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# CRREL Environmental Wind Tunnel Upgrades and the Snowstorm Library

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# CRREL Environmental Wind Tunnel Upgrades and the Snowstorm Library

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# Abstract

Environmental wind tunnels are ideal for basic research and applied physical modeling of atmospheric conditions and turbulent wind flow. The Cold Regions Research and Engineering Laboratory's own Environmental Wind Tunnel (EWT)—an open-circuit suction wind tunnel—has been historically used for snowdrift modeling. Recently the EWT has gone through several upgrades, namely the three-axis chassis motors, variable frequency drive, and probe and data acquisition systems. The upgraded wind tunnel was used to simulate various snowstorm conditions to produce a library of images for training machine learning models. Various objects and backgrounds were tested in snowy test conditions and no-snow control conditions, producing a total of 1.4 million training images. This training library can lead to improved machine learning models for image-cleanup and noise-reduction purposes for Army operations in snowy environments.

# Contents

# Figures and Tables

## Figures



## Tables

# Preface

This study was conducted for the US Army Corps of Engineers (USACE) under Project Element 0603463A, Project Number BP4, Task Number 14, “CRREL Environmental Wind Tunnel Upgrades and the Snowstorm Library.”

The work was performed by the Engineering Resources Branch of the Research and Engineering Division, US Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Melisa Nallar was branch chief; and Dr. John Weatherly was acting division chief. The deputy director of ERDC-CRREL was Dr. Ivan P. Beckman, and the director was Dr. Joseph L. Corriveau.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

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# 1 Introduction

## 1.1 Background

The US Army Corps of Engineers, Engineer Research and Development Center (ERDC) has made extensive use of physical modeling for studying atmospheric and environmental conditions. Even as computational modeling capabilities increase, there will always be the need for physical modeling. One example of physical modeling of environmental conditions is an atmospheric wind tunnel, which simulates turbulent airflow around buildings and other structures.

The Cold Regions Research and Engineering Laboratory (CRREL) has an active atmospheric wind tunnel, the Environmental Wind Tunnel (EWT), since 1995 (Torres et al. 2019). The EWT is an open-circuit suction wind tunnel. Air is drawn in through a contraction cone (which serves to compress airflow and increase air pressure), flows through a large test section or working section of the tunnel through a fan, and is released into an open hopper where entrained particles are captured. This design is advantageous for atmospheric studies as the air is already turbulent, and the open-circuit design allows for a larger test section at a lower cost. The EWT has historically been used for snowdrift modeling, which helps to determine how snowdrifts form and to verify physically if methods for mitigating them are effective (Haehnel et al. 1997; Lever and Haehnel 1995; Song and Haehnel 2012).

While computational modeling has largely become the primary method for most modeling needs, there still exists a need for physical modeling, especially in the case of machine learning. Machine learning models often require large databases of training data, such as a library of images, to train the models and help them understand various cases for classification (Sarker 2021). In the case of image cleanup and snow, rain, or haze removal, a major issue is the source and quality of training data. Often, training data comes from external online sources, such as social media (Liu et al. 2017). These images are not originally intended for research purposes, and thus lack control and have noisy image pairing. As a result, the usual practice is to find quality images to serve as a control, and then to add synthetic noise to serve as its pair (Liu et al. 2017).

One flaw of this method is that the control images are usually taken in conditions where snow or rain are not normally present, such as at beaches or deserts. This means there is a stark difference between background conditions and the synthetic noise mask, which may lead to an overstatement of a model's effectiveness. Another flaw is the synthetic noise mask may not accurately represent genuine falling snow or rain, and as it is added over an image the concept of visual depth is lost and not considered by the model during cleanup (Liu et al. 2017).

A solution to both of these concerns is to simulate snowstorms with controlled conditions and taking images of objects placed inside. This would ensure that the images are taken in realistic conditions, and that there is no need for a synthetic noise mask. A viable route to this solution would be to produce images inside an atmospheric wind tunnel, such as the EWT, and to simulate snow using visually similar particles, such as polystyrene pellets, as seen in Figure 1.

Figure 1. Expanded polystyrene pellets. Pellets were sprayed with industrial cleaner by the manufacturer to negate surface charge.

## 1.2 Objectives

Our objective was to upgrade the EWT to perform novel snowstorm modeling and to produce a new image library of objects in a simulated snowstorm for training the next generation snow-removal machine learning models.

## 1.3 Approach

In 2021 we upgraded three major components of CRREL's EWT: the three-axis chassis motors, the variable frequency drive, and the anemometer probe and its data acquisition system. The upgraded EWT was used for simulations of snowstorms, which were recorded as comparative videos of clear and snowy conditions. These videos were then parsed into individual frames and then into 96 × 96 px, resulting in a database of 582,567 control images and 883,201 test images.

# 2 Wind Tunnel Upgrades

In 2021, components of the CRREL EWT were upgraded and refurbished to provide increased reliability, versatility, and performance of the tunnel for a variety of research applications. Modern control designs were incorporated into the carriage system and fan operation. Vital instrumentation, such as the anemometer system, was repaired and upgraded to maximize efficiency. Structural upgrades to the EWT were executed by AeroLab, and instrumentation upgrades were executed by TSI, Inc. Details about the original structural design, specifications, and capabilities of the CRREL EWT are documented in the Technical Report ERDC/CRREL TR-19-1 (Torres et al. 2019).

## 2.1 Carriage system

The carriage system in the test section of the EWT consists of slender steel rails that traverse the three dimensions of the tunnel, *X* (across the span), *Y* (vertical), and *Z* (down the length) (Torres et al. 2019). The rails were designed to provide the capability of taking measurements at different locations in the test section, while minimizing disturbances in the airflow. The original controller design for the carriage relied on stepper motors and linear positioners operated via the LabView virtual instrument software. The primary drawback of this setup was the need for calibration of the carriage before each use, which required knowledge of its last known position within the tunnel. If the position was not known, the carriage could be programmed to extend beyond its safe range of operation.

To improve the safety and versatility of the carriage system, the existing rails were outfitted with new servo motors and limit switches for each direction of travel. The upgraded design allows for constant and precise spatial awareness of positioning and prevents movement beyond the safe range of operation. Updated LabView software was installed with connection to a National Instruments data acquisition and control system for the servo motors.

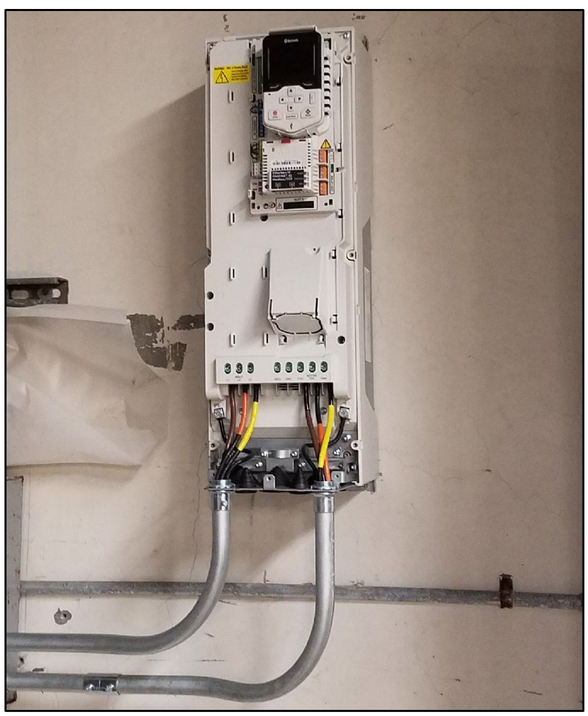
## 2.2 Fan control

The original fan installed in the CRREL EWT was a six-blade, shaft-driven system by Joy Technologies, Inc. (Torres et al. 2019). This fan was used as a fixed-speed, variable-pitch system to control airflow through the tunnel.

The pitch angle of the blade needed to be manually adjusted using an outdated control panel that was separate from other controls for the tunnel operation.

Upgrades to the fan focused on improving its performance and operability as well as the control of airflow in the tunnel. The fan control was upgraded to a modern and robust variable frequency drive (VFD), as seen in Figure 2. This was completed by fixing the fan to an optimal pitch angle and removing the controls for the variable pitch system. The 460 V, three phase VFD is controlled using the same LabView software as the carriage system, allowing for seamless access and operation of both systems simultaneously during an experiment.* The VFD was designed to automatically adjust the revolutions per minute needed to maintain a specified velocity in the event of changes in air temperature and moisture using a feedback loop of sensors installed in the tunnel. The upgraded system improved the performance and control of airflow through the tunnel, with a new maximum airspeed of 2.66 m/s at 1760 RPM.

Figure 2. Upgraded variable frequency drive (VFD).



*. For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

## 2.3 Anemometer system

Measuring air velocity inside a wind tunnel is commonly completed using a hot-wire anemometer and corresponding constant temperature anemometer (CTA) system. The CRREL EWT has three one-dimensional hot-wire anemometers available for use in the tunnel. The associated CTA system prior to upgrades had six operational channels to measure and record velocity, where one channel can record data in one dimension. The systems are manufactured by TSI, Inc. and use their software ThermalPro to collect, visualize, and store data.

The primary goal of this upgrade was to calibrate and repair the hot-wire anemometer probes, improve the capacity and replace necessary components of the CTA, and update the ThermalPro software. All associated connecting cables between the probe and CTA, and between the CTA and computer, were replaced or repaired. The controller board in the CTA was replaced to expand the capacity from six channels to eight channels. These upgrades were crucial for experiments to be completed in the EWT.

# 3 The Snowstorm Library

## 3.1 Test plan

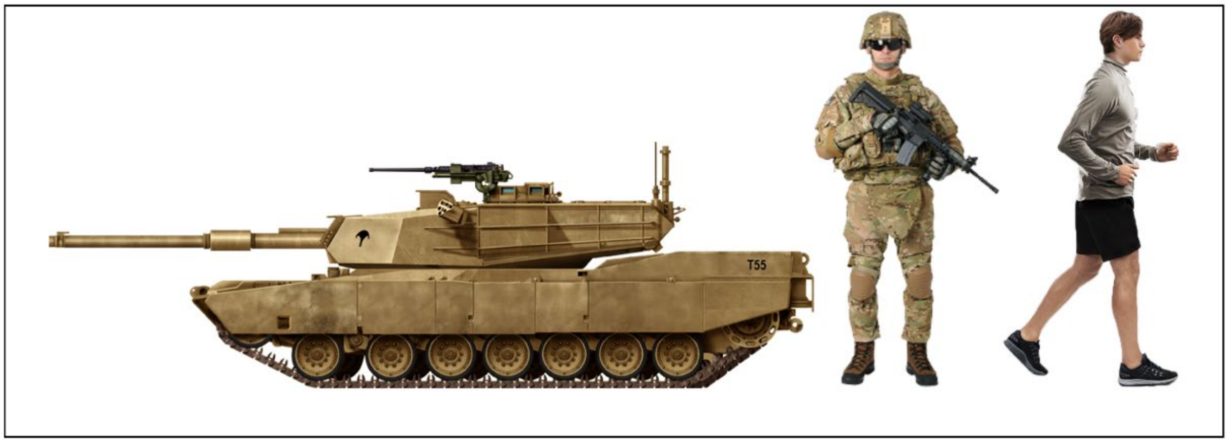
The EWT has a 9.75 m long text section with a 2.4 m by 1.2 m cross-sectional area. It is an open-circuit suction wind tunnel, with any particles intended to simulate snow added upstream of any imaging. The selected particles were expanded polystyrene pellets spray coated with soap to neutralize their natural electric charge. The particles ranged in size from 2 to 5 mm, and behaved visually similar to snow while falling. Particles were place in a flume above the wind tunnel and slowly released into the tunnel during testing. Wind tunnel fan speeds were held constant and conditions were set to produce a turbulent flow to mimic an active snowstorm.

Imaging was made using the GoPro Black 9 camera, with videos recorded in 120 fps (frames per second) with 1080p resolution. The camera was secured against the outside of the EWT's acrylic wall and oriented perpendicular to flow. On the opposite acrylic wall was a background image representing a variety of arctic environments, as seen below in Figure 3. Because of lighting requirements from the high framerate and resolution of the GoPro, floodlights were positioned over the wind tunnel to illuminate the scene.

Figure 3. Selected backgrounds. Backgrounds, from left to right, are referred to as *A*, *B*, and *C* in the library. Creative commons.

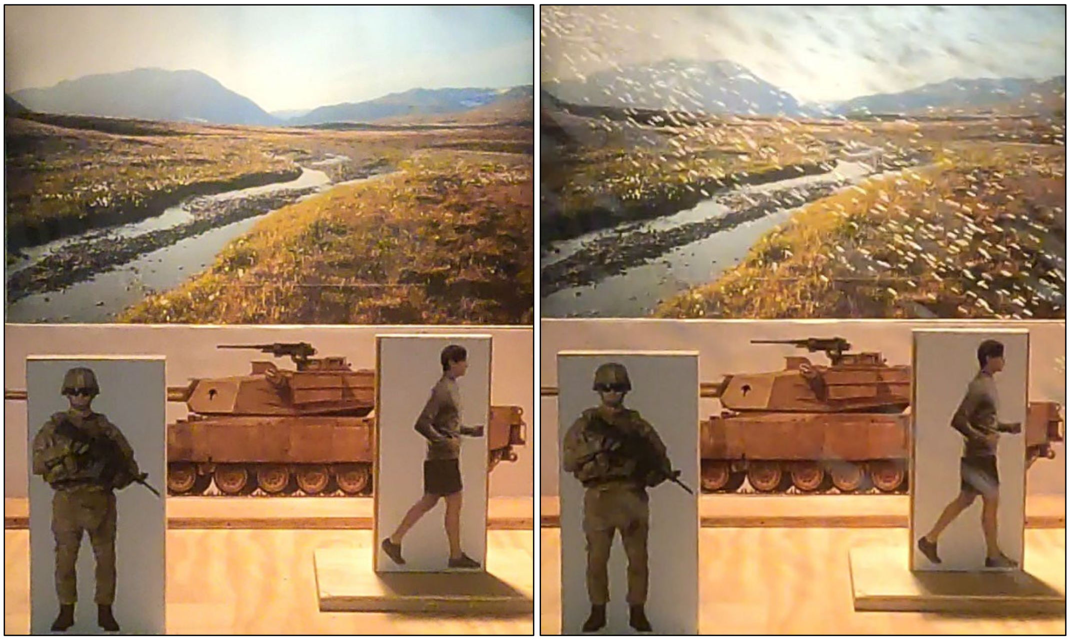
In front of these backgrounds and inside of the tunnel, various objects were placed to simulate a complex scene. These objects were wooden stands with various images on them, such as a soldier, a tank, or a civilian, as seen in Figure 4. The objects were positioned in various combinations, to provide the library a variety of potential interactions.

Figure 4. Object images used for scene composition: a tank (*left*), a soldier (*middle*), and a civilian *(right*). Open access.




Selected backgrounds were from tundra and arctic locales, and chosen to represent conditions where snowfall was expected and would be the most relevant for a training library. Objects chosen were selected both for army relevance and having a mixture of similarities that may reduce classification accuracy, such as the soldier and civilian images appearing similar, while the tank is distinct from both. In total, three backgrounds and several combinations of objects were tested, accounting for 17 total combinations. All combinations were filmed with and without the presence of falling snow, allowing for a frame-by-frame comparison, as seen in Figure 5.

Figure 5. Comparison of control and snowy conditions. Background *B* used, with tank, soldier, and civilian present. *Left*, control condition without falling snow. *Right*, target condition with falling snow.

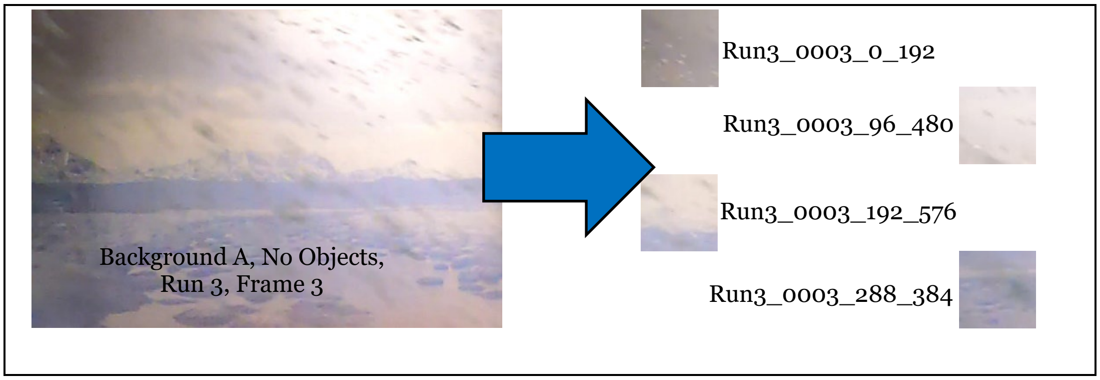


## 3.2 Conversion process

Because of the large file size of the recorded videos and their framerate, it was infeasible to release the library files in their original form. To reduce the file size of the library, several measures were taken both to reduce the number of frames and their dimensions. The framerate of these videos was reduced using the FFmpeg software to one frame per second, and individual frames were extracted from the video and converted from the original MP4 format into a set of PNG images. Extraneous information at the edges of the images, such as the walls of the EWT, were removed, which reduced the dimensions of the images. This reduction in scale lowered the database size from approximately 500 GB to approximately 20 GB, making distribution more feasible.

To further simplify the individual frames for use as a training library, each frame was spliced into 96 × 96 px units, similar to other training libraries for machine learning. The individual units were then labeled by frame and pixel position within the frame. Several example pixel units with their labels can be seen in Figure 6. To train a machine learning model on this library, comparisons were made over a timespan for individual frames, or between the same location and conditions both with and without the presence of artificial snow.

Figure 6. Conversion of individual frames (*left*) into 96 × 96 px units (*right*).




## 3.3 Library organization

The Snowstorm Library is organized by background, objects used, and run number, allowing backgrounds, specific objects, and conditions to be individually selected for model training. Individual images are 96 × 96 px in PNG format, and are labeled with run type (control or target run), run number, frame number, and coordinates of the upper left pixel of the image. For example, a target run frame that used background *A*, with only the soldier object, would be found in directory *BackgroundA/Soldier/Run2* and would have a filename such as *Run2_0084_384_288.png* which contains an image of the soldier object's face at coordinates (385, 288) obscured by snow at 84 s into the target run. For comparison with a control example of what that image should look like without visual degradation, any control example ending in *_384_288.png* should be used.

The library in total contains 582,567 control images and 883,201 test images, or approximately 3 h of control frames and 4.5 h of target frames. The individual quality and distribution of control and target images can be seen below in Table 1. To access the library, please consult the information found in the Appendix: Snowstorm Library.

Table 1. Snowstorm Library organization.

| Background | Object(s) Used | Frame Dimensions (px) | # of Units per Frame | Control | | | Target | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | # of Runs | Total Length | # of Images | # of Runs | Total Length | # of Images |
| *A* | None | 672 × 480 | 35 | 1 | 6 min, 18 sec | 13,230 | 5 | 13 min, 49 sec | 29015 |
| | Soldier | 672 × 576 | 42 | 3 | 4 min, 53 sec | 12306 | 2 | 7 min, 23 sec | 18606 |
| | Tank | 864 × 672 | 63 | 6 | 22 min, 22 sec | 84546 | 7 | 29 min, 26 sec | 111258 |
| | Soldier, Runner | 672 × 768 | 56 | 2 | 10 min, 50 sec | 36400 | 4 | 24 min, 11 sec | 81256 |
| | Soldier, Tank | 672 × 768 | 56 | 6 | 16 min, 39 sec | 55944 | 5 | 20 min, 58 sec | 70448 |
| | Soldier, Tank, Runner | 672 × 768 | 56 | 7 | 20 min, 2 sec | 67312 | 4 | 21 min, 20 sec | 71680 |
| *B* | None | 672 × 480 | 35 | 1 | 10 min, 2 sec | 21070 | 2 | 12 min, 23 sec | 26005 |
| | Soldier | 672 × 672 | 49 | 1 | 14 min, 31 sec | 42679 | 5 | 36 min, 58 sec | 108682 |
| | Tank | 960 × 768 | 80 | 1 | 8 min, 16 sec | 39680 | 3 | 18 min, 5 sec | 86800 |
| | Soldier, Tank | 672 × 768 | 56 | 4 | 19 min, 1 sec | 63896 | 4 | 22 min, 39 sec | 76104 |
| | Soldier, Tank, Runner | 672 × 768 | 56 | 2 | 8 min, 22 sec | 28112 | 4 | 16 min, 7 sec | 54152 |
| *C* | None | 672 × 480 | 35 | 1 | 7 min, 39 sec | 16065 | 1 | 14 min, 12 sec | 29820 |
| | Soldier | 672 × 672 | 49 | 1 | 6 min, 29 sec | 19061 | 1 | 13 min, 2 sec | 38318 |
| | Tank | 768 × 672 | 56 | 1 | 11 min, 20 sec | 38080 | 1 | 11 min, 23 sec | 38248 |
| | Soldier, Tank | 672 × 672 | 49 | 1 | 12 min, 47 sec | 37583 | 1 | 12 min, 47 sec | 37583 |
| | 3 Soldiers, Tank, Runner | 864 × 864 | 81 | 1 | 0 min, 59 sec | 4779 | 1 | 0 min, 42 sec | 3402 |
| | 3 Soldiers, Tank, Runner* | 768 × 576 | 48 | 1 | 0 min, 38 sec | 1824 | 1 | 0 min, 38 sec | 1824 |

*Designates a nonstandard layout of objects.

# 4 Conclusion

The upgrades to the EWT proved useful in developing a novel capability for physical modeling, keeping it relevant when compared to computational modeling. The EWT upgrades led directly to development of the Snowstorm Library, which contains over 1.4 million images for training machine learning models on snow-induced visual degradation. This library will lead to novel models for computer vision, which may remove visual degradation from images more accurately, and will reduce dependence on artificially generated training libraries. To develop libraries like this one further, focus is recommended on more accurately simulating other snowfall-related phenomena, such as snowdrifts and snow accumulation. Varying snowfall conditions and camera position may also help to produce more robust machine learning libraries. The end result of this research will be better models for cleaning visually-degraded images and video, improving military operations in the Arctic, especially in network-denied environments.

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# Appendix A: Snowstorm Library

Due to current cybersecurity requirements, the Snowstorm Library is not publicly available without prior request. To request access to the Snowstorm Library, please contact one of the below individuals.


- Scott Slone, Scott.M.Slone@usace.army.mil
- Robert Ibey, Robert.F.Ibey@usace.army.mil
- Simone Whitecloud, Simone.S.Whitecloud@usace.army.mil

# Abbreviations

| | |
|---|---|
| CRREL | Cold Regions Research and Engineering Laboratory |
| CTA | Constant temperature anemometer |
| ERDC | Engineer Research and Development Center |
| EWT | Environmental Wind Tunnel |
| fps | Frames per second |
| VFD | Variable frequency drive |

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**14. ABSTRACT**
Environmental wind tunnels are ideal for basic research and applied physical modeling of atmospheric conditions and turbulent wind flow. The Cold Regions Research and Engineering Laboratory's own Environmental Wind Tunnel (EWT)—an open-circuit suction wind tunnel—has been historically used for snowdrift modeling. Recently the EWT has gone through several upgrades, namely the three-axis chassis motors, variable frequency drive, and probe and data acquisition systems. The upgraded wind tunnel was used to simulate various snowstorm conditions to produce a library of images for training machine learning models. Various objects and backgrounds were tested in snowy test conditions and no-snow control conditions, producing a total of 1.4 million training images. This training library can lead to improved machine learning models for image-cleanup and noise-reduction purposes for Army operations in snowy environments.

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