Manual for Airplane Wing Anti-icing Fluid Tests in Wind Tunnel

Antti Rinne

Trafin julkaisuja
Trafis publikationer
Trafi Publications

2/2013

Trafin julkaisuja 2/2013

Manual for Airplane Wing Anti-icing Fluid Tests in Wind Tunnel

Antti Rinne

Aalto University School of Engineering, Department of Applied Mechanics

Liikenteen turvallisuusvirasto Trafi
Trafiksäkerhetsverket Trafi
Helsinki Helsingfors 2013

ISBN 978-952-5893-67-0
ISSN 1799-0157

Foreword

This research report is focused on the wind tunnel testing methodology of anti-icing fluid flow off from an aircraft wing, which is an important subject in aviation safety. It forms part of the first year studies in the Icewing project initiated by the Finnish Transport Safety Agency, Trafi. In the initiation of the work participated Trafi's Director General of the Civil Aviation Pekka Henttu, Head of Department (Traffic analyses) Heli Koivu, Head of Department (Research and Development) Sami Mynttinen, Chief Adviser (Research and Development) Inkeri Parkkari, and Chief Adviser (Aeronautics) Erkki Soinne, who also supervised the research team.

The research was performed by the team of the Aerodynamics research unit of the Aeronautics research group, headed by professor Olli Saarela, at Aalto University at Helsinki in Finland. Following people in the unit participated in the work: MSc Mika Hurme, laboratory engineer MSc Juha Kivekäs, PhD student Airline captain Pekka Koivisto and BSc Antti Rinne.

Helsinki, April 8th 2013

Erkki Soinne
Chief Adviser, Aeronautics
Finnish Transport Safety Agency, Trafi

Sisällysluettelo
Index

TIIVISTELMÄ

Tässä tutkimuksessa suunnitellaan ja toteutetaan kolme koejärjestelyä lentokoneen jäänpoisto- ja jäänestonesteiden tuulitunnelikokeita varten. Koejärjestelyjen avulla voidaan tutkia nesteiden vaikutusta matkustajalentokoneen lentoonlähtösuoritusarvoihin. Raportissa kuvataan koejärjestelyjen rakentaminen ja kokeiden suorittaminen Aalto-yliopiston alisoonisessa tuulitunnelissa. Lisäksi annetaan ohjeet tulostenkäsittelystä ja esitetään menetelmä, jolla tuulitunnelimallin pinnalla olevasta nestekerroksesta otetuista kuvista voidaan määrittää keskimääräinen nestepaksuus.

Ensimmäisessä koejärjestelyssä käytetään valmiiksi olemassa ollutta tuulitunnelimallia nesteen poistumismekanismin selvittämiseen. Koe videoidaan ja kuvakaappauksista määritetään keskimääräinen nestepaksuus. Toista koejärjestelyä varten suunnitellaan SAE Aerospace Standard AS5900 -standardiin perustuva tasolevykoekanava. Kanavan mittoja suurennetaan, koska kokeisiin käytettävän tuulitunnelin mittatila on suurempi, kuin mihin standardi on tarkoitettu. Kokeessa mitataan rajakerroksen siirtymäpaksuus kanavan pohjalla. Kolmannessa koejärjestelyssä käytettävä malli on nykyaikaisen matkustajalentokoneen siipeä edustava siipiprofiili, joka on varustettu säädettävillä lisänostovoimalaitteilla. Kokeessa simuloidaan matkustajalentokoneen lähtökiihdytystä ja rotaatiota ja siinä mitataan nostovoimakerroin.

Suunnitelluilla järjestelyillä tehdään koeajoja ja niistä saatuja tuloksia esitellään. Nestepaksuuden määrittämiseen kehitetyn menetelmän havaitaan antavan suuruusluokaltaan järkeviä tuloksia. Tasolevykokeesta saatavien tulosten havaitaan olevan vertailukelpoisia AS5900:n mukaisista kokeista julkaisujen tulosten kanssa.

ABSTRACT

Three wind tunnel test set-ups for the research of the effects of de- and anti-icing fluids on transport airplane takeoff performance are designed. Implementation of the set-ups and performing the tests in the Aalto University subsonic wind tunnel are described. Processing of the results is instructed and a method is developed for determining the average thickness of a fluid layer on a wind tunnel model surface from pictures of the layer.

In the first test set-up an existing wind tunnel model is utilised to study the fluid flow-off mechanism. A video is shot of the test and the average fluid thickness is determined from the screen captures. For the second set-up a flat plate elimination test (FPET) duct is designed on the basis of SAE Aerospace Standard AS5900. The dimensions are enlarged to ensure operation in a wind tunnel with a larger test section than for which the standard was developed. In this test the boundary layer displacement thickness on the duct floor is measured. In the third set-up a wing profile model representative of a modern transport airplane wing and equipped with adjustable lift-enhancing devices is used. Takeoff run and rotation of a transport airplane are simulated and the lift coefficient is measured in this test.

Test runs with the set-ups are performed and the results are processed. The results obtained with the fluid thickness determination method are observed to be reasonable. Also the flat plate elimination test results are observed to be comparable to the published results from AS5900 compliant tests.

NOMENCLATURE

Symbols

C_L	lift coefficient
c	chord
d	fluid layer thickness
F_x	force in the direction of X-axis
L	lift force
p	static pressure
p_{tot}	total pressure
q	kinetic pressure
q_c	dynamic pressure
Re	Reynolds number
t	time
U	flow velocity
V	voltage
V_1	takeoff decision speed
x	distance from leading edge
α	angle of attack
$\delta*$	boundary layer displacement thickness
Θ	diffuser opening angle
ν	kinematic viscosity

Abbreviations

AOA	Angle of Attack
DAQ	Data Acquisition Device
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administration
FPET	Flat Plate Elimination Test
LED	Light Emitting Diode

1 Introduction

Transport airplane operating regulations require that the airplane must not commence takeoff unless the external surfaces are clear of any deposit of ice or other contaminants which might adversely affect the performance and controllability of the airplane [1]. Contamination of critical surfaces such as wings, control surfaces or propellers with frost, snow or ice can reduce both performance and handling qualities [2]. Several fatal takeoff accidents are attributed to the presence of such contaminants [2]. Thus, Newtonian fluids containing freezing point depressant such as glycol are used to wash the contaminants off the critical surfaces.

Nowadays the surfaces of an airplane wing are secured for takeoff through a two-phase process. The contaminated surfaces are first washed with a Newtonian fluid but this does not provide any long term protection against icing. This treatment is referred to as de-icing and the fluid used for this purpose is classified as a type I fluid. However, in certain meteorological conditions a longer anti-icing protection is necessary, therefore non-Newtonian fluids classified as type II were developed for this purpose in the 1980s. This type of fluid is applied on critical surfaces after de-icing. Due to high viscosity of a type II fluid it remains on the surfaces during the ground operations and manoeuvres. The increasing velocity in the takeoff run, and thus the correspondingly increasing shear stress of the fluid causes a degradation of viscosity at the threshold speed. The fluid is then expected to flush off the surfaces before rotation is commenced.

When the type II fluids were introduced it became apparent that the flow-off before rotation was not always complete. Both wind tunnel tests and a flight test evaluation with a Boeing 737-200 (ADV) indicated that these fluids could cause adverse aerodynamic effects [2]. From the results of these tests a correlation was found between the lift loss on an actual airplane and the displacement thickness of the boundary layer of a flat plate covered with anti-icing fluid [2]. Based on this correlation and on the determined maximum acceptable lift loss (5.24 %) a certification test (SAE Aerospace Standard AS5900) was developed for the acceptance of the fluids [2, 3].

In the 1990s the type II fluids were replaced by type IV fluids which provide a significantly longer anti-ice protection. Some operators that had an airplane treated with a type IV fluid experienced an increase in stick force required to rotate the airplane, reduced control effectiveness, reduced pitching moment and a sense of increased drag [4]. In 2010 a Safety Information Bulletin by EASA was published. It described the effects of thickened anti-icing fluids on takeoff rotation, specifically for unpowered elevator controls: The flight crews reported that on some cases even slightly above normal pull force on the control column was not sufficient to rotate the airplane during takeoff and, assuming a flight control system failure, the crews rejected the takeoff at speeds above V_1 [5].

An investigation of suitability of the certification test specified in AS5900 was conducted at the request of the FAA in 2003. It was concluded that no full-scale or model airfoil testing of type IV fluids was necessary and that the certification process requires no changes [4]. Nevertheless, Transport Canada financed a flight test project of the effects of type IV fluids on a Falcon 20 airplane. The following report published in 2004 recommended further tests on different airplane and wing types [6].

Due to the problems encountered by the operators and the contradicting test reports there is an interest for more research on the effects of type IV anti-icing fluids. The objective of this report is to design and implement the necessary wind tunnel test set-ups to be used for de- and anti-icing fluid tests in a research program funded by the Transport Safety Agency Trafi.

Three different test set-ups and therefore three wind tunnel models are needed for the program. A relatively large airfoil model is utilized in the determination of the fluid flow-off characteristics. The effect of the fluid on the lift and drag coefficients is determined using a smaller airfoil model that can be fitted on the balance of the wind tunnel. The model fitted on the balance can be rotated during the wind tunnel run for an accurate simulation of takeoff conditions. The two models of different size can also be used to observe the scale effects of the fluid flow-off mechanism. Additionally, a test set-up based on the AS5900 is necessary to compare the results of the certification test to the airfoil model test results.

The processing of the results is different for each set-up. For the determination of the flow-off mechanism a video of the fluid behaviour is shot during the test. A method is developed for obtaining the average fluid thickness from this video. Lift coefficient is obtained with the wind tunnel balance. On the flat plate elimination test the boundary layer displacement thickness is derived from the pressures measured at different locations of the test duct.

The three wind tunnel models are described in the next chapter. In Chapter 3 the necessary equipment is presented and a description of performing the tests in the Aalto University subsonic wind tunnel is given. Methods for processing of the results are described and their use instructed in Chapter 4. A summary is given in Chapter 5. Chapters 1 to 5 and Appendix D of this report are also published in a Master's Thesis [7].

2 Wind Tunnel Models

The fixed angle of attack (AOA) model is available for use but the flat plate elimination test (FPET) duct and the variable AOA model are designed and manufactured specifically for the respective test set-ups. The FPET duct is based on SAE Aerospace Standard AS5900 but the dimensions are changed to secure the proper operation of the model in the Aalto University subsonic wind tunnel. Design of the duct is a part of this report and the drawings are presented in Appendix F. The variable AOA model is designed and constructed at the Aerodynamics Research Group as a generic supercritical wing profile to represent the wing of a modern transport airplane.

2.1 Fixed AOA Model

The fixed AOA model was manufactured already in 1984 for anti-icing fluid tests at the Helsinki University of Technology. The model is quite large with a chord of 1.8 metres to minimise scale effects in fluid behaviour. Due to the large size the model cannot be mounted on the balance of the wind tunnel. Therefore, no direct aerodynamic coefficient data can be obtained and the attitude of the model is fixed.

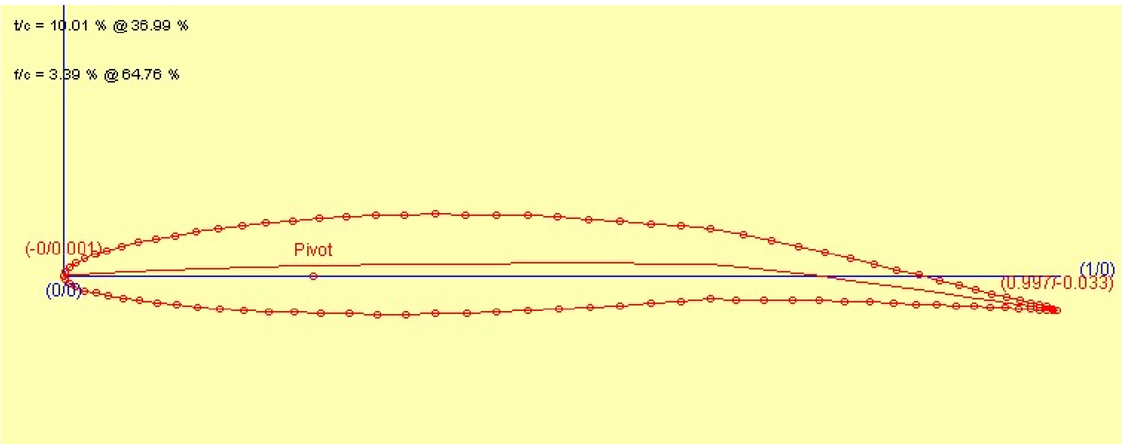


Figure 2-1 Fixed AOA model profile.

The profile is based on NACA 63-210 but to duplicate a typical pressure distribution effect of a flap setting of 10 degrees the profile mean line is folded downward 5.5 degrees at 0.65*c* as shown in Figure 2-1. The contour lines are modified to retain a smooth airfoil shape. Wall interference causes an increase of the effective camber of the profile and partly for this reason the model flap angle is less than on a real airplane. Three dimensional effects present on a real wing are compensated for by a further reduction. After wall corrections the effective profile has a thickness of 10.4 % at an angle of attack of 0.3 degrees. This represents a typical transport airplane wing profile at taxiing attitude. [8]

The model is built mainly of wood although the central part of the upper surface from the leading edge to 0.6*c* is built as a coolant tank from aluminium [8]. The tank is detachable and can be cooled to the temperature specified for a given test. If the tank is cooled there is a large temperature gradient between the rear edge of the tank and the fixed part of the model.

2.2 FPET Duct

AS5900 specifies the cross-sectional dimensions of the FPET duct as 102 mm × 302 mm at the upstream end and 110 mm × 302 mm at the downstream end [3]. The duct length is specified as 1.5 m [3]. The dimensions are presented in Figure 2-2. The duct is quite small, presumably because it is supposed to be used in a cryogenic wind tunnel. In a cryogenic tunnel the mass flow has to be relatively small to keep the required cooling power within reasonable limits so the test section also has to be small. In the Aalto University subsonic wind tunnel there is no such a need and the test section area is 2 m × 2 m. The duct specified in AS5900 is small for a test section of that size so the mass flow through the duct might not be sufficient. Therefore, the duct has to be enlarged. Twofold dimensions compared to those specified in AS5900 are taken as a starting point. Duct length is also increased to 1.8 m since this is the same value as the chord of the fixed AOA model.

Although the dimensions of the Aalto University FPET duct are different from the ones specified in AS5900 a similar velocity gradient has to be obtained. The gradient specified in AS5900 is given for a dry duct, that is a duct without anti-ice fluid on the duct floor. While calculating the velocity gradient the flow is assumed to be non-viscous outside the boundary layer. The boundary layers of the duct inside surfaces are assumed to be thin enough so that they do not merge anywhere in duct. The viscous effects are accounted for using the boundary layer displacement thickness δ^*. With these assumptions the velocity gradient can be calculated when the values of δ^* are known. Values for both dry and wet duct δ^* at 1.5 m (the downstream end of the duct) in an AS5900 compliant test are obtained from an earlier study, at which dry duct δ^* of 2.8 mm and wet duct δ^* of 9.3 mm has been measured [9].

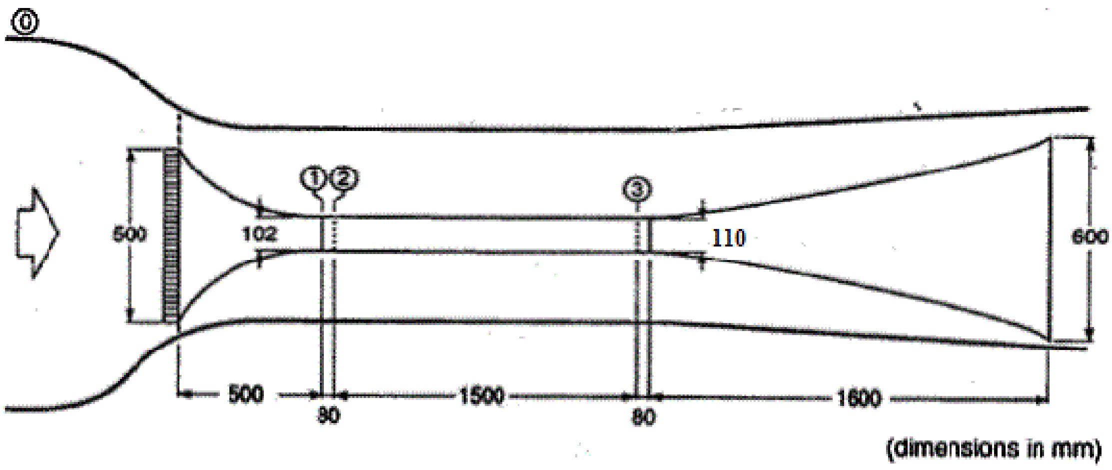


Figure 2-2 Dimensions of the FPET duct as specified in AS5900.

The velocity gradient is then calculated applying the Bernoulli equation from the relation of the duct upstream and downstream end effective areas presented in Equation 2-1. Subscript d denotes value at the downstream end and subscript u at the upstream end of the duct.

$$\frac{V_d}{V_u} = \frac{A_u}{A_{d,eff}} \qquad 2\text{-}1$$

δ^* at the upstream end is assumed to be negligibly small. At the downstream end a value of 2.8 mm on the duct sidewalls and ceiling and 9.3 mm on the fluid-covered floor is assumed. The velocity gradient is V_d / V_a = 1.09. For the dry case δ^* is 2.8 mm for all surfaces and V_d / V_a = 0.97. These are taken as the target values for the design of the Aalto University FPET duct.

According to Schlichting [10] the turbulent boundary layer displacement thickness on a flat plate can be calculated from the following equation:

$$\delta^* = 0.0463x\left(\frac{U_\infty x}{\nu_a}\right)^{-\frac{1}{5}} \qquad 2\text{-}2$$

In this equation the free-stream velocity gradient is assumed to be zero [10] which is incorrect in the case of the FPET duct. In an earlier study δ^* was calculated first from Equation 2-2 and then with an integral numerical method taking into account a shape factor [9]. With the first method δ^* of 2.8 mm was obtained while the numerical method produced δ^* of 2.9 mm when transition to turbulent flow was assumed to take place at the entrance of the test section of the duct [9]. The results are similar enough that the following equation can be considered valid for the dry duct case.

However, a different form is needed to estimate δ^* for the wet duct. The boundary layer thickness profile is assumed to be similar for the dry and the wet cases and the Slichting equation is then modified by replacing the coefficient 0.0463 with a coefficient a that would correspond to a generic wet-surface δ^* value. At a 20 °C reference case wet-surface δ^* values in the order of 12 mm have been observed [9] and this value is selected for modifying Equation 2-2. Transition is assumed to take place at the test section entrance. Replacing 0.0463 with a and solving for a the following equation is obtained:

$$a = \frac{\delta^*}{x\left(\frac{U_\infty x}{\nu_a}\right)^{-\frac{1}{5}}} \qquad 2\text{-}3$$

Using approximate values δ^* = 12 mm, U_∞ = 65 m/s, $\nu_a = 1.2\times10^{-5}$ m^2/s and x = 1.5 m the value of a becomes 0.1929 and the following equation is obtained for the wet δ^* thickness:

$$\delta_f^* = 0.1929x\left(\frac{U_\infty x}{\nu_a}\right)^{-\frac{1}{5}} \qquad 2\text{-}4$$

At x = 1.8 m the wet-surface δ^*_f and the dry surface δ^* are solved using Equations 2-4 and 2-2, respectively. Different values of height and width of upstream and downstream ends of the duct are evaluated. Finally, upstream end dimensions of 200 × 600 mm and downstream end dimensions of 206 × 600 mm are chosen. The velocity gradients for this configuration are V_d / V_a = 1.01 for the dry case and V_d / V_a = 1.07 for the wet case. The wet case gradient is close to the target value. However, the dry case is different from the specification of AS5900 since in the Aalto University duct the velocity is increasing also in this case. This is accepted since the wet case is considered more important.

Research conducted with an AS5900 specified duct has indicated that ceiling and floor boundary layers merge during a test [3]. Testing with a modified duct without this problem has been recommended. The enlarged duct eliminates this problem.

The nozzle through which air enters the duct is designed so that the pressure loss would be as small as possible. Thickness ratio of the elliptical upper and lower surfaces is selected on this basis using data from Applied Fluid Dynamics Handbook [11]. A turbulator strip with an average particle diameter of 764 µm is installed on all nozzle surfaces approximately 120 mm behind the leading edge. The diffuser is designed so that its outlet area is 1.5 times the test section entrance area and the opening angle Θ is 4 degrees. The outer surfaces of the duct are designed to be smooth so that good diffuser trailing edge condition is achieved. General configuration of the duct is presented in Figure 2-3.

To control the fluid temperature during a test the duct floor consists of six coolant tanks made of aluminium which are detachable so that they can be taken to a freezer to be cooled to a specified temperature. Otherwise the duct is constructed mainly of plywood, except nozzle upper and lower surfaces which are made of urethane foam. The duct is fastened on a frame made of steel which places the duct on a correct height in the tunnel and supports the model in maintaining the correct dimensions.

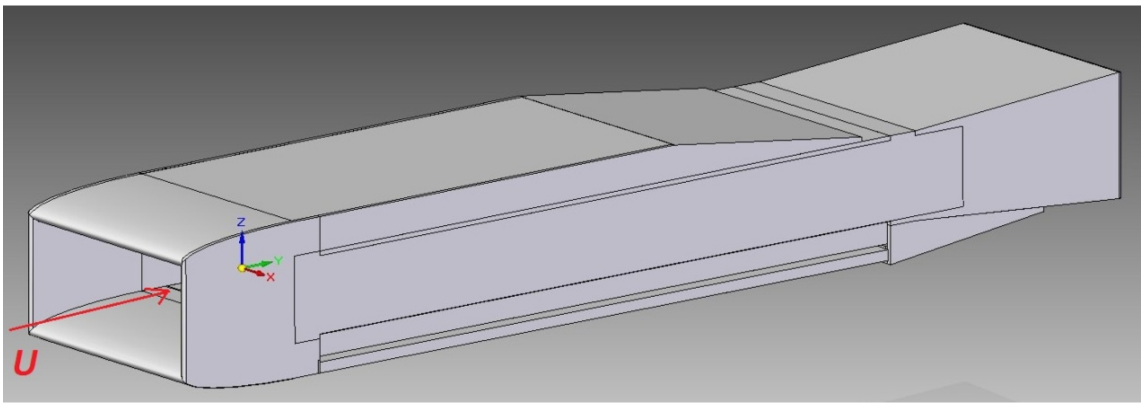


Figure 2-3 General configuration of the Aalto University FPET duct.

2.3 Variable AOA Model

The variable AOA model is designed to be representative of a wing of a modern transport airplane and is equipped with a leading edge slat and a trailing edge flap, both of which are adjustable. The profile used is a DLR-F15 shown in Figure 2-4 with a chord of 0.65 m and a span of 1.528 m. The model is equipped with plates on both ends to reduce the tip vortices. The size of the model is such that it can be fitted on the balance of the Aalto University subsonic wind tunnel to measure the lift, drag and pitching moment coefficients and to adjust the angle of attack during a tunnel run.

The DLR-F15 profile is a research configuration representing a state-of-the-art high-lift transonic turbulent wing section [12]. Two and three-element versions are available, of which the three-element one was selected for the variable AOA model. The slat and the flap settings possible with the model are presented in Figure 2-4. For the purpose of de- and anti-ice fluid research both a clean configuration and a takeoff configuration are required. In takeoff configuration the slat and the flap settings are such that the resulting pressure distribution on the model is representative of the pressure distribution on a transport airplane wing at a takeoff situation. Since the lift coefficient depends on the pressure distribution the slat and the flap settings are based on achieving C_L values similar to a transport airplane wing at angles of attack that are reasonable for ground roll and initial climb situations.

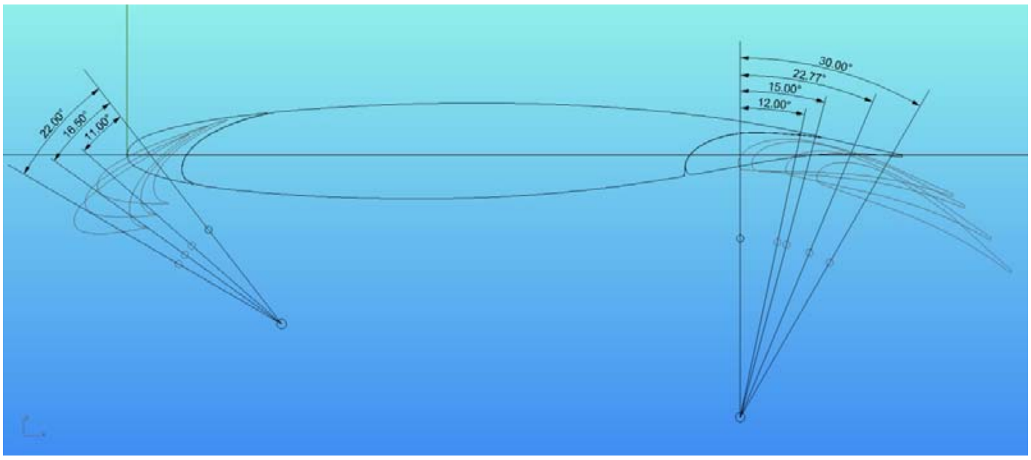


Figure 2-4 Variable AOA model profile and the possible slat and flap settings.

To obtain an estimate of the pressure distribution on a real airplane wing, an example case is calculated using the program Javafoil. Since Javafoil is a potential flow solver, it produces highly unrealistic results on areas where there is a sharp angle in the profile surface. The sharp corners on the slat and the mainplane lower surfaces are therefore rounded as shown in Figure 2-5 to avoid excessive pressure peaks. The representative slat and flap settings used here are 22 degrees and 14 degrees, respectively.

A three-dimensional straight wing with an aspect ratio of 10 is studied. At an angle of attack of 5 degrees, a C_L value of approximately 1.6 is obtained. This value is representative of a transport airplane lift coefficient at an initial climb situation. The corresponding pressure coefficient distribution is presented in Figure 2-5.

The construction of the model is such that there is a coolant tank in the area between 0.215c and 0.615c, approximately where the fuel tank is located in a transport airplane wing. By cooling the fluid in the coolant tank the temperature distribution of the model upper surface can be made to represent a situation at which the fuel in the tank of a real airplane is colder than the ambient temperature. That is a situation where frost is likely to form on the wing. In the area surrounding the tank the model is built of ureol blocks and these are fastened on aluminium built ribs as shown in Figure 2-6. The tank is sealed with epoxy. The slat and the flap are constructed of ureol blocks and aluminium profiles and an adjustment plate is fastened on their both ends. The model with the slat and the flap at extended position is presented in Figure 2-7. The surface of the model is covered with aluminium plates. Since the coolant tank is an integral part of the model structure the whole model needs to be transported to a freezer to cool the fluid.

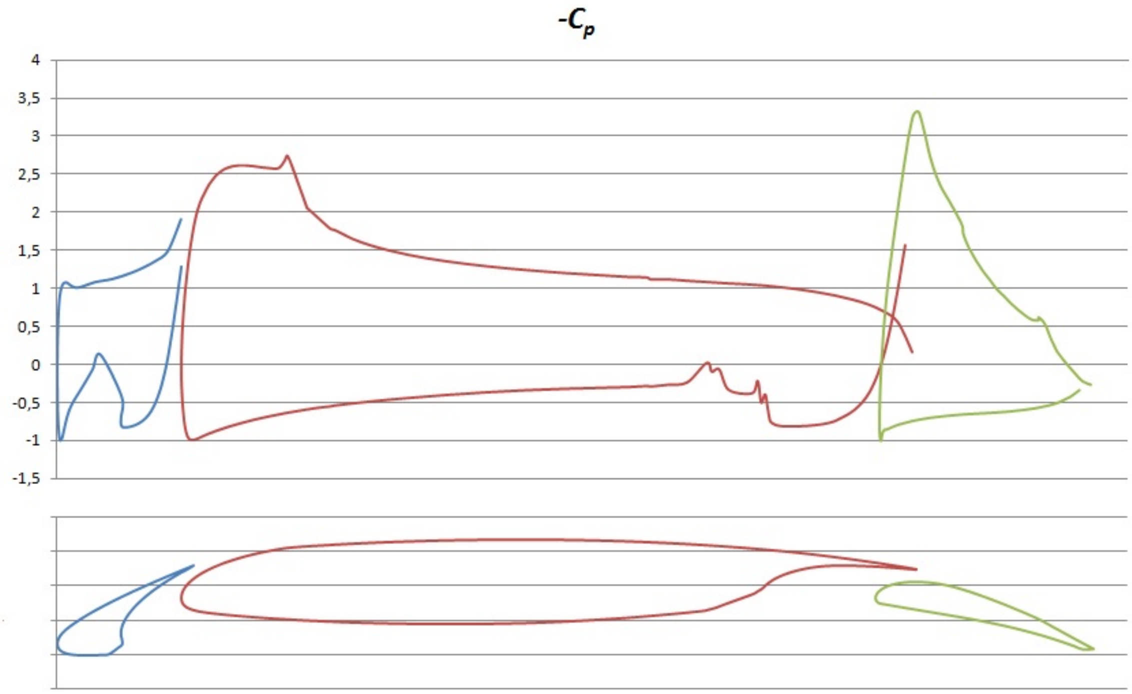


Figure 2-5 **The pressure coefficient C_p distribution on the DLR-F15 when a three-dimensional case of a straight wing with an aspect ratio of 10 is studied. The angle of attack is 5 degrees. The modifications of the slat and the mainplane are visible in the lower part of the figure.**

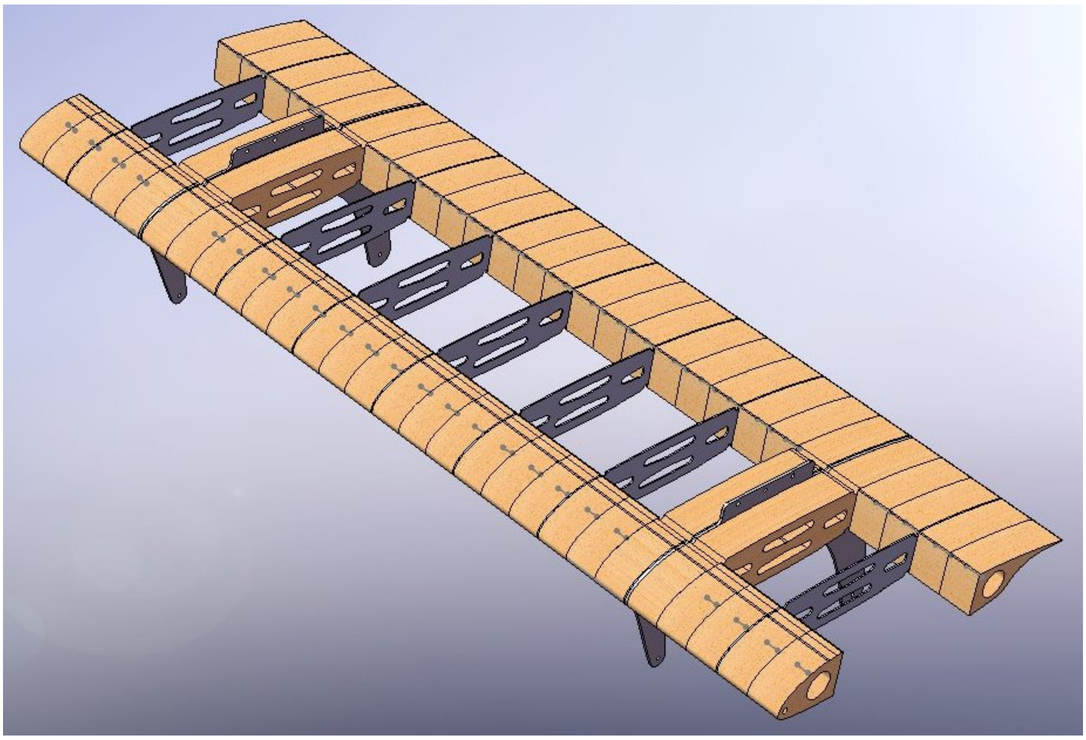


Figure 2-6 **Basic structure of the variable AOA model with the space reserved for the coolant tank at the middle and the ribs and the polyurethane profiles visible.**

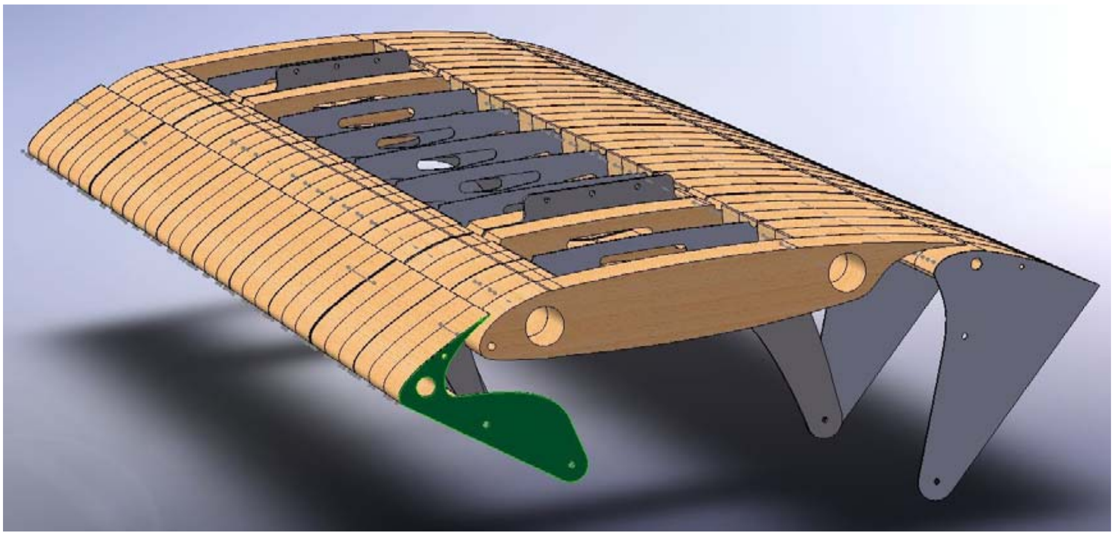


Figure 2-7 Variable AOA model with the slat and the flap extended.

3 Test Procedures

In this chapter, the equipment utilised in the test is presented and a description of the test procedures is given. Detailed instructions necessary for building the set-ups, preparing the necessary equipment and performing the tests are given in the corresponding appendices A, B and C. A reader familiar with the Aalto University subsonic wind tunnel and its control and measuring equipment can use the instructions to perform de- or anti-icing fluid tests with the models presented in Chapter 2.

3.1 Fixed AOA Model Test Equipment and Procedure

The structure of the wind tunnel is such that the model cannot be placed on the middle of the test section since the tunnel access door prevents the attachment of the model. However, as a part of the tunnel structure there is a vertical aluminium beam on the both sides of the tunnel immediately downstream of the door. The wing spar of the model is fastened to the beam on the both sides of the tunnel. Furthermore, there is another attachment point on the both sides of the model 840 mm behind the spar which can be fastened directly to the tunnel wall made of plywood. The loads directed to the model are mainly transferred to the vertical aluminium structural beams. Figure 3-1 shows the model placed on the wind tunnel.

Figure 3-1 Fixed AOA model placed on the wind tunnel.

The most important objective of this test is to determine the flow-off mechanism of the fluid by shooting a video of the behaviour of the fluid from above and then analysing screen captures from the video. For this purpose, a minimum window with dimensions of 695 mm × 250 mm is made on the roof of the test section. Above the window is an I-beam, to which a camera stand is fitted. Analysing of the screen captures is explained in Chapter 4.1.1.

The quantities measured of the airflow are velocity, density, temperature and relative humidity. Volume and thickness of the de- or anti-icing fluid spread prior to the test are measured as well as the fluid run-off before the wind tunnel run. After the run, the fluid volume and the thickness distribution are measured again. The temperature of the model upper surface is measured both before and after the run. The fluid temperature is measured continuously during the test.

Velocity, density, temperature and humidity of the airflow are measured using the equipment installed permanently in the tunnel. The data is processed with the program “Alisoonisen mittausohjelma.vi” installed on the computer in the wind tunnel hall. Use of these devices is not described in this text. Since it is not recommended to install extra programs on the computer described earlier, another computer is required for the test to run the voltage measurement program “Icewing.vi”. A data acquisition device (DAQ) and an indicator LED are also needed for synchronising the flow velocity and the video. NI USB 6210 DAQ and a red LED are recommended.

A jug equipped with a scale of accuracy of 0.05 litres is required for fluid volume measurements. Fluid running off the model surface before the start of the tunnel run is captured with two wide containers. Spreading of type I fluid can be done from an ordinary watering can. Due its properties type IV fluid should be spread with a tool that gives an even spanwise fluid distribution. For this purpose the nozzle of a watering can may be replaced with a 600 mm long pipe to which holes are made at equal distances as presented in Figure 3-2.

Figure 3-2 **Watering can with a pipe-derived nozzle.**

Fluid thickness is measured with an Elcometer which is shown in Figure 3-3. It is a simple tool designed for fluid film thickness measurements in range of 0.025 mm – 3 mm. The accuracy of the scale varies depending on the order of magnitude of the film thickness to be measured, and ranges between 0.025 mm at small thickness values to 0.200 mm at thicknesses between 1.200 and 3.000 mm. To achieve the best accuracy it is necessary to ensure that a proper amount of lighting is available for reading the Elcometer. The fluorescent tubes installed in the tunnel are inadequate especially near the trailing edge of the model. The fluid thickness is measured in the chordwise direction with a spacing of 0.05*c*. In the spanwise direction the measurements are performed at three points at each chordwise step, so that the total number of measurement points is 60. To ease the work the points are marked on the model surface.

The model surface temperature is measured at the same points as the fluid thickness. An infra-red probe is recommended for this measurement, since it is fast and easy to use, and therefore suitable for a measurement with a large number of data points. A thermocouple can also be used, in which case the probe has to be attached to a small piece of insulating material to insulate it from air surrounding the surface during the measurement.

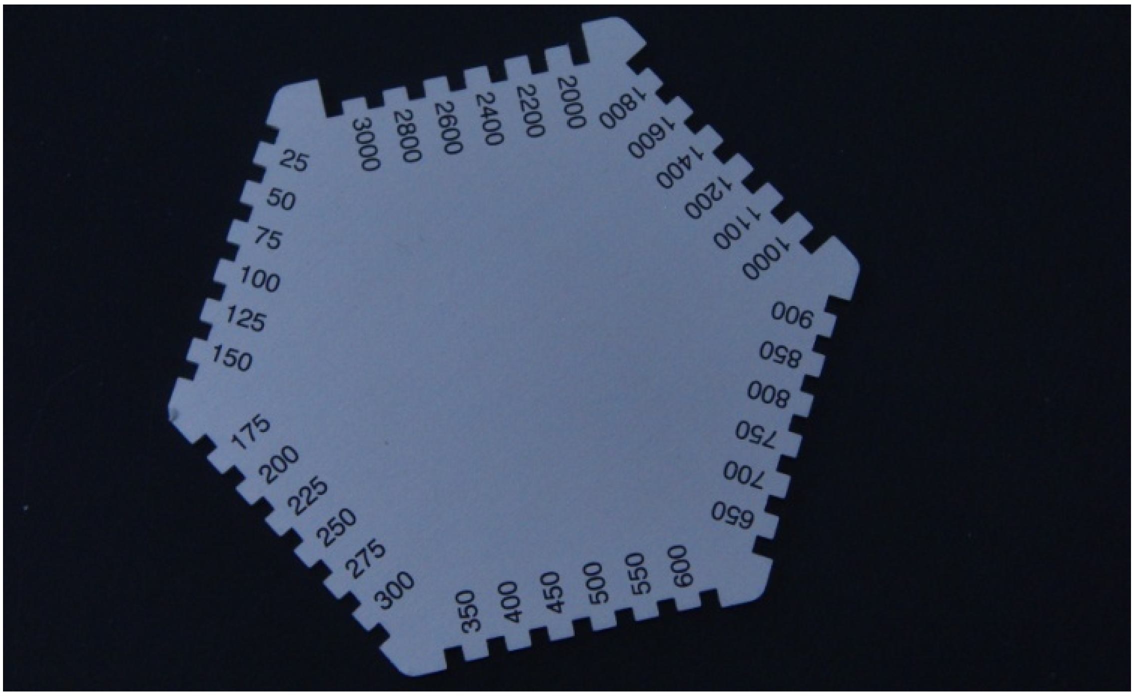


Figure 3-3 Elcometer.

The fluid temperature is measured with two K type thermocouples which are connected to the DAQ that is controlled by the program “Icewing.vi”. Alternatively, the thermocouples can be connected to multimeters through appropriate amplifiers. In this case it is necessary to shoot a video of the multimeter displays during a wind tunnel run, since the temperature changes are fast enough so that the values cannot be written on a log sheet. The thermocouples are placed at the spanwise centreline of the model at the locations shown in Figure 3-4.

The foremost thermocouple can also be placed into a bore hole located 10 mm in front of the rear edge of the coolant tank. If this location is used, the sensor has to be removed every time the tank is removed, and when the sensor is re-installed care must be taken to prevent the sensor from slipping off the intended position. Therefore this location is not recommended. As fluid flows off during a tunnel run the measured temperatures become unreliable after the fluid wave has passed the sensor.

The video of the fluid flow-off has to be synchronised with the velocity, the temperature and the humidity of the air flowing in the tunnel. For this purpose a LED is connected to one of the digital output channels of the DAQ controlled by “Icewing.vi”. The LED is fitted close to the border of the area that is visible in the video so that the switch-on is easily detected.

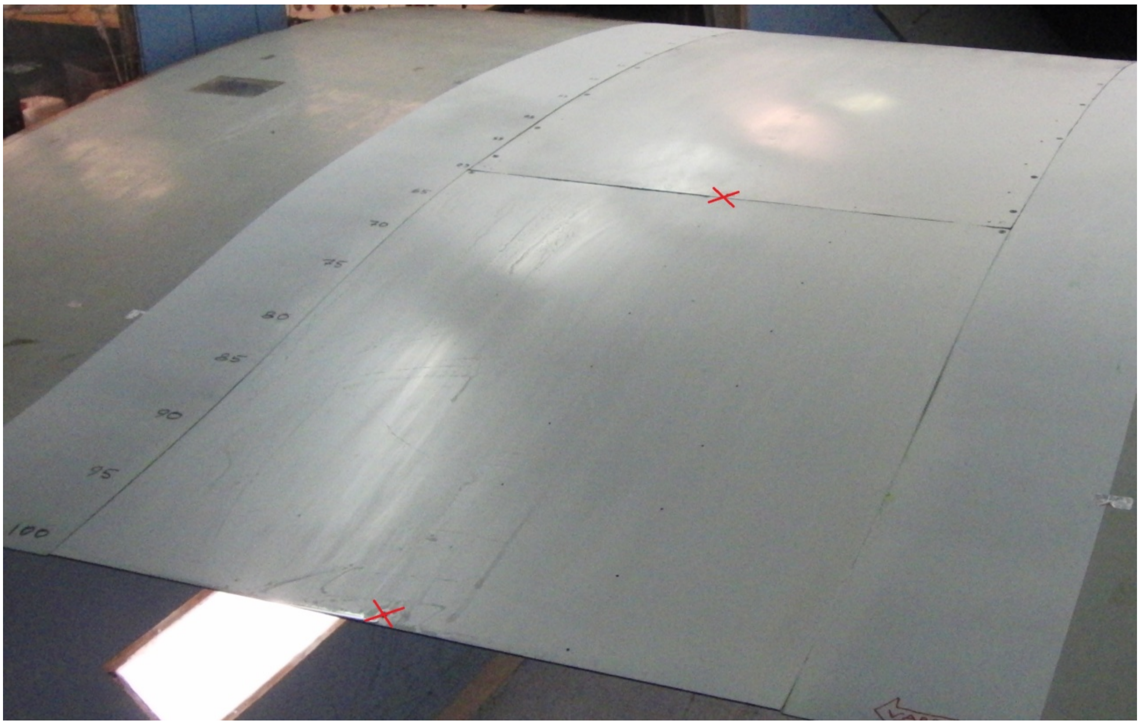


Figure 3-4 Locations of the temperature sensors marked with a red cross on the upper surface of the model.

The preparation for the test is started by filling the coolant tank with a water-glycol solution. The tank is cooled in the freezer on the third floor of the K4 building. To achieve the desired temperature the cooling process has to be started well before the test, practically in the previous evening. Depending on the desired test conditions it may also be necessary to cool the type IV fluid before the test. Cooling of type I fluids is not necessary since the temperature of this type of fluid is always considerably above 0 °C in practise.

When the temperature of the tank has reached the specified value, it is placed on its position in the model. It is unpractical to remove the tank between the tests conducted during one working day. The tests have to be planned so that the one specified with the coldest surface temperature is performed first. A rough estimate of a temperature rise of 5 °C between consecutive tests can be used and the number of tests a day is three to four at most.

For the purpose of determining the fluid layer thicknesses during the test, a video presenting known thicknesses as well as a video of the model surface clear of fluid are required. A more detailed description of this is given in Chapter 4.1.1. The known thickness values are achieved by spreading an even fluid layer on a calibration plate, which is presented in Figure 4-1 in Chapter 4. Due to the characteristics of type IV fluids the spreading of an even fluid layer requires great accuracy. If the layer is thicker than what is expected based on the depth of the grooves, the calibration process fails, and misleading results are obtained.

Next, fluids to be used are prepared and the surface temperature of the model is measured. Fluid is then spread on the model. The spreading process depends on whether only type IV fluid or both type I and type IV fluids are used. Due to its viscous qualities type IV fluid does not spread evenly when a watering can shown in Figure 3-4 is used. This concerns especially the area between 0 – 0.65*c* where the model upper surface is relatively flat and fluid does not spread by pouring. On this area the fluid layer has to be evened by using a spattle or by running the tunnel at a low speed for a few minutes. Both methods provide approximately similar results. The latter one can be considered equal to taxiing of a real airplane. The fluid run-off is insignificant and the viscous qualities of type IV fluid are unaffected. However, neither of these methods provides good repeatability or an even fluid layer. When the spreading is finished the fluid thickness and the surface temperature are measured.

Before the wind tunnel run is started all the equipment used for fluid spreading and the previously described measurements is removed from the tunnel. The camera (or two cameras if multimeters are used to obtain the fluid temperature) and the program "Icewing.vi" are prepared and the lights of the tunnel hall are switched off. The run is then initiated.

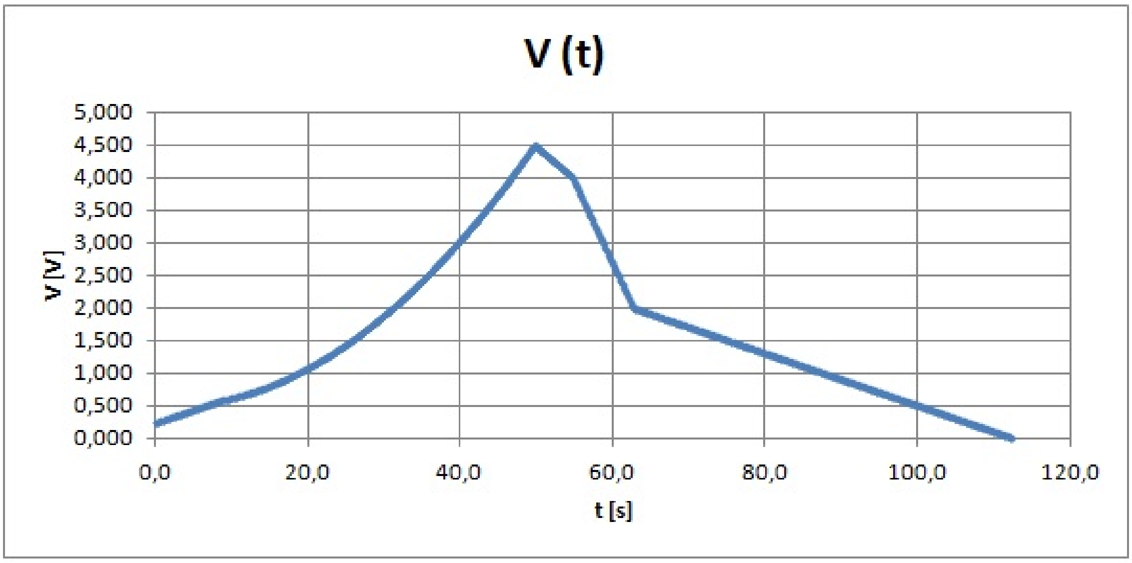


Figure 3-5 Control voltage of the Ward Leonard drive system as a function of time.

In a test where a takeoff run is simulated, the flow velocity in the tunnel has to be increased rather linearly from zero to 60 m/s. For this purpose the program "Alisoonisen varakäyttöohjelma.vi" has a control voltage ramp function, to which the desired control voltage of the Ward Leonard drive system of the wind tunnel is entered at time steps of 0.1 seconds as a .txt file. The ramp that is used on a takeoff run test is presented in Figure 3-5 as a plot of voltage against time. A more detailed description is given in Appendix A. It is important to note that the control voltage directs the power output of the motor driving the fan. The velocity corresponding to a certain control voltage depends on the atmospheric conditions. In a test in which a taxiing airplane is simulated the speed control can be performed manually.

After the run is finished the thickness of the remaining fluid layer and the temperature of the model surface are measured. The remaining fluid is then removed and the surface temperature measured again. A preparation of the next test can then be started.

3.2 Flat Plate Elimination Test Equipment and Procedure

The flat plate elimination test (FPET) is largely based on the instructions given in SAE Aerospace Standard AS5900 although the measurement set-up is somewhat different [3]. The objective of the test is similar to AS5900, that is to determine the boundary layer displacement thickness δ^* on the duct floor during a test run. Total pressure is measured at station 1 and static pressure is measured at station 1 and either at station 2 or 3. The displacement thickness δ^* is calculated using these pressures as explained in Chapter 4.2. The air temperature is measured at station 1 and the fluid temperature at the rear edge of the coolant tanks. Volume and thickness of the fluid spread on the model surface as well as the surface temperature are measured before and after a wind tunnel run. Stations 1, 2 and 3 are defined in Figure 3-6 and are also marked on the outer surface of the ceiling of the FPET duct.

The position at which the FPET duct is installed in the wind tunnel test section is mainly affected by the limits imposed by the tunnel structure and the objective of getting a low turbulence ratio in the duct. For the latter reason the duct should be positioned close to the upstream end of the test section. However, the final position is constrained by the metallic parts of the tunnel structure on which it is impractical to place fasteners. The duct positioned in the tunnel is shown in Figure 3-7.

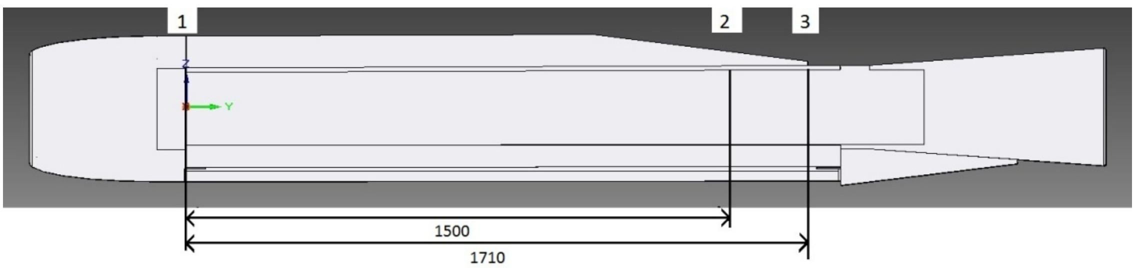


Figure 3-6 Definition of stations 1, 2 and 3.

Two pressure transducers and a pitot tube are needed for the measurement of total and static pressures. A pitot-static tube can also be used but the static pressure line is not needed. A 3 kPa transducer is used to obtain the dynamic pressure q_{c1} by measuring the difference between $p_{tot\ 1}$ and p_1. A 1 kPa transducer is used to obtain the static pressure difference $p_1 - p_2$ or $p_1 - p_3$. The subscripts refer to the respective stations. The static pressures are measured at the middle of the duct ceiling and the pitot tube is installed slightly off the centreline closer to the right sidewall. The pressure transducers are connected to the data logger at the wind tunnel hall and the results are recorded using the program “Alisoonisen mittausohjelma.vi” running on a computer located at the same hall. The same program and the equipment installed permanently in the tunnel are used to measure airflow velocity, density, temperature and relative humidity at the tunnel test section entrance in front of the duct.

The air temperature at station 1 and the fluid temperature at the rear edge of the coolant tanks are measured with two K type thermocouples. It is recommended to use the program “Icewing.vi” to record the temperatures. This program must not be installed on the computer running “Alisoonisen mittausohjelma.vi” so another computer is necessary, and a DAQ is also required. Alternatively the thermocouples can be connected to multimeters through appropriate amplifiers. In this case it is necessary to shoot a video of the multimeter displays during a wind tunnel run, since the temperature changes are fast enough so that the values cannot be written on a log sheet. At station 1 the temperature sensor is placed 5 mm below the ceiling slightly off the centreline to avoid disturbing the static pressure measurement. The sensor measuring the fluid temperature at the rear of the tanks is placed at the centreline. As fluid flows off during a tunnel run the measured fluid temperature becomes unreliable after the majority of the fluid has left the surface.

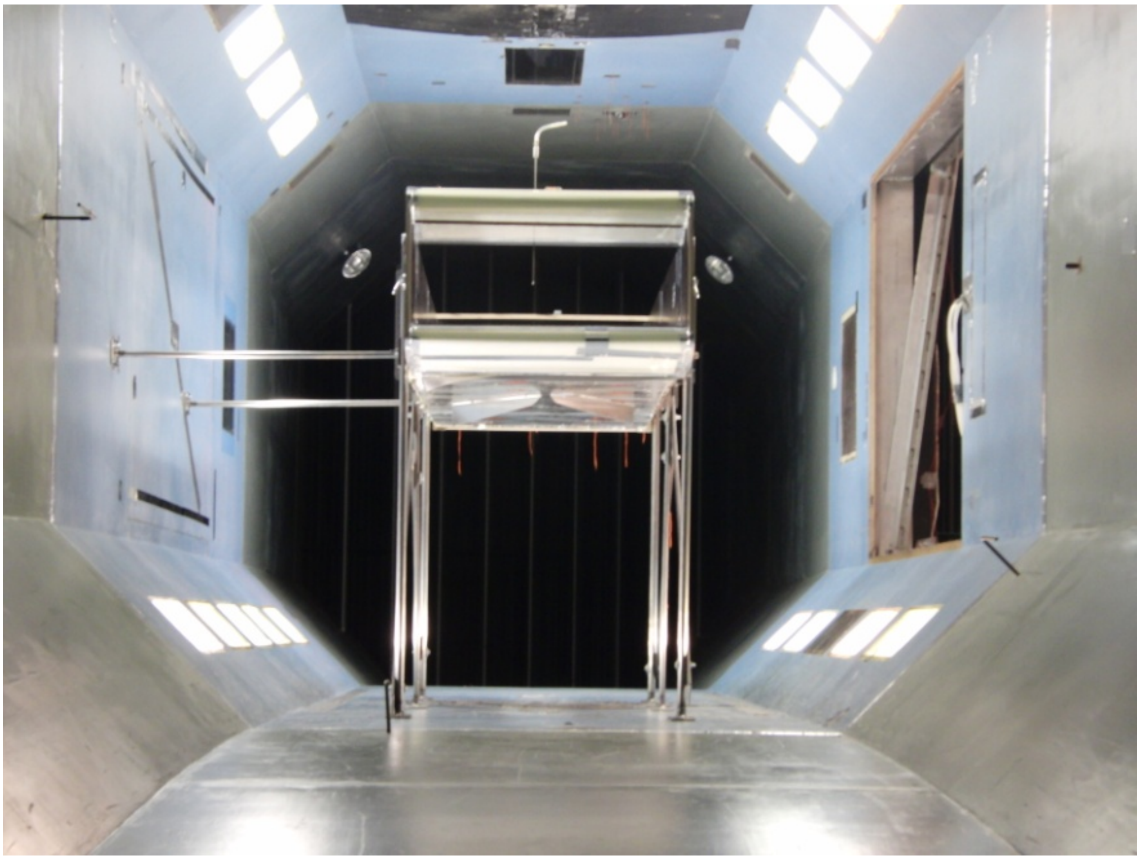


Figure 3-7 FPET duct in the wind tunnel.

Fluid thickness is measured with an Elcometer which has been described in Chapter 3.1 pp. 10-11 of this report. Instructions of use are also given in that chapter. A thickness measurement is performed in the longitudinal direction with a spacing of 0.18 metres. In the transverse direction the measurements are performed at six points at each longitudinal step, so that the total number of measurement points is 60. To ease the work the points are marked on the upper surfaces of the coolant tanks as shown in Figure 3-8.

Similarly to the fixed AOA model test a jug with a scale of accuracy of 0.05 litres is required for fluid volume measurements. For spreading of type IV fluid a modified watering can described in Chapter 3.1 on page 10 can be used. Model surface temperature is measured at the same points as the fluid thickness and an infra-red probe is recommended for this as reasoned in Chapter 3.1.

The construction of the FPET model is such that the coolant tanks need to be placed on position at the beginning of the assembly. Therefore the preparation of the assembly is started by filling the tanks with a water-glycol solution and by cooling the tanks in the freezer on the third floor of the K4 building. To achieve the desired temperature the cooling process has to be started practically in the evening before the test. It may also be necessary to cool type IV fluid to achieve the specified test conditions.

Figure 3-8 Fluid layer on the FPET duct floor. Markings indicating the measurement points of the fluid thickness and the surface temperature are visible.

The FPET model is assembled in the wind tunnel. Since the model is constructed mainly of plywood, it experiences significant deformations caused by changes of the air humidity. Therefore, the correct dimensions of the duct are only achieved by fastening the vertical oval tubes of the frame on the tunnel floor in such positions that the duct is forced straight. Sidewalls are installed before fastening of the frame. Their straightness and the duct width at both of its ends have to be observed constantly during the fastening process.

The assembly of the model is continued by installing the expansion tank and by connecting the tank to the six coolant tanks. The hoses connecting the tanks are long enough so that the expansion tank can be placed outside the tunnel. The nozzle and the diffuser are fitted to their respective ends of the duct and an 1800 mm × 600 mm plate of insulating material is placed below the coolant tanks. All the gaps resulting from the assembly are sealed using aluminium tape.

Before fluid testing can be conducted, tests with a clean duct have to be performed to obtain the boundary layer displacement thickness in a duct without fluid. This test has to be repeated also after the fluid tests. Flat plate elimination tests are normally carried out only for type IV fluid which is difficult to spread as has been described in Chapter 3.1 on pages 12-13. Since the tank upper surfaces that serve as the floor of the FPET duct are not cambered, spreading the fluid evenly on them is even more difficult than spreading on the fixed AOA model surface. A recommended method is to spread the fluid mainly on the upstream area of the duct floor and then run the tunnel at a velocity of approximately 10 m/s which causes the fluid to flow slowly towards the downstream area. The method of correcting the fluid layer with a spattle as instructed for the fixed AOA model in Chapter 3.1 has not been tried and it would probably require an extensive amount of time. Type IV fluid layer on the FPET duct is shown in Figure 3-8. When the spreading is finished the fluid thickness and the surface temperature are measured.

After the fluid is spread the ceiling and the roof are placed on and the pressure hoses are connected. All the equipment used for fluid spreading and the previously described measurements is removed from the tunnel. The program “Icewing.vi” is started or alternatively the camera recording the multimeter displays is switched on. The run in then initiated.

AS5900 requires that the flow velocity in the duct is accelerated from $U_I \leq 0.5$ m/s to (65 ± 5) m/s within (25 ± 2) s which gives a constant acceleration of 2.6 m/s^2 [3]. The control voltage ramp function of “Alisoonisen varakäyttöohjelma.vi” described in Chapter 3.1 is used also in this test. However, the ramp is different from the one used in the fixed AOA model test since the required velocity of 65 m/s in the duct corresponds only to approximately 50 m/s in the tunnel. The ramp that is used in this test is presented in Figure 3-9 as a plot of voltage against time. A more detailed description is given in Appendix B.

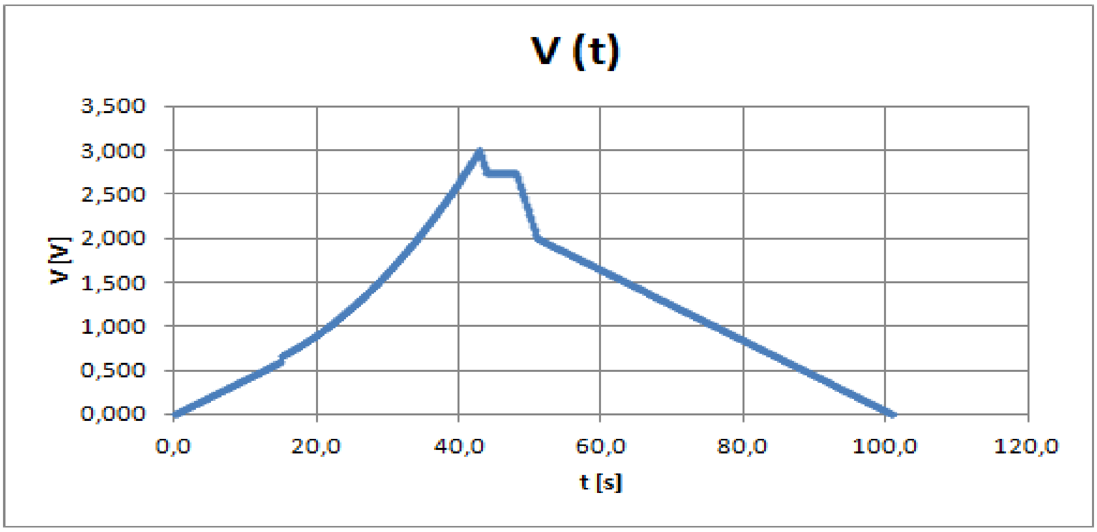


Figure 3-9 Control voltage as a function of time.

When the wind tunnel run is complete the fluid remaining in the diffuser is removed and the duct is then disassembled so that the thickness of the fluid remaining on the tank surfaces and the surface temperature can be measured. Finally the remaining fluid is removed and the tank surface temperature is measured again. A preparation of the next test can then be started.

3.3 Variable AOA Model Test Equipment and Procedure

The variable AOA model is installed on the wind tunnel balance as shown in Figure 3-10. Unlike the usual practice the attitude of the model is such that the upper surface of the profile faces to the ceiling of the test section. This kind of installation is necessary to allow the de- or anti-ice fluid to be spread on the model upper surface. The design of the model is such that it can also be installed upside down if used for other purposes than fluid testing.

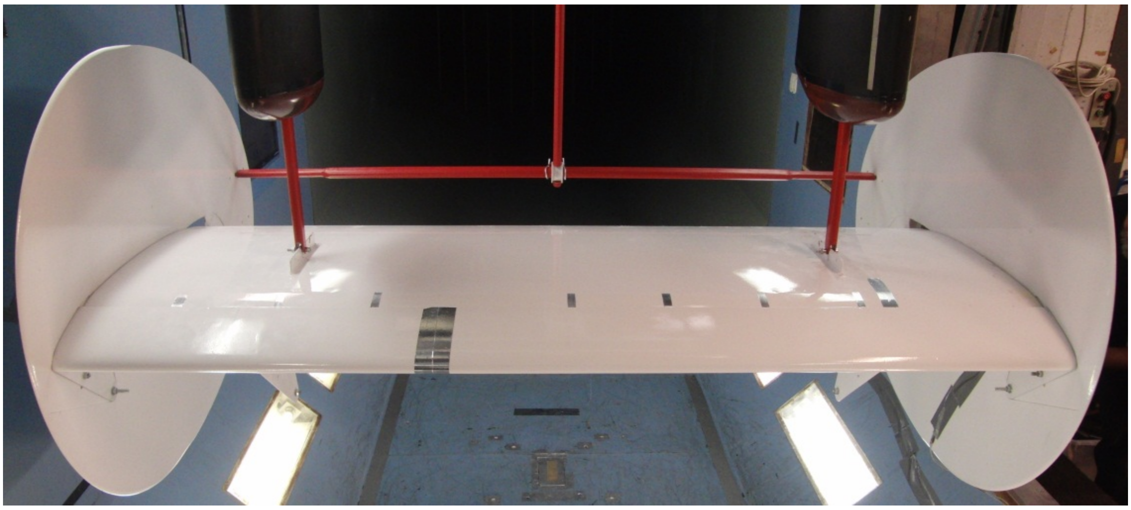


Figure 3-10 Variable AOA model placed on the wind tunnel. The slat and the flap are retracted.

The objective of this test is to measure the lift acting on the model and then calculate the lift coefficient applying the necessary wind tunnel corrections. Angle of attack at which the model is positioned is recorded. Similarly to the fixed AOA model test airflow velocity, density, temperature and relative humidity are measured. Also volume of the fluid spread on the model, the fluid run-off and the fluid layer thickness before the run as well as volume and thickness distribution of the remaining fluid layer after the run are measured similarly to the fixed AOA model test. Temperature distribution of the model surface is measured before and after the run. Additionally the temperatures of the anti-ice fluid and the coolant fluid are measured continuously during the test.

The flow-off mechanism can be determined with a method similar to the one used in the fixed AOA model test. However, since the model is placed in a different location than the fixed AOA model, a new window on the test section ceiling and a new camera installation are required. The camera is installed to the centre of the overhead balance turntable. The instructions given in Chapter 3.1 and Appendix A for using the camera and the calibration plate as well as synchronising the flow velocity and the video can be followed [7].

Lift as well as airflow velocity, density, temperature and humidity are measured using the equipment installed permanently in the tunnel. The data is processed with the program “Alisoonisen mittausohjelma.vi” installed on the computer in the wind tunnel hall. The flow velocity and the angle of attack are controlled using the program "komentaja.vi" installed on the same computer and recorded by "Alisoonisen mittausohjelma.vi". Use of these devices is not described in this text.

An Elcometer described in Chapter 3.1 pp. 10-11 is used for fluid thickness measurement. Instructions of use are also given in that chapter. Thickness measurement is performed in the chordwise direction with a spacing of $0.10c$ except that the rearmost point is $0.95c$ instead of $0.90c$. In the spanwise direction measurements are performed at three points at each chordwise step, so that the total number of measurement points is 27. To ease the work the points are marked on the model surface.

Similarly to the fixed AOA model test a jug with a scale of accuracy of 0.05 litres is required for fluid volume measurements. For spreading of type IV fluid a modified watering can described in Chapter 3.1 can be used. The model surface temperature is measured at the same points as the fluid thickness and an infra-red probe is recommended for this as reasoned in Chapter 3.1.

Temperatures of the anti-ice fluid and the coolant fluid are measured with two K type thermocouples. It is recommended to use the program "Icewing.vi" to record the temperatures, in which case a computer and a DAQ are needed. Alternatively the thermocouples can be connected to multimeters through appropriate amplifiers and a video has to be shot of the multimeter displays during a wind tunnel run. One of the thermocouples is placed inside the coolant tank and the other is placed at the spanwise centreline directly above the rear spar. As anti-ice fluid flows off during a tunnel run the measured temperature becomes unreliable after the fluid wave has passed the sensor.

The preparation for the test is started by cooling the model. Since the coolant tank is not detachable the tank is first filled with a water-glycol solution and then the whole model is taken to the freezer on the third floor of the K4 building. To achieve the desired temperature the cooling process has to be started well before the test, practically in the previous evening. As explained in Chapter 3.1 it may also be necessary to cool type IV fluid before the test, but cooling of type I fluids is not necessary.

When the temperatures of the model surface and the coolant fluid have reached the specified value, the model is taken to the wind tunnel and fixed on the balance. It is impractical to take the model back to the freezer between the tests conducted during one working day. However, the model can be cooled between individual tests by pouring liquid nitrogen to the two copper pipes that are led through the coolant tank in the spanwise direction. This at least reduces the rate of increase of temperature between the tests but it is, nevertheless, recommended to plan the tests so that the one specified with the coldest surface temperature is performed first.

The preparation is continued by preparing the fluids to be used and by measuring the surface temperature of the model. The fluid is then spread on the surface. The spreading is always carried out with the slat at a retracted position. In a real airplane also the flap is retracted during anti-icing treatment. However, in this test the slot of the flap can be closed using rubber seal instead of retracting the flap.

As in the fixed AOA model test the spreading process depends on whether only type IV fluid or both type I and type IV fluids are used. The difficulty of spreading type IV fluid evenly has been described in Chapter 3.1. However, with the variable AOA model the spreading is much easier since the angle of attack can adjusted during the process. Most of the fluid is first spread on the area at approximately $0.30c$ – $0.70c$ and α is then decreased to make the fluid pour toward the model leading edge. The front edge of the fluid layer can be kept straight using a spattle. Next, α is increased to pour the fluid toward the trailing edge, and a spattle is used to straighten edge of the fluid layer. There is no need to run the wind tunnel to even the fluid layer. When the spreading is finished the fluid thickness and the surface temperature are measured.

Next, the slat and the flap are extended and locked to angles of 11 and 5 degrees, respectively, if takeoff configuration is specified for the test. All the equipment used for fluid spreading and the previously described measurements is removed from the tunnel. The program “Icewing.vi” or alternatively the camera recording the multimeter displays is switched on. The run is then initiated.

In a test where a takeoff run is simulated, the flow velocity in the tunnel has to be increased rather linearly from zero to 60 m/s. During the acceleration the angle of attack is 1.0 degrees which corresponds to a C_L of 0.60 with no fluid applied. When 60 m/s is reached the angle of attack is increased at a rate of two to three degrees per second to 7.5 degrees corresponding to a C_L of 1.30 with no fluid. The C_L values are based on measured Airbus A321 revenue flight data. The corresponding angles of attack at several slat and flap settings have been determined on test runs as explained in Chapter 4.3. The acceleration and the angle of attack are controlled by loading one of the scripts described in Appendix C to the program “komentaja.vi”. The control voltage ramp function is not used in this test.

After the run is finished the thickness of the remaining fluid layer and the model surface temperature are measured. Fluid is then removed and the surface temperature measured again. A preparation of the next test can then be started.

4 Processing of the Results

4.1 Fixed AOA Model Test Results

The fixed AOA model test results are processed to determine the fluid flow-off mechanism and the flow-off volume as well as the corresponding test conditions. Fluid flow-off is calculated from the measured amount of fluid spread on the model, the fluid run-off before the wind tunnel run, and the amount of fluid remaining on the surface after the run. Fluid remnants in the containers are also taken into account. The flow-off mechanism is determined from a video and the method is described in Chapter 4.1.1.

The most important test condition parameter is the fluid temperature since it has a large effect on the qualities of the fluid. The model surface temperature as well as the air temperature and humidity affect the fluid temperature but also give information whether the test conditions correspond to the conditions at which de- and anti-icing fluids are used in reality. The flow velocity as a function of time affects fluid flow-off and should be similar to a take-off acceleration of a transport airplane.

Results obtained on the 11th fixed AOA model test on spring 2012 are presented in Chapter 4.1.2 as an example of the possibilities of the test procedure and the result processing methods. The test was one of the last tests conducted and was selected as an example since the test procedure had matured by the time of this test.

4.1.1 Fluid Thickness Determination Method

To analyse the behaviour of the fluid layer during a wind tunnel run a method is developed to determine the fluid thickness distribution in the chordwise direction from the videos shot during the tests. Screen captures are taken from the videos and the program Matlab is used for their analysis. The Matlab scripts written for this purpose are presented in Appendix A.

Matlab treats images as $h \times w \times 3$ matrices where h and w are height and width of the image, respectively, so that a matrix element specifies one pixel of the image. The three values of each element are the RGB colour model values. In the method presented here the R and B values are analysed since they experience large variation when the thickness of the green de-icing fluid on a white surface changes.

The analysis is started by obtaining a correlation between fluid thickness and the R and B values using an image of a calibration plate presented in Figure 4-1. The calibration plate has 12 grooves, the depths of which are 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 5.0, 6.0, 8.0 and 10.0 mm. A Matlab script “Kalibrointi.m” is developed to read the average of the product of the R and B values from each groove.

To obtain a more accurate calibration it is recommended to determine also the R and B values corresponding to zero fluid thickness. In each test a video of the model surface clear of fluid is shot and the zero thickness R and B values can be read from screen captures of these videos with the Matlab function “imtool”. Zero thickness product of R and B and the values obtained with the calibration plate are then plot against the known fluid thicknesses. A curve is fitted to the plot with the Matlab function “cftool”. An example of the resulting plot and a curve fitted to it is shown in Figure 4-2.

Figure 4-1 Calibration plate.

The equation of the curve is of a Gaussian type:

$$y = a_1 e^{\left(-\frac{x-b_1}{c_1}\right)^2} + a_2 e^{\left(-\frac{x-b_2}{c_2}\right)^2} \qquad 4\text{-}1$$

This form of equation is observed to give the best fit in all cases that are treated in this report. When the curve is fitted, the “cftool” gives the values of the coefficients of Equation (4.1). These are the calibration coefficients.

For the next part of the calibration process an image of the fluid layer on a surface of the model before the wind tunnel run is required. A Matlab script “Korjauskerroin.m” first calculates the average of the product of R and B values for every column of the image. Next, using Equation 4-1 and the calibration coefficients, it calculates the average fluid thickness on that column. Finally, the results are modified to be a 1 × 1800 vector which is a standard size used by the three scripts presented here.

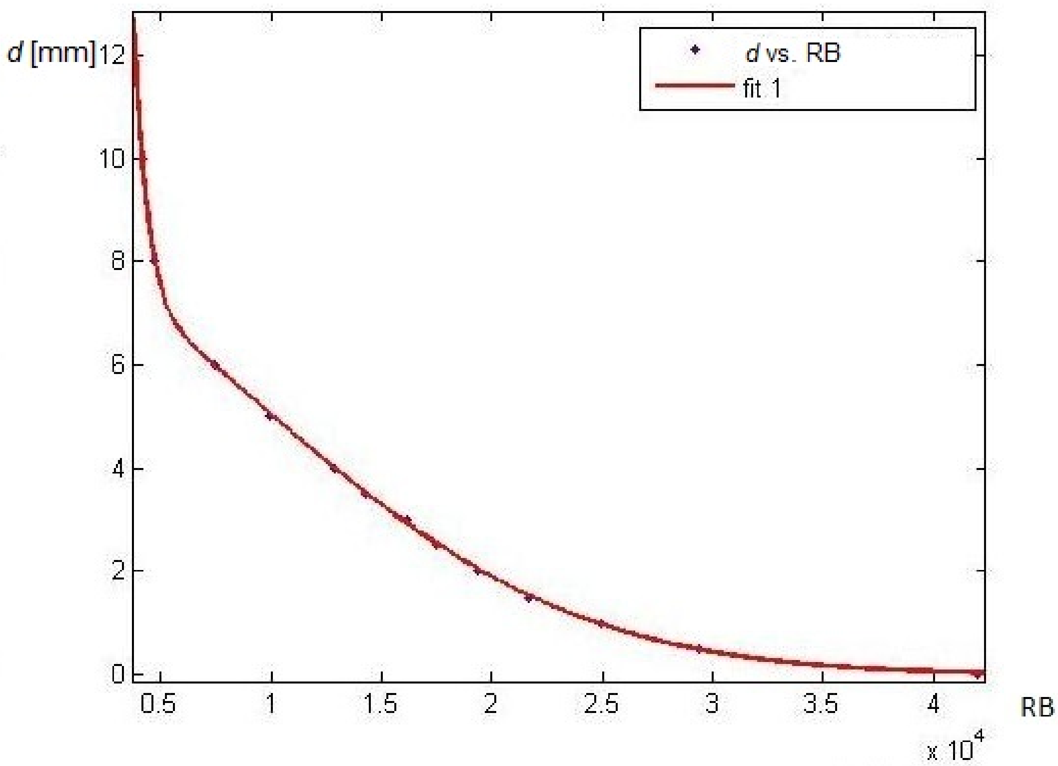


Figure 4-2 Example on fitting a curve to a plot of fluid thickness *d* and RB values.

However, the thickness distribution thus obtained is anything but accurate. Due to camber of the model surface, and the differences in lighting conditions, the plate-based calibration produces erroneous results on other parts of the surface than at the maximum thickness position. As can be expected the error is greatest near the leading and trailing edges. A correction factor has to be determined to correct the results.

As a part of the test procedure the fluid layer thickness is measured before the tunnel run is carried out. The results of this measurement are interpolated by the script and then used to calculate the correction factor: The interpolated thicknesses are simply divided by the thicknesses determined from the image at the previous step to produce a 1 × 1800 vector. The image showing the fluid layer before the test must not have spanwise areas not covered by fluid. This will cause the correction factor to become zero in these areas and, therefore, cause problems while analysing the results.

The calibration process is now complete since both the coefficients of Equation 4-1 and the correction factor are known. The behaviour of the fluid thickness during the test can now be analysed. Screen captures of the video are taken, from which the Matlab script “Tulokset.m” first calculates a preliminary result using the calibration coefficients. The results are then modified to be a 1 × 1800 vector, and finally the preliminary results are multiplied by the correction factor to get the final result. This can be plotted to show the chordwise fluid thickness distribution. The result can also be integrated to obtain the area of a chordwise section of the fluid layer. If the width of the fluid layer is known or can be estimated the volume of the fluid can finally be calculated.

4.1.2 Example of Results Obtained in Spring 2012

In the test number 11 a total of 1.5 litres of type IV fluid at a temperature of -11 °C was to be spread on the model surface. The surface temperature ranged between -4.5 and -8.5 °C on the coolant tank area (0 – 0.65*c*) and was approximately 0 °C behind the tank. In this test there was no fluid run-off before the wind tunnel run. Total remnant in the containers used was 0.07 litres, thus 1.43 litres was actually spread on the model. After the spreading the surface temperature had evened to be between -2.6 °C and -4.2 °C on the tank area and between 1.4 °C and 2.6 °C behind the tank. Fluid temperature was not measured after the spreading.

The tunnel was accelerated with the control voltage shown in Figure 3-5 and the resulting flow velocity as a function of time is presented in Figure 4-3. The air temperature at the start of the tunnel run was -1.56 °C and the relative humidity was 75.5 %. After the tunnel run a total 0.3 litres of fluid was collected from the model surface.

The fluid thickness distribution during the test run at a speed of 31 m/s determined with the method described in Chapter 4.1.1 is presented in Figure 4-4. The discontinuity at x = 1100 mm is caused by the gap between the coolant tank and the fixed part of the model which presents a dark spanwise area that cannot be taken into account in the calibration.

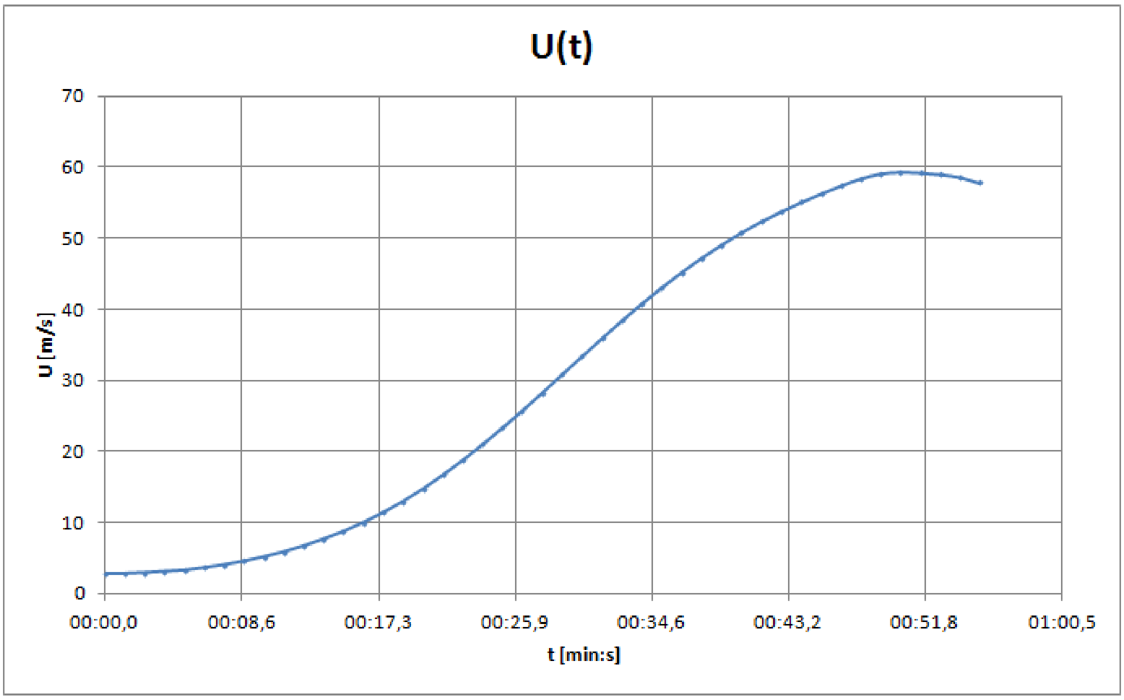


Figure 4-3 **Velocity as a function of time in the fixed AOA model test number 11.**

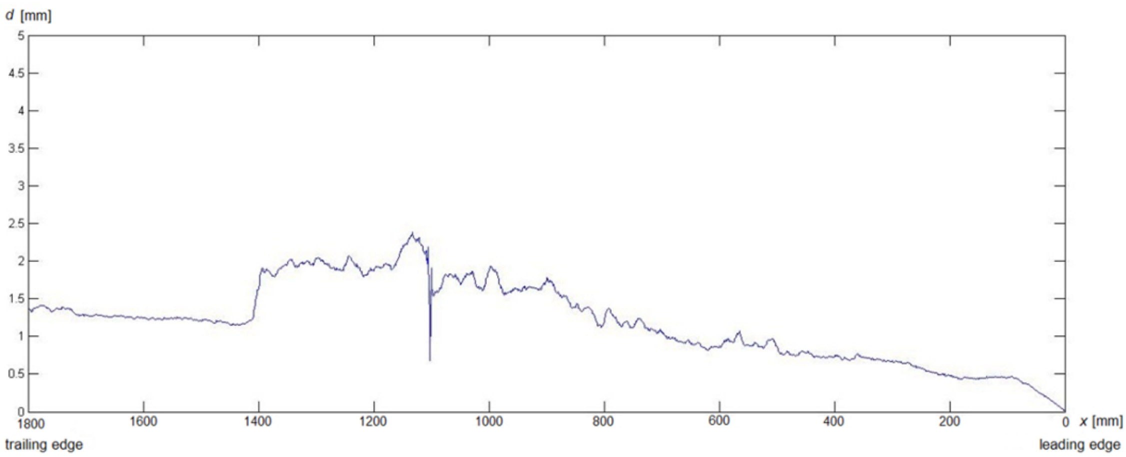


Figure 4-4 **Example of fluid thickness distribution obtained using the method presented in Chapter 4.1.1.**

More results are presented in Appendix D where four screen captures of the video shot during the test and the corresponding thickness distributions are shown. In both the screen captures and the thickness distribution plots the model leading edge is on the right. It can be observed that the fluid elimination mechanism is well visible and the values of thickness are reasonable. Volume of the fluid was also calculated which required an estimation of the fluid layer width based on the video. The calculated volume is 1.4 litres for Figures D-3, D-5 and D-7, and 1.3 litres for Figure D-9 where fluid elimination has started.

4.2 Flat Plate Elimination Test Results

The purpose of the flat plate elimination test is to determine the boundary layer displacement thickness δ^* at the end of the wind tunnel acceleration at the given test conditions [3]. The quantities that are necessary for calculating δ^* are presented in Table 4-1. A method for obtaining δ^* from these quantities is presented in this chapter. The values of δ^* have been found to correlate with the loss of lift on an actual airplane and an acceptance criteria has been developed on this basis [2, 3].

AS5900 sets limits on the allowable δ^* values as a function of temperature. Since the wind tunnel at the Aalto University is not cryogenic the temperatures of the fluid, model surface and air can be different from each other. However, the closer they are, the more the test conditions resemble a cryogenic tunnel. Time when the acceleration is finished can be obtained when the flow velocity as a function of time is known. Fluid flow-off is calculated from the measured amount of fluid spread on the model and the amount of fluid remaining on the surface after the run. Fluid remnants in the containers are also taken into account.

The displacement thickness can be calculated either at station 2 or at station 3. If δ^* at station 3 is to be calculated then $p_1 - p_2$, w_2, h_2 and s_2 are not needed. This is the case in the following presentation. To calculate δ^* at station 2 the quantities with subscript 3 are replaced by quantities with subscript 2. The measured values of w, h and s are used, not the design values.

Table 4-1 The quantities that are necessary to calculate δ^*.

q_1	Kinetic pressure at station 1
$p_1 - p_2$	Difference of static pressures at stations 1 and 2
$p_1 - p_3$	Difference of static pressures at stations 1 and 3
U	Tunnel flow velocity
q	Tunnel kinetic pressure
w_2	Duct width at station 2
w_3	Duct width at station 3
h_2	Duct height at station 2
h_3	Duct height at station 3
s_2	Duct perimeter at station 2
s_3	Duct perimeter at station 3

In the following an incompressible flow is assumed, therefore the dynamic and kinetic pressures can be assumed equal so that $q_{c1} = q_1$. The flow is assumed to be non-viscous outside the boundary layer and the effect of the boundary layer is accounted for using its displacement thickness $\delta*$. According to the Bernoulli's equation the total pressure remains unchanged from station 1 to station 3:

$$p_1 + \frac{1}{2}\rho U_1^2 = p_3 + \frac{1}{2}\rho U_3^2 \tag{4-2}$$

Solving for U_3 yields the following equation:

$$U_3 = \sqrt{\frac{2}{\rho}\left(p_1 - p_3\right) + U_1^2} \tag{4-3}$$

The kinetic pressures at station 1 and at the tunnel test section entrance are known so the flow velocity U_1 can be calculated:

$$U_1 = U\sqrt{\frac{q_1}{q}} \tag{4-4}$$

Next, density can be solved:

$$\rho = \frac{2q_1}{U_1^2} \tag{4-5}$$

Combining Equations 4-3 and 4-5 yields:

$$U_3 = \sqrt{U_1^2\left(\frac{1}{q_1}\left(p_1 - p_3\right) + 1\right)} \tag{4-6}$$

Combining Equations 4-4 and 4-6 finally yields:

$$U_3 = U\sqrt{\frac{1}{q}\left(p_1 - p_3\right) + 1} \tag{4-7}$$

In accordance with Equation 4-8, the difference between velocities U_1 and U_3 results from the difference between effective areas A_1 and A_3 in which $\delta*$ is accounted for:

$$A_3 = A_1\frac{U_1}{U_3} \tag{4-8}$$

At station 1 $\delta*$ is assumed to be zero and at station 3 the average displacement thickness $\delta*_{ave}$ is used.

$$A_1 = w_1 h_1 \tag{4-9}$$

$$A_3 = \left(w_3 - 2\delta_{ave}^*\right)\left(h_3 - 2\delta_{ave}^*\right) \tag{4-10}$$

Effective area A_3 is solved from Equations 4-4 and 4-7 to 4-9:

$$A_3 = w_1 h_1\sqrt{\frac{q_1}{(p_1 - p_3) + 1}} \tag{4-11}$$

$\delta*_{ave}$ can then be solved from Equation 4-10:

$$\delta^*_{ave} = \frac{2\left(w_3 + h_3\right) \pm \sqrt{\left(-2\left(w_3 + h_3\right)\right)^2 - 16\left(w_3 h_3 - A_3\right)}}{8} \qquad \text{4-12}$$

The value obtained from Equation 4-12 with the plus sign is clearly physically impossible and is, therefore, rejected. Finally, the boundary layer displacement thickness at the fluid-covered duct floor δ^*_f can be obtained from equation

$$\delta^*_f = \frac{s_3}{w_3}\left(\delta^*_{ave} - \left(\frac{s_3 - w_3}{s_3}\right)\delta^*_d\right) \qquad \text{4-13}$$

where δ^*_d is the dry duct displacement thickness obtained from the calibration runs [3]. In a dry case it is assumed that the boundary layer thickness is equal on all surfaces and, therefore, δ^*_d can be calculated using Equation 4-12.

4.2.1 Example of Results Obtained in Spring 2012

During the assembly of the duct it was found to be difficult to achieve the designed dimensions. Duct widths and heights measured after the assembly are presented in Table 4-2. The width was measured at the level of the ceiling and the height on the both sides at six locations. Distance from the duct test section entrance is denoted by x.

Table 4-2 Measured width and height of the FPET duct.

x [mm]	Width [mm]	Height left / right [mm]
0	599	201 / 201
450	601	202 / 202
890	601	205 / 203
930	601	205 / 203
1300	602	205 / 203
1760	600	205 / 204

A calibration run was performed and dry δ^* values in a range of 1.3 – 1.6 mm at a velocity range of 58 – 63 m/s were observed. Then 1.7 litres of type IV fluid was spread on the model surface. Fluid and surface temperatures and fluid remnants in the containers were not measured in this test. The air temperature at the start of the tunnel run was 16.0 °C and the relative humidity 38.6 %. After the tunnel run a total 0.175 litres of fluid was collected from the model surface.

The tunnel was accelerated with the control voltage shown in Figure 3-9 in both the calibration run and the type IV fluid test. The fluid flowing off the tank surfaces flows into the diffuser and disturbs it, therefore, the maximum duct flow velocity in the fluid test is significantly less than in the calibration run. In this test the velocities at station 1 were 63 m/s in the fluid test and 69 m/s in the calibration run. Flow velocity as a function of time in the fluid test is presented in Figure 4-5.

At the end of the tunnel acceleration the δ^*_f values in a range of 8 – 11 mm were obtained. There is a large difference compared to values of δ^*_d so the effect of the fluid is clearly visible in the results. Results of the test are presented in Table 4-3. The δ^*_f values are in accordance with those obtained with an AS5900 specified duct [9].

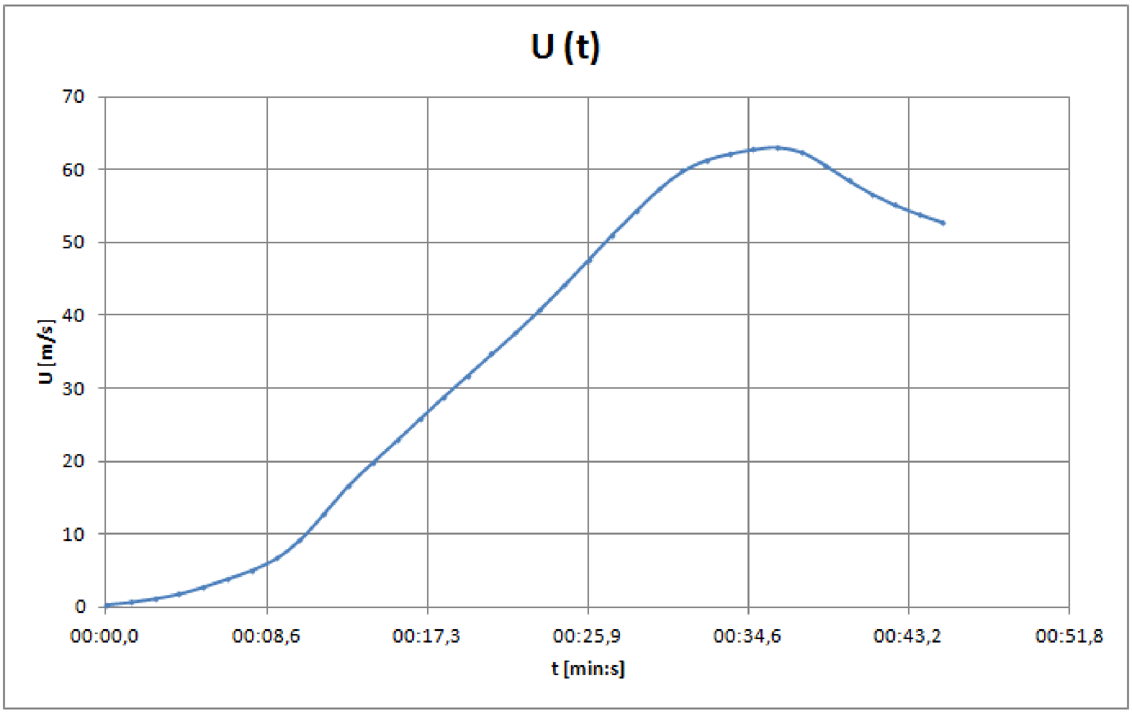


Figure 4-5 Velocity at station 1 as a function of time in a flat plate elimination test with a type IV fluid.

Table 4-3 Displacement thickness δ^*_f as a function of flow velocity in a flat plate elimination test with a type IV fluid.

U_1 [m/s]	δ^*_f [mm]
51.1	13.8
54.3	13.0
57.4	12.4
59.8	11.4
61.4	10.7
62.2	10.2
62.8	9.8
63.1	9.2
62.5	8.5
60.7	7.8
58.5	7.3

4.3 Variable AOA Model Test Results

The most important result of the variable AOA model test is the lift coefficient as a function of time during the simulated takeoff run. The C_L is affected by the parameters describing the anti-ice treatment conducted before the test run. The parameters are the type and the amount of fluid spread on the model, the fluid temperature before and during the test run and the fluid thickness before the run.

In addition the fluid flow-off is calculated and the flow-off mechanism can be determined with a procedure similar to the one used in the fixed AOA model test. To calculate the flow-off it is necessary to know the amount of fluid spread on the model, the fluid run-off before the wind tunnel run, and the amount of fluid remaining on the surface after the run. Fluid remnants in the containers are also taken into account. To determine the flow-off mechanism the scripts developed for the fixed AOA model can be used if small modifications are made.

The model surface temperature and the air temperature and the humidity are measured since they affect the fluid temperature. They can also be used to judge whether the test conditions correspond to the conditions at which de- and anti-icing fluids are used in reality. Flow velocity as a function of time affects fluid flow-off and should be similar to take-off acceleration of a transport airplane.

To estimate the effect of wind tunnel corrections, the correction procedure determined for the Aalto University subsonic wind tunnel was applied on results obtained from a variable AOA model test [13]. The effect of corrections on lift was observed to be minimal and therefore no corrections are necessary when the test results are processed. In case that drag and pitching moment are to be measured the necessity of the corrections has to be re-estimated. However, it is worth noting that the tunnel walls increase the effective camber of the model and, therefore, a larger angle of attack is required to achieve a given C_L value in a free flow situation than in a wind tunnel. This effect is not given further consideration in this report.

An important correction required in the result processing is the difference between the measured and actual angles of attack at velocities higher than 25 m/s. The error is caused by the bending of the horizontal beam fitted between the endplates and connected to the vertical beam which is used to adjust and measure the angle of attack. The bending is caused by the aerodynamic moment acting on the model. The required correction $\Delta\alpha$ as a function of the moment M_y is presented graphically in Figure 4-6. The equation of the linear trendline fitted on the results is

$$\Delta\alpha = 0.0079 M_y - 0.0043 \qquad \text{4-14}$$

The graph and the Equation 4-14 are valid when the middle suspension point of the model is used to fix the model on the balance!

To study the effect of anti-icing fluid on C_L a reference case with no fluid applied is required. The reference case is a takeoff run simulation similar to the fluid test to account for the unsteady aerodynamic effects caused by the accelerating flow and the change of the angle of attack. The effect of fluid is determined by simply comparing the C_L values obtained in a fluid test to those of the reference case.

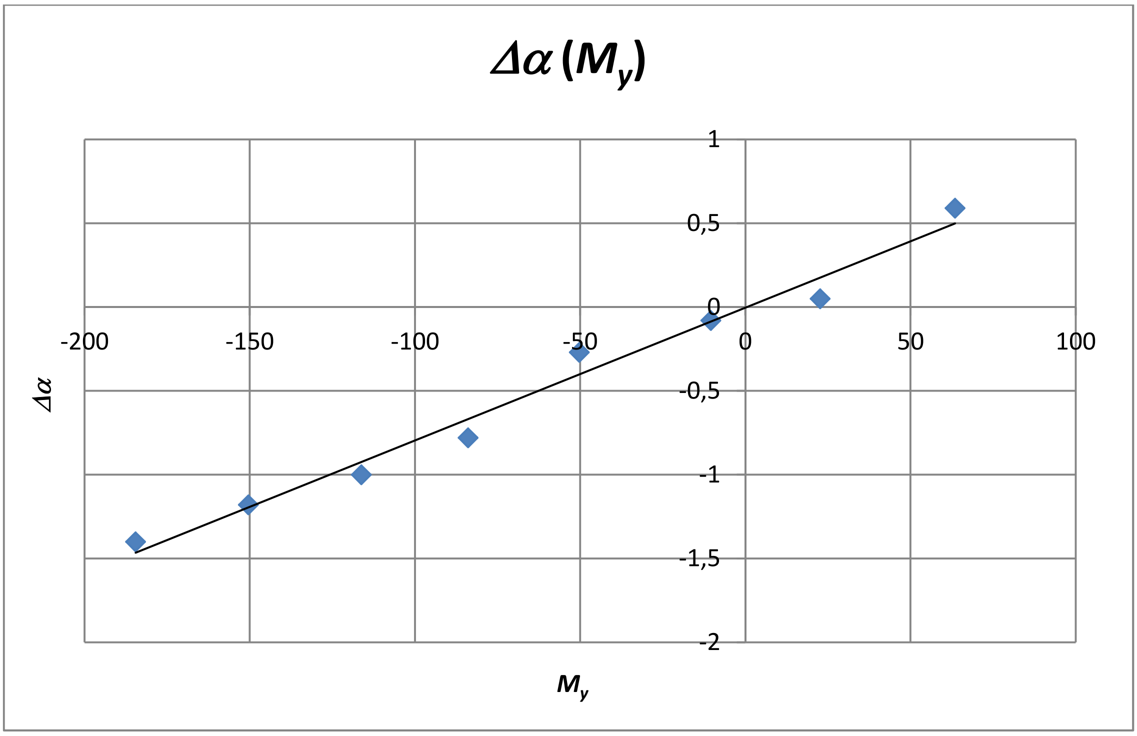


Figure 4-6 **The angle of attack correction $\Delta\alpha$ as a function of the aerodynamic moment M_y.**

4.3.1 Example of Results Obtained in Spring 2013

The initial test runs with the variable AOA model were performed to obtain the steady state C_L as a function of the angle of attack with several different slat and flap settings. With a slat setting of 11 degrees and a flap setting of 5 degrees the desired C_L values of 0.60 (takeoff run) and 1.30 (initial climb after rotation) were obtained at angles of attack of 1.0 and 7.5 degrees, respectively. In a free flow situation, angles of attack of 2.6 and 10.7 degrees, respectively, would be required to obtain the stated C_L values. These settings were selected as the takeoff configuration. The results of a test run in this configuration are presented in Figure 4-7. The tunnel flow velocity was 25 m/s corresponding to a Reynolds number of approximately 10^6.

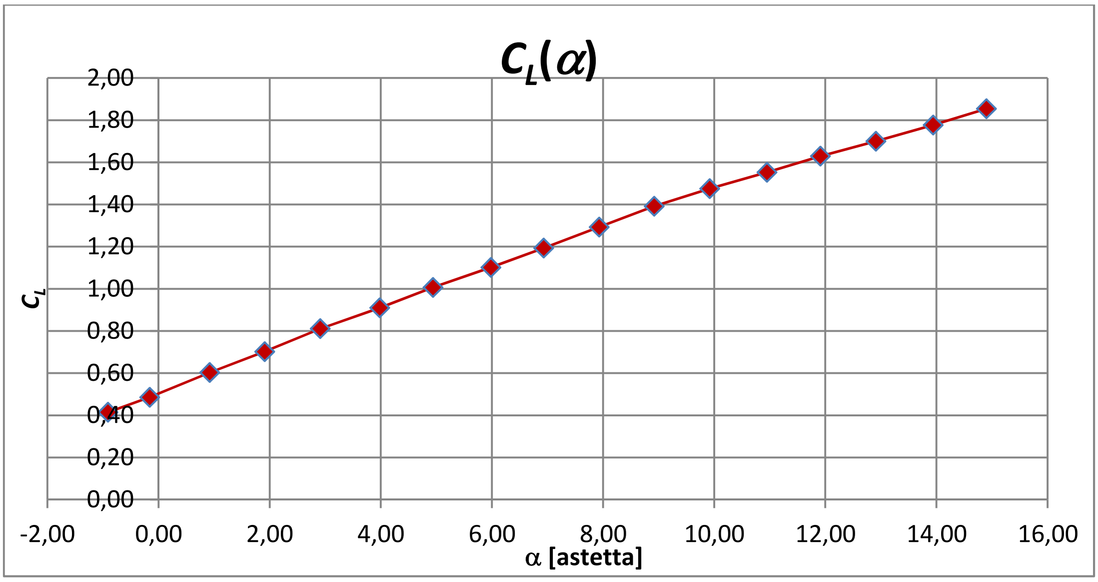


Figure 4-7 Lift coefficient as a function of the angle of attack at *Re* = 10^6.

Next, reference tests and fluid tests were performed. In the example case, a total 2.0 litres of type IV fluid was spread on the model surface. The tunnel was accelerated using the script presented in Appendix C for faster acceleration. The resulting flow velocity as a function of time is presented in Figure 4-8. The lift coefficient measured during the example case, as well as C_L measured at a reference test, are presented as a function of time in Figure 4-9.

The C_L value immediately after the rotation is complete is 1.20 in the example test and 1.28 in the reference test. The difference is 6.25 %, which is greater than the maximum acceptable lift loss of 5.24 %. The acceleration time of 25 seconds is shorter than the one used in the certification test. However, the time is realistic for an Airbus A321 when full takeoff thrust (TOGA thrust) is used.

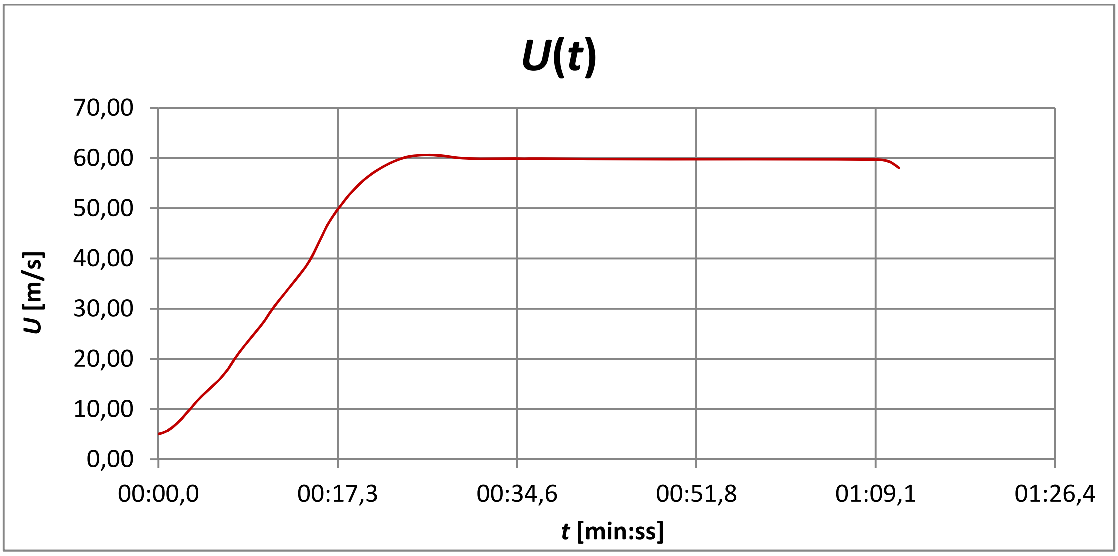


Figure 4-8 **Velocity as a function of time in the example variable AOA model test.**

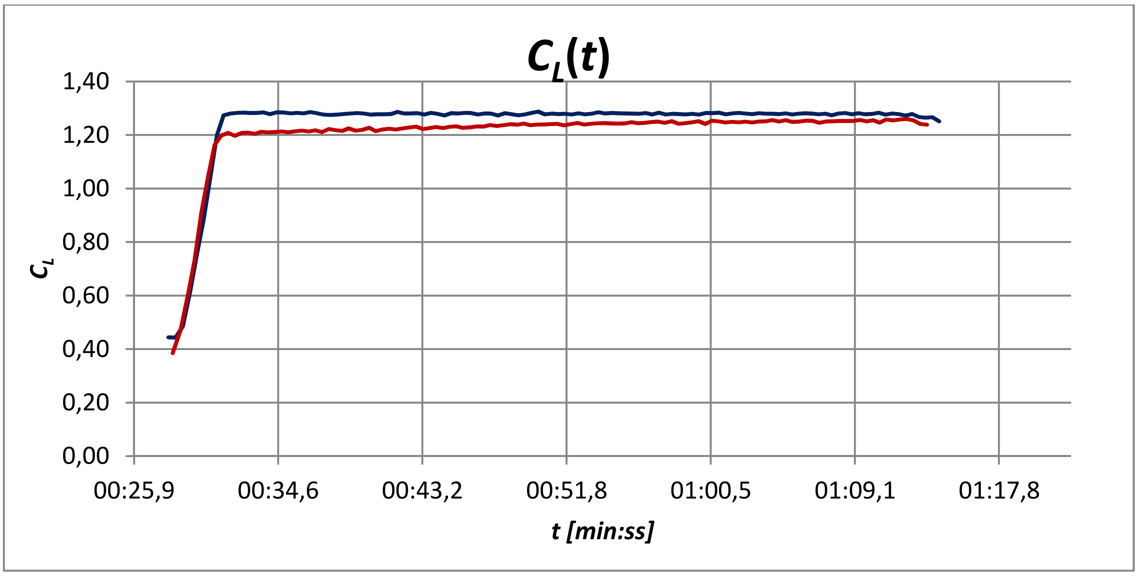


Figure 4-9 **Lift coefficient as a function of time in the example variable AOA model test in red and in the reference test in blue.**

4.3.2 Error Analysis

The lift coefficient C_L is calculated using equation

$$C_L = \frac{L}{q_c S} \qquad \text{4-15}$$

when the dynamic pressure q_c and the Z-directional force $F_Z = L$ are measured. Therefore, error in the C_L results is caused by the error in the measurement of q_c and F_Z. The error sources related to the tunnel flow quality are negligible and not considered in this report.

The q_c measurement error is caused by the pitot tube misalignment error, the error in the pressure transducer and the error in the measurement of the output voltage of the transducer. The effect of pitot tube misalignment is small: As long as the angle between the flow and the tube axis is smaller than 5 degrees, the error is approximately 0.1 % of the result. The pressure transducer error is stated as ±1 Pa at coverage factor 1. The effect of voltage measurement error is negligible and not considered further. Therefore, the error in the q_c measurement is

$$\Delta q_c = q_c \sqrt{\left(\frac{\pm 1Pa}{q_c}\right)^2 + 0.001^2} \ . \qquad \text{4-16}$$

Increasing the coverage factor to 3 to obtain a level of confidence greater than 99 %, the following equation for Δq_c is obtained:

$$\Delta q_c = 3q_c \sqrt{\left(\frac{\pm 1Pa}{q_c}\right)^2 + 0.001^2} \qquad \text{4-17}$$

The total error in the F_Z measurement has been specified as

$$\Delta F_Z = 0.2 \pm 0.0005 F_Z \ . \qquad \text{4-18}$$

Finally, Equation 4-15 is modified to take into account the errors Δq_c and ΔF_Z:

$$C_L = \frac{F_Z \pm \Delta F_Z}{(q_c \pm \Delta q_c)S} = \frac{F_Z(1 \pm 0.0005) + 0.2}{q_c S\left(1 \pm 3\sqrt{\left(\frac{\pm 1Pa}{q_c}\right)^2 + 0.001^2}\right)} \qquad \text{4-19}$$

To calculate the error ΔC_L the values of q_c and F_Z have to be specified. The most illustrative way to do this is to calculate ΔC_L during the example variable AOA model test presented in Chapter 4.3.1. Using this method, it is realised that ΔC_L decreases with increasing flow velocity, even though F_Z at the numerator of Equation 4-19 increases proportionally to U^2. For $q_c > 400$ Pa (corresponding to $U > 25$ m/s) the error $|\Delta C_L| < 0.005$ and is therefore not visible in the results presented using two decimal number accuracy.

The most important results of the variable AOA model test are obtained immediately after completing the rotation. The corresponding values of q_c and F_Z are approximately 2300 Pa and 2800 N, respectively. The yields a $|\Delta C_L|$ of approximately 0.0025.

5 Summary

In this work, three wind tunnel test set-ups to study the effects of de- and anti-icing fluids on transport airplane takeoff performance were designed and implemented on the Aalto University subsonic wind tunnel. The set-ups are to be utilized in a research project funded by the Transport Safety Agency Trafi. The objectives of that project are to study the fluid flow-off mechanism and to measure the loss of lift caused by the fluid during a takeoff acceleration and rotation of a transport airplane. In addition the measured reduction of the lift coefficient caused by the fluid is compared with the results obtained by a flat plate elimination test similar to the one used for certification of the fluids. This report provides a description of the necessary wind tunnel models, the setting up of the test equipment, performing the tests and processing the results. The detailed step-by-step instructions are documented in the appendices.

For determining the fluid flow-off mechanism a relatively large airfoil model built for an earlier project was utilized to minimize scale effects. However, since this model could not be fitted on the wind tunnel balance to measure the aerodynamic forces a smaller model was also required. This was designed to be representative of a modern transport airplane wing profile equipped with a slat and a flap. Furthermore, a flat plate elimination test duct was designed on the basis of SAE Aerospace Standard AS5900, but with the dimensions largely modified to ensure the compatibility of the duct with the Aalto University wind tunnel.

To observe the flow-off mechanism of the fluid a method for determining the fluid thickness from a video recorded during a test run was developed. In the method the relationship between the fluid thickness and the R and B colour model values is first obtained using a calibration plate. Screenshots of the video are the analysed and the corresponding fluid thicknesses are calculated. Fluid thicknesses measured before the start of the test run together with a screenshot of the same moment are also needed for correcting the effects of the camber of the model surface and the differences in lighting conditions.

A number of fluid tests were conducted with two test set-ups, the large fixed AOA model and the flat plate elimination test, to evaluate the set-ups and the result processing methods. It was concluded that the method for calculating the fluid thickness from the screenshots provides reasonably accurate results. Also in the flat plate elimination test the effect of fluid on boundary layer displacement thickness was observed to be comparable to the values obtained with an AS5900 specified duct despite the different dimensions. The third test set-up with the balance-fitted airfoil model was finished during the warm autumn months and therefore no testing with anti-ice fluid could be reasonably performed.

Future improvement should be carried out on the thickness determination scripts, the lighting of the wind tunnel in the fixed AOA model test and the fluid spreading methods. In the present form the thickness determination scripts are enough to validate the applicability of the method based on R and B values, but for a more regular use the required user input could well be reduced. A more even lighting of the wing profile would reduce the effect of the correction factor on the final results obtained with the scripts. Accuracy of the results would be improved, especially for a thin fluid layer. Additionally, the spreading methods for which instructions are given in this report are slow to apply and their ability to produce repeatable results is limited. More tests per day with more consistent starting fluid thickness values could be conducted if a better method was developed.

6 References

[1] OPS Part 1: Commercial Air Transportation (Aeroplanes), Commission Regulation (EC) No 8/2008, Availability as of August 2012: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:254:0001:0238:EN:PDF

[2] Zierten, T., Hill, E.G., Hoefs, K.W., Aerodynamic Acceptance Test for Aircraft Ground De/Anti-icing Fluids, Report D6-55573, Boeing Company, Renton Division Aerodynamics Engineering, 1992.

[3] SAE Aerospace Standard AS5900, Revision B, 2007.

[4] Beisswenger, A., Fortin, G., Laforte, J.L, Investigation of Type II and Type IV Aircraft Ground Anti-icing Fluid Aerodynamic Certification Standards, Report DOT/FAA/AR-03/55, Federal Aviation Administration, Office of Aviation Research, Washington, D.C., 2003.

[5] Possible Effects of Thickened Anti-icing Fluids on Take off Rotation for Airplanes with Unpowered Elevator Controls, EASA Safety Information Bulletin No: 2010-28, Availability as of August 2012: http://ad.easa.europa.eu/ad/2010-28

[6] Bastian, M., Hui, K., Lift-loss Due to the Presence of Anti-icing Fluid on a Falcon 20 Aircraft in Out-of-ground effect conditions, Report TP 14184E, Transport Canada, Transportation Development Centre, Montreal, 2004. Availability as of August 2012 (Abstract only): http://trid.trb.org/view.aspx?id=745510

[7] Rinne, A., Design of Airplane Wing Anti-icing Fluid Tests in Wind Tunnel, Report T-298, Aalto University, Aerodynamics Research Group, 2012 (not published).

[8] Fagerström, B., Preliminary Report on Wind Tunnel Simulation of Take-off Runs with Anti-ice Covered Aerofoil , Report 84-11, Series T, Helsinki University of Technology, 1984 (not published).

[9] Laforte, J. L., Louchez, P.R., Bouchard, G., Experimental Evaluation of Flat Plate Boundary Layer Growth Over an Anti-icing Fluid Film, Canadian Aeronautics and Space Journal, Vol. 39, No.2, 1993.

[10] Schlichting, H., Boundary Layer Theory, 4th edition, McGraw-Hill Book Company, 1960.

[11] Blevins, R. D., Applied Fluid Dynamics Handbook, Krieger Publishing Company, 1992, ISBN 0-89464-717-2.

[12] Wild, J., Experimental Investigation of Mach- and Reynolds-number Dependencies of the Stall Behaviour of 2-element and 3-element High-lift Wing Sections, AIAA 2012-0108, AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, Nashville, Tennessee, 2012.

[13] Sailaranta, T., TKK:n piennopeustuulitunnelissa käytettävä tunneli-interferenssin korjausmenettely, Muistio No MP-84-90, Helsinki University of Technology, 1990 (in Finnish, not published).

Appendix A. Fixed AOA Model Test Procedures

Model installation

1. Place a bracket shown in Figure A-1 inside the tunnel on both walls and fasten it to the beam on the other side of the tunnel wall.
2. Place the wing spar of the model on the bracket as shown on Figure A-2.
3. Fasten the rear attachment point located 840 mm behind the spar directly to the tunnel wall.

Figure A-1 Bracket placed on the tunnel wall next to the access door.

Figure A-2 Wing spar of the model placed on and fastened to the bracket. A thermocouple line led out of the model through the spar is also visible.

Preparing for the test

1. Take the type IV fluid to the freezer if required by the test specification.
2. Weigh all the containers that are used to handle the fluid.
3. Place the fluid temperature measurement thermocouples in position on the model. It is essential to install them so that the highest point is no more than 1 mm above the model surface, otherwise they measure air temperature instead of fluid.
4. Lead the lines of the thermocouples out of the model through the spar. There is a hole in the tunnel wall close to the spar attachment through which the lines can be led from the tunnel, as visible in Figure A-2.
5. Connect the thermocouples to the DAQ controlled by “Icewing.vi”. Alternatively connect the thermocouples to multimeters through appropriate amplifiers and proceed to step 7.
6. Set the DAQ channels to be used, the input terminal configuration, the minimum and maximum input values and scan rate at page 1 of the user interface of the program. Set the coefficients of the channels at page 2 of the user interface.
7. Place the indicator LED on the test section ceiling close to the border of the area that is visible in the video. Connect it to one of the digital output ports of the DAQ.
8. Open page 1 of the user interface of “Icewing.vi”. Specify the DAQ port to which the LED is connected from dropdown menu “Lediportti”.
9. Enter the file path of the results file at “Tulostiedosto” on page 3 of “Icewing.vi” user interface.
10. Set the clocks of the computer running the program “Alisoonisen mittausohjelma.vi” and the computer running the program “Icewing.vi” to the same time. <u>This must be checked at the start of every test!</u>
11. Fill the coolant tank with a water-glycol solution, the mixture ratio of which depends on the temperature at which the test is conducted. Freezing points for three different solutions are given in Table A-1.

Table A-1 Freezing points of different water-glycol solutions [13].

Glycol [weight %]	40 %	45 %	50 %
Freezing point [°C]	-22	-28	-35

12. Take the coolant tank to the freezer at the third floor of the K4 building. When selecting the target temperature for cooling, consider that the temperature of the coolant and the tank always rises during the transportation to the tunnel.
13. Place in position the camera that records the flow-off mechanism. Above the test section ceiling window is an I-beam, to which a camera stand is fitted. The camera position in the tunnel longitudinal direction and the angle between the window and the camera recording area can be adjusted with the stand. In the tunnel transverse direction the camera position is adjusted by moving the stand.
14. Take the coolant tank back into the wind tunnel and install it. It is recommended that the gap between the tank rear edge and the fixed part of the model is sealed to reduce the amount of fluid flowing into the structure of the model.

15. Spread the type IV fluid on the calibration plate so that the fluid surface is on the top level of the grooves and the fluid layer thickness corresponds to the groove thickness. It is important to check that no more fluid is spread than what is the capacity of the grooves, otherwise the calibration fails. There should be no fluid on the areas next to the grooves.
16. Place the calibration plate on the model surface on the position of maximum thickness and shoot a video of the plate. Then remove the plate and shoot another video of the empty model surface. The duration of these videos needs not be more than a couple of seconds. Note that that the lighting conditions in these videos have to be similar to the video shot during the wind tunnel run. Switch off the lights of the tunnel hall if necessary.
17. If a solution of type I fluid and water is to be used in the test, prepare the mixture of these.
18. Measure the amounts of both types of fluid to be used with a scale-equipped jug. Place the fluids to the cans from which they are spread. It is forbidden to handle type I and type IV fluids on the same containers, since this will alter the qualities of type IV fluid and therefore cause misleading results from the test. For the same reason the containers used with type IV fluid must be dry before the fluid is placed in.
19. Measure the surface temperature of the model with an infra-red probe at the 60 positions marked on the model surface.
20. Place the containers that collect the run-off fluid on the tunnel floor at the leading and trailing edges of the model.

Spreading of the fluid

1. The spreading process depends on whether only type IV fluid or both type I and type IV fluids are to be used. If only type IV is used, start from step 2. If both types are used, start from step 11.

2. If frost has formed on the model surface scratch it off with a plastic spattle. Do not use a metallic one since it will damage the paint.
3. It is recommended that a small amount of fluid, approximately 0.05 litres, is saved for later corrections of the fluid layer.
4. Fluid is to be spread on the 600 mm wide area marked clearly on the model surface with points A and E. Whole chord of the model is to be covered with fluid. However, start the spreading on the area between 0 – 0.65*c*.
5. In the area behind 0.65*c* where the surface folds downwards the fluid spreads by pouring, therefore place all the fluid intended for this area at 0.65*c* immediately behind the gap on the rear edge of the coolant tank.
6. Even the surface with a plastic spattle. The best method has been observed to be to tap the spattle on the surface simultaneously when sliding it. The small grooves that are thus formed on the fluid layer flatten in a short time due to the surface tension of type IV fluid.
7. In the rear area of the surface keep the edge of the fluid layer straight and keep the fluid on the desired area as it pours toward the model trailing edge.

8. The small amount of fluid that was saved earlier may now be used on areas that cannot be smoothed using the spattle.
9. Measure fluid thickness with an Elcometer at the 60 positions marked on the model surface.
10. Measure surface temperature at the 60 positions marked on the model surface.

11. If frost has formed on the model surface it must not be scratched off, since the type I fluid washes it away as it does when a real airplane is de-iced.
12. It is recommended that a small amount of fluid, approximately 0.05 litres, is saved for later corrections of the fluid layer.
13. Pour type I fluid on the 600 mm wide area marked clearly on the model surface with points A and E. Whole chord of the model is to be covered with fluid and enough fluid must be used to wash the surface clear of frost. Type I fluid spreads easily due to its low viscosity.
14. Also the type IV fluid is to be spread on same 600 mm wide area and whole chord of the model is to be covered with fluid. However, start the spreading on the area between 0 – 0.65*c*.
15. In the area behind 0.65*c* where the surface folds downwards the fluid spreads by pouring, therefore place all the fluid intended for this area at 0.65*c* immediately behind the gap on the rear edge of the coolant tank.
16. Even the fluid layer by running the wind tunnel at a speed of approximately 10 m/s for five minutes. The different types of fluids must not be intentionally mixed since this does not happen on a real application of de- and anti-icing fluid so <u>do not even the fluid with a spattle.</u>
17. The small amount of fluid that was saved earlier may now be used on areas that have not been smoothened by the airflow.
18. Measure fluid thickness at the 60 positions marked on the model surface.
19. Measure surface temperature at the 60 positions marked on the model surface.

Performing the test

1. In case a takeoff run is to be simulated in the test, the tunnel is controlled by the control voltage ramp function in "Alisoonisen varakäyttöohjelma.vi". In the ramp used in this test the variation of voltage against time can be divided into five parts:
    a. On the first part, the voltage is increased linearly from zero to 0.588 V during 8.7 seconds.
    b. On the second part, the voltage is increased to 4.488 V between 8.7 and 49.7 seconds, according to equation

    $$V = 0.001725t^2 - 0.0055t + 0.5$$

    c. At 49.8 seconds the voltage is increased to 4.9 V. The voltage is then reduced linearly to 4.0 V between 49.9 and 54.7 seconds.
    d. Between 49.8 and 62.7 seconds the voltage is reduced linearly to 2.0 V.

e. Between 62.8 and 112.7 seconds the voltage is reduced linearly to zero.

Enter this ramp into “Alisoonisen varakäyttöohjelma.vi”.

2. In case a taxiing airplane is simulated in the test, the speed control can be performed manually and no control voltage ramp is required.

3. Weigh all the containers that were used to measure or spread the fluid to obtain the amount of fluid that was left in them.
4. Remove from the tunnel the containers collecting the run-off fluid and measure their weight.
5. Switch off the lights of the tunnel hall.
6. Switch on the camera which records the flow-off mechanism.
7. Click the button “Mittaus ja tallennus POIS” in page 3 of “Icewing.vi” user interface to switch on the LED and also the recording of fluid temperature if the two thermocouples are connected to the DAQ. The text on the button should then become “Mittaus ja tallennus PÄÄLLÄ”.
8. If the two thermocouples are connected to the multimeters switch on the camera recording their displays.
9. Perform the wind tunnel run.
10. When the wind tunnel run is finished, switch off all cameras.
11. Click the button “Mittaus ja tallennus PÄÄLLÄ” on Icewing.vi user interface to switch off the LED and also the recording of fluid temperature if the two thermocouples are connected to the DAQ. The text on the button should change to “Mittaus ja tallennus POIS”.
12. Copy the file to which “Icewing.vi” saves the results. The time on the first row of the file is when the LED was light up.
13. Measure fluid thickness at the 60 positions marked on the model surface.
14. Measure surface temperature at the 60 positions marked on the model surface.
15. Scrape the remaining fluid to a clean scale-equipped jug and read the volume of the fluid remnant.
16. Measure surface temperature at the 60 positions marked on the model surface.

Appendix B. Flat Plate Elimination Test Procedures

Model installation

1. Fill the six coolant tanks with a water-glycol solution, the mixture ratio of which depends on the temperature at which the test is conducted. Freezing points for three different solutions are given in Table A-1. Each tank has two openings, the larger of which is intended for filling the tank and the smaller for airing and connection to the expansion tank.
2. Take the coolant tanks to the freezer at the third floor of the K4 building. When selecting the target temperature for cooling, consider that the temperature of the coolant and the tank always rises during the transportation to the tunnel.
3. Place the frame on the tunnel. Take the coolant tanks back into the tunnel and lift them on their position. The two tanks fitted with a small plate on the middle of one side are placed as the leftmost and the rightmost tanks so that the plate faces to the tunnel wall.
4. Attach the front end of each coolant tank to the frame using a spigot.
5. Press the coolant tanks on each other using the screws placed on both sides of the middle oval tube marked with red arrows on Figure B-1.
6. Fasten the sidewalls on the frame.

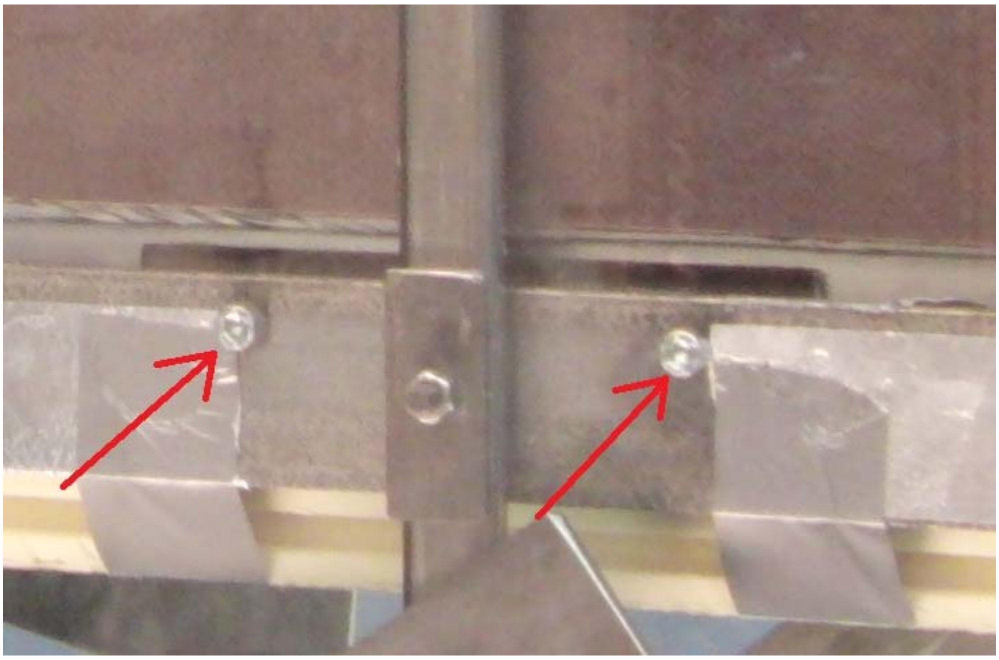


Figure B-1 **Screws placed on both sides of the middle oval tube used to press the coolant tanks on each other.**

7. Find the positions on the tunnel floor on which the vertical oval tubes of the frame have to be fastened to force the duct into the correct dimensions. Sidewall straightness and the duct width at both of its ends have to be observed. Adjust sidewall straightness between the points at which they are fastened to the frame with screws placed outside of the wall as shown in Figure B-2. Recommended starting values for distances between the oval tube lower ends are given in Figure

B-3, however the final adjustment must be based on the measured dimensions of the duct.

Figure B-2 **Screws placed on an L-beam that are used to straighten the sidewalls.**

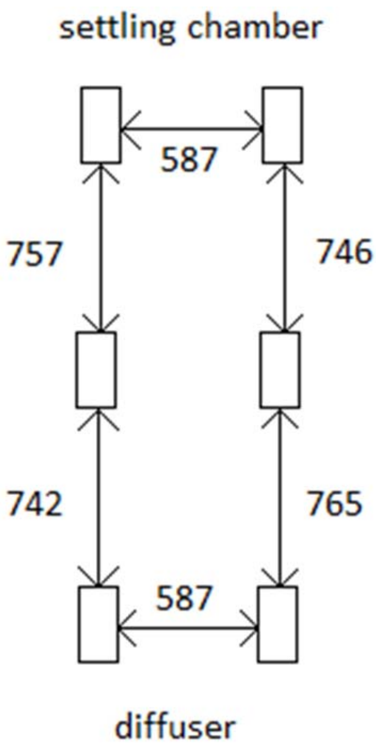


Figure B-3 **Rectangles represent the plates fitted to the lower ends of the oval tubes. Recommended starting values for distances between the plates are marked next to the corresponding line in millimetres.**

8. Install the expansion tank, fill it with the appropriate amount of fluid and connect it to the six coolant tanks. Use hoses that are long enough so that the expansion tank can be placed outside the tunnel.
9. Fit the nozzle and the diffuser on their positions. Seal all the resulting gaps with aluminium tape.
10. Fasten an 1800 mm × 600 mm plate of insulating material below the coolant tanks.
11. Measure the final values of width and height of the duct at stations 1, 2 and 3 when the assembly is finished. Values presented in Table 4-2 can be referred to as an example of acceptable difference between the real and nominal dimensions.

Preparing for the test

1. Take the type IV fluid to the freezer if required by the test specification.
2. Weigh all the containers that are used to handle the fluid.
3. Place the air temperature measurement thermocouple to station 1 approximately 5 mm below the ceiling and off the centreline so that it does not disturb the static pressure measurement. (Refer to station definitions in Figure 3-6.)
4. Place the fluid temperature measurement thermocouple to the rear edge of the coolant tanks at the tank centreline. The sensor must be no more than 1 mm above the tank upper surface, otherwise it measures air temperature instead of fluid.
5. Connect the thermocouples to the DAQ controlled by the program “Icewing.vi”. Alternatively connect the thermocouples to multimeters through appropriate amplifiers and proceed to step 9.
6. Set the DAQ channels to be used, the input terminal configuration, the minimum and maximum input values and scan rate at page 1 of the user interface of the program. Set the coefficients of the channels at page 2 of the user interface.
7. Enter the file path of the program results file at “Tulostiedosto” on page 3 of “Icewing.vi” user interface.
8. Set the clocks of the computer running the program “Alisoonisen mittausohjelma.vi” and the computer running the program “Icewing.vi” to the same time. <u>This must be checked at the start of every test!</u>
9. Connect the pressure transducers to the data logger at the wind tunnel hall.
10. Connect the hoses on the transducers and lead them to the wind tunnel through the opening slightly upstream from the access door. The pressures are measured as follows:
    a. Total pressure at station 1 (measured with the pitot tube) and static pressure at station 1 are connected to the 3 kPa transducer. Dynamic pressure q_{c1} is obtained.
    b. Static pressure at station 1 and either static pressure at station 2 or at station 3 are connected to the 1 kPa transducer. Static pressure difference $p_1 - p_2$ or $p_1 - p_3$ is obtained.
11. If a solution of type I fluid and water is to be used in the test, prepare the mixture of these.
12. Measure the amounts of both types of fluid to be used with a scale-equipped jug. Place the fluids to the cans from which they are spread. <u>It is forbidden to handle type</u>

I and type IV fluids on the same containers, since this will alter the qualities of the type IV fluid and therefore cause misleading results from the test. For the same reason the containers used with type IV fluid must be dry before the fluid is placed in.

13. Measure the coolant tank surface temperature with an infra-red probe at the 60 positions marked on the surfaces.
14. Before any fluid testing is conducted, tests with a dry duct have to be performed to obtain the boundary layer displacement thickness in a duct without fluid. This test has to be repeated also after the fluid tests. Perform the test with a dry duct by skipping the instructions on the part “Spreading of the Fluid”. Then proceed to fluid testing.

Spreading of the fluid

1. A flat plate elimination test is normally performed for a type IV fluid. At the time of this writing, type I fluids have not been tested at the Aalto University FPET duct and therefore no instruction for that is given. The following steps are valid for spreading of type IV fluid.
2. If frost has formed on the tank upper surfaces scratch it off with a plastic spattle. Do not use a metallic one since the aluminium surface may be damaged.
3. Spread the fluid mainly on the upstream area of the duct floor. The fluid layer has to be of uniform thickness in the transverse direction.
4. Run the tunnel at a velocity of approximately 10 m/s which causes the fluid to move slowly towards the downstream area of the duct. Direct the flow by moving a small plate over the fluid layer which causes an increase in flow velocity in the area immediately below the plate.
5. Correction of the fluid layer with a spattle can be attempted though it probably requires an extensive amount of time. Follow the instructions given in Appendix A, part Spreading of the Fluid, step 6.
6. Measure fluid thickness with an Elcometer at the 60 positions marked on the model surface.
7. Measure coolant tank surface temperature at the 60 positions marked on the model surface.

Performing the test

1. The tunnel is controlled by the voltage ramp function in “Alisoonisen varakäyttöohjelma.vi”. In the ramp used in this test the variation of voltage against time can be divided into six parts:
   a. On the first part, the voltage is increased linearly from zero to 0.600 V during 15.0 seconds.
   b. At 15.1 seconds the voltage is set to 0.663 V, and then increased to 2.995 V between 15.2 and 42.9 seconds, according to equation

$$V = 0.00155t^2 - 0.006t + 0.4$$

c. At 43.0 seconds the voltage is increased to 3.000 V and then decreased linearly to 2.750 V between 43.1 to 43.9 seconds.
d. The voltage is constant at 2.750 V between 44.0 to 48.0 seconds.
e. Between 48.1 and 51.0 seconds the voltage is decreased linearly from 2.750 to 2.000 V.
f. Between 51.1 and 101.0 seconds the voltage is reduced linearly to zero.

Enter this ramp into “Alisoonisen varakäyttöohjelma.vi”.

2. Place the ceiling on position and close the gaps between the wall tops and the ceiling with aluminium tape.
3. Place the pitot tube on position at station 1. A pitot-static tube can also be used.
4. Place the roof on top of the duct ceiling and simultaneously lead the static pressure hoses through the roof openings. Connect the hoses on the static pressure orifices.
5. Connect the total pressure hose on the pitot tube. If a pitot-static tube is used the static pressure line is not connected anywhere.
6. Check that the latches that fix the duct parts together are closed.
7. Weigh all the containers that were used to measure or spread the fluid to obtain the amount of fluid that was left in them.
8. If the two thermocouples are connected to the DAQ controlled by “Icewing.vi”, click the button “Mittaus ja tallennus POIS” in page 3 of “Icewing.vi” user interface to switch on the measurement. The text on the button should then become “Mittaus ja tallennus PÄÄLLÄ”. Then proceed to step 10.
9. If the two thermocouples are connected to multimeters, switch on the camera recording their displays.
10. Perform the wind tunnel run.
11. If the two thermocouples are connected to DAQ controlled by “Icewing.vi”, click the button “Mittaus ja tallennus PÄÄLLÄ” in page 3 of “Icewing.vi” user interface to switch off the measurement. The text on the button should then become “Mittaus ja tallennus POIS”.
12. Copy the file to which “Icewing.vi” saves the results. Then proceed to step 14.
13. If the two thermocouples are connected to multimeters, switch off the camera recording their displays.
14. Remove the fluid remaining in the diffuser. This amount of fluid is considered as run-off.
15. Raise the roof and disconnect the static pressure hoses from their orifices. Remove the roof and the ceiling.
16. Disconnect the dynamic pressure hose from the pitot tube and remove the tube.
17. Measure fluid thickness at the 60 positions marked on the coolant tank surfaces.
18. Measure surface temperature at the 60 positions marked on the coolant tank surfaces.
19. Scrape the remaining fluid to a clean scale-equipped jug and read the volume of the fluid remnant.

Measure surface temperature at the 60 positions marked on the coolant tank surface.

Appendix C. Variable AOA Model Test Procedures

Model installation

1. Fill the coolant tank with a water-glycol solution, the mixture ratio of which depends on the temperature at which the test is conducted. Freezing points for three different solutions are given in Table A-1.
2. Take the model to the freezer at the third floor of the K4 building. When selecting the target temperature for cooling, consider that the temperature of the coolant and the model always rises during the transportation to the tunnel.
3. Take the model back into the wind tunnel and install it on the balance.

Preparing for the test

1. Take the type IV fluid to the freezer if required by the test specification.
2. Weigh all the containers that are used to handle the fluid.
3. Connect the thermocouple lines to the DAQ controlled by the program “Icewing.vi”. Alternatively connect the thermocouples to multimeters through appropriate amplifiers and proceed to step 5.
4. Set the DAQ channels to be used, the input terminal configuration, the minimum and maximum input values and scan rate at page 1 of the user interface of the program. Set the coefficients of the channels at page 2 of the user interface.
5. Enter the file path of the program results file at “Tulostiedosto” on page 3 of “Icewing.vi” user interface.
6. Set the clocks of the computer running the program “Alisoonisen mittausohjelma.vi” and the computer running the program “Icewing.vi” to the same time. <u>This must be checked at the start of every test!</u>
7. If a solution of type I fluid and water is to be used in the test, prepare the mixture of these.
8. Measure the amounts of both types of fluid to be used with a scale-equipped jug. Place the fluids to the cans from which they are spread. <u>It is forbidden to handle type I and type IV fluids on the same containers</u>, since this will alter the qualities of type IV fluid and therefore cause misleading results from the test. For the same reason the containers used with type IV fluid must be dry before the fluid is placed in.
9. Measure the surface temperature of the model with an infra-red probe at the 30 positions marked on the model surface.
10. Place the containers that collect the run-off fluid on the tunnel floor at the leading and trailing edges of the model.

Spreading of the fluid

1. The spreading process depends on whether only type IV fluid or both type I and type IV fluids are to be used. <u>If only type IV is used, start from step 3. If both types are used, start from step 9.</u>
2. Retract the slat and seal the slot of the flap using a rubber seal.
3. If frost has formed on the model surface scratch it off with a plastic spattle. Do not use a metallic one since it will damage the paint.

4. Spread most of the fluid on the area approximately between $0.30c - 0.70c$.
5. Reduce α to pour the fluid towards the leading edge. Use a spattle to keep the front edge of the fluid layer straight.
6. Increase α to pour the fluid towards the trailing edge. Again use a spattle to keep the front edge of the fluid layer straight.
7. Measure fluid thickness with an Elcometer at the 27 positions marked on the model surface.
8. Measure surface temperature at the 27 positions marked on the model surface.

9. If frost has formed on the model surface it must not be scratched off, since the type I fluid washes it away as it does when a real airplane is de-iced.
10. Pour type I fluid on the whole upper surface of the model. Enough fluid must be used to wash the surface clear of frost. Type I fluid spreads easily due to its low viscosity.
11. Also the type IV fluid is to be spread on whole upper surface. However, spread most of the fluid on the area approximately between $0.30c - 0.70c$.
12. Reduce α to pour the fluid towards the leading edge. Use a spattle to keep the front edge of the fluid layer straight.
13. Increase α to pour the fluid towards the trailing edge. Again use a spattle to keep the front edge of the fluid layer straight.
14. Measure fluid thickness at the 27 positions marked on the model surface.
15. Measure surface temperature at the 27 positions marked on the model surface.

Performing the test

1. In case a takeoff run is to be simulated in the test, the flow velocity and the angle of attack are controlled by “komentaja.vi”. Two scripts have been developed for this purpose, the difference of them being the acceleration. The one presented first accelerates the tunnel to 60 m/s in approximately 30 seconds, and the latter in approximately 25 seconds. Load one of the scipts to “komentaja.vi”.
    a. Use the following script for slower acceleration:

```
nopeussaadin hidaskiihdytys 1
kulmasaadin  kohtauskulmanopeus         3.00
nopeussaadin nopeus   8.00 5 0.1
nopeussaadin nopeus   15.80 5 0.1
nopeussaadin nopeus   23.60 5 0.1
nopeussaadin nopeus   31.40 5 0.1
nopeussaadin nopeus   39.20 5 0.1
nopeussaadin nopeus   47.00 5 0.1
nopeussaadin hidaskiihdytys 0
nopeussaadin nopeus   54.80 5 0.1
nopeussaadin nopeus   63 5 0.1
nopeussaadin nopeus   60
kulmasaadin  kohtauskulma 7.5
komentaja    nuku     40
nopeussaadin hidaskiihdytys 1
```

```
nopeussaadin nopeus   40
komentaja    lopeta
```

b. Use the following script for faster acceleration:

```
nopeussaadin hidaskiihdytys 1
kulmasaadin  kohtauskulmanopeus         3.00
nopeussaadin nopeus   8.00 5 0.1
nopeussaadin nopeus   15.80 5 0.1
nopeussaadin nopeus   23.60 5 0.1
nopeussaadin nopeus   31.40 5 0.1
nopeussaadin nopeus   39.20 5 0.1
nopeussaadin hidaskiihdytys 0
nopeussaadin nopeus   47.00 5 0.1
nopeussaadin nopeus   54.80 5 0.1
nopeussaadin nopeus   61 5 0.1
nopeussaadin nopeus   60
kulmasaadin  kohtauskulma 7.5
komentaja    nuku     40
nopeussaadin hidaskiihdytys 1
nopeussaadin nopeus   40
komentaja    lopeta
```

2. In case a taxiing airplane is simulated in the test, the speed control can be performed manually.

3. Weigh all the containers that were used to measure or spread the fluid to obtain the amount of fluid that was left in them.
4. If takeoff configuration is specified for the test, extend the slat to 11 degrees and remove the rubber seal fitted in the slot of the flap. If clean configuration is specified, the slat and the flap are set at a retracted position.
5. Remove from the tunnel the containers collecting the run-off fluid and measure their weight.
6. Unlock the balance, set angle of attack to zero degrees, and measure the zero values at “Alisoonisen mittausohjelma.vi”.
7. Set the angle of attack to 1.0 degrees.
8. If the two thermocouples are connected to DAQ controlled by “Icewing.vi”, click the button “Mittaus ja tallennus POIS” in page 3 of “Icewing.vi” user interface to switch on the measurement. The text on the button should then become “Mittaus ja tallennus PÄÄLLÄ”. Proceed to step 10.
9. If the two thermocouples are connected to multimeters, switch on the camera recording their displays.
10. Start the wind tunnel and switch on the speed control at “Alisoonisen käyttöohjelma.vi”. Set flow velocity at 5 m/s.
11. When flow velocity has settled on 5 m/s, start the test sequence loaded on “komentaja.vi”. The wind tunnel run is then performed.

12. If the two thermocouples are connected to DAQ controlled by “Icewing.vi”, click the button “Mittaus ja tallennus PÄÄLLÄ” in page 3 of “Icewing.vi” user interface to switch off the measurement. The text on the button should then become “Mittaus ja tallennus POIS”.
13. Copy the file to which “Icewing.vi” saves the results. Proceed to step 15.
14. If the two thermocouples are connected to multimeters, switch off the camera recording their displays.
15. Measure fluid thickness at the 27 positions marked on the model surface.
16. Measure surface temperature at the 27 positions marked on the model surface.
17. Scrape the remaining fluid to a clean scale-equipped jug and weigh the jug.
18. Measure surface temperature at the 27 positions marked on the model surface.

In case the model is to be cooled before the next test pour liquid nitrogen to the spanwise copper pipes. Obtain instruction on hazards of handling the liquid nitrogen before using it!

Appendix D. The Scripts for Fluid Thickness Determination

Kalibrointi.m

```
function [RB_ave] = Kalibrointi(kuva, t)

s = size(kuva);
w = s(2);   % Kuvan leveys
h = s(1);   % Kuvan korkeus

r = (1:h);
RB = (1:w);

i = 1;

% Luetaan RB-arvot sarakkeittain
while i <= w
    c = i*(ones(1,h));          % h kappaletta vakioita
    P = impixel(kuva, c, r);    % Käy läpi sarakkeen kaikki pikselit
                                % (eli kaikki r:n arvot, c vakio)
    R = P(:,1,:);
    B = P(:,3,:);
    R_ave = sum(R)/h;           % R-arvojen keskiarvo tälle sarakkeelle
    B_ave = sum(B)/h;           % B-arvojen keskiarvo tälle sarakkeelle
    RB(i) = R_ave*B_ave;        % RB-keskiarvo sarakkeelle i
    i = i+1;
end

% RB-keskiarvot tunnetaan nyt sarakkeittain, mutta ne halutaan tietää
% kalibrointilevyn urista

RB_ave = (1:12);            % Levyssä 12 uraa

rb = 0;
for k = 1:(floor(w/12))     % Kuvan leveys jaetaan 12 osaan
    rb = rb + RB(k);        % Lasketaan yhteen RB-arvot ensimmäisen
                                % uran sarakkeista
end
RB_ave(1) = rb/(w/12);      % Lopuksi lasketaan keskiarvo

rb = 0;
for k = (ceil(w/12)):(floor(w/6))
    rb = rb + RB(k);
end
RB_ave(2) = rb/(w/12);

rb = 0;
```

```
for k = (ceil(w/6)):(floor(w/4))
    rb = rb + RB(k);
end
RB_ave(3) = rb/(w/12);

rb = 0;
for k = (ceil(w/4)):(floor(w/3))
    rb = rb + RB(k);
end
RB_ave(4) = rb/(w/12);

rb = 0;
for k = (ceil(w/3)):(floor((5*w)/12))
    rb = rb + RB(k);
end
RB_ave(5) = rb/(w/12);

rb = 0;
for k = (ceil((5*w)/12)):(floor(w/2))
    rb = rb + RB(k);
end
RB_ave(6) = rb/(w/12);

rb = 0;
for k = (ceil(w/2)):(floor((7*w)/12))
    rb = rb + RB(k);
end
RB_ave(7) = rb/(w/12);

rb = 0;
for k = (ceil((7*w)/12)):(floor((8*w)/12))
    rb = rb + RB(k);
end
RB_ave(8) = rb/(w/12);

rb = 0;
for k = (ceil((8*w)/12)):(floor((3*w)/4))
    rb = rb + RB(k);
end
RB_ave(9) = rb/(w/12);

rb = 0;
for k = (ceil((3*w)/4)):(floor((5*w)/6))
    rb = rb + RB(k);
end
RB_ave(10) = rb/(w/12);
```

```
rb = 0;
for k = (ceil((5*w)/6)):(floor((11*w)/12))
    rb = rb + RB(k);
end
RB_ave(11) = rb/(w/12);

rb = 0;
for k = (ceil((11*w)/12)):w
    rb = rb + RB(k);
end
RB_ave(12) = rb/(w/12);

plot(RB_ave, t);
```

Korjauskerroin.m

```
function[k] = Korjauskerroin(kuva, a1, b1, c1, a2, b2, c2, t_mitattu)

s = size(kuva);
w = s(2);               % Alkutilanteen kuvan leveys
h = s(1);               % Alkutilanteen kuvan korkeus

r = (1:h);
t = (1:w);

i = 1;

% Lasketaan nestepaksuudet alkutilanteen kuvasta kalibrointikertoimien
% avulla. Aluksi luetaan RB-arvot sarakkeittain.

while i <= w
    c = i*(ones(1,h));          % h kappaletta vakioita
    P = impixel(kuva, c, r);    % Käy läpi sarakkeen kaikki pikselit
                                % (eli kaikki r:n arvot, c vakio)
    R = P(:,1,:);
    B = P(:,3,:);
    R_ave = sum(R)/h;           % R-arvojen keskiarvo tälle sarakkeelle
    B_ave = sum(B)/h;           % B-arvojen keskiarvo tälle sarakkeelle
    RB = R_ave*B_ave;           % RB-keskiarvo tälle sarakkeelle
    % Laskennallinen nestepaksuus sarakkeelle i:
    t(i) = a1*exp(-((RB-b1)/c1)^2)+a2*exp(-((RB-b2)/c2)^2);
    i = i+1;
end


% Seuraavaksi halutaan muuttaa laskennalliset paksuudet matriisiksi jonka
% leveys on 1800.
```

```
s = size(t);                % Edellä lasketun t-matriisin koko
x = s(2)/1800;              % s(2) on t-matriisin leveys ja 1800 on
                            % haluttu leveys, x on näiden suhde
t_1800 = (1:1800);          % Uusi paksuusmatriisi
i = 1;

while i <= 1800
    n = 1+floor((i-1)*x);
    t_1800(i) = t(n);
    i = i+1;
end


% Mitatut paksuudet ennen koetta interpoloidaan matriisiksi, jonka leveys
% on myös 1800. Mittauspisteitä on 20, ja niiden välillä paksuuden
% oletetaan muuttuvan lineaarisesti. Mittauspisteiden väli on siis 90
% pikseliä.

x = 0:20;
xi = 0:0.011112:20;

t_interpoloitu = interp1(x, t_mitattu, xi);

% Lasketaan korjauskerroin jakamalla interpoloitu mitattu nestepaksuus
% kuvasta lasketulla nestepaksuudella:

k = (1:1800);
i = 1;

while i <= 1800
    k(i) = t_interpoloitu(i)/t_1800(i);
    i = i+1;
end
```

Tulokset.m

```
function [paksuudet] = Tulokset(korjauskerroin, kuva, a1, b1, c1, a2, b2, c2)

s = size(kuva);
w = s(2);
h = s(1);

r = (1:h);
t = (1:w);

i = 1;
```

```
    while i <= w
        c = i*(ones(1,h));
        P = impixel(kuva, c, r);
        R = P(:,1,:);
        B = P(:,3,:);
        R_ave = sum(R)/h;
        B_ave = sum(B)/h;
        RB = R_ave*B_ave;
        t(i) = a1*exp(-((RB-b1)/c1)^2)+a2*exp(-((RB-b2)/c2)^2);
        i = i+1;
    end

    s = size(t);
    x = s(2)/1800;
    t_1800 = (1:1800);
    i = 1;

    while i <= 1800
        n = 1+floor((i-1)*x);
        t_1800(i) = t(n);
        i = i+1;
    end

    paksuudet = (1:1800);
    i = 1;

    while i <= 1800
        paksuudet(i) = korjauskerroin(i)*(t_1800(i));
        i = i+1;
end
```

Instructions of use

1. Start Matlab and ensure that the scripts “Kalibrointi.m”, “Korjauskerroin.m” and “Tulokset.m” are in the window “Current folder”.
2. Read the image of the calibration plate, the image of the model surface clear of fluid, the image of the fluid layer at the start of the tests, and the images you wish to analyse by using the command *imread(‘filename’)*. Matlab reads the images as an $h \times w \times 3$ matrix. The images have to be cropped as shown in Figure D-1 for the calibration plate and in Figure D-2 for the other images.

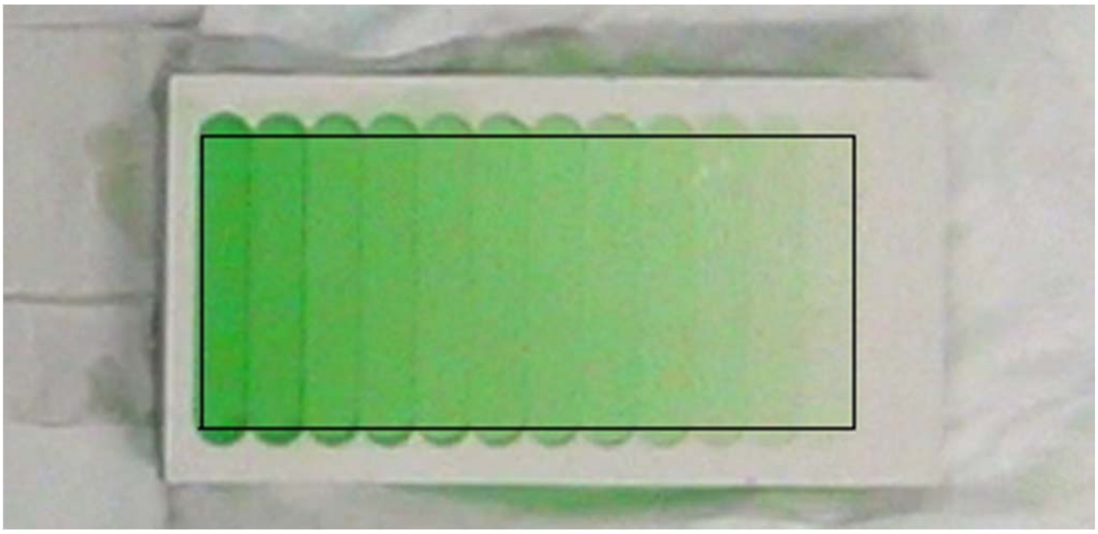


Figure D-1 The area outside the black rectangle has to be cropped.

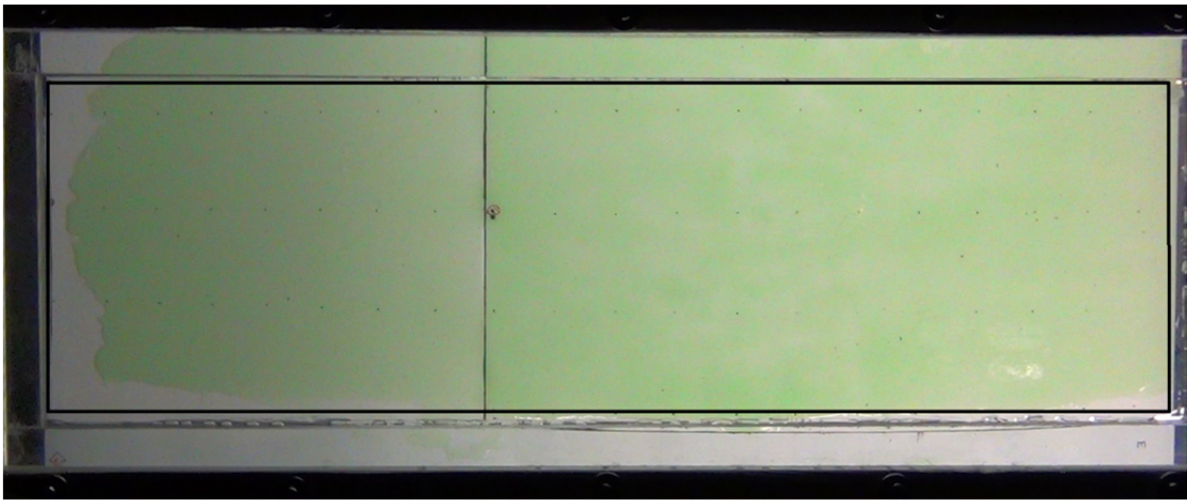


Figure D-2 The area outside the black rectangle has to be cropped.

Steps 3 to 7 are conducted to obtain the calibration coefficients and the correction factor and they are performed only once before analyzing a set of images from a given test run.

3. Enter the thicknesses of the grooves of the calibration plate as a 1×12 matrix. Also enter the thicknesses that were measured at the start of the test being analysed as a 1×21 matrix. Notice that the thickness values have to be in the same order as they are on the images you read at step 1. This means that if the picture of the calibration plate is such that the 10 mm groove is on the left side of the image, start entering the thicknesses from 10.0. In the thickness values

measured at the start of the test enter zero value as the thickness at the leading edge (21st entrant of the matrix).

4. Run the script “Kalibrointi.m” with the command *Kalibrointi(image_name, t_plate)*. Here “image_name” refers to the name you have given to the image of the calibration plate when reading with “imread()” and “t_plate” refers to the name you have given to the matrix containing the thicknesses of the grooves of the calibration plate. The script returns a 1×12 matrix of the RB values corresponding to the calibration plate groove thicknesses.
5. If you wish to use the zero thickness RB value for the calibration, open the image presenting the model surface clear of fluid with the command *imtool(image_name)*, where “image_name” refers to the name you have given to the image of the clear model surface when reading it with “imread()”. When the image is opened read the R and B values from pixel info at lower left corner of the imtool window. When you have obtained the RB value corresponding to zero fluid thickness, enter it to the matrix returned by “Kalibrointi.m” as the 13th entry, as the value corresponding to zero fluid thickness. Also enter zero as the 13th entry of calibration plate thickness matrix as it was the depth of the shallowest groove of the plate.
6. Type *cftool* on the command line. Select the values returned by “Kalibrointi.m” as X Data and calibration plate thicknesses as Y Data. Then fit a curve to the data by selecting “Type of fit: Gaussian” and from the different equations available select the one which corresponds to equation 4-1 (Second highest in Matlab 7.10.0). When the fit is done, enter the values of the coefficients a1, a2, b1, b2, c1 and c2 on the command line.
7. Run the script “Korjauskerroin.m” with the command *Korjauskerroin(image_name, coefficients, t_start_measured)*, where “image_name” refers to the name you have given to the image of the start of the test when reading it with “imread()”, “coefficients” refers to the names you have given to the six calibration coefficients obtained at the previous section and “t_start_measured” refers to the fluid thicknesses that were entered in section 3.

Steps 8 to 9 are performed for every image from which the fluid thickness is to be determined.

8. Run the script “Tulokset.m” with the command *Tulokset(cf, image, coefficients)*, where “cf” refers to the correction factor returned by “Korjauskerroin.m”, “image” refers to the name you have given to the image to be analysed when reading it with “imread()”, and “coefficients” refers to the names you have given to the six calibration coefficients that were obtained at section 6.
9. In the end you have a 1×1800 matrix returned by “Tulokset.m”. You can plot it to get an image of the calculated thickness distribution.

Example results

Figure D-3 Screenshot at 1 min 29 seconds.

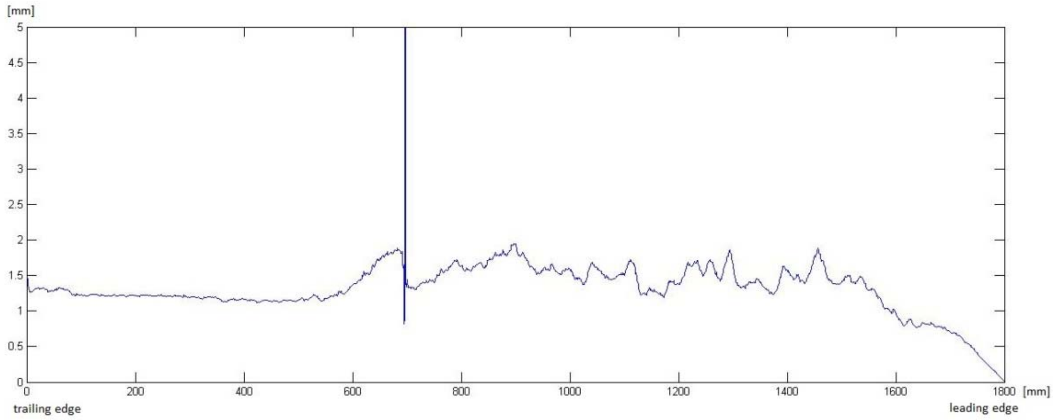


Figure D-4 Thickness distribution at 1 min 29 seconds.

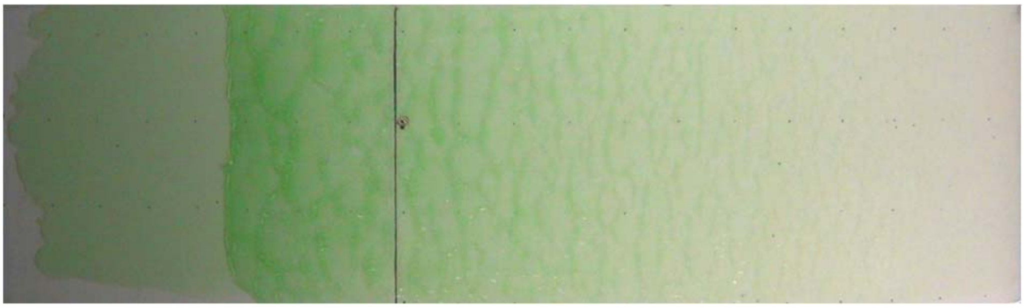


Figure D-5 Screenshot at 1 min 34 seconds.

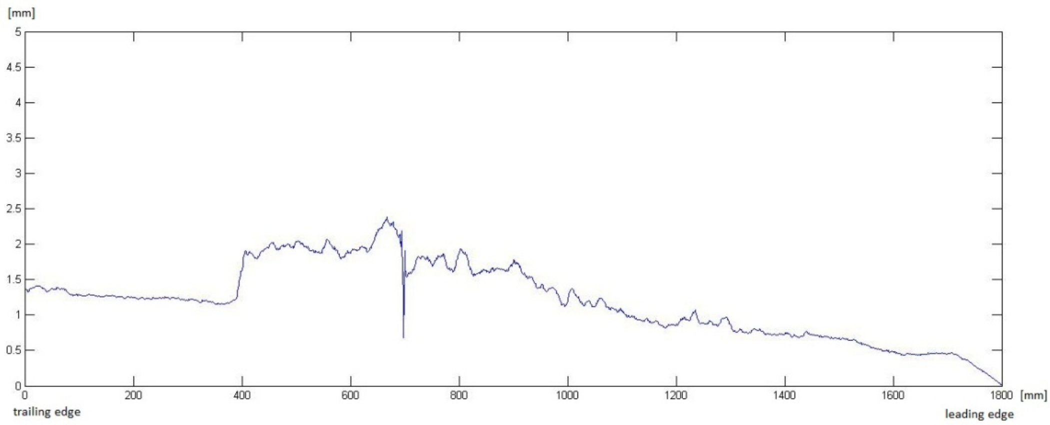


Figure D-6 Thickness distribution at 1 min 34 seconds.

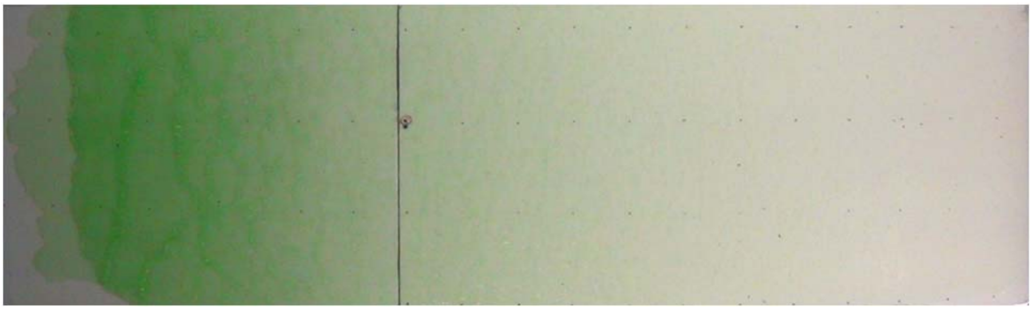


Figure D-7 Screenshot at 1 min 39 seconds.

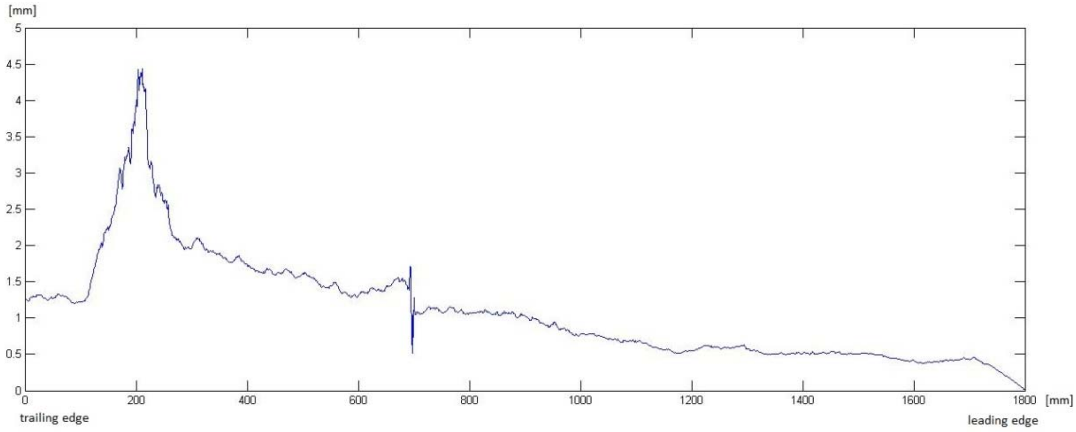


Figure D-8 Thickness distribution at 1 min 39 seconds.

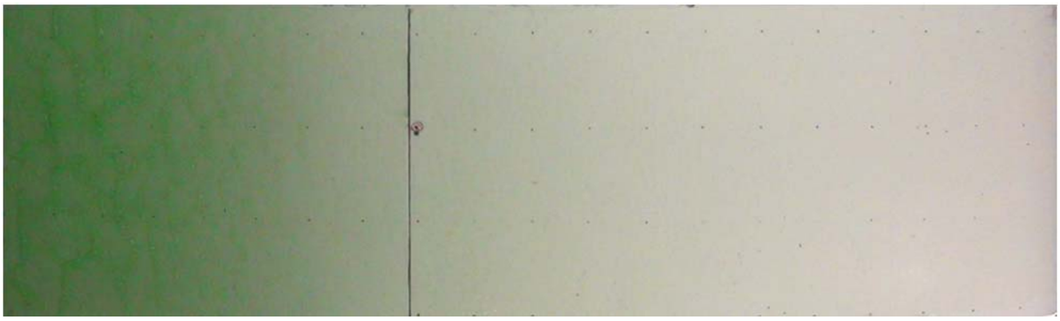


Figure D-9 Screenshot at 1 min 44 seconds.

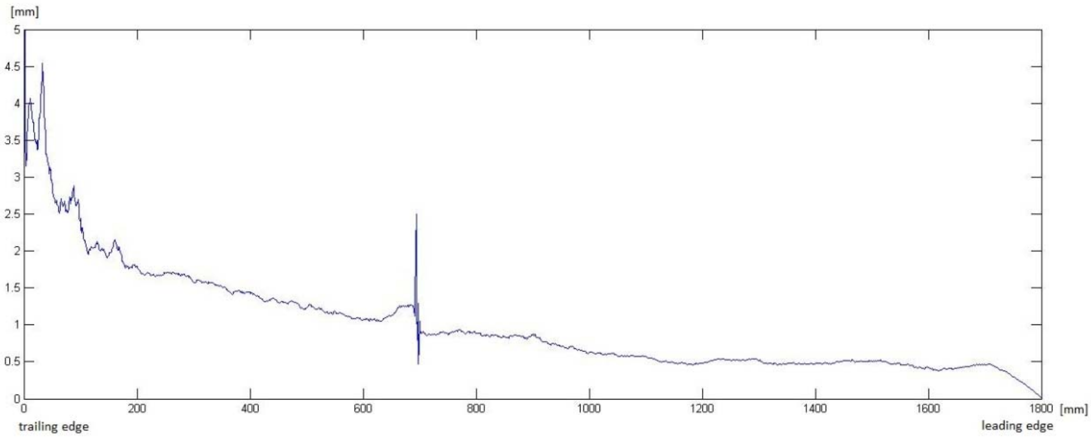


Figure D-10 Thickness distribution at 1 min 44 seconds.

Appendix E. Revision Status

The test setup documentation status.

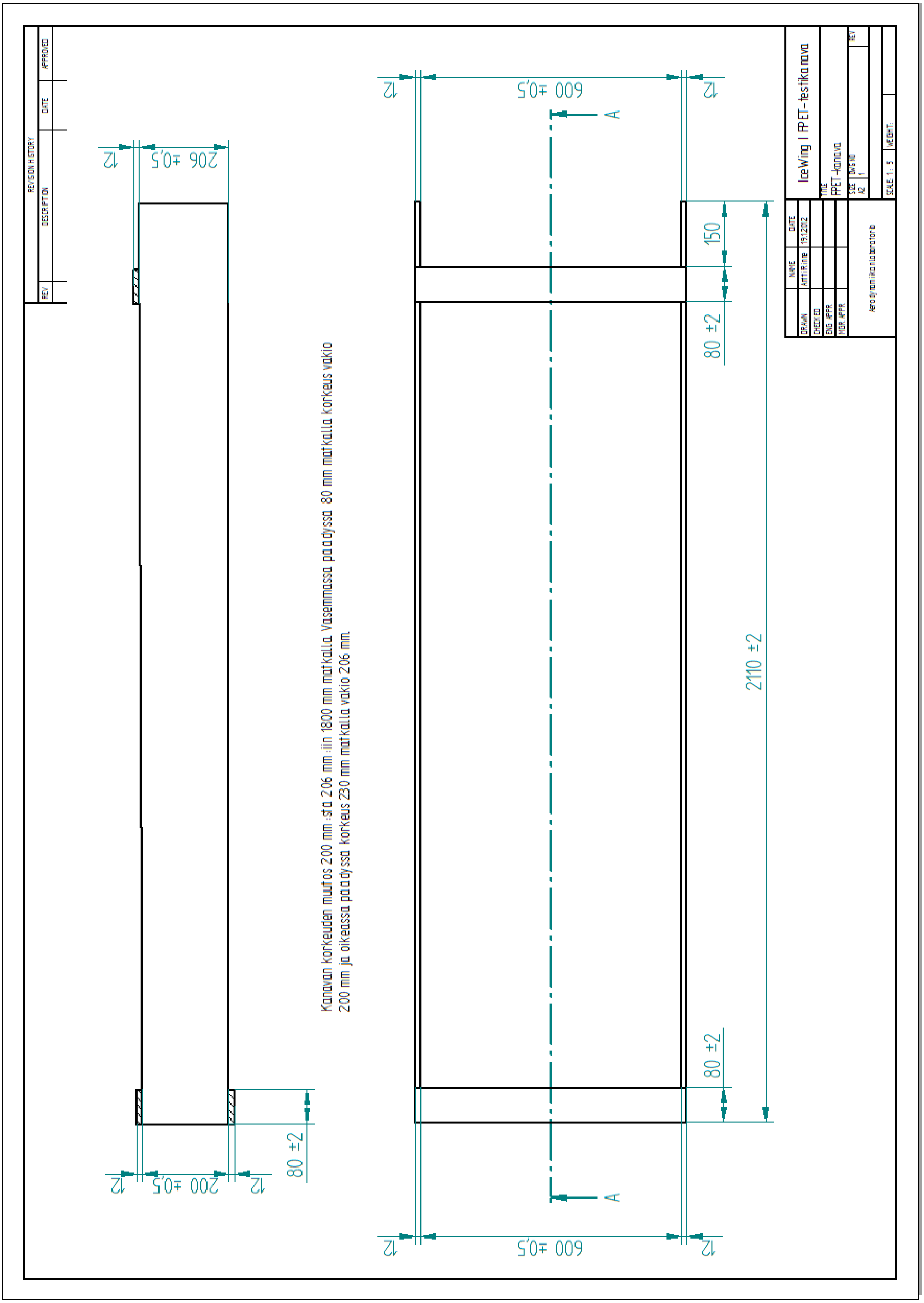
T-series	Report name	Publish date	Note
T-298	Manual for Airplane Wing Anti-icing Fluid Tests in Wind Tunnel	January 29th 2013	

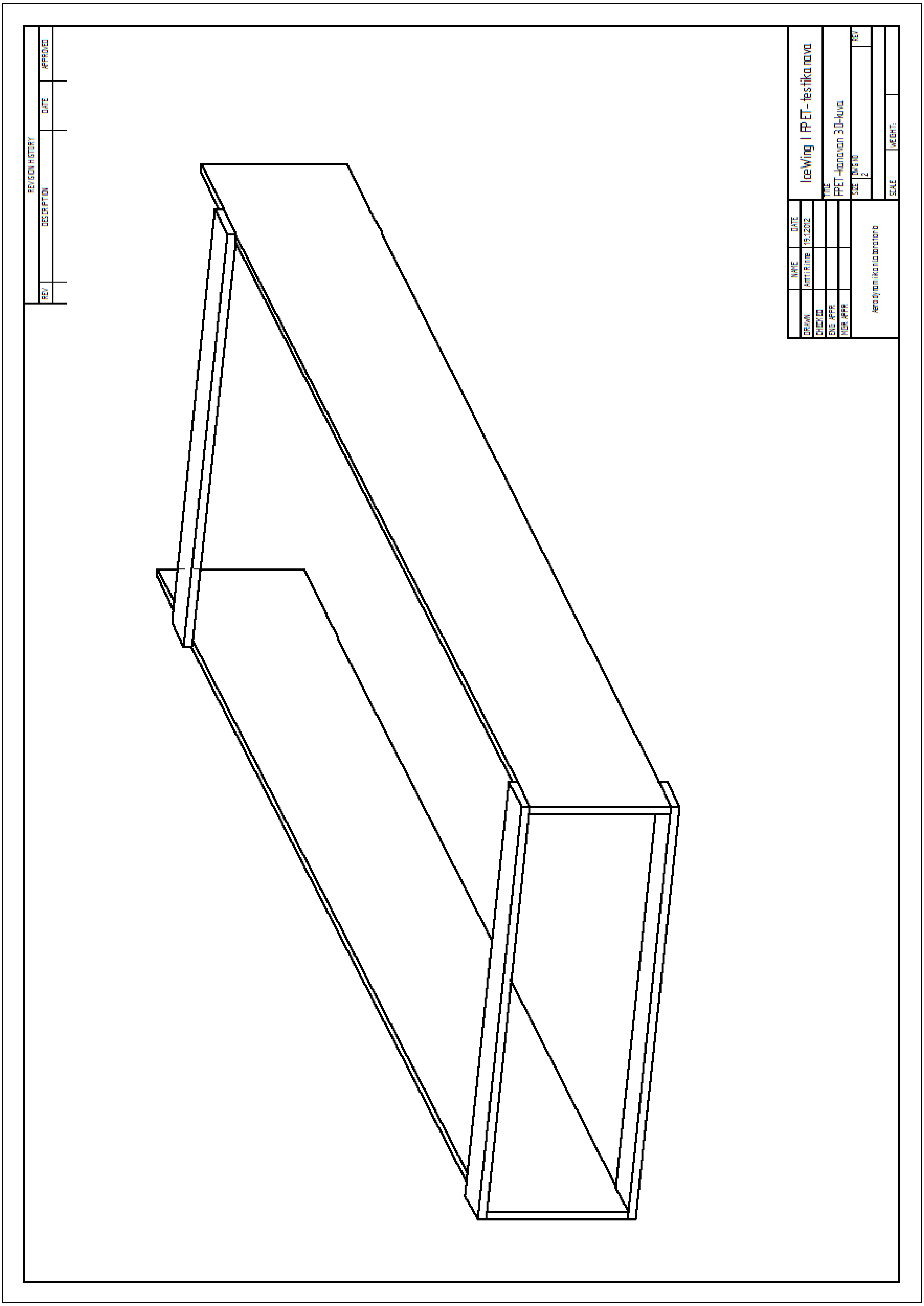
Appendix F. FPET Duct Drawings

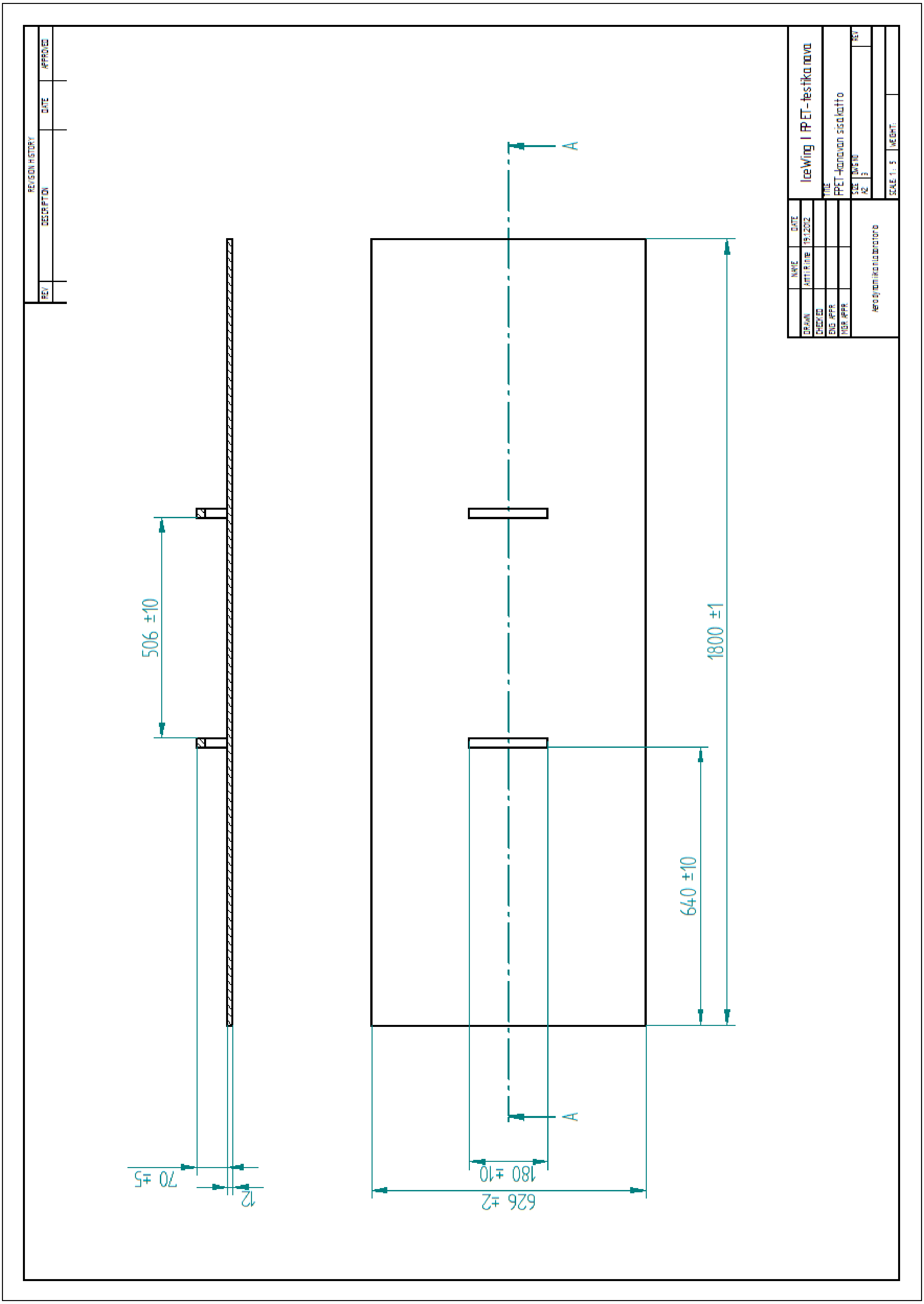
Table F-1 List of FPET duct drawings.

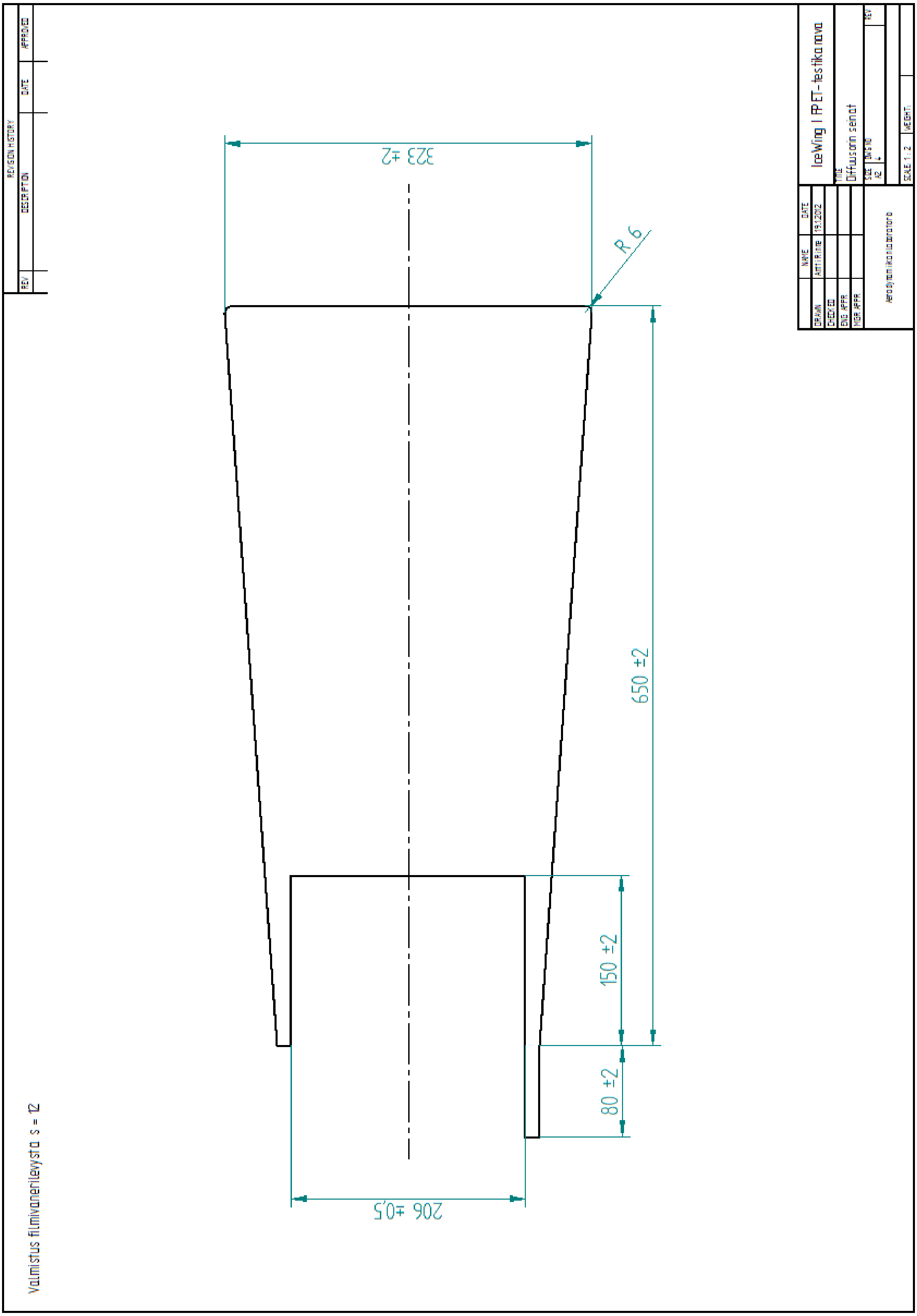
Drawing number	Title (in Finnish)
1	FPET-kanava
2	FPET-kanavan 3D-kuva
3	FPET-kanavan sisäkatto
4	Diffuusorin seinät
5	Diffuusorin ylä- ja alapintalevyt
6	Diffuusorin etupääty
7	Diffuusorin takapääty
8	Suuttimen seinät
9	Suuttimen ellipsimuoto
10	Suuttimen etupääty
11	Suuttimen takapääty
12	Suuttimen 3D-kuva edestä
13	Suuttimen 3D-kuva takaa
14	Ulkokaton seinät ja sovitteet
15	Ulkokaton etulevy
16	Ulkokaton takalevy
17	Ulkokaton 3D-kuva
18	Kehikko sivulta
19	Kehikko edestä
20	Kehikko ylhäältä
21	Pohjan seinät
22	Pohjan alalevy

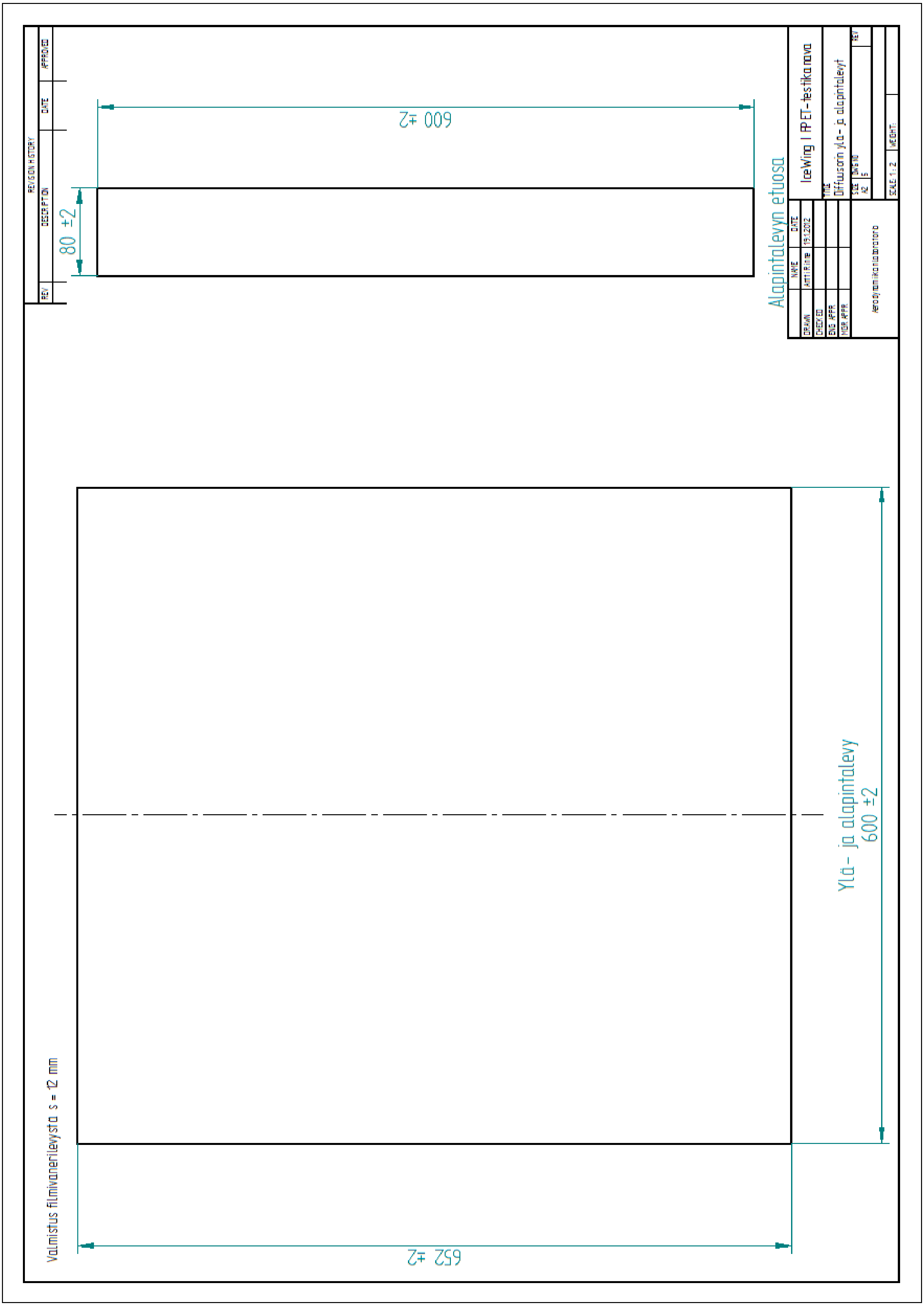
The drawings have to be printed on A2 sheet to obtain the correct scales which are marked on the drawings. In the following pages the scales are therefore incorrect since the drawings are printed on A4 sheets.


Kanavan korkeuden muutos 200 mm :sta 206 mm :iin 1800 mm matkalla. Vasemmassa paadyssa 80 mm matkalla korkeus vakio
200 mm ja oikeassa paadyssa korkeus 230 mm matkalla vakio 206 mm.
600 ±0,5
12
206 ±0,5
200 ±0,5
150
80 ±2
2110 ±2
A
IceWing I FPET-testikanava
FPET-kanava
Antti Rinne 19.1.2012
Aerodynamiikan laboratorio
SCALE 1 : 5

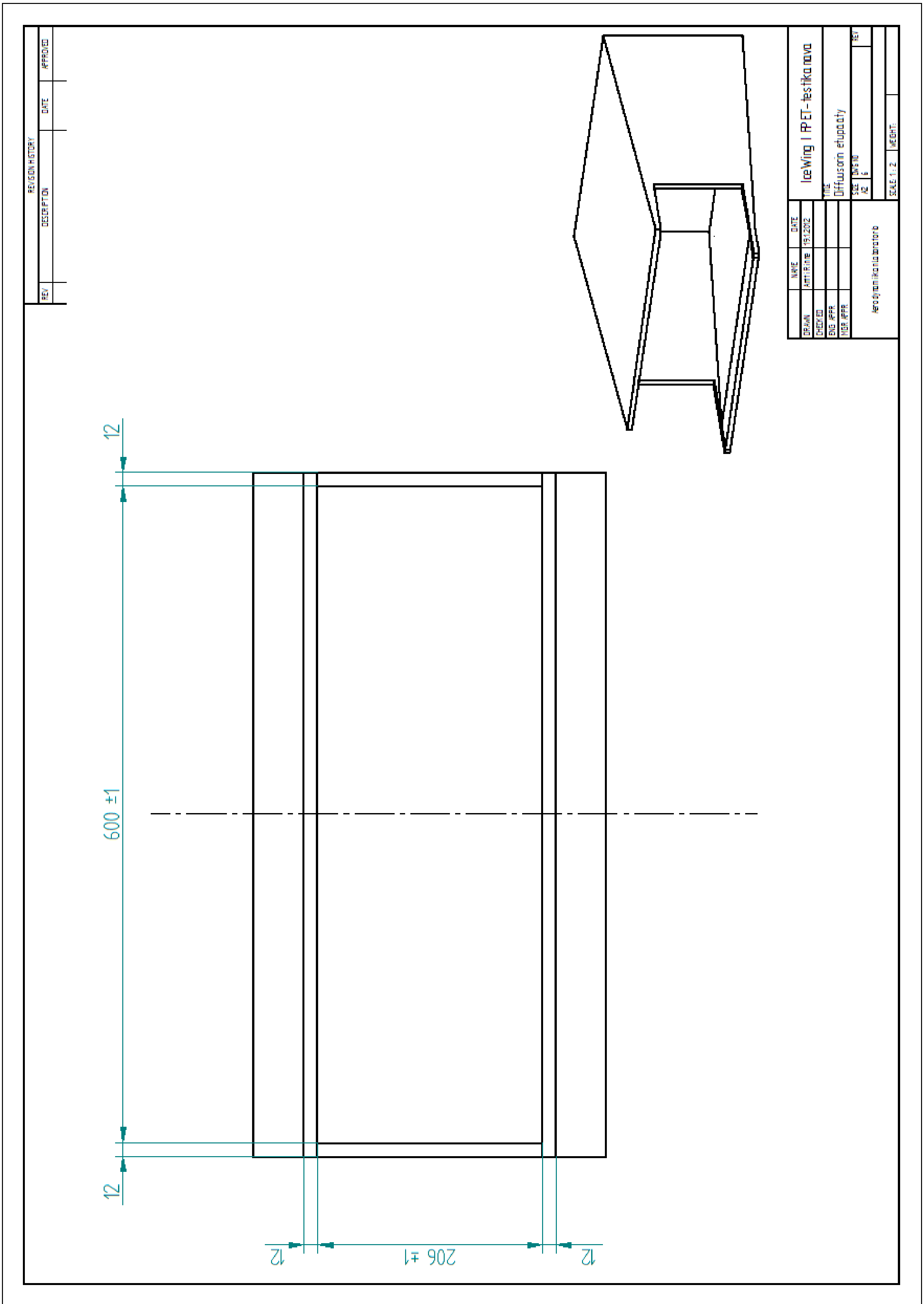

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FPET-testikanava
TITLE
FPET-kanavan 3D-kuva
SIZE
DWG NO
2
REV
SCALE
WEIGHT:
NAME
DATE
DRAWN
Antti Rinne
19.1.2012
CHECKED
ENG APPR
MGR APPR
Aerodynamiikan laboratorio

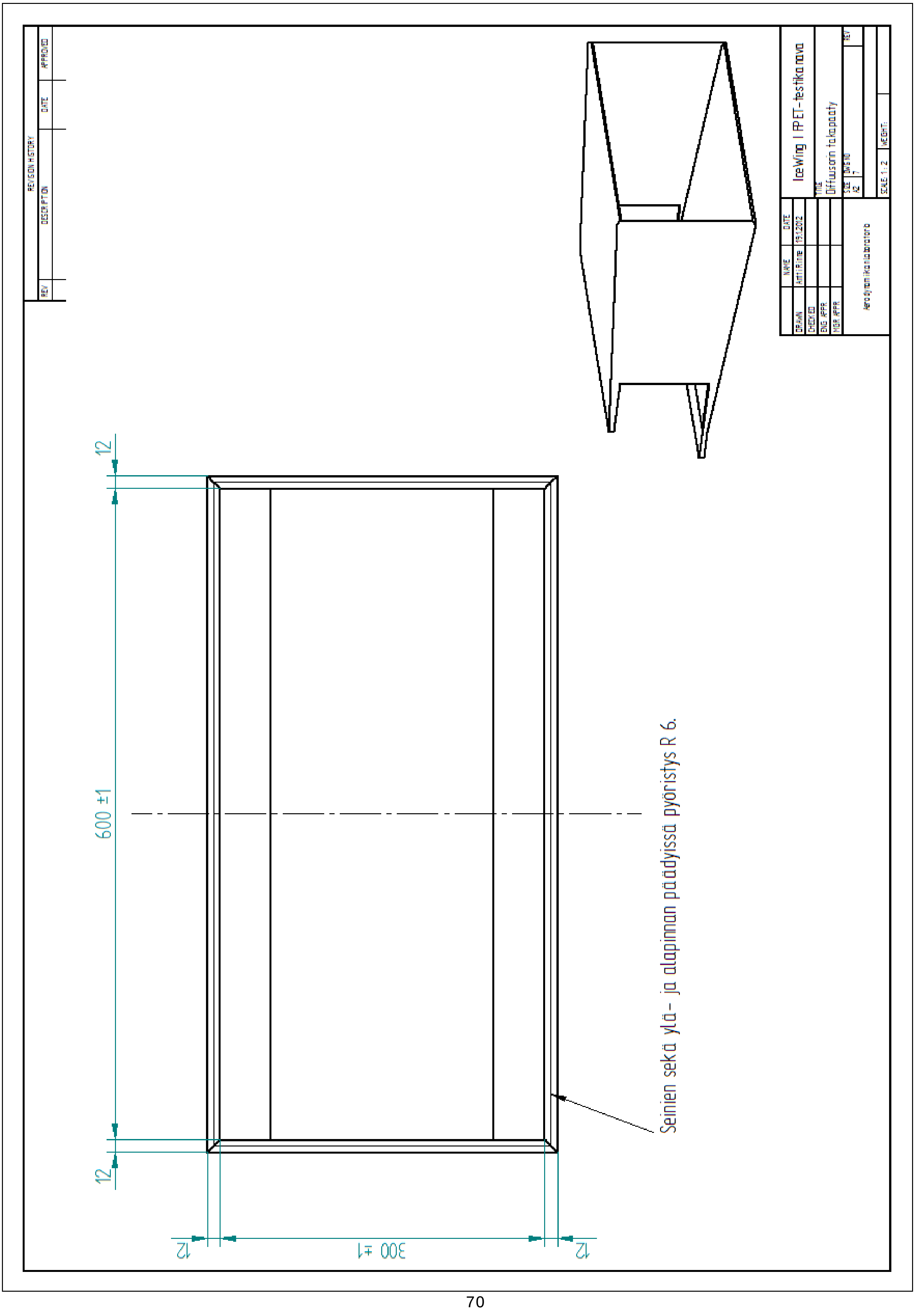

IceWing I FPET-testikanava
FPET-kanavan sisäkatto
A
A
506 ±10
1800 ±1
640 ±10
180 ±10
626 ±2
70 ±5
12

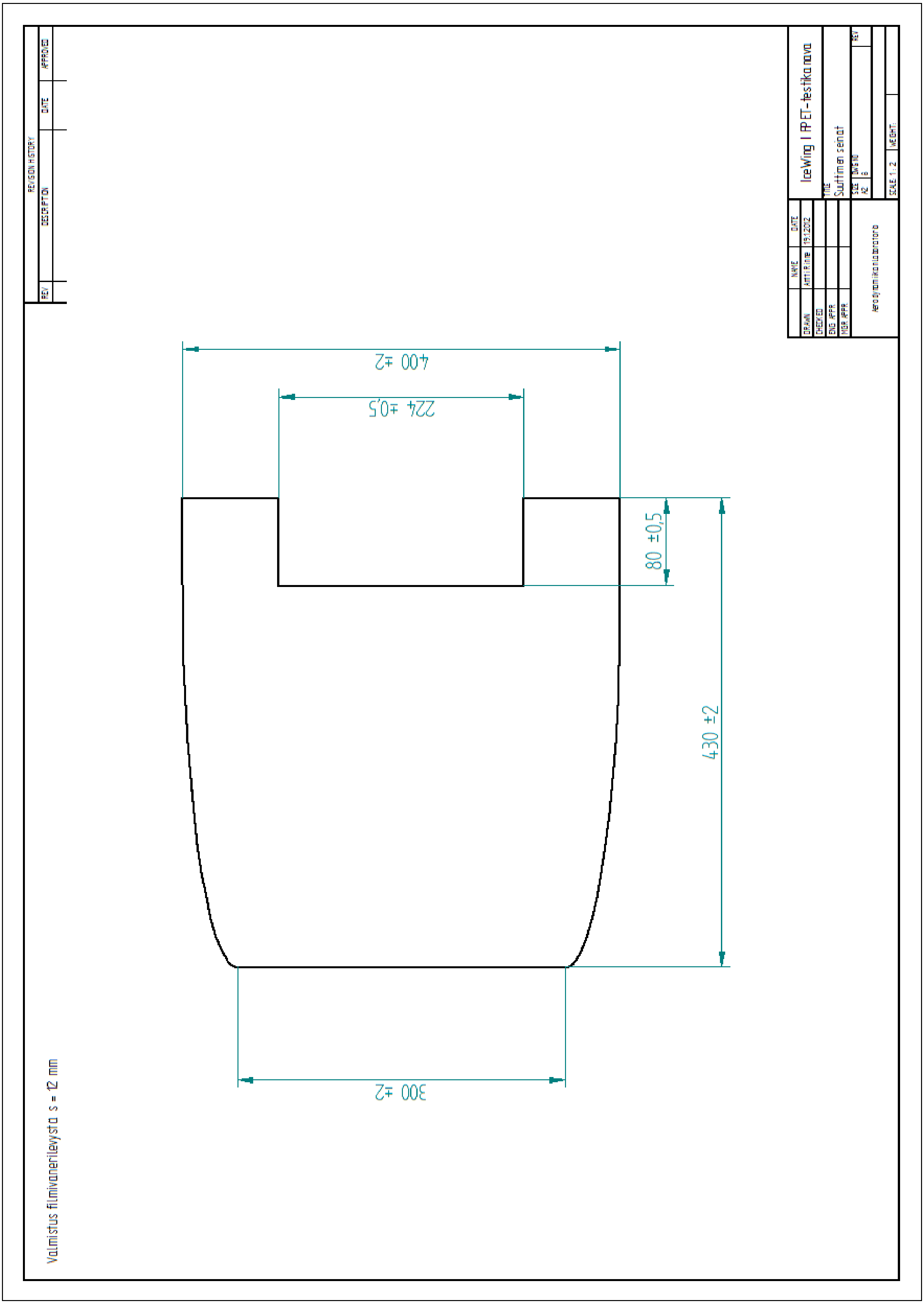

IceWing I FPET-testikanava
Diffuusorin seinät
Antti Rinne
19.1.2012
SCALE 1:2
Valmistus filmivanerilevystä s = 12
323 ±2
R 6
650 ±2
150 ±2
80 ±2
206 ±0,5

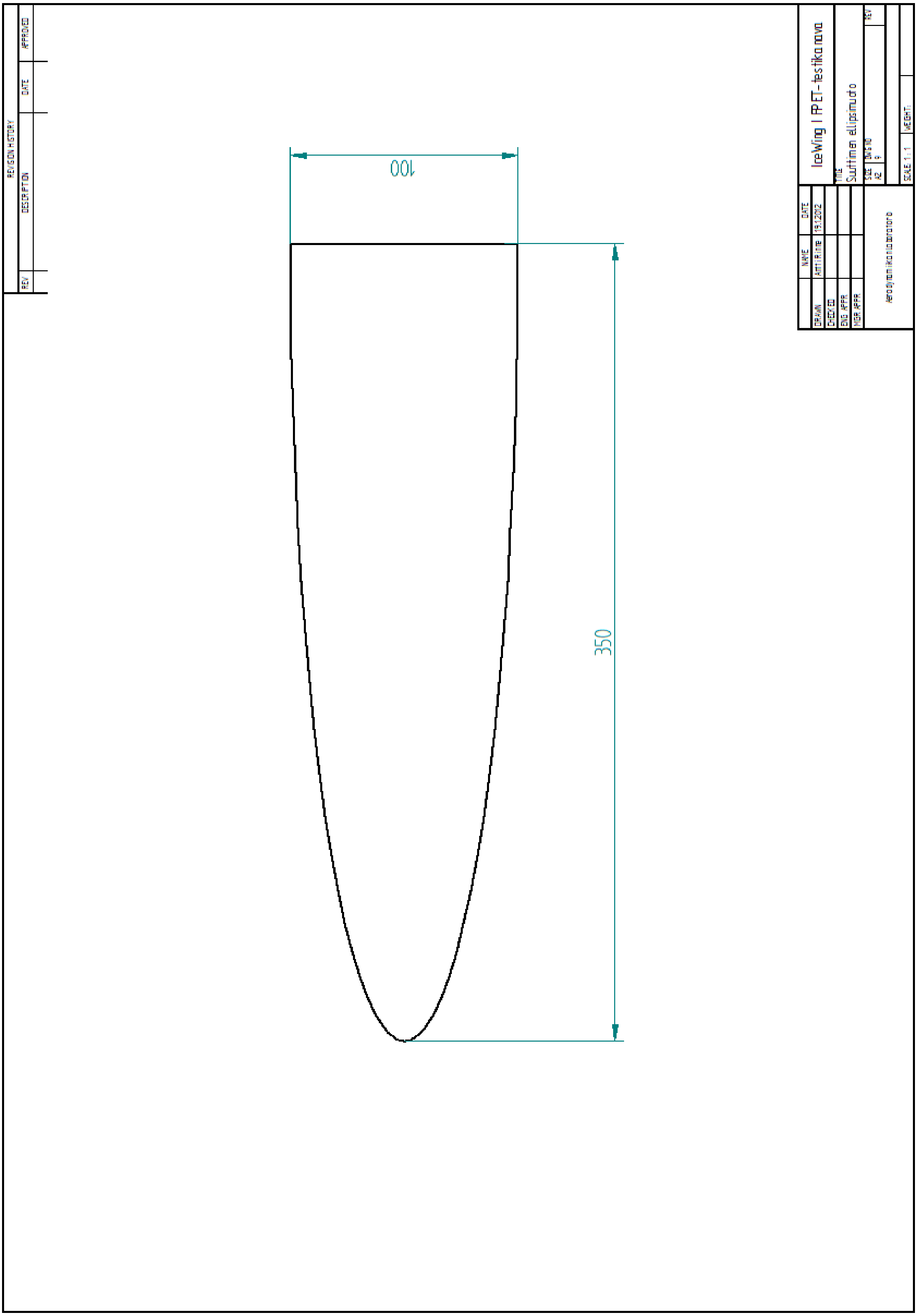


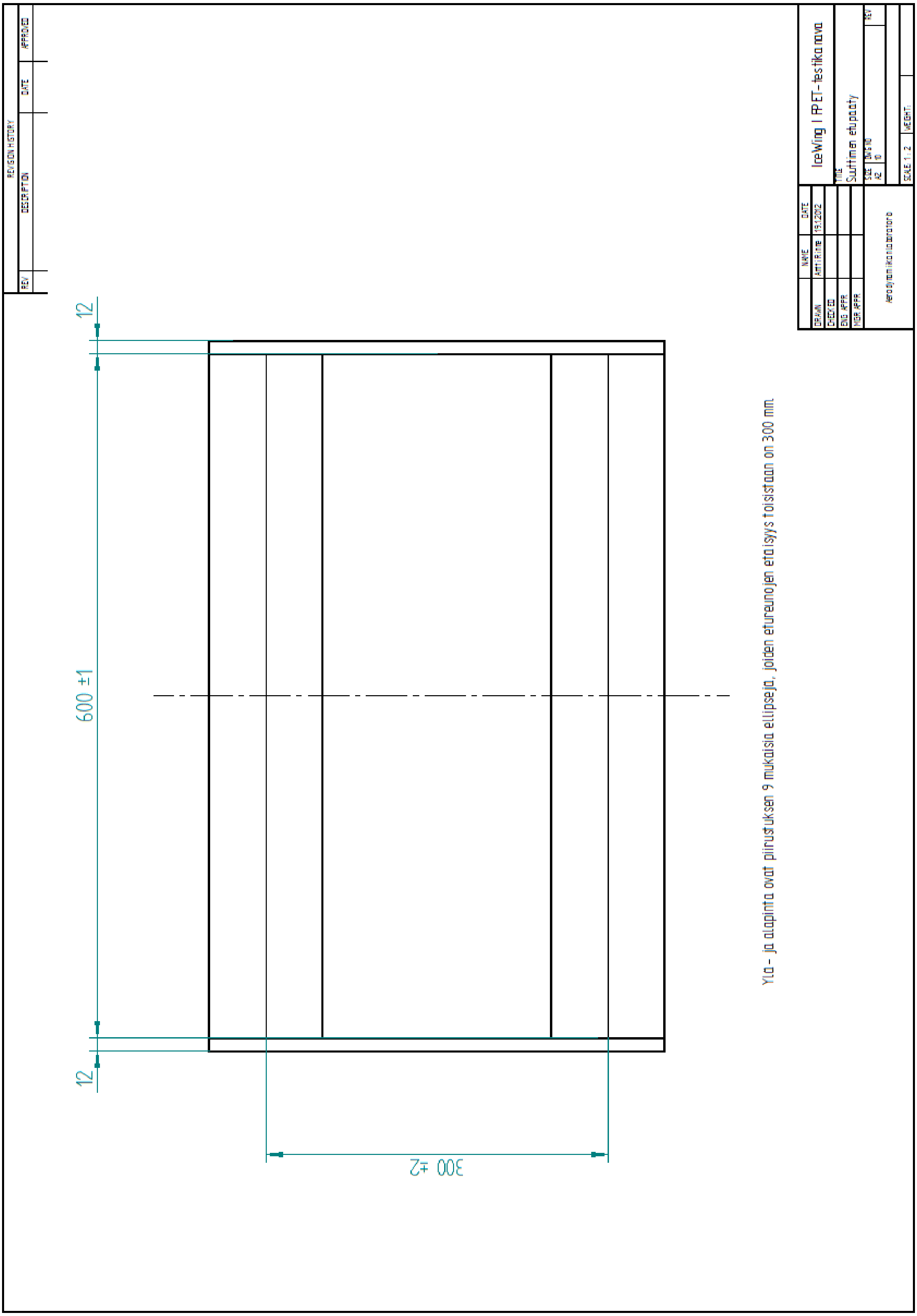
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
600 ±2
80 ±2
Alapintalevyn etuosa
IceWing I FPET-testikanava
TITLE
Diffuusorin ylä- ja alapintalevyt
NAME
DATE
DRAWN
Antti Rinne
19.1.2012
CHECKED
ENG APPR
MGR APPR
SIZE
A2
DWG NO
5
REV
SCALE 1:2
WEIGHT:
Ylä- ja alapintalevy
600 ±2
652 ±2
Valmistus filmivanerilevystä s = 12 mm


REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
12
600 ±1
12
12
206 ±1
12
IceWing I FPET-testikanava
TITLE
Diffuusorin etupääty
SIZE
A2
DWG NO
6
REV
SCALE 1:2
WEIGHT:
NAME
DATE
DRAWN
Antti Rinne
19.1.2012
CHECKED
ENG APPR
MGR APPR
Aerodynamiikan laboratorio

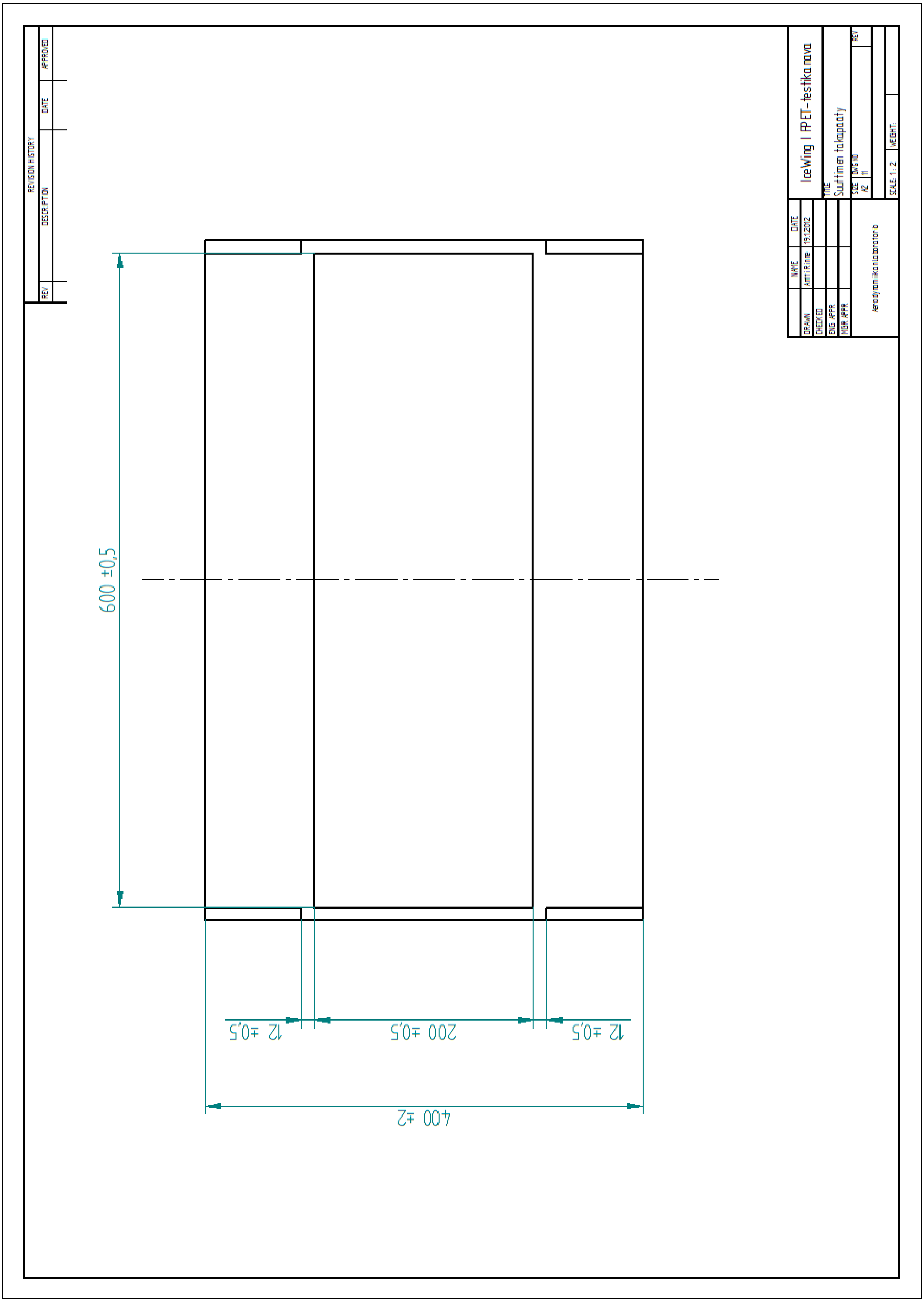

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FPET-testikanava
TITLE
Diffuusorin takapääty
SIZE
A2
DWG NO
REV
SCALE 1 : 2
WEIGHT:
NAME
DATE
DRAWN
Antti Rinne
19.1.2012
CHECKED
ENG APPR
MGR APPR
Aerodynamiikan laboratorio
12
600 ±1
12
12
300 ±1
12
Seinien sekä ylä- ja alapinnan päädyissä pyöristys R 6.

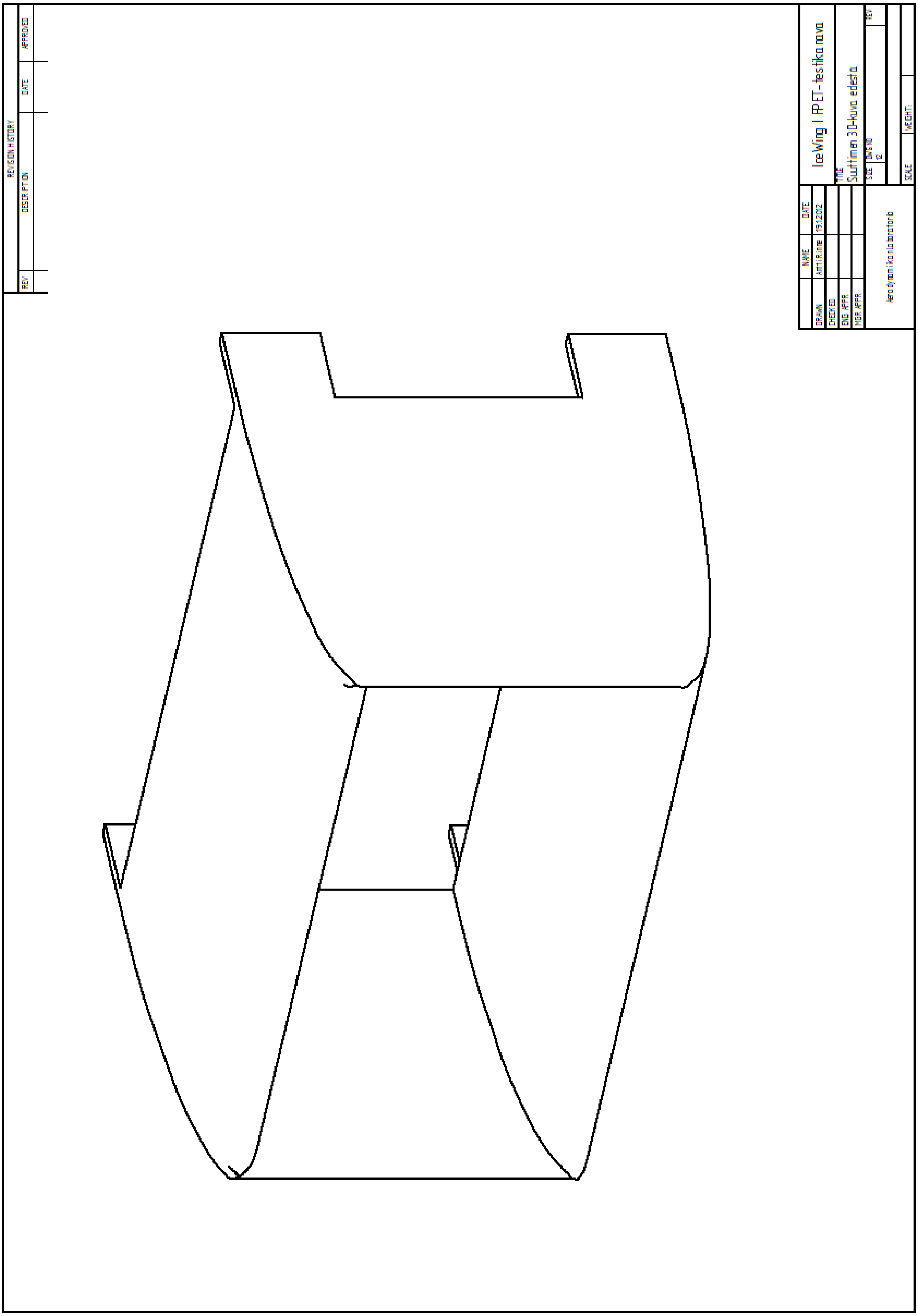

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I PET-testikanava
TITLE
Suuttimen seinät
SIZE
A2
DWG NO
REV
SCALE 1 : 2
WEIGHT
NAME
DATE
DRAWN
Antti Riihinen
19.1.2012
CHECKED
ENG APPR
MGR APPR
Aerodynamiikan laboratorio
400 ±2
224 ±0,5
80 ±0,5
430 ±2
300 ±2
Valmistus filmivanerilevystä s = 12 mm

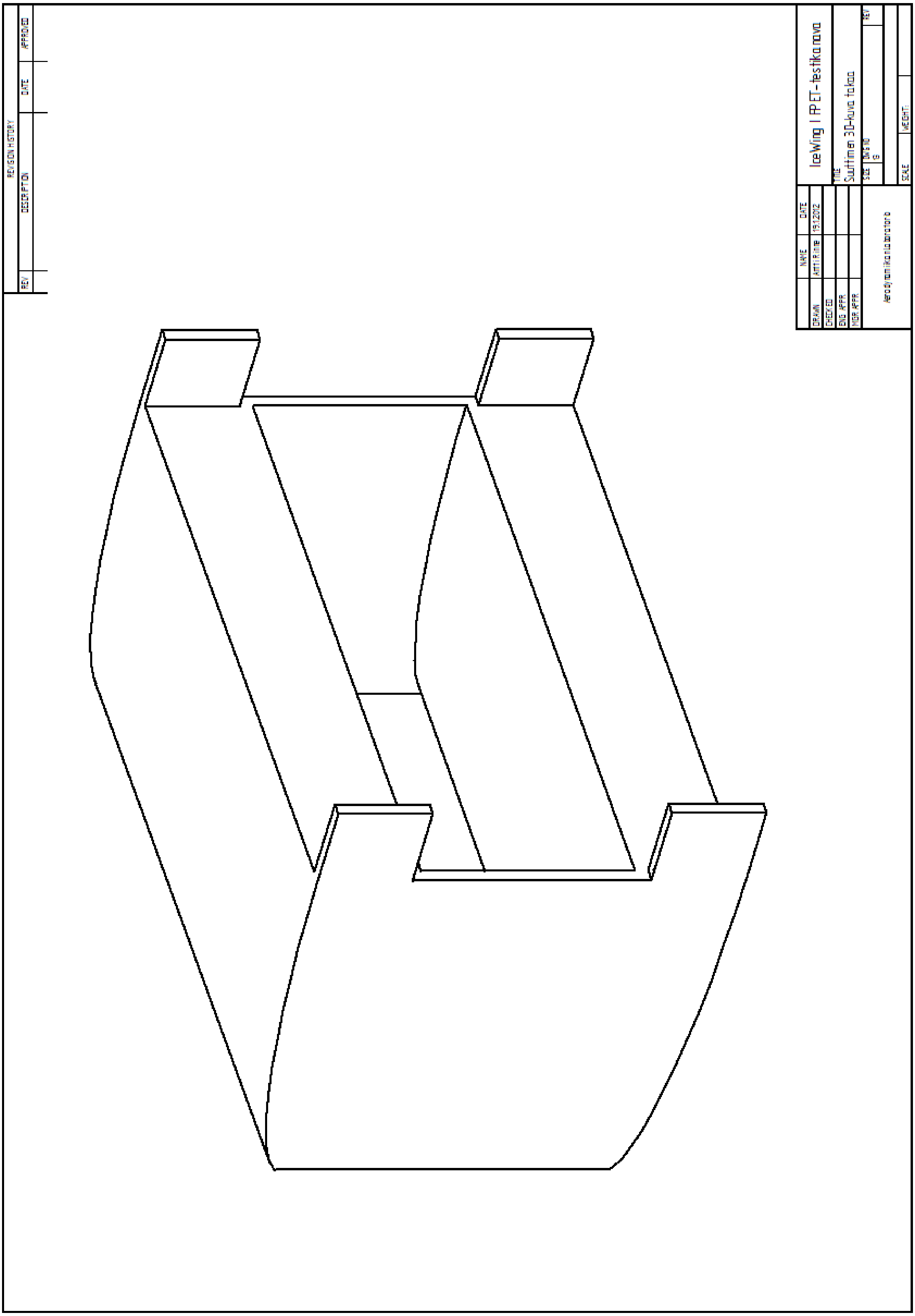

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
100
350
IceWing I FPET-testikanava
TITLE
Suuttimen ellipsimuoto
SIZE A2
DWG NO 9
REV
SCALE 1 : 1
WEIGHT:
NAME
DATE
DRAWN
Antti Rinne
19.1.2012
CHECKED
ENG APPR
MGR APPR
Aerodynamiikan laboratorio

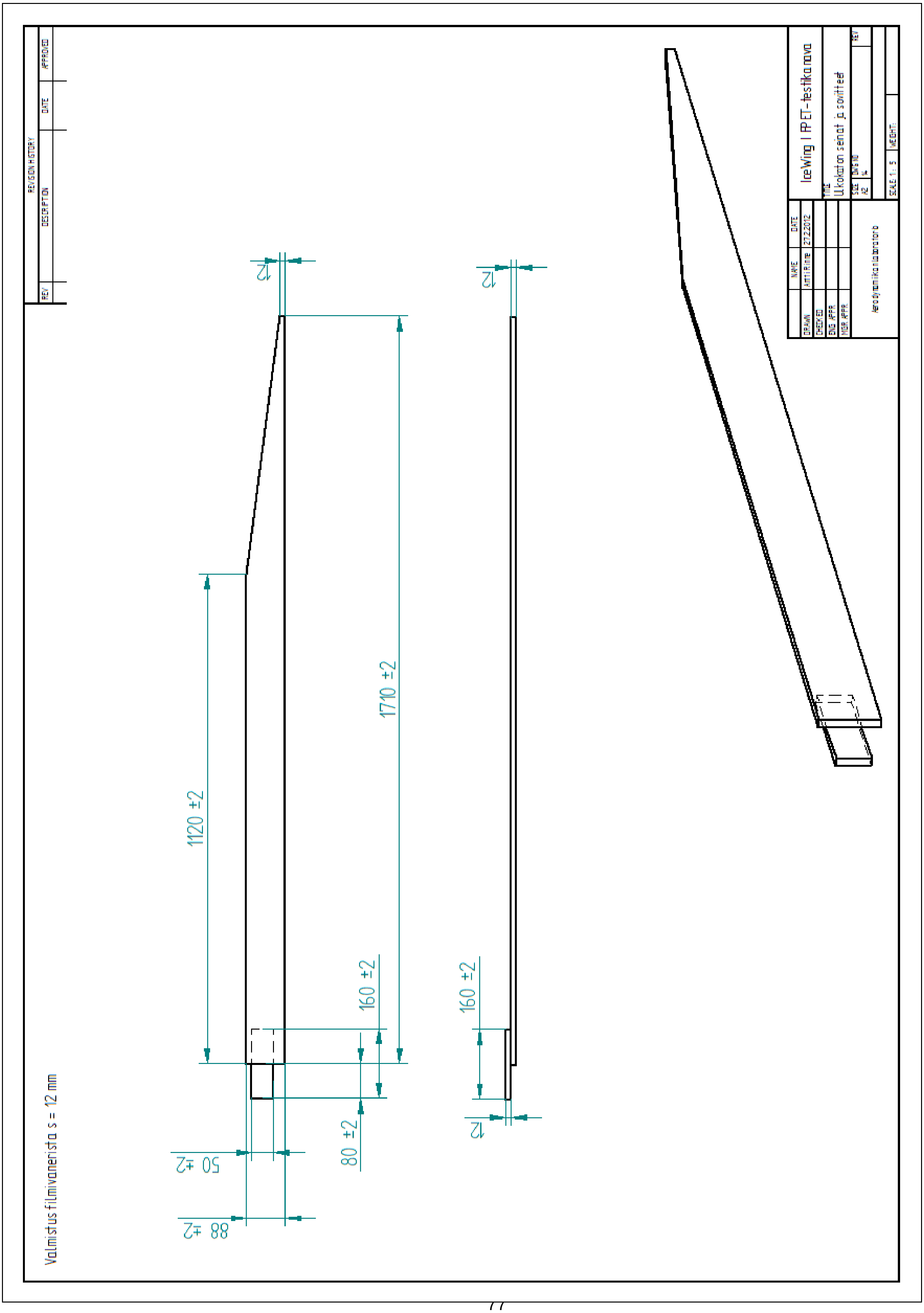


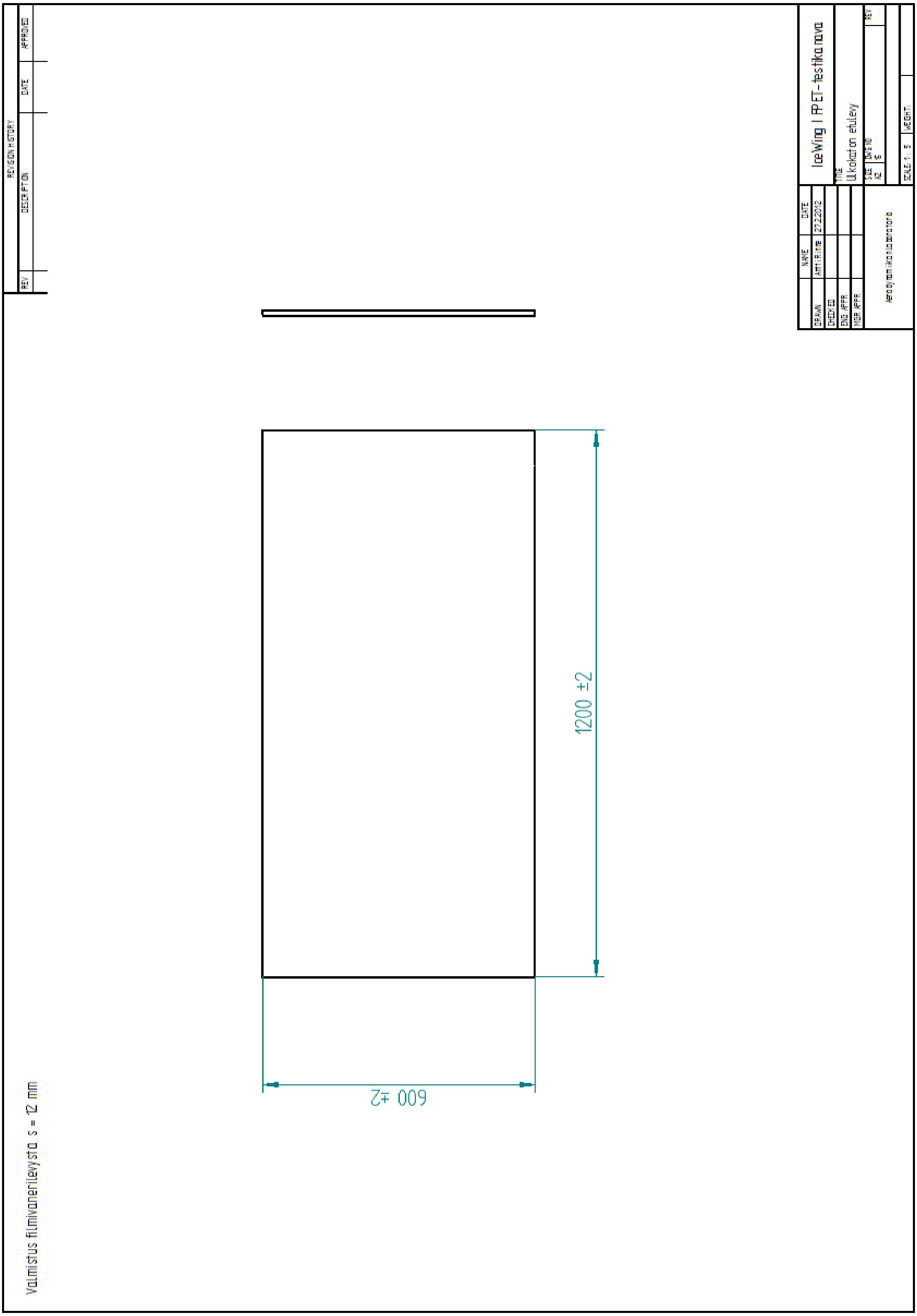
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
12
600 ±1
12
300 ±2
Yla - ja alapinta ovat piirustuksen 9 mukaisia ellipseja, joiden etureunojen etaisyys toisistaan on 300 mm.
IceWing I FPET-testikanava
TITLE
Suuttimen etupaaty
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
Antti Rinne
19.1.2012
SIZE
A2
DWG NO
10
REV
SCALE 1 : 2
WEIGHT:
Aerodynamiikan laboratorio

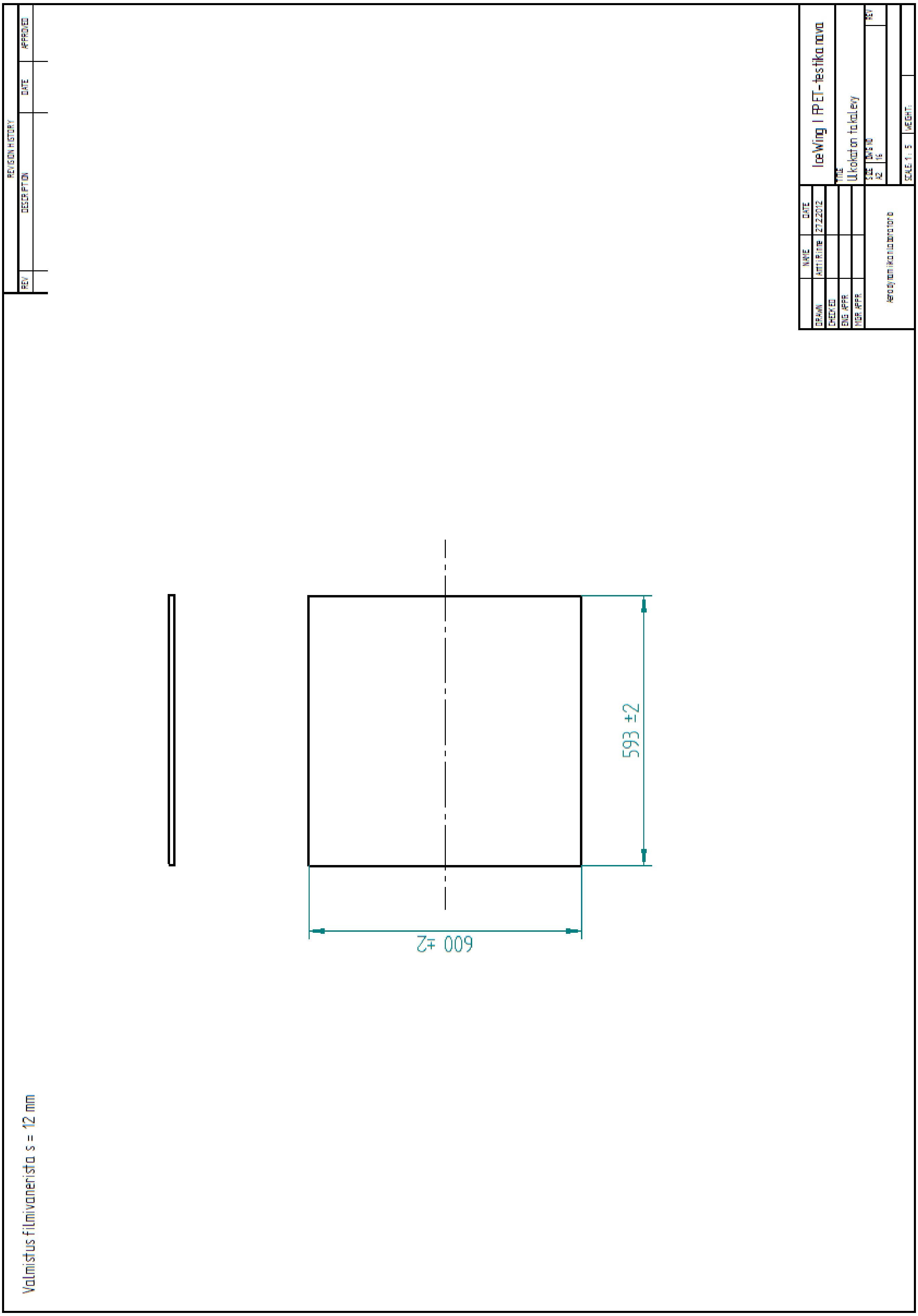

IceWing I FPET-testikanava
Suutimen takapääty
Antti Rinne
19.1.2012
Aerodynamiikan laboratorio
SCALE 1 : 2
600 ±0,5
12 ±0,5
200 ±0,5
12 ±0,5
400 ±2

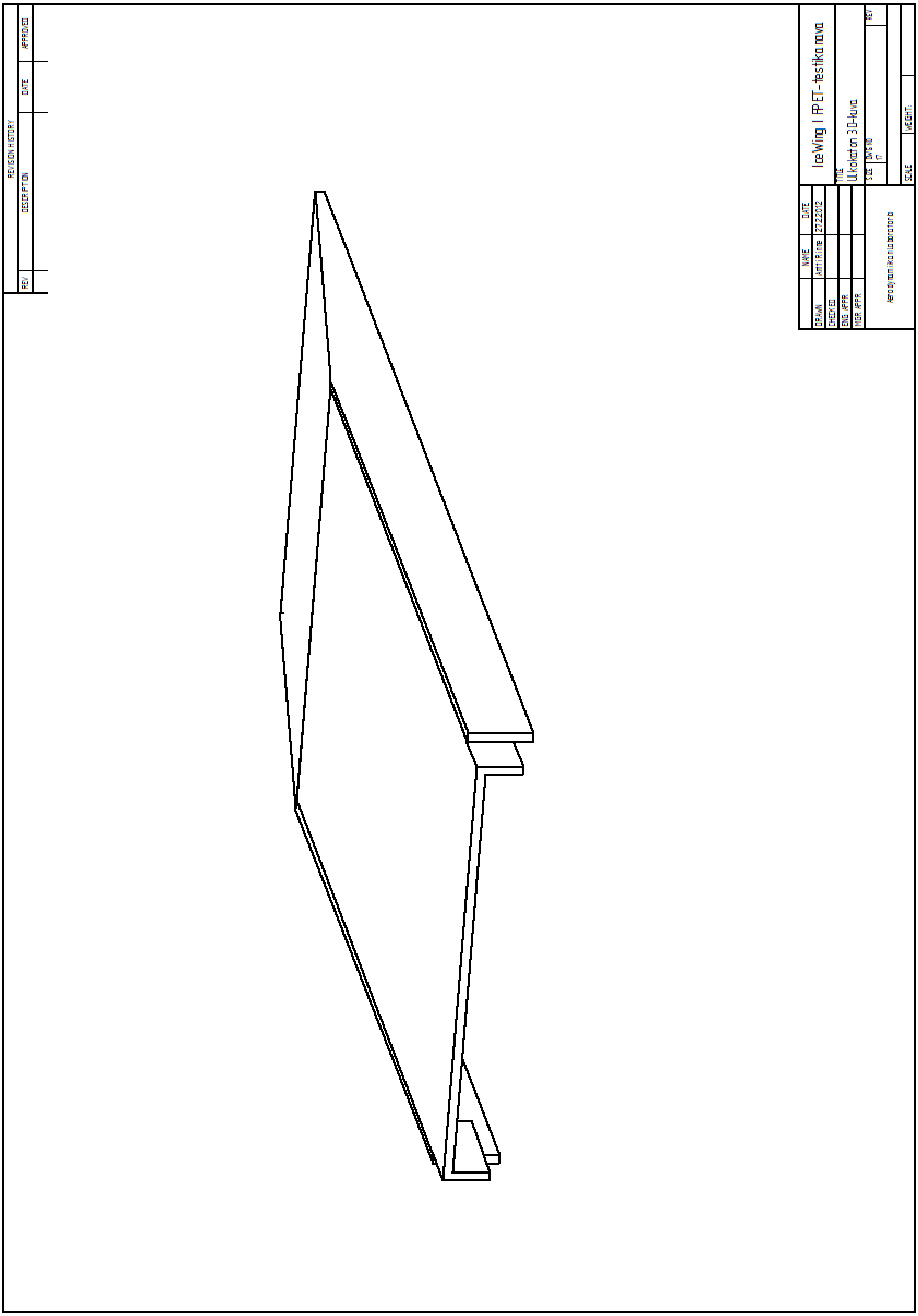

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FPET-testikanava
TITLE
Suuttimen 3D-kuva edesta
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
19.1.2012
SIZE
DWG NO
REV
SCALE
WEIGHT:

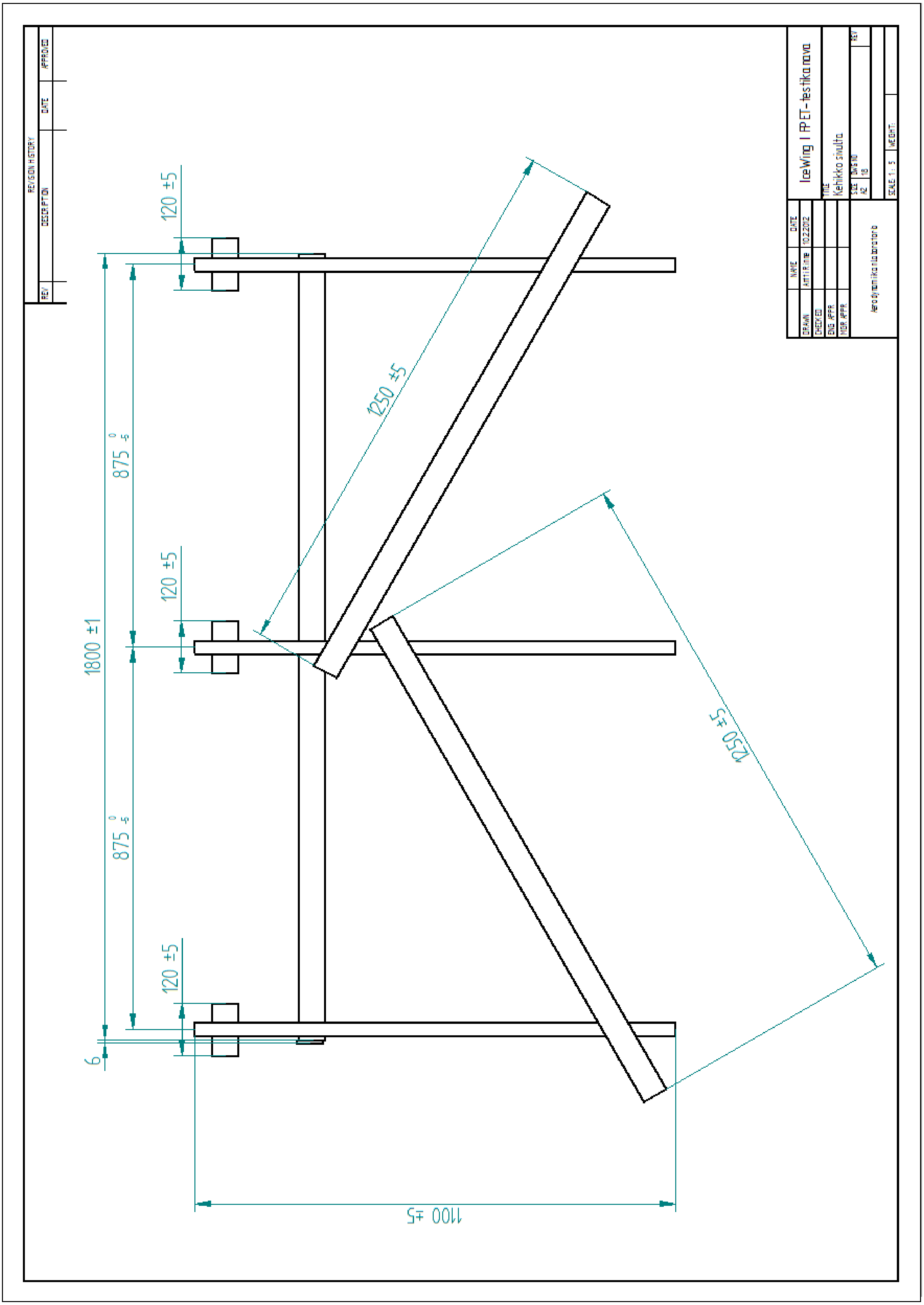

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FPET-testikanava
TITLE
Suuttimen 3D-kuva takaa
NAME
DATE
DRAWN
Antti Rinne
19.12.2012
CHECKED
ENG APPR
MGR APPR
SIZE
DWG NO
REV
SCALE
WEIGHT:
Aerodynamiikan Laboratorio

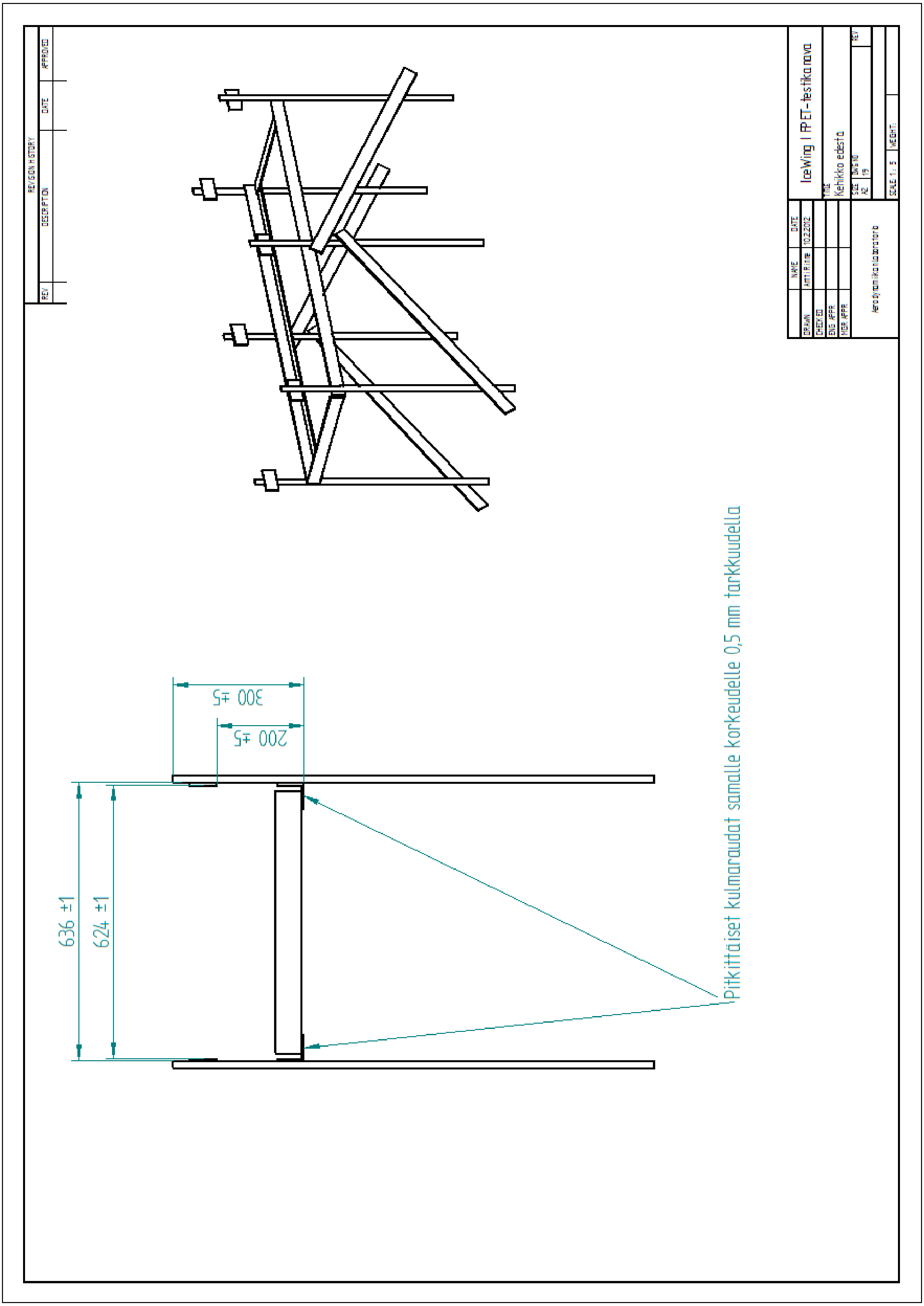

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
Valmistus filmivanerista s = 12 mm
12
1710 ±2
1120 ±2
160 ±2
80 ±2
50 ±2
88 ±2
12
160 ±2
12
IceWing I FPET-testikanava
TITLE
Ulkokaton seinät ja sovitteet
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
Antti Rinne
DATE
27.2.2012
Aerodynamiikan laboratorio
SIZE
A2
REV
SCALE 1 : 5
WEIGHT:

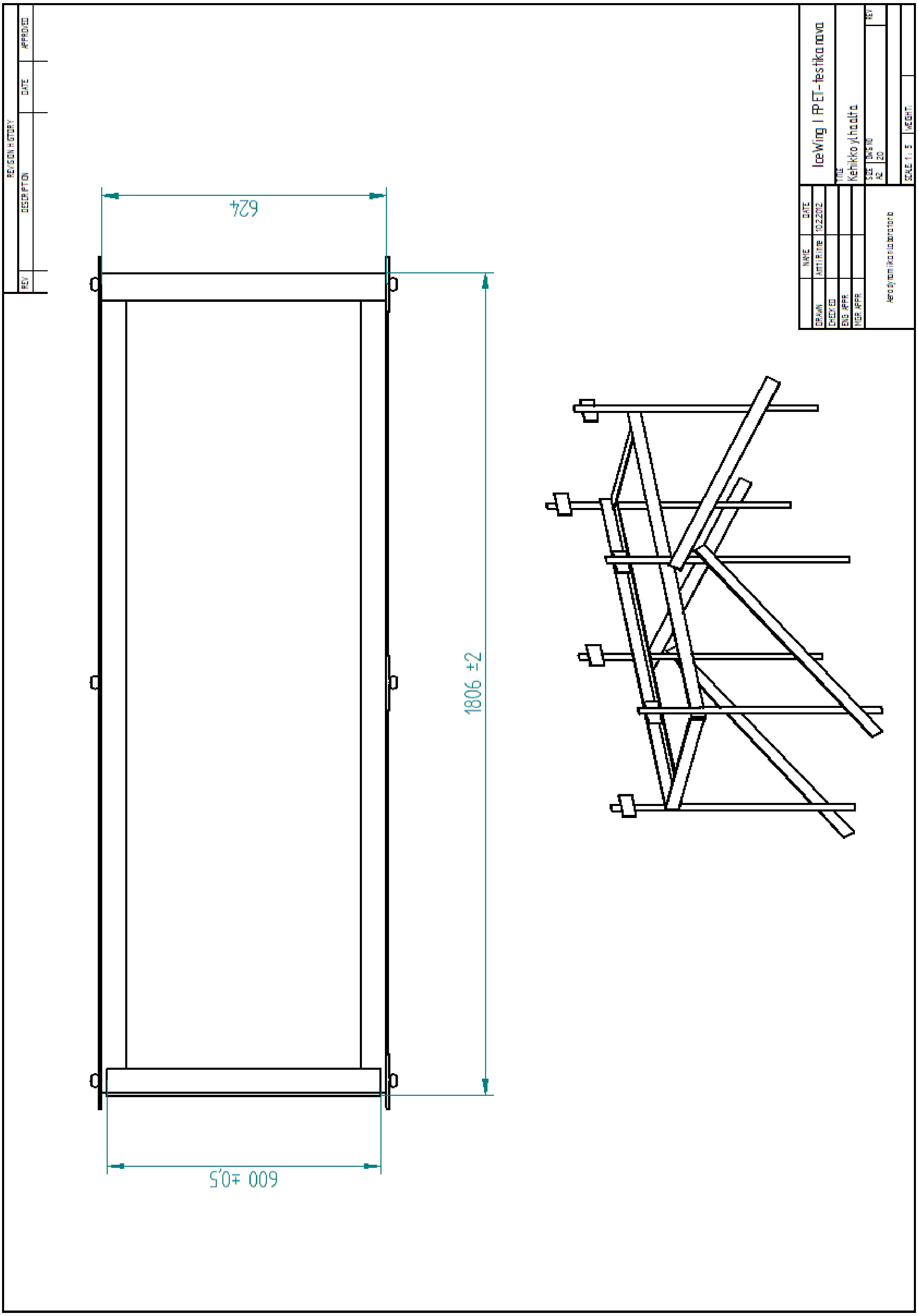

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FPET-testikanava
TITLE
Ulkokaton etulevy
SIZE
A2
DWG NO
REV
SCALE 1 : 5
WEIGHT:
NAME
DATE
DRAWN
Antti Rinne
27.2.2012
CHECKED
ENG APPR
MGR APPR
Aerodynamiikan laboratorio
1200 ±2
600 ±2
Valmistus filmivanerilevystä s = 12 mm

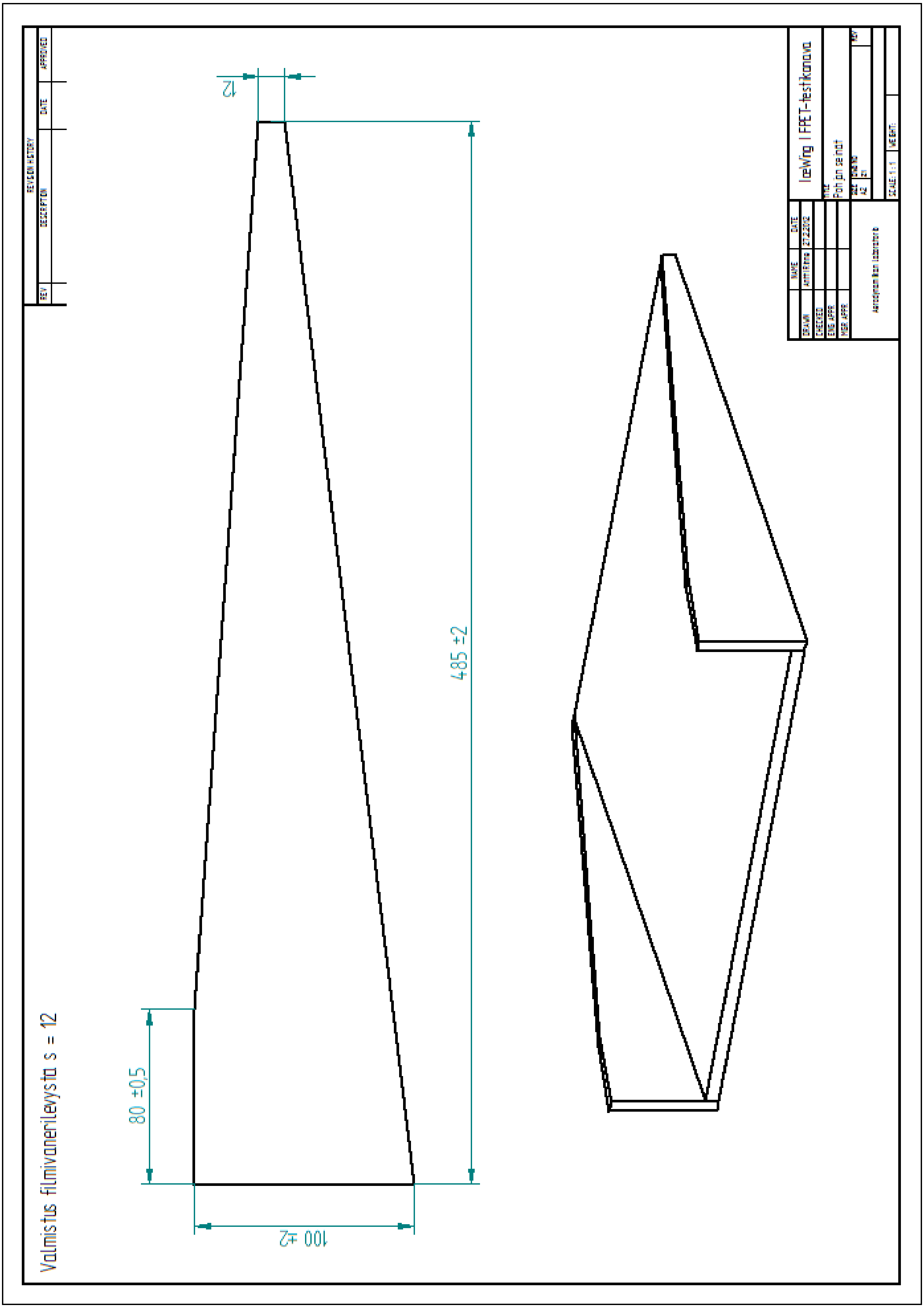

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FPET-testikanava
TITLE
Ulkokaton takalevy
SIZE
A2
DWG NO
16
REV
SCALE 1 : 5
WEIGHT:
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
Antti Riime
DATE
27.2.2012
Aerodynamiikan laboratorio
593 ±2
600 ±2
Valmistus filmivanerista s = 12 mm

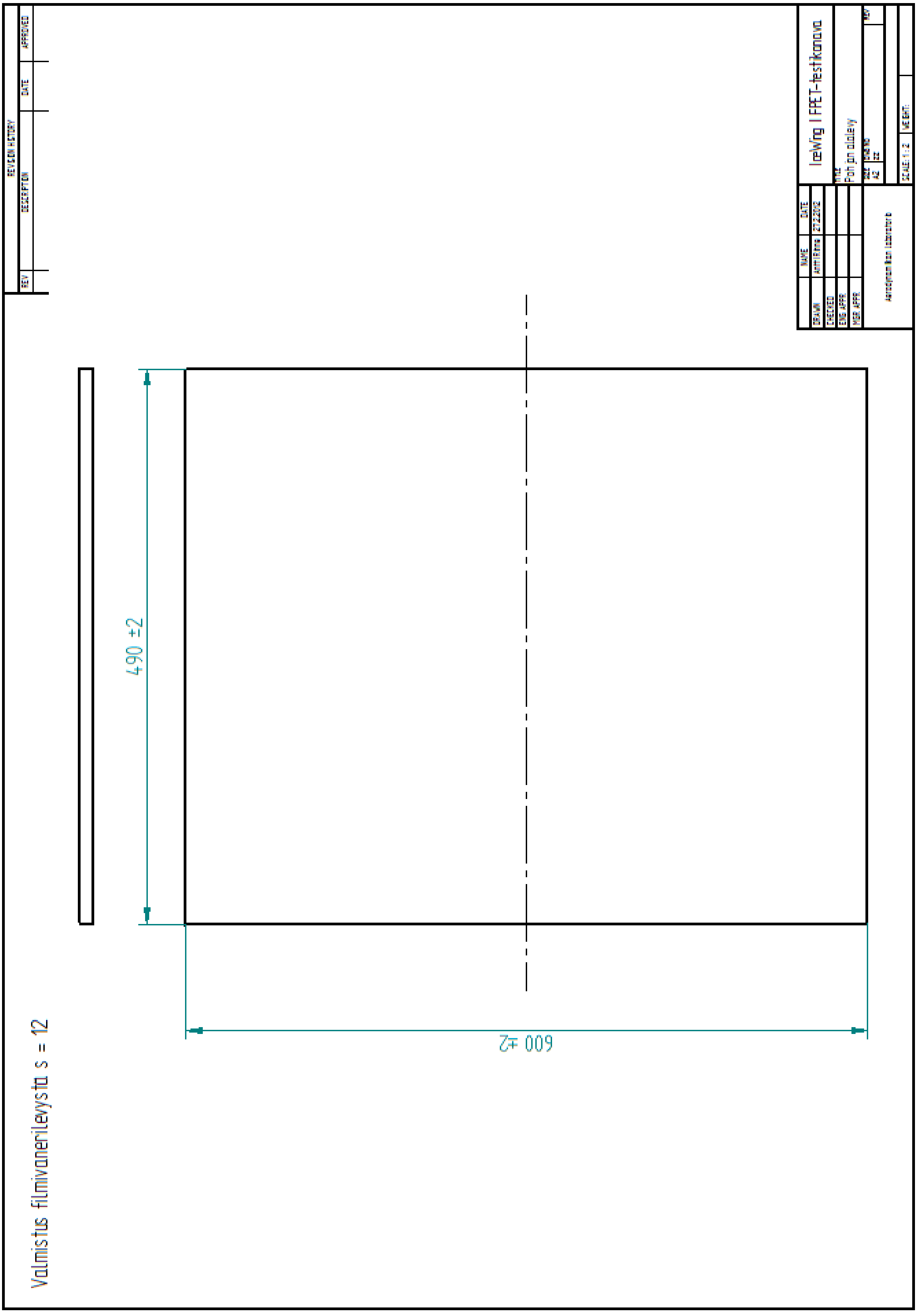

REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
NAME
DATE
DRAWN
Antti Rinne
27.2.2012
CHECKED
ENG APPR
MGR APPR
IceWing I FPET-testikanava
TITLE
Ulkokaton 3D-kuva
SIZE
DWG NO
17
REV
Aerodynamiikan laboratorio
SCALE
WEIGHT:


IceWing I FPET-testikanava
Kehikko sivulta
1800 ±1
875
875
120 ±5
120 ±5
120 ±5
1250 ±5
1250 ±5
1100 ±5
6
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
TITLE
SCALE 1 : 5
WEIGHT


IceWing I FPET-testikanava
Kehikko edestä
Pitkittäiset kulmaraudat samalle korkeudelle 0,5 mm tarkkuudella
300 ±5
200 ±5
636 ±1
624 ±1
REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
DRAWN
CHECKED
ENG APPR
MGR APPR
NAME
DATE
TITLE
SIZE
A2
DWG NO
19
REV
SCALE 1 : 5
WEIGHT:


IceWing I FPET-testikanava
Kehikko ylhäältä
624
1806 ±2
600 ±0,5
Aerodynamiikan laboratorio


IceWing I FRET-testikanava
Pohjan seinät
SCALE: 1:1
WEIGHT:
12
485 ±2
80 ±0,5
100 ±2
Valmistus filmivanerilevystä s = 12



REVISION HISTORY
REV
DESCRIPTION
DATE
APPROVED
IceWing I FRET-testikanava
TITLE
Pohjan alalevy
DRAWN
CHECKED
NAME
DATE
SCALE 1:2
WEIGHT
490 ±2
600 ±2
Valmistus filmivanerilevystä s = 12