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Cold Testing has become hot

A mechanical testing journey from -55°C (218K /-67°F), through -180°C (93K /-292°F) to finally -253°C (20K /-423°F)

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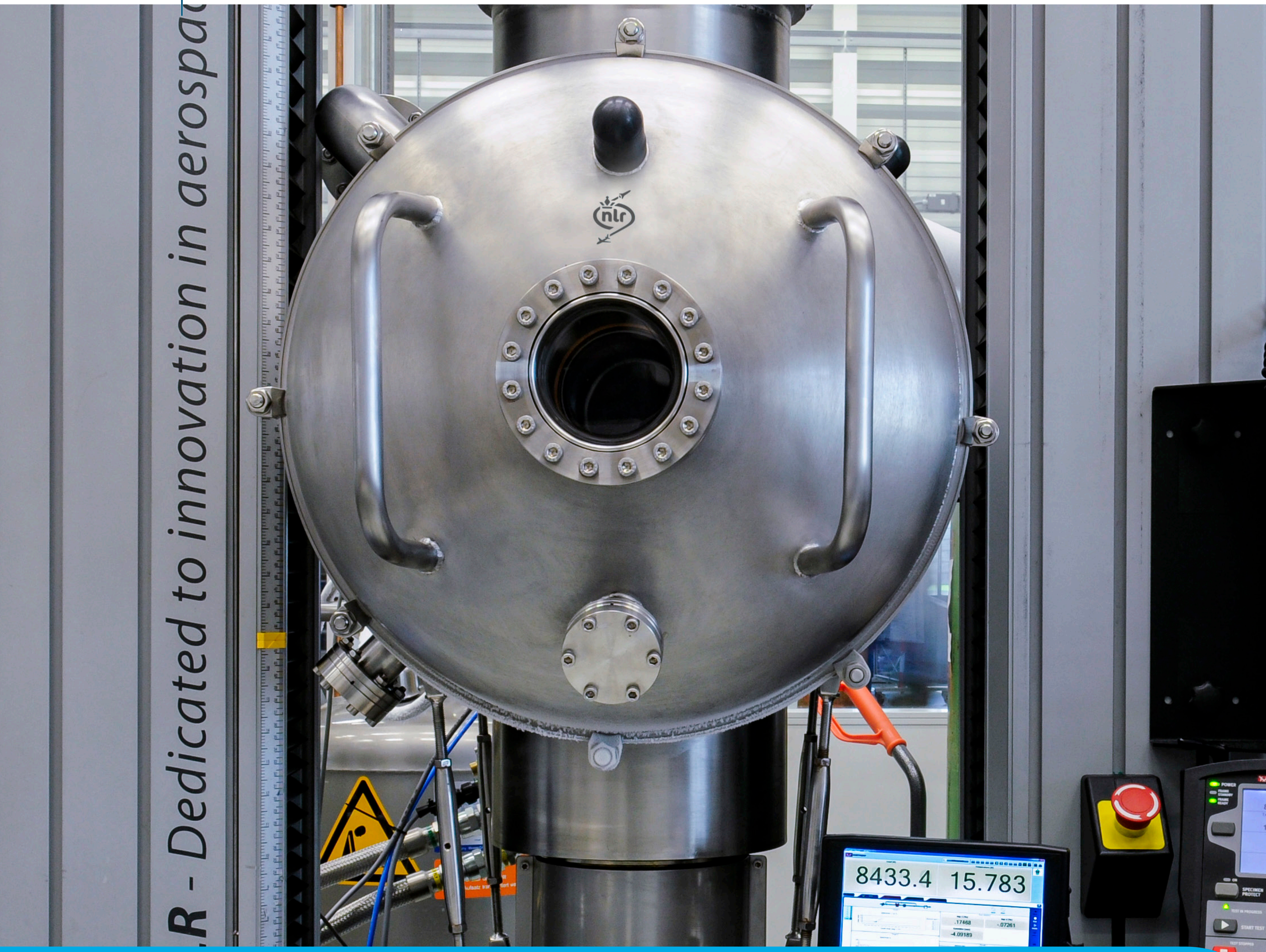


NLR has pioneered advanced cooling systems for material and structural testing, on a journey that started at -55°C and eventually reached extreme temperatures, such as -253°C. NLR's future goals include testing of full-scale hydrogen tanks, fuel system components and hydrogen-electric powertrains. Pursuing these goals is vital for achieving net-zero emissions by 2050. The continuous technological advancements and high demands highlight the crucial role of cold testing technology in the aerospace industry.

Advances in aircraft testing: from cold to deep cryogenic conditions

In the “old days”, perhaps a decade ago, the aviation industry was facing significant challenges from a highly competitive market and stringent environmental regulations. This meant that affordable and efficient aircraft had to be developed that were durable and easy to maintain. Fuel consumption and engine emissions were major concerns, primarily dependent on aircraft weight and gas turbine performance. The design phase focused heavily on evolutionary optimisations of the structural components and mechanical subsystems that made up the airframe, as well as the efficiency of fossil fuel-consuming engines.

EVOLUTION OF TESTING AND MATERIAL CHARACTERISATION

Aircraft structures and materials were increasingly being pushed to their limits. Despite advances in simulation and modelling capabilities, testing remained crucial for verifying material strength, durability and damage tolerance to meet the requirements needed for flight safety. Testing began in the early design stages to formally establish so called “material allowables”. Later on, testing is required to validate structural design solutions and analysis methods. And finally, full-scale tests on complete aircraft or major structural components are required to generate inputs for the certification process. For all these tests, attention must be given to the effects ascribable to various parameters other than loads if such effects are expected to be significant (or if that cannot be excluded). An important parameter in this respect is temperature. Material properties are known to change with temperature and predicting the temperature dependence of specific structural properties such as buckling behaviour and subsequent failure is far from straightforward. Additionally, certifying the endurance (i.e. resistance to wear and tear) of a large mechanical subsystem under ambient test laboratory conditions might encounter serious objections from the authorities when actual service conditions include temperatures down to -55°C / 218K.

THE SHIFT TO SUSTAINABLE AVIATION

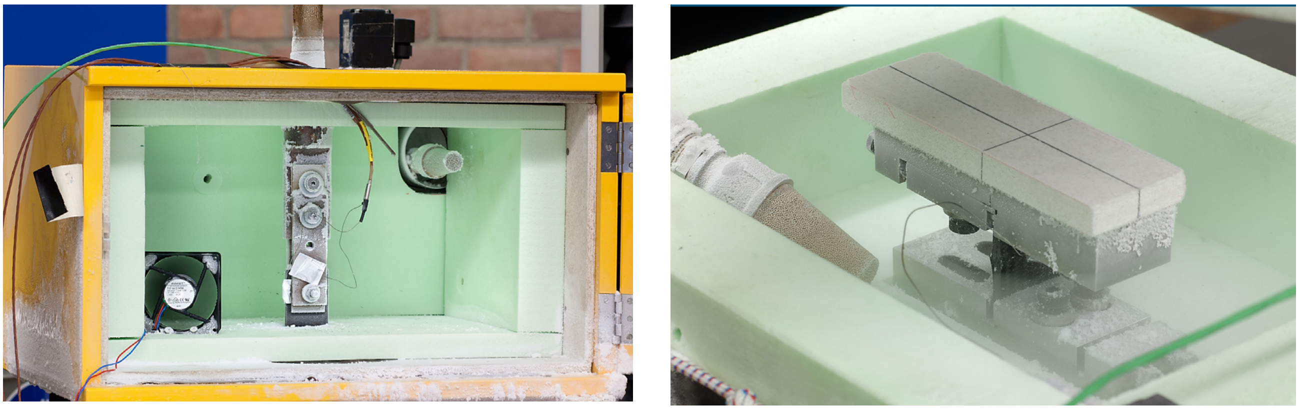
Today, the focus has shifted towards minimising engine emissions to achieve net-zero emissions by 2050. This has led to a disruptive design paradigm shift, particularly towards sustainable aviation fuel (SAF) and, in Europe, hydrogen-based propulsion systems. With an eye on that second alternative to kerosene, the Netherlands Aerospace Centre (NLR) is focusing on energy storage solutions for large long-distance aircraft, so that liquid hydrogen can be safely stored and used as an energy source. The design phase now emphasises the thermal system design of the aircraft, and (thermo-) mechanical design of the fuel system under deep cryogenic conditions (-253°C / 20K).

One of the research objectives of the European Clean Sky 2 research project TRANSCEND, is to estimate the effect of introducing hydrogen (H_2) powered aircraft on global greenhouse gas emissions by 2050.

Developing testing capabilities at deep cryogenic conditions at 20K

Establishing “material allowables” at 20K is crucial due to the lack of prior experience with such conditions. Testing capabilities at this temperature had to be developed from scratch. Over the past decade, NLR’s test house has developed modular and specific cooling solutions for material and structures testing, utilising various cryogenics and thermal equipment. NLR’s approach prioritises affordability, maintainability, safety, scalability and accuracy, over a broad operating temperature range. The developed systems are highly autonomous, suitable for continuous (24/7) operation. Typical testing temperatures include:

- **Cold -55°C / 218K** Standard temperature for aircraft flying at cruise conditions.
  - Using liquid nitrogen (LN2) coolant combined with a control loop for the temperature.
- **Cryogenic -169°C / 104K** Temperature for pipe structures transporting LNG (Liquified Natural Gas).
  - -180°C / 93K Temperature for specific space structures.
  - Using LN2 coolant combined with a control loop for the temperature.
- **Deep Cryogenic -253°C / 20K** Temperature for liquid hydrogen applications (the boiling point of hydrogen).
  - Using various cryogenic gases for temperature control.
  - Using thermal equipment for cooling efficiency.



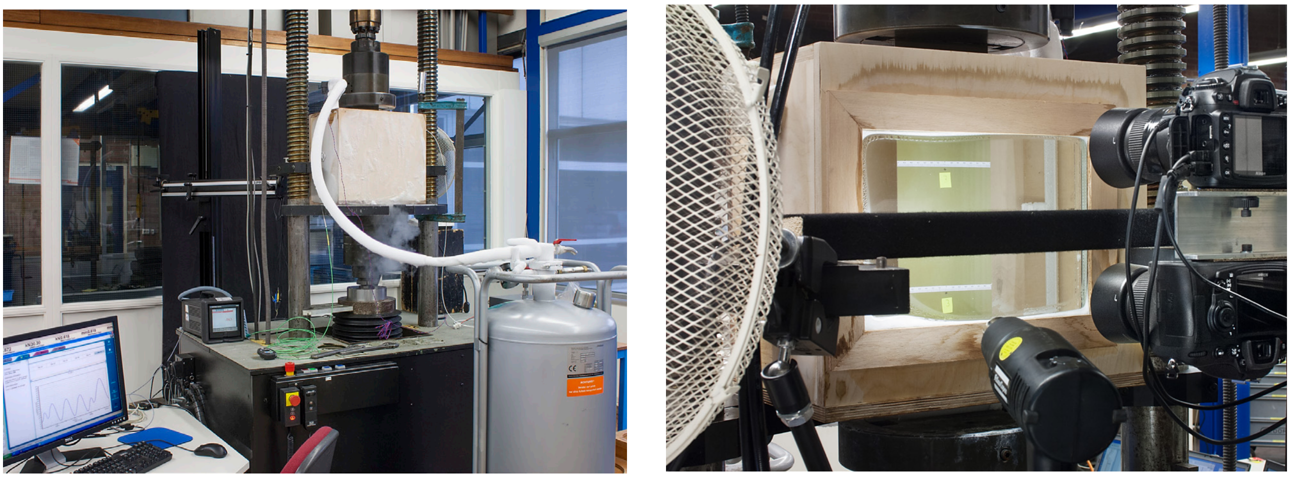
Starting practice of the cooling of material test specimens by pouring liquid nitrogen in the climate chamber.

Development of cooling methods

Some decades ago, developments involved a simple system for testing material coupons at low temperatures, typically -55°C, using liquid nitrogen (LN2) to cool a climate chamber around the specimen. A controlled amount of liquid nitrogen was poured per unit time into the chamber until the temperature of the specimen had stabilised. Manual adjustment in a slow feedback loop was subsequently applied to the flow of liquid nitrogen until the desired temperature level was reached.

At that time, NLR's space department employed more advanced cooling methods, but these were (and still are) too costly for standard mechanical coupon testing for commercial applications. The simple 'pouring' method worked acceptably, at least for relatively small coupons, but there were some disadvantages, the main one being spillage. The amount of nitrogen escaping from the setup was considerable and the area around the test setup plus the operators were exposed to low temperatures too. A sufficient supply of nitrogen for a static test on a smaller specimen was no problem, but the supply was an issue for larger specimens or lengthier tests and the performance of the cooling system was far from ideal. Moreover, the spillage of nitrogen was unacceptable and led to undesirable safety issues. Nitrogen is not toxic; at sea level, the atmosphere contains about 78% nitrogen. However, if sufficient liquid nitrogen is vaporised, the normal oxygen percentage of 21% will drop below 19.5%, increasing the risk of asphyxiation significantly. As nitrogen is colourless and odourless, this can happen without much warning.

Another problem was the lack of control over the temperature gradient across the specimen. Depending on its size, the test specimen would have two or more independent temperature sensors that were bonded to the specimen. It turned out to be difficult or impossible to maintain the temperature over the complete specimen within a small bandwidth. In practice, only the temperature at the centre of the specimen was controlled and only this area would meet tight specifications. The grips of the test machine at the ends of the specimen acted as bridges that conducted heat from outside the climate chamber into the specimen. Active cooling of these clamps required a great deal of both time and nitrogen, and insulating them was not always possible.



New approach of cooling of a fatigue test specimen: crack growth testing of Glare, 24/7 at -55°C.

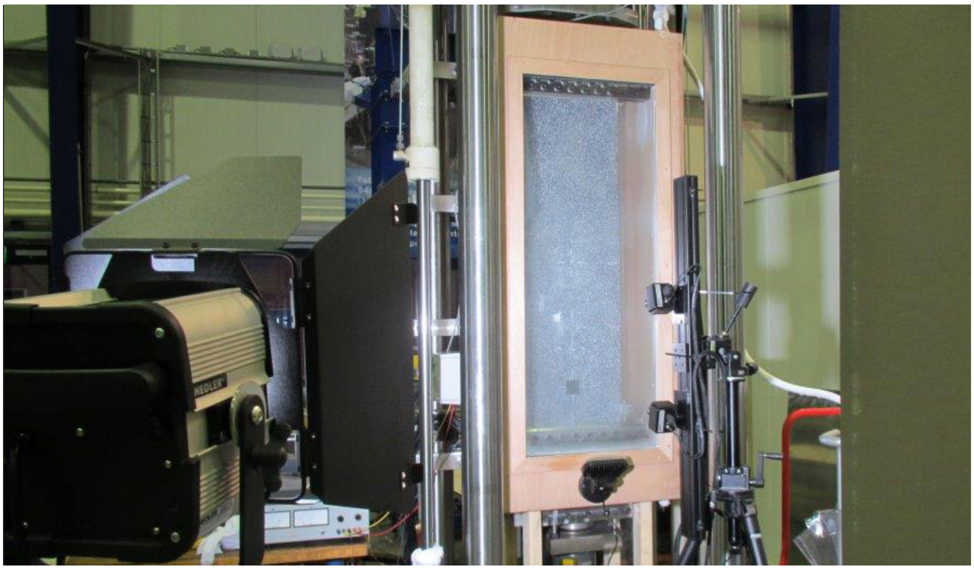
TESTING OF LARGE STRUCTURAL COMPONENTS

In the meantime, various existing and prospective customers of the Test House had expressed a requirement for low-temperature testing of larger structural items, such as stiffened panels and even full-scale structural components and mechanical systems. The endurance testing of large components at -55°C for 24 hours a day and seven days a week that some customers wanted required a radically new approach to be developed. This new approach still involves using liquid nitrogen. The control is much more elaborate, however. Instead of pouring liquid nitrogen in bulk into the climate chamber that encloses the test piece, nozzles are used to evaporate and spray controllable amounts of liquid nitrogen towards the test piece at specific locations. This cools the test item very efficiently because of the swirling evaporation near the specimen. This is quicker and more accurate.

Additionally, optimising the number and placement of the nozzles allows the temperature gradients in the test item to be minimised. This is done empirically, prior to starting a structural test. After a successful series of low-temperature static specimen tests using the new approach, a fatigue crack growth test was performed at -55°C on a specimen made of Glare (aluminium layers interspersed with glass fibre layers; this material is used in the Airbus A380). This test had to run continuously for several days in a row. No significant technical problems were encountered and the test was completed successfully. The amount of nitrogen used was relatively small and the multi-point controllability of the temperature across the test item was excellent. Minor problems such as frost on the test item and frozen windows were easy to solve. Frost on the test piece and the inside of the (double-glazed) window pane can be prevented by pre-filling the cabinet with dry nitrogen; no humid air (no water = no problem). A paint stripper to heat the outer window pane solves the problem of a condensed or frozen outside window pane.

LARGE-SCALE LOW-TEMPERATURE TESTING

The next step in the development was increasing the scale: doing panel tests at low temperatures. For this purpose, a stiffened panel was tested on an MTS 500 testing machine under fatigue loading, at -55°C. Again the nitrogen was sprayed near the test article at several locations with the nozzles, controlled by a temperature measuring and control system. A complicating factor was the presence of the Digital Image Correlation (DIC) optical measurement system that was used to survey the strain field in the panel. This system required an unobstructed view of the painted pattern that had been applied to the test panel surface. The door of the climate chamber was therefore given a glass panel. Because of the low window temperature, water condensed on the outside glass surface. This required work to wipe and clean the window to maintain its transparency when taking the DIC pictures.



Panel fatigue testing -55°C, combined with DIC optical measurements.

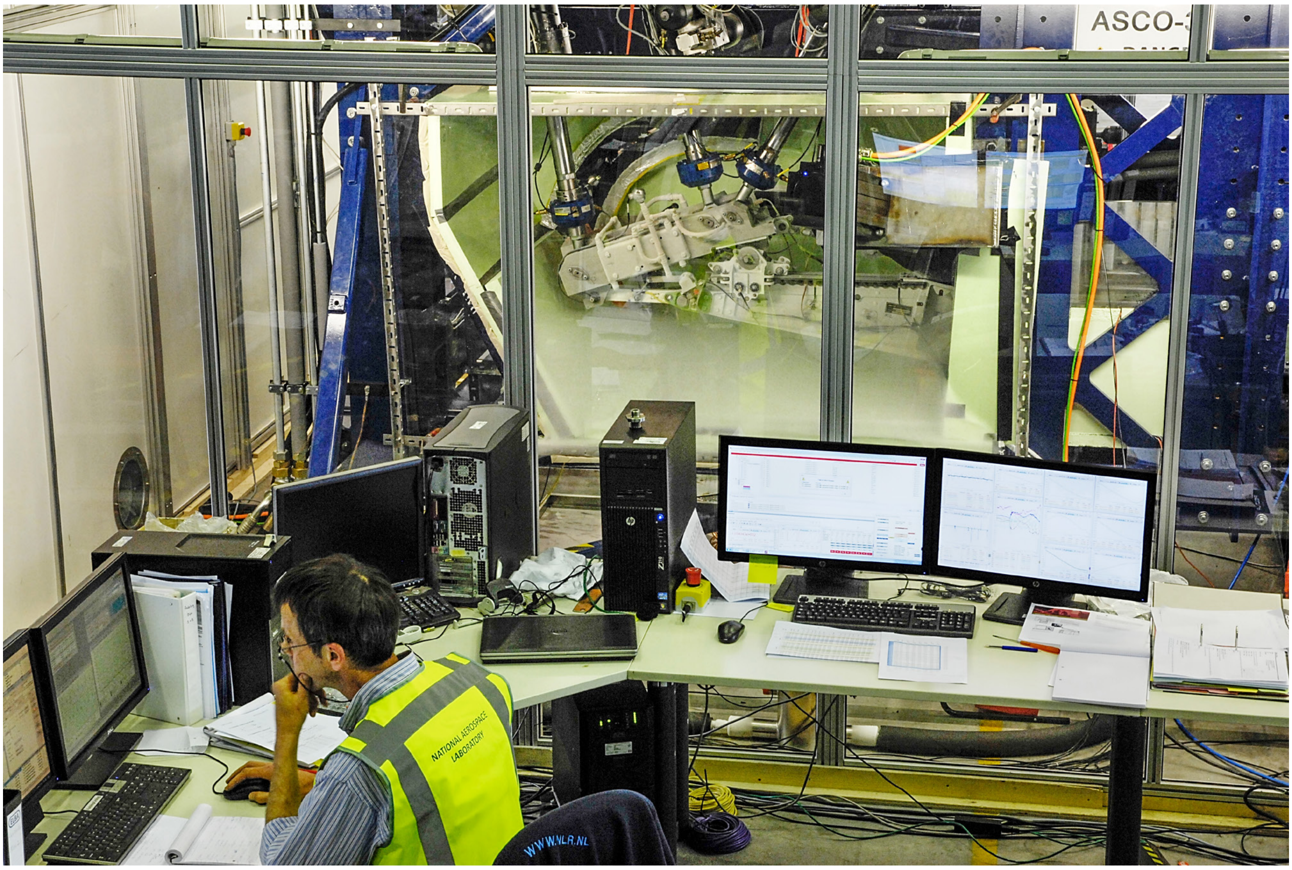
FULL-SCALE STRUCTURE TESTING

The final step in cold testing development was a considerable one, both in scale and in complexity. It was taken in the context of the certification programme of the Bombardier C-series flap tracks. These flap tracks are designed and manufactured by the Belgian company ASCO Industries. NLR was tasked with conducting the full-scale static, endurance, fatigue and damage tolerance tests required by the certification authority, Transport Canada Civil Aviation. This test programme was a milestone in the development of the full-scale structure testing capabilities at NLR.

The test setup consists of three independent modular rigs (one for each of the different tracks tested), each combined with an advanced electro-hydraulic actuation system. An electric rotary actuator is used to dynamically control the position of the carriage on the track, through the original gearbox. The loads on each flap track are distributed over its carriage and rear link through what is known as a Load Introduction Device (LID) that essentially mimics the flap. Six independently controlled hydraulic actuators per test rig are connected to the LID. Three of the actuators are displacement controlled and are for enforcing the subtle and complicated out-of-plane (i.e. lateral) movement and orientation of the flap (represented by the LID in the test program) during extension and retraction. The other three actuators are force controlled and are used for applying the complex dynamic loads that are a function of the flap position.

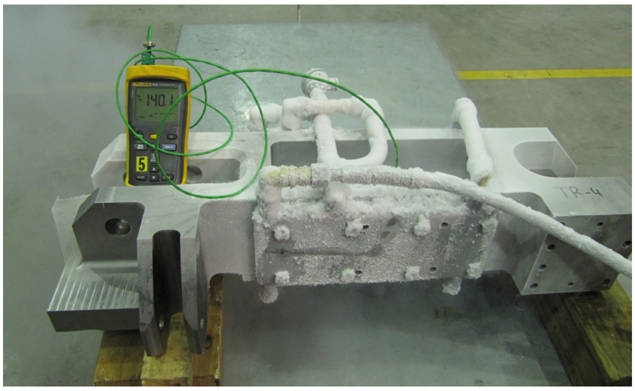
The position-dependent actuator loads have been determined using 6-DOF (degrees of freedom) vector decomposition. They are provided to the Moog/FCS load control system by means of a look-up table. This allows fatigue loading and endurance loading to be applied as if flight-by-flight and possible changes in the test specifications can be handled very flexibly without having to redesign any hardware. Especially for the endurance test programme, this turned out to be a major technical advantage.

The endurance test programme is essentially a full-scale system test in which the tracks are exposed to various contaminants (sand, dust, oil, de-icing fluid, etc.) while operating at the true extension/retraction speed under representative flight loads. A significant part of the endurance testing is to be performed at -55°C, for several weeks in a row, around the clock. In 2014, the mandatory part of cold cycling was achieved. At this scale, it was probably a world first! Cold testing was continued during 2015.



Overview of full scale flap track test setup at -55°C.

The size and complexity of the test setup necessitated the use of an inner climate chamber, measuring roughly 3 x 1 x 1m, and an outer cabinet of 5 x 5 x 5m. The outer cabinet acted as 1. a thermal buffer between the inner chamber and the ambient laboratory conditions, 2. a safety barrier to collect the nitrogen that inevitably leaked from the inner chamber due to the slots needed for the moving hydraulic actuators. Pre-filling the outer cabinet with dry nitrogen gas was instrumental in avoiding condensation and ice formation in the inner cabinet. To prevent heat from the hydraulics being transferred to the cold test piece, what are known as 'thermal blocks' were used to create a thermal barrier.



Thermal blocks, or heat sinks, to thermally insulate the test article from the test rig.

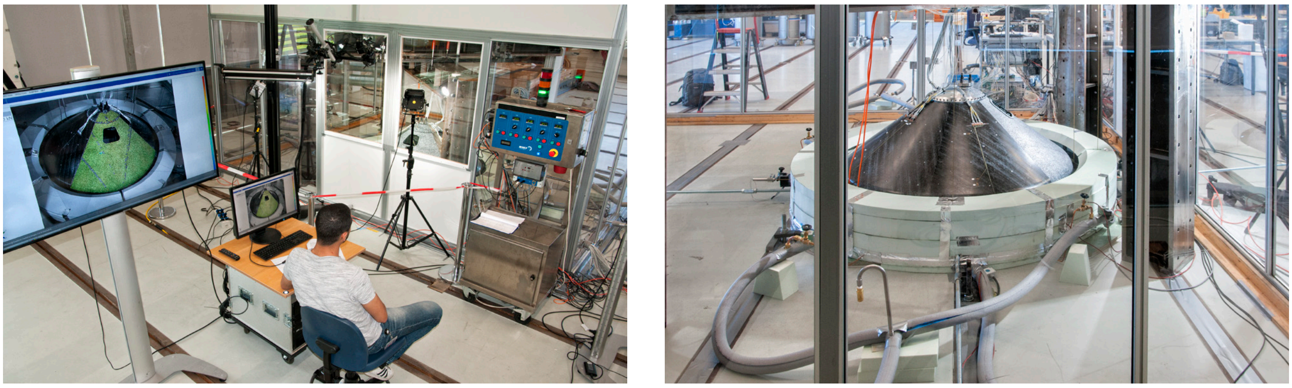
These blocks act as heat sinks and insulate the cold test item from external heat sources. The thermal blocks are cooled down using special thermal pads and liquid nitrogen. The pads can be cooled to -170°C/103K (-275°F) within minutes and have been developed in cooperation with experts from a local cryogenic engineering company. Some problems were obviously encountered during development. As the endurance test has to run 24/7, i.e. unattended at night, a fully automated safety system was required. On one particular night, the system was triggered and the test was automatically shut down. The next morning the operator on duty had significant problems restarting the test. It turned out that, because the test had stopped running, the hydraulic oil circulated less and froze under these non-operational circumstances. Additional oil heating elements were therefore attached and the hydraulic actuators are also monitored and electrically heated when necessary. This enabled easier restart after a cold shutdown and also made the daily operations smoother.

SPACE STRUCTURES AT VERY LOW TEMPERATURES

The development of cold testing at NLR continued. A logical application is full-scale testing of space structures at very low temperatures, down to -180°C. To prepare for this, a prototype setup was built to test an aluminium plate with a thickness, size and geometry equivalent to those of a segment of the Ariane Engine Thrust Frame (ETF).

Next step; cross section of prototype setup to explore full-scale space structures testing at -180°C.

This development test was conducted successfully in October 2014. It was demonstrated that the system as developed is capable of cooling a representative structural component down to -180°C in a reasonable amount of time. We are now confident that we can perform the actual full-scale static strength test on the ETF, or any similar structure, affordably at this very low temperature. The actual Ariane Engine Thrust Frame (ETF) test was performed several years later. The cooling principles are similar to the ASCO setup, in terms of containment of nitrogen, controlling the cooling temperature and power, was well as using LN2 as the basic cooling source.



Actual full-scale space structures testing at -180°C.

Transition to deep cryogenic testing

CHALLENGES AND INNOVATIONS

The step from “cold” to “cryogenic” was relatively simple, as it remained based upon already established cooling methods. The step to “deep cryogenic” testing, however, cannot be done using LN2. Additionally, being so close to absolute zero in terms of temperature means that all kinds of new considerations must be taken into account.

Insulation is crucially important. A simple foam or volume of cold gas is not longer sufficient. Besides convection, also conduction and radiation must be taken into account. Heat influxes must be minimised, which translates to lower voltages for strain gauges and minimised bodies that transfer heat flux, which is somewhat contradictory for a body that also has to transfer mechanical loads.

To characterise materials at 20K, a deep cryogenic cryostat was developed: a double walled, vacuum-isolated, MLI-shielded vessel, in which most ASTM/AITM material characterisation testing can be performed. All the throughputs had to be designed carefully to minimise the heat influx. As it was also designed for transferring tensile loads up to +100kN and -250kN, the load transfer path has become a jewel of thermomechanical engineering.

The methods for cooling to 20K require careful design to avoid inefficient cooling.
Testing using LN2 is a kind of “brute force” cooling. As the availability of LN2 is good and the costs are relatively modest, massive use of LN2 solves most cooling needs down to -196°C / 77K. Further cooling from -196°C / 77K to -253°C / 20K requires far more sophisticated cooling methods. Without disclosing commercially sensitive details, we can state that – in addition to the LN2-based precooling – cooling using various additional cryogenic gases and thermal equipment minimises the thermal inefficiencies.

ROUTINE DEEP CRYOGENIC TESTING

NLR now routinely tests static properties of various materials for several customers at 20K, a capability shared by only a few test houses globally (if any). Our journey is not ending here either. Two distinct future developments include:

- Full-scale structure testing at 20K, using actual liquid hydrogen (LH2) to cool down to the required temperature.
- Material testing at 20K, with dynamic loading and under hydrogen conditions (“in situ”).

About the author:

Paul Arendsen has been the head of the Testing and Evaluation department for 16 years. He has a background in structural design, analysis and software development. With the knowledge and expertise of Paul’s team and the available facilities, NLR offers a one-stop shop for what is referred to as ‘non-standard testing’ and certification of aircraft structural parts and materials.

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Future developments and industry impact

FULL-SCALE HYDROGEN TESTING

NLR is building an “Energy to Propulsion Test Facility” (EPTF) for full-scale testing of liquid hydrogen tanks and hydrogen-electric power trains. The first goal is to test entire tanks, filled with liquid hydrogen and subjected to static and dynamic loads. An initial project (COCOLIH2T, in the European Clean Hydrogen programme) involves testing a 1.2 m³ tank in the second quarter (Q2) of 2025. A second project –Hydrogen Conversion Turbofan or ‘HOT’ as part of the ‘Luchtvaart in Transitie’ (LiT) programme supported by the Dutch National Growth Fund (Nationaal Groeifonds) – involves testing a 12m³ tank in 2026. The second goal is to test fully functional hydrogen-electric power trains. This involves a 500kW power train (from the Clean Avion’s Hypotrade project) to be tested on gaseous hydrogen in Q3 2024 and on liquid hydrogen in Q3 2025. A second project (LiT HAPSS, which stands for ‘Hydrogen Aircraft Powertrain and Storage Systems’) will focus on testing a 2MW power train in 2026.

EMISSION-FREE AVIATION GOALS

Driven by the urgent need to address climate change, the aerospace industry is transitioning towards net zero emissions by 2050 and ultimately emission-free flight by 2070. This shift is fuelling active technological development, high customer demand and government support, making cold testing a hot topic in aerospace research and development.