# Flush air data sensing system

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**Flush air data sensing system (FADS) forms a mission-critical subsystem in re-entry vehicles. It makes use of surface pressure measurements from the nose cap of the vehicle for deriving air data parameters such as angle of attack, angle of sideslip, Mach number, etc. of the vehicle. These parameters are used by the flight control and guidance systems, and also assist in the overall mission management. The overall system engineering of FADS, including selection of pressure transducers, tubing size, port geometry, FADS algorithm and associated processing electronics along with the integration scheme is addressed in this article. Details of the qualification tests carried out in wind tunnel for end-to-end verification of the entire FADS system are covered in brief. Majority of the tests were carried out in a low-speed wind tunnel at a wind speed of 65 m/s (Mach number 0.2). The flight performance of FADS is also discussed in this article.**

**Keywords:** Angle of attack, flushed air data system, hypersonic flight vehicles, subsonic, wind tunnel.

AIR data parameters like angle of attack, angle of sideslip, dynamic pressure, Mach number and free stream static pressure with sufficient accuracy in real time are required for any flight control system. These parameters also assist in the overall mission management. The raw data are suitably processed/interpreted during flight and enable the vehicle to be maneuvered along a profile, which limits the vehicle load, manages the thermal environment and also keeps the vehicle trajectory within the desired flight envelope.

Several types of air data systems like laser velocity meter systems, on-board inertial measurement unit (IMU)-based systems and intrusive boom-type instruments like Pitot tube and mechanical vanes are available for this purpose. Due to the high-energy nature of the flow and the wide range of Mach numbers to be covered, most of the above systems cannot be implemented for use in re-entry vehicles. So, hypersonic flight vehicles essentially adopt the concept of flush air data sensing system (FADS). Here, static pressures measured from the blunt nose cap of the vehicle using a matrix of pressure orifices located in and around the nose cone, for example, are used to compute the air data parameters[1–6]. One benefit of FADS is that it enables sensing of more pressure measurements than minimally needed to determine the flow angles, and also to minimize the pressure measurement error used in the estimation of air data parameters. In FADS, the air data parameters are estimated using pressure measurements from orifices which are in flush with the surface of the vehicle. To perform this estimation, air data states are related to the surface pressure by an aerodynamic model that captures the salient features of the flow, and is valid over a large Mach number range from hypersonic to subsonic speeds. FADS has been developed for the Space Shuttle[7,8], and its performance has also been demonstrated through a number of flight tests[1,9,10].

## Region of operation of FADS

In general, FADS is intended to work at altitudes below 35–40 km. The low magnitude of the nose cap pressures limits the usage of FADS at higher altitudes. Above an altitude of typically 40 km, the pressures become extremely small, the effects of pneumatic latency become large and the pressure sensor signal to noise ratio becomes very low. All these effects collectively increase the noise in the FADS calculations, leading to erroneous air data estimates.

The guidance and control system of re-entry vehicles mainly relies on air data parameters derived from the inertial navigation system (INS) for altitudes above 40 km. These estimates tend to be erratic at lower altitudes due to wind effects and other errors of the navigation system used for deriving the air data parameters. For example, sideslip angle estimated using the INS system can be significantly different from the true sideslip angle in the presence of cross winds. The erroneous sideslip angle when fed back to the flight control system can severely affect the flight dynamics of the re-entry vehicle. Hence the exclusive use of inertial system measurements for air data computations can lead to significant limitation in the performance of the vehicles under typical operational conditions, especially at lower altitudes.

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Monte Carlo (MC) analysis was carried out to estimate the errors in the INS-derived air data parameters under typical operational conditions. Six degree of freedom (DoF) simulations were also done to estimate angle of attack and sideslip angle error build-up due to wind perturbations. For the present application, INS-derived air data estimates were found to be sufficiently accurate for Mach numbers beyond 2. Hence, FADS computations were configured to be used from Mach number 2 and lower. Figure 1 shows a typical Mach number–altitude profile of the Technology Demonstrator Vehicle. From the graph it can be seen that Mach number 2 is encountered around 22 km altitude. Based on the above studies, the region of operation of FADS in the demonstrator vehicle was fixed to be from 20 km altitude and downwards during the descent phase.

## Operational range and accuracy of air data parameters

The range and accuracy of the air data parameters are derived based on the requirements of the guidance and control system of the vehicle. The angle of attack and sideslip angle are the guidance commands given to the autopilot. The guidance and control system demands an accuracy of less than 1 deg for these parameters. The Mach number and dynamic pressure are used by the control system for gain scheduling and also for switching of control to the aerodynamic control surfaces. The accuracy demanded in Mach number and dynamic pressure for meeting the present performance is less than 5% of the measured value. The range of these parameters was set based on the worst-case values obtained from MC simulations. Table 1 shows the range and accuracy of the air data parameters.

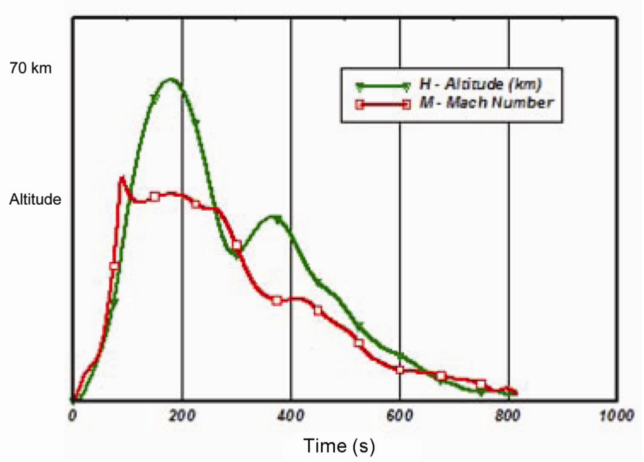

**Figure 1.** Mach number–altitude profile of technology demonstrator vehicle.

**Table 1.** Range and accuracy of air data parameters

| Parameter | Range | Accuracy |
|---|---|---|
| Angle of attack (deg) | –5 to 45 | ± 1 deg |
| Angle of side slip (deg) | ± 20 | ± 1 deg |
| Mach number | 0.2–2 | ± 5% |
| Dynamic pressure | 0–100 kPa | ± 5% |

## Selection criteria for pressure port configuration

The FADS makes use of an algorithm which relies on the surface pressure measurements from suitably located flush orifices on the nose cap of the vehicle. The measured pressures are a function of free-stream static pressure, impact dynamic pressure, local angle of attack and sideslip. Since there are four air data states and a calibration parameter to be estimated, at least five independent pressure measurements must be available to derive the entire set of air data states. This puts the minimum number of pressure ports as five. The pressure ports are arranged in a crucifix pattern. Even though the minimum number of pressure ports required is five, a configuration having a total of nine ports was selected. This was done so as to provide adequate redundancy and to facilitate computation of air data parameters even after failure of a pressure sensor, or blockage of a pressure port. The pressure ports are arranged in a crucifix fashion; with five pressure ports in the vertical meridian and the remaining four in the horizontal meridian. Two horizontal ports are provided on either side of the vertical meridian. Each pressure port is identified by two angles known as the clock angle and cone angle of the vehicle. The cone angle ($\lambda$) is the total angle made by the normal to the surface at the port location with respect to the longitudinal axis of the nose cap, and the clock angle ($\phi$) is the clockwise angle looking from aft about the axis of symmetry starting at the bottom of the fuselage (Figure 2).

## Selection criteria of pneumatic tubing

The tube geometry/sizing is selected considering thermal, mechanical and frequency response requirements. The pressure ports are located on the C–C nose cap, which encounters very high temperatures during re-entry. The tube length should be selected such that thermal response during the passage of air ensures a temperature at sensor location of <40°C. Further, the tube dimensions (length and diameter) should result in a frequency response of at least >10 Hz, and the frequency response of the present pressure measurement system is found to be >50 Hz. Dynamic characteristics of the tube (natural frequency/damping) vary significantly with altitude and hence pose difficulty in selecting the optimal geometry for achieving satisfactory response at all altitudes.

The thermal analysis and thermal modelling of FADS are carried out using an axi-symmetric model of the FADS tubing geometry along with the C–C nose cap. The following thermal environment cases are considered.

(i) Convective heating on C–C nose cap at the location of FADS (heat flux history shown in Figure 3).
(ii) Radiative heating on Inconel tube from the hot inner wall of C–C.
(iii) Convective heating of Inconel tube/sensor due to hot gas entry.

Different tube lengths are analysed and the temperature at the end of tube where the sensor is mounted is estimated. It is seen that for tube length of 450 mm, the temperature is 107°C without plasmask and 71°C with plasmask. For a tube length of 550 mm, the temperature is 37°C with plasmask provided for a tube length of 450 mm. Another constraint for selecting the length is that there should be sufficient space/provision for mounting the nine pressure transducers. Thus, even though only 550 mm length is found to be adequate; due to non-availability of mounting provision, it is suggested to keep the pressure transducers at the first bulk head with a nominal length of 800 mm considering thermal, mechanical and frequency response aspects (Figure 4). Considering these aspects and availability, Inconel tube has been selected for FADS. Analysis of frequency response of the above tubing shows that it has a frequency response >50 Hz for the operating altitude of up to 20 km.

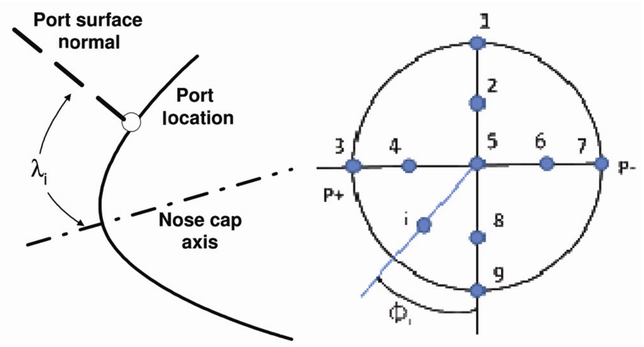

**Figure 2.** Cone and clock angles of port.

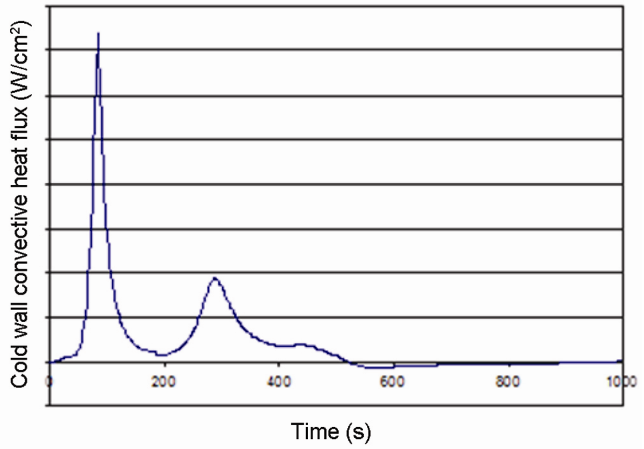

**Figure 3.** Heat flux history at stagnation point.

## Selection criteria of pressure sensors

In order to keep pace with the technological advancements and simplify the assembly procedures for mass production, a new class of sensors based on silicon technology having higher output, lower power, lower cost, better accuracy, higher reliability and faster response with low weight, is proposed, i.e. using state-of-the-art MEMS technology.

A high-sensitivity piezoresistive silicon chip is used for pressure sensing. Compared to the metallic strain gauge-based pressure sensor, the semiconductor-type pressure sensors are made using single-crystal silicon material with diffused piezoresistors, which have more than 50 times higher sensitivity (a value of approximately 3.5 kΩ).

The triplex sensor configuration selected consists of three one-bar pressure sensors for each port. Thus, there are a total of 27 pressure sensors in the system. It is found through simulations that the maximum pressure encountered by the system is 130 kPa (ref. 11). Hence, the full scale of the sensor is selected as 140 kPa. Absolute pressure transducer having a 3 × 140 kPa configuration is thus used as it meets the accuracy and other operational requirements, triple model redundancy (TMR) logic facilitates transducer fault detection and provides redundancy with simple pneumatic plumbing. Figure 5 shows the magnitude of the pressures to be sensed at the nine pressure ports for the nominal trajectory case.

The excitation voltage to the transducer is 5.0 ± 0.1 V DC. Output voltage for zero pressure is 0.25 ± 0.05 V

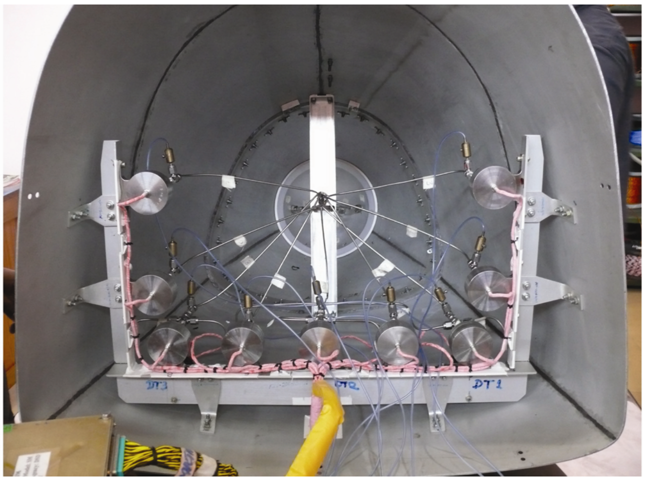

**Figure 4.** Flush air data sensing system tubing and pressure sensor mounting.

DC. The full scale output is 4.25 ± 0.05 V DC. Nonlinearity and hysteresis is <0.1% FS. The sensors are actively temperature compensated from 5°C to 75°C, in 2°C steps. A Wheatstone bridge configuration is used. The 140 kPa pressure transducer is capable of measuring pressure to within an error of <100 Pa over the temperature range of operation. Figure 6 shows the triplex pressure transducer arrangement developed for the purpose. The contribution of error from acquisition electronics is limited to <65 Pa. The criteria for selecting the maximum pressure sensor error as 100 Pa and error in acquisition electronics as 65 Pa are arrived at based on simulation studies. The above errors in pressure sensor and acquisition electronics contribute to a net root sum square (RSS) error of 119.26 Pa. MC simulations indicate that an RSS error of 150 Pa in measured pressure values will result in an error of 0.7 deg in angle of attack and 0.6 deg in angle of sideslip for the operating Mach number regime. The higher accuracy of less than 100 Pa over the full measurable range of 140 kPa is achieved through a four-step split range calibration with hysteresis. A hysteresis logic is also incorporated into the pressure calibration scheme to avoid back-and-forth switching of the scale factor and offset values in a given pressure range at the transition boundaries.

## FADS algorithm

The fundamental concept of FADS is that air data parameters can be estimated from surface pressure measurements from suitably located flush orifices on a flight vehicle. Different algorithms have been used for this purpose. The Space Shuttle has used a nonlinear regression-based algorithm for this. 'Triples'-based algorithm was proposed for the X-33 vehicle. Neural network-based systems were also developed for FADS.

To perform this estimation, air data states must be related to the surface pressures by an aerodynamic model that captures the salient features of the flow, and is valid over a large Mach number range. The complex flow scenario must be described with a model simple enough to be inverted in real time for air data parameter extraction. For this purpose, the aerodynamic model is postulated as a compromise between a simple potential flow model on a sphere, and modified Newtonian flow theory for blunt objects in hypersonic flow. Both potential flow and modified Newtonian flow describe the measured pressure coefficient in terms of the local surface incident angle. To blend the two solutions different schemes are employed. One method uses a calibration parameter $\varepsilon$. Figure 7 shows the concept of air data parameter estimation.

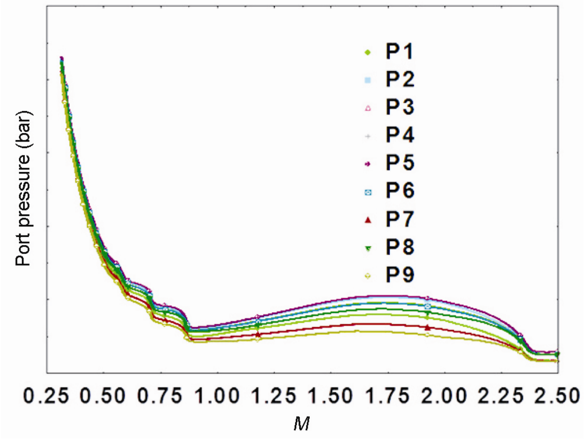

**Figure 5.** Absolute pressure at the nine ports.

**Figure 6.** Absolute pressure transducer used in the system.

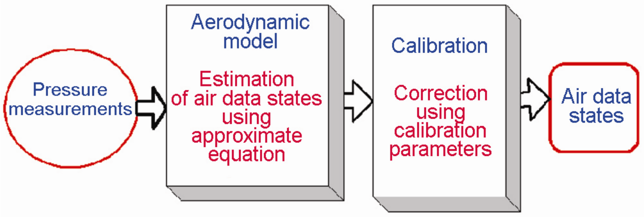

**Figure 7.** Aerodynamic model and calibration factor.

The measured pressure at $i$th port is defined by

$$P_i = q_c[\cos^2\theta_i + \varepsilon\sin^2\theta_i] + P_\infty, \tag{1}$$

where $P_\infty$ is the free stream pressure, Pa; $P_i$ the incident pressure at a port, Pa; $q_c$ the impact pressure, Pa; $\theta_i$ is the flow incidence angle between the surface normal at the $i$th port and the velocity vector. The incidence angle is related to the local (or effective) angle of attack ($\alpha_e$) and angle of sideslip ($\beta_e$) by

$$\cos\theta_i = \cos\alpha_e\cos\beta_e\cos\lambda_i + \sin\beta_e\sin\phi_i\sin\lambda_i + \sin\alpha_e\cos\beta_e\cos\phi_i\sin\lambda_i, \tag{2}$$

where the cone angle ($\lambda$) is the total angle made by the normal to the surface at the port location with respect to the longitudinal axis of the nose cap, and the clock angle ($\phi$) is the clockwise angle looking from aft about the axis of symmetry starting at the bottom of the fuselage (Figure 2).

The other parameters in eq. (1) are impact pressure ($q_c$) and the free stream static pressure ($P_\infty$). These are the basic equations from which the air data parameters are extracted. An indigenously developed algorithm has been used to derive the air data parameters from the sensed pressures.

The FADS aerodynamic model used for estimation of air data parameters is an approximate model. Hence, calibration of the estimated air data parameters is a must for enhanced accuracy. The calibration parameters are functions of $M$ (Mach number), $\alpha$ and $\beta$. There are three calibration parameters which must be evaluated for the FADS, which can be estimated from the wind tunnel data.

## Aerodynamic data generation

Wind tunnel tests are carried out to obtain the steady pressure data on all the ports located on the nose cap. Wing body truncated model with scale of 1 : 8 is used for wind tunnel test; Figure 8 shows the model components. Pressure data generation for low speed of Mach number 0.2 has been carried out at IIT Kanpur and for Mach number regime 0.6–3 the National Aerospace Laboratories (NAL) wind tunnel facility, Bengaluru. The calibration parameters are generated based on these wind tunnel data.

## FADS electronics and instrumentation

FADS electronics design demands air data parameters at every minor cycle (20 ms) to be sent to the on-board computer. To meet the above requirement of the computationally intensive algorithm for generation of the air data parameters, the electronics is designed using a digital signal processing (DSP) processor having excellent processing capability, thereby ensuring sufficient computation time margin. For meeting the high accuracy requirement of FADS air data parameters, total pressure chain accuracy better than 150 Pa is essential. To meet this requirement, the digital system is configured along with pressure sensor using a separate sigma delta ADC acquisition module having high resolution. The output of the pressure sensors is digitized using a Sigma delta A/D converter and then provided to the ADSP 210160 processor-based electronics. The FADS algorithm is embedded and executed by this processing electronics. There is adequate redundancy in the sensor processing electronics and in the ADSP processor electronics to take care of single-point failures.

## Algorithm validation and flight performance

The FADS experiments conducted in the wind tunnel are the final confirmatory test undertaken on ground before the flight, and are an important part of its development and provide end-to-end evaluation of the system. It can be considered as an equivalent of the hardware in loop simulation carried out on a full-scale model of the nose cone of the vehicle with pressure sensors, pneumatic tubing and electronics as in flight configuration. The estimated output of FADS is compared with the wind tunnel set conditions, and the performance of the end-to-end system is thus validated in a wind tunnel. The testing has been carried out at the National Wind Tunnel Facility at IIT Kanpur at subsonic speed of Mach number 0.2. This tunnel is a closed-circuit, continuous, atmospheric

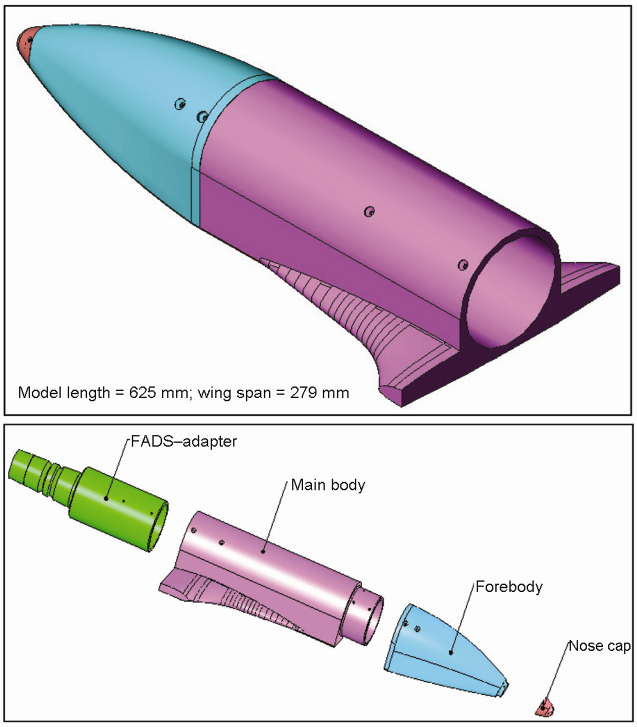

**Figure 8.** TDV truncated model with 1 : 8 scale used for wind tunnel test.

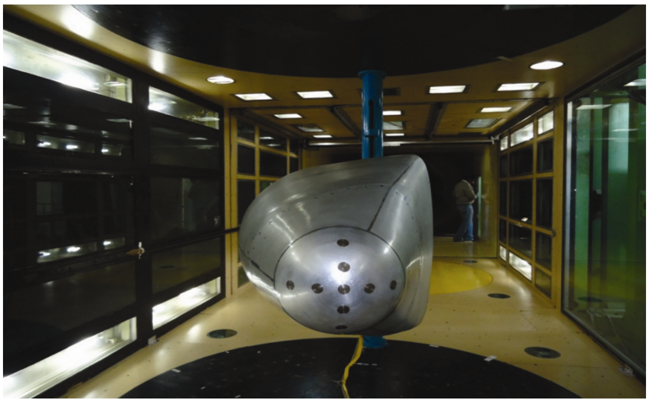

**Figure 9.** End-to-end system of FADS housed inside the nose cone model and mounted in a low-speed tunnel.

wind tunnel, with 2.25 × 3 m and 8.75 m long test section. Figure 9 shows the FADS system installation in the tunnel. Analysis of the results based on this test show that the targetted accuracy of <1 deg in angle of attack and sideslip angle is achieved by the system. Tests at higher Mach numbers have been carried out at NAL, Bengaluru.

FADS has been tested in actual flight during the ascent and descent phases of RLV-TD HEX-01 mission. During the ascent phase, FADS has computed the air data parameters from 10 to 70 s and during the descent phase air data have been computed for altitude less than 20 km. These computations are performed according to pre-flight plan. The measurement accuracy of pressure sensors observed in flight is within the specification of 100 Pa. The calibration parameters are generated using wind tunnel and CFD, and performance of the FADS algorithm assessed by comparing these results with the flight test data. The maximum difference in angle of attack and sideslip observed between FADS values computed and reconstructed (from INS measurements and pre-flight-measured winds) is within the targetted accuracy of 1 deg. The accuracy demanded of <5% of the measured value for Mach number, dynamic pressure and free stream pressure is also achieved during flight.

## Conclusion

This article addresses the system-level engineering concepts of FADS for a re-entry vehicle. It presents an overview of the main design considerations, which include criteria for selection of the number and location of the pressure ports, pneumatic tube sizing, pressure sensor characteristics and computational algorithm, etc. The FADS electronics architecture used for the experiment is also included. The aerodynamic data generation/analysis carried out and validation of the system in a subsonic tunnel are highlighted. Analysis of the results from end-to-end wind tunnel tests carried out shows that the initial design objectives are met by the system. The flight performance of FADS is also briefly addressed in this article.

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