Winter Contaminants on Surfaces During Friction Tests at Munich Airport – February 2000

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and
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16. Abstract

The Joint Winter Runway Friction Measuring Program (JWRFMP) was extended to include trials at Munich Airport in Germany during the week of February 21-27, 2000. Thirteen ground-friction measuring devices from different countries were assembled and used at Munich Airport. During the week, five commercial passenger aircraft also participated in the tests. They included one Airbus A320-DALAE from Aero Lloyd airline, one Airbus A321 from Sabena airline, one Boeing B737-300 from Deutsche British Airways, one Dornier D328-100 from Dornier aircraft manufacturer and one Airbus A319 from Swissair airline. This report concerns information on environmental conditions during the tests and surface contaminants collected during the tests. Due to the environmental limitations, man-made winter contaminants from stored snow were used for testing. Consequently, most of the tests were carried out under conditions that may be far from real-life airport operational conditions. The highlight of the Munich program was a test series of 12 ground-friction measuring devices running parallel to each other at the same time on a 600-m long uniform, flawless pavement covered with a uniform layer of freshly fallen snow.

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16. Résumé

Le Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH) a été élargi pour englober des essais menés à l'aéroport du Munich, en Allemagne, du 21 au 27 février 2000. Ces essais mettaient en jeu treize appareils de mesure du frottement au sol, provenant de différents pays, de même que cinq avions commerciaux de passagers, soit un Airbus A320-DALAE de la compagnie Aero Lloyd, un Airbus 321 de Sabena, un Boeing B737-300 de Deutsche British Airways, un Dornier D328-100 de l'avionneur Dornier et un Airbus A319 de Swissair. Ce rapport donne des renseignements sur les conditions environnementales dans lesquelles se sont déroulés les essais et sur les contaminants colligés au cours de ces travaux. Vu les faibles précipitations naturelles, les chercheurs ont eu recours à de la neige ramassée et mise en dépôt lors de précipitations antérieures, pour produire des contaminants artificiels. Par conséquent, la plupart des essais ont été réalisés dans des conditions qui ne représentent pas nécessairement les conditions normales d'exploitation d'un aéroport. Le point saillant du programme de Munich était la mise à l'essai simultanée de 12 appareils de mesure du frottement au sol, suivant des trajectoires parallèles sur une piste uniforme et sans défaut de 600 m de longueur, couverte d'une couche uniforme de neige fraîche.

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EXECUTIVE SUMMARY

A five-year project was initiated in December 1995 to understand and to quantify the factors that influence aircraft braking friction and the contamination drag of various aircraft on winter contaminated runways, in order to estimate landing and take-off distances on wet and winter contaminated runways. A collaborative agreement was made between the National Aeronautics and Space Administration (NASA) and Transport Canada (TC) to conduct field tests using variously instrumented aircraft and ground friction measuring vehicles. The U.S. Federal Aviation Administration (FAA), the National Research Council Canada (NRCC) and organizations from other countries, including the Norwegian Civil Aviation Administration, eventually joined this program, which is now called The Joint Winter Runway Friction Measurement Program (JWRFMP).

The JWRFMP was extended to include trials at Munich Airport in Germany during the week of February 21-27, 2000. Thirteen ground friction measuring devices from different countries were assembled and used at the Munich Airport. During the week, five commercial passenger aircraft also participated in the tests. They included one Airbus A320-DALAE from Aero Lloyd airline, one Airbus A321 from Sabena airline, one Boeing B737-300 from Deutsche British Airways, one Dornier D328-100 from Dornier aircraft manufacturer and one Airbus A319 from Swissair airline.

This report concerns information on environmental conditions during the tests and surface contaminants collected during the tests. Due to the environmental limitations, man-made winter contaminants from stored snow were used for testing. Harvesting previously removed snow and grooming that material to create man-made snow, which was spread on the runway immediately before the tests, resulted in covers that behaved in a significantly different manner than natural snow. The density of the groomed snow was significantly higher than that of natural snow covers. The particles of stored snow were orders of magnitude larger that the size of snow particles found in freshly fallen snow. Moreover, the particle size varied across the width of the test strips made for the tests. Consequently, most of the tests were carried out under conditions that may be far from real-life airport operational conditions.

The wide (20 m or more) and long (1000 m) uniform concrete asphalt surface of the test site at Munich Airport provided an ideal, textbook-type platform for conducting vehicular tests on a winter contaminated surface. Tests could be performed with a number of vehicles at the same time, running on different tracks parallel to each other. This avoided the condition of running the vehicles in sequential manner on previously travelled and disturbed surfaces. The highlight of the Munich program was a test series of 12 ground-friction measuring devices running parallel to each other at the same time on a 600-m long uniform, flawless pavement covered with a uniform layer of freshly fallen snow. No such tests had ever been performed in the past five years of JWRFMP runway friction tests. Munich Airport is a unique facility and should be used for future testing.

SOMMAIRE

En décembre 1995, était lancé un projet quinquennal visant à mieux comprendre et quantifier les facteurs qui influent sur la performance en freinage des avions et sur la traînée due à la présence de contaminants sur les pistes, afin d'établir des distances de décollage et d'atterrissage valables pour des pistes mouillées ou contaminées. Une entente de collaboration a été conclue par la National Aeronautics and Space Administration (NASA) et Transports Canada (TC) pour la conduite d'essais en vraie grandeur, à l'aide d'avions diversement instrumentés et de véhicules de mesure du frottement au sol. La Federal Aviation Administration (FAA) des États-Unis, le Conseil national de recherches du Canada (CNRC) et des organismes d'autres pays, dont l'administration de l'aviation civile de Norvège, se sont graduellement joints au programme, que l'on désigne maintenant sous le nom de Programme conjoint de recherche sur la glissance des chaussées aéronautiques l'hiver (PCRGCAH).

Le PCRGCAH a récemment été élargi pour englober des essais menés à l'aéroport de Munich, en Allemagne, du 21 au 27 février 2000. Ces essais mettaient en jeu treize appareils de mesure du frottement au sol, provenant de différents pays, de même que cinq avions commerciaux de passagers, soit un Airbus A320-DALAE de la compagnie Aero Lloyd, un Airbus 321 de Sabena, un Boeing B737-300 de Deutsche British Airways, un Dornier D328-100 de l'avionneur Dornier et un Airbus A319 de Swissair.

Ce rapport donne des renseignements sur les conditions environnementales dans lesquelles se sont déroulés les essais et sur les contaminants colligés au cours de ces travaux. Vu les faibles précipitations naturelles, les chercheurs ont eu recours à de la neige ramassée et mise en dépôt lors de précipitations antérieures, pour produire des contaminants artificiels. Cette neige, conditionnée pour former de la neige artificielle et répandue sur la piste immédiatement avant les essais, se comportait très différemment de la neige naturelle. En effet, elle était beaucoup plus dense que la neige naturelle et ses particules étaient plus grosses de plusieurs ordres de grandeur que celles de la neige fraîche. De plus, la taille de ces particules variait d'une bande d'essai à l'autre. Par conséquent, la plupart des essais ont été réalisés dans des conditions qui ne représentent pas nécessairement les conditions d'exploitation normales d'un aéroport.

La piste de béton bitumineux, d'une largeur d'au moins 20 m, de 1 000 m de longueur et à la surface unie, sur laquelle se sont déroulés les essais de Munich, représentait une surface d'essai idéale. Car plusieurs véhicules pouvaient être essayés simultanément, sur des bandes parallèles, plutôt que séquentiellement, sur une seule et même surface, dérangée par le passage préalable d'autres véhicules. Le point saillant du programme de Munich était la mise à l'essai simultanée de 12 appareils de mesure du frottement au sol, suivant des trajectoires parallèles sur une chaussée uniforme et sans défaut de 600 m de longueur, couverte d'une couche uniforme de neige fraîche. Ce genre d'essai n'avait jamais été mené encore, au cours des cinq années d'essais de frottement du PCRGCAH. L'aéroport de Munich possède des atouts uniques, dont il y aura lieu de tirer avantage dans l'avenir.

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GLOSSARY OF TERMS

ASFTAERO	Saab Airport Surface Friction Tester
BMWSEDAN	BMW Sedan (Experimental Car)
BV11STDVIE	Trade Name for Friction Measuring Device Manufactured by Skiddometer - from Vienna airport
BV11STDZUR	Trade Name for Friction Measuring Device Manufactured by Skiddometer - from Zurich airport
ERD	Electronic Recording Decelerometer
ERDBLAZER	Electronic Recording Decelerometer in a Blazer
FAA	Federal Aviation Administration, USA
GT-STD	GripTester-Standard
IMAGSTD	Instrument de Mesure Automatique de la Glissance (Standard)
IRFI	International Runway Friction Index
IRVSTD	International Runway Friction Standard
ITTV	Instrumented Tire Test Vehicle (NASA, Langley Research Center)
JWRFMP	The Joint Winter Runway Friction Measurement Program
NASA	National Aeronautics and Space Administration
NRCC	National Research Council Canada
RFT1551100	Runway Friction Tester
SFTHANAERO	Saab Surface Friction Tester - from Hanover Airport
SFTMUNAERO	Saab Surface Friction Tester - from Munich Airport
SFTDUSAERO	Saab Surface Friction Tester - from Dusseldorf Airport
TC	Transport Canada
TDC	Transportation Development Centre of Transport Canada

Winter Contaminants on Surfaces During Friction Tests at Munich Airport – February 2000

1. INTRODUCTION

1.1 Background

In December 1995, a five-year project was initiated to understand and to quantify the factors that influence aircraft braking friction and the contamination drag of various aircraft on winter contaminated runways, in order to estimate landing or take-off distances on wet and winter contaminated runways. A collaborative agreement was made between the National Aeronautics and Space Administration (NASA) and Transport Canada (TC) to conduct field tests using variously instrumented aircraft and ground friction measuring vehicles. The Federal Aviation Administration (FAA) of the USA and the National Research Council Canada (NRCC) also joined this project as additional collaborating agencies. This was known as the NASA/FAA/TC/NRCC winter runway aircraft operation and surface friction measuring program. Several organizations from other countries (i.e., the Norwegian Civil Aviation Administration) eventually joined the program, which is now called "The Joint Winter Runway Friction Measurement Program" (JWRFMP).

The first three years of testing were conducted at North Bay airport, Ontario, Canada during the winters of 1995/1996, 1996/1997 and 1997/98. These three sets of field tests were successful in providing initial comparative data between four different types of aircraft (the NRCC Falcon 20, the NASA B737, the FAA B727 and the deHavilland Dash 8) and several ground friction measuring vehicles or devices. During the winter of 1997/98, ground vehicle testing was also conducted on specially made test tracks beside the main runway of the newly constructed Oslo international airport in Norway. JWRFMP was then expanded to include K.I. Sawyer airforce base in Michigan, USA, during the winter of 1998/99, in addition to tests at North Bay airport. NASA's newly instrumented B757 aircraft participated in this test series. North Bay was used again in January 2000 when the NRCC's Falcon 20 was the only aircraft deployed. A series of tests involving a number of passenger aircraft were then carried out at Munich airport in Germany from February 20-27, 2000.

Considerable efforts have been expended over the past several years to understand the correlation between the friction factors measured by the ground vehicles or devices on runways, and the friction coefficients derived from the performance of aircraft operating on runways (TDC, 1999; Croll et al., 1998). JWRFMP has gained increasing international support and recognition, and stakeholders are working cooperatively towards an approved International Runway Friction Index (IRFI) based on the most accurate and comprehensive data possible (TDC, 1999).

1.2 Objectives and Scope

The test objectives for the ground friction measuring vehicles were primarily to assess the effectiveness of these devices in making friction measurement on various winter contaminated runway surfaces, and to standardize their outputs into an International Runway Friction Index (IRFI). The main objective of the Munich Airport tests was the validation of IRFI correlation between the ground devices. Devices that participated under this objective included those that were harmonized in previous field tests in 1998 and 1999. The other objectives were to explore IRFI relative to aircraft-type braking performance, to explore the new IRFI reference device equipped with aircraft test tires, to develop operational runway measurement techniques for IRFI, and to expand the IRFI for slush conditions.

Thirteen ground vehicles or friction measuring devices from different countries were assembled and used at Munich Airport during the week of February 21-27, 2000. During this period five commercial passenger aircraft also participated in the tests. They included one Airbus A320-DALAE from Aero Lloyd airline, one Airbus A321 from Sabena airline, one Boeing B737-300 from Deutsche British Airways, one Dornier D328-100 from Dornier aircraft manufacturer and one Airbus A319 from Swissair airline.

This report contains information on environmental conditions during the tests and surface contaminants collected during the tests carried out at Munich Airport during the week of February 20-27, 2000. The information is presented chronologically and by test numbers. The results of the ground vehicle tests and aircraft tests will be published in separate Transport Canada (TC) reports, for which data collected by the author and recorded in TC field books will be used.

2 TEST PROGRAM

2.1 Aircraft and Ground Vehicles

Four commercial airlines participated in the program and provided opportunities for using regular passenger aircraft for the tests. Dornier aircraft manufacturing company also participated in the program by providing a D328-100 aircraft. The five aircraft used in the tests are listed below according to the order they were involved:

Airbus A320-DALAE	from Aero Lloyd airline
Airbus A321	from Sabena airline
Boeing B737-300	from Deutsche British Airways
Dornier D328-100	from Dornier aircraft manufacturer
Airbus A319	from Swissair airline

The following thirteen ground vehicles (devices) were used to conduct contaminated surface friction measurements during the test period at Munich Airport.

IMAGSTD	Instrument de Mesure Automatique de la Glissance (Standard)
IRVSTD	International Runway Friction Standard
ERDBLAZER	Electronic Recording Decelerometer in a Blazer from Transport Canada, Ottawa
BV11STDZUR	Trade Name for Friction Measuring Device Manufactured by Skiddometer - from Zurich airport
BV11STDVIE	Trade Name for Friction Measuring Device Manufactured by Skiddometer - from Vienna airport
SFTHANAERO	Saab Surface Friction Tester - from Hanover Airport
SFTMUNAERO	Saab Surface Friction Tester - from Munich Airport
SFTDUSAERO	Saab Surface Friction Tester - from Dusseldorf Airport
ASFTAERO	Saab Airport Surface Friction Tester
GT-STD	GripTester-Standard - from the U.K.
RFT1551100	Runway Friction Tester
BMWSEDAN	BMW Sedan (Experimental Car) - from Munich
ITTV26	Instrumented Tire Test Vehicle - from NASA, Langley Research Center, USA

The above list included two **I**nstrument de **M**esure **A**utomatic de la **G**lissance (**IMAG**) devices from France in two different configurations. One was designated as the regular or standard IMAG (code IMAGSTD) for control, and one was designated as the IRFI Reference Vehicle (code IRVSTD). These two devices were used in pairs for comparison purposes. The Transport Canada **E**lectronic **R**ecording **D**ecelerometer (**ERD**) mounted in a Chevrolet Blazer (code ERDBLAZER) was also used as one of the standard devices because of the correlation already established earlier with NRCC's Falcon 20 aircraft (Croll et al., 1998).

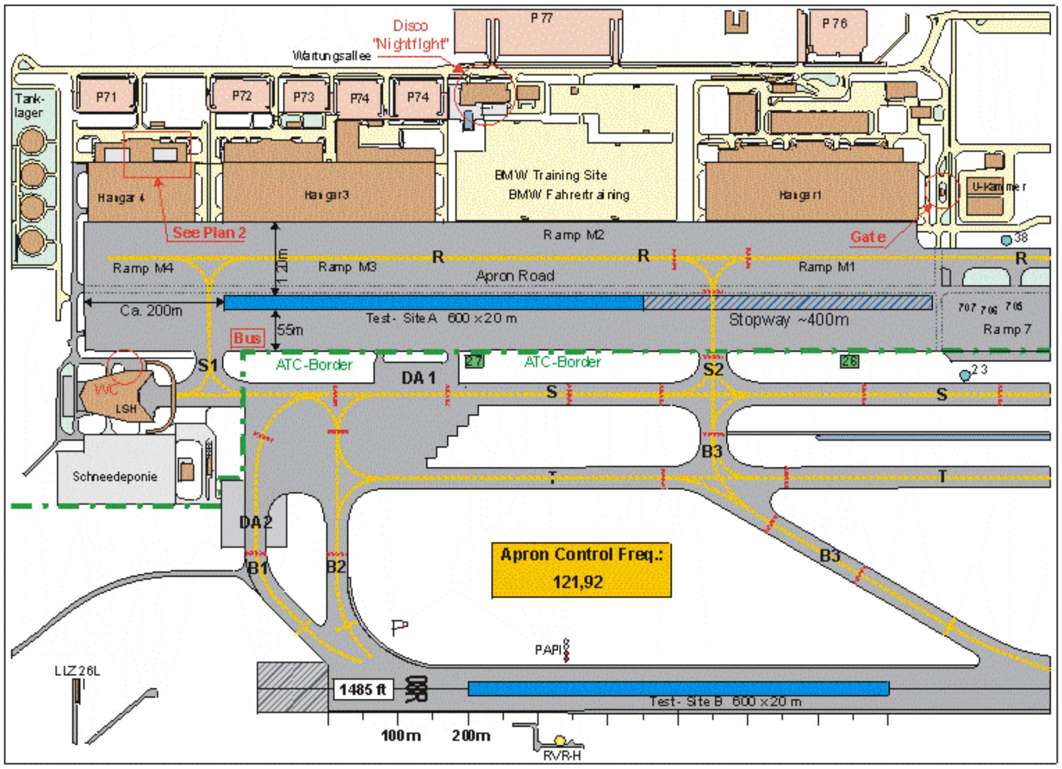

Figure 1. Section of Munich Airport used for Joint Winter Runway Friction Measurement Program (JWRFMP) in February 2000.

2.2 Test Facility

The Munich Airport authority decided to use the flight operation area of the entire "Maintenance" section (1200 m x 200 m) in the southern area of the roadway, in front of Hangars 1 to 4 as shown in Figure 1. Hangar 4 was used as the home base of the operation. The huge ramp area was made of asphalt concrete with a textured surface. The texture was produced by wire brushes moving in a wavy fashion on top of the concrete surface. This pavement was only a few years old. It was flat and almost flawless. No damaged areas or visible cracks were noticeable in the entire section. Consequently, the area provided an ideal base surface for conducting the friction tests.

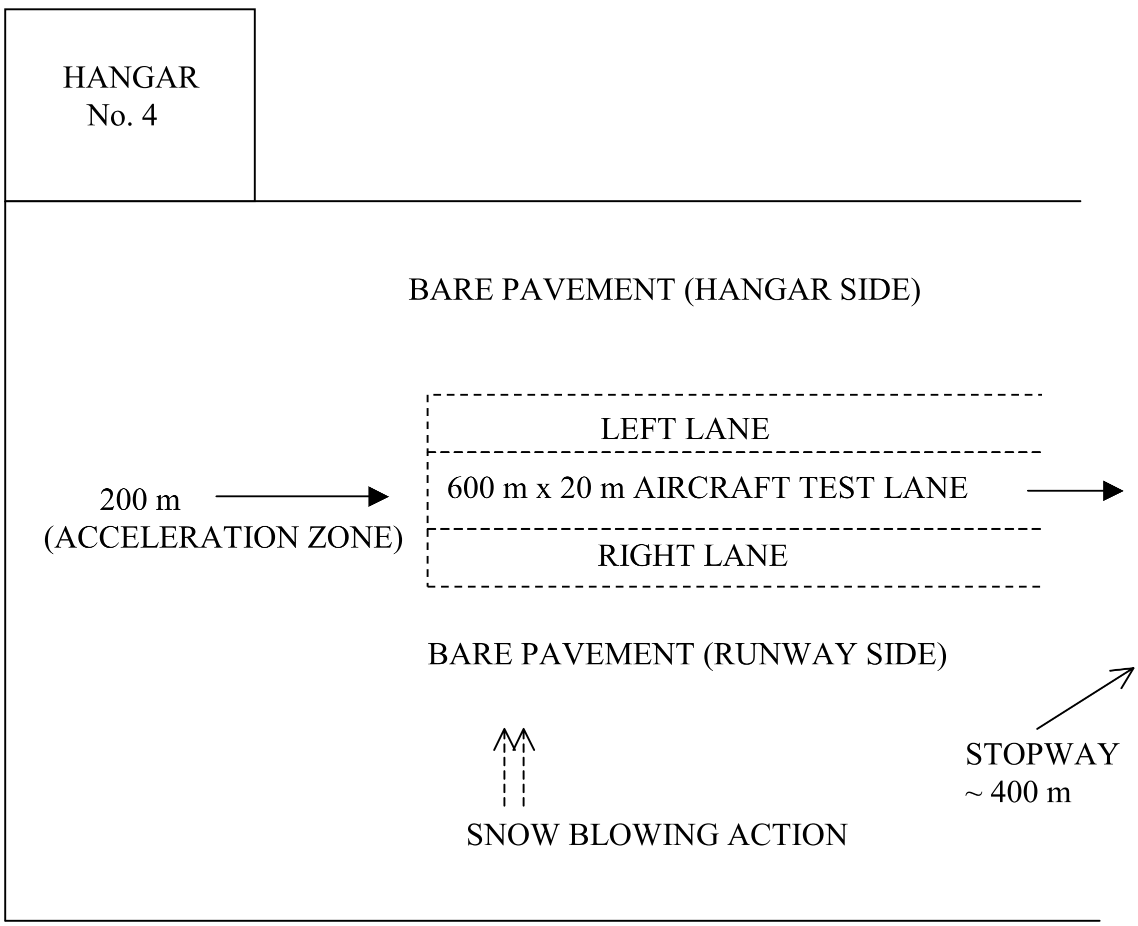

Figure 2. Schematic diagram of test site (not to scale)

According to the plan, this maintenance section was closed off for the specified duration of the friction measurements. Tests for both ground devices and aircraft were carried out in this section of the airport. Because of the generally warm weather, the surface of the 20 m wide and 600 m long test strip, as marked in Figure 1 with details given in Figure 2, were contaminated with stored snow from the disposal sites. A fleet of plough trucks and snowblowers was used in preparing the contaminated surfaces. A snow cannon, used for making artificial snow in a ski resort, was also acquired in the event that it did not snow during the test period, but the weather conditions were favourable to the production of artificial snow. This was stored in Hangar 4, which also provided a shelter for all the ground vehicles used in the tests.

The training rooms of an airline on the second floor at the north side of Hangar 4 provided the required office space and briefing room for the participants. The briefing room was well equipped with telephones, a photocopier and a fax machine. The facilities were excellent, but the hangar was huge and the walking distance between the office space and the entrance doors of the hangar, near which the test vehicles were parked, made it difficult from a communication point of view. A lot of time was wasted looking for people.

The police helicopter squadron at Munich Airport provided a helicopter for aerial photography during many of the daytime tests. This was the first use of a helicopter for taking photographs during any JWRFMP test. Video recording and still photography were used. A team of four photographers participated in this field program. Two photographers, including one from NRCC, represented Transport Canada. Two other photographers were from NASA's Langley Research Center in Hampton, VA. In addition to these four, a photographer from Munich Airport also took some photographs.

3 OBSERVATIONS

Observations made on the environmental conditions and characteristics of the contaminants on the test strip were given on a daily basis in a chronological manner. An attempt was also made here to link the author's observations with the test numbers, but this was not always possible for each and every test because of unavoidable technical difficulties due to logistics.

Still photographs were taken to keep records of ever-changing characteristics of the contaminants and the interaction processes between the contaminants, the aircraft and ground vehicle tires. These were taken in an almost continuous manner during most of the tests. The photographs taken by the NRCC photographer (Harry Turner) have been submitted to Transport Canada and are retained by the TC Aerodrome Safety Branch. The photographs taken by the NASA photographer (Margaret Hopkins), who worked closely with the author during most of the tests, have been retained by NASA's Langley Research Center.

Figure 3. An aerial view, looking towards the 08 direction of the test strip (600 m x 20 m) on the maintenance ramp between the hangars and the 08-26 runway on the right

3.1 Saturday 19 February 2000

The author arrived at Munich Airport on Saturday 19 February at 10:30 and was taken to Hangar 4 (see Figure 1) to set up his field laboratory. This was followed by a tour of the entire facilities, including an inspection of the mountain of stored snow and the grooming process of the stored snow on the test bed.

The air temperature was just above the freezing point at this time. The operation of building a man-made snow cover on the concrete surface of the test strip (600 m x 20 m) was very impressive. A number of hauling trucks brought moist and dense (density of about 700 $kg.m^{-3}$) snow from the storage area. This moist and compacted snow was dumped on the concrete surface along a row parallel to the length of the test strip. This row was about 20 m south of the runway side of the intended test strip (Figure 2). A powerful snowblower was then used to spread the snow on the test strip. It took about two hours to cover the entire test area with a layer of snow about 20 mm in thickness. After completion of the task of spreading, excess materials on both sides of the planned test strip were removed, leaving a stretch of groomed material on the test strip. An example of a man-made test bed of processed and stored snow can be seen on the right side (runway side) of the hangars in Figure 3.

Because of the high ambient air temperature and diffused sun, the snow was melting during the grooming process and developing a test bed of slush. The slush was brown in colour and contained sand and other particles. This practice of using man-made snow cover was thought to be highly successful during the initial period.

Approximately 500 m^3 of snow had been used to make the test bed. This amounted to about 350 metric tons of snow if the average density of the stored compacted snow was assumed to be 700 $kg.m^{-3}$ (Sinha, 1998). A quick estimate showed that this volume would lead to a 20 mm thick snow cover if it was assumed that the material was evenly spread over an area of 600 m x 40 m before removing the excess materials from the sides.

After practicing making a test bed, the maintenance crew started to clean the entire slush strip for next day's normal use of the area. At the request of the author, a 50 m long strip of slush was left near the entrance point or 08 end (Figure 2). The main purpose was to test whether the slush would survive through the night, when the air temperature could go down a few degrees below the freezing point. The secondary goal was to examine the sand and debris in the material that would be deposited on the surface if the slush did not survive and the water drained off.

3.2 Sunday 20 February 2000

The air temperature during the previous night did not drop significantly. Certainly the pavement temperature remained above the melting point of ice. The slush in the 50 m long test section that was left on the pavement melted completely during the night and the water drained off. The deposit of solid materials was essentially dry this morning at around 10:00. The pavement surface was covered with a layer of sand, gravel, pieces of ropes, earplugs, foam cups, wires and metallic objects like nuts and bolts. Obviously, the stored snow contained all kinds of debris picked up during the snow removal operations. The presence of sand in the snow would certainly affect the interaction processes between the tires and the pavement surface. Moreover, the presence of gravel and other foreign objects in the surface contaminants could damage aircraft during testing. In fact, a damaging incident to NRCC's Falcon 20 aircraft did occur in North Bay during tests on a strip made with stored snow containing sand and gravel. The presence of undesirable foreign objects in the contaminants and the author's concern were reported to the Munich Airport authorities.

Sunday afternoon was used to explore the potential of various working groups within the airport management team. A visit was also made to the weather forecasting station. The author learned that this group used temperature and humidity data from a number of permanent stations within the airport for monitoring and maintenance actions. These stations provide information on air temperature, pavement surface temperature, soil temperature below the pavement and the humidity of air just above the pavement surface. One of these stations (No. 38) was situated between Hangar 1 and Ramp 7 (see Figure 1). This was close to the strip to be used for friction testing. Arrangements were made to get continuously recorded data from this station.

3.3 Monday 21 February 2000

The morning was cool and calm. There had been snowfall during the night, though very sporadic. During the 30 km trip from the village of Nandlestat, where the author was staying, to Munich Airport, from 06:30 to 07:00 significant spatial variation in the depth of snow deposition on the ground was noticed. There was only a light dusting of snow on the pavement and the taxiways at Munich Airport when the author arrived there. The absence of snow was due primarily to the fact that the maintenance crew had removed all the snow deposited during the night. Unfortunately they had cleaned the test area too.

The air temperature and the pavement surface temperatures, measured by a hand-held digital thermometer, were both at –2.2ºC at 08:00. This agreed extremely well with the corresponding temperature data (Figure 4) recorded by the temperature probes at Station No. 38, near Hangar 1.

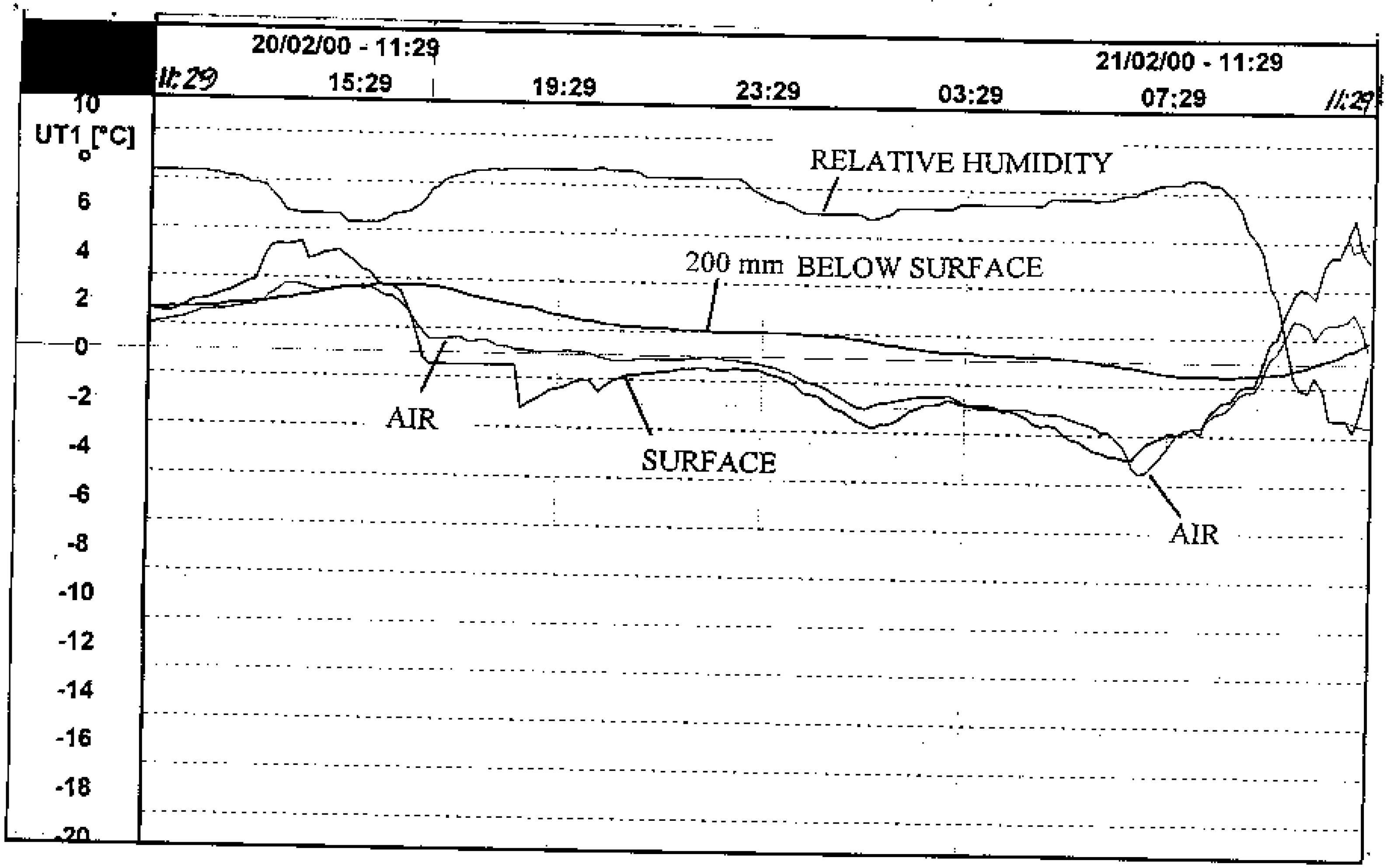

Figure 4. Air temperature, pavement surface temperature, temperature at 200 mm below the surface and relative humidity from 11:29 on Sunday 20 February 2000 to 11:29 on Monday 21 February 2000

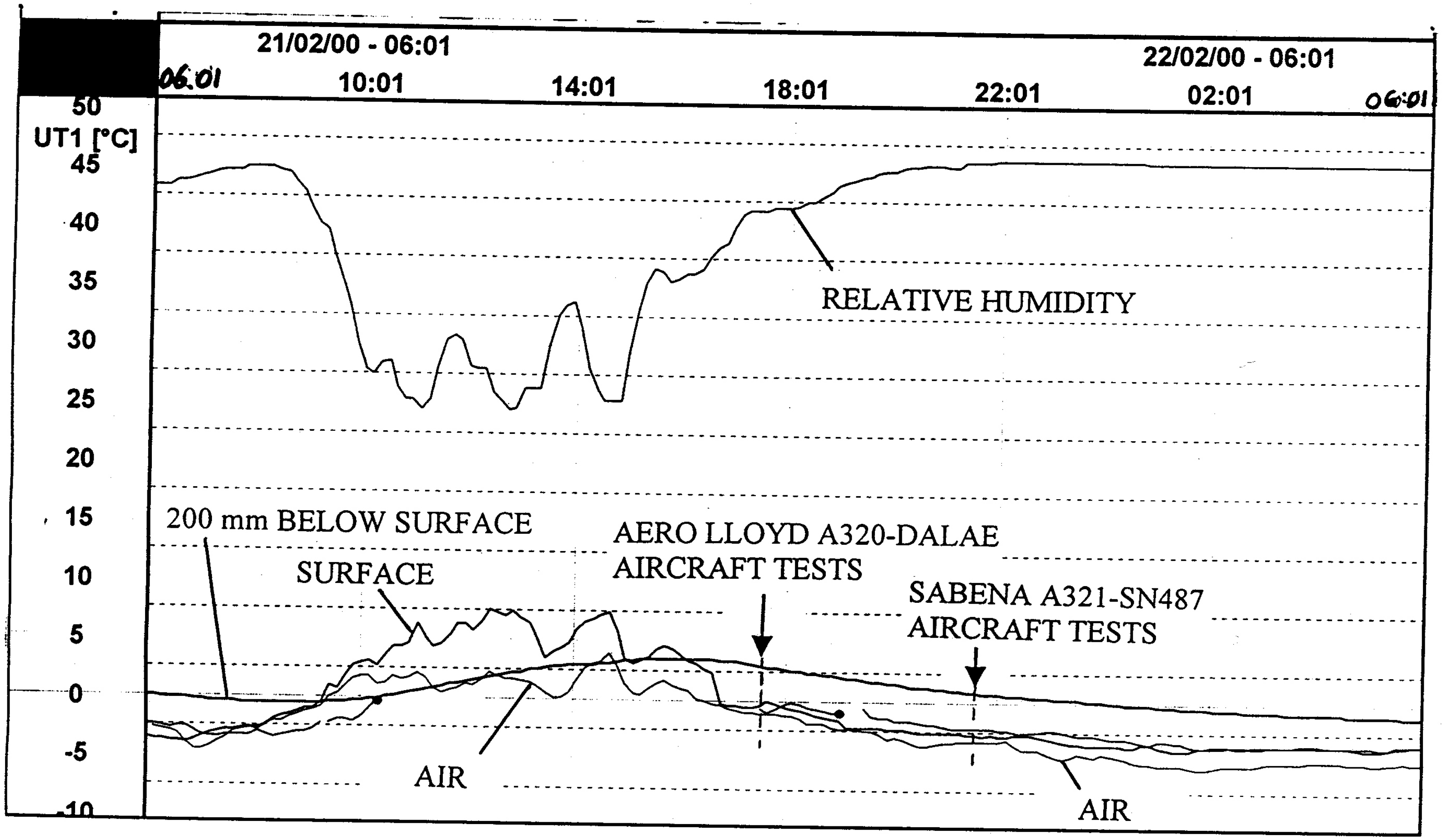

Figure 5. Air temperature, pavement surface temperature, temperature at 200 mm below the surface and relative humidity from 06:01 on Monday 21 February 2000 to 06:01 on Tuesday 22 February 2000

The briefing session for the JWRFMP tests at Munich Airport took place in the morning from 09:00 to 10:30. Mr. Thomas Torsten-Meyer of Munich Airport opened the meeting with a welcome speech. He was followed by an introductory talk on the history of the winter friction test program given by Mr. Angelo Boccanfuso of Transport Canada's Transportation Development Centre. Mr. Tom Yagar of NASA described the status of the program, after which followed discussions on the security, safety, accommodation, meals and test methods to be used for ground vehicles and aircraft, data collection and so forth.

While the meetings were going on inside the briefing room, the airport maintenance crew was busy preparing a test strip of stored and processed snow following the procedures worked out on Saturday.

At 12:00, a careful examination of the snow strip was conducted by walking along the entire length of the 600 m long strip. The snow cover was far from uniform in depth and quality. The depth of the snow cover varied from 10 mm to 20 mm. There was a gradation of snow particle size along the width of the strip. The particle size was about 1 mm to 2 mm on the right or runway side of the strip, but it increased to about 2 mm to 25 mm on the left or hangar side. Moreover, there were large aggregates in the snow, some of which were as large as 50 mm. This was because of the blowing process used to spray snow on the pavement from the runway side. The blowing process also affected the distribution of the debris on the strip. The runway side was relatively cleaner than the hangar side. Large debris was thrown away to the other side. The snow density in the middle of the strip was measured to be 0.786 $kg.m^{-3}$. This high density for processed snow was consistent with previous observations (Sinha, 1998).

The unusually large snow particles noticed here were developed because of morphological changes that had occurred during the storage of ploughed snow dumped at the storage site. However, this bed also consisted of some freshly fallen (during the previous night) snow collected from the pavement, including the test bed. Consequently, the test bed consisted of a mixture of old and new processed snow. Comparatively speaking, this test section was more uniform than that produced on Saturday 19 February using only old snow. There were stones, sand and other unwanted foreign objects in this bed also, but their numbers and sizes were smaller than those seen on Sunday 20 February in the leftover 50 m long section, from that made on Saturday.

Air temperature (T_a) was –0.3ºC and the temperature of snow (T_s) was –0.3ºC at 12:10. The air temperature was comparable to the recorded data in Figure 5, but the pavement surface temperature here (without any snow cover) was certainly higher than that at the test bed. Under the snow cover at the test site, the pavement surface temperature was close to 0ºC.

The first series of calibration tests (**Test No. 0052.1**), involving IRVSTD and IMAGSTD at a speed of 65 km/h, were conducted at 12:45 on the extreme right-hand side (runway side) of the strip. Here the snow particles were relatively small – about 1 mm in diameter. It was partly cloudy at this time and there was diffused sun. The air temperature was still just below the freezing point (–0.3ºC) at this time, but the snow temperature had increased to 0ºC because of the diffused sun and it started to melt. Three runs were made and it took about 10 minutes to complete these runs.

Test No. 52.2, involving 3 runs using IRVST and GT-STD, was made between 13:01 and 13:07 on the extreme left-hand side (hangar side). On this side the particles ranged from 2 mm to 25 mm and some aggregates were as large as 50 mm in diameter. The moisture content was high – about 10%.

Test No. 52.3, involving 3 runs using IRVST and RFT1551100, was made between 13:10 and 13:19 on the extreme right-hand side (runway side).

Test No. 52.4, involving 3 runs using IRVST and ERDBLAZER, was made between 13:23 and 13:30 on the extreme left-hand side (hangar side). At this time, T_a increased to + 0.6ºC, but it started to snow and the wind started to blow.

As planned, **Aero Lloyd Airbus A320 DALAE** aircraft arrived at the test site at around 16:30 when most of the snow on the test track was gone excepting a 5 m to 7 m wide track in the middle. This was slush containing about 50% water. However, the air temperature started to drop (Figure 5) and heavy snow flurry activities started. Visibility decreased to about 400 m. The solid precipitation certainly increased the viscosity of the slush. In fact, at one point, the entire test strip appeared to be covered with fresh snow. There was some accumulation (about 5 mm) of freshly fallen snow on top of the slush. The aircraft tests were completed within about 20 minutes at around 17:00. During this time, T_a = –1.0ºC. The passage of the aircraft, however, melted the snow in the central lane used by the aircraft. Figure 6 clearly shows the movement of snow and slush when the aircraft performed a braking run. It also shows the pavement covered with freshly fallen snow.

Figure 6. View of Aero Lloyd Airbus A320-DALAE aircraft during a braking run on Monday 21 February 2000. Note the freshly fallen snow in the foreground.

Test No. 52.5, involving IRVST and ERDBLAZER, was made at 17:58. These runs were made on a pavement that was covered by a mixture of snow and slush, because the warm pavement was melting the freshly fallen light snow particles in the form of 0.5 mm diameter granules.

Test No. 52.6, involving 11 out of 13 devices (excepting SFTMUNAERO and ITTV), was carried out during the period 18:46 to 19:20. This series consisted of two loops around the right and left lanes. At this time T_a = –1.8ºC, but the test lanes consisted of slush 2 mm to 3 mm in thickness. This slush essentially consisted of freshly fallen snow. However, there were sand and other particles in the slush. These objects were in the stored snow that was initially used to make the test bed.

Around 19:00, the maintenance crew started to haul stored snow and build a new strip in the test section. The evening was ideal from an environmental point of view. There was no wind during this operation and the air temperature was around –3ºC and decreasing (Figure 5). The process of blowing the snow in the cold air allowed the material to cool down. It also allowed the material to dry because of the freezing of internal moisture. The crew completed their job by about 21:00, when the author took the opportunity to examine the strip. It was certainly more even than the previous strips. The thickness varied from 10 mm to 20 mm. The snow was almost dry. However, as before there was a gradation of particle size across the width of the strip and there were large (golf-ball sized) ice aggregates in the contaminants. Moreover, there were also undesirable foreign objects in the material.

Aircraft tests with a **Sabena Airbus A321-SN487** were conducted on the newly prepared contaminated strip during the dark hours of the evening from 21:30 to 22:00. It was cold and damp during this time as can be seen in Figure 5. The air temperature just above the test strip was –3.2ºC and the snow temperature was –2.3ºC. The test planning was less than ideal. Most of the test crew were asked to leave and the author was not comfortable standing alone by the test track at this time in the dark without any communication link. The aircraft performed two tests – one tare and one with braking. No photographs were taken at this time because the photographers were gone. A hand-held 8 mm video camera belonging to the Munich Airport authority was used by the author to record the two aircraft tests. Fortunately the tape turned out to be fair considering the low ambient light level at the site. This videotape was handed over to the Munich Airport authorities and, although requests were made for a copy of this tape for safekeeping and submission to the data bank of the program, no such copy was made during the following days.

Ground vehicle **Test No. 52-7**, involving only IRVST and ERDBLAZER, was conducted soon after the completion of the aircraft tests.

The test strip was not cleaned after the testing. The snow was left there because of the sub-freezing air temperature.

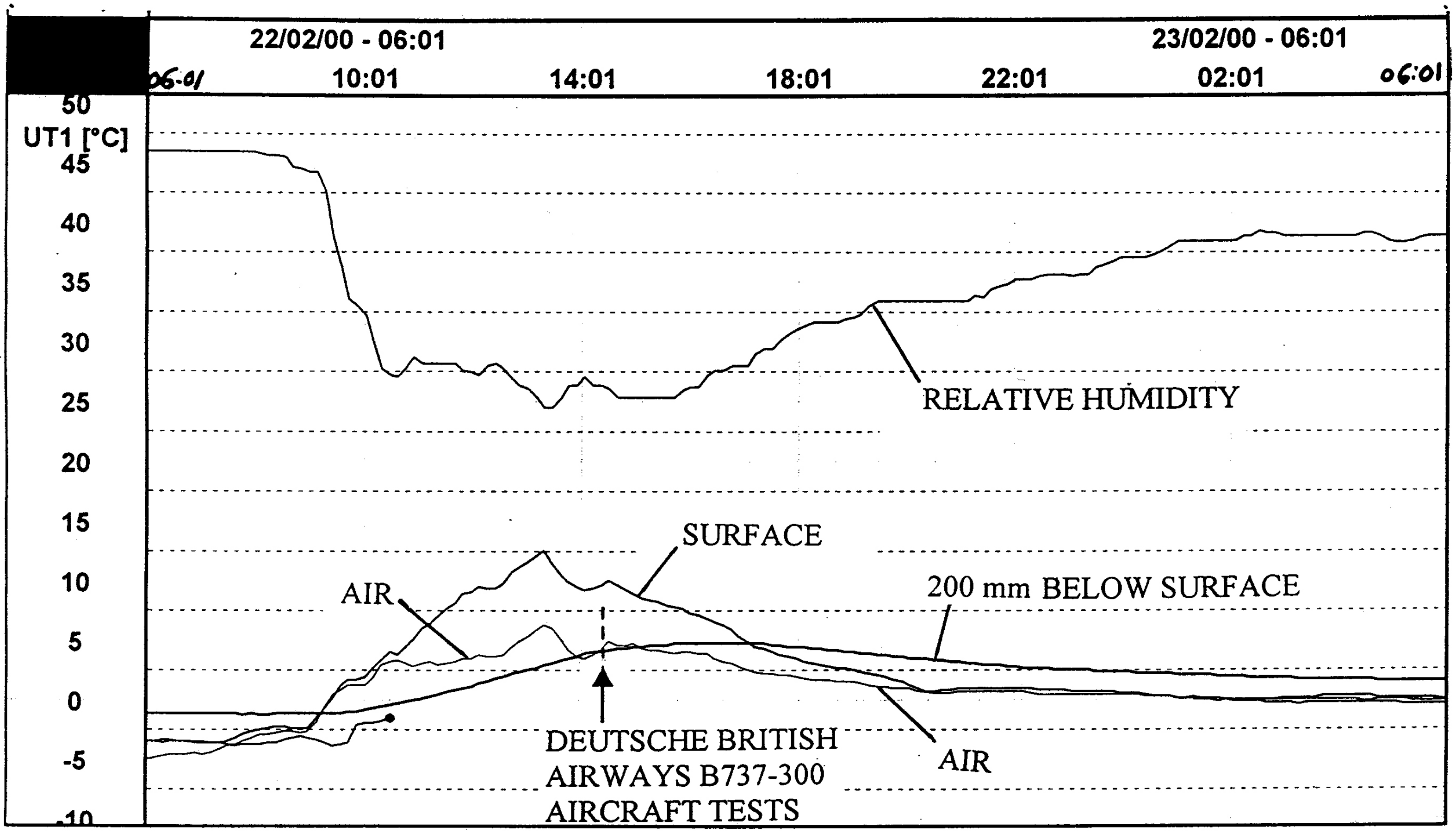

Figure 7. Air temperature, pavement surface temperature, temperature at 200 mm below the surface and relative humidity from 06:01 on Tuesday 22 February 2000 to 06:01 on Wednesday 23 February 2000

3.4 Tuesday 22 February 2000

As can be seen in Figure 5, it was cold on the evening of February 21 and the morning hours of February 22. This decreased the temperature of the contaminants and the pavement. At 07:00, when the strip was examined, both the snow and air temperatures were –3.8ºC. The low temperature allowed the ice particles on the test strip to develop bonds between them. This process of developing inter-particle bonds led to a compacted mass in the morning. However, because of aircraft and ground vehicle testing during the previous night, the contaminant strip was very uneven. The depth of snow along the lane on the runway side of the central lane was around 5 mm, whereas there were areas on the hangar side where it was as deep as 50 mm. The surface was wavy with long gullies made by the tires of the aircraft and ground vehicle.

The first series of the morning ground vehicle tests did not start until 10:47. The air temperature had climbed to 1.5ºC and a rapidly increasing trend in the air temperature was established by this time, as can be seen in Figure 7. The snow mass lost all the inter-particle bonds that had developed during the night. The particles became loose and started to melt.

Ground vehicle **Test Nos. 53-1 to 53-12** were conducted during the period 10:47 to 11:15. The last series of tests involving all the ground devices was completed at 11:15 when the air temperature rose to 3.8ºC and the test strip had become a complex mixture of slush and puddles of water. In fact, the water depth increased to 20 mm in certain areas. Conducting any tests under such conditions could not produce any results that could be related to runway operational conditions.

Immediately after the completion of the last ground vehicle test, the 600 m long test strip was cleaned and the melting snow, slush and debris were removed completely. The maintenance crew then prepared a new test strip in an efficient display of teamwork. It took about 2.5 hours to complete the job and a new strip was ready by 13:54.

The **Deutsche British Airways Boeing B737-300** aircraft was waiting at the end of the ramp for testing. Consequently, there was no time to inspect the conditions of the strip. Ground vehicle **Test No. 53-13** was conducted on the side lanes.

The first tare run by the aircraft was made at 13:55. As the aircraft went to the exit end of the track and was turning for a rerun, a quick inspection of the test strip was made. The air temperature above the test bed was 3.1ºC, and the concrete base and contaminant were in isothermal conditions; the temperature was 0ºC. The diffused sun and high ambient temperature were playing a big role in the melting process of the contaminant with low albedo (due to discolouration). There was a layer of meltwater at the interface between the cover and the base. There was dust, sand and garbage in the contaminant. As before, there was a gradation of grain size, distribution and coverage of the contaminant and debris across the width of the strip. The ice particle sizes were finer, 2 mm to 5 mm at the right side (where the ground vehicle tests were performed), but were big, up to 30 mm, on the left side where the aircraft tare run was performed. The passage of the aircraft created huge displacement and redistribution of slush with heights up to 200 mm. The tracks produced by the aircraft tires were filled with water.

Figure 8. Aerial view of Deutsche British Airways Boeing B737-300 aircraft during the second run on Tuesday 22 February 2000

A braking run by the B737-300 was conducted at 14:16. Figure 8 shows an aerial shot of the aircraft during this run. The photograph also shows the tracks left by the ground vehicles and the aircraft mentioned above. These tracks can be seen in front of the aircraft. Note four tracks on the right side of the strip, produced by the ground vehicles. Three pairs of tracks (two main gears and the nose gear), left by the aircraft during the tare run, are clearly visible on the left side of the strip. Note also the passage of snow and slush over the wing area of the aircraft. This can also be seen in Figure 9 taken from the ground level. Note the flume of slush produced by the nose gear. This photograph also shows the texture of the pavement surface, puddles of water on the pavement and the presence of large, golf-ball-sized ice particles in the contaminant.

Figure 9. Ground level view of Deutsche British Airways Boeing B737-300 aircraft during the second run on Tuesday 22 February 2000

Figure 10. View of the test track, looking towards entrance point, after the last Deutsche British Airways Boeing B737-300 aircraft test at 14:35 on Tuesday 22 February 2000

The aircraft made the third and final run at 14:35. Figure 10, looking towards the entrance point (or 26 direction), shows the condition of the test strip after completion of the last aircraft test.

Ground vehicle **Test No. 53.14**, involving all 13 devices, was conducted after 14:55.

All the contaminants were removed completely and the test strip was then cleaned as much as possible. A thin layer of meltwater, however, stayed on top of the pavement surface.

It was reported later that the aircraft's wing and flaps were damaged during the tests by the foreign objects present in the contaminant.

3.5 Wednesday 23 February 2000

Figures 7 and 11 show that the air temperature late Tuesday night and early Wednesday morning remained steady at about 0ºC or just below the freezing point. This allowed the pavement surface to cool and freeze the surface moisture. A thin layer of ice, less than 1 mm, formed on the surface.

Early in the morning, snow fell and accumulated to a depth of up to 3 mm on the icy surface in the maintenance ramp area. The deposition of snow was very uniform because of the near absence of wind in the area. At 07:00 the maintenance crew, following strict orders from the airport authorities, was in the process of removing all this natural snow cover to replace with a bed of stored snow. They had already managed to clean most of the area assigned for usual testing, but there still remained a section at least 40 m wide of undisturbed snow in the area between the cleaned strip and the hangars. The cleaners were asked to stop removing the snow. This was highly irregular, but the crew complied. Test authorities were asked to conduct a series of concurrent ground vehicle tests on this cover of virgin snow. Arrangements were then made to perform a series of tests using all 13 ground vehicles running parallel to each other at the same time on this undisturbed snow cover. It took more than an hour, however, to assemble all the devices for testing and to prepare the test plan.

The first parallel run with 12 devices, excepting the BMW experimental car, (**Test No. 54.1**) took place at 08:40 when the air temperature, T_a = 0.2, snow temperature, T_s = 0.3ºC and the pavement surface temperature, T_p = 0.5ºC.

This test, involving 12 different devices, was the best test ever performed in the last five years of JWRFMP tests. This was because of the number of different devices involved, the uniformity of the snow cover, the uniformity of the thermal regime, the flatness of the test area, the uniformity of the texture of the pavement surface, and undisturbed paths for all the devices.

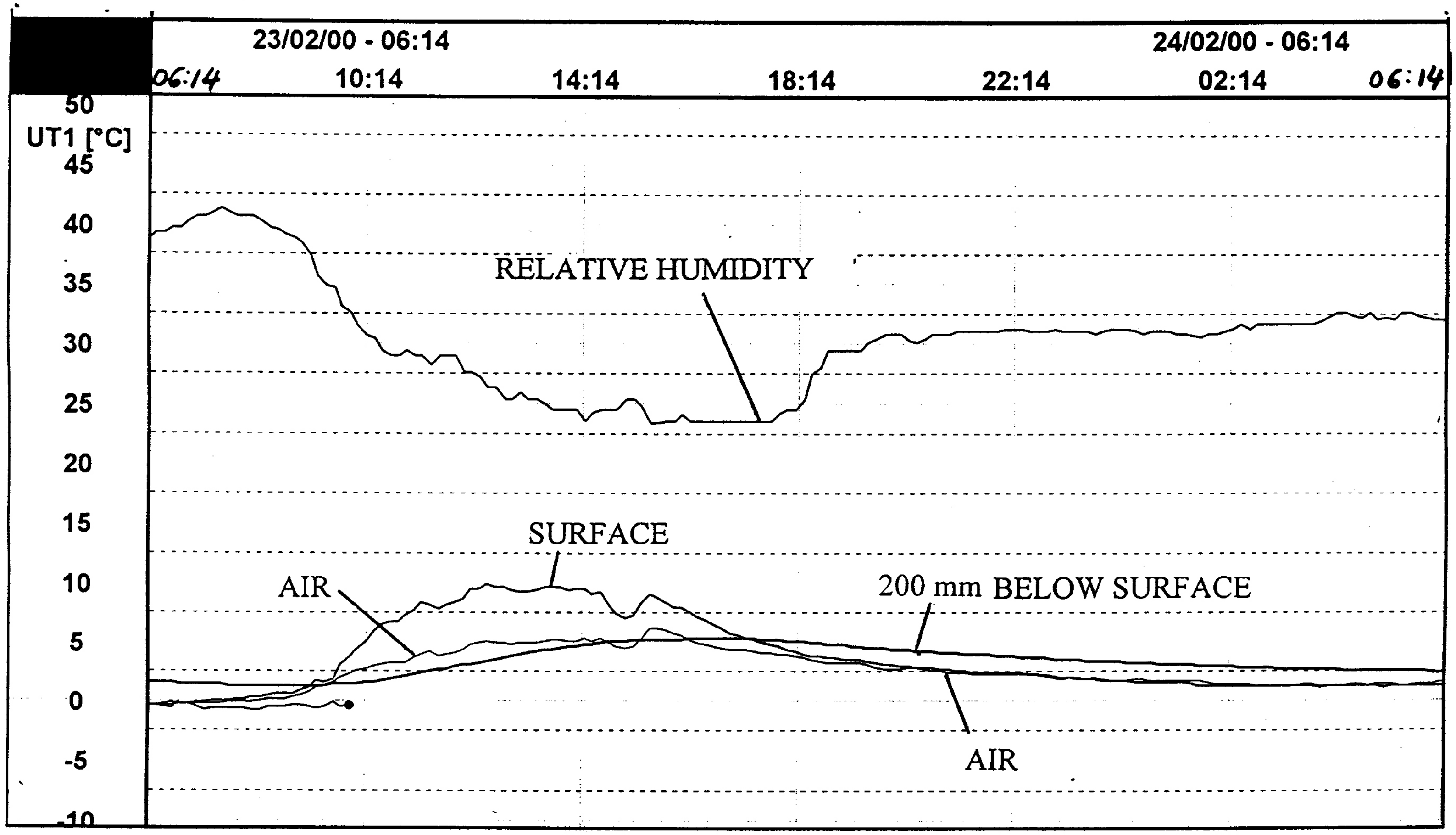

Figure 11. Air temperature, pavement surface temperature, temperature at 200 mm below the surface and relative humidity from 06:14 on Wednesday 23 February 2000 to 06:14 on Thursday 24 February 2000

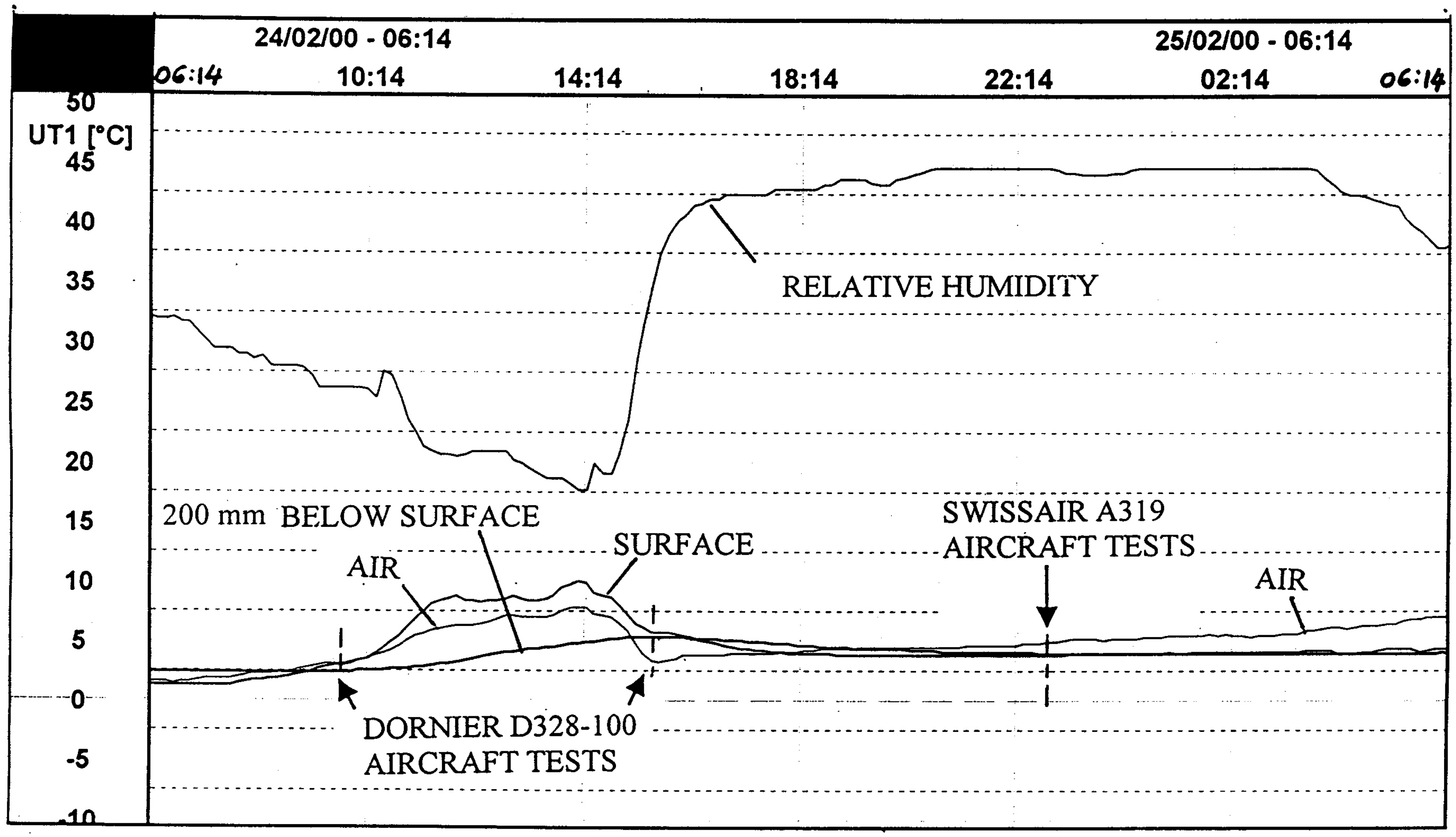

Figure 12. Air temperature, pavement surface temperature, temperature at 200 mm below the surface and relative humidity from 06:14 on Thursday 24 February 2000 to 06:14 on Friday 25 February 2000

Several other runs (**Test Nos. 54.2 to 54.15**) were performed on the same strip of natural snow, but the strip deteriorated rapidly because of the disturbances created by the movement of the vehicles. All the snow melted eventually because of these tests and the diffused sun. There was only water on the pavement during the last of the morning tests at 09:40.

A new man-made snow strip was made in the afternoon. **Test No. 54.16**, involving 12 devices except the ITTV, was conducted after 14:50. The air temperature increased to 4.7ºC during this time. The test bed was covered with a 5 mm to 25 mm thick slush mixed with sand and debris. Water content of the slush was estimated to be about 70%.

3.6 Thursday 24 February 2000

On Wednesday night and in the morning hours of Thursday, the air temperature remained above the freezing point (Figure 11). Consequently, the pavement temperature also increased a few degrees above 0ºC. The trend in warm weather continued through Thursday afternoon and night and through Friday (Figure 12).

Figure 13. Manual cleaning action of picking up undesirable foreign objects from the strip before the commencement of the Dornier D328-100 aircraft test on 24 February 2000. Note the tire marks left on the snow by the front loader that crushed the large ice particles.

The crew prepared a test strip of melting stored snow in the morning. This test bed was produced with ice particles that varied, as before, between 2 mm and 30 mm. A front loader was used to crush the large particles. The crushing process was induced by dragging the bucket of the front loader along the length of the strip. This dragging process helped in reducing the size distribution of the ice particles, but produced a cover that was not at all uniform. Tire marks were clearly visible (Figure 13). The thickness of the contaminant varied from 0 mm to 10 mm. There were bare and wet patches. The right lane, where the aircraft tests were carried out later, was 80% covered (about 20% bare spots) with wet snow (about 10% water content). The depth of snow varied in the range of 0 mm to 5 mm. The left lane, where the vehicular tests were performed, had a thicker snow cover – up to about 10 mm in thickness. The contaminant had sand and other debris in it. To avoid any further damages to the aircraft, a manual cleaning process was carried out for the first time, by mobilizing all the people at the test site to pick up all visible foreign objects (Figure 13).

Figure 14. View of the Dornier D328-100 aircraft making a tare run on a freshly prepared and cleaned contaminated strip on 24 February 2000. Note the meltwater formed on the pavement after several runs.

The **Dornier D328-100** aircraft was the first device that was used to initiate the testing of this morning (Figure 14). The aircraft made a slow pass through the right side of the test bed at 09:55. At this time, the air temperature was 3.5ºC, the contaminant was wet (about 10% water content), but no standing water was visible.

The first ground vehicle test of the morning (**Test No. 55.1)**, involving BMWSEDAN, IRVST and ERDBLAZER, was conducted in the left lane at 09:56.

The second test (a braking run) by the aircraft was made at 10:02. Free water in the aircraft tire tracks could be seen after this run. It was possible that the heat generated during the braking action melted some of the snow mass.

A total of five aircraft runs were made. The aircraft testing was completed at 10:20 when the air temperature was 5.0ºC.

After the aircraft tests, ground vehicle **Test No. 55.2,** involving all the ground-vehicle devices, was made at 10:30. The air temperature was 6.3ºC at this time and the test strip consisted of slush with 50% water. This slush also included a generous amount of sand.

Ground-vehicle **Test No. 55.3**, involving all the devices on wet pavement containing water 1 mm to 5 mm deep, was carried out on the test strip at 13:45. The air temperature was high (8.3ºC), but the pavement surface temperature was near 0ºC. Snow and slush that were there during the morning tests kept the pavement surface cold.

Following the technique of crushing and manual cleaning actions similar to those used in the morning, a new test strip was prepared in the afternoon. The thickness of the contaminant varied from 2 mm to 15 mm. Again, about 20% of the area was bare, but wet. **Test No. 55.4**, involving IRVST and ERDBLAZER, was performed at 15:10 when the air temperature was 4.3ºC and the test bed contained about 50% water.

The **Dornier D328-100** aircraft performed four runs during the next 15 minutes, from 15:10 to 15:25. It started to rain during the third run at 15:20. By the time the last aircraft run was made, the water content of the slush had increased to about 80%.

Ground vehicle **Test No. 55.5**, involving all the devices, was made in the slush at 15:26.

The slush was removed from the test strip and at 21:30 the crew started to make a new test cover by blowing snow on the pavement. It was dark and it was raining. Moreover, the wind had also picked up some speed. The blowing rain slowed the entire strip-making process. Working conditions were not optimal. At 21:50, a big ice particle hit and broke one of the glass windows of the 'command van'. Fortunately only one person was injured in the accident.

The command van was well equipped with high-tech communication instruments including a generator, but there was neither a first-aid box nor a small broom or brush. A small snow removing brush from ERDBLAZER (brought from Canada) was used to clean the debris of glass particles inside the van before taking the van to the test site.

The test bed was ready for operation at 22:30. It was very uneven. The slush contained about 50% water at this time. The ice particles in the slush varied from 3 mm to 10 mm. The average depth of slush was about 30 mm, but the depth varied significantly from 20 mm to 45 mm. The grooming process used to crush the large ice particles with a front loader was responsible for creating this large variation in depth. The centre lane was higher than the sides. There were ridges parallel to the length of the strip. The water content was changing with time because of continuous liquid precipitation that also was helping to melt the ice particles and generate more water.

Pre-aircraft ground-vehicle **Test No. 55.6,** using IRVST and ERDBLAZER, was conducted at 22:37.

The **Swissair Airbus A319** aircraft conducted the first and the last test run at around 22:45. Due to technical difficulties, it could not stop within the stopping distance and crashed into another aircraft parked on the ramp beyond Ramp 7 (Figure 1).

3.7 Friday 25 and Saturday 26 February

The warm weather continued to persist. There was no point in trying to perform any tests. The next two days were used for data reductions, cleaning up the equipment and packing them for shipment.

4 CONCLUSIONS AND RECOMMENDATIONS

The wide (20 m or more) and long (1000 m) uniform concrete asphalt surface of the test site at Munich Airport provided an ideal, textbook-type platform for conducting vehicular tests on a winter contaminated surface. Tests could be performed with a number of vehicles at the same time, running on different tracks parallel to each other. This avoided the condition of running the vehicles in sequential manner on previously travelled and disturbed surfaces. One series of tests involving 12 devices, conducted on freshly fallen snow (on February 23 at 08:40), proved the real possibility of conducting such concurrent parallel tests. No such tests had ever been performed in the past five years of runway friction tests conducted so far as part of JWRFMP. Munich Airport is certainly a unique facility and should therefore be used in the future.

The author would like to make additional recommendations that would improve the test conditions and working environment.

Under real-life operational conditions at major airports, dense snow or slush would not be allowed to build up to a thickness of 10 mm or more and left on the runways longer than the maximum time required to clear them (environmental and operational conditions permitting). During this short time, there could never be a significant morphological change in the snow unless, of course, it were compacted locally by cleaning vehicles or aircraft tires. Melting processes, if present, would increase the water content of deposited snow and make the snow particles rounder, but large aggregates of ice in the form of solid balls as large as golf balls (found in stored snow) would never develop. Nature often produces rounded snow particles, about 1 mm or less in diameter, depending on the ambient temperature, humidity, and the weather conditions. These are often clusters of tiny crystals with inter-particle voids. Consequently, the particles are of lower densities. Nature also produces hail with densities close to ice, but then the airport would be closed if a severe hailstorm occurred and covered the surface with large objects. In short, stored snow should never be used for tests.

Snow on runways and other movement areas relevant to realistic operational conditions should always be used. This will, of course, seriously limit the number of tests that can be carried out during a given time. This could also hamper previously arranged test plans and schedules. However, nature could provide excellent opportunities if flexible plans are adopted depending on weather conditions. A few well-executed tests with documented data on the test conditions and the characteristics of surface contaminants are more useful than a thousand bad ones with little or no information.

There should be no compromise on safety issues. Often the environmental conditions during the tests, particularly in the evenings and at night, made the test conditions very unsafe. This was made worse when the test personnel, standing beside the test track, also had also to pay attention to the local non-participating vehicular traffic close to the test site. The author was almost run over a few times by surface vehicles moving at high speeds. No vehicles in the vicinity of the test area should be allowed to move at high speeds at any time when test personnel are on the track. Night tests should be avoided if possible.

The project participants from other countries were accommodated in six different guest-houses/bed-and-breakfast establishments in different towns and villages in the vicinity, within a radius of about 40 km of the airport. This was primarily because of the financial convenience, but made it very difficult, if not impossible, to communicate with each other during the nights when participants were not in the field. Moreover, travelling times were long and very tiring. This arrangement of widely scattered accommodations should be avoided in future.

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