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FFI-RAPPORT

Evaluation of frozen sand descaling on operational airport surfaces

Jostein Brændshøi
Aleksander V. Skaldebø
Kjetill Løvbrøtte

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Summary

This report is a modified (UNCLASSIFIED) version of the original FFI-report 22/01432 (EXEMPT FROM PUBLIC DISCLOSURE).

The Norwegian Defence Materiel Agency (NDMA) has observed significant wear on internal jet engine components in the Norwegian fleet of F-16A/B "Fighting Falcon" (F-16) combat aircraft related to the use of cover sand on ice covered operational airport surfaces. Deployed as frozen sand (a sand-water mixture freezing onto the ice), cover sand provides good traction for traversing aircraft, but the sand may still descale and be ingested into the jet engine inlet, causing wear over time. The recent deployment of the F-35A "Lightning II" (F-35) and P-8A "Poseidon" (P-8) at Evenes Air Station necessitated an investigation into the use of cover sand to avoid similar increased maintenance costs related to jet engine wear.

The Norwegian Defence Research Establishment (FFI) was tasked to develop and execute low-cost tests in order to quantify descaling potential from various types of cover sand. A method using an industrial vacuum cleaner was developed as a proxy to a jet engine. A main descaling test event at Evenes Air Station was executed with success. Additional lab tests on the cover sand types were performed at FFI to further understand jet engine wear potential.

Frozen sand descaling was generally found to increase linearly with deployed amount, and using sweeper trucks on frozen sand removed nearly all descaling potential. One cover sand type (Crushed Rock) showed significantly more descaling, causing increased ingestion, and slightly larger abrasivity than the other (Natural Evenes).

Based purely on descaling and lab tests, FFI recommends that the use of Crushed Rock cover sand is halted where possible, due to its larger wear potential, and is replaced by a natural sand with a particle size distribution that is more even (containing significant amount of stone particles of different sizes) and includes fine matter (dust). Also, cover sand deliveries should be periodically sieved to ensure the particle size distribution is correct. These recommendations should be viewed in conjunction with friction studies and practical concerns.

Sammendrag

Denne rapporten er en modifisert (UGRADERT) versjon av den originale FFI-rapporten 22/01432 (UNNTATT OFFENTLIGHET).

Forsvarsmateriell (FMA) observerte betydelig slitasje på interne jetmotorkomponenter i den norske kampflyflåten av F-16A/B "Fighting Falcon" (F-16) relatert til bruk av strøsand på isdekkede flyoperative overflater. Strøsand som legges ut som fastsand (en blanding av sand og vann som fryser på isen), gir god friksjon, men strøsanden kan fremdeles skalle av og bli sugd inn i motorinntaket. Dette fører til slitasje over tid. Den nylige utplasseringen av F-35A "Lightning II" (F-35) og P-8A "Poseidon" (P-8) på Evenes flystasjon førte til et behov for å undersøke bruken av strøsand og unngå liknende økte vedlikeholdskostnader relatert til slitasje på jetmotorer.

Forsvarets forskningsinstitutt (FFI) fikk i oppgave å utvikle og gjennomføre en lavkostnads-test for å kvantifisere avskallingspotensial for ulike typer strøsand. En metode sentrert rundt en industriell støvsuger ble utviklet som en proxy til en jetmotor, og en hovedtest på Evenes flystasjon ble gjennomført. Ytterligere labtester ble gjort for å videre forstå slitasjepotensialet i en jetmotor.

Avskalling av fastsand ble funnet å øke lineært med utlagt mengde, og effekten av feiebiler på fastsand fjernet omtrent alt avskallingspotensial. Den ene typen strøsand (Crushed Rock) ble påvist å avskalle betydelig mer (og dermed forårsake økt inntak) og utvise litt større abrasjonsevne enn den andre (Natural Evenes).

Basert kun på avskalling og labtester, anbefaler FFI å stanse bruken av Crushed Rock strøsand der det er mulig, på grunn av dens høyere slitasjepotensial, og erstatte den med en natursand med en jevnere distribusjon i størrelse (med betydelige mengder av steinpartikler i alle størrelser) som også inkluderer finstoff (støv). I tillegg bør strøsandleveranser siktes jevnlig for å sikre at partikkelstørrelsesdistribusjonen er korrekt. Disse anbefalingene bør ses i sammenheng med friksjonsstudier og praktiske hensyn.

Contents

Preface

The involved FFI personnel would like to thank the Royal Norwegian Air Force 133 Air Wing at Evenes Air Station, Avinor and Bardufoss Air Station Airport Rescue and Fire Fighting Services for their essential participation and support during the main test event at Evenes Air Station.

Kjeller, August 16th 2022

Jostein Brændshøi Aleksander V. Skaldebø Kjetill Løvbrøtte

1 Introduction

This report is a modified (UNCLASSIFIED) version of the original FFI-report 22/01432 "Evaluation of frozen sand descaling on operational airport surfaces" (EXEMPT FROM PUBLIC DISCLOSURE) [1].

The Norwegian Defence Materiel Agency (NDMA) has observed significant internal jet engine wear on the now decommissioned Norwegian fleet of General Dynamics F-16A/B "Fighting Falcon" (F-16) aircraft, directly linked to the use of *cover sand* to achieve friction on icy surfaces. The cover sand may *descale* and be ingested into the engine. Similar wear and increased maintenance costs have been reported by the civilian sector as well.

To avoid such problems for future air operations in northern Norway, NDMA opened an investigation into the use of cover sand. The Norwegian Defence Research Establishment (FFI) was approached with the request of testing cover sand descaling and the wear potential once ingested into the engine.

The primary airport of interest, Evenes Air Station (located at roughly 68.49N, 16.68E), is heavily reliant on winter operation. Starting in 2022, the Royal Norwegian Air Force (RNoAF) has deployed the Lockheed Martin F-35A "Lightning II" (F-35) combat aircraft to Evenes in order to serve the North Atlantic Treaty Organization (NATO) Quick Reaction Alert (QRA) mission [2], replacing the F-16 that previously served QRA from Bodø Air Base. Additionally, Evenes will be the main operating base for the Boeing P-8A "Poseidon" (P-8) Maritime Patrol Aircraft (MPA). The first P-8 arrived in February 2022 and will begin to patrol Norway's maritime areas in 2023 [3].

Figure 1.1 Sweeper truck performing maintenance on a frozen sand test field (curved lines on the ice) on a taxiway at Evenes Air Station. Photo: FFI.

Personnel directly involved in daily maintenance of airport surfaces report that there exist few standard guidelines for usage of cover sand and that the approach may differ substantially between the civilian and military domain and between airports. Combined with the increased presence of

RNoAF at Evenes, this deemed a cover sand investigation necessary.

The cover sands ability to generate friction and refrain from descaling are of particular interest. A popular deployment method seemingly fitted for the purpose is *frozen sand* (norsk: *fastsand*) which can be seen in figure 1.1. Frozen sand involves mixing dry cover sand with hot water immediately before spreading the mixture onto the ice. This method aims at producing high levels of friction while reducing loose particles and thereby descaling.

The investigation culminated in a main test event at Evenes Air Station. NDMA led the event and performed friction testing, while FFI was tasked to develop and execute a low-cost/low effort test method for descaling. FFI supplemented the results with lab tests and further analysis of the relevant cover sand types, with a focus on wear inside the engine. The overall goal of FFI's study was to uncover relative differences in total engine wear potential between cover sand types (deployed as frozen sand), in order to aid decision making regarding winter operations at Evenes. This report documents the role of FFI, and the complete report will be published by NDMA.

1.1 NDMA request

NDMA requested support from FFI in late February 2021. The request is summarized below:

NDMA will evaluate different types of cover sand for use at Evenes Air Station. NDMA will perform friction testing, but requests FFI support to test descaling of the cover sand.

The process to evaluate descaling was to be low cost/low effort: Both to comply with the original timetable of a test event close to Easter 2021 and to keep within budget and resource constraints. It was agreed with NDMA that this would limit any testing to only provide relative data between the different cover sand types. Realistically replicating the air flow field conditions surrounding a relevant aircraft engine inlet would increase cost and complexity outside realistic means of completion within the required time and cost frame.

NDMA considered Evenes Air Station of particular importance due to its historical use of coarse quartz cover sand and its recent hosting of the F-35 and P-8. Coarse quartz provides good friction, but was believed to descale easily and be fairly abrasive towards internal engine components. Uncertainties about suitable replacements necessitated comparative testing.

In addition to the descaling issue, NDMA requested FFI to investigate other relative differences between several types of cover sand. Properties of interest were:

- Particle size distribution
- Visual inspection of particle roughness
- Cover sand abrasivity
- Cover sand salt content
- Cover sand hardness

Combined with the descaling test, this information could be used to assess relative differences in total engine wear potential between the cover sand types.

2 Background

The overall phenomena of descaling and subsequent abrasive engine wear is complex and governed by a variety of physical properties and processes. These include, but are not limited to, cover sand deployment method and amount, particles size distribution, abrasivity, engine inlet flow/pressure field, inlet placement/geometry and internal engine design (materials, geometry, etc.). This chapter offers background information on relevant processes.

2.1 Motivation

The enhanced wear observed by NDMA on the ageing and now decommissioned F-16's was traced back to frequent use of cover sand in Norway, compared to other operators. This caused a concern for the future operations of F-35 in similar conditions.

Figure 2.1 Norwegian F-35 (left) [4] and F-16 (right) [5] with their engine inlets outlined.

Figure 2.2 Norwegian P-8 [6].

In general, a turbofan jet engine consists of the fan, compressor section, combustion chamber, turbine section and the exit nozzle. It is the forward-most components, i.e. the fan- and compressor section that are most exposed to Foreign Object Damage (FOD) following Foreign Object Ingestion (FOI). Ground Vortex (GV) generation between the engine inlet and the ground is also a common problem [7], including on the F-16 [8]. The presence of a GV would be a major contributor to descaling, and its effects are outlined in section 2.4.

The F-16 uses the Pratt & Whitney F100 engine [9], while the F-35 uses the F135 [10], with different thrust, engine internals, air intake design and position above ground. Images of the external part of the intakes are shown in figure 2.1. Considering the difference in engines and surrounding design, it is assumed that overall cover sand descaling and resulting engine wear will differ between the two aircraft. However, it is also assumed that, should the effects on F-35 prove to be smaller than on F-16, it could still result in a significant increase in life-time maintenance costs, compared to aircraft operating in areas where cover sand is not used.

Similar damage has been reported on passenger aircraft from the civilian sector, also linked to operations at airports using cover sand. This means this could be a problem for P-8 operating out of Evenes Air Station as well. The P-8 has two CFM56-7B27A turbofan engines [11], and is shown in figure 2.2.

2.2 Airport winter operations

Winter operation of airports require special maintenance of operational ground surfaces in order to achieve the necessary friction requirements for aircraft to safely navigate taxiways and decelerate after landing (or aborted takeoff) on runways. Relatively speaking, this is a straightforward task in summer conditions, but becomes increasingly difficult in the winter. The winter season presents climatic conditions conducive to slippery taxi- and runways, in particular, due to build up of ice.

Several mitigating measures are applied to minimize this problem. The airport operator may strive for bare surfaces by mechanical snow plowing and application of de-icing chemical compounds. While optimal in end result, this approach comes with its limitations; the sheer amount of plowing/sweeping is time and resource consuming, and the release of chemicals may be damaging to both environment and aircraft (corrosion) and must comply with local government emission limits. Alternatively, one may accept icy winter surfaces and attempt to achieve required friction through the use of cover sand.

Using cover sand at airports is however not straightforward. The primary goal is to ensure normal flight operations. While required friction is the main driver for this, the potential for damage to the aircraft due to descaling of cover sand particles is an important consideration.

When a jet aircraft traverse cover sand covered taxi- and runways, the engine inlet suction has the potential to descale loose sand particles that gets ingested into the engine. Over time, this leads to accelerated wear on internal engine components and increased maintenance costs.

Salt content may further amplify wear on both engine components and external aircraft surfaces such as landing gear and the underside of the fuselage and wings. It is generally known that salt accelerates corrosion. Titanium alloys, of which variants are popular in aerospace engine applications, are also known to be susceptible to hot salt stress corrosion [12], [13], [14]. Purely from this point of view, it is likely that cover sand with higher salt content is undesirable due to increased corrosive wear.

This motivates the need for an approach to cover sand that minimizes descaling while still providing good friction, and if particles are ingested into the engine, it is desirable with a cover sand type that is not very abrasive. Achieving this depends on several factors such as the type of cover sand (particle distribution, roughness, salt etc.), deployed amount, deployment method and weather conditions.

Of specific importance to this test is the deployment of cover sand in the form of *frozen sand* (norsk: fastsand). This is an alternative to dry deployment, and they have the necessary equipment at Evenes Air Station. When deploying cover sand, NDMA reports that it is normal to use $\sim 100 - 200$ g/m^2.

2.3 Frozen sand

Frozen sand (or *warm-wetted sand*) is a deployment method for applying cover sand to icy surfaces. When deploying conventional dry sand, a spreader truck is loaded with the cover sand type of choice and a controlled amount is dropped onto the rotating spreader plate at the rear of the truck, dispersing cover sand as the truck moves forward.

The frozen sand method extends this process by heating water to ~ 70°C and mixing it with the cover sand immediately before it hits the spreader plate. The warm sand-water mixture then impacts the ice and melts the very top layer before freezing onto the ice. Due to the mechanics of the spreader truck, in particular the rotating spreader plate, the resulting sand layer is in the form of a field of "patches" of frozen sand. The patches consist of fine matter in the cover sand mixing with the water to produce a paste-like substance that acts as a binding material for the larger cover sand particles. It is these larger stones that produce the majority of the friction. An example of deployed frozen sand is shown in figure 2.3. Notice the patches of frozen sand and the occasional "rogue"/loose particle in between.

Figure 2.3 Frozen sand test field with Evenes Natural cover sand at Evenes. Photo: FFI.

There are mainly two advantages to frozen sand compared to dry sand deployment: The frozen mixture is stuck on the ice, meaning it has more support when exposed to forces by the aircraft wheels and thus able to produce more friction. The frozen paste also binds the majority of particles together resulting in fewer loose particles that could be picked up by the engine airflow.

2.4 Physical mechanisms of Foreign Object Ingestion

Jet aircraft manoeuvring on the ground are at risk of ingesting foreign objects that may damage the jet engine. At low speeds and high power settings, a vortex can form between the inlet and the ground. This Ground Vortex may be instrumental in lifting objects or particles from the ground and into the flow field of the jet engine inlet. It may also cause airflow distortion, which may affect fan vibration. In humid conditions the GV can sometimes be visible as shown in figure 2.7.

Figure 2.4 Visible Ground Vortex on an F-16 [15].

The presence of a GV requires the existence of a stagnation point on the ground which acts as a focal point for the GV. The stagnation point is generally unstable, meaning the focal point on the ground will wander and so will the termination point at the inlet. The existence of the stagnation depends on the capture streamtube interacting sufficiently with the ground surface. The capture streamtube, shown in figure 2.5, is defined as a streamtube which divides the airstream into an internal flow and an external flow. The air inside the streamtube is ingested, and the air outside the streamtube travels downstream.

The interaction between the capture streamtube and the ground depends primarily on two non-dimensional parameters. The first parameter H/D_i is the non-dimensional height of the inlet, where H typically is defined as the centerline height of the inlet, and D_i is the inlet inner diameter. The second parameter is the velocity ratio U_i/U_∞ which is defined as the inlet velocity U_i divided by the free stream velocity U_∞. In order for the capture streamtube to interact with the ground, U_i/U_∞ needs to be large and H/D_i needs to be small. Figure 2.5 illustrates the different parameters.

The three dimensional flow field of the GV generates a low pressure in the vortex core. When the GV passes over an object, the low pressure of the vortex core may lift the particle from the ground and into the flow field of the inlet, further carrying it into the engine. The aerodynamic lifting force will depend upon the strength, size and shape of the GV. The particle size, shape and weight will influence the response and movement of the particle. While a small and light particle will follow

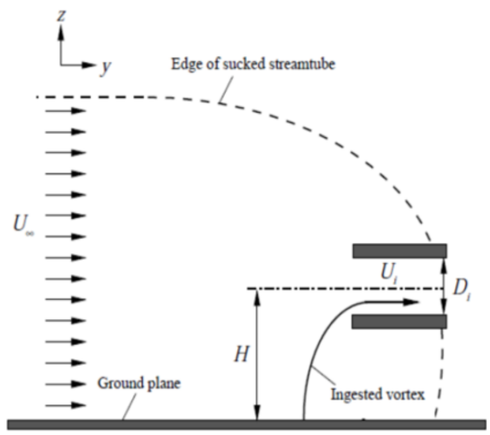

Figure 2.5 The capture streamtube interacting with the ground plane [16].

the flow field into the inlet, a heavy particle will likely follow a ballistic path after the initial lift of the GV as shown in figure 2.6.

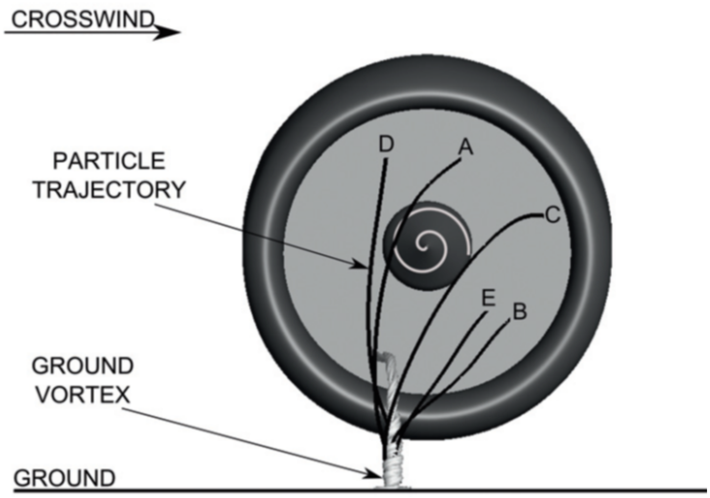

Figure 2.6 Ballistic particle trajectories [17].

In general, given the existence of a GV, a smooth taxi- or runway surface will result in fewer ingested particles because the GV horizontal velocity components will disperse many of the particles. On a rough taxi- or runway surface, many particles might get embedded in cracks. The embedded particles will remain in place until the GV passes directly above and violently lifts them up into the flow field.

Combinations of H/D_i and U_i/U_∞ have been correlated by researchers to establish the vortex/no vortex map in figure 2.7. The map shows that in order to avoid GV formation, U_i/U_∞ should be small and H/D_i should be large.

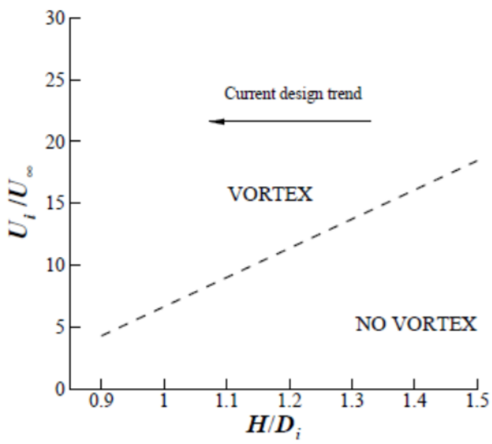

Figure 2.7 The vortex/no vortex map [16].

An operational technique to maintain small U_i/U_∞ and help reduce the problem of Foreign Object Ingestion could therefore be a gradual throttle increase as the aircraft accelerates during takeoff in order to stay in the no vortex area of figure 2.7. Peak particle ingestion risk occurs at low speeds and high power. As the aircraft gains ground speed during takeoff acceleration, the velocity ratio U_i/U_∞ is reduced until the capture streamtube no longer interacts with the ground, as depicted in figure 2.8, and the risk of ground particle FOI is removed.

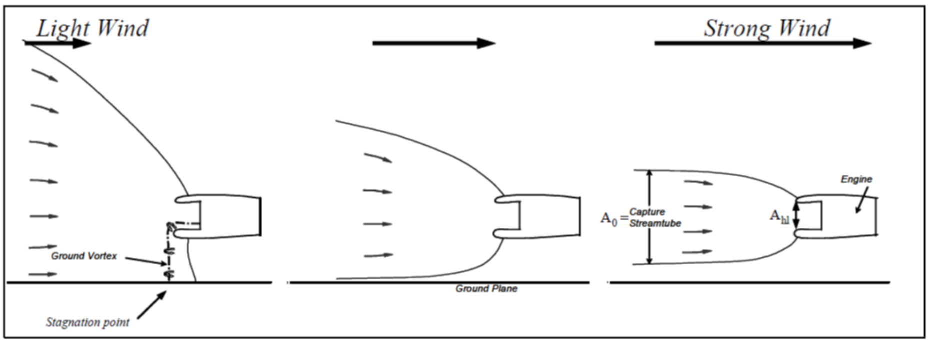

Figure 2.8 Shape of the streamtube with increasing headwind [18].

The fraction of FOI due to GV relative to FOI caused by the general laminar engine inlet airflow depends on the mass of the particles under influence. The light (and likely least damaging) particles will presumably be lifted by the general airflow, while a GV is required for lift at a certain mass. Hence, the particle size distribution of the particles are likely be important in determining this fraction. The mass crossover point, i.e. how heavy a particle needs to be before requiring a GV to lift it, is unknown, but could possibly be quantified through Computational Fluid Dynamics (CFD) simulations.

3 Main test event

NDMA's investigation into cover sand culminated in a main test event at Evenes Air Station. Successful test completion depended upon proper preparation of the test concept, acquiring the necessary equipment, planning the test event and execution of the test itself. The test was initially planned to take place around Easter 2021 at Bardufoss Air Station, but was postponed due to weather conditions and test personnel availability. The test was ultimately performed in February 2022 at Evenes Air Station.

3.1 Preparation

Necessary preparations prior to the main test event includes research, development of the descaling test concept and equipment procurement.

3.1.1 Defined test requirements

After receiving the request from NDMA, FFI formulated the actual test requirements. This includes which effects the tests would have to capture, which assumptions could safely be made, and how this relates to hardware needs.

A literature search of open sources did not reveal any relevant test methods for evaluating cover sand descaling and subsequent engine wear from the ingested foreign particles. Lockheed Martin informs they are unaware of any descaling testing done on the F-16 [8]. Some information about the aircraft, its engine and the physical mechanics of FOI was known. This formed the foundation for defining the test requirements.

Following the original timetable, with a test event close to Easter 2021, there would not be enough time to purpose-build a test bench. Any custom solution was also deemed highly probable to drastically increase the required cost and effort.

The actual airflows around the F-35 and P-8 engine inlets were not known when developing the test concept. NDMA later requested relevant information from Lockheed Martin and Pratt & Whitney and some airflow data for the F-35 was received [19]. While P-8 was a relevant case, F-35 was the main focus and the driver for the requirements of this test.

To get a rough estimate, publicly available numbers for the CFM56-5C4 engine used on Airbus A340-300 was used [20]. The reasoning was that CFM56-5C4 has a maximum takeoff thrust similar to the F-35 and P-8, with the knowledge that it could only be used as a guideline when looking at possible solutions. The CFM56-5C4 has an inlet airflow of approximately 500 kg/s (at 0°C and 1 atmosphere), or $\sim 400\ m^3/s$, during takeoff. This provides a rough estimate of the airflow one must simulate across an area on the ground to perform a realistic test.

The possibility of a Ground Vortex between the engine inlet and the ground was a further complication. This leads to uncertainties beyond the unknown in engine air intake volume, without any means of easily assessing its impact.

These tests were to be performed on actual taxi- or runways at Evenes Air Station. This necessitated a portable test setup that could easily be moved to different parts of the Air Station and operated without immediate access to infrastructure such as mains power. All equipment had to withstand outdoors operations in cold and possibly somewhat adverse weather situations (e.g. wind and light snow). The descaled particles would most likely include some snow and ice, requiring waterproof equipment.

The deployment method is an important factor for frozen sand. The descaling tests would therefore have to be performed on cover sand deployed by the actual spreader trucks that would normally be used at the Air Station.

NDMA reports a normal deployed amount of cover sand in the range ~ 100 – 200 g/m^2. The assumption was that the descaled fraction would be well below 100% for frozen sand, and that one would need to test descaling across a few square meters to get a statistically significant result. A measurement setup would then need ~ 1 gram sensitivity to accurately differentiate between the cover sand types and deployed amounts.

To measure descaling, one either has to weigh the material on the ground before and after exposing it to the airflow, or collect the particles as they are sucked up into the airflow and weigh those. The first solution was deemed impractical when measuring on an actual taxi- or runway. There is no feasible way to embed a large scale into the ground. It would need to cover several patches, each of multiple square meters, to accommodate testing of several cover sand types and deployed amounts. Additionally, measurements after sweeping/maintaining the surface were also reported as relevant, further complicating an embedded scale.

Several commercially available solutions were investigated to find a suitable approach. A 1 kW heavy duty fan can move air in the order of 9000 m^3/h (2.5 m^3/s) [21], a factor of 100 less than the assumed need. Such a fan would require a filter solution to capture particles for subsequent weighing. This approach was not very practical, and the filter would reduce the airflow through a fan.

After reviewing commercially available equipment, it was deemed too expensive, complicated and time consuming to get anything close to ~ 100 m^3/s. Combined with the uncertainties of the actual airflow around the F-35 engine inlet (at the time), the decision was made to abandon the search for solutions with fully realistic conditions.

Instead of looking at a larger ground area, a commercially available industrial vacuum cleaner could be used to achieve a relatively powerful airflow around a smaller ground area. Testing could then be performed over a given area and time followed by weighing of the vacuum cleaner system to measure descaled mass of cover sand.

With an airflow much weaker than the F-35 engine inlet airflow, it would only be possible to look at the *relative descaling* of the different cover sand types and deployed amounts. The test would not be able to replicate realistic airflows, and could as such not represent the actual amount of particles entering the engine inlet.

Using a vacuum cleaner moves the air inlet very close (~ millimeters) to the surface compared to the air inlet of an aircraft. This means the total airflow of the vacuum cleaner can be a lot less than from the aircraft while still providing a relatively high pressure differential for particles on the ground. The exact effect of this has not been investigated, but it should somewhat close the gap between the capacity of the vacuum cleaner compared to the aircraft, making the test scenario more realistic than the airflow values themselves suggest.

These uncertainties and limitations were presented to NDMA, who approved of the approach. Their main concern was to compare cover sand types and deployed amounts in a low cost/low effort way, which a relative assessment would achieve. Investigating actual engine inlet particle intakes was a desire, but not at the predicted increase in cost and complexity.

3.1.2 Equipment

FFI was only be responsible for equipment to perform the descaling process itself. Test area and cover sand preparations etc. would be performed by local organizations at Evenes Air Station. FFI acquired an industrial vacuum cleaner, an industrial high-precision scale and an air+contact temperature probe.

3.1.2.1 Industrial vacuum

The Festool Cleantec CTL 36E [22] vacuum cleaner, with the pre-separator CT-VA-20 [23] (see figure 3.1) was selected due to its high volume flow, resistance to liquids/water and the availability of a pre-separator to collect most of the cover sand particles in. The CTL 36E has a maximum volume flow of 3900.00 l/min (0.0065 m^3/s), presumably slightly reduced with the pre-separator and water filters installed. The pre-separator uses a gravity trap to separate out any heavy particles in the ingested air before it reaches the filters and the vacuum bag.

Figure 3.1 Festool Cleantec CTL 36E (left) with the pre-separator CT-VA-20 (right). Photo: FFI.

Lab testing (appendix A.2) consistently showed that with the available test cover sand (0 – 4 mm cover sand from Kjeller Air Station), around 97% was caught in the pre-separator when descaled from a clean surface. It was hence deemed sufficient to weigh only the pre-separator, and not the whole vacuum system, to measure the amount of descaling.

Lab testing was also conducted to verify that weighing the pre-separator yielded consistent results as shown in appendix A.1.

3.1.2.2 High resolution scale

The Kern EOC 30K-4S High resolution scale [24] has a resolution of 0.5 g up to 15 kg total load and 1.0 g up to 35 kg total load. The max total load would allow the complete vacuum cleaner to be weighed at once if needed, with the required resolution of $\sim$ 1 g. The scale is portable and easy to use and has an operating temperature down to $-10°$C.

3.1.2.3 Temperature probe

The Comark N9002 Differential Thermometer [25] is a versatile dual-input thermometer. It was used with the Comark AK27M air sensor, and the Comark SK25M contact sensor, for simultaneous measurements of the air and ice surface temperature. It is an easy to use rugged thermometer and has an operating temperature down to $-25°$C.

3.2 Planning

Several planning meetings were held ahead of the test, and a formal test plan was developed by NDMA [26]. FFI and the other test participants communicated their needs in the process, and the final test plan incorporated these. Specifically for FFI, the planning process revolved around designing the descaling test procedure and managing some complicating test elements.

3.2.1 Overview of the full NDMA test

F-35 QRA and the arrival of P-8 strongly motivated Evenes Air Station as the test location. This would provide access to the actual cover sand types and related equipment (spreader truck, sweeper truck and friction instrument) that the aircraft of interest would be exposed to on a regular basis, thereby increasing the relevance of the test outcome.

The actual test region within Evenes Air Station can be seen in figure 3.2. The runway itself was deemed impractical for testing due to daily airport operations, but a taxiway with representative ice cover was found to be the perfect test area. A part of the network of taxiways in the southern part of the Air Station would be closed off and dedicated to the test, ensuring safe and uninterrupted test execution.

The test period would be two days; the first day would include travelling, meetings and test area inspection, with the second day being the actual test day.

The two types of cover sand used at Evenes would be tested; "Evenes Natural", a natural sand consisting of particles in the size range 0 - 4 mm, and "Crushed Rock" made up of presumably rougher/sharper particles in the range 2 - 4 mm. They were thought to each have their strengths and

Figure 3.2 Satellite image highlighting the test region within Evenes Air Station. Image taken from NDMA's test plan [26], figure 1.

weaknesses and were likely candidates for future winter operations at Evenes. Specifications for the cover sand types will be detailed in section 4.1.

The cover sand would be deployed as frozen sand, each with different amounts per square meter (regulated by the spreader truck). Discussions between test participants concluded that three different deployed amounts would be used; one "normal" (140 g/m^2), one small (90 g/m^2) and one large (180 g/m^2). Testing different deployed amounts was motivated by the desire to uncover if one may accomplish satisfactory friction using less cover sand, which presumably would be beneficial in terms of descaling and cover sand costs.

Test field	Surface	Type	Method	Amount
RN1	Asphalt	Natural Evenes	Dry	90
RN2	Asphalt	Crushed Rock	Dry	90
F1	Ice	Natural Evenes	Frozen	140
F2	Ice	Natural Evenes	Frozen	90
F3	Ice	Natural Evenes	Frozen	180
KF1	Ice	Crushed Rock	Frozen	140
KF2	Ice	Crushed Rock	Frozen	90
KF3	Ice	Crushed Rock	Frozen	180

Table 3.1 Table listing the setup of the descaling test fields used at the test.

Frozen sand descaling for the two types and three deployed amounts of cover sand would be tested for friction, descaling and maintenance impact, i.e. the effects by sweeping/blowing of a surface on the two former parameters. This resulted in the planned test fields described by NDMA and is summarized in table 3.1.

The test fields, RN1 and RN2, represent reference fields on dry/bare asphalt intended for dry sand descaling. They would serve the purpose of verifying that the vacuum cleaner was sufficiently powerful to descale loose particles. The reference fields would use 90 g/m^2. It was initially planned with a slight variation of the test fields in table 3.1, but some modifications occurred on the test day, as discussed in section 3.3.

Figure 3.3 shows the intended layout of each test field. While friction testing would require a fairly large zone for high speed operation of the friction instrument, the descaling test could be done on a fairly small zone. Friction and descaling test zones were intentionally planned as fully separated; in the case of overlap, friction measurements would impact following descaling measurements (and vice versa) by removing or displacing cover sand particles.

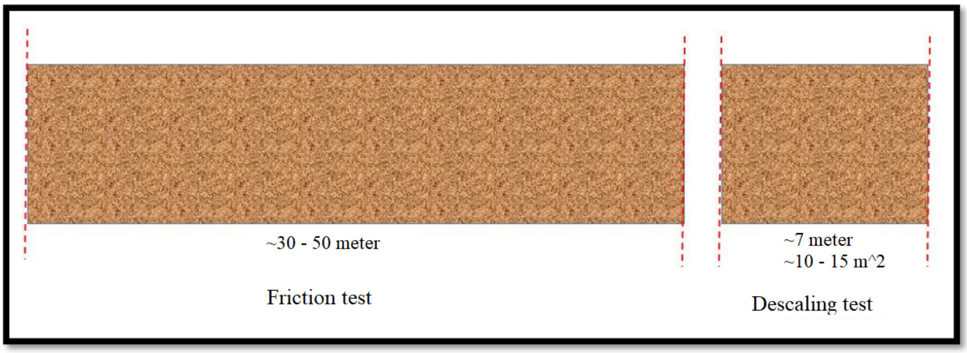

Figure 3.3 Sketch of the test field for a given cover sand type and deployed amount. Image taken from NDMA's test plan [26], figure 2.

The test was based on using the two available cover sand types at Evenes. Logistical challenges prevented additional types to be tested as they would have to be delivered in large quantities by potential suppliers, and there was a limited number of spreader trucks. However, there was interest in gaining knowledge on additional cover sand types even without testing them at Evenes. Test participants from Bardufoss Air Station would provide FFI with samples of three cover sand types from Bardufoss Air Station and local suppliers. FFI would bring these, along with samples of the ones tested at Evenes, back to Kjeller to perform lab tests. This will be presented in section 4.

3.2.2 Test personnel

It was clear from the outset of planning that the execution would require support from key personnel at Evenes Air Station and Bardufoss Air Station. They would have important roles in the test and provide invaluable input based on years of experience from winter operation of airports. Below are the test participants and their role outlined:

- **Norwegian Defence Materiel Agency:**
  NDMA would have the overall responsibility for the test, i.e. plan, organize, coordinate and oversee all activities related to the test.
- **The Royal Norwegian Air Force:**
  RNoAF would facilitate logistics on-site, i.e. providing closed-off taxiways dedicated to the

test, provide transport inside the Air Station for all test participants, coordinating with Avinor as well as organizing meeting arrangements.

- **Avinor:**
  The Evenes airport operator would supply and operate essential equipment; friction measuring instrument, spreader trucks for deploying cover sand and a sweeper truck for removing loose particles as well as providing a power generator for the descaling test equipment.
- **Airport Rescue and Fire Fighting Services (ARFFS) (norsk: *Brann-, Redning- og Plasstjeneste* (BRP)):**
  Representatives from ARFFS at Bardufoss Air Station would employ their experience to assist in the practical execution of the test and provide FFI with samples of cover sand types used at Bardufoss.
- **Norwegian Defence Research Establishment:**
  FFI would be responsible for developing and executing the descaling component of the test.

3.2.3 Descaling test procedure

This section details the descaling test procedure prepared and executed by FFI. The industrial vacuum cleaner and precision scale were the main tools. Descaling would be measured in the form of cover sand mass ingested into the vacuum cleaner over the course of one "descaling session", i.e. the amount of mass picked up by the vacuum cleaner when moved over a given area in a given time.

Various considerations played a part in deciding the area and time for a descaling session. The area would have to be large enough such that sufficient mass would be picked up in order for the differences in descaled cover sand mass between two test fields to dominate over the uncertainties such as pickup of impurities in the ice surface, small wind effects on the scale and small inconsistencies in vacuum cleaner operator technique and time usage. Practice tests at FFI (with sample cover sand from Kjeller airport) helped to understand these uncertainties and supported an appropriate area of 2 m^2 and a time of 50 seconds for each descaling session.

Two descaling test zones were set up for each test field to provide information on the consistency of the measurements. If these two values would differ significantly, especially if similar in magnitude to the differences between values from separate test fields, it would be detrimental for the usefulness of the data.

Below is the step-by-step procedure that would be used to perform the descaling test for each 2 m $\times$ 1 m = 2 m^2 test zone within each test field:

(a) Measure air temperature and surface (contact) temperature.
(b) Connect power to vacuum cleaner and precision scale.
(c) Perform reference mass measurement of pre-separator.
(d) Perform descaling session, i.e. smoothly move the head of the vacuum cleaner with the aim to cover all 2 m^2 in 50 seconds.
(e) Detach pre-separator and perform mass measurement.
(f) Compute descaled mass as the difference between mass before and after the descaling session.

3.2.4 Impact of climatic conditions

Successful test completion posed some demands on the climatic conditions. Conditions would have to correspond to those in which deployment of cover sand to increase friction is an appropriate measure. Ice covered taxiways and fairly stable air temperatures below freezing point were required. Variable temperature around 0°C could create puddles of melted water on top of the ice detaching the frozen sand from the ice.

Precipitation (snow) would be an issue; depending on the severity, snow would accumulate on the ice and affect the measurements of both friction and descaling.

Wind could pose a problem by displacing loose particles from a given test field before measurement. Additionally, outdoors tests at FFI indicated that the precision scale would be sensitive to wind forcing on the container during weighing.

Mitigating measures were prepared to reduce the risk of another test postponement. NDMA facilitated flexibility to the test date and location. A backup day was instated in the test plan in case of unfavourable conditions. The test could be moved forwards/backwards a few days, and Bardufoss Air Station was planned as a backup location. In such an event, the test personnel and FFI test equipment would travel by car (provided by RNoAF) from Evenes to Bardufoss on short notice. FFI contacted RNoAF who generously provided wind sheltering for the precision scale to eliminate uncertainties from wind.

3.2.5 Impact of available time for testing

Time management was an important factor for FFI to be able to perform descaling measurements on all test fields. Due to the sheer size of each test field (dominated by the large area demand for the friction test), each descaling test field would be separated by considerable distance. Consequently, it would be crucial for FFI to have a mobile power source for the vacuum cleaner and precision scale.

FFI and NDMA contacted RNoAF and Avinor who would provide a vehicle with an attached power generator trailer. The vehicle would also act as the wind shelter for the precision scale. FFI would then be able to drive the vehicle between each test field and perform descaling and weighing in the immediate vicinity, saving valuable time and facilitating test completion within the planned test day.

3.3 Test execution and modifications

The first day involved travel for the test participants not stationed at Evenes (NDMA, FFI and ARFFS Bardufoss), followed by meetings to plan specifics for the test the next day. The day concluded with inspection of cover sand storage facilities and the actual test area. A fairly large region of the taxiway network was at the test's disposal, and inspection helped to determine particularly suitable test areas.

The second day started with a test brief and a motivational presentation by NDMA showing effects of cover sand descaling in the civilian sector. The vast majority of the day was dedicated to executing the test itself.

The test day provided excellent weather; clear skies, nearly no wind and stable cold temperatures around −10°C. Every weather concern from section 3.2.4 was non-existent except a light breeze that could impact the precision scale, but was taken care of by the transport vehicle.

FFI initially performed descaling tests on the test fields described in table 3.1. All descaling tests were conducted following the test procedure described in section 3.2.3. Figure 3.4 shows the descaling test setup in action, and figure 3.5 shows frozen sand test fields for both Crushed Rock and Natural Evenes.

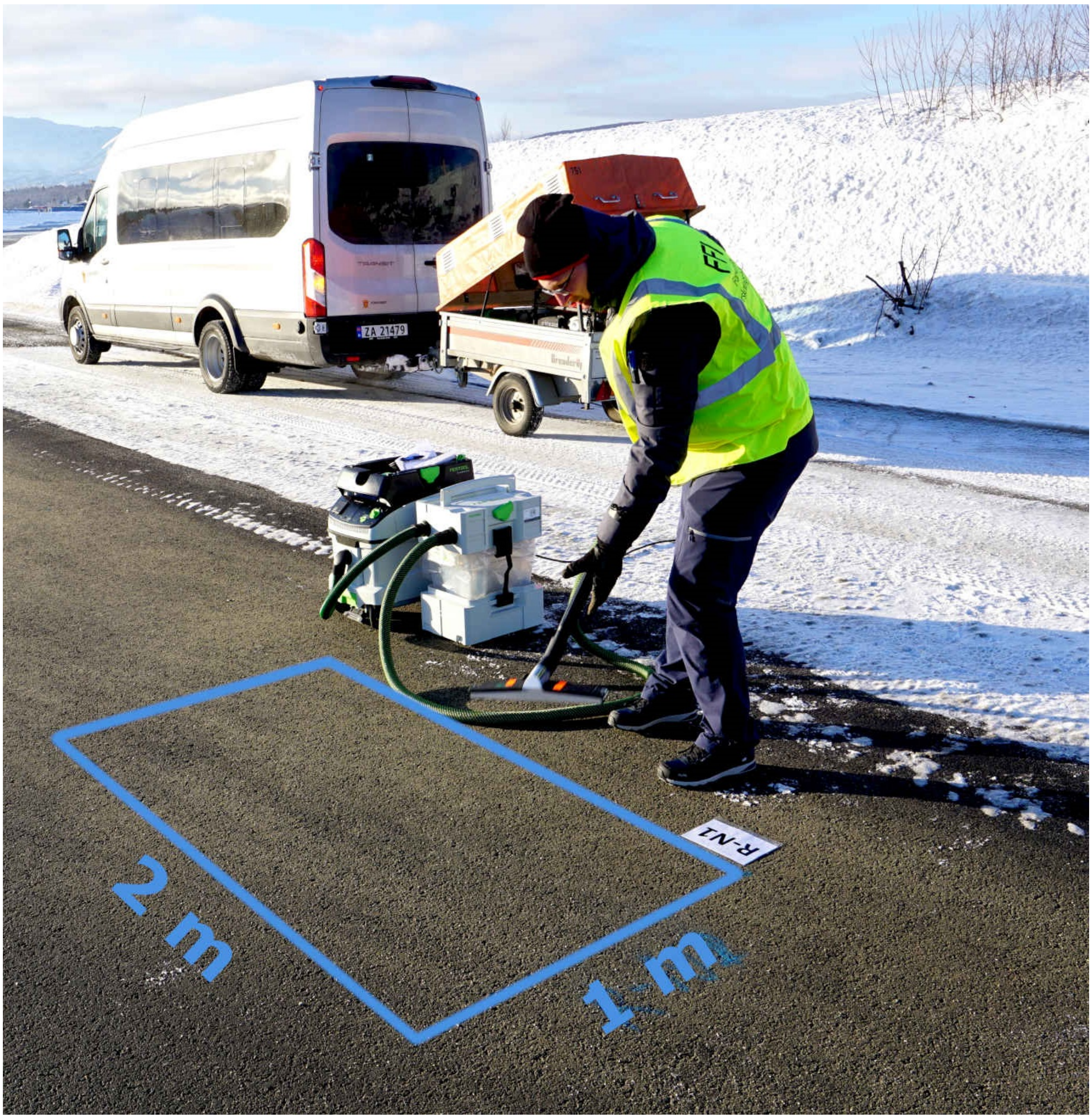

Figure 3.4 FFI personnel performing dry sand descaling test on an asphalt reference test field. The transport vehicle and generator are visible behind. Photo: FFI.

NDMA was very flexible with regard to emerging needs on-site at Evenes requiring modifications to the overall test plan summarized in section 3.2.1. Observations, experiences and communication between test participants at Evenes uncovered test elements that became increasingly important and others less so. This prompted a few modifications to the test:

- Test fields with dry sand on ice were also initially planned. This was ultimately deemed unnecessary as dry deployment was considered of limited benefit. The general consensus is that frozen sand is superior in both friction and descaling.
- Descaling tests on frozen sand test fields after sweeping was abandoned. Visual and physical inspection made it evident that next to none loose particles were left behind after the sweeper truck had passed. It was thus known a priori that the descaled mass would be zero for both cover sand types. However, the frozen sand patches themselves were still fairly intact suggesting significant friction may prevail.
- It was initially planned to construct a test field using a different speed on the spreader truck (dispersion and cooling of released sand-water mixture sand depends on truck speed). This was not prioritized on a tight time schedule.

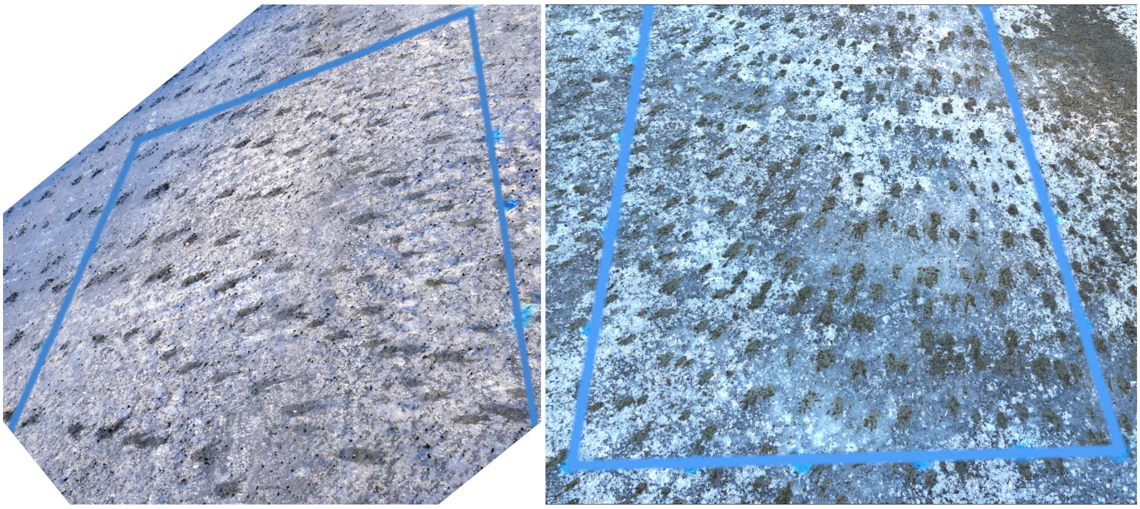

Figure 3.5 Frozen sand test fields deployed with 140 *g/m*^{2} *of Crushed Rock (left) and* 180 *g/m*^{2} *of Natural Evenes (right). Photo: FFI.*

4 Lab tests

At the request of NDMA and initiative taken by FFI, a series of lab tests were conducted to supplement and extend the results from the main test event at Evenes. They were intended to both deepen the understanding of descaling and to uncover relative differences wear potential once ingested into the engine.

4.1 Cover sand types

FFI was supplied with a total of five samples of cover sand types from Evenes and Bardufoss during the test at Evenes. These include the two tested for descaling at Evenes and three additional types. The samples were subjects to lab test analysis at FFI. Table 4.1 describes the sand types and their size ranges as provided by the suppliers.

Cover sand type	Prescribed size [mm]	Region
Natural Bardufoss	0 – 4	Bardufoss
Nystad Maskin	0 – 4	Bardufoss
Natural Evenes	0 – 4	Evenes
Crushed Rock	2 – 4	Evenes
Gravel Løkstad	N/A	Bardufoss

Table 4.1 Overview of the five cover sand types subject to lab testing at FFI together with their prescribed size range specifications.

4.2 Particle size distribution

The relevance of the particle size distribution for a cover sand type is mainly twofold: The frozen sand deployment method benefits from fine matter to create the binding material, and larger particles generate more wear in the engine.

Determining the particle size distribution was done through sieving at FFI using lab sieves of sizes 0.125, 0.250, 0.500, 1.000, 2.000 and 4.000 mm installed in a Fritsch sieve shaking machine. This sieve selection provided a decent resolution in the relevant size ranges for the cover sand types.

The sieving process was as follows:

(a) Measure total mass of cover sand sample to be sieved.
(b) Stack sieves on top of each other.
(c) Place cover sand sample in the top most sieve.
(d) Insert sieves in the sieving machine and sieve for 5 minutes.
(e) Measure mass of cover sand retained on each of the sieves.

The total mass of the sieved sample would preferably be as large as possible to minimize the effects of uncertainties. It is however limited by the physical size of the sieves and therefore sample masses were used as shown in appendix table 4. Experienced FFI personnel recommended a sieving time of 5 minutes for each cover sand type. The particle size distribution was computed by dividing the retained mass on each sieve by the total sample mass.

It is worth pointing out one uncertainty with the sieving process. Whether or not a particle slips through a sieve depends on both its size and its geometric shape. Particles that are elongated in one direction and narrow in the two others may pass through even if they are longer than the sieve size. The significance of this uncertainty is likely small, but it is worth keeping in mind if dealing with cover sand types whose particles are heavily biased towards elongated thin stones.

4.3 Visual inspection

Visual inspection of the cover sand types provided qualitative information on the particle size distribution and surface roughness. Each of the five cover sand types were placed on a white sheet of paper under a standard lab microscope at FFI. Observations through x25 and x40 magnifications were made using representative sub samples of each cover sand type. Examples of large particles from each type were also examined and compared to the quantitative particle size distributions.

4.4 Abrasivity

The abrasive properties of the cover sand is important in understanding the wear it may cause once inside the engine. Ingested particles impact components like the fan, compressor blades, engine shaft, turbine blades and engine walls with high relative velocity and scratch away surface mass (abrasion) from the components over time. Therefore, an abrasivity test would ideally need to approximate the abrasion conditions in the engine both in terms of replicating cover sand impacting components with high velocity and in terms of materials used.

Abrasivity testing equipment was not available at FFI. As such, external opportunities were explored and FFI made contact with SINTEF's Rock and Soil Mechanics laboratories in Trondheim [27] which were employed for this test.

Initially, the Soil Abrasion Test (SAT) [28] appeared promising, but further dialogue with SINTEF exposed the Laboratoire Central des Ponts et Chaussèes (LCPC) test [29] to better replicate the type of impact abrasion experienced by the engine components. With the support of NDMA, it was decided to perform one LCPC test for each of the five cover sand types, which would provide good relative wear data.

The LCPC abrasivity testing device operated by SINTEF is shown in figure 4.1. The test process was as follows:

(a) Cut out a metal test piece to act as the metal impeller and measure its mass.
(b) Fill the sample container with 500 g of sand.
(c) Lower the metal impeller, power the motor and rotate the impeller at 4500 revolutions per minute (RPM) for 15 minutes inside the sample container.
(d) Measure the mass loss of the metal impeller.

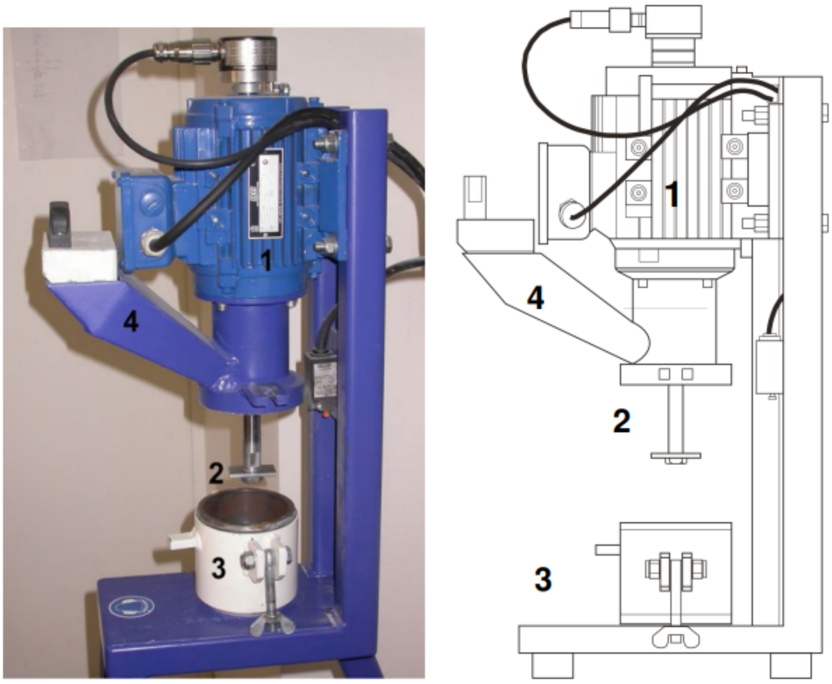

Figure 4.1 LCPC abrasivity testing device ("abrasimeter"). 1 - motor, 2 - metal impeller, 3 - sample container (93 × 100 mm), 4 - funnel tube. Image taken from the LCPC test article by K. Thuro et al. [29].

The measured mass loss on the impeller is in itself a direct metric for the abrasivity of the sand. The more mass that is scratched off the surface of the impeller, the more wear that cover sand type is likely to generate when ingested into the jet engine.

One caveat with the LCPC test as an indicator for engine wear lies in the fact that it employs a standardized steel impeller that differs in material composition to actual engine components. FFI suggested customizing the LCPC test by replacing the standardized steel impeller with actual jet engine compressor or turbine blades. Ideally, blades from the F135 (F-35) or CFM56-7B27A (P-8) would be used, but this was not possible. NDMA was however very quick in supplying decommissioned compressor blades from the F100 engine used on the Norwegian F-16's. According to NDMA, the F100 blades consist of a Titanium (Ti), Silicon (Si) and Aluminium (Al) alloy and the F135 blades are comparable in material composition. Using actual engine components would make the test results more relevant.

SINTEF was very open to accommodate the custom needs of FFI and NDMA and sub-contracted The Norwegian University of Science and Technology (NTNU) to produce cutouts from the compressor blades to be used for the metal impeller. Each LCPC test consists of two parallel tests (to reduce uncertainties) and so at least a total of ten impellers were required for the five cover sand types. Figure 4.2 shows the F100 blades after performing cutouts and the resulting impellers. Four 1st stage, three 2nd stage and three 3rd stage compressor blades were available, and several backup impellers were made.

Due to the assumed superior strength of the F100 blade alloy compared to the standardized steel,

Figure 4.2 Left panel: 1st (left and top right) and 2nd (bottom right three) stage compressor blades from the F100 engine after extraction of custom LCPC impellers. Right panel: The extracted impellers. Photo: FFI.

FFI suggested performing a preliminary LCPC test using a testing time of 15 minutes in case the default time of 5 minutes was too short to produce significant wear on the F100 blade impeller. The LCPC machine allowed only 5 and 15 minute settings. The 15 minutes test showed reasonable wear and was thus chosen for the rest of the actual tests.

The LCPC abrasivity test is in general intended for sand with a particle size distribution between 4 - 6.4 mm and with a test duration of 5 minutes, while the cover sand types that were tested consist of 0 - 4 mm particles and was run for 15 minutes. Combined with the use of custom material impellers, this meant the test would deviate from the LCPC standard and thus the results could not be classified using the LCPC Abrasivity Coefficient (LAC) and consequently not be compared to historic LCPC results. This was done intentionally, as the primary concern was relative differences between the cover sand types and relevance to engine wear.

Execution of the tests occurred over two days in late spring 2022. FFI travelled to Trondheim to partake in final test preparation and to safe keep the F100 blades, preventing undesired loss during transport. After test completion, the used F100 blade impellers were brought back to FFI.

4.5 Salt content

A (soluble) salt content test was motivated by the risk of accelerated corrosion inside the engine (and on other aircraft surfaces).

A simple approach was taken for measuring soluble salt content:

(a) Select a cover sand sub sample of pre decided mass.
(b) Mix with water and apply heat to facilitate dissolving the salt.
(c) Pour sand-water mixture carefully through a fine filter.
(d) Boil water that slipped through filter until only solid salt remain.
(e) Compute salt content through dividing mass of solid salt by initial mass of total cover sand sample.

It is important that a sufficiently large initial mass of cover sand is chosen such that the mass of the dissolved salt dominates over the uncertainties of salt getting stuck in the small water amount that is absorbed in the filter fabric.

It is also important that the filter is very fine such that only negligible amounts of fine matter from the cover sand may slip through. In light of this, FFI bought the Scheppach 0.3 μm filter bags [30]. This was deemed sufficient based on the particle size distributions and very simple tests with coffee filters ($\sim 10 - 20$ μm).

This test was not completed in time for this report and will be documented in a later report.

5 Results

5.1 Evenes test results

The results from the descaling tests performed at Evenes are in the form of descaled cover sand mass values for each test zone on each test field, i.e. how much cover sand was picked up by the vacuum cleaner in each descaling session. The test procedure in section 3.2.3 was executed for each test zone in each of the eight test fields in table 3.1. Below is the data presented, its implications interpreted and associated uncertainties discussed.

5.1.1 Dry reference test fields

Results from the dry deployed reference fields RN1 and RN2 can be seen in tables 5.1 and 5.2. Two test zones were descaled for each of the two cover sand types.

Deployed amount [g/m^2]	Descaled mass [g]	Descaled fraction [%]
90	78.5	43.6
	85.5	47.5

Table 5.1 Descaling results for Natural Evenes reference test field. The descaled fraction is relative to total deployed mass in the test zone. Area used for descaling was 2 m^2*, meaning total deployed mass is twice the "deployed amount" value.*

Deployed amount [g/m^2]	Descaled mass [g]	Descaled fraction [%]
90	67	37.2
	81	45.0

Table 5.2 Descaling results for dry Crushed Rock reference test field. The descaled fraction is relative to total deployed mass in the test zone. Area used for descaling was 2 m^2*, meaning total deployed mass is twice the "deployed amount" value.*

For both Natural Evenes and Crushed Rock reference fields, roughly 40% – 50% of the cover sand mass (that was spread over the 2 m^2 test zone) was descaled in each descaling session. This provides good evidence that the vacuum cleaner test concept is in fact able to descale loose particles of the relevant cover sand types. This conclusion was also supported by lab tests at FFI (e.g. the test in appendix A.2 verified this). Had this not been the case, i.e. with descaled fractions close to 0%, it would indicate that the test concept would have been unable to provide any knowledge on the relative descaling between cover sand types and deployed amounts and would thus have been insufficient as a test method.

The reason for the descaled fractions not being closer to 100% is mostly due to a descaling session of 50 seconds; if the vacuum cleaner operator was not limited by time, the whole test zone could be thoroughly vacuumed leaving next to none particles left.

5.1.2 Frozen sand test fields

The results for the main frozen sand test fields, i.e. F1-3 (Natural Evenes) and KF1-3 (Crushed Rock) are shown in table 5.3 and 5.4, respectively. Two test zones were descaled for each cover sand type and each deployed amount.

Deployed amount [g/m^2]	Descaled mass [g]	Descaled fraction [%]
90	2.5	1.4
	1.5	0.8
140	1.5	0.5
	3.0	1.1
180	6.5	1.8
	0.0	0.0

Table 5.3 Descaling results for frozen Natural Evenes test fields. The descaled fraction is relative to total deployed mass in the test zone. Area used for descaling was 2 m^2*, meaning total deployed mass is twice the "deployed amount" value.*

Deployed amount [g/m^2]	Descaled mass [g]	Descaled fraction [%]
90	20.5	11.4
	3.5	1.9
140	17.5	6.3
	9.5	3.4
180	19.5	5.4
	20	5.6

Table 5.4 Descaling results for frozen Crushed Rock test fields. The descaled fraction is relative to total deployed mass in the test zone. Area used for descaling was 2 m^2*, meaning total deployed mass is twice the "deployed amount" value.*

Relative to the dry reference fields, it is immediately visible that both cover sand types descale significantly less when deployed on ice and using the frozen sand deployment method. This is directly related to the main feature of frozen sand, i.e. the sand-water mixture freezes onto the ice.

While this reduction in descaling is expected, a test field with dry sand on ice would have been necessary to further study the differences in descaling between frozen and dry sand. This was, however, abandoned due to no relevance, as mentioned in section 3.3.

Figure 5.1 shows a scatter plot of the data in tables 5.3 and 5.4. It is evident that frozen Crushed Rock descale more than frozen Natural Evenes using this test method. While values vary between test zones, the descaled fraction is roughly 1% for Natural Evenes and 5% for Crushed Rock throughout. This is perhaps surprising, as the two sand types behaved quite similarly on the asphalt reference fields. It is likely due to more loose particles for Crushed Rock when deployed as frozen sand. Visual and physical inspection of the test fields support this. It seems to be attributed to differences in particle size distributions of the two cover sand types. Natural Evenes have a prescribed size range of 0-4 mm compared to 2-4 mm particles for Crushed Rock. Specifically, the lack of fine matter in Crushed Rock is believed to be the root cause. The actual measured particle size distribution is presented in section 5.2.1.

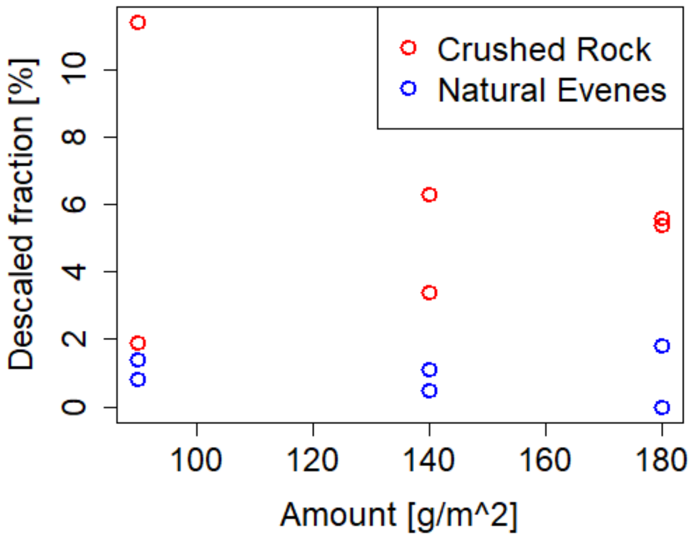

Figure 5.1 Results for descaled fraction of frozen sand with deployed amount along the x-axis.

The frozen sand deployment method benefits from fine matter mixing with hot water to create the binding material for the larger particles. While a small amount of fine matter exists in Crushed Rock too (even though specifications say no less than 2 mm), it is significantly less. This means the sand-water mixture mostly consists of water glazed large particles that appear to not hold together as well as the sticky paste-like substance created when deploying frozen Natural Evenes. See figure 5.2 for a close-up comparison. The frozen patches in Crushed Rock are much clearer due to being mostly frozen water (more easily visible in figure 3.5), while Natural Evenes is completely opaque and resembles mud.

Figure 5.1 also suggests that descaled fraction is fairly constant as a function of deployed amount. This means descaled mass increases linearly with deployed amount, i.e. the more deployed frozen sand, the more descaled frozen sand.

5.1.3 Uncertainties

While the frozen sand results are fairly clear, the associated uncertainties, and how these are managed, should be discussed in order to shed more light on the value of the data.

Emphasized in section1.1, FFI was tasked with developing and executing a low-cost test method for descaling. While this results in a gain in terms of resource and time requirements, it has some drawbacks related to accuracy. Below are the main sources of descaling uncertainty:

(a) The vacuum cleaner has a suction pressure different to that of a real F-35 and P-8, and thus the absolute values for descaled mass is likely to differ significantly to the real aircraft.

Figure 5.2 Side by side comparison of frozen Crushed Rock (left) and Natural Evenes (right). Beware that the images were taken at slightly different angles and lighting. Photo: FFI.

Therefore, the test concept was from the onset focused on generating knowledge on the relative differences in descaling between the cover sand types and deployment amounts, under the assumption that descaled sand is monotonically increasing with increasing suction.

(b) The spreader truck is a source of some uncertainty. It is unlikely that the driver is able to perform deployment in exactly the same speed for all test fields. This has an effect on the frozen sand methodology; larger speeds provides a greater cooling effect on the sand-water mixture whilst in the air on its way to the ground, and thus affects the subsequent freezing and subduction into the ice surface. Also, "micro"-variability in the sand particle's interaction with the spreader mechanism causes small differences in deployment amount (g/m^2) even within a test field and test zone. While not quantified, these uncertainties are assumed to be small and to have little effect on the data.

(c) The descaling test concept is dependent on the vacuum cleaner operator. While the operator was trained to perform each descaling test zone in 50 seconds, some inconsistencies are inevitable. Using more time is likely to lead to more descaling as more time is spent over each sub-section of the test zone.

(d) The precision scale's sensitivity to wind and temperature variations was largely managed by placing the weighing station inside the vehicle.

(e) The six different frozen sand test fields had small variations in their ice surfaces. While care was taken to find areas on the taxiways that minimized this, it could not be eliminated entirely. Some test fields had slightly more small patches of semi-firm snow that could be partially descaled. Descaling reference tests were performed on similar ice surface (without sand) next to the Crushed Rock test fields. These tests suggested that some snow particles would be descaled, but not enough to invalidate the results. Most snow particles are too light to end up in the gravity well of the pre-separator.

The combined effect of the uncertainties slightly impacted the interpretation of the results. FFI are confident in that Crushed Rock descales more than Natural Evenes, but the descaling data *should not* be used for the exact *amount* by which they differ in descaling.

5.2 Lab tests

The results of the lab tests supplement the Evenes descaling test with a main focus on the wear potential once the cover sand has been ingested into the jet engine. Relative differences in particle size distribution, surface roughness and abrasivity were uncovered for the sand types in table 4.1

5.2.1 Particle size distribution

The particle size distribution for each of the cover sand types were determined through sieving. Lab sieves of sizes 0.125, 0.250, 0.500, 1, 2 and 4 mm, were used. Figure 5.3 shows the statistical distribution of mass for each cover sand type and is a plot of the actual data shown in appendix A.3 based on samples with masses as detailed in table 4.

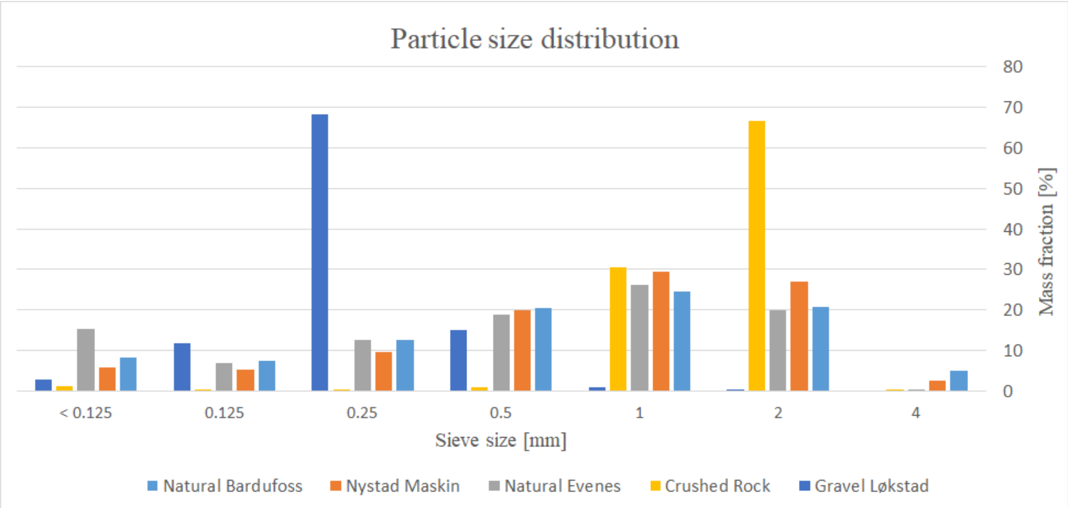

Figure 5.3 Particle size distribution for all five cover sand types obtained through sieving. The x-axis is the sieve size and the y-axis is the mass fraction retained on that sieve, relative to the total mass of the sieved sample.

Focus first on Natural Evenes, Natural Bardufoss and Nystad Maskin. These are prescribed to have particles in the range 0 – 4 mm. All three cover sand types are quite similar, especially for the particles that make up the bulk of the mass; particles between 0.5 mm and 4 mm make up roughly 70% of the mass for these three types, with Nystad Maskin skewed towards slightly larger particles. However, more noticeable differences are seen at the lower and upper end of the spectrum.

Evenes natural sand has considerably more fine matter, i.e. particles < 0.125 mm. This is beneficial in the frozen sand deployment method. However, there is a balancing act at play here; zero fine matter would be detrimental and increase the number of loose particles due to little binding material. On the other hand, having too much fine matter comes at a cost to the larger particles, meaning the overall particle size distribution would then be heavily skewed towards fine dust with no stones to create the majority of friction. The optimal combination for frozen sand is somewhere in between these two extremes, but frozen sand descaling (and friction) tests with a wide range of particles distributions would have to be conducted in order to conclude, which is a task outside the scope of this work.

The upper end of the spectrum provides a more conclusive observation. Natural Bardufoss and Nystad Maskin contain particles larger than the prescribed maximum of 4 mm. While the mass fraction for > 4 mm is quite small, it is significant, especially with over 5% for Natural Bardufoss. Larger particles create a larger hazard for the jet engines.

Figure 5.4 A selection of a few of the largest particles found in the sieving samples in each of the five cover sand types. Photo: FFI.

Figure 5.4 shows a comparison between some of the largest particles present in each of the provided samples. The large particles in Natural Bardufoss stand out. These are not just slightly above 4 mm, but around 1 cm in size. Nystad Maskin has large particles > 4 mm, but not as extreme as Natural Bardufoss sand and to a smaller mass fraction. Natural Evenes and Crushed Rock satisfy their upper boundary spec of 4 mm. FFI are not aware of the spec size for the Gravel Løkstad, but its largest particles are a lot smaller than the others.

Consider now figure 5.3 focusing on the clear stand-outs, starting with Crushed Rock. Prescribed size range is 2 – 4 mm. The sieving results indeed confirm that around 70% of the mass exist in this range, although there is a significant portion in the 1 − 2 mm range as well. A very small amount of fine matter also exists. While significantly less than in the three 0 − 4 mm sand, there is still some dust that may mix with the water when deploying frozen sand. That being said, the particle distribution of Crushed Rock does not appear favourable for frozen sand deployment compared to the others. The lack of fine matter creates less binding material for the larger particles and is likely the primary cause for the increase in loose particles and thus increase in descaling that was observed in section 5.1.2.

Gravel Løkstad is significantly finer than all others. Next to none particles exist above 1 mm and almost 70% are located in the 0.250 − 0.500 mm range. Perhaps surprisingly though, this type has less fine matter than the three 0 − 4 mm sands. As with Crushed Rock, it is suspected that this negatively impacts its effectiveness as frozen sand compared to the 0 − 4 mm types. It is however not clear how fine the fine matter must be to be effective in creating the binding material.

5.2.2 Visual inspection

Simple visual inspection using a microscope was done for the five cover sand types. As observed in the particle size distributions in section 5.2.1, Natural Evenes, Natural Bardufoss and Nystad Maskin are also visually quite similar, as depicted in figure 5.5. They contain a large range of particle sizes and significant fine matter is visible. They appear comparable in terms of surface roughness as well, with Natural Evenes perhaps exhibiting slightly sharper edges in general.

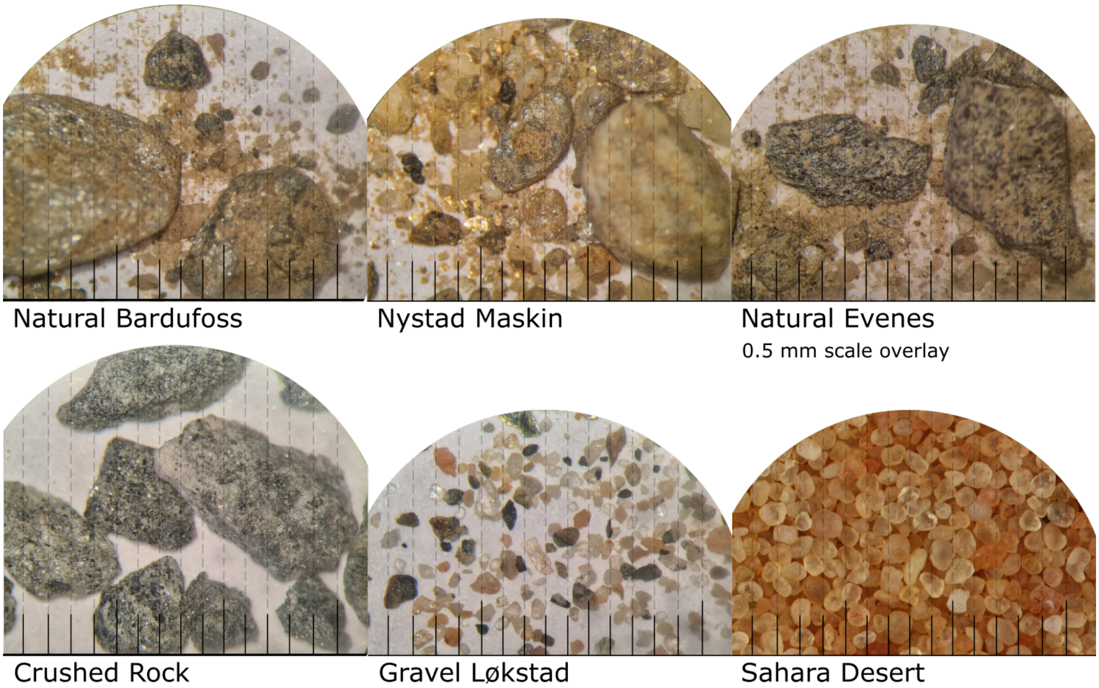

Figure 5.5 Microscope image using 25 times magnification of a representative sub sample of the five cover sand types. Photo: FFI. The bottom right panel is a reference image of desert sand from Sahara [31].

Crushed Rock is distinctly different, having a much narrower particle size range and no visible fine matter. It also appears to have a somewhat rougher surface and sharper edges. Gravel Løkstad also stands out, containing only small particles and, perhaps surprisingly, very little fine matter. Based purely on visual impression, Gravel Løkstad also appears to differ more substantially from the others in terms of mineral content.

They are all vastly different compared to the reference sand from the Sahara Desert, which contains very rounded and small (mostly) quartz particles. The Sahara Desert sand presents an interesting comparison, as this is more similar to the type of sand that aircraft are exposed when operating in desert conditions. In such conditions, the aircraft is exposed to sand in flight as well compared to the cover sand case where ground traversal is responsible for all sand exposure. Nevertheless, desert sand is significantly finer, more rounded and is closer to what the F-35 is usually exposed to in its global operating environments. Icy runway cover sand is a less common theater.

Figure 5.6 shows a typical large particle for each sand type using the highest magnification (x40) on the available microscope. The images attempt to give a visual impression of the surface roughness of some stones that could be ingested into the jet engines. The shape and roughness varies between particles within the same sand type, so these images are purely meant for illustration.

Figure 5.6 Microscope image using 40 times magnification of some large particles extracted from the five cover sand types. Photo: FFI. The bottom right panel is a reference image of desert sand from Sahara [31].

5.2.3 Abrasivity

The abrasivity of the five cover sand types were tested by SINTEF Rock and Soil Mechanics laboratories [27] using the LCPC test. The results are centered around the mass loss on the F100 blade impellers and is shown in table 5.5.

Gravel Løkstad exhibits by far the lowest abrasivity of the five tested cover sand types. The F100 blade impeller mass loss is less than half of the others and indicates significantly less engine wear potential. This can likely, at least partially, be attributed to its particle size distribution. It has no particles above 1 mm, and its distribution is centred around particles about 5-10 times smaller than the other cover sand types. According to SINTEF, larger particles generally produce more abrasive wear. However, this may not be the only reason; the topic of material composition is of importance as well, as shall be seen below. The total available amount of Gravel Løkstad meant only one LCPC test could be performed for this type.

Natural Bardufoss and Natural Evenes show roughly similar abrasivity, coinciding with their similar particle size distributions. They also share similar distribution with Nystad Maskin, but this cover

	Natural Bardufoss	Nystad Maskin	Natural Evenes	Crushed Rock	Gravel Løkstad
Sample mass [g]	500	500	500	500	500
Test 1 [g]	0.291	0.413	0.326	0.355	0.151
Test 2 [g]	0.307	0.492	0.346	0.450	N/A
Mean [g]	0.299	0.453	0.336	0.403	0.151

Table 5.5 LCPC abrasivity results for the five cover sand types. The rows are: The sand sample mass used for each test, the F100 blade impeller mass loss for each test and the resulting mean value.

sand is shown to be significantly more abrasive than the other two. The visual inspection of these three types also showed little difference. This leads to the hypothesis that the enhanced abrasivity of Nystad Maskin is primarily not linked to particle size distribution or surface roughness/sharpness, but rather the material composition. Different rock minerals have different abrasive properties, and it is likely that this makes Nystad Maskin abrade engine components more aggressively.

Crushed Rock performs somewhere in-between the two Natural sands and Nystad Maskin. It is fairly abrasive, but not much more than the two Natural sands. Crushed Rock is quite unique in its particle size distribution, being skewed towards larger particles. Combined with its visually slightly sharper surface, it was expected to be more abrasive, but it might compensate in other areas, e.g. material composition. This remains unknown.

The abrasivity test involves some uncertainties mainly related to the slight geometric variation between the F100 blade impellers. The differences were small and managed during testing, and consequently assumed not to significantly impact the results. Test 1 and Test 2 utilized two different sets of F100 blade impellers (that were geometrically near-equivalent within each set), and is assumed to be the cause of the generally larger mass loss for Test 2.

Figure 5.7 F100 blade impeller not used for testing (left) and after completed LCPC Test 1 with Nystad Maskin (right). Photo: FFI.

Figure 5.7 shows an example of the wear on the F100 blade impeller after a completed LCPC test compared to a fresh impeller not used for testing. The high frequency rotation causes especially the edges (as these are the furthest away from the axis of rotation and hence the move the fastest) to abrade away from impact with the cover sand particles.

6 Conclusion

NDMA requested support from FFI to perform descaling testing on different airport cover sand types and deployed amounts. The main test event was performed with success on the 22nd of February 2022 at Evenes Air Station. Afterwards, FFI performed additional lab tests to uncover more relative differences in the various cover sand types' ability to damage the jet engines.

The tests uncovered several differences between the cover sand types:

(a) Particle size distribution and shape

- (a)1. The three cover sand types Natural Evenes, Natural Bardufoss, and Nystad Maskin all have fairly similar particle size distributions.
- (a)2. Natural Bardufoss contains a significant amount ($\sim 5\%$) of too large particles (> 4 mm), exceeding the specification given by the cover sand supplier. Nystad Maskin has $\sim 2\%$ particles > 4 mm.
- (a)3. The cover sand type Crushed Rock contains very little fine matter (particles below $\sim 0.125\ \mu$m in size).
- (a)4. The cover sand type Gravel Løkstad is significantly finer than the others (no particles above ~ 1 mm).
- (a)5. Crushed Rock visually appear to have a slightly rougher surface and sharper edges compared to the others.

(b) Descaling potential

- (b)1. Deployed as frozen sand, Crushed Rock descales significantly more than Natural Evenes.
- (b)2. Measurements and observations suggest fine matter content is important in the frozen sand deployment method for the larger particles to properly freeze to the ground and reduce descaling.
- (b)3. Lack of fine matter content is likely the primary reason Crushed Rock descales more than Natural Evenes.
- (b)4. Frozen sand descaling increases linearly with increasing deployed amount (g/m^2).
- (b)5. Frozen sand descaling was not tested for Natural Bardufoss, Nystad Maskin and Gravel Løkstad. Based on their particles size distribution, Natural Bardufoss and Nystad Maskin are likely to descale similarly to Natural Evenes while Gravel Løkstad remains an unknown.
- (b)6. Test field inspection indicates that sweeping frozen sand may be an effective measure for removing the majority of descaling potential.
- (b)7. Gradual throttle increase during taxi- and takeoff acceleration reduces probability of Ground Vortex formation and consequently the descaling potential.

(c) Abrasivity

- (c)1. The cover sand types Natural Bardufoss and Natural Evenes show similar abrasivity, with Crushed Rock being slightly more abrasive.
- (c)2. Nystad Maskin is the standout most abrasive cover sand type.
- (c)3. Gravel Løkstad exhibit significant lower abrasivity (less than half) compared to the others.

(c)4. Both particle size distribution and material composition appear important for the abrasivity.

(d) Jet engine wear potential

(d)1. The *total* wear potential is a combined effect of the abrasivity and the amount of descaled cover sand ingested into the engine.

(d)2. Both the frozen sand descaling and abrasivity results suggest Natural Evenes presents less total wear potential than Crushed Rock.

6.1 Recommendations

The differences in friction or practical concerns were outside the scope for FFI's participation. Based solely on the results from descaling and lab tests, FFI recommends that:

(e) The use of Crushed Rock cover sand is halted where possible, due to its likely larger total wear potential, and is replaced by a natural sand with a more even particle size distribution that includes fine matter.

(f) Cover sand deliveries are periodically sieved to ensure the particle size distribution is correct.

6.2 Future Work

Three tests were not completed in time for this report, but which will be part of a future report:

(a) Cover sand hardness - This could provide information about how particles are shattered when exposed to high pressure from an aircraft tire or sweeper truck. This would impact descaling to some degree, but likely be of more significance to friction properties.

(b) Computer Fluid Dynamics analysis - By measuring the actual air pressure field surrounding the vacuum cleaner using an FFI developed pressure sensor grid, the measurements could be compared to a CFD analysis based on F-35 inlet flow data FFI have received from NDMA and Pratt & Whitney, to extrapolate the descaling results towards more realistic engine inlet flow fields.

(c) Cover sand salt content - The simple method in section 4.5 could be used to determine salt content, which is an indicator for enhanced corrosive wear on the aircraft.

NDMA have observed material depositing inside the engines, specifically around the heat exchangers. It could be possible to perform high heat testing of the cover sand types to evaluate their tendency to melt and create deposits.

During planning of the abrasivity test, SINTEF informed of the possibility of performing X-Ray Diffraction (XRD) analysis on the cover sand types. This test would provide the material composition, including a more accurate way to measure salt content. It could help to understand the significance of material composition relative to particle size distribution, on abrasivity. Due to the time and resources required to perform this test, its value was not investigated further. FFI did however leave samples of the five cover sand types at SINTEF in Trondheim that may be used for XRD analysis in the future if necessary.

List of abbreviations

ARFFS	Airport Rescue and Fire Fighting Services
BRP	Brann, redning- og plasstjenesten
CFD	Computational Fluid Dynamics
F-16	General Dynamics F-16A/B "Fighting Falcon"
F-35	Lockheed Martin F-35A "Lightning II"
FFI	Forsvarets forskningsinstitutt Norwegian Defence Research Establishment
FMA	Forsvarsmateriell
FOD	Foreign Object Damage
FOI	Foreign Object Ingestion
GV	Ground Vortex
LAC	LCPC Abrasivity Coefficient
LCPC	Laboratoire Central des Ponts et Chaussèes
MPA	Maritime Patrol Aircraft
NATO	North Atlantic Treaty Organization
NDMA	Norwegian Defence Materiel Agency
NTNU	Norges tekniske-naturvitenskapelige universitet Norwegian University of Science and Technology
P-8	Boeing P-8A "Poseidon"
QRA	Quick Reaction Alert
RNoAF	Royal Norwegian Air Force
RPM	Revolutions per minute
SAT	Soil Abrasion Test
XRD	X-Ray Diffraction

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Appendix

A Lab tests

A.1 Scale consistency

Consider the pre-separator described in section 3.1.2.1. Its bottom surface area is larger than that of the scale. Tests at FFI showed that differences in container placement on the scale caused significant differences in mass measurements due to weight distribution. It was therefore necessary to have a consistent method for using the scale. The underside of the particle container has slightly protruding surfaces permitting consistent alignment with the scale. This technique was tested on 20 measurements of the particle container, resulting in table 1. The test shows that the uncertainty (standard deviation and spread) is comparable to the resolution of the scale itself. Expected differences in descaling between sand types would significantly exceed this, and thus this scale technique was deemed sufficient.

Mean [g]	Median [g]	Std. Deviation [g]	Spread [g]
6709.09	6709	0.34	1.5

Table 1 Statistics for weighing the identical particle container $N = 20$ times using a consistent placement technique.

A.2 Pre-separator fraction

Measuring descaling as described in section 3.2.3 involves weighing the pre-separator. However, the pre-separator is only intended to catch "heavy" particles via gravity, and thus it is not guaranteed that all descaled sand will end up here; some will bypass the pre-separator and reach the conventional dust bag, and some will be stuck in the hose or other parts of the system. In the case that a significant portion of the descaled cover sand would bypass the pre-separator, or the fraction caught by the pre-separator would vary significantly across multiple descaling measurements, the approach of weighing the pre-separator would be insufficient.

A simple lab test was conducted to quantify the fraction of sand caught by the pre-separator. A known mass of cover sand (200 g) from Kjeller Air Station was spread on the floor and all 200 g was descaled. Weighing the pre-separator before and after descaling and repeating this $N = 6$ times, yielded the results shown in table 2.

Mean [g]	Median [g]	Std. Deviation [g]	Spread [g]
195	195	1.04	3

Table 2 Statistics for fraction of cover sand caught in pre-separator using Kjeller Airport cover sand ($0 - 4$ mm) when descaling 200 g of sand repeated $N = 6$ times.

The test shows that around 97% of the descaled sand is caught by the pre-separator. Only a very small fraction gets stuck elsewhere in the system. Also, the standard deviation and spread are only slightly larger than the resolution of the scale, indicating fairly consistent measurements across multiple tests. This weighing approach was deemed sufficient.

A.3 Particle size distribution

Sieve [mm]	Natural Bardufoss	Nystad Maskin	Natural Evenes	Crushed Rock	Gravel Løkstad
4.000	5.06	2.55	0.01	0.34	0.00
2.000	20.68	27.07	19.80	66.72	0.09
1.000	24.56	29.35	26.28	30.60	0.86
0.500	20.42	19.81	18.75	0.87	15.02
0.250	12.62	9.60	12.47	0.01	68.39
0.125	7.46	5.34	6.92	0.06	11.73
< 0.125	8.25	5.69	15.16	1.11	2.75

Table 3 Sieving results for the five cover sand types. Displayed values are mass fraction (relative to total mass of the sieved sample) retained on the various sieve sizes, e.g. a data point for 2 mm *represents the mass fraction of particles between* 2 *and* 4 mm *for that cover sand type.*

Cover sand type	Mass [g]
Natural Bardufoss	276.69
Nystad Maskin	275.65
Natural Evenes	286.68
Crushed Rock	246.15
Gravel Løkstad	277.83

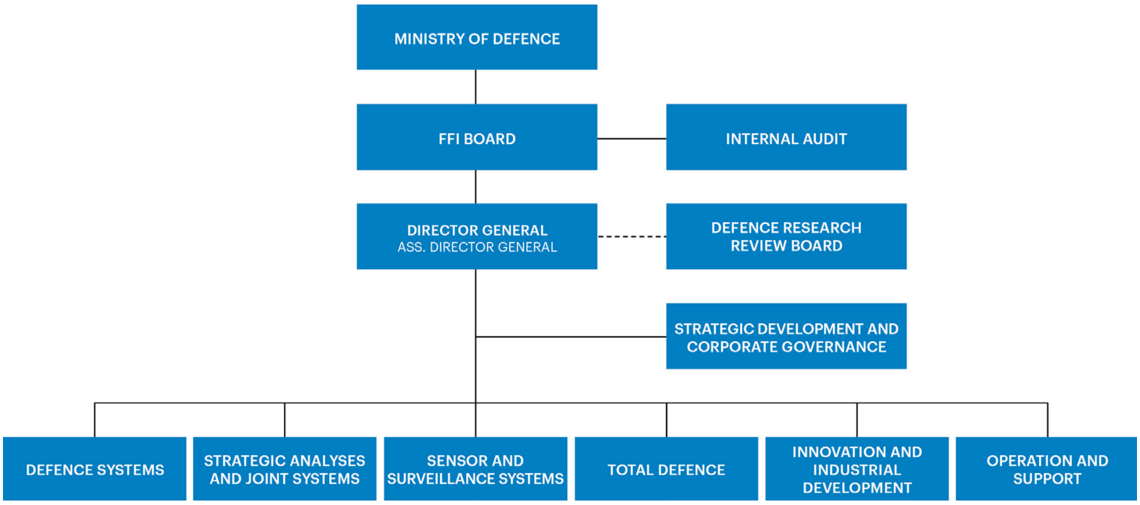
Table 4 Total mass of sieve samples for of the five cover sand types.

About FFI
The Norwegian Defence Research Establishment (FFI) was founded 11th of April 1946. It is organised as an administrative agency subordinate to the Ministry of Defence.

FFI's mission
FFI is the prime institution responsible for defence related research in Norway. Its principal mission is to carry out research and development to meet the requirements of the Armed Forces. FFI has the role of chief adviser to the political and military leadership. In particular, the institute shall focus on aspects of the development in science and technology that can influence our security policy or defence planning.

FFI's vision
FFI turns knowledge and ideas into an efficient defence.

FFI's characteristics
Creative, daring, broad-minded and responsible.



Forsvarets forskningsinstitutt (FFI)
Postboks 25
2027 Kjeller

Besøksadresse:
Kjeller: Instituttveien 20, Kjeller
Horten: Nedre vei 16, Karljohansvern, Horten

Telefon: 91 50 30 03
E-post: post@ffi.no
ffi.no

Norwegian Defence Research Establishment (FFI)
PO box 25
NO-2027 Kjeller
NORWAY

Visitor address:
Kjeller: Instituttveien 20, Kjeller
Horten: Nedre vei 16, Karljohansvern, Horten

Telephone: +47 91 50 30 03
E-mail: post@ffi.no
ffi.no/en