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Tracking Historical NASA EVA Training: Lifetime Surveillance of Astronaut Health (LSAH) Development of the EVA Suit Exposure Tracker (EVA SET)

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1.0 Introduction

During a spacewalk, designated as extravehicular activity (EVA), an astronaut ventures from the protective environment of the spacecraft into the vacuum of space. EVAs are among the most challenging tasks during a mission, as they are complex and place the astronaut in a highly stressful environment dependent on the spacesuit for survival. Due to the complexity of EVA, NASA has conducted various training programs on Earth to mimic the environment of space and to practice maneuvers in a more controlled and forgiving environment. However, rewards offset the risks of EVA, as some of the greatest accomplishments in the space program were accomplished during EVA, such as the Apollo moonwalks and the Hubble Space Telescope repair missions.

Water has become the environment of choice for EVA training on Earth, using neutral buoyancy as a substitute for microgravity. During EVA training, an astronaut wears a modified version of the spacesuit adapted for working in water. This high fidelity suit allows the astronaut to move in the water while performing tasks on full-sized mockups of space vehicles, telescopes, and satellites. During the early Gemini missions, several EVA objectives were much more difficult than planned and required additional time. Later missions demonstrated that "complex (EVA) tasks were feasible when restraints maintained body position and underwater simulation training ensured a high success probability".[1,2] EVA training has evolved from controlling body positioning to perform basic tasks to complex maintenance of the Hubble Space Telescope and construction of the International Space Station (ISS). Today, preparation is centered at special facilities built specifically for EVA training, such as the Neutral Buoyancy Laboratory (NBL) at NASA's Johnson Space Center ([JSC], Houston) and the Hydrolab at the Gagarin Cosmonaut Training Centre ([GCTC], Star City, outside Moscow).

Underwater training for an EVA is also considered hazardous duty for NASA astronauts. This activity places astronauts at risk for decompression sickness and barotrauma as well as various musculoskeletal disorders from working in the spacesuit. The medical, operational and research communities over the years have requested access to EVA training data to better understand the risks. As a result of these requests, epidemiologists within the Lifetime Surveillance of Astronaut Health (LSAH) team have compiled records from numerous EVA training venues to quantify the exposure to EVA training. The EVA Suit Exposure Tracker (EVA SET) dataset is a compilation of ground-based training activities using the extravehicular mobility unit (EMU) in neutrally buoyant pools to enhance EVA performance on orbit. These data can be used by the current ISS program and future exploration missions by informing physicians, researchers, and operational personnel on the risks of EVA training in order that future suit and mission designs incorporate greater safety. The purpose of this technical report is to document briefly the various facilities where NASA astronauts have performed EVA training while describing in detail the EVA training records used to generate the EVA SET dataset.

2.0 EVA Training Facilities

NASA has used the EVA capability to perform a variety of tasks outside space vehicles since Ed White performed the first American EVA in June 1965 during the Gemini IV mission. Early EVAs were simulated on the ground and in the zero-g aircraft, but crew members found that the tasks on orbit required more time and effort than the simulations. Fatigue was always a concern on orbit as body positioning was difficult to control due to a lack of body restraints on the vehicles. After returning from Gemini IX, Gene Cernan performed an underwater simulation of his EVA at a Langley Air Force Base (LAFB) pool. This simulation was part of a July 1966 exercise that included a partial task evaluation of the proposed Gemini X EVA and other tasks to evaluate the validity of neutral buoyancy as an EVA training tool.[3] EVAs during Gemini X and XI continued to be difficult, and the exertion required often exceeded the capabilities of the suit

cooling system. After Gemini XI, Richard Gordon said that "a little simple task that I had done many times in training to the tune of about 30 seconds lasted about 30 minutes Gene Cernan warned me about this. I knew it was going to be harder [than on the ground], but I had no idea of the magnitude."[4] Neutral buoyancy simulation was not yet a mandatory EVA training tool. Because of the tight timelines of the Gemini flights, Gemini X and XI crews spent little time underwater preparing for EVA.

By the November, 1966 Gemini XII mission, NASA had implemented many suggestions from the July simulation at Langley. Buzz Aldrin conducted five neutral buoyancy training sessions (not a large number by modern standards) in preparation for his Gemini XII EVAs, in addition to the usual zero-g aircraft training.[4] These neutral buoyancy training sessions occurred at the McDonogh School, a boys' military school in Owings Mills, Maryland, near the offices of Environmental Research Associates, a NASA contractor working on airlock seals, which quickly became a pioneer in neutral buoyancy simulation.[5] Training on a Gemini adapter section submerged in the McDonogh pool (Figure 1), Aldrin ran through a series of exercises working out how to use footholds, handrails, tethers, and tools.[6] The successful Gemini XII EVAs launched NASA into the Apollo era, confident that EVA was feasible and that underwater simulation was valid in solving body restraint problems and in assessing workloads.[1,5–7] A significant recommendation following the Gemini program evaluation was that underwater simulation provided a high-fidelity duplication of the EVA environment that was very effective for procedures development and crew training. Strong evidence indicated that tasks which could be readily accomplished in a valid underwater simulation could also be accomplished in orbit.[1]

Now convinced that neutral buoyancy training was essential to the success of EVA, NASA built three successive facilities at the Marshall Spaceflight Center (MSFC) in Huntsville, Alabama. The third facility, the Neutral Buoyancy Simulator (NBS), was completed in 1967 and was used for EVA training during the Apollo, Skylab and early Space Shuttle programs and had a diameter and depth of 22.9 x12.2 m (75 x 40 ft).[8] Skylab 2's crew used the NBS to practice deploying the sunshields and for gaining access to and using the tools designed to free the stuck solar array.[8,9] Training in the NBS declined when JSC opened the Weightless Environment Training Facility (WETF) in 1980 (Figure 3). However, the NBS continued to support the development and training of large payloads such as the first Hubble Space Telescope servicing mission (STS-61) that launched in December 1993. The WETF was sized to hold the Space Shuttle's cargo bay and airlock at 23.8 m long, 10.1 m wide, and 7.6 m deep (78 x 33 x 25 ft). The WETF was integral in the training for Space Shuttle EVAs until its closure in 1998. The possible construction of a space station necessitated an even larger pool to handle training for multiple missions simultaneously. The NBL at the Sonny Carter Training Facility near JSC opened in March 1997 and consists of a 23.8 million liter (6.2 million gal) water tank that is 61.6 m long, 31.1 m wide, and 12.2 m deep (202 x 102 x 40 ft). The NBL can house full-sized mock-ups of the Space Shuttle cargo bay, flight payloads, and modules of the ISS (Figure 4).[10]

Other nations have also used water to simulate weightlessness and train for EVAs. The Russian space agency, Roscosmos, has a training facility similar to the NBL named the Hydrolab. The Hydrolab was put into operation at the GCTC in 1980 and is used extensively to date. The China National Space Administration (CNSA) operates the Neutral Buoyancy Facility (NBF) at the China Astronaut Research and Training Center in Beijing; however, US astronauts do not use this facility. The European Space Agency (ESA) built the NBF at the European Astronaut Centre in Cologne, Germany, where "pre-familiarization" sessions are conducted in preparation for NBL training in Houston. Japan had a facility, the Weightlessness Environment Test System (WETS), online beginning in 1997 at the Tsukuba Space Centre, but extensive damage due to an earthquake closed the facility in 2011. The size and the capabilities of each

facility vary with the program objectives of each national space agency. A comparison of the relative size of each facility is shown in Figure 5.

3.0 EVA Training Records

NASA has utilized multiple facilities throughout the years of the space program to perform neutral buoyancy training in preparation for EVA. Additionally, NASA astronauts have trained periodically in facilities in other nations. Documentation of EVA training has not been consistent among facilities as data collection and management procedures were determined by each facility and have changed tremendously throughout the years. The goal of early record keeping was to track the use of hardware components and little or no data about the astronaut was recorded (i.e., component sizes). Training records since 1985 are fairly precise with the person, date, suit type, and size as well as the name of the activity noted. Epidemiologists within LSAH attempted to be as comprehensive as possible in compiling the EVA SET dataset and sought records from every training facility to include all ground-based training in neutrally buoyant pools for EVA (Table 1). LSAH epidemiologists approached representatives from each training facility to inquire about any records of EVA training. In facilities that have closed, epidemiologists researched NASA photographs to identify employees that may still be working at other NASA facilities. EVA training records that included any of the following data elements were pursued: astronaut name, date of training, type of training session, duration, suit type, suit size, suit components.

TABLE 1. EVA TRAINING FACILITIES AND DATA SOURCES FOR EVA SET

Space Agency	Facility	Period of Use	Data Description	Included in EVA SET	Notes
NASA	LAFB	1964	Photographs	No	Some Gemini training with many feasibility dives
NASA	McDonogh School	1964-1967	Photographs	No	Gemini training
NASA	NBS	1968-1997	Located records but were not able to pursue	No	Mostly Apollo and early Space Shuttle mission training
NASA	WETF	1980-1998	Logs and computerized records	Yes	Space Shuttle training until NBL opened
NASA	NBL	1997 to present	Computerized records	Yes	Space Shuttle and ISS training
Roscosmos	Hydrolab	1980 to present	Computerized records provided by GCTC staff	Yes – US spacesuit only	Primarily Russian Orlan suit used, but some NASA suits were used in training
Japan Aerospace Exploration Agency (JAXA)	WETS	1997-2011	None	No	Closed in 2011 due to extensive earthquake damage
ESA	NBF	2002 to present	None	No	“Pre-familiarization” sessions for ESA astronauts
China	NBF	Unknown opening to present	None	No	NASA does not use this facility

LSAH epidemiologists found only photographs from the earliest training at LAFB and the McDonogh School. At the NBS at MSFC, Melvin McKinstry and Leigh Anne McMahon assisted us with locating records of EVA training. They located records pertaining to the facility and agreed to make them available to us; however, they did not have the resources to sort through them or ship them to JSC. These records were not pursued due to cost and the suspected low number of training runs completed by NASA astronauts. The early WETF training records consisted of handwritten dive logbooks and personal records of an EVA Systems Group employee, Randall S. McDaniel-Aerospace Engineer, NASA JSC. From 1981-1996 he kept a series of 11 logbooks that included 2,249 training records detailing the astronaut's name, date of training, type of training session, and in some records the length of the training session. Computerized records beginning in 1982 were also found for the WETF and included 2,483 total records, but many were duplicates of the logbooks. Overall, 3,743 unique records were identified from the WETF.

The majority of EVA training records were obtained from Terry W. Dunn (former NBL Training Operations Manager, United Space Alliance, LLC) and beginning in 2014, from Kevin B. Thomas (NBL Training Operations Manager, Stinger Ghaffarian Technologies, Inc.) at the NBL. The NBL data file is by far the largest, with more than 13,000 training records from June 1995 to March 1, 2016. In 2011, the NASA Human Life Sciences directorate deployed the Exercise Injury System (EIS), an additional data collection tool to track EVA training and astronaut injuries. The EIS system captures additional EVA suit configuration details that are viewed as possible injury risk factors to determine relationships between EVA training and astronaut injuries. The EIS system duplicates training records included in the NBL dataset, but both datasets have unique details that are valuable when evaluating overall training. For example, the NBL dataset lists the crew member name, date of training, suit used, and suit size for all NBL runs including fit checks and classes. The EIS includes the crew member name, date of training, suit used, suit components, total time of the run, and inverted time. Notably missing from EIS is the suit size, and only full NBL runs are captured, so fit checks and classes are not included. Because both the NBL and EIS datasets have unique data, the records were merged to provide the best description of each training session.

Almost all EVA training performed by NASA astronauts has occurred in facilities within the United States, but a small number of training sessions have been conducted in other space agency facilities. The Hydrolab at GCTC in Star City, Russia, predominantly uses the Russian Orlan suit for training, but during certification of a Russian airlock, a small number training sessions were conducted using the NASA planar hard upper torso (HUT) suit. NASA astronauts have performed a total of 229 training sessions in the Hydrolab, and 28 of these used the NASA planar HUT and were included in EVA SET. In Tsukuba, Japan, NASA astronauts completed several sessions in the WETS facility using the NASA planar HUT suit, but these were short and considered "development" runs to test the facility. WETS sessions were not included in EVA SET. Similarly, the "pre-familiarization" sessions conducted at the NBF at the European Astronaut Centre are not included in EVA SET.

4.0 Data Management

The data collected from each EVA training session has varied over the years and even among facilities and data sources within a facility. To construct the EVA SET dataset, LSAH epidemiologists gathered over 19,000 records from the five data sources: logs, WETF, NBL, EIS and Russia (Table 2). Established practices of epidemiological data management were followed according to *Quality Control and Good Epidemiological Practice*.[11] All steps in data management, from raw file to final dataset, were performed in SAS (SAS Institute; Cary, North

Carolina) to document each step in the code and to accurately reproduce the process when data updates are received.

TABLE 2. DATA SOURCES AND RECORD NUMBERS

Source	Records
Logs	2,249
WETF	2,483
NBL	13,499
EIS	1,160
Russia	229
Total records	**19,620**

The first task of data management for EVA SET was archiving the five data sources in their original format prior to any manipulation or editing.[11,12] Next, each data file was evaluated for data consistency and several data "cleaning" steps were implemented.[12,13] The most common inconsistency needing cleaning was the astronaut's name field. Frequently a nickname or call sign was recorded in the name field, so epidemiologists used an internal LSAH Astronaut demographic information file to standardize each record with the full legal name of each astronaut. Also during the data cleaning stage, obvious extreme values in the data were flagged as possible outliers. In a handful of records, the duration of a training session was zero or a very low number of minutes, but other time variables, such as inverted time, were greater than the total duration of training. Both fields were flagged, as epidemiologists could not determine exactly which field was in error.

After each data file was cleaned, epidemiologists merged the five datasets for a total of 19,620 records. Upon inspection, these records contained several duplicates and non-crew members who participated in a training session, so the following data processing steps were taken:

1) Records of training with the Russian Orlan suit were deleted
2) Records of classes or other tasks that did not include don or doff of EVA suit were deleted
3) Records of non-crew members or international astronauts were deleted
4) Duplicate records between data sources were reconciled
5) Records of non-EVA training activities were deleted

Additionally, not all data fields were available from each dataset. Frequently, the duration of training and the EVA suit size are missing because they were not collected by each data source.

LSAH epidemiologists evaluated the data integrity[14] or completeness of EVA SET by matching a list of flight EVAs to the ground-based EVA training. This ensured that each flight EVA was preceded by a typical pre-flight training flow. During this data integrity check, epidemiologists concluded that Winston Scott's EVA training is missing from all data sources. Winston Scott participated in EVA training for both STS-72 and STS-87. Training records for STS-72 are recorded in McDaniel's logs, but STS-87 training is not included in the logs, WETF or NBL datasets. Winston Scott performed two on-orbit EVAs with JAXA crew member Takao Doi during STS-87, but the associated ground-based training is missing. LSAH attempted to reconcile the missing data, but no records have been found that show Winston Scott participated in training at the NBL. As a result, LSAH has attached a note to the first tab of the EVA SET file that describes this discrepancy in the data.

Data quality or accuracy[14] was evaluated by asking a small group of six astronauts, who were at JSC in 2015, to review and verify their personal EVA training records from EVA SET. Five of the six astronauts responded to our request and did not note any issues with the EVA SET data. However, two of the five astronauts noted that they had not maintained their own records, so the records looked correct but there was no way to verify them with 100% accuracy.

The last step in data management for EVA SET was the creation of a data dictionary.[11,15] The data dictionary is a file that defines the basic organization of the EVA SET dataset (see Appendix). The EVA SET data dictionary contains a list of the following:

- Variable name
- Type of data (numeric, text, date)
- Format of each variable (0,1,2; yes/no; mm-dd-yyyy)
- Descriptive information on data contained in each field

5.0 Final EVA SET Dataset

After all data management was completed, the total number of records in EVA SET for NASA astronauts was 12,360. Of the entire population of 338 NASA astronauts, 232 have records documenting participation in an EVA training session utilizing a NASA suit as of July 1, 2016. One hundred and six astronauts (31.4%) have no records pertaining to EVA training. A majority of these individuals were employed at NASA prior to the Space Shuttle program, and many of the remaining astronauts were Space Shuttle pilots and commanders who did not perform EVAs. A select few (13) of these astronauts were mission specialists assigned to missions without EVAs. As agency objectives changed at the end of the Space Shuttle program and most ISS crewmembers perform an EVA during their mission, all astronauts are now required to be EVA certified for ISS missions.

The final EVA SET dataset is stored in two convenient formats depending on the needs of the project - Summary and List views. The Summary View is a summarized chart of all EVA training sessions by each astronaut, and includes all 338 NASA astronauts with the total number of EVA training sessions performed in each type of suit. The List View of EVA SET preserves the individual data session and includes one entry for each EVA training session. This view is 12,630 rows of data and is stored as a Microsoft Excel® spreadsheet so it can be easily sorted according to project needs. The List View contains EVA training records for the 232 NASA astronauts who have records of participation in EVA training.

6.0 Conclusions

EVA SET is currently the most complete single source of data regarding EVA training sessions performed by NASA astronauts. However, as noted above, it is not 100% complete. This dataset was compiled by LSAH epidemiologists to study the relationship of EVA training to possible shoulder injuries but has many other non-medical applications. This dataset is current to July 1, 2016, and can be provided to assist other groups in responding to program and research questions with proper board approvals.

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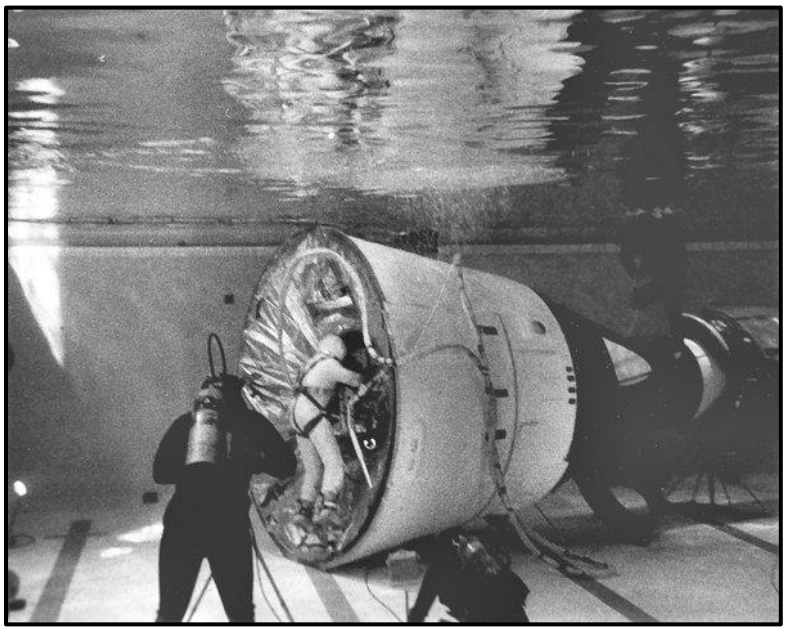

Figure 1. Buzz Aldrin (in white) works on a Gemini mockup in the McDonogh School's pool (photo courtesy of NASA).

Figure 2. The Neutral Buoyancy Simulator (NBS) at Marshall Spaceflight Center (MSFC)(photo courtesy of NASA).

Figure 3. The Weightless Environment Training Facility (WETF) with the Space Shuttle cargo bay and robotic arm submerged in the pool (photo courtesy of NASA).

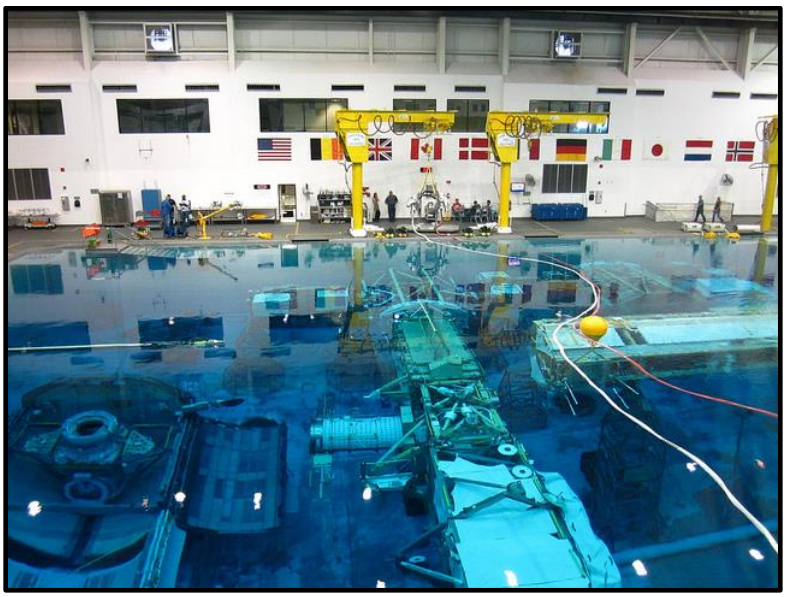

Figure 4. The Neutral Buoyancy Laboratory (NBL) with the Space Shuttle cargo bay (left) and ISS modules (right) in August, 2011 (photo courtesy of NASA).

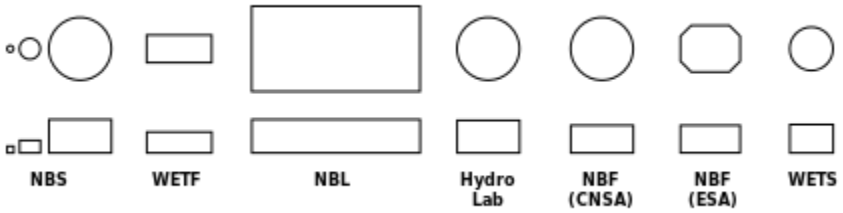

Figure 5. Scale comparison of neutral buoyancy pools[16] (top images depict overhead views; the bottom images depict side views)

Appendix A – Data Dictionary

List View

Variable Name	Data Type	Format	Description
Last Name	Text		
First Name	Text		
Middle Name	Text		
Sex	Text	M or F	Male or Female
Event Date	Date	dd-mmm-yy	Date training session occurred
Event Name	Text		Name of training session or class
HUT	Text		Planar or Pivoted
Size	Text		X-Small, Small, Medium, Large, or X-Large
Actual Time (Min)	Numeric	XXX	Actual length of training session in minutes
Estimated Time (Min)	Numeric	XXX	Estimated length of training session in minutes
Time Inverted (Min)	Numeric	XXX	Time inverted in minutes
Waist Bearing	Text		Aluminum or Steel
Shoulder Harness?	Text	Yes or No	Was shoulder harness used during run?
Shoulder Pads?	Text	Yes or No	Was shoulder pads used during run?
Teflon Inserts?	Text	Yes or No	Were Teflon inserts used during run?
DateOfBirth	Date	dd-mmm-yy	Astronaut date of birth
EnteredAstronautDate	Date	dd-mmm-yy	Date astronaut entered the corps
LeftAstronautDate	Date	dd-mmm-yy	Date astronaut retired from the corps

Summary View

Variable Name	Data Type	Format	Description
Last Name	Text		
First Name	Text		
Sex	Text	M or F	Male or Female
Runs Total	Numeric	XXX	Total number of training runs
Planar HUT Runs	Numeric	XXX	Training runs performed in planar HUT
Pivoted HUT Runs	Numeric	XXX	Training runs performed in pivoted HUT

Appendix B – Acronyms

CNSA	China National Space Administration
EIS	Exercise Injury System
EVA	Extravehicular Activity
EVA SET	EVA Suit Exposure Tracker
GCTC	Gagarin Cosmonaut Training Centre
HUT	Hard Upper Torso
ISS	International Space Station
JSC	Johnson Space Center
LAFB	Langley Air Force Base
LSAH	Lifetime Surveillance of Astronaut Health
MSFC	Marshall Spaceflight Center
NBF	Neutral Buoyancy Facility
NBL	Neutral Buoyancy Laboratory
NBS	Neutral Buoyancy Simulator
WETF	Weightless Environment Training Facility
WETS	Weightlessness Environment Test System

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During a spacewalk, designated as extravehicular activity (EVA), an astronaut ventures from the protective environment of the spacecraft into the vacuum of space. EVAs are among the most challenging tasks during a mission, as they are complex and place the astronaut in a highly stressful environment dependent on the spacesuit for survival. Due to the complexity of EVA, NASA has conducted various training programs on Earth to mimic the environment of space and to practice maneuvers in a more controlled and forgiving environment. The EVA Suit Exposure Tracker (EVA SET) dataset is a compilation of ground-based training activities using the extravehicular mobility unit (EMU) in neutrally buoyant pools to enhance EVA performance on orbit. These data can be used by the current ISS program and future exploration missions by informing physicians, researchers, and operational personnel on the risks of EVA training in order that future suit and mission designs incorporate greater safety. The purpose of this technical report is to document briefly the various facilities where NASA astronauts have performed EVA training while describing in detail the EVA training records used to generate the EVA SET dataset.

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17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
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