PERFORMANCE TESTING WITH HIGH PRODUCTIVITY IN A LOW SPEED FLIGHT REYNOLDS NUMBER TEST CAMPAIGN

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Abstract

The European Transonic Windtunnel (ETW) provides the capability for achieving flight Reynolds numbers (Rn) by testing at varying pressures and cryogenic temperatures. This capability was recently exploited to assess the low speed flight performance characteristics for the Boeing 787 commercial transport. High productivity combined with high data quality in both tunnel operations and model design / manufacture has provided early access to a substantial flight Rn performance database. The final determination on how well the ETW data characterized flight performance will follow flight testing in 2007-2008.

Introduction

Increasingly aggressive performance targets for large transport airplanes require high-lift designers to seek out methods of improving high-lift system performance (reduced weight, complexity and cost) without increasing program risk to unacceptable levels. Since the viscous interactions of complex high-lift systems are both Reynolds number (Rn) and configuration dependent, performance characteristics are difficult to reliably predict via either established prediction processes or state-of-the-art CFD methods. Gaining insight into the physics of high-lift systems while quickly acquiring a large high quality performance database can today only be achieved via ground-based flight Rn testing. Boeing is committed to understanding the potential of applying flight Rn data to high-lift systems earlier in a new airplane development cycle than ever before.

A measure of uncertainty is incurred when extrapolating sub-flight Rn wind tunnel data up to flight. Therefore, to mitigate the risk in making guarantees using such an extrapolated database, airplane performance is typically "left on the table". Performance may further be penalized by flexible designs intended to accommodate possible adjustments to the configuration during the flight test program. Penalties to in-flight performance for these overly conservative designs can only be estimated once flight test data are acquired. On the other hand, acquiring flight Rn data sufficiently early in a new airplane program enables one to quantify, with confidence, the value of configuration trades and decisions many years prior to first flight. Below are impacts on performance for a generic large twin engine aircraft [1], [2]:

- A 0.10 increase in lift coefficient at constant angle of attack is equivalent to reducing approach attitude by approximately 1 degree. For a given aft body-to-ground clearance angle, the landing gear may be shortened resulting in a weight savings of 1,400 lbs.
- A 0.05 increase in CLmax is equivalent to a 1.8 knot decrease in approach speed at constant weight or a 10,700 lb increase in landing weight at constant approach speed.
- A 1% increase in takeoff L/D is equivalent to a 2,800 lb increase in payload or a 150 nmi increase in range.
- A one drag count decrease is equivalent to a 200 lb increase in payload capability for a high altitude field on a hot day.

The high-level objectives of the ETW test discussed in this paper were to:

- Validate and influence the 787 high-lift configuration prior to achieving the Firm Configuration program milestone.
- Validate the wind tunnel database against our current high-lift flight prediction processes.
- Develop and validate database against 787 flight test data, available beginning in 2007.
- Reduce flight test schedule risk.

In order to successfully achieve the high-level objectives, a project plan was developed as follows:

- Conduct the requisite wind tunnel verification tests with an existing model (completed in 2004).
- Design and manufacture a high-lift half-model designed to provide a large number of repeatable configurations while maximizing in-tunnel productivity within a cryogenic environment.
- Maximize both productivity and data quality associated with tunnel operations by allowing for test plan flexibility while strictly adhering to established operational processes and procedures;
- Establish, and then assess, quantifiable productivity and data metrics for future high-lift cryogenic tests.

The focus of this paper will be on the last three items in this list. This paper is organized into a discussion of ETW capabilities (Section 1), followed by project requirements to productivity, schedule and data quality (Section 2), an assessment of realized productivity, schedule and data quality (Section 3) and finally the summary (Section 4).

The final model installation in the ETW test section is shown in Figure 1.

Fig. 1. 787 half model in ETW test section

1 ETW capabilities

The ETW facility [3] is a high Rn transonic wind tunnel using nitrogen as the test gas. High Rns are achieved by testing at cryogenic temperatures down to 115K (-253°F) and at pressure levels ranging from 115 kPa up to 450 kPa (16.7 psi – 65.3 psi). The Mach number ranges from 0.13 through the high subsonic speeds representative for cruise conditions of modern transport aircraft, up to 1.3 for supersonic aircraft or space vehicles. The test section size in conjunction with the available pressure and temperature ranges represent the best combination of parameters to achieve, with full span models (spans up to 1.56m / 5.12ft), a Rn of 50 million at cruise conditions and up to 90 million with vertically mounted semi-span models. The operating range expressed as Rn versus Mach number is presented in Figure 2. The full span model capability was established from the onset of ETW's operation with first client tests being performed in 1995. The semi-span capability was subsequently developed, and following commissioning trials in 1999, a first validation test was performed at low speed – high lift conditions within the European framework EUROLIFT [4]. This validation test demonstrated ETW's ability to test at low speed conditions at flight Rns. This low speed capability now accounts for around 25% of ETW's workload.

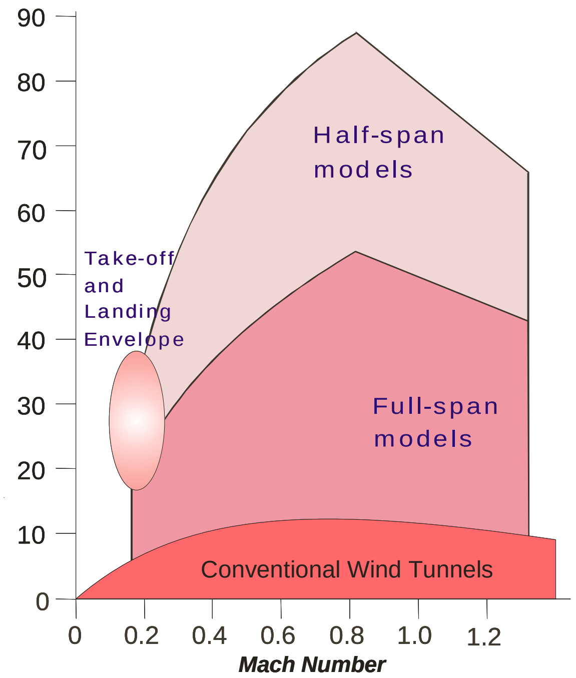

Fig. 2. ETW testing envelope

ETW has a closed aerodynamic circuit (Figure 3) contained inside an internally insulated pressure shell. The compressor with a maximum drive power of 50 MW circulates the nitrogen gas around the circuit. To achieve and maintain the desired low temperature of the test gas, liquid nitrogen is injected into the tunnel upstream of the compressor where it immediately vaporizes. In order to maintain the desired pressure, a corresponding mass flow of gaseous nitrogen is exhausted upstream of the stilling chamber. The overall layout of the circuit, especially the stilling chamber, nozzle, and test section, is consistent with the high flow quality required for high Rn testing. The test section is 2.4m (7.9ft) wide, 2.0m (6.56ft) in height, and 9.0m (29.53 ft) in length. The test section is equipped with the capability of having all four walls individually closed or slotted. For half model testing the standard test section configuration has slotted side walls with an overall porosity of 4.6 %.

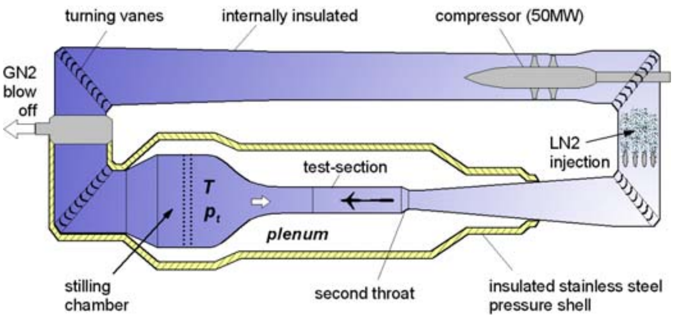

Fig. 3. ETW tunnel circuit

In addition to providing high standards in terms of the flow quality and range of test conditions, one of ETW's primary design objectives was to ensure that good productivity can be achieved. In order to meet the productivity goals demanded by industry, ETW has developed a removable model cart system for operation in the cold environment. Along with the model and its supporting structure, a model cart consists of the test section top wall, the pressure door (hatch cover) of the tunnel and the instrumentation cabin. This entire assembly of approximately 200 tonnes (220 tons) is removed in one unit by the remotely controlled model cart transporter.

Throughout this paper several references are made to various operations and dedicated areas that are used throughout a test campaign. Figure 4 can be used as a graphical reference.

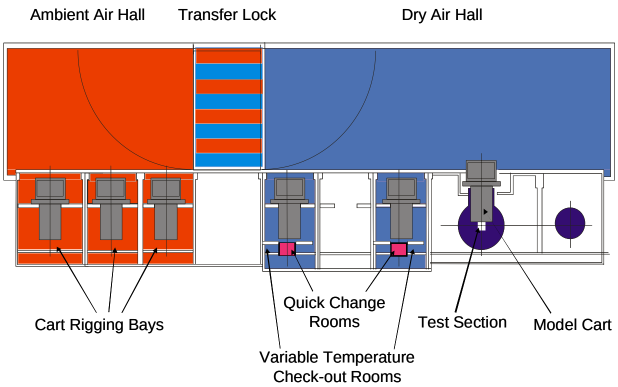

Fig. 4. ETW tunnel layout

The initial model preparation and installation activities are performed in one of the

Cart Rigging Bays (CRB). The assembly of the model onto the model cart enables all instrumentation to be fully checked before releasing the model assembly for test. Once lifted from the CRB, the transporter can move and lower the model cart assembly into any of the other rooms along the transfer hall including the test section of the tunnel. This transfer hall consists of two primary sections: one above the CRBs at ambient air conditions and the other above the Variable Temperature Checkout Rooms (VTCRs) and the test section. The transfer hall contains ambient temperature dry air with a dew point around -70°C (-94°F) to prevent frost and ice build-up when the model and cart assemblies are cold. The VTCRs are also fed with dry air that can be varied in temperature from 313K (104°F) down to 110K (-262°F). The VTCRs are divided into two main areas by means of large horizontally sliding doors: the Temperature Conditioning Room (TCR) for the model cart above these doors and the Quick Change Room (QCR) below the doors. The QCR receives the model and provides the possibility of conditioning just the model for quick configuration changes between two test runs, without changing the temperature of the complete model cart. By using the VTCR / QCR facility, the model changes are performed at ambient temperature while the wind tunnel and model cart can be maintained at cryogenic conditions. This concept offers substantial savings in terms of both time and cost and enables good levels of productivity to be achieved while also ensuring that ice contamination on the model is prevented.

2 Project requirements

Requirements for the 787 test entry relating to productivity and data quality are discussed in this section as they relate to expectations and targets, schedule, tunnel capabilities, model design and fabrication, test planning, etc. Strict and explicit guidelines were established early in the project to maximize the chances of success.

2.1 Productivity

Productivity as measured in a wind tunnel is a function of many factors, such as:

- Data quantity (e.g. polars/hour).
- Tunnel health (i.e. hardware, software).
- Test section access / model change time.
- Off-shift access to the facility.
- Onsite support (e.g. instrumentation, broad testing expertise, machine shop).
- Incorporating a dynamic test plan with the requisite online data visibility.
- Overall schedule (calendar time) required to achieve the test objectives.
- Value for the money.

2.1.1 Quantitative productivity metrics

Boeing has published desirable low speed wind tunnel testing productivity metrics in [2] for a typical non-cryogenic pressure tunnel as follows (Table 1):

Table 1. Typical values in non-cryogenic pressure tunnels for high-lift testing

Metric	Typical values in non-cryogenic pressure tunnels
Polars/occupancy hour[1]	1.5
Polars/fan-on hour	3.0
Fan on time (%)	50%
Facility down time[2] (%)	5%
Ave. model access time[3]	8 minutes
Ave. model change time[4]	45 minutes
Start up time[5]	< 1 hour

Notes:
1.) Occupancy = Total time - Facility down time
2.) Down time due to facility problems.
3.) Time from fan stop to hands on the model.
4.) Time to change some model parameter such as a flap deflection.
5.) Time from start of first shift to acquisition of first data point.

However, due to the unique complexities involved in conducting a cryogenic test, quantities for the current test were not expected to match these values. Questions which the metrics and values in Table 1 raise are: what are the best productivity metrics with which to rate high Rn cryogenic wind tunnel tests? What quantifiable productivity targets do we assign to these metrics? A desired outcome from this test was therefore to determine not only the appropriate cryogenic productivity metrics but to offer a productivity standard for future cryogenic high-lift flight Rn tests.

2.1.2 Project schedule

As stated in the introduction to this paper, one of the primary objectives of this test was to obtain high quality flight Rn data early enough in the 787 program to have an opportunity to influence the high-lift design. For wind tunnel driven changes to the airplane configuration to be considered late in the design cycle (just prior to the Firm Configuration milestone, see Figure 5), a high degree of confidence was required in both the exactness of detail of the wind tunnel model relative to the actual airplane as well as in the data itself. A key challenge to the model project schedule was balancing the conflicting need between waiting as long as possible before releasing representative lofts to the model designers, while simultaneously striving to shrink the design / build time such that the data need date was not compromised. The challenge for this project was even more pronounced as the Boeing aerodynamics team was working with a diverse and international design / build team on a very demanding and complex high-lift model.

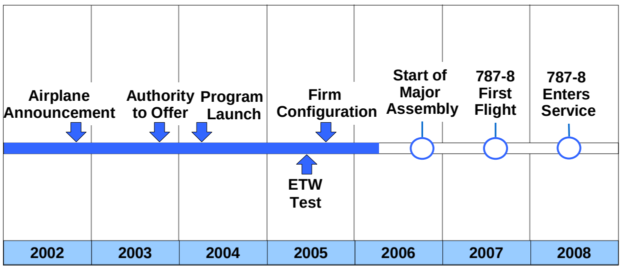

Fig. 5. 787 program timeline

2.1.3 Dynamic test plan

The benefits of a dynamic test plan for high-lift testing cannot be understated, especially when operating within a fixed budget and constrained by a demanding schedule. A dynamic test plan can be used to maximize productivity by minimizing tunnel conditions. After all, for a given budget, it is the quantity of high quality relevant data that every test director is really after. Even so, a dynamic test planning philosophy requires a paradigm shift from the comfort level of a static test plan to the burden of managing an ever-changing test plan in real-time.

A minimum set of requirements for enabling a dynamic test plan are as follows:

- An upfront understanding of the comprehensive desired testing envelope.
- A known “do-not-exceed” budget.
- A consistently corrected set of “final” data from the first test point to the last.
- Final data available as close to real-time as possible. The target for this test was final data transfer between the ETW and Boeing computing systems within 120 seconds after the completion of a polar.
- Agreement by the entire test team that, given the myriad of constraints (time of day, staff availability, test priorities, etc.), the proposed test plan change was feasible.

2.2 Model design and fabrication

Model design and build requirements were challenging. Not only was the model required to be manufactured to very high tolerance levels, but the model also was required to be designed and manufactured in such a way that ensured the highest quality repeatable data while minimizing model change times in a cryogenic environment. Following are some specific model design / build requirements:

- Model sized for a 70% span-to-tunnel height ratio in the ETW facility. Additionally, the model must be able to be tested at both the ETW and NASA-Langley National Transonic Facility.
- Surface finish and contour requirements consistent with the Rn’s to be tested.
- Reproducibility of each model configuration must be extremely repeatable in the tunnel environment.
- Large number of parts (e.g. multiple takeoff and landing configurations) were required.
- Representatively sized exposed brackets, auxiliary tracks, fairings, etc. while satisfying model component loads.

- Minimize the intrusiveness of static pressures and instrumentation.
- Realistic seals between components.
- No leak paths under load between any components.
- Minimize aeroelastic effects.
- Minimize thermal inertia while not sacrificing strength.
- Flexibility to adapt to different configurations (e.g. body lengths, high-lift configurations).

In addition, all of the above requirements were constrained to fixed cost and schedule. Aircraft Research Association, Ltd (ARA), based in the United Kingdom, was selected as the prime vendor. Mitsubishi Heavy Industries (MHI), based in Japan, was the major sub-vendor. The part breakdown by vendor, as shown in Figure 6, was as follows:

- ARA: Wing / fuselage / trailing edge high-lift system / support structure.
- MHI: Horizontal tail, incidence blocks, and complete leading edge high-lift system.

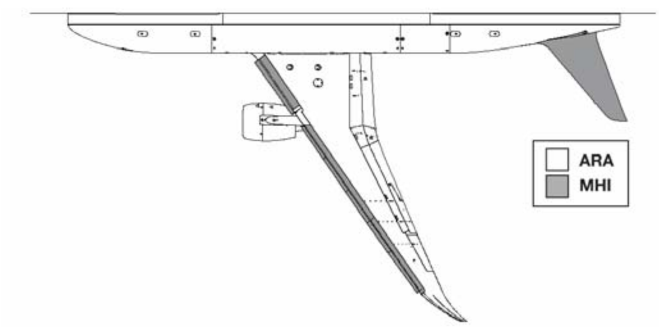

Fig. 6. Model planview *(courtesy of ARA)*

The model-to-wall standoff (or *peniche*) design philosophy was based on work done in [5].

2.3 Data quality metrics

Boeing has published desired low speed wind tunnel testing data quality metrics [2] for lift, drag and pitching moment for a typical non-cryogenic pressure tunnel as follows (Table 2):

Table 2. Repeatability requirements for high-lift testing*

Parameter	Repeatability (95% tolerance intervals)		
	Min	Target	Max
Takeoff:			
α	+/- .030	+/- .010	+/- .001
C_{Lmax}	+/- .030	+/- .010	+/- .001
C_{LV2}	+/- .015	+/- .005	+/- .0005
C_{DV2}	+/- .0015	+/- .0005	+/- .00005
C_{MV2}	+/- .015	+/-.005	+/- .0005
Approach:			
α	+/- .040	+/- .020	+/- .002
C_{Lmax}	+/- .030	+/-.010	+/- .001
C_{Lapp}	+/- .030	+/-.010	+/- .001
C_{Dapp}	+/- .0030	+/-.0010	+/- .0001
C_{Mapp}	+/- .015	+/-.005	+/- .0005

*adapted from reference 2.

Acceptable minimum, target and maximum levels required to enable useful configuration decisions are given for the coefficients listed in Table 2. The “min” level is the level beyond which the data is not useful, while the “max” level is the level beyond which further improvement in the data repeatability provides no further benefit. “Target” levels are indicative of what Boeing configuration developers need, and are accustomed to getting, from top quality low speed facilities. These metrics were therefore used to establish the baseline data quality objectives for the 787 high-lift test.

3 Project results

As was stated earlier, the acquisition of high quality data is not enough. Also, it is critical that the data be acquired and applied in time to satisfy 787 program need dates. An assessment of the wind tunnel model and test schedules (i.e. productivity), as well as data quality, is discussed in this section.

3.1 Productivity

3.1.1 Project schedule

Certain key milestones in the overall 787 airplane program are shown in Figure 5. The key milestones in the 787 wind tunnel model design/ build schedule are noted below in Figure 7. The entire cycle from request for proposal

(RFP) to wind-on was under one year. Note particularly the time from prime vendor purchase order (PO) to wind-on of approximately eight months. The loft release timeline shown includes both standard release dates as well as the impact due to late configuration changes. The close proximity of the end of test (EOT) to the Firm Configuration milestone necessitated real-time discussion between Cologne and Seattle of the results while the data were still being collected.

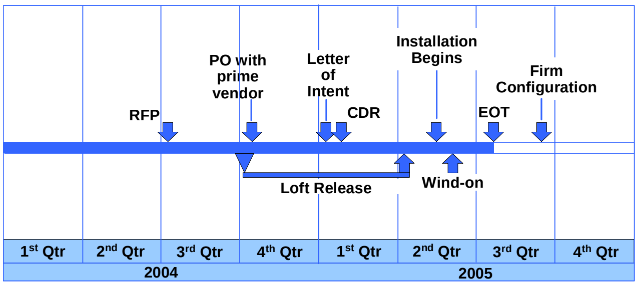

Fig. 7. 787 half-model project timeline

3.1.2 Dynamic test plan

The benefits to productivity of utilizing a dynamic test plan philosophy were discussed earlier. The practicality of conducting the ETW test with this philosophy is discussed here.

As stated in the project requirements section, access to final data as quickly as possible (120 second target time) after polar completion was essential. This goal was achieved. A significant amount of pre-test preparation was required by both ETW and Boeing to ensure a safe, secure and rapid final data transfer process between the ETW and Boeing computing systems.

Even with a static test plan, reliably predicting the precise operational state in a cryogenic facility more than a few hours in advance is notoriously difficult. Continual monitoring and adjustment of the plan throughout each day was required to maximize that day's productivity levels. The following charts (Figures 8 and 9) are graphical examples of dynamic test planning tools utilized during this test entry. Figure 8 displays the complete cryogenic low speed testing envelope within which data was desired for the landing configuration. However, acquiring all of these conditions is rarely required for a given configuration. Figure 9 contains the same underlying envelope, only with testing envelope sub-domains mapped out to better communicate scenarios for discussion and for precisely communicating rapid changes to the test plan based on the real-time data. The rapidity of communicating the change was not simply to minimize tunnel conditions (i.e. maximize relevant data collection, minimize cost/condition), but also to allow efficient real-time management of tunnel operations. The complex machinations of the cryogenic tunnel environment do not respond efficiently to rapid and sudden change in direction (think large ocean-going container ship). Inefficiencies are expensive for the customer and bad for morale for tunnel staff. The challenge for this campaign then was to collect and analyze real-time data, discuss "what-ifs" with the tunnel staff, and then decide on the practicality of a course change. Charts such as Figures 8 and 9 were instrumental in maximizing the collection of cost-effective relevant data while minimizing miscommunication. Both simple graphically-based as well as more sophisticated tools were created and implemented during this campaign.

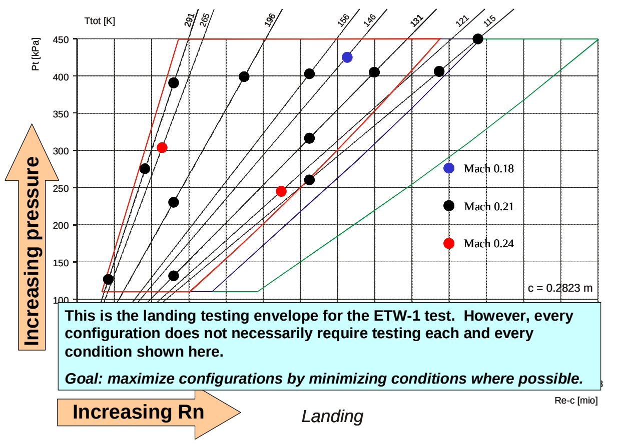

Fig. 8. Complete landing testing envelope

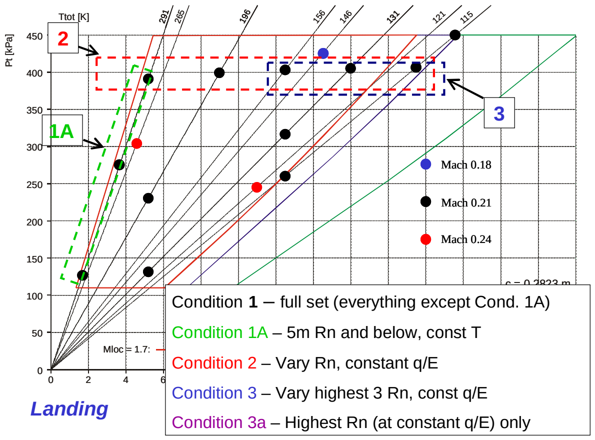

Fig. 9. Landing envelope with sub-domains

3.1.3 Test productivity

The test campaign absorbed two calendar months, with approximately two weeks for buildup and removal and six weeks of actual testing. A total of 41 series were completed (each set of conditions associated with a configuration is called a "series"). The testing calendar is shown in Figure 10. This calendar was useful as both a running summary of test productivity (series / calendar day) as well as a high-level one-page test plan for inter-continental (and across the room) communication.

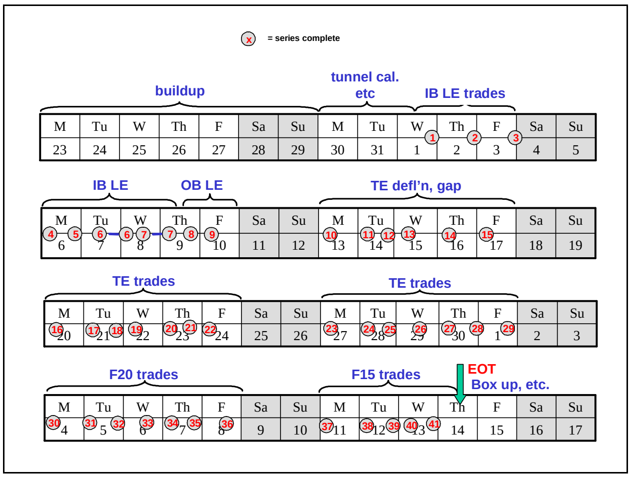

Fig. 10. Test calendar

Productivity in a cryogenic facility is difficult to compare to either atmospheric or pressure tunnels where air is the fluid of choice. The cryogenic nature of the facility adds a complexity to test planning and productivity tracking that is many times non-intuitive or new to the experienced tester who has not previously tested in a cryogenic facility. Obviously if a customer wanted to acquire data primarily at one atmosphere and warm temperatures, fan-on productivity would be artificially skewed to higher levels approaching those of a non-cryogenic facility. The same misrepresentation of productivity would occur if data were only acquired at any other single tunnel condition, e.g. temperatures and pressures associated with flight Rn. However, the typical customer of a variable temperature and pressure facility desires data utilizing the full capabilities of cryogenic testing: for example, atmospheric to flight conditions at varying Rn and constant q/E; trades at flight conditions only; full Rn/Mach/aeroelastic sweeps.

In an attempt to normalize the productivity metrics which follow, a breakdown of the types of series acquired during the 787 half-model entry is shown in Figure 11.

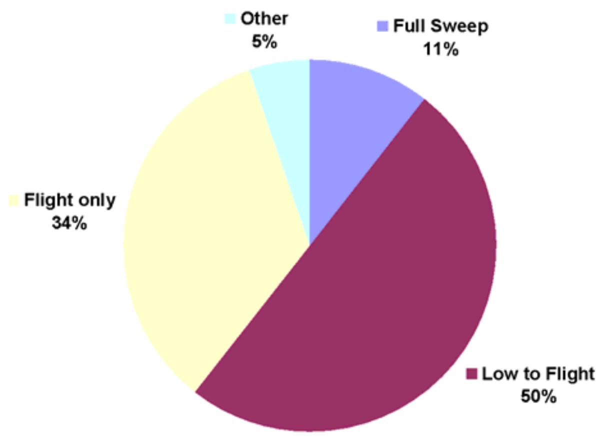

Fig. 11. Breakdown of series tested

As can be seen in this figure, the majority of the test series were run in order to obtain low to flight Rn trend data, followed by flight Rn trades and full Rn/aeroelastic/Mach sweeps.

3.1.4 Productivity metrics and definitions

Productivity terminology used for the productivity metric assessment is defined in Table 3. This table includes a list of "time parameters" associated with any wind tunnel test in the ETW facility (not just the current test entry) along with the definition for each.

Table 3. Productivity terminology

Time Parameter	Definition
Total occupancy time	Total time spent in tunnel minus typical days off (e.g. weekends, holidays). Includes all productive <u>and</u> unproductive time (Indication of schedule).
Productive time	Includes installation, model changes, transport time, productive wind-off, tunnel conditioning time, data acquisition, etc. Does not include facility downtime, weekends or holidays.
Chargeable occupancy	The portion of productive time charged to the customer.
Unproductive facility downtime	All facility related problems.
Model change time	From QCR doors open to doors closed. Includes inspections.
Transport time*	<u>Test section -> QCR:</u> from the end of the last data point in a series to model access. Includes conditioning time associated with the transport. <u>QCR -> test section:</u> from doors closed to model installed in test section. Includes conditioning time associated with the transport.
Tunnel conditioning	Non-transport related conditioning (pressurization and temperature cycles, fan speed, etc) required to achieve each tunnel condition.
Productive fan-off	Wind-off polars, pressure calibrations, etc.
Data acquisition time	The actual fan-on time to acquire a polar. Used to calculate polars per hour.

*"Transport time" as defined above can be further subdivided into two distinct components: (1) non-data related variable conditioning time required before either the actual transport from the test section can commence or before model access can occur and (2) non-variable transport time of the model between the test section and QCR environments, independent of any conditioning constraints. This time averaged 35 minutes during this entry.

Figure 12 is important when assessing ETW's ability to hold a calendar schedule. The total occupancy time for this entry, when split into productive and unproductive time, indicates that 89% of the entire calendar time the test team was onsite in Cologne was considered productive. The 11% unproductive time, when broken down further, can be used to highlight areas of facility improvement (unproductive time details are not discussed here). It should be noted that the 11% downtime is, surprisingly, not dramatically different from the typical 5% downtime considered acceptable in a traditional non-cryogenic pressure test (see Table 1). Total calendar time is of course also useful data when laying out the preliminary schedule and budget for any follow-on testing.

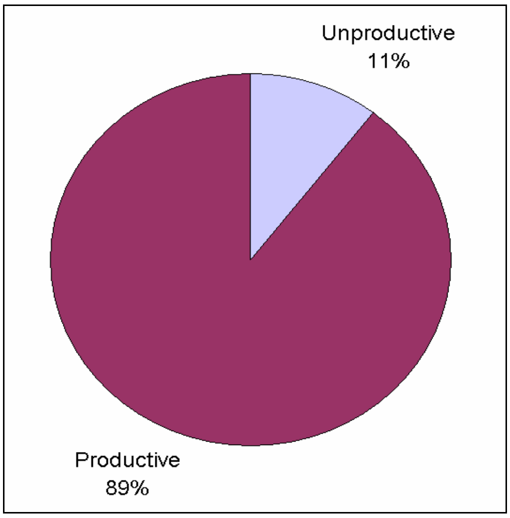

Fig. 12. Productive / unproductive breakdown

Figure 13 shows a detailed breakdown of the 89% productive time. These data can be used to highlight areas of improvement to productive time. This breakdown also can be used to identify areas where technology money might be invested. For example, Figure 13 shows that 21% of the total productive time was spent on model changes. If this time could be reduced through either designing a model more amenable to in-tunnel (QCR) changes, or investing in technology allowing for remotely actuated parts, the cost trade between new technologies and cryogenic testing time could be favorable.

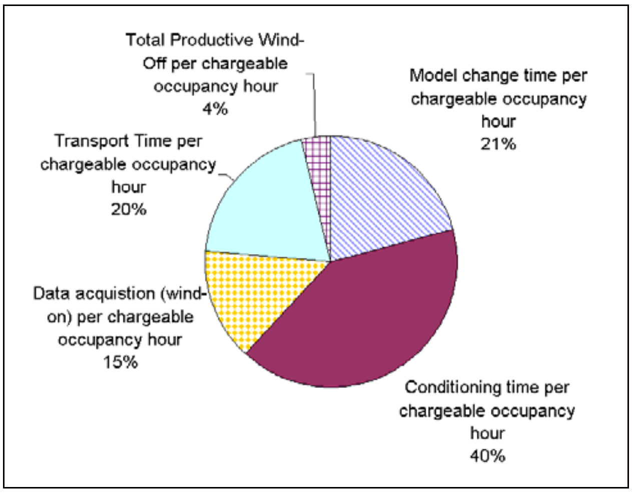

Fig. 13. Productivity breakdown

When comparing data between Figure 13 and Table 1, certain cryogenic-specific testing characteristics become obvious. For example, transport time accounts for 20%, and conditioning time 40%, of the total productive time achieved for this entry. Gaining access to the model in a traditional (non-cryogenic) pressurized wind tunnel, on the other hand, averages eight minutes. Tunnel conditioning time is an order of magnitude less in a traditional wind tunnel when the complexity of cryogenics is not a factor.

After analyzing each of the operational aspects of the current campaign, a table of key productivity metrics and values was tabulated and populated with actual data, and can be seen in Table 4.

Table 4. Key high-lift productivity metrics

Metric	ETW Values
Polars / total occupancy hour	0.77
Polars / fan-on data acquisition (on condition) hour	5.0
Polars / fan-on data acquisition + chargeable conditioning hour. Same as above metric only including conditioning time as well.	1.61
Series / typical calendar day (but not including weekends)	1.28
Series / total calendar days (includes build-up, weekends, holidays, fan-on, etc)	0.9
Average model change time	3.0 hrs
Average chargeable occupancy hours / day	11.5

The “polar / hour” metrics are an indicator primarily of tunnel productivity, while “series / day” metrics combine both tunnel and model related productivity. There would appear to be room for improvement in the model change time, even accounting for the extremely cold temperature encountered on the model hardware when first gaining access. Reducing the thermal inertia of the model further is one possible solution. Improvements to the daily metrics (e.g. series / day; average chargeable occupancy / day) could be made by simply increasing the available running time each day – of course, the facility would have to approve!

3.2 Data Quality

The focus in this section is on the precision (repeatability) of the data collected. The accuracy to flight data will be determined over the next few years.

Long-term within-test repeatability for representative landing configurations is shown in Figures 14 to 16. The solid and dashed boundaries are the 95% confidence and prediction intervals, respectively, calculated using representative curvefits of the data. These data – a total of 13 runs - were collected within three separate repeat series, spread over three weeks. A total of 16 configuration changes occurred between these three series, so the long-term repeats are an indication of not only tunnel repeatability but the reproducibility of the model as well. The landing configuration should provide a conservative bound of the within-test repeatability of the system, as this type of high-lift configuration is typically the more challenging one to reproduce. The results are summarized in Table 5 below.

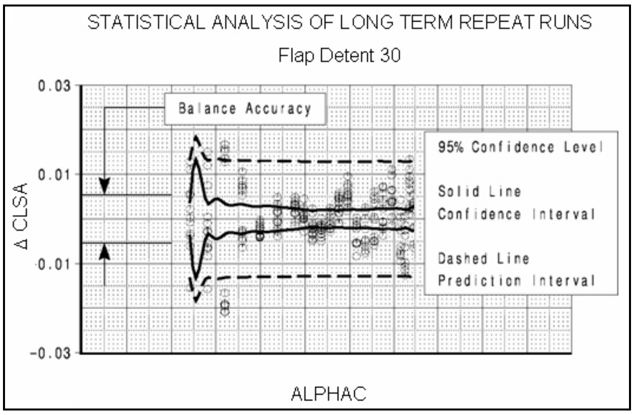

Fig. 14. Statistical analysis of landing C_L

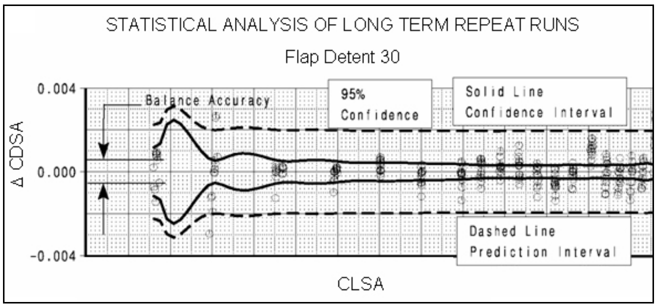

Fig. 15. Statistical analysis of landing C_D

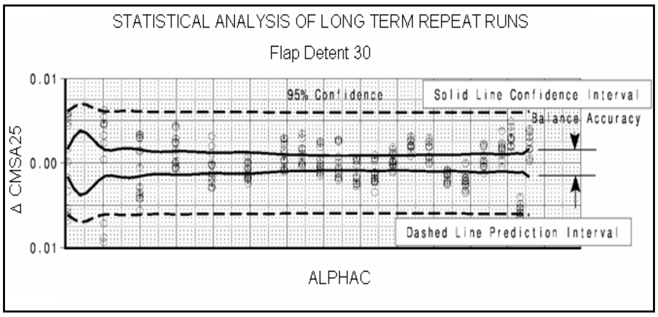

Fig. 16. Statistical analysis of landing C_M

Note the bounds in each chart labeled “balance accuracy”. Balance accuracy is defined here as 0.10% of the balance maximum load, with an additional weighting factor assigned by the facility based on historical data.

Table 5. Long-term within-test repeats for the landing configuration

Parameter	Repeatability (95% confidence interval)			ETW (95% CI)
	Min	Target	Max	Actual
Approach:				
α	+/- .040	+/- .020	+/- .002	**+/- .010**
C_{Lmax}	+/- .030	+/-.010	+/- .001	**+/- .008**
C_{Lapp}	+/- .030	+/-.010	+/- .001	**+/- .005**
C_{Dapp}	+/- .0030	+/-.0010	+/- .0001	**+/- .0008**
C_{Mapp}	+/- .015	+/-.005	+/- .0005	**+/-.002**

Table 5 is simply Table 2 with an extra column for the current ETW test results. The results indicate that the long-term, within-test data collected during this campaign satisfy the repeatability target criteria previously published [2].

A statistical analysis also was done on typical near-term repeat runs for both landing and takeoff configurations. “Near-term” is defined as back-to-back runs within a single series. Typical results from the current campaign are shown in Table 6. The repeatability target levels were achieved.

Table 6. Near-term within-test repeats for the landing and takeoff configurations

Parameter	Repeatability (95% confidence intervals)			ETW (95% CI)
	Min	Target	Max	Actual
Takeoff:				
α	+/- .030	+/- .010	+/- .001	**+/- .010**
C_{Lmax}	+/- .030	+/- .010	+/- .001	**+/- .005**
C_{LV2}	+/- .015	+/- .005	+/- .0005	**+/- .005**
C_{DV2}	+/- .0015	+/- .0005	+/- .0005	**+/- .0005**
C_{MV2}	+/- .015	+/-.005	+/- .0005	**+/- .002**
Approach:				
α	+/- .040	+/- .020	+/- .002	**+/- .010**
C_{Lmax}	+/- .030	+/-.010	+/- .001	**+/- .005**
C_{Lapp}	+/- .030	+/-.010	+/- .001	**+/- .004**
C_{Dapp}	+/- .0030	+/-.0010	+/- .0001	**+/- .0006**
C_{Mapp}	+/- .015	+/-.005	+/- .0005	**+/-.002**

4 Summary

A wind tunnel test of the 787 high-lift configuration at varying Rn, Mach and aeroelastic conditions was successfully conducted in the ETW facility. In addition to rapidly acquiring valuable performance data for use within the 787 program, the opportunity was taken to assess the entire test campaign for productivity and data quality from model design, to model manufacture and through tunnel operations.

It was demonstrated that a flight Rn test entry, while challenging and expensive, is capable of providing substantial amounts of valuable and high-quality data within acceptable levels and at relatively high productivity. Opportunities exist for further increases in cryogenic testing productivity such as model design improvements based on lessons learned and an expansion of facility operational hours. Tunnel productivity terminology and metrics for future cryogenic ground based testing are offered here for comment by the larger aerodynamic testing community.

The final determination on how well the data characterized flight performance will follow flight testing of the 787 aircraft in 2007-2008.

5 References

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