Date.xls
28. Next student should start subsequent run starting from step 12. Take recordings for the additional RPMs subscribed by the professor.

WARNING: BEFORE STARTING EACH SUBSEQUENT RUN, WAIT FOR EXIT GAS TEMPERATURE TO DROP BELOW 100 DEGREES C

29. When the experiment is completed, shut down engine and store equipment.

Data Reduction:

1. Provide a $T - s$ diagram and a $P - v$ diagram for the ideal and actual Brayton cycle for each test speed.

2. Calculate the thermal efficiency for the Brayton cycle for each engine speed.

3. Perform a first law analysis of each section of the SR-30 engine at each engine speed.

4. Calculate the efficiency of the compressor section and turbine section for each engine speed.

5. Calculate the back work ratio for each engine speed.

Note: Due to a bug in PdaqView Program, T3 (TIT - Turbine Inlet Temperature) and T4 (Turbine Exit Temperature) are interchanged with T4 > T3. Please correct these values by replacing T3 by T4 and T4 by T3.

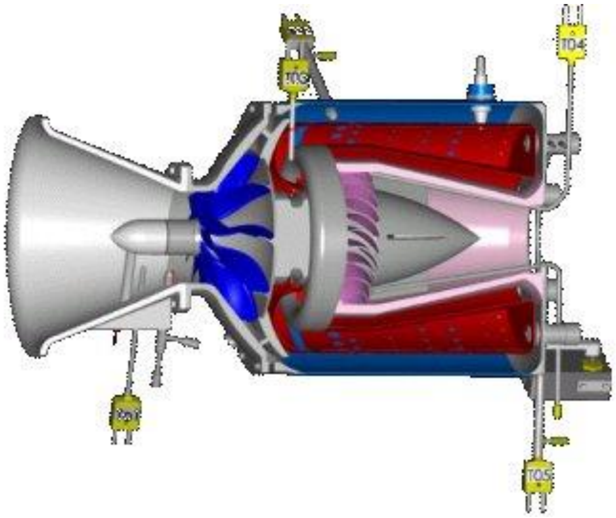


Figure 8: Cut-away of the SR-30 engine

Sensor Identification

P_{01} – Compressor stage static pressure.
P_{02} – Compressor stage stagnation pressure.
P_{03} – Combustion chamber pressure.
P_{04} – Turbine exit stagnation pressure.
P_{05} – Thrust nozzle exit stagnation pressure.

T_{01} – Compressor inlet static temperature.
T_{02} – Compressor stage exit stagnation temperature.
T_{03} – Turbine stage inlet stagnation temperature.
T_{04} – Turbine stage exit stagnation temperature.
T_{05} – Thrust nozzle exit stagnation temperature.