A MODEL FAN TO TEST THE TRAIN PISTON EFFECT AT GRAND PARIS EXPRESS METRO

Elisa BÉRAUD, Benoît HOUSEAUX, Fabrice DUET

Eiffage Énergie Systèmes, Underground Space Ventilation,
10 boulevard Marcel Dassault – 69330 Jonage, France

SUMMARY

The "Grand Paris Express" railway network is currently under construction. It has been very quickly predicted that piston effect created by train operated at 110 km/h (68 mph) through a succession of 1,000-2,000 m tunnels and stations with a cadence of 90 seconds in rush hours will differ from the traditional Parisian metropolitan network. The piston effect created in front and behind the train has been estimated to a total pressure variation of +900 Pa / -1400 Pa in a few seconds. The piston effect will be reflected in the stations and in the shafts positioned roughly every 800 m in the tunnels for the intervention of emergency services.

These shafts are also used for ventilation, first to control smokes and protect the stations in case of fire in the tunnel, then to ensure air quality in the tunnel when natural ventilation is not sufficient. As a consequence, the equipment in the shafts will face with piston effect and will be subjected to strong variations in pressure. At reduced speed, for comfort use, it is expected the fans will be passed through with a negative airflow and operated in negative pressure. Therefore they will be operated in areas that are not defined by the usual.

In order to characterize a "Grand Paris Express" type fan, Eiffage carried out a test bench to test the train piston effect. This test bench is made up of a circuit in which is inserted a Ø1000 mm model fan that has the same aeraulical and mechanical characteristics of the 300 fans that will be installed in the service structures of this new network. The model fan has been first tested in the unexplored area of negative pressure and negative flowrate to define the behavior in the three quadrants of the curve. It is now operated with successive negative and positive forced pressure on hundreds of thousands of cycles to ensure the durability of the equipment on several years of operation.

INTRODUCTION

When a train travels through a tunnel, it pushes the mass of air in front of it, which creates an overpressure zone at the front of the train. On the opposite, an area of depression due to the "void" is created behind the train. The passage of trains is therefore manifested by strong variations in pressure in the tunnel. This is called the “piston effect”.

Due to the combination of infrastructure with operation, it was expected that the piston effect will be exceptional in the tunnels, stations and every shafts of the Grand Paris Express.

Equipment ventilation are installed in the shafts and connected with tunnels. As a consequence, they are subjected to strong variations in pressure which will modify the operating points. Therefore, they could be operated in areas of negative pressure and / or negative flow rates that are not defined for fans. With each passage of trains, the fans could be taken to unexplored operating zones.

People involved were aware that the consequences could be dramatic for operation: the fans could explode quickly after commissioning and would cause restrictions (or closure) of lines while operating.

Therefore these new operating zones had to be explored. Several tests have been carried out with manufacturer to characterize the behavior of the fan in the 3 quadrants of the curve (including negative flow and negative pressure) according international standards.

Then the endurance and resistance of the fans to these stresses had to be assessed. That is why a test bench has been designed, developed and build on Eiffage site to study the piston effect on a model fan which is similar but in smaller scale to the fans installed in Grand Paris Express shafts. Continuous operation of the bench makes it possible to simulate the operation of the real fan over several years and to test its durability.

The paper is about the model fan. After a brief presentation of piston effect on Grand Paris Express network, the paper will present the definition of the test fan and its characterization in the three quadrants of the pressure flow curve. Then the paper will present the principle of the test to reproduce the piston effect on the model fan.

THE GRAND PARIS EXPRESS

Grand Paris Express will be a 100 % automatic metro system of the Capital Region in France. With its 68 brand new interconnected stations and 200 kilometers of new railway lines, this transit network will consist of a ring route around Paris (line 15) and lines connecting developing neighborhoods (lines 16, 17 and 18). Additionally, Grand Paris Express will also involve the extension of existing metro lines (line 14 to South). They will provide connections with Paris’ airports, business districts and research clusters. It will service 165,000 companies and daily transport 2 million commuters.

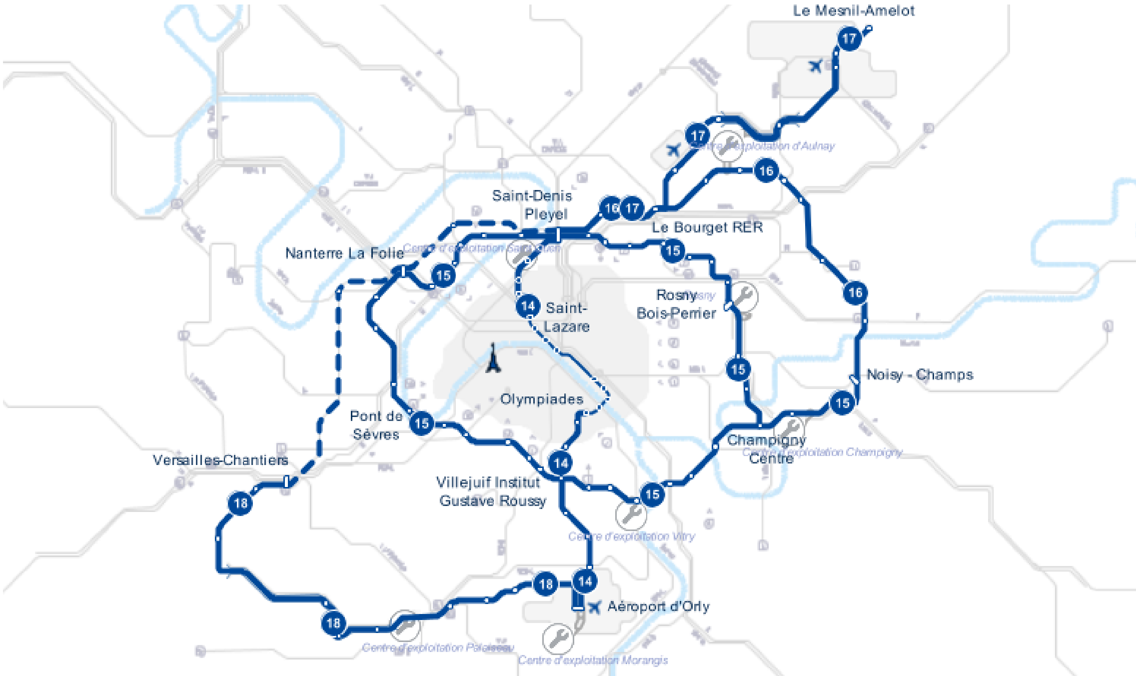

Figure 1: the Grand Paris express network

With 90 % of lines built underground, the good functioning of the new metro is ensured by the essential "service structure" positioned between stations.

Three times more numerous than stations, the 160 service structures will combine several functions, in particular related to passenger comfort and safety. Especially 120 of them will feature smoke extraction ventilation equipment.

THE PISTON EFFECT

The equipment in the shafts will be subjected to strong piston effect. In the following, it is explained why this is seen as a concern in the construction of this network.

This new network differs from the traditional Parisian metropolitan network for several combined reasons: on the one hand, the infrastructure is constituted of a succession of 1,000-2,000 m tunnels and stations and, on the other hand, it is operated with trains that travel at 110 km/h (68 mph) with a maximum speed of 120 km/h (75 mph) in tunnel.

The piston effect is specific to each part of the line depending of interdistance between stations, the slope and the curve of the track giving accelerating and braking behavior of the train.

Piston effect is a function of the operating curve of the train but also of frequency passage of train varying between 90 s during rush hours (8:00 to 10:00 am then 5:00 to 8:00 pm) to few minutes during weekend.

The effects of pressure fluctuations in the tunnel due to train traffic could be very important both in amplitude and gradient and in frequency. The following figure gives an illustration of the total pressure in the tunnel at the bottom of a ventilation shaft during the passing of two carousels of 10 trains spaced 90 s apart:

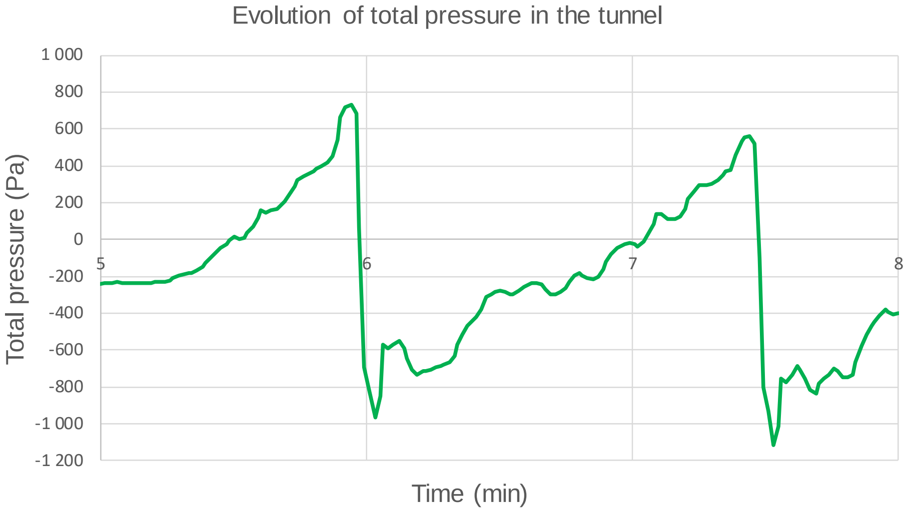

Figure 2: the evolution of total pressure in the tunnel (calculated by 1D code)

The piston effect of the trains could be characterized as follow:

- A criterion of total pressure of + 900 Pa and – 1400 Pa (conservative);
- A criterion of pressure gradient that is:
  - A decrease in pressure of 2,100 Pa at a rate of decrease of up to -500 Pa/s,
  - An increase in pressure of 1,600 Pa at a rate of up to 450 Pa/s.

These pressure fluctuations are reflected in the ventilation shafts located between the stations where the ventilation equipment is installed. And this at each train passage.

It was identified that the fans were impacted by two different notions in terms of pressure variations:

- An extreme stress with very strong pressure gradients both positive and negative over a very short time interval that will be able to generate mechanical fatigue on the fan;
- Overpressure in positive pressure and negative pressure that will generate significant airflow disturbances in the operation of the fan.

This last point can be illustrated on the operating curve of the fan.

In case of fire, the fan has to generate a flowrate of 150 m³/s (540,000 m³/h) and to counter a network resistance of 1,200 Pa. The operating point is represented in red. In normal mode, the fan will work half speed and will generate a flowrate of 75 m³/s (270,000 m³/h) for a total pressure of 300 Pa The operating point is represented in blue.

The effect of train arriving (overpressure of +900 Pa in the tunnel experienced as decrease of 900 Pa for the fan) and train leaving (underpressure of -1400 Pa in the tunnel) is represented with the two green dotted lines.

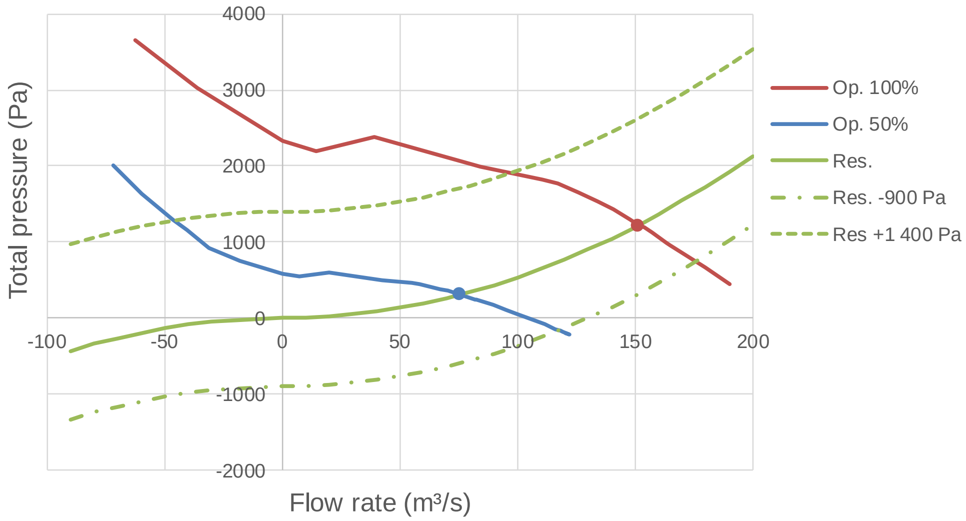

Figure 3: the piston effect on fan operation

The blue curve at reduced speed shows the displacement on the operating curve implying the need for anti-stall treatment. At the maximum pressure point (+1400 Pa), the fan will be passed through with a negative airflow even though the fan is still running the same direction of rotation.

Extrapolation of the blue curve with the network curve for a tunnel pressure of +900 Pa, suggests that the two curves would intersect in negative pressure. This implies *a priori* the operation of the motor as a generator (negative mechanical power).

The fans will be taken in operating zones never encountered and unknown. As a consequence, they have to be characterized in these zones and then operated to test their resistance with strong pressure variations.

THE MODEL FAN

The test bench

To reproduce the phenomenon, we conceived a test bench made up of a circuit in which is inserted a model fan, the one that is wanted to test, and a generator fan which makes it possible to impose a pressure in this circuit. By means of a damper system, the model fan can be forced to flow in one direction or the other, thus making it possible to simulate the effect of alternative overpressure and underpressure.

Continuous operation of the bench makes it possible to simulate the operation of the fan over several years and to test its durability. Over its lifetime, a fan may be exposed to 1.5 million cycles.

Figure 4: the piston effect test bench – Eiffage, France

It was feasible but not reasonable to test a real size fan. For reason of size, energy consumption, sound level, etc. it has been decided to test a homothetic model fan with a diameter of 1,000 mm.

The Grand Paris Express fan

The fans that will be installed by Eiffage in the ventilation service structures of lines 15 South, 16 and 17 of GPE are from Howden. The model ANR-2371-1122 will allow an operation for both fire extraction mode at 150 m³/s (operating point 1) and normal mode ventilation (operating point 2) at half speed rotation. The characteristics of the real size fan are presented in the table 1 below:

Table 1: real size and model fan characteristics

	Real size	**Model**
Impeller diameter	2,371 mm	1,000 mm
Hub diameter	1,122 mm	473 mm
Blade number	7	7
	Operating point 1	
Airflow	150 m³/s	25,6 m³/s
Total pressure	1,200 Pa	1,200 Pa
Rotation speed	980 rpm	2,300 rpm
Tip velocity	122 m/s	120 m/s
	Operating point 2	
Airflow	75 m³/s	12,8 m³/s
Total pressure	300 Pa	300 Pa
Rotation speed	490 rpm	1,150 rpm
Tip velocity	61 m/s	60 m/s

The model fan

The model fan is ANR-1000/473.

Scaling of fans

In order to be able to establish the performance of a full size fan from a model fan, both geometric and dynamic similarity is required. The ratio between the real size fan diameter and the model fan diameter is 2,371.

In order to have the same blade loading, the tip speed has to be the similar. With a speed of 980 rpm (490 rpm) for the real size fan, the model fan will be performed with a speed of around 2,300 rpm for OP1 (and 1,150 rpm for OP2). The flow and pressure from the model fan at this speed are adequate to the instruments capabilities and in safe distance from the speed interval limits.

With a speed of 1,150 rpm, the Reynolds number calculated on the tip speed and tip diameter is $4\ 10^6$ that is superior to $3\ 10^6$ as recommended by AMCA 802 to avoid scale effect.

The tip speed Mach parameter of the real size fan at 490 rpm is 0.181. The tip speed Mach parameter of the model fan should be inferior to 0.35 in accordance with AMCA-802, which corresponds to a speed of 1,670 rpm.

The requirements for dynamic similarity are respected.

THE MODEL FAN CHARACTERISATION

The test fan has to be characterized by manufacturer for the specified operating points in smoke extraction mode and normal mode. It has also to be tested at negative pressure and negative flow, both in forward and reverse direction. In total, 6 tests have to be conducted.

Figure 5: the tests at manufacturer facilities – Howden Denmark (left), Howden France (right)

Aerodynamic test in Howden Denmark

First the model fan has been characterized by manufacturer in Howden facilities (Denmark). The test has been conducted in accordance with AMCA 802.

The operating curve at 1,150 rpm is presented on the figure 6:

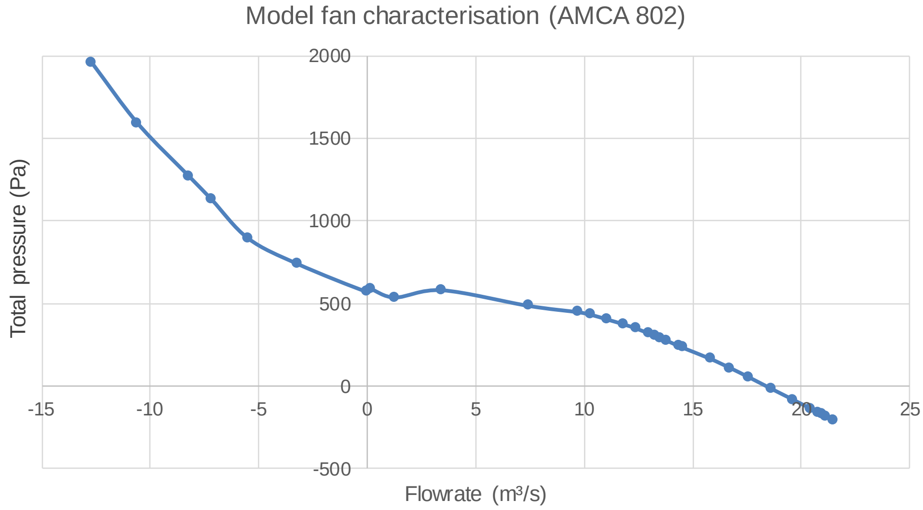

Figure 6: the characterization of model fan according AMCA 802

Aerodynamic test in Howden France

Then the model fan has been characterized in accordance with standard ISO 5801 (ex NF X 10-200) in Howden France facilities. The test has been realized with many diaphragms from 1.400 to 0.035 m that has allowed to determine total pressure for a flowrate from 20 to 0.01 m³/s in both direction.

The tests have been carried out at the nominal speed of 1,470 rpm. The results have been transposed at 1,150 rpm, which is the speed rotation for normal mode. The transposed operating curve is presented on the figure 7 below:

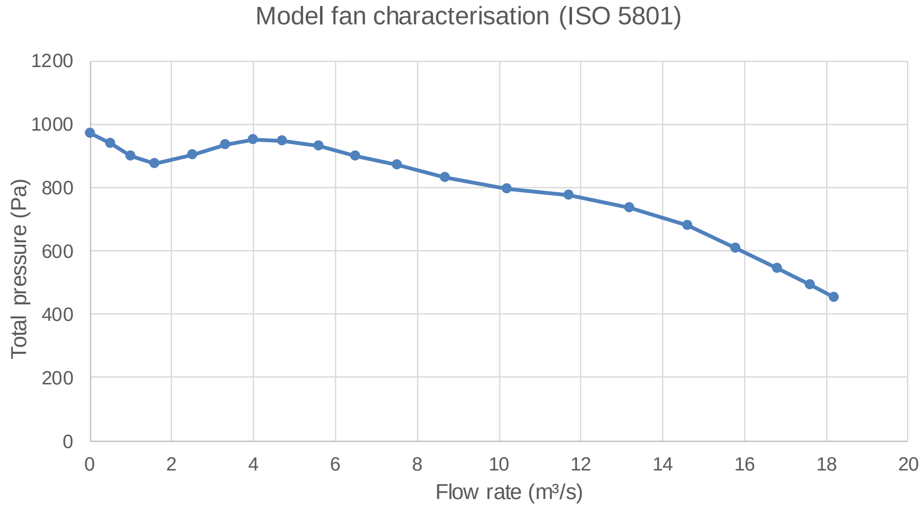

Figure 7: the characterization of model fan according ISO 5801

The model fan has been tested by two methods: the first one (in Denmark) has allowed to characterize the operating curve in negative airflow and negative pressure; the second one (in France) carried out in a second time has allowed to refine the “stall” zone of the operating curve. The both measurements series are complementary.

We may notice some differences but we can see quite good agreement between the results.

Anti-stall ring

The stall effect can be removed by choosing a fan and especially a blade pitch angle that does not have a stall point. But it will affect the efficiency of the fan.

The best solution consists in adding an anti-stall ring that allows to strongly reducing the stall zone. There are several types of anti-stall rings. The so-called "Ivanov" device has been considered for our real size fan and consequently for the model fan in order to maintain relatively high efficiencies in both directions of operation.

The model fan has been tested on our test bench with Ivanov ring. It has been compared with the same fan without Ivanov ring by manufacturer. It is clearly identified that Ivanov ring has allowed to largely reduce stall and to slip it to very low flowrate.

The operating curves with and without Ivanov ring are presented on the figure 8 below:

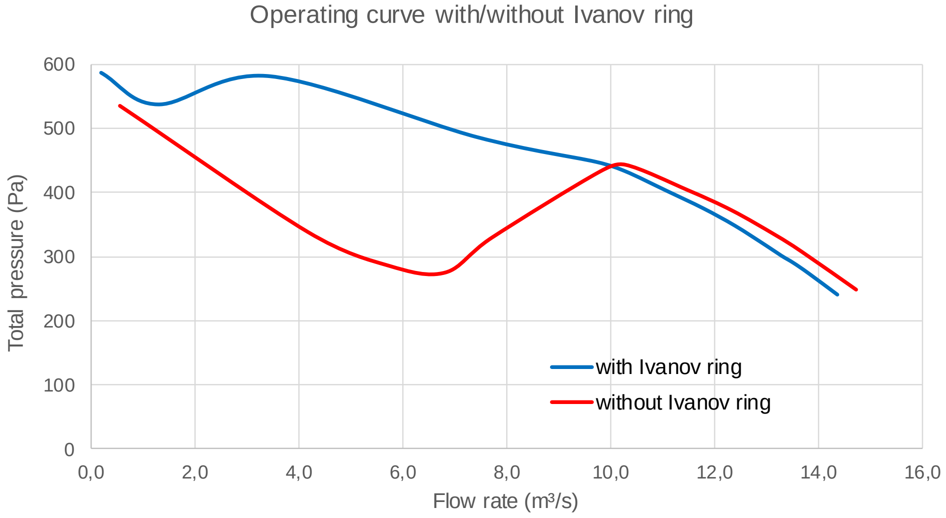

Figure 8: the effect of Ivanov ring on model fan

Endurance test on Eiffage test bench

The model fan is now tested on the test bench since several months. More than 100,000 cycles have been set with positive and negative pressure.

An example of fan total pressure variation is represented in the figure 9 below:

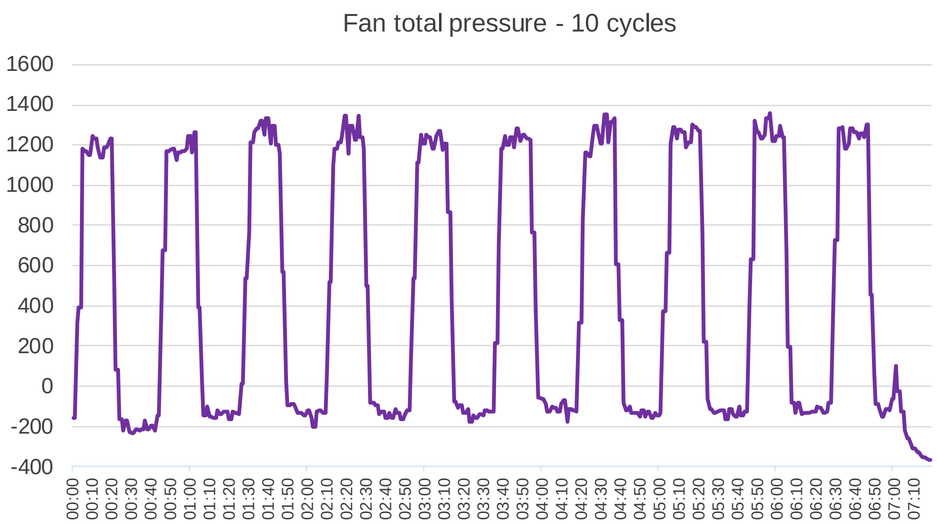

Figure 9: fan total pressure variation

Airflow, pressures, motor temperatures and fan vibrations are measured on the test bench; voltage, intensity, torque, power, etc. are also recorded.

CONCLUSION

The model fan has been characterized in the first quadrant by two different methods with two different test arrangements. It has also been characterized in negative flowrate and with negative total pressure. The benefits thanks to an Ivanov ring have been demonstrated for operation in the stall zone. Without the Ivanov ring, the fan would have exploded long ago during test bench operation. In total, more than 350,000 cycles have been realized so far, demonstrating the integrity and the proper operation of the fans of the Grand Paris Express. We will continue to survey the behavior of the model fan for each train passage.

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