

# FAST <sup>26</sup>



 **AIRBUS INDUSTRIE**

# FAST <sup>26</sup>



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*Cover photo: first A340-600 wing and centre-fuselage section*

*This issue of FAST has been printed on paper produced without using chlorine, to reduce waste and help conserve natural resources. Every little helps.*





# Dialogue

Airbus Industrie and its Suppliers have always helped the Operators of its aircraft to get the best out of them through dialogue. There is a constant wish of all parties to improve and an essential part of this improvement process is by holding and attending operators' conferences and liaison meetings. This is a continuous process that benefits the airlines in different ways. For example Airbus aircraft enjoy very high levels of Dispatch Reliability and low Direct Maintenance Costs; an innovative spare parts investment policy has significantly lowered capital investment; with the Airbus fly-by-wire concept about 50% of the airliners being sold today have the same systems, same cockpit and same operating procedures. This allows greatly reduced

flight crew and maintenance training costs which lead to Cross Crew Qualification (CCQ) and Mixed Fleet Flying (MFF) and provides unheard of levels operational flexibility to the airlines.

Two recent conferences covered the A330 and A340, and Training. Three others will take place in the coming months covering the A320 family, Performance and Operations, and A300/A310.

The study of human behaviour and cultural effects in the cockpit environment are particularly important to Airbus and the airline industry. To this end Airbus run a series of very popular regional conferences on Human Factors. The 11<sup>th</sup> was in Melbourne earlier this year and the 12<sup>th</sup> will be in the USA in the autumn.

## Coming up

### **A319, A320, A321 Technical Symposium**

**Sevilla, Spain, 4-8 Dec 2000**



The Airbus A320 product line is the world's fastest-selling jetliner family. More than 1,300 aircraft from the A320 family have been delivered to airlines and operators worldwide. Airbus Industrie's upcoming Technical Symposium in Sevilla, Spain will provide operators with an update of the technical status on the A320 family in service, and give them the opportunity to report on their experience and share it with others.

### **11th Performance and Operations Conference**

**Puerto Vallarta, Mexico  
26-30 March 2001**



This conference, held on a two to three year rotational cycle, is organised in different parts of the world, and will be held next year in Latin America. It provides a dialogue between Airbus Industrie and the operators of Airbus aircraft on all operational aspects.

### **12th Human Factors Symposium**

**Aspen, Colorado, 17-19 Oct 2000**

This symposium is being held in cooperation with Human Factors Committees of the Air Transport Association and various US Airline Pilots' Associations for management, pilots' unions and Human Factors specialists from US airlines. The themes for discussion are Human Factors issues in design, training, operations and safety. The symposium is structured to minimise formal presentations and maximise interactive discussions in ten panels.

## Recent Events

### **4th A330/A340 Technical Symposium**

**Cairo, Egypt, 22-26 May 2000**



The purpose of this conference was to present technical solutions for subjects raised by the operators, and provide a forum for discussion between the operators themselves, and with Airbus and the suppliers. In this respect it was very successful with 371 attendees from 55 airlines and a number of suppliers. A CD-ROM containing all the presentations, questions and answers is available to Customer Airlines from their Customer Support Managers.

### **5th Training Symposium**

**Toulouse, France 22-26 May 2000**



The importance of good training cannot be over emphasised and this importance was reinforced by the strength of the attendance. 434 people representing 94 airlines, 10 Airworthiness Authorities and 72 suppliers attended. Besides getting people together to discuss current and future training philosophy and techniques, it was an excellent opportunity to display advanced training equipment to a professional community whose advice and comments were invaluable. A CD-ROM containing all the presentations and panels is available upon request.

### **11th Human Factors Symposium**

**Melbourne, Australia  
4-6 July 2000**



Airbus Industrie is an industry leader in human factors' aspects of aircraft design training and operations. Regional meetings have been regularly held since 1995. This Symposium was organised for airlines in the Asia Pacific region with the cooperation of Ansett Australia and the Australian Transport Safety Bureau. Its specific objectives were to diffuse the Airbus culture, showing its rationale for design and automation, philosophy for training and operations and its balanced approach towards prevention and reaction in safety management.

To reflect the importance of cultural aspects in the cockpit, panels were organised on the development of a "Culture of Organisational Safety", and "Cultural needs for Crew Resource Management (CRM)".

160 persons, from airlines, civil aviation authorities and organisations, airforces and defence organisations, universities, accident investigation boards and even a railway authority participated in this regional forum, having ample time for discussion and exchange with experienced experts in their fields.

Prominent airline pilots and academic speakers from the region were also involved throughout the symposium.



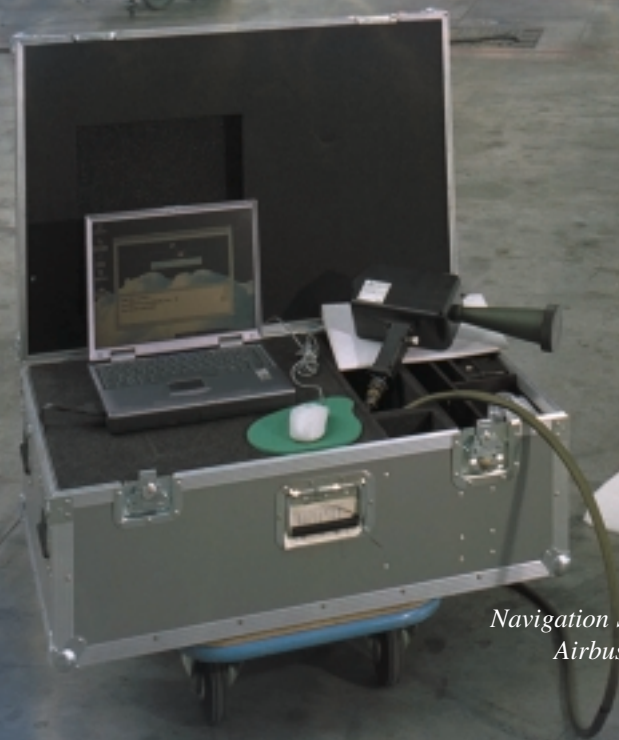




# Portable equipment for testing the radomes

Airbus Industrie & Aerospatiale Matra  
Airbus, Test & Services have developed a new tool for testing the radio-frequency performance level of the radomes.

This tool provides the operator with an in-house means to test the radome, in contrast to the traditional anechoic chamber or double horn methods requiring transport of the radomes to specialised facilities.



*By Bernard Carayon  
Senior Engineer  
Navigation Systems Engineering Services  
Airbus Industrie Customer Services*





## Reasons for testing the radome

The function of the radome is to protect the antennas installed in the nose of the aircraft from airflow, rain, hail, lightning strike, bird strike, etc. At the same time it must provide a radio-frequency transparent window, suitable for the microwave signals of the weather detection radar, instrument landing system and microwave landing system. The most demanding system in terms of radome radio frequency specification is the weather radar.

## Predictive windshear detection mode

In the predictive windshear detection mode, the radar detects small raindrops “flying” in opposite directions (microburst event). It generates an aural warning and displays the area where the windshear is present on the navigation display. The predictive windshear detection system identifies microbursts up to five nautical miles ahead, giving up to sixty seconds of advance warning to the crew. This allows the crew to avoid entering a windshear, thus further increasing aircraft safety in the air. However, the detection must be highly reliable in order to avoid false warnings.

One way to reduce those false warnings is to limit false echoes due to poor quality of radomes. This is the reason why radomes installed on aircraft equipped with a predictive windshear detection system, must comply with more stringent specifications.

To ensure optimum operation of the weather radar system, the quality of the radome in terms of radio frequency performance is critical.

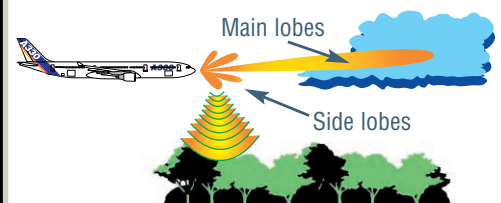
**Note:** With the technology available today windshear and turbulence cannot be detected in dry air conditions.

## How a degraded radome affects the radar system

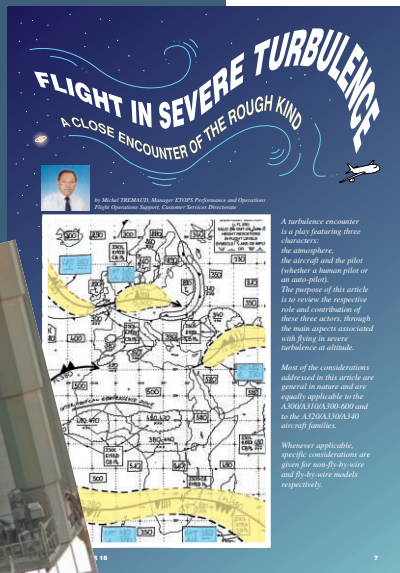
### Weather detection

The radar transmits a radio-frequency pulse. Then it listens for the return pulse reverberated by an obstacle (rain, terrain) and measures its elapsed time. The distance between aircraft and obstacle is proportional to the elapsed time. The larger size and reflectivity of the target means a stronger return.

A low transparency to radio frequency of a radome directly affects range detection and target size computation. This could end up underestimating a weather hazard. The measured signal must be the one returned by the main lobe of the antenna. A return signal from secondary lobes (also called “side lobes”) may generate false weather targets from ground echoes.



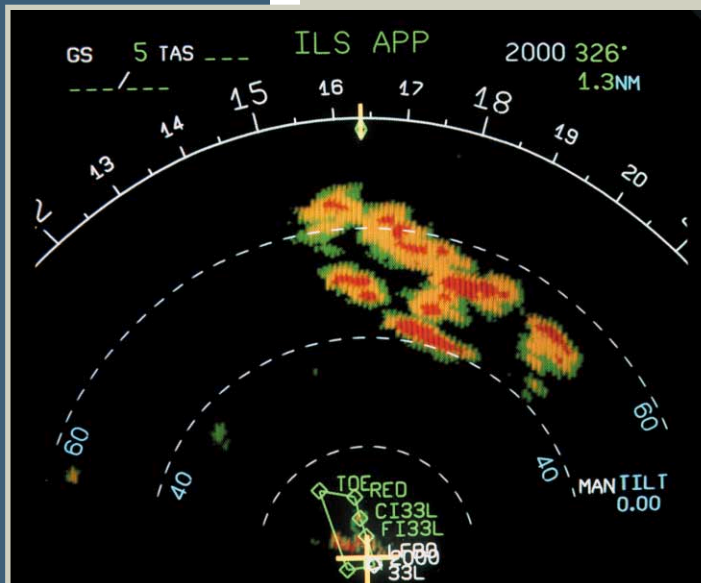
Ground return = echo at aircraft altitude



The most recent type of weather-radar features two functions: weather detection function and predictive wind shear detection. Both functions are essential to a smooth flight. (see FAST magazine number 18 'Flight In Severe Turbulence').

### Weather detection mode

In the weather detection mode, the radar detects precipitation of water or ice particles present in clouds. Weather targets are colour coded in function of the precipitation intensity (drop size, density, reflectivity of target). The crew interprets the resulting picture. It is therefore of prime importance that the picture be as accurate as possible and representative of the actual precipitation. Only this will allow the crew to make the right assessment and take the appropriate flight path to avoid adverse weather, turbulence and lightning strikes.



## Windshear detection

The radar processor detects the Doppler frequency shift of the microwave pulses caused by the microbursts of wind direction. Return microwave signals must not be disturbed, to allow the measurement of direction and speed of the precipitation of the tiny droplets. So a poor transparency to radio frequency from the radome may lead to undetected windshear.

As for the weather function, return signals from secondary lobes may disturb the radar system and cause the radar to trigger false windshear alarms. Therefore both functions demand an undistorted forward view in terms of radio-frequency performance. That is, a high-performing radome in terms of radio-frequency transparency and level of side lobe capability.

## Sources of radome degradation

There are many reasons for the performance level of a radome to degrade below minimum requirements. They range from lightning strike, bird strike, natural erosion, water ingress for some types of radomes, ageing, poor repairs such as wrong material used, or over-painting.

## Characteristics to be checked

There are two main characteristics to be checked to ensure that the radome will not affect the weather radar system:

- ▮ Its transparency to radio-frequency waves. Transparency relates to unobstructed forward view in terms of radio frequency to minimize the loss of outgoing and return signals.
- ▮ The side lobe level. Side lobe level difference between main beam and side beams of the antenna ensures that the return microwave signal being measured comes from the main beam and not from the side beams. So the measured return wave is the desired wave from the front of the antenna and is undisturbed. Both are defined in the RTCA document DO213 in chapters 2.2.1 and 2.2.2.

## Transmission efficiency

The average and minimum transmission efficiencies within the window area should not be less than indicated for the following classes:

	Average	Minimum
<b>Class A</b>	90%	85%
<b>Class B</b>	87%	82%
<b>Class C</b>	84%	78%
<b>Class D</b>	80%	75%
<b>Class E</b>	70%	55%

## Side lobe level

The radome should not increase antenna side lobe levels. For side lobe levels between  $-21\text{dB}$  and  $-26\text{dB}$ , the increase should not be more than  $2\text{dB}$  for Category 1 requirements.



## Status of new Airbus Industrie radomes

Part Number	Technology	Aircraft family	Class	Cat
A923 20242 000 10	Glass fiber	A300	C	2
A923 20242 000 11	Glass fiber	A300	C	2
A923 20242 000 12	Kevlar	A300/ A310/ A300-600	B	1
A923 20606 005 00	Kevlar	A300/ A310/ A300-600	B	1
A923 20606 006 00	Kevlar	A300/ A310/ A300-600/ A330/ A340	B	1
A923 20606 007 00	Kevlar	A300/ A310/ A300-600/ A330/ A340	B	1
A340 32201 000 00	Quartz	A300/ A310/ A300-600/ A330/ A340	A	1
A340 32202 000 00	Quartz	A300/ A310/ A300-600/ A330/ A340	A	1
D531 10477 000 02	Kevlar	A320	B	1
D531 10477 000 03	Kevlar	A320	B	1
D531 10477 000 04	Kevlar	A320	B	1
D531 10477 000 05	Kevlar	A320	B	1
D531 10477 000 07	Quartz	A319/ A320/ A321	A	1

## Methods, means & procedures available

To check the performance level of a radome, a number of techniques are described in the ARTC 4 and RTCA MOPS D0213 documents such as anechoic chamber, test in 'free' area, two-horn transmission test tools. However, all of them require extensive, costly means and specialised personnel, quite unaffordable to most operators. In addition, a considerable burden is placed upon the operators to send the radome to specialised repair stations sometimes halfway across the world. A tool 'light' enough to be usable in airline facilities and cheap enough was definitely required.

## History of tools development

Airbus Industrie and Aerospatiale-Matra initiated work on the development of the portable radome test equipment in 1990 on airline request. First, a review of all the techniques used to measure the radio-frequency characteristics was carried out to assess the most promising method. It was decided that only a method using a single horn, about six centimeters (2.3 inches) in diameter could meet the requirements of the operators. Yet, the method had to be first demonstrated as workable.

Consideration was given for a robot to move the horn over the radome surface. Measurements would be performed along the path of the horn. This solution was quickly abandoned due to its prohibitive cost. It was then decided to use a single hand-held horn including both transmitter and receiver and to manually move the horn point-by-point in close contact over the radome surface, performing the measurements all along a path of the radome surface to be covered. Obviously each type and size of radome would require a specific path to be developed. The collected data would then be converted to meaningful data to determine the performance level of the radome.

The data collected from the measurements does not provide a direct reading of the radio-frequency performance level of the radome. The relation (mathematical model) between the collected data and the transparency level with side lobes level had to be determined. Airbus Industrie then tested a high number of radomes both with a

prototype tool and with a referenced anechoic chamber. The data collected from the prototype of the 'light' test tool were then compared with the data collected from the anechoic chamber. A two-day run on a Cray 2 computer sorted out the data.

To carry out a test of the radome's radio-frequency performance level, two sets of measurements have to be collected:

- ▮ Reflection coefficient in open circuit which, once converted, gives an indication of transparency.
- ▮ Reflection coefficient in short circuit which, once converted, indicates the size of the side lobe levels.

A conversion formula was compiled and the software was written for use on a laptop computer. Various types of radomes were again tested with the Aerospatiale Matra Airbus Test & Services portable test equipment and with a referenced anechoic chamber. The two sets of results were compared to enable the validation of the principle of the portable test equipment. In the course of the development different levels of radome degradation were simulated on an A320 aircraft. The results met the official requirements laid out in various documents such as ARTC 4, RTCA D0213, ARINC 708, ARINC 708A... and therefore is a clear qualification of the design.

The portable test equipment is now in industrial production and is available for purchase. (See page 8).

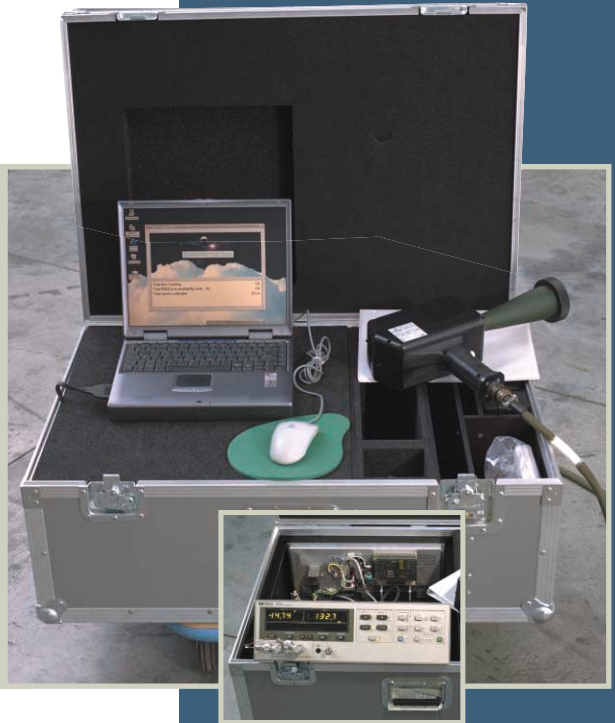




## Brief description of the equipment

### The equipment is composed of:

- ▶ **A hand-held horn** which includes a radio-frequency transmitter/receiver and a converter to intermediate radio frequency. A liquid crystal display on the back of the horn provides instructions to the operator.
- ▶ **A radio-frequency analyser** to pick up the measurements.
- ▶ **A portable computer (PC)** to collect, control and process data, and manage the interface to the operator.

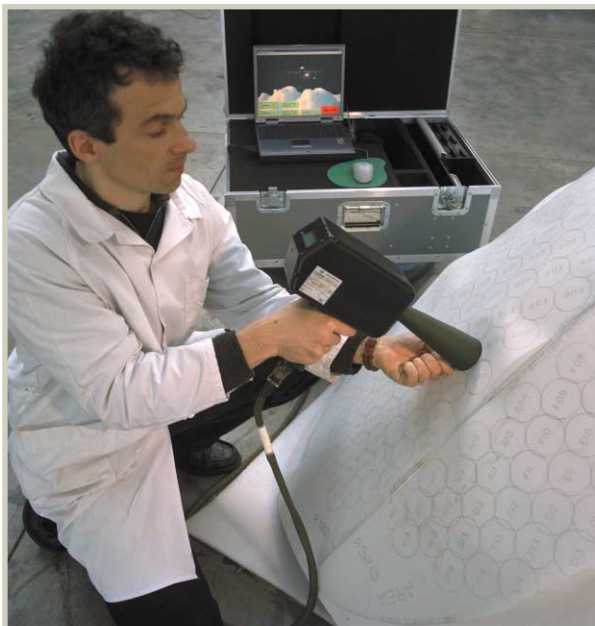


## The test procedure

The procedure is divided mainly in two parts: transparency measurement and phase shift measurement.

### Transparency Measurement

- 1 The radome is placed on a layer of radio-frequency-absorbing foam to avoid return echoes from the floor.
- 2 The grid is positioned over the radome (see photo below).
- 3 The operator checks the serviceability of the tool and calibrates it.
- 4 The operator does the measurements point-by-point following the instructions displayed on the screen of the horn (see photo below).



### Phase shift measurement

- 1 The operator places an electrically conductive sheet or foil inside the radome. It is used to reflect the microwaves. It must be maintained in close contact with the radome inner surface, so a rubber sheet is placed on top of the foil and sealed around the edges. By vacuuming the trapped air between the rubber sheet and radome inner surface, the atmospheric pressure will gently maintain the foil pressed against the radome surface.

- 2 The serviceability of the tool is again checked.
- 3 A new set of measurements is performed.
- 4 The PC computes the serviceability of the radome and the report of the test may be printed out for filing and traceability purposes as required by the regulations.

Referenced radome samples are provided to check the serviceability of the tool and to calibrate it prior to any radome testing. This ensures good repeatability of the measurements. The equipment only requires a standard 110/220V AC, 50/60 Hz power supply. No specific room is required. However, a sheet of radio-frequency-absorbing foam (ref API 28 from Hyfral, vendor code FAFK8 or equivalent) is required for the open circuit measurement. A conductive sheet or foil (kitchen aluminum foil) and a rubber sheet along with a vacuum bag and vacuum pump (ref ANITA NG9201 made by GMI, vendor code F07856 or equivalent), as used for composite repairs are also required for the short circuit measurement.

...One set of measurements to compute the radio-frequency transparency.  
One set of measurements to compute side lobes level.





## Portable test equipment optional features

**Development is still continuing and the following optional features are foreseen:**

- ▶ *Graphic display of non-acceptable area of the radome*
- ▶ *Radome life-time tracking*
- ▶ *Point-by-point measurement to directly compare two areas of the radome*

## Price & delivery quotation

Operators who wish to receive a price quotation for the Radome Portable Test Equipment, part number LCRAD0100HM0100, are invited to send their requests to **Aerospatiale Matra Airbus, Test & Services** in Toulouse France, fax: +33 (0)5 61 93 03 09.

**Note:** *The vacuum pump, the conductive foil, the rubber sheet and the radio-frequency absorbing foam can be procured from the suppliers mentioned on page 7.*

## Conclusion

Aerospatiale Matra Airbus Test & Services' portable radome test equipment provides operators with a low cost in-house capability to test radomes for serviceability and to identify non-acceptable areas. The test procedure using this tool will be referenced in the relevant Airbus technical documentation such as the Component Maintenance Manual (CMM) and the Structure Repair Manual (SRM).



### Main advantages for the operator are:

- ▶ Short out-of-service time for the radome
- ▶ No specific test facilities needed
- ▶ Test equipment easily transportable (less than 45kg)
- ▶ Test equipment easy to set-up
- ▶ Less than one day per radome for testing by one technician
- ▶ On-site testing and repair (*see FAST magazine number 18 'Infrared Thermography for In-Service Inspection'*), applicable to all Airbus Industrie radomes
- ▶ No transportation cost to specialised repair centres
- ▶ No cost of sub-contract test and repair
- ▶ Reduced quantity of spare radomes ■

For any questions or complementary information, please contact:

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# Methodology *for* Analysis *of* Operational Interruption Costs



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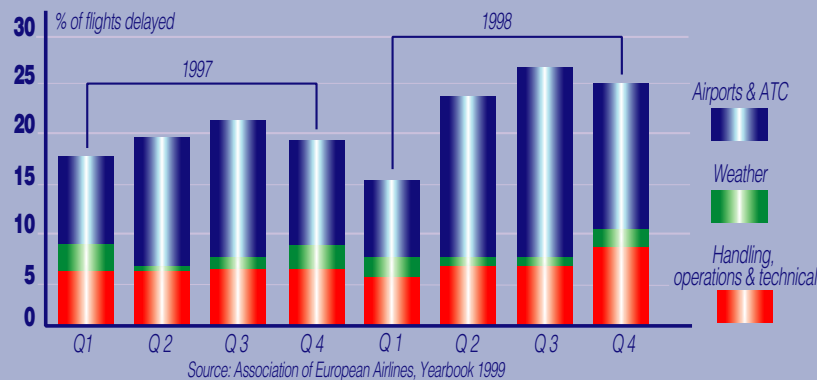


## Introduction

Airlines are continuously under pressure to improve their punctuality (*i.e. on-time performance*), setting ambitious and very challenging objectives.

Increased awareness, new generations of travellers and changing attitudes have led to a change in demand. Punctuality has become one of the most significant factors for defining a passenger's satisfaction with an airline.

Delays, cancellations and other operational interruptions cost airlines money. Passenger ill-will, associated losses of revenue and compensations are among these costs. Operational interruptions also pose extra costs to airlines due to higher fuel burn, additional maintenance, crew and aircraft utilisation. Airlines are extremely concerned about controlling costs.



**Fig. 1** Main causes of departure delays over 15 minutes

## Objective

Operational disruptions result from many different causes. *The International Air Transport Association* already lists more than 70 different factors that cause delays. This research has been designed by Airbus Industrie with the aim of providing airlines with a methodology to clearly identify and appraise the costs hidden behind the various operational interruptions.

As clearly presented by AEA, the Association of European Airlines, technical faults only account for a small proportion of total disruptions (*see Fig. 1 above*).

However, this proportion of operational interruptions, although small, is under airlines' responsibility and control. This is what they can improve. This is also where the manufacturer can bring all its expertise and support to further improve airlines' on-time performance.

## Questionnaire

To undertake the above research, two different questionnaires were designed and sent to target both passenger carriers and integrators (package carriers) respectively. Nearly 65 different Airbus operators were contacted to provide a large enough sample on which to base the analysis.

The questionnaires included seven sections related to the different operational interruption types classified as follows:

### Ground Interruptions:

- ▶ Flight dispatch delays
- ▶ Ground turnbacks
- ▶ Aborted take-offs
- ▶ Aircraft substitutions
- ▶ Flight cancellations (at main base/out-station)

### Air Interruptions:

- ▶ Air turnbacks
- ▶ Diversion

A checklist of cost items, adapted to each particular type of operational interruption, was provided within the appropriate section. The purpose of these checklists was to give airlines the ability to specify which costs and their respective percentage of the total interruption costs were included in their calculations. A presentation of the section related to delays is given in *Fig. 2*.

# Questionnaire feedback

Very good feedback was received from many airlines that found these checklists helpful and good starting points for internal analyses.

Operators, wishing to undertake their own internal analysis, may obtain the lists from the address at the end of this article. It could be of interest to many carriers to undertake such analysis, as only 13 airlines were at this time able to participate in this survey.

The aim of the questionnaires was to collect information regarding existing industry models so as to analyse operational interruption costs. The information received has formed the basis of the following analysis, providing a presentation of what operators considered as the driving factors affecting their operational interruption costs.

Data are based on their respective fleet, including many different aircraft types from different aircraft manufacturers. Unfortunately, out of the different operational interruption types, only the delays and cancellations were presented. Moreover, not enough information came back from integrators, therefore limiting the scope of research to passenger carriers only.

## Analysis

### Related to passenger-carriers

Each airline has its own specific environment, route and station network, aircraft utilisation, maintenance concept and other operational specifications. Furthermore, it has its own marketing strategy, targeting specific customers, with dedicated levels of services. Therefore, it seems obvious that operational interruption costs differ from airline to airline, depending on their respective marketing and operational specifications.

Figures 3 and 4 present the delay costs, as reported by the airlines, and clearly show how big the differences between operators can be. Due to a lack of information we could not make any specific conclusion about the differences between geographic areas, their economic environments, between different fleet sizes, or even between scheduled and charter operations.

From such a small sample of respondents, it is very difficult to conclude anything about an average delay cost. The large amplitude of reported delay cost values would

certainly distort any average figure. We came to the same conclusion about cancellation costs.

The chart on figures 5 and 6 present the reported cancellation costs for both single-aisle and wide-body operations. Reported cancellation costs from single-aisle operators are within the same band, with the exception of *Sce 7* in figure 5. This gives a good idea of the cost of cancelling a single-aisle flight

This is far from being true for wide-body reported values. Therefore, trying to apply average delay or cancellation cost values to all airlines would be inappropriate. However, what would be appropriate is that each airline should carry out its own internal operational interruption costs analysis based on its specific operation type. In that respect, Airbus Industrie has identified a methodology for delay and cancellation cost analysis, and provides explanations on some of the driving factors affecting these costs.

<b>Crew</b>		Y	N	SUB-TOTAL / %	<input type="text"/>
	Cockpit Crew Overtimes	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Cabin Crew Overtimes	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Salaries of Stand-by Crew	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Hotel & Meals Expenses	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Other costs to be specified	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
<b>Ramp Services</b>				SUB-TOTAL / %	<input type="text"/>
	Station / gate Agent Overtimes	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Airport Facility Expenses	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Others	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
<b>Passengers</b>				SUB-TOTAL / %	<input type="text"/>
	Hotel & Meal Expenses	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Rerouting of Passengers	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Lost of Delayed Luggage	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Passenger ill-will	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Revenue lost from connecting pax	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Others	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
<b>Aircraft</b>				SUB-TOTAL / %	<input type="text"/>
	Fuel Cost	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Extra APU / Ground Unit Expenses	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Stand-by Aircraft Amortization	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Airport Fees	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Others	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
<b>Cargo</b>				SUB-TOTAL / %	<input type="text"/>
	Penalties for the delay	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
	Others	<input type="checkbox"/>	<input type="checkbox"/>		<input type="text"/>
<b>COST OF A DELAY</b>				TOTAL / %	<input type="text"/> 100 %

Fig. 2 Questionnaires: list of cost items to consider for delay costs



### Crew-related expenses

The crew-related costs can be evaluated by accounting the extra flight labour costs (cockpit and cabin crews) incurred when a flight is delayed. Pilot and flight attendant salaries vary from airline to airline.

The substitution of crews by stand-by crews also increases these expenses.

Additional hotel and meal expenses have also to be taken into account. These increase airlines' delay costs.

The aircraft type and its associated staff requirement also affects delay costs, and therefore, should be considered when calculating them.

### Ramp-related expenses

These are the lowest contributing costs and should not exceed 3 or 4 % of total delay costs.

Only ramp-agent overtime and other additional airport facility expenses should be included.

### Aircraft-related expenses

Aircraft-related expenses are strongly dependent on operational specifications. Therefore the costs associated with fuel burn, navigation charges, extra aircraft utilisation and maintenance will vary accordingly.

It is expected that the cost per seat will be lower for wide-body than for single-aisle aircraft.

Long-haul flights also lead to significantly lower aircraft-related expenses per seat.

When airlines have the opportunity to speed-up their operations so as to catch up from delays, additional costs should be added taking into account, for example, the increased fuel burned.

When airlines have high frequencies of flights on a given route, their operations are exposed to delays in a completely different way to those with low frequency operations. Delays can have significant knock-on effects on their operations. Furthermore, combined with short sector lengths and short turn-around times, the opportunity to speed-up their operations in order to catch up remains very limited.

To cope with the problem of knock-on effect, airlines sometimes add flexibility within their fleet by operating stand-by aircraft. This of course has a cost, but leads to significantly improved service quality and reduction in the cost of the operational interruption. Therefore this should also be taken into account for the calculation. Stand-by aircraft are either owned by the airline, used from a pool between airlines or chartered under specific agreements.

## Reported Costs

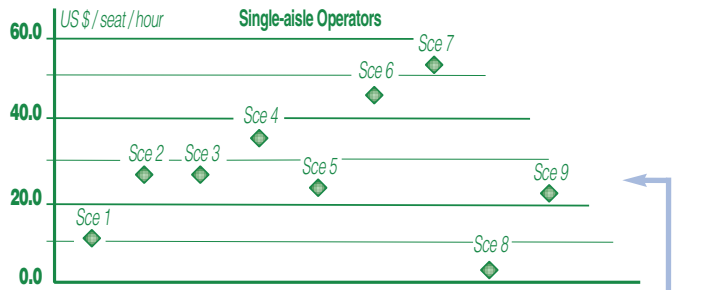


Fig. 3

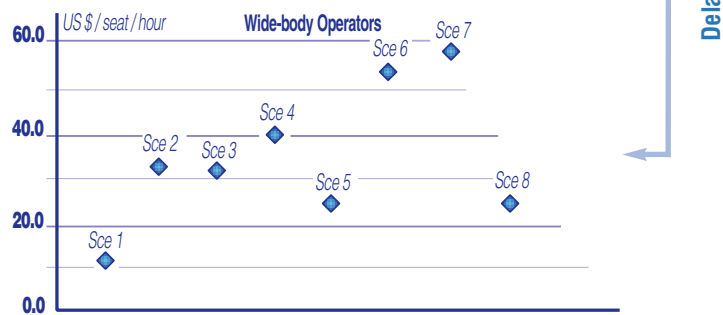


Fig. 4

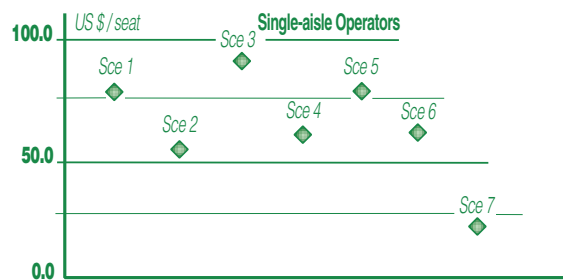


Fig. 5



Fig. 6

Delay Costs

Cancellation Costs



# Methodology

## For delay analysis

In reviewing the different delay cost analyses done by operators, two different approaches have clearly been identified. The chart in figures 7 reflects these two different approaches. It can be seen from this chart, that some airlines reported having delay costs entirely due to passenger-related costs. However, it was confirmed that it was simply due to their way to allocate their operating costs. In other words, they consider extra aircraft and crew-related expenses as part of their annual aircraft and crew budgets, remaining out of the delay cost equation.

All reporting operators therefore recognise that crew, ramp, aircraft and passenger-related costs contribute to their respective delay costs, but simply have different ways to allocate these costs. We believe that all costs incurred from delays should be identified as being part of these delay costs. In other words, we recommend that the operators, wishing to appraise their delay costs, should apply the following

approach. This approach considers all contributing factors and splits delay costs between the above four related expenses.

The table in figure 8 presents this approach with an example of delay cost calculation. The presented examples of percentages are not appropriate for any particular airline. This is the reason why we recommend individual analysis. It gives, however, the appropriate list of cost items to follow for delay cost appraisal.

The contribution of each particular cost item varies from airline to airline, depending on their environmental specifications. To get a better understanding of these differences, each contribution is developed individually in the blue columns.

To conclude this chapter, by analysing internally these different cost items and adding them all, airlines will be able to estimate their respective delay costs.

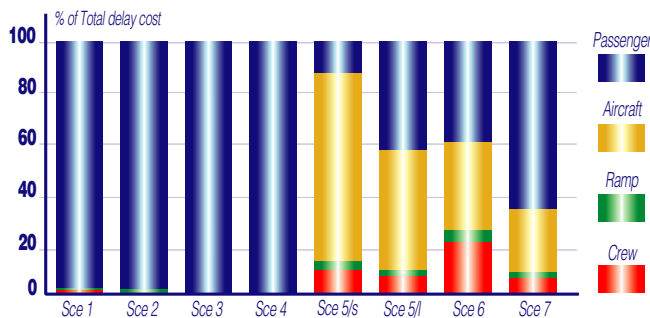


Fig. 7 Reported delay cost drivers

Category	Total / %	\$ / Seat / hour
<b>Crew</b>	74%	\$xx
Cockpit Crew Overtimes		
Cabin Crew Overtimes		
Hotel & Meals Expenses		
<b>Ramp Services</b>	4%	\$xx
Gate Agent Overtimes		
Airport Facility Expenses		
<b>Aircraft</b>	48%	\$xx
Fuel Cost		
Navigation Charges		
Stand-by Aircraft Amortization		
Extra Aircraft Utilisation		
Extra Maintenance		
<b>Passengers</b>	34%	\$xx
Hotel & Meal Expenses		
Rerouting of Passengers		
Luggage Complaints		
Revenue Losses*		
*Due to miss-connections, walk-away passengers & passenger ill-will		
<b>TOTAL / \$</b>		\$xx

Fig. 8 Items contributing cost to delays

## Passenger-related expenses

Passenger-related expenses are among the greatest contributing factors to delay costs. These were estimated to have a contribution of between 35% on short-haul to more than 60% on long-haul flights.

These are incurred from:

### a) Hotel and meal expenses:

They are greater for long-haul flights, since in most cases frequencies are lower than for short-haul flights and passengers often have to wait for the next daily departure.

### b) Costs associated with re-booking and re-routing of passengers:

Dealing with a delay, the bigger the aircraft, the more passengers airlines have to handle.

### c) Luggage complaints

### d) Revenue losses from:

**Missed-connections.** The resulting revenue losses can be appraised by compiling airlines' statistics, looking at how many passengers are expected to miss their connection following X minutes of delays.

**Walk-away passengers.** Airlines operating on high density and highly competitive routes, where passengers can easily opt for competing air or ground services, have much greater losses of this type.

**Passenger ill-will.** A flight is commonly considered delayed when it departs or arrives 15 minutes after its scheduled time. Passenger satisfaction is dependent on getting to a destination on time. This satisfaction is affected well below 15 minutes, according to previous surveys on the subject.

The resulting passenger dissatisfaction, in other words passenger ill-will, can be considered as a loss of passenger loyalty. Repurchase intention will then be reduced, generating losses of future revenue for the airlines. These losses are difficult to appraise and quantify. It is assumed that these passenger-related costs are incurred from the beginning of every delay, therefore from the first minute of delay.

To prevent dramatic passenger dissatisfaction, some airlines offer compensation to their passengers. When delays occur, the higher the fares, the higher the compensation levels.





## Methodology

### For cancellation analysis

The table in figure 9 below presents the methodology used by airlines to appraise their cancellation costs with examples of percentages. It highlights that cancellation costs are driven by passenger-related costs. However, some operational savings from not operating the flight reduce cancellation costs.

Depending on airlines' type of operations and their respective environment, passenger-related expenses and the amount of operation cost savings are expected to vary significantly. Therefore it is recommended that all operators should do their own calculation based on their respective operation type.

Passengers-related cost	Total / %	Single-aisle
Hotel & Meal Expenses	130%	\$xx
Rerouting of Passengers		
Luggage Complaints		
Revenue Losses		
<b>Total cost savings</b>	<b>-30%</b>	
Hotel & Meal Expenses		
Rerouting of Passengers		
Luggage Complaints		
Revenue Losses		
		<b>TOTAL: \$ / SEAT</b>
		\$xx / seat

Fig. 9 Items contributing cost to cancellations

For example, domestic operators based in North America face significantly lower airport and navigational charges compared with European operators, leading to lower operating costs and, therefore lower potential savings. Moreover, the savings can also be different depending on when the cancellation occurs. Catering sometimes cannot be saved if it is already on board the aircraft.

When do cancellations occur? The question is: "Are there any alternatives?" As reported by the airlines, when dealing with a delay, if it is expected to last for some time and alternatives are available to dispatch the passengers, airlines often balance the flight cancellation cost with that of the expected delay and take the appropriate measure.

Cancellation costs are fixed costs. On the contrary, delay costs are running, as a function of time, and are often reported as costs per minute. It is therefore possible to determine whether it is more cost effective to cancel the flight or not. The sooner the decision is taken (if possible prior to the scheduled departure), the lower the final costs. If, on the other hand, no alternatives are available, the cost of delays will go well above the cancellation costs, and delays can last for more than 24 hours.

## Application

### of delay and cancellation costs

Delay and cancellation costs can be used to evaluate the cost benefit of modifications to improve the dispatch reliability of an aircraft fleet. A balanced computation between the airline's cost of delays and cancellations, the cost of improvement actions, and the savings over a specified amortisation period can be done.

In other words, by knowing the rate of delays and cancellations caused by a specific component or a specific system, the average delay time they cause, their repercussion on operational interruption costs and the necessary investment for reliability improvement, the break-even point and further cost savings can be calculated.

In this respect, all operators wishing to carry out such analyses will find Airbus Industrie's computerised Service Bulletin Cost Benefit Model of much help. It is available on request from the address below, free of charge for Airbus Industrie's customers.

## Conclusion

Airlines, airframe and engine manufacturers, and equipment suppliers all have a degree of responsibility and control of operational interruptions due to technical reasons. Reduction in the number of operational interruptions can lead to substantial cost savings. However, there is always a cost associated with these improvements. Therefore, this cost should be properly balanced with the potential resulting savings.

Working closely with the manufacturers and suppliers, operational reliability can be improved, to the benefit of the airlines and to the satisfaction of their passengers. The method presented for the analysis of delay and cancellation costs can help airlines appraise their operational interruption costs, and therefore, identify future reliability improvement benefits ■

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# The new A340-500/-600

## Fuel System

*& the principal differences with  
the A340-200/-300*



**By Ross WALKER**

*Senior Fuel Systems Engineer  
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*The fuel system of the A340-500/600 aircraft differs significantly from the A340-200/300. The principal reason for the difference is the change of the wing design resulting in an increase in the wing sweep. The effect of this is to change the trajectory of any debris from an uncontained engine rotor failure, preventing the use of tank boundaries similar to those on the A340-200/300.*

*For certification reasons the boundaries for the engine feed tanks and associated system architecture had to be changed.*

*Additional changes to the system architecture have also been made as a result of the requirement for increased refuelling flow rates (400,000 litres/hour).*



## In summary

## Differences

Below, you have a summary of the differences for A340-500/-600 fuel system:

- ▶ An increase in the number of fuel tanks
- ▶ A revised ECAM fuel system page
- ▶ Secondary wing refuel and transfer galleries
- ▶ Dedicated fuel jettison/transfer & engine feed pumps
- ▶ Separate APU and trim transfer lines
- ▶ Segregation of computing and fuel probe interface functions into separate boxes
- ▶ (-500 only) A fuel tank positioned between the forward end of the rear cargo hold & the centre landing gear bay
- ▶ Change of vendor to Parker for fuel control monitoring system

## Functions

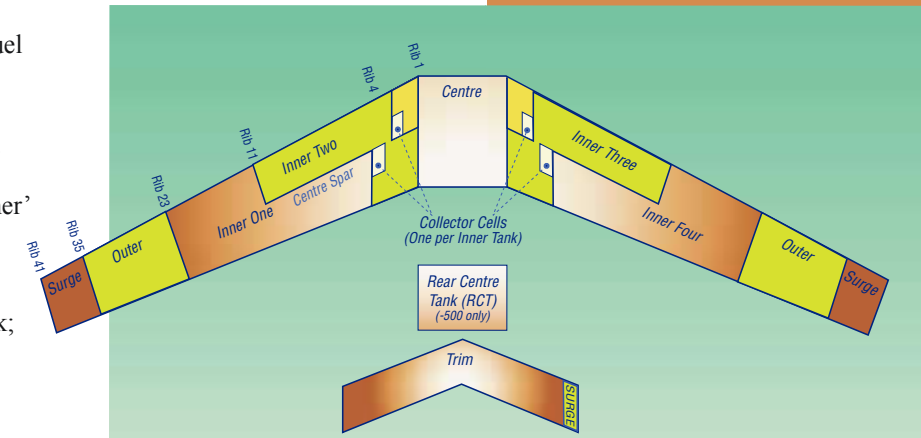
The functions of the A340-500/-600 fuel system remain similar to the A340-200/-300:

- ▶ Fuel storage and tank venting
- ▶ Engine and APU fuel feed supply
- ▶ Fuel quantity indication
- ▶ Temperature indication
- ▶ Refuel/Defuel control
- ▶ Transfer control
- ▶ Centre of gravity control
- ▶ Fuel level sensing
- ▶ Fuel system advisories and warnings
- ▶ Maintenance BITE indication
- ▶ Fuel jettison

## Fuel storage

On the A340-500 fuel is stored in nine fuel tanks:

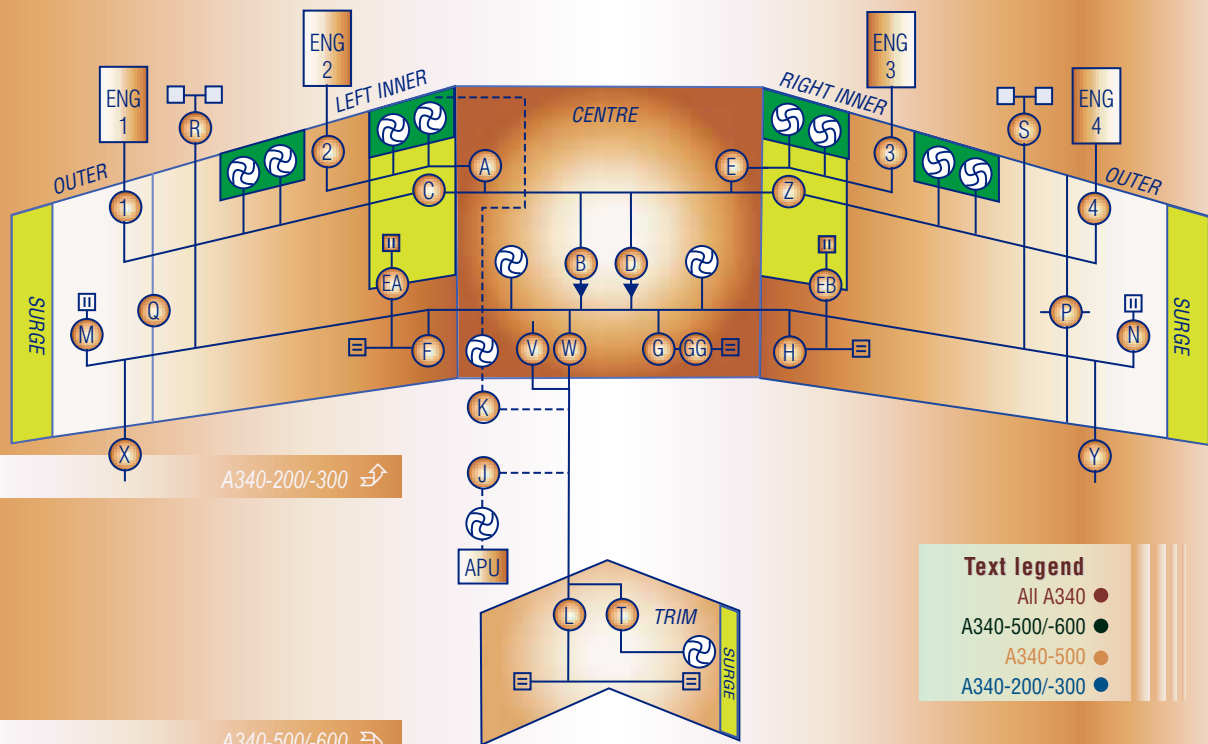
- Three** Tanks in each wing, comprising:
  - One** 'Outer' wing transfer tank;
  - Two** Engine feed tanks called 'Inners'. (Within each 'Inner' tank is a dedicated engine feed collector cell);
- One** Transfer tank in the centre wing box called the 'Centre' tank;
- One** Transfer tank in the horizontal stabiliser called the 'Trim tank';
- One** Transfer tank positioned at the forward end of the rear cargo hold. This tank is called the 'Rear Centre Tank' or 'RCT'.



At each wing tip and on the right wing tip of the horizontal stabiliser is a surge tank. These tanks do not normally contain fuel but are used as part of the tank ventilation system to link the fuel tank system to the outside air and prevent fuel spillage during refuelling, aircraft manoeuvres or due to thermal expansion of the fuel. These tanks are the interface to outside air through flame arrestors and flush non-icing inlets.

A340-500/-600 Fuel tanks

## Fuel system



### REFUEL/DEFUEL VALVES

#### AIRCRAFT

- R Left refuel isolation
- S Right refuel isolation
- BM Auxiliary refuel
- BN Defuel

#### INNER

- BA Inner 1 inlet
- F Inner 2 inlet
- H Inner 3 inlet
- BB Inner 4 inlet

#### OUTER

- M Outer inlet
- N Outer inlet

#### CENTRE

- G Centre inlet
- GG Centre restrictor
- BC Inner 1 transfer
- BG Inner 2 transfer
- BH Inner 3 transfer
- BD Inner 4 transfer

#### TRIM

- W Trim pipe isolation
- L Trim inlet

#### RCT

- CA RCT isolation
- CB RCT inlet

### TRANSFER PUMPS

#### CENTRE

- Centre left
- Centre right

#### TRIM

- Left trim transfer
- Right trim transfer
- Trim transfer

#### RCT

- RCT forward
- RCT aft

### TRANSFER VALVES

#### OUTER

- Q Left outer transfer
- P Right outer transfer

#### TRIM

- T Trim isolation
- V Trim forward transfer

#### RCT

- CC RCT transfer
- CD RCT auxiliary transfer

#### AFT

- B Left aft transfer
- D Right aft transfer

### JETTISON VALVES

- X Left
- Y Right

### Text legend

- All A340 ●
- A340-500/-600 ●
- A340-500 ●
- A340-200/-300 ●

A340-500				A340-600			
Volume		Mass		Volume		Mass	
litres	US gals	kg	lb	litres	US gals	kg	lb
6,360	1,680	5,088	11,216	6,360	1,680	5,088	11,216
6,360	1,680	5,088	11,216	6,360	1,680	5,088	11,216
25,690	6,786	20,552	45,305	25,690	6,786	20,552	45,305
33,280	8,792	26,624	58,698	33,280	8,792	26,624	58,698
33,280	8,792	26,624	58,698	33,280	8,792	26,624	58,698
25,690	6,786	20,552	45,305	25,690	6,786	20,552	45,305
55,980	14,788	44,784	98,729	55,980	14,788	44,784	98,729
8,238	2,177	6,590	14,534	8,238	2,177	6,590	14,534
19,930	5,265	15,944	35,151	Not fitted			
214,808	56,746	171,846	378,854	194,878	51,481	155,902	343,703

(For mass figures a density of 0.8 kg/litre = 6.676 lb/US gallons is used)

- Left Outer
- Right Outer
- Inner 1
- Inner 2
- Inner 3
- Inner 4
- Centre
- Trim
- RCT
- Total

### JETTISON/TRANSFER PUMPS

- Inner 1 jettison/transfer
- Inner 2 jettison/transfer
- Inner 3 jettison/transfer
- Inner 4 jettison/transfer
- Left Centre jettison/transfer
- Right Centre jettison/transfer

### ENGINE/APU FEED PUMPS

- MAIN
- Engine 1 main
- Engine 2 main
- Engine 3 main
- Engine 4 main

### STANDBY

- Engine 1 standby
- Engine 2 standby
- Engine 3 standby
- Engine 4 standby

### APU

- APU forward feed
- APU aft feed

### ENGINE / APU FEED VALVES

- ISOLATION
- EC Transfer control 2
- ED Transfer control 3
- EA Left Inner
- EB Right Inner

### APU

- J APU LP
- K APU isolation

### LP

- 1 Engine 1 LP
- 2 Engine 2 LP
- 3 Engine 3 LP
- 4 Engine 4 LP

### CROSSFEED

- C Crossfeed 1
- A Crossfeed 2
- E Crossfeed 3
- Z Crossfeed 4

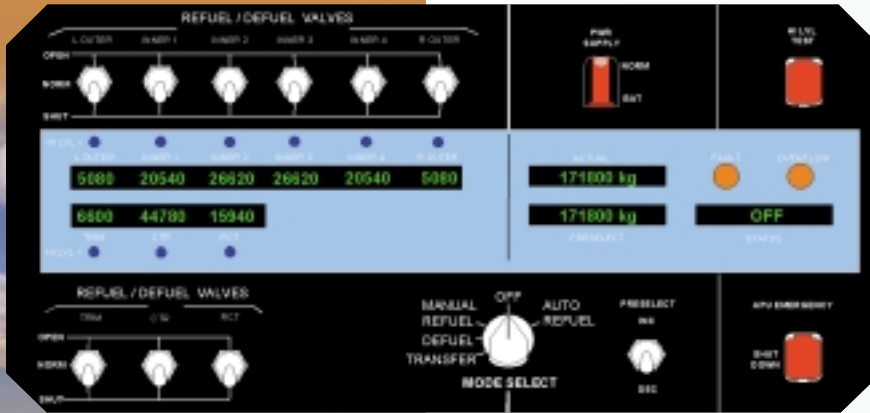
## Refuel

The refuel system is designed to refuel the aircraft from empty to full in 33 minutes on the A340-500 and 30 minutes on the A340-600, when a refuel pressure of 3.45 bar is applied at all four of the refuel couplings. (A slower refuel time will be obtained if the refuel pressure is lower). The four couplings are fitted as two pairs, one pair fitted to each wing.

The total aircraft and individual tank usable fuel capacities

# Refuel/defuel control panel

Control of the refuel function is by the two FCMCs (Fuel Control and Monitoring Computers) and two FDCs (Fuel Data Concentrators). The operator interface is either through the standard refuel panel fitted in the lower surface of the fuselage just aft of the undercarriage bay, or through the optional refuel panel and MCDU (Multipurpose Control and Display Unit) in the cockpit.



Normal refuel is fully automatic, however in the event of system failures a manual refuel facility is available through the standard refuel/defuel control panel.

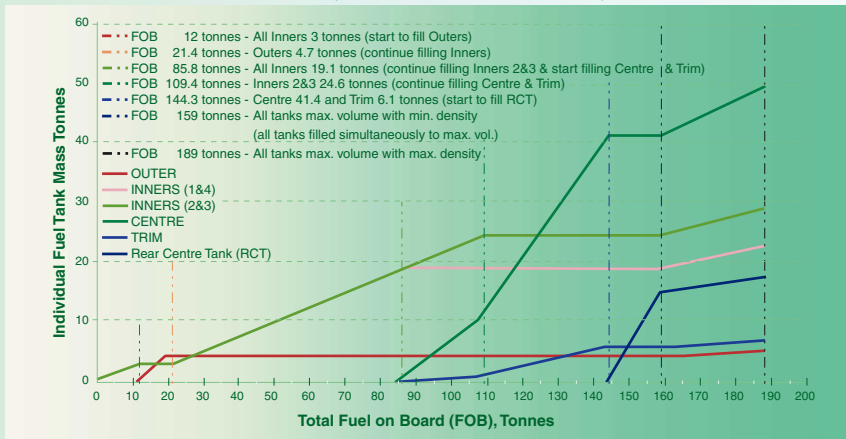
## Refuel distribution

The automatic refuel distribution is defined in two steps in a first stage by specific masses for each tank followed by a second 'top-up' phase to the volumetric high level for all tanks.

A & B - The automatic refuel distribution for the complete range of fuel densities and fuel quantities



**A** A340-500 Refuel Distribution (All Densities 0.74 - 0.88 kg/litre)

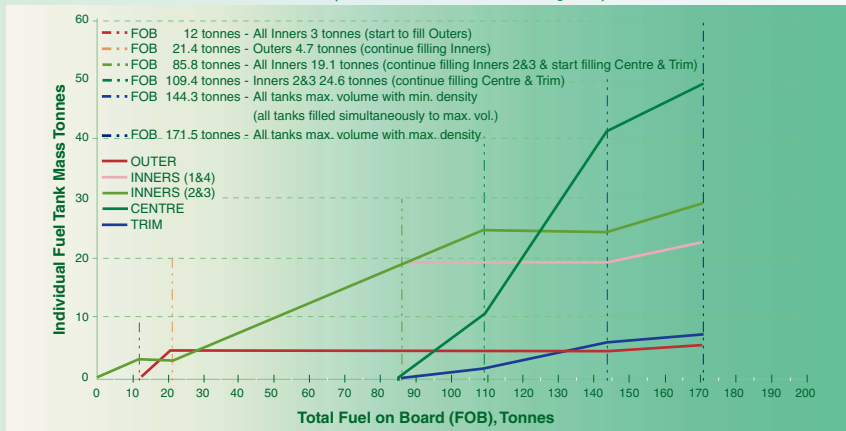


The Outer, Trim and RCT tanks each have a single tank inlet valve. To minimise any surge pressures in the refuel gallery the Centre and Inner tanks have two valves which are closed in sequence. The Centre tank has a tank inlet valve in series with a restrictor valve and the Inner tanks each have two tank inlet valves in parallel.

To enter the aircraft, fuel must pass through one of the two refuel isolation valves which form part of the refuel couplings fitted to each wing. To prevent spillage of fuel, the detection of fuel within either of the wing tip surge tanks or a Jettison valve detected open will automatically stop the refuelling of the complete aircraft by closing the refuel isolation valves.

In addition, detection of the fuel in the horizontal stabiliser surge tank will automatically stop automatic refuelling and manual refuelling of the Trim tank.

**B** A340-600 Refuel Distribution (All Densities 0.74 - 0.88 kg/litre)





## Engine feed

Under normal operation each engine is fed by an independent fuel feed system. This consists of main and standby engine feed booster pumps located within a collector cell, which in turn is located within an engine feed tank (Inner). The main pump operates continuously, the standby pump only operates if the main pump becomes defective or is set to OFF.

The collector cells are maintained full until the Inner wing tanks are near empty (see fuel transfer section) to help ensure a supply of fuel to the engine under negative 'G' manoeuvres. The collector cells are maintained full by the use of jet pumps driven by fuel flow taken from the main engine feed booster pumps.

All engine feed systems can be joined to the crossfeed gallery by their independent crossfeed valves. The crossfeed system is used under abnormal operational conditions such as loss of all electrical power requiring gravity feeding or to connect all engines to a single engine feed boost pump when only the emergency electrical supply is available or to allow the crew to correct an imbalance between symmetrical wing tanks.

In common with all other Airbus Industrie programmes, all fuel pump and valve electrical wiring is routed outside of the fuel tanks to eliminate the potential for introducing ignition sources into the fuel tanks.

*Note: Identical pumps are used for engine feed, jettison and transfer on all A340s.*

## APU Feed

The APU is fed via a dedicated line from a tapping off the number one engine fuel feed line. The number one engine booster pumps normally supply the fuel pressure. However, if these pumps are not selected then a dedicated APU pump is installed in the line to supply the fuel pressure.

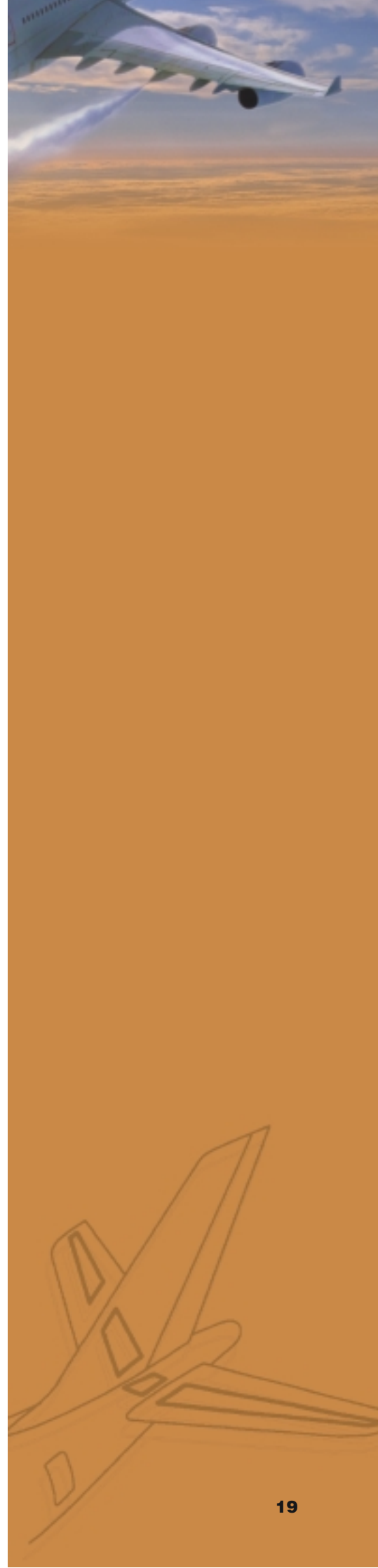
## Jettison

A jettison system is provided to avoid the necessity for heavy maintenance tasks, by providing a means to minimise the potential for an overweight landing. (The system is not required for certification reasons relating to the performance of the aircraft). The system is activated by means of two dedicated pushbuttons 'Arm' and 'Active' located on the cockpit overhead panel. The system can be manually stopped by de-selection of either of these pushbuttons, or automatically if all jettison/transfer pumps are running dry (low pressure) or when the fuel quantity drops below a predetermined target input into the MCDU by the flight crew.

The system jettisons fuel through two jettison valves positioned in the number three flap fairing between the two engines on each wing. Up to ten jettison/transfer pumps are used to provide the fuel flow, one situated in each of the four Inner tanks and two in the centre tank, two in the Trim tank and Two in the RCT. The refuel gallery is used to connect the jettison valves to the pumps. The Centre, Trim and RCT pumps only function if the associated tank contains fuel. In addition, if the Outer tanks contain fuel, a transfer of the fuel to the Inner tanks is automatically initiated.

## Fuel transfers & usage

On the A340-600 under normal operation all fuel transfers, except those for centre-of-gravity control, are to the four Inner tanks, prior to transfer to the collector cells, and are controlled automatically. Automatic transfers are controlled to balance the fuel quantities in symmetrical wing tanks to prevent an imbalance which could adversely effect the aircraft handling. On the A340-500 transfers from the RCT are to the Centre tank. On the cockpit overhead panel four pushbuttons are provided to allow manual transfer control of the Outers to Inners, Centre to Inners, Trim to Centre and RCT to Centre.



## A340-500 fuel usage & transfer sequencing

The normal tank usage sequence is in the following order:

- |          |                   |
|----------|-------------------|
| 1 Centre | 4 Outers          |
| 2 RCT    | 5 Inners          |
| 3 Trim   | 6 Collector cells |

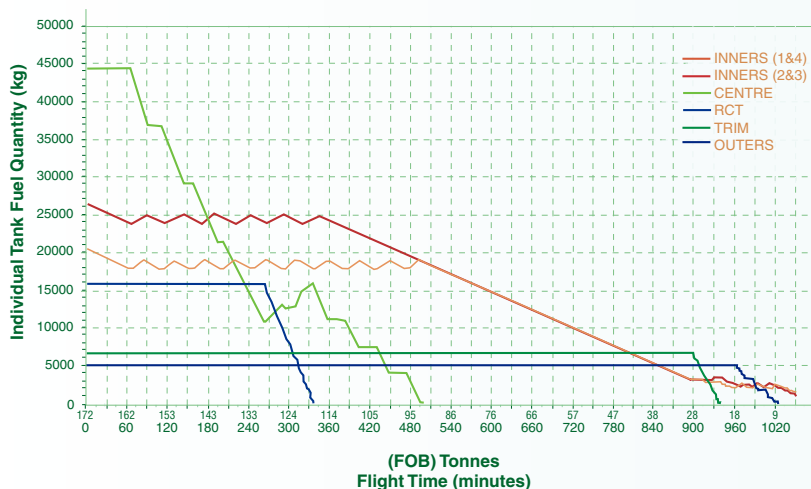
Transfers from the RCT to the Centre tank are by means of two pumps located in the RCT and two valves, one valve situated at each end of the RCT refuel/transfer line.

Transfers from the Centre to the Inner tanks are normally by means of two pumps located in the Centre tank which are connected to the

forward refuel/transfer gallery and independently controlled tank inlet valves, one for each Inner tank. In the event of certain failures, transfers are by means of two pumps located in the Centre tank which are connected to the aft refuel/transfer gallery and independently controlled tank inlet valves, one for each Inner tank.

Transfers from the Trim to Inners are by means of two pumps located in the Trim tank, two valves situated at opposite ends of the Trim tank transfer line and independently controlled tank inlet valves, one for each Inner tank, connected to the aft refuel/transfer gallery. If the centre tank contains usable fuel then trim transfers will be to this tank.

Transfers from the Outer tanks to the Inner tanks are by gravity. For transfers to Inner tanks one and four the refuel inlet valves, for the concerned tanks and refuel gallery, are used. For transfers to Inner tanks two and three dedicated transfer valves and associated pipework is used.



### Centre of gravity control

In order to minimise the aircraft's aerodynamic drag in cruise the fuel system is used to optimise the aircraft's angle of attack by controlling the aircraft's aft centre-of-gravity (CG). Depending on the aircraft's zero fuel weight (ZFW), CG and the actual fuel on board, the fuel system will control the aircraft's CG to a target of 2% mean aerodynamic chord (MAC) forward of the certified aft limit.

Control is achieved by means of fuel transfers to and from the Trim tank and in addition on the A340-500 transfers from the RCT. Aft transfers to the Trim tank are performed if the tank is not full and the aircraft's CG is forward of the target. Forward transfers from the Trim tank are performed if the aircraft's CG drifts aft, due to fuel burn, of the target. On the A340-500 forward transfers from the RCT are delayed until the aircraft's CG drifts aft, due to fuel burn, of the target or the centre tank has less than 11 tonnes of fuel. (At the end of cruise all Trim tank fuel is transferred forward).

For integrity of the system, an independent CG monitor is performed by the flight management system.

### Fuel quantity measurement & level sensing

Unlike all other Airbus aircraft, the fuel quantity measurement/indication and level sensing functions are combined and use similar capacitive type probes to perform the two functions. The probe excitation and return signal processing is performed within two independent FDCs. The conditioned data from the FDCs is sent to both FCMCs, which process the data for fuel quantity indication (FQI), fuel level indication, refuel control, CG calculations and control and general fuel transfer control. Automatic compensation is applied for changes in fuel density, fuel permittivity and aircraft effective attitude.

The probes are configured into two separate groups per tank and the interfaces through the FDCs and FCMCs are designed so that any single failure (e.g. probe, harness, FDC or FCMC) will not cause a loss of indication.



## Fuel quantity measurement & level sensing (cont'd)

Within the normal ground standing attitude range of the aircraft the accuracy of the FQI system will be in the order of 0.4% of the full capacity near empty to 1% at full.

To further enhance the security of the fuel system designs on Airbus aircraft the potential for an ignition source to be present in a fuel tank has been mitigated by the following measures:

- ▶ The harnesses to the capacitive probes are segregated from all other aircraft wiring ;
- ▶ The length of the harnesses is minimised (the FDCs being fitted within the centre fuselage section).

*These measures limit the potential for a short circuit to power cables.*

In the case of a complete failure of the fuel control and monitoring system (FCMS), a secondary manual fuel level indication system is installed in the six wing tanks and the centre tank for ground use. Height data from the probes is used in conjunction with aircraft attitude information, fuel density measurement and a set of look up tables to calculate the fuel mass in the tank being measured.

The level sense function is used to detect high and low fuel level states in all fuel tanks and a fuel overflow in the three surge tanks.

This information is used to control:

- ▶ Refuel
- ▶ Inter tank transfers
- ▶ Transfer pump shut-down
- ▶ Overflow protection
- ▶ Indication of low fuel state.



## Fuel temperature measurement

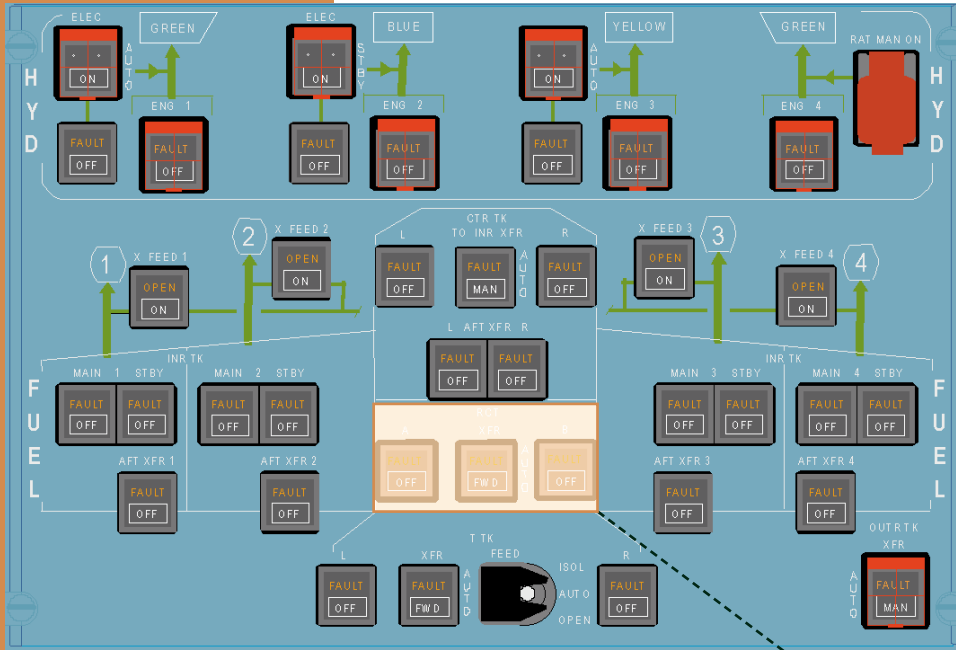
Dual element in-tank temperature sensors are fitted to the Trim, Outer and Engine feed tanks. These sensors enable the flight crew to monitor the evolution of the tank fuel temperatures to ensure that they are within the operational limitations for the specific fuel types being used (e.g., JET A or JET A1).

# Cockpit control panels & indication

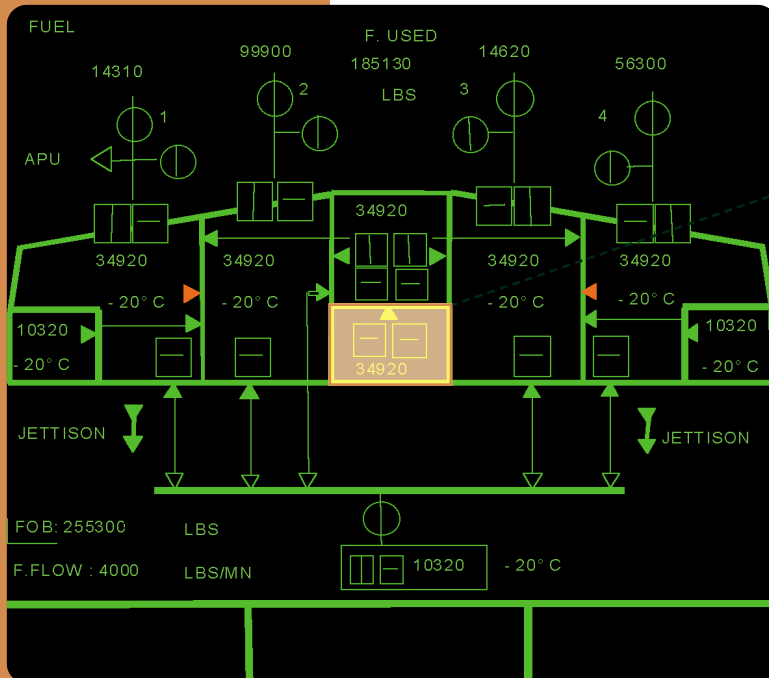
A340-500/600 Cockpit Hydraulic & Fuel Control Panel

Due to the differences in the fuel system architecture, the fuel system control panel and ECAM system page differ from the A340-200/-300.

Despite the differences, there is still a pushbutton for each engine feed and transfer pump, for each crossfeed valve and each transfer function, as



well as a dedicated toggle switch associated with the Trim tank isolation, as can be seen on the main fuel system overhead panel. Under normal operation, after initialisation at the start of a mission, no crew action is required on the panel. Manual transfer control is by selection of the dedicated transfer pushbuttons or the deselection of the transfer pump pushbuttons. Adjacent to the main panel are the pushbuttons for jettison and the Inner 2 and 3 wing tank isolation valves.



A340-500/600 ECAM fuel page

On the ECAM fuel page fuel system data is displayed including:

- ▶ fuel quantity
- ▶ fuel temperature
- ▶ fuel transfers
- ▶ pump status
- ▶ fuel used
- ▶ fuel flow.

Warnings and the total fuel on board are displayed on the engine page.

## Conclusion

The A340-500/-600 have been designed taking into account lessons learnt from the in-service experience of the A340-200/-300 ■

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# MODERN TECHNOLOGY



*By William WAINWRIGHT  
Chief Test Pilot  
Airbus Industrie*

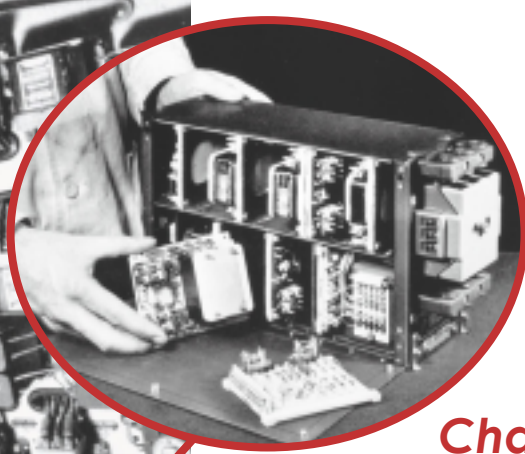
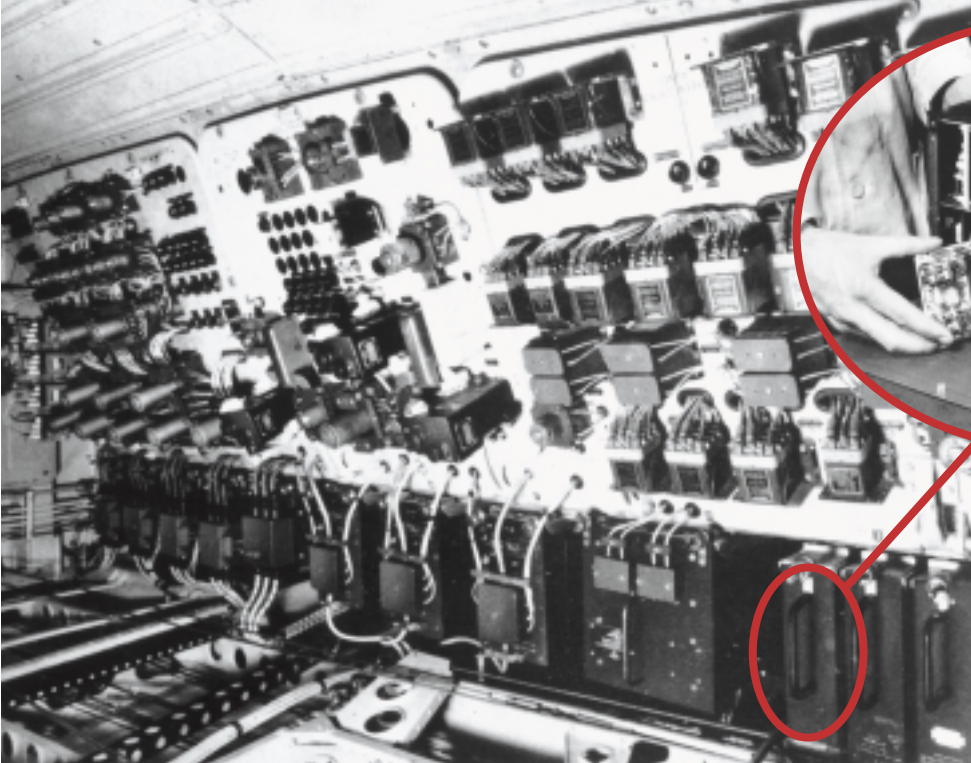
*“My view on technology has changed a lot over the years. I see this particularly with my attitude towards my cars. I have always liked cars, particularly fast cars. When I was younger I spent most of my weekends working on them; tuning carburettors or tweaking electrical points. Now, even when I buy a new car, quite a time passes before I open the bonnet, and then it is just to marvel at the technical beauty of the modern engine.*

*I never touch it. It even tells me when I have to add some oil. A similar evolution has taken place in aviation, but I believe that we have not yet realized how it has revolutionized our life and how we should change our attitude towards modern technology.*

*In Flight Test, we are often asked to do an investigation after a complaint about system behaviour, and we sometimes find in the data analysis report, that it was working ‘as designed’. I believe that this is because we have not always understood how the advent of digital systems has changed the way that automatic systems behave. I would like to explain my point of view. My intention is to provoke some thought, and perhaps some discussion, about how to adapt the way that we live with and think about automatic systems”.*

## What has changed?





## Changes in technology

Not so long ago sophisticated aircraft systems, such as autopilots and autothrottles, were made up of complicated linkages involving cogs, cams, springs, and gears. They could clog up, seize up, slip a gear, or just slow down because they were contaminated.

Computer rack in a  Hawker Siddeley Trident

This has all changed...

They are now made up of various electrical components, and some software.

Computer rack in an A340 



from COGS  
to software...

This is similar to the revolution that occurred with watches. The watch that I received for my 21st birthday was a Swiss-made chronometer of a very famous mark. It is a mechanical marvel, complicated, and expensive. It kept time wonderfully, with remarkable accuracy for many years. But then it became less accurate – it needed cleaning. Nowadays, even after cleaning, it is somewhat erratic. Modern watches can be much simpler mechanically. The invention of the quartz watch has changed everything. They are not only very accurate when new, but there is nothing in them to wear out or get dirty. Of course, they can still break down, but it is most likely to be a sudden failure, rather than a gradual and slow deterioration.

And of course, the electrical components can fail, so that aircraft computers suddenly stop working. But they do not start working more slowly, or less efficiently. Generally, if they do something that you do not like, it is because they have been programmed to do it. It is not because they are not working correctly and should be changed.



Sudden failure!

Modern aircraft systems are similar. Software does not wear out or get dirty. It always does the same thing under the same circumstances.

This is not to deny that computers do not sometimes have 'glitches'. But that is different, and I will talk about it later.

As I said in my introduction, we often find cases where computers have been criticised, and after examination, it is proved that they were working 'as designed'. This is often in airline service, but it also occurs during our production testing, and customers sometimes try to reject systems, such as autopilots or autothrottles, which are working correctly, although not in the way that they would like them to do. I would like to take a few examples to illustrate my point.



## Software Design

Designing any flight control system is a compromise. I will take autothrust as an example. To have good accuracy of speed tracking you need a high *gain* system. However, a high gain system is susceptible to overcontrolling, which in the extreme case may lead to instability, which in this example might be oscillations in power setting. And even with a system free of instability, frequent thrust variations in the cruise will increase fuel consumption and annoy the passengers. Thus, you have to find a compromise that will give you reasonable comfort together with acceptable accuracy. For example, in the cruise we set a reasonably high gain initially, allowing quite high thrust variations, so that the autothrust system can quickly find a mean thrust setting to maintain the selected speed.

*Gain is a number in a formula used in a control law. High gain means a high multiplication of a parameter.*

Thereafter, a lower gain is used to minimize thrust variations whilst allowing a looser speed tracking with variations in speed of up to +/-4kt. If the speed goes outside this bracket, due to the wind suddenly changing, the system progressively switches back to its high gain until the stabilised situation is regained. Thus, in certain conditions speed tracking may be less accurate than some pilots think it should be.

## Extreme Conditions

Furthermore, if a large windshear is encountered, particularly when flying at speeds near V<sub>mo</sub>/M<sub>mo</sub>, we need the autothrust to act quickly to prevent or minimize an overspeed. Thus, it may happen that the autothrust varies between high and low power settings for a short time. Even though the relatively high gain that is used is still rather low by comparison with what a pilot would have used in these circumstances to do his initial correction, we cannot change the gain, as he would do, after the possibility of overspeed has been avoided.

In addition, we always avoid using very high gains, which may cause instability. Therefore, we use compromises which will work very well in most cases, but which might not be optimum in some extreme cases.

It may even happen that the engines reduce to idle to avoid the speed increasing too quickly. Then, when the shear reverses, and thrust has to be increased, the engine acceleration will be relatively slow, as with all modern big-fan engines at high altitude, such that a speed excursion occurs briefly in the opposite sense. This behaviour has been criticised when it has occurred in service because it was considered to be due to a faulty autothrust system. This may have been true in the past, with autothrottles full of gears, cams, levers etc., but this is no longer true of digital systems. We have designed our autothrust system to work that way, for very good reasons, which may not always be obvious to the pilot.

### *With modern technology*

*Computers, having the same hardware, and the same software, will always work in the same way. Thus, changing the autothrust computer to another of the same standard, will have no effect. No matter how many new boxes you try, the only way to correct what has happened is to change the software. Unlike some popular perceptions, this is not an easy matter and it is certainly not cheap. We have designed our software as it is for good reasons, and it is always based on a compromise solution. Of course, sometimes we realise that we could have done it in a different, perhaps a better, way. But you always have to be very careful when you change the software to correct something that you do not like, that you don't make it worse somewhere else. This is why, when we change something, we always do a lot of extra flight tests to prove that there is no degradation.*

Computers work  
'as  
designed'...



## Characteristics of Automatic Systems

*"I believe that one of the reasons why it is not always obvious to the pilot that a system is working 'as per design', when it is working below his expectations, is that we all expect a little too much of modern automatic systems".*

Also, we sometimes meet conditions where we have never seen them working before. They work better than the human being in some aspects, but not as well in others. For example, they never get tired, and thus they can follow a speed target for hours with excellent accuracy if the conditions do not change. But they cannot adjust their strategy when the conditions change. In fact, they are less adaptable than human beings.



### Adaptability in autoland

*Autoland was developed to land an aircraft when the pilot could not see where he was going; blind landings in fog. This put the emphasis on landing the aircraft in a reasonable touchdown zone. The comfort of the landing was of secondary importance. Now autoland is being used in many different conditions, and on many different runways, which are not always ideally suited to automatic landings, because they have rising ground before them, or cliffs, or they have significant slopes.*



Blind landing in fog ↗

Unlike a human pilot, the autopilot cannot change the way it flies to cope with different local conditions. It cannot change its priorities between making a smooth landing when the weather conditions are good and landing relatively firmly but right in the centre of the touchdown

zone when they are bad. It cannot decide to change its flare height to suit a rising runway, nor can it change its technique to cater for thermal activity. Of course, we could attempt to give them a lot of complicated logic that would try to cater for this. But this may cause problems elsewhere, because it is often better to have simple logic. And you have to be careful not to have a system which copes perfectly with all the fringe situations but does a poor job on a good runway in real Category 3 conditions.

Thus, although the dispersion in touchdown distance is low, the dispersion in the way the flare is done and the touchdown rate of descent can be quite

large, particularly when landing on difficult runways or in difficult weather conditions. A variation in touchdowns between 2ft/second and 5ft/second is not unusual. The autopilot should never do a 'kiss' landing. This is because we design it to touchdown in the correct landing zone. Therefore, we have to make sure that it will not float.

For this reason we have incorporated a sort of anti-long flare. If after a certain time, the aircraft has not touched down, it is programmed to make a slight nose-down pitch change to search for the ground. This means that in certain conditions, which cause the aircraft to have a tendency to float, it will suddenly pitch nose-down to touchdown relatively firmly. In fact the touchdown will still be within our normal dispersion, but it may disappoint the pilot who was expecting something better, and it may be rather untidy.

### The reality

*We had a customer's pilot, come to accept a new aircraft, who asked to re-fly his aircraft after such an autoland. The repeat test was done at the same airport in the same weather conditions and the same thing happened again. Another flight was requested. The pilot was expecting a perfect performance from his new aircraft, which he had every right to expect, but in fact, a new aircraft will not do better autolands than an older aircraft. The form of autoland depends on the external conditions and not on the age of the computer, provided it has the latest software.*

Automatic systems  
are less  
adaptable...



## What never changes

The flying characteristics in normal law never change. They depend on a set of software, and as I have already said, that always works in the same way. At least unless, or until, we make a change to it. You may or may not like all the characteristics, and occasionally you may be surprised by something that you had not noticed before. But changing the computers to others of the same standard will do nothing.

During a customer acceptance flight on an A340, the customer's pilot suddenly complained about the rate of roll. He was doing a part of the programme that checked the flying characteristics in normal law. This calls for some more vigorous manoeuvring than is normally done in line service, and he found the roll rate to be less than he expected. I said that it was probably because he was not used to using such a large sidestick input. Perhaps he was looking for an instantaneous 15° per second roll rate, as might be interpreted from the book. Whereas we have to design the aircraft, with all its inertia, to have roll characteristics which start with a gentle acceleration initially before arriving at the maximum stabilised roll rate, which will always be 15° per second.

I have to admit that we ask the customer's pilot to verify the handling characteristics during their acceptance flight. We also do this during our own production test flights. This is an easy way to manoeuvre the aircraft a bit more vigorously than would normally happen in service with passengers aboard. In fact, we are verifying that no other anomalies occur. We are not really checking roll rates or maximum bank angles. They are always the same, although some small variations may be seen according to the exact way in which the manoeuvres are done.

## What can change

Although the software will not change, an external parameter that is used by the software may be deficient, either permanently or temporarily. A good example is the transition into another phase of a law – both in manual flight and in autoland. This may be a reason to either change the equipment or to change the software by producing a new standard.

### Rectification action

*We had one case on a production first flight of an aircraft that passed into the de-rotation phase of an*

*autoland whilst still airborne. The test pilot had to intervene to prevent a hard*

*landing. It was due to an error in the wiring that caused the autopilot to see the wheels as turning permanently. As soon as the radio altitude part of the condition was seen, the aircraft started its de-rotation. This is a good example of why autolands must be done during production test flights and is a case where rectification action was necessary.*

We have also seen cases where aircraft did not pass into flare law during manual landings. The aircraft remained in its normal 'g' and pitch rate law for the landing, which is less dramatic, but still requires us to do some corrective action. However, in this case, working on the aircraft would have been ineffective; a change of design was necessary. In fact, it was due to the way in which the transition was triggered and the way the radio altitude signal was sampled. We discovered that a particular runway profile could cause a perturbation in the signal around the height for changing the laws which meant that the transition did not take place. In fact, the aircraft over-flew a lighting post at the exact instant where it passed below 100ft.

At that time the transition was triggered by the aircraft passing 100ft when in descent. This was hidden by the momentary blip in altitude caused by the post. The cure was to change the trigger mechanism to be when below 100ft and not when passing 100ft.

they always work in the same way...





“System failures are software...”

## Computer faults

*“I have to admit that computers are not infallible, and they can stop working correctly. I imagine that we have all experienced a home computer that has blocked and has to be re-started to clear itself. Of course a similar situation can occur to an aircraft computer. But it is important to realize which part of the computer can block, and which will always work exactly in the same way.”*

We had one case where all three Primary Computers were lost, and I know that various explanations are circulating, as rumours do, which have nothing to do with what actually happened. But, before I tell you what did cause this incident, I will explain how the system works.

To illustrate my point, even though I am not a software expert, I will use an example from the world of home computers. As I understand it, it is the software that manages the computer that may block. The programme software always works as designed. For example, in terms of the home computer, it would be an interaction between programmes that might provoke a blockage whereas each

individual programme, such as Word or Excel, always works as it is meant to. In aviation terms, the equivalent of Word or Excel might be the flight control law software, which I have already said will always work ‘as designed’.

The equivalent of Windows, or any other management software, is the Command/Monitoring structure that supervises each computer and manages the system, which consists of several individual computers, just like a network. I will give an illustration of how our ‘network’ works, and an example of a ‘glitch’, which has now been cured by a re-design of the managing software.

### How our ‘network’ works

We can consider the three Primary flight control computers on the A330/340 as three generals who just happen to be identical triplets commanding identical army divisions (called Prim 1,2,3). Being identical triplets they all think and work in exactly the same way and have the same reactions to each and every situation. Having identical army divisions under their command they each have identical resources to cope with any situation. But in any well disciplined army, only one general can be the supreme commander. This is the case for our flight control system.

Only one Prim is in command at any one time. It passes its orders to the others who continue, however, to calculate their own commands which they keep to themselves. Of course, being identical and having access to the same information, the orders calculated within each Prim are identical. Thus, if one Prim falls sick and passes the command to one of its brothers, the brother continues to give orders which will be identical to those

*which would have been given by the first Prim if it had not fallen sick. In fact, only one Prim is required to be active to maintain full normal law capability, provided of course that both Secondary computers are serviceable. Incidentally, the Secondary computers (Sec) are dissimilar to the Prims in both hardware and software. One of them can control the aircraft on its own. It is as if the three generals had two twin colonels in reserve, less capable, with smaller forces, but absolutely reliable.*



### The cured ‘glitch’

*We had one case where all three Prims were lost whereas only one Prim was sick.*

*This was due to a weakness in the monitoring process.*

*To ensure that we never leave a sick computer in charge of normal law, each Prim continuously sends messages to its brothers about the state of its health.*

*In this case, when Prim 1 started to feel sick it stammered and did not get its message out straight away.*

*Prims 2 and 3 hearing a garbled message thought that they were themselves sick, and they declared themselves faulty.*

*Prim 1 then got his message out to say that he was faulty and was handing over control, but there was no one left to hear him.*

*Thus, the aircraft passed into Direct Law under the command of its two Secondary computers until Prims 2 and 3 were reset.*

*This was a case where one of the Prims (Prim 1) was defective and needed changing. However, changing Prims 2 and 3 for new ones would not prevent this situation happening again, because they would be identical to the ones replaced. It was an unlikely occurrence that does not happen every time a Prim is faulty. However, it could not be ruled out that it would never happen again. The solution lay in re-designing the monitoring process, which has been done.*

## Fail soft

This latter example is a very good illustration of our philosophy which leads us to design monitoring circuits in the way that we do. Our philosophy is quite clear; it is to never leave a sick computer in charge of normal law.

Thus, the monitoring circuits are designed so that the slightest doubt leads to the relevant computer declaring itself faulty and dropping off-line. Therefore, failures are soft, and we have eliminated the hard-over failures which were a significant risk factor with previous generation aircraft. This may lead us to have more technical defects, but the effect on the aircraft and the pilot will be minimal due to the redundancy that is built into the flying control systems.

## Summary and conclusion

In conclusion, software design is a compromise and may not always please everyone. But the programme software, such as that used in Normal Law or autopilot or autothrust, will always behave in the same way in an identical set of circumstances. Failures that occur to computers are usually in the supervising and management part of the system. They will cause the system to fail soft. We have a similar situation with aircraft to that prevailing in the car industry. You no longer have to spend your weekends tuning carburettors or tweaking electrical points. Thanks to fuel injection and electronic ignition your car will give maximum performance just until there is a failure in the hardware, usually in the electronic circuit. You don't have any redundancy on your car; it just stops working. In aircraft, systems failures are soft and hard-overs have been eliminated ■



“...and hard-overs have been eliminated”

For any questions or comments, please contact:

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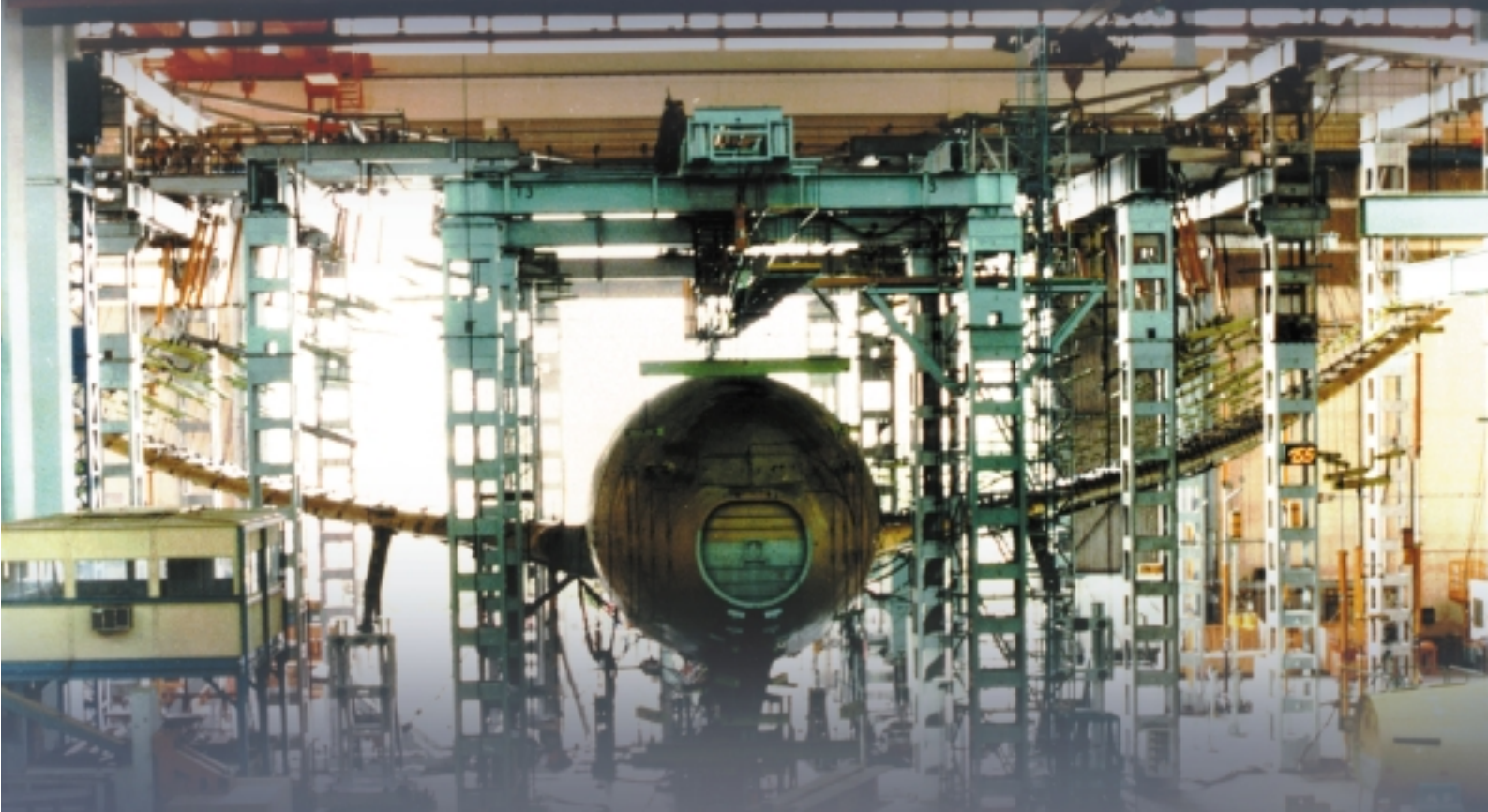
## *Changes to Technology (cont'd)*



In the 1920s static tests of wing structures were fairly simple affairs. All you needed were a few sand bags.

*Static test of an upturned Dewoitine D27 wing. The D27 first flew on 3rd June 1928 piloted by Marcel Doret.*

*Sixty years later life had become more complicated and expensive. Complete aircraft, special hangars and test equipment. Fatigue tests as well as static tests had become the standard in Europe with the arrival of the jet transport age in 1949 when the de Havilland Comet first flew.*



*A310 static test at CEAT Toulouse in 1983*






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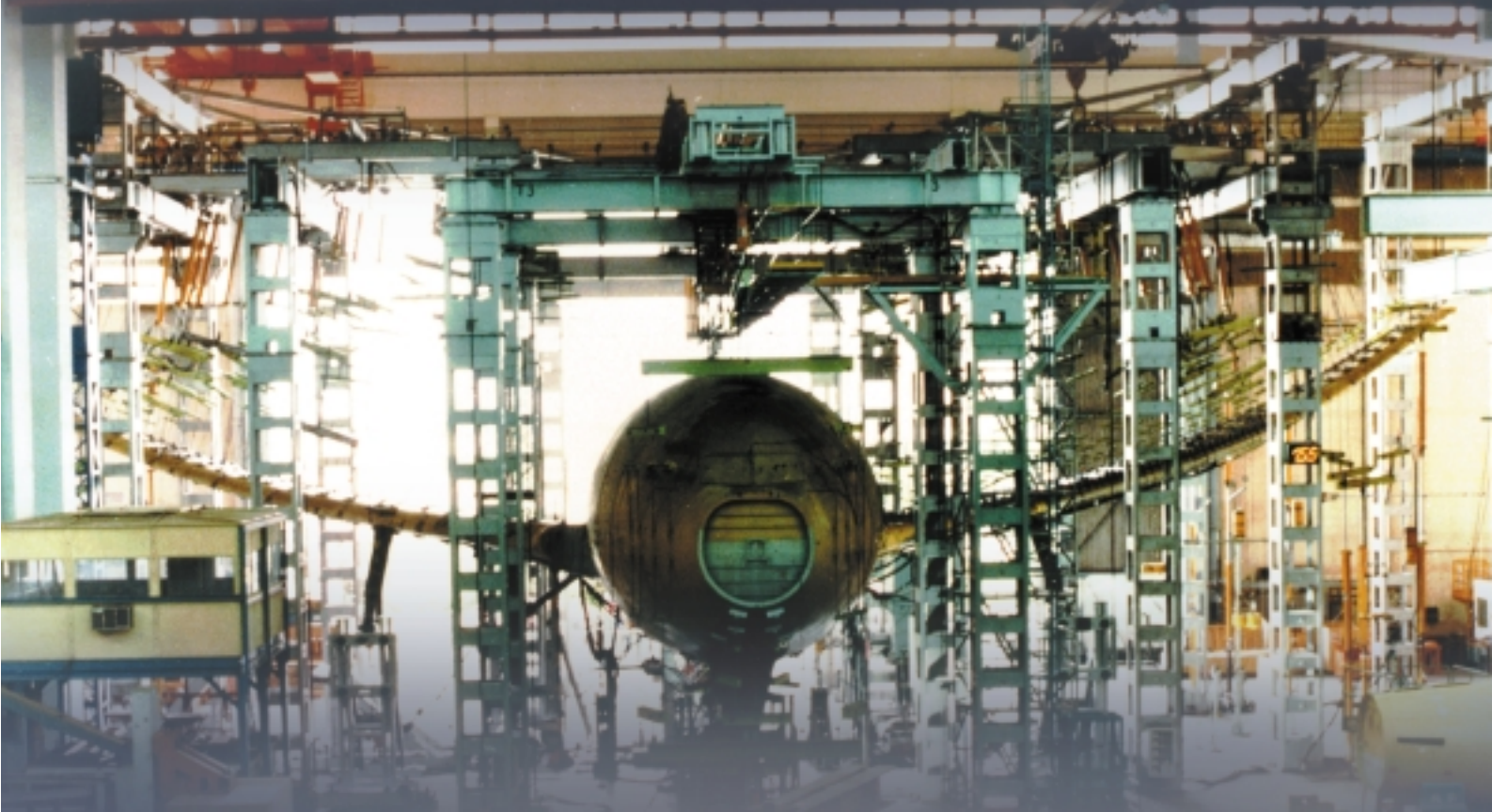
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