REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
17-10-2019	Technical Report	11 March 2015 - 30 Sept 2017

4. TITLE AND SUBTITLE
Evaluation of Air Mitigation Procedures to Improve the Accuracy of Temperature Compensated Turbine Flow Meters

5a. CONTRACT NUMBER
N00024-12-D-6404/0317

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Joel Schmitigal, Scott Nielsen, Ted Kline

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Penn State Applied Research Lab
3075 Research Drive
State College, PA 16801

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Ground Vehicle Systems Center
FCDD-GVS-IEE (MS 110)
6501 E. 11 Mile Road
Warren, MI 48397-5000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
OPSEC3315

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.
OPSEC#: OPSEC3315

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The most problematic issue preventing the utilization of turbine flow meters to calculation the inventory of CFT's is the induction of air bubbles during the receipt of fuel from delivery trucks. Air bubbles displace fuel in the hose line and are recorded as total fuel volume by the receipt meter. Procedures for minimizing the error of measurement caused by air bubbles is analyzed in this paper.

15. SUBJECT TERMS
Fuel, Collapsible Fuel Tank, Gauging, Gain-Loss, accountability, turbine fuel meters

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Joel Schmitigal
					19b. TELEPHONE NUMBER *(Include area code)*
unclassified	unclassified	unclassified	unclassified	19	586-282-4235

INSTRUCTIONS FOR COMPLETING SF 298

1. REPORT DATE. Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. REPORT TYPE. State the type of report, such as final, technical, interim, memorandum, master's thesis, progress, quarterly, research, special, group study, etc.

3. DATES COVERED. Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. TITLE. Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. CONTRACT NUMBER. Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. GRANT NUMBER. Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. PROGRAM ELEMENT NUMBER. Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. PROJECT NUMBER. Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. TASK NUMBER. Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. WORK UNIT NUMBER. Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. AUTHOR(S). Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES). Self-explanatory.

8. PERFORMING ORGANIZATION REPORT NUMBER. Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES). Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. SPONSOR/MONITOR'S ACRONYM(S). Enter, if available, e.g. BRL, ARDEC, NADC.

11. SPONSOR/MONITOR'S REPORT NUMBER(S). Enter report number as assigned by the sponsoring/ monitoring agency, if available, e.g. BRL-TR-829; -215.

12. DISTRIBUTION/AVAILABILITY STATEMENT. Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/ restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. SUPPLEMENTARY NOTES. Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. ABSTRACT. A brief (approximately 200 words) factual summary of the most significant information.

15. SUBJECT TERMS. Key words or phrases identifying major concepts in the report.

16. SECURITY CLASSIFICATION. Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. LIMITATION OF ABSTRACT. This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

Citation of manufacturers or trade names does not constitute an official endorsement or approval of the use thereof.

Destroy this report when it is no longer needed. Do not return it to the originator.

– Technical Report –

Registration No.

OPSEC3315

Date of Report

17/10/2019

Title: Evaluation of Air Mitigation Procedures to Improve the Accuracy of Temperature Compensated Turbine Flow Meters

Author(s): Joel Schmitigal and Scott Nielsen
Force Projection Technology

Ted Kline
The Pennsylvania State University Applied Research Laboratory

DISTRIBUTION STATEMENT A. Approved for public release. Distribution is unlimited.

OPSEC#: OPSEC3315

U.S. Army Combat Capabilities Development Command
Ground Vehicle Systems Center
Detroit Arsenal
Warren, Michigan 48397-5000

Contents

List of Figures

List of Tables

List of Equations

List of Symbols, Abbreviations, and Acronyms

°C	Degrees Celsius
AR	Army Regulation
atm	Atmosphere
CBB	Closing Book Balance
CFT	Collapsible fabric tanks
DA	Department of the Army
DD	Department of Defense
DLA-E	Defense Logistics Agency – Energy
FSSP	Fuel System Supply Point
ft	feet
gal	Gallons
HEMTT	Heavy Expanded Mobility Tactical Truck
in	inch
JP-8	Jet Propellant 8
k	Thousand
kg/L	Kilograms per Liter
kPa	Kilopascal
NSN	National Stock Number
OI	Opening Inventory
PCI	Physical Closing Inventory
POL	Petroleum Oils and Lubricants
Rec	Receipt volume
TB	Technical Bulletin
TI	True Inventory
TVM	Tactical Volume Meter

1. Introduction

For decades the United States Military has used collapsible fabric tanks (CFT) to store liquids such as fuel and water. CFT's can have capacities ranging from 500 to 210,000 gallons and are built to stringent military specifications. They are now used in the mining and petroleum industry, farms, humanitarian relief, emergency response, and remote re-fueling areas to name a few applications. When not in use, the CFT's themselves are stored in containers made from a variety of materials, with the most common being wood crates, where they can be unfolded and installed in a few hours. CFT'sy can be found in extreme environmental and remote locations and are highly efficient for semi-permanent and tactical liquid storage. CFTs are a major player in the US military's fuel storage and distribution systems and although the tactical advantage to CFTs is obvious, they pose challenges as well. Measuring an accurate volume contained inside a CFT has been problematic for tactical fuel systems due to the following reasons:

- The tank fabric is dynamic under load and does not maintain a static geometric shape.
- Jet Fuel, has a thermodynamic expansion ratio defined as $y = 7.210\times10^{-7} x^2 + 9.994\times10^{-4} x + 0.9837$, with x being temperature °C, and y being multiples of volume at 15.5°C, 1.01 kPa × 102 (1 atm). For example, 20,000 gallons of fuel at 15.5°C would expand to be 20,710 gallons of fuel at 50°C (1).
- CFTs are most commonly placed inside earthen berms for secondary containment and the base can shift under the tank's load and during changes in environmental conditions. The berms are also commonly constructed quickly due to mission demands and cannot always be adequately leveled or graded.
- The tank design and fabric are fabricated for specific maximum capacities, so tank materials stresses are non-linear depending on fuel volume, and these stresses vary based on CFT surface location, making space-dependent calculations difficult.
- CFTs are open vent structures and not closed systems that allow for vapors to escape, therefore fuel can be lost through permeation and volatilization at all times, with the temperature being the largest variable.

Accountability of fuel within Army fuel distribution networks depends on accurate measurements from supply chains issuing to Army customers, as well as accurately monitoring fuel transactions within the Army force structure, other services, and military allies. Policies for Class 3 Petroleum Oils and Lubricants (POL) management is included in Army Regulation (AR) 710-2, Supply Policy Below the National Level (2). AR 710-2 documents the policy for Army Bulk Fuel Accountability for Army owned fuel allows for a gain loss of 0.5%. Defense Logistics Agency Energy's Standard Operating Procedures for Defense Working Capital Fund (DWCF) owned Fuel at Defense Fuel Support Points Supporting Operation Enduring Freedom, specifies the requirements for the inventory of capitalized product, which is owned by the Defense Logistics Agency - Energy (DLA-E), and includes Army operated DLA-E sites (3). DLA-I-11 documents aspects of fuel inventory requirements, documentation and reporting, and out of tolerance reconciliation procedures and allows for a 0.25% gain/loss percentage on JP-8 in CFT's. These requirements are contingent on accurate measurements of fuel volume when distributed through the supply chain and issued to consuming platforms.

The difficulty in obtaining accurate CFT volume measurements makes maintaining fuel accountability to these desired levels difficult. The Army has been researching the use of density and temperature compensated C-LB45-A model inline FloCat turbine meters to track fuel entering and leaving CFT's as a method for measuring the physical inventory of the CFT. The most problematic issue preventing the utilization of flow meters to calculation the inventory of CFT's is the induction of air bubbles during the receipt of fuel from delivery trucks. Air bubbles displace fuel in the hose line and are recorded as total fuel volume by the receipt meter. Procedures for minimizing the error of measurement caused by air bubbles is analyzed in this paper.

Due to environmental considerations, water was used in place of fuel for these experiments.

2. Approach

Accuracy

The accuracy of flow meter gauging procedures was evaluated by transferring known volumes water into a collapsible fabric fuel tank. The source of the water determined to be True Inventory (TI) was an M969A3 5,000-Gallon Semitrailer tanker that was equipped with a model VE205338 Vega radar fuel level sensor.

The accuracy of the model VE205338 Vega radar fuel level sensor was calibrated against three C-LB45-A model inline FloCat turbine meters placed in series, **Table 1**. The Vega radar fuel level sensor varied from the FloCat model inline turbine meter by an average of 6.1 gallons against four series of approximately 4950 gallons total volume, for a variation of approximately 0.1%, this meter variance is source of error when accounting for fuel volumes but for this effort it was decided that the Vega radar fuel level sensor with its 0.1% accuracy was sufficient to utilize as a TI value for a known acceptable fluid volume.

Table 1. Gallons of water recorded by the three inline flow meters and the Vega radar fuel level sensor installed on the M969A3.

Event	Meter 1	Meter 2	Meter 3	Avg Meter	Vega	Average Difference	Variation
Receipt #1 into tanker	4,951	4,954	4,940	4,948.3	4,945	3.3	0.07%
Receipt #2 into tanker	4,953	4,951	4,937	4,947.0	4,964	-17.0	-0.34%
Receipt #3 into tanker	4,971	4,957	4,959	4,962.3	4,964	-1.7	-0.03%
Receipt #4 into tanker	4,947	4,933	4,933	4,937.7	4,940	-2.3	-0.05%

Two 20,000 gallon collapsible fabric fuel tanks were set up as a Fuel System Supply Point (FSSP) to determine the accuracy of gauging procedures, schematic provided in **Figure 1**. The hose lines were filled with water to negate any volumetric loss into the CFTs due to the volume of the hoses, this accounted for 200 gallons of liquid. Following this initial verification and calibration step, approximately 60,000 gallons of water were received and issued from each CFT to simulate a total of 120,000 gallons of fuel movement in a FSSP. At the midpoint and completion of each simulated event, the receipt and issue meters at each collapsible fabric fuel tank were recorded to calculate the physical inventory of water in CFT to compare against the TI of water as established by the M969A3 onboard Vega sensor to determine the percent error in the measurement technique.

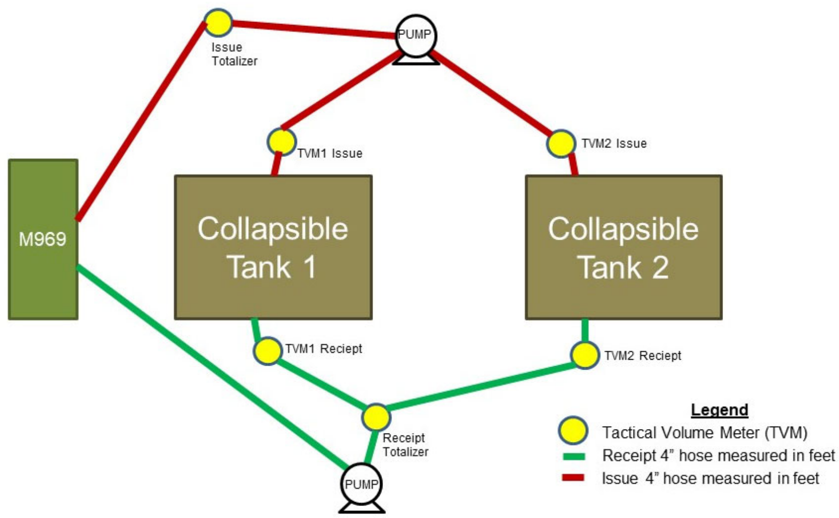

Figure 1.Schematic of Fuel System Supply Point layout for gauging evaluation.

Precision

Four different fuel receipt scenarios were tested to evaluate the effect that air bubbles into the fuel stream had on meter readings. The first test was a normal state test in which the download valves of the M969A3 were opened and fuel was discharged from the trailer following normal field. The second test was a “No-Air” test in which only partial downloads from the M969A3 were performed thereby not inducing any air into the fuel stream which would then pass through the flow meters. The third test was an “Air Mitigation” test in which complete downloads from the M969A3 were performed while reducing air induction through the meters. This was achieved by closing the pump discharge valve when the air induction starts while continuing to downloading from the truck to fill the discharge hose, which is then pushed through the meter when the next tanker discharges fuel. The fourth test was a second "Air Mitigation" technique in which for each tanker download, the pump discharge valve was closed when significant air was observed in the hose line. The pump idled to continue pulling from a tanker to fill hoses from a tanker. The discharge valve was briefly opened and closed as the operator observed the pump site glass. This was done several times until just a trickle flowed out of the tanker. With roughly 10,000 gallons of water in each collapsible fuel tank, approximately 60,000 gallons of water were received and issued from each bag to simulate a total of 120,000 gallons of fuel movement per month in a FSSP, following the each of the four receipt techniques described above.

The precision of the tank or system volume is determined by calculation the gain/loss percentage for the tank or system. DA Form 4702-R provides the basis for performing this calculation to have a gain or loss percentage of with DLA-I-11 allowing for a 0.25% gain/loss percentage on JP-8 in while AR 710-2 allows for a gain loss of 0.5%. The receipt and issue data for these calculations can come from various sources, of which there may not be consistent throughout a single reporting period. For instance, if a unit is receiving into a 5K tanker or M978 Heavy Expanded Mobility Tactical Truck (HEMTT) from another Army unit's 5K, then you generally gauge your tank before and after and sign for the difference on the DA Form 2765-1. If a unit issuing or receiving into a 5K or HEMTT from a tactical fuel farm the truck gauge or gauging stick is utilized to measure fuel volume transferred as there are not issue meters utilized in the field. This data is collected on DA Form 2765-1. If a unit is receiving into a 5K, HEMTT, or tactical fuel farm from a commercial truck, the unit receives the amount signed for on the DD 250. Operators validate that amount through gauging, gauging sticks can vary and should not be interchanged between systems. This can cause additional sources of error as what volume of fuel recorded as received depends on was the fuel purchase contract being either freight on board origin or freight on board at the destination. Origin means it is paid for when the fuel is put into the commercial truck, destination means you only pay for what you receive through your process (i.e., through meters or gauging).

The gain or loss percentage values reported in this report were developed utilizing Error! Reference source not found., which was derived from DA Form 4702-R and calculated at the midpoint and completion of the simulations.

$$GL\% = ((PCI - CBB)/(OI + Rec)) \times 100\%$$

Equation 1 Gain or Loss %

Data for **Error! Reference source not found.** is derived as follows: Physical Closing Inventory (PCI) is calculated by taking the volume of fuel in the collapsible tank adding the volume of fuel received through the receipt meter at the tank minus the volume of fuel recorded to have passed through the issue meter at the tank, the PCI of the FSSP is the sum of each of the tanks individual PCI; Opening Inventory (OI) is equal to the physical closing inventory from the previous reporting period (actual volume based on M969A3 Vega sensor data calculations in the case of this experiment); Receipt (Rec) volume as measured by the M969 Vega volume sensor volume; Closing Book Balance (CBB) is equal to the OI plus the Rec as measured by the M969 Vega volume sensor minus issue volume as measured by the issue meter at the tank.

3. Evaluation and Analysis

Normal Receipt Procedures

Test scenario one was to simulate normal state fuel receipt in which the download valves of the M969A3 were opened and fuel was discharged from the trailer following normal field procedures. At the midpoint of the test, a total of 64,360 gallons of water had been discharged from the M969A3 per the Vega radar fuel level sensor on the trailer, **Table 2**. At the midpoint of the test the three receipt meters upstream of the collapsible fuel bag, exposed to error bubbles displayed an average error of 0.67% from the accepted volume values, while the three-issue meters downstream of collapsible fuel tanks displayed an average error of 0.19%. This difference in error between the upstream and downstream meters is theorized to be attributable to air that displaced volume in the fuel affecting the meters on the receipt side of the collapsible fuel tank, but not being present in the water exposed to the meters on the issue side of the collapsible fuel tank. The receipt meters at each bag differed from the receipt totalizer meter by only 0.01%, with only an 8-gallon difference between them. The issue totalizer showed a volume difference from the individual issue meters at the collapsible by 0.44% or 284 gallons.

Table 2. Calculated collapsible fuel tank inventories and associated errors for normal receipt procedures simulation

Time of measurement	Tank 1 midpoint	Tank 1 final	Tank 2 midpoint	Tank 2 final	FSSP midpoint	FSSP final
Opening Inventory	9,813	9,813	8,638	8,638	18,451	18,451
True Inventory Reciepts	29,709	59,366	34,651	59,363	64,360	118,729
True Inventory Issues	34,651	59,363	29,709	59,376	59,376	118,739
CBB True Inventory	4,871	9,816	13,580	8,625	23,435	18,441
Meter Reciepts	29,865	61,258	34,932	61,614	64,789	119,569
Meter Issue	34,634	59,444	29,751	59,487	64,669	119,404
CBB true receipt and issue meter	4,888	9,735	13,538	8,514	18,142	17,776
Physical Closing Inventory (meters)	5,044	11,627	13,819	10,765	18,863	22,392
Reciept Meter % error	-0.53%	-3.19%	-0.81%	-3.79%	-0.67%	-0.71%
Issue Meter % error	0.05%	-0.14%	-0.14%	-0.19%	-8.91%	-0.56%
Tank Volume % error	-3.55%	-18.45%	-1.76%	-24.81%	19.51%	-21.43%
Gain Loss %	0.39%	2.73%	0.65%	3.31%	0.87%	3.36%

After the evaluation, the totalizer meters were compared to the accepted volume receipt of 118,729 gallons simulating one month of Fuel System Supply Point (FSSP) fuel movements, **Table 2**. At this point in time, the totalizers on the collapsible fuel bags had an error of 3.19% and 3.79% respectively from the TI volume, while the totalizer meter measuring all water received into the FSSP was off from accepted volumes by 0.71%. The meters on the issue side of the FSSP were observed to have an error from accepted values of 0.14%, 0.19%, and 0.56% each. After the test, the receipt meters at each bag and the receipt totalizer differed by an unexplainable 2.76%, accounting for 3,303 gallons of water between them. The issue totalizer showed a volume difference from the downstream collapsible tank meters by 0.40%, accounting for 473 gallons, closely to the same level of error seen at the midpoint of the evaluation.

After the test, the accepted closing book balance TI for CFT 1 was calculated from the M969A3's VEGA sensor to be 9,816 gallons. The meters on tank 1 calculated a volume of 11,627 gallons of water remaining in the collapsible fuel tank 1 after recording the receipt 61,258 gallons and issuance of 59,444 gallons, for an error of -18.45% from accepted TI volume. The calculated gain loss for tank 1 as calculated per Error! Reference source not found. utilizing the meter data is 2.73%. Collapsible tank 2 had a TI volume of 8,625 gallons after the evaluation. The meters on tank 2 calculated a tank volume of 10,765 gallons of water remaining in the collapsible fuel tank 2 after recording the receipt of 61,614 gallons and issuing 59,487 gallons, for an error of -24.81% from the TI accepted value. The calculated gain loss for tank 2 as calculated per Error! Reference source not found. is 3.31%.

After normal receipt procedures evaluation, the tanks were also manually gauged utilizing the procedures found in Technical Bulletin for Collapsible Fabric Fuel Tanks, TB 10-5430-253-13 (3). Utilizing the manufacturer developed strapping chart, measurements at two different reference points for tank 1 provided volumes of 7,358 and 7,238 gallons for an error of 25.04% and 26.26% respectively, giving a gain-loss calculation of -3.44% and -3.61%. Tank 2 with the manufactures strapping chart had a calculated volume of 11,016 and 10,792 gallons for the methods utilized for an error of -27.72% and -25.12% and a gain-loss calculation of 3.68% and 3.35%. Utilizing a locally developed strapping chart, measurements at two different reference points for tank 1 provided volumes of 9,159 and 7,927 gallons for an error of 6.69% and 19.25% respectively, giving a gain-loss calculation of -0.83% and -2.61%. Tank 2 with the custom strapping chart had a calculated volume of 10,650 and 10,695 gallons for the methods utilized for an error of -23.48% and -24.00% and a gain-loss calculation of 3.14% and 3.21%. Further details on these measurements can be found in US Army Combat Capabilities Development Command Ground Vehicle Systems Center technical report 29934 (4).

Air Elimination Procedures

The second test scenario was designed to not allow any air bubbles into the receipt meters was by which only partial downloads from the M969A3 to prevent air from entering into the fuel stream. After 41,825 gallons of water had been received into the FSSP all the meters were read and measured values recorded Table **3**. The receipt meters showed an error from the accepted value of 1.00% and 1.14% at the collapsible fuel bags and 0.53% at the receipt totalizer meter. The totalizer meters on the issue side of the FSSP had an error of 1.14%, 1.55%, and 1.75% respectively. The percent error is theorized to be larger than seen in other tests due to the accuracy of the Vega radar fuel level sensor on the M969A3 being verified at full and not in the 200-300 gallon range where the discharges were stopped, therefore the TI volumes determined under this scenario are questionable. The receipt meters, at each CFT and the receipt totalizer, differ by

0.56%, with a 233-gallon difference between them, while the issue totalizer showed a volume difference from the issue meters at the collapsible tank 0.45%, or 187 gallons.

Table 3. Calculated collapsible fuel tank inventories and associated errors for air elimination procedures simulation

Time of measurement	Tank 1 midpoint	Tank 1 final	Tank 2 midpoint	Tank 2 final	FSSP midpoint	FSSP final
Opening Inventory	13,610	13,610	4,599	4,599	18,209	18,209
True Inventory Reciepts	16,757	58,550	25,068	62,545	41,825	121,095
True Inventory Issues	25,382	62,854	16,798	58,590	42,180	121,444
CBB True Inventory	4,985	9,306	12,869	8,554	17,854	17,860
Meter Reciepts	16,589	57,898	24,783	61,835	41,605	119,721
Meter Issue	25,092	62,109	16,538	57,660	41,443	120,003
CBB true receipt and issue meter	5,275	10,051	13,129	9,484	18,591	19,301
Physical Closing Inventory (meters)	5,107	9,399	12,844	8,774	18,371	17,927
Reciept Meter % error	1.00%	1.11%	1.14%	1.14%	0.53%	1.13%
Issue Meter % error	1.14%	1.19%	1.55%	1.59%	1.75%	1.19%
Tank Volume % error	-2.45%	-1.00%	0.19%	-2.57%	-2.90%	-0.38%
Gain Loss %	-0.55%	-0.90%	-0.96%	-1.06%	-0.37%	-0.99%

After the second evaluation, the totalizer meters were recorded for comparison to the TI volume received into the FSSP of 121,095 gallons simulating one-month fuel movements, **Table 3**. The receipt meters on the collapsible fuel bags had an error of 1.11% and 1.14% respectively, while the totalizer meter measuring all fuel received into the FSSP was off from accepted volumes by 1.13%. The receipt meters, at each bag and the receipt totalizer, differed by only 12 gallons or 0.01%. The meters on the issue side of the FSSP were observed to have an error from the TI of 1.19% and 1.59% on the collapsible fuel tank, while the totalizer meter on the issue hose line had an error of 1.19%. The issue totalizer showed a volume difference of 234 gallons from the downstream collapsible tank meters or just 0.19%.

After the air elimination procedure test, the accepted TI for tank 1 was calculated from the difference between the M969A3's VEGA sensor starting and ending readings to be 9,306 gallons, **Table 3**. The meters on tank 1 provided a calculated volume of 9,399 gallons of water remaining in the collapsible fuel tank 1 after recording the receipt of 57,898 gallons and issuance of 62,109 gallons, for an error of -1.00% from accepted value, and a gain-loss calculation of -0.90%. Collapsible tank 2 had a TI volume of 8,554 gallons after the evaluation. The meters on tank 2 calculated a tank volume of 8,774 gallons of water remaining in the collapsible fuel tank 2 after recording the receipt of 61,835 gallons and issuing 57,660 gallons, for an error of -2.57% from the TI accepted value, and a gain-loss of -1.06%.

After the air elimination procedure evaluation, the tanks were also manually gauged utilizing the procedures found in Technical Bulletin for Collapsible Fabric Fuel Tanks, TB 10-5430-253-13 and the manufacturer developed a strapping chart (3). These measurements at two different reference points for tank 1 provided volumes of 7,873 and 8,464 gallons for an error of 15.40% and 9.05% respectively, and a gain-loss calculation of -3.02% and -2.20%. Tank two had a calculated volume of 8,710 and 8,029 gallons for the methods utilized for an error of -1.82% and 6.14% and a gain-loss calculation of -1.15% and -2.17%. Utilizing a locally developed strapping chart, measurements at two different reference points for tank 1 provided volumes of 9,683 and 9,372 gallons for an error of -4.06% and -0.71% respectively, giving a gain-loss calculation of -0.51% and -0.94%. Tank two with the custom strapping chart had a calculated volume of 8,356 and 8,211 gallons for the methods utilized for an error of 2.31% and 4.01% and a gain-loss calculation of -1.68% and -1.90%. Further details on these measurements can be found in US Army Combat Capabilities Development Command Ground Vehicle Systems Center technical report 29934 (4)

Air Mitigation Receipt Procedure 1

The third test scenario was designed to mechanically mitigate air bubble induction into the receipt side meters. This was achieved by closing the pump discharge valve when the air induction starts while continuing to downloading from the truck to fill the discharge hose, which is then pushed through the meter when the next tanker discharges fuel. After 29,112 gallons of water had been received into the FSSP all the meters were read and measured values recorded Table **4**. The receipt meters at the tactical fuel tanks showed an error from the accepted value of -0.55% and -1.01% while the receipt totalizer meter had an error of -0.75% from the TI volume. The totalizer meters on the issue side of the FSSP had an error of -0.15%, 0.97%, and -0.04% respectively. The receipt meters, at each fuel tank and the receipt totalizer, differed by only 6 gallons for just a 0.02% difference, while the issue totalizer showed a volume difference from the downstream collapsible tank meters of 186 gallons for an error of 0.64%.

After air mitigation receipt scenario 1 the totalizer meters were recorded for comparison to the TI volume received into the FSSP of 124,534 gallons simulating one month of fuel movements, **Table 4**. The totalizers on the receipt side of the collapsible fuel tanks had an error of -1.02% and -0.70% respectively, while the totalizer meter measuring all fuel received into the FSSP was off from accepted volume by -0.80%. The receipt meters, at each bag and the receipt totalizer, differed by 86 gallons for an error of 0.07%. The meters on the issue side of the FSSP were observed to have an error of 0.57% and 0.21% for the meters located at each collapsible fuel tank, while the totalizer meter on the issue hose line had an error of -0.09%. The issue totalizer showed a volume difference of 604 gallons from the downstream collapsible tank meters for a calculated error of 0.48%.

Table 4. Calculated collapsible fuel tank inventories and associated errors for air mitigation receipt procedure 1

Time of measurement	Tank 1 midpoint	Tank 1 final	Tank 2 midpoint	Tank 2 final	FSSP midpoint	FSSP final
Opening Inventory	9,358	9,358	8,903	8,903	18,261	18,261
True Inventory Reciepts	11,420	63,800	17,702	60,734	29,122	124,534
True Inventory Issues	19,415	62,439	9,709	62,085	29,124	124,524
CBB True Inventory	1,363	10,719	16,896	7,552	18,259	18,271
Meter Reciepts	11,535	64,453	17,799	61,159	29,340	125,526
Meter Issue	19,227	62,081	9,724	61,952	29,137	124,637
CBB true receipt and issue meter	1,551	11,077	16,881	7,685	18,246	18,158
Physical Closing Inventory (meters)	1,666	11,730	16,978	8,110	18,464	19,150
Reciept Meter % error	-1.01%	-1.02%	-0.55%	-0.70%	-0.75%	-0.80%
Issue Meter % error	0.97%	0.57%	-0.15%	0.21%	-0.04%	-0.09%
Tank Volume % error	-22.23%	-9.43%	-0.49%	-7.39%	-1.12%	-4.81%
Gain Loss %	0.55%	0.89%	0.36%	0.61%	0.46%	0.69%

At the conclusion of the test, the accepted TI for tank 1 was calculated to be 10,719 gallons as calculated from the M969A3's VEGA sensor readings, **Table 4**. The meters on tank 1 provided a calculated volume of 11,730 gallons of water remaining in the collapsible fuel tank 1 after recording the receipt 64,453 gallons and issuance of 62,081 gallons, for an error of -9.43% from accepted value and gain loss percentage of 0.89%. Collapsible tank 2 had a TI volume of 7,552 gallons after the first air mitigation receipt procedures evaluation. The meters on tank 2 calculated a tank volume of 8,110 gallons of water remaining in the collapsible fuel tank 2 after recording the receipt of 61,159 gallons and issuing 61,952 gallons, for an error of -7.39% from the TI accepted value and a gain-loss error of 0.61%.

At the completion of the air mitigation receipt procedure, one evaluation of the tanks was also manually gauged utilizing the procedures found in Technical Bulletin for Collapsible Fabric Fuel Tanks, TB 10-5430-253-13 and the manufacturer developed strapping chart (4). These measurements at two different reference points for tank 1 provided volumes of 11,161 and 10,586 gallons for an error of 2.20% and -1.91% respectively, and a gain-loss calculation of 0.11% and -0.30%. Tank two had a calculated volume of 6,554 and 6,612 gallons for the methods utilized for an error of 13.22% and 12.45% and a gain-loss calculation of -1.62% and -1.54%. Further details on these measurements can be found in US Army Combat Capabilities Development Command Ground Vehicle Systems Center technical report 29934 (5)

Air Mitigation Receipt Procedure 2

In the fourth test scenario, another procedure designed to mechanically mitigate air bubble induction into the receipt side meters was applied. This a second "Air Mitigation" technique in which for each tanker download, the pump discharge valve was closed when significant air was observed in the hose line. The pump idled to continue pulling from the tanker to fill hoses from the tanker. The discharge valve was briefly opened and closed as the operator observed the pump site glass. This was done several times until just a trickle flowed out of the tanker. After 59,378 gallons of water had been received into the FSSP all the meters were read and measured values recorded Table **5**. The receipt meters at the tactical fuel tanks showed an error from the accepted value of 0.80% and 0.85% while the receipt totalizer meter had an error of 0.93% from the TI volume. The meters on the issue side of the FSSP had an error of 0.03%, 0.19%, and 0.31% respectively. The receipt meters, at each bag and the receipt totalizer, differed by 62 gallons for a difference of 0.10%, while the issue totalizer showed a volume difference from the downstream collapsible tank meters of 250 gallons for an error of 0.42%.

Table 5. Calculated collapsible fuel tank inventories and associated errors for air mitigation receipt procedure 2

Time of measurement	Tank 1 midpoint	Tank 1 final	Tank 2 midpoint	Tank 2 final	FSSP midpoint	FSSP final
Opening Inventory	3,649	3,649	13,476	13,476	17,125	17,125
True Inventory Reciepts	29,670	64,307	29,708	59,440	59,378	123,747
True Inventory Issues	29,708	59,440	29,670	64,307	59,378	123,747
CBB True Inventory	3,611	8,516	13,514	8,609	17,125	17,125
Meter Reciepts	29,908	64,828	29,961	59,908	59,931	124,930
Meter Issue	29,700	59,300	29,615	64,178	59,565	124,042
CBB true receipt and issue meter	3,619	8,656	13,569	8,738	16,938	16,830
Physical Closing Inventory (meters)	3,857	9,177	13,822	9,206	17,491	18,013
Reciept Meter % error	-0.80%	-0.81%	-0.85%	-0.79%	-0.93%	-0.96%
Issue Meter % error	0.03%	0.24%	0.19%	0.20%	-0.31%	-0.24%
Tank Volume % error	-6.81%	-7.76%	-2.28%	-6.93%	-2.14%	-5.19%
Gain Loss %	0.71%	0.77%	0.59%	0.64%	0.72%	0.84%

After air mitigation receipt scenario 2 the totalizer meters were recorded for comparison to the TI volume received into the FSSP of 123,747 gallons simulating one-month fuel movements, **Table 5**. The meters on the receipt side of the collapsible fuel tanks had an error of 0.81% and 0.79% respectively, while the totalizer meter measuring all fuel received into the FSSP was off from accepted volume by 0.96%. The receipt meters, at each bag and the receipt totalizer, differed from the TI volume by 194 gallons for an error of 0.16%. The meters on the issue side of the FSSP were observed to have an error of 0.24% and 0.20% for the meters located at each collapsible fuel tank, while the totalizer meter on the issue hose line had an error of 0.24%. The issue totalizer showed a volume difference of 564 gallons from the downstream collapsible tank meters for a calculated error of 0.45%.

The TI for tank 1 was calculated to be 8,516 gallons as calculated from the M969A3's VEGA sensor readings after the air mitigation receipt procedure 2 evaluation. The meters on tank 1 provided a calculated volume of 9,177 gallons of water remaining in the collapsible fuel tank after recording the receipt of 64,828 gallons and issuance of 59,300 gallons, for an error of -7.76% from accepted value, while the calculated gain loss from Error! Reference source not found. is 0.77%. Collapsible tank 2 had a TI volume of 8,609 gallons after the air mitigation receipt procedures evaluation. The meters on tank 2 calculated a tank volume of 9,206 gallons of water in the recording the receipt of 59,908 gallons and issuing 64,178 gallons, for an error of -6.93% from the TI accepted value, and a gain-loss calculation of 0.64%.

4. Conclusions and recommendations

Although the data set utilized in this experiment is limited, the two air mitigation procedures showed improvements in error and gain/loss calculations. The air elimination procedure might have shown the greatest improvements in error and gain/loss calculations, but the unknown error associated with the VE205338 Vega radar fuel level sensor at low levels of fuel in the M969A3 affected the measurements, in reality, this method may allow for meeting the 0.25% or 0.50% gain loss requirement.

The temperature and density compensated C-LB45-A model inline FloCat turbine meters demonstrated an improvement over the manual tank gauging methods in both error and gain/loss calculations when combined with air mitigation procedures. The Army should invest in a material solution for air elimination if they desire to obtain the most out of the deployment of inline flow meters.

Additional work should be undertaken over a longer period of time to obtain additional measurements to develop a more comprehensive accuracy and precision data set utilizing fuel rather than water and to account for fabric stretching and accounting for tank squatting.

References

1. **HANDBOOK OF AVIATION FUEL PROPERTIES.** ***CRC Report No. 663.*** **Alpharetta, GA : COORDINATING RESEARCH COUNCIL, INC., 2014. Vol. Fourth Edition.**

2. Army, Headquarters Department of the, [ed.]. Supply Policy Below the National Level. ***Army Regulation 710–2.*** **Washington, DC : s.n., March 28, 2008.**

3. Defense Logistics Agency Energy. STANDARD OPERATING PROCEDURES FOR DEFENSE WORKING CAPITAL FUND (DWCF) OWNED FUEL AT DEFENSE FUEL SUPPORT POINTS SUPPORTING OPERATION ENDURING FREEDOM. Fort Belvoir, VA : s.n., June 26, 2012. DLA Energy I-11.

4. Headquarters Department of The Army. Technical Bulletin for Collapsible Fabric Fuel Tanks. Washington DC : s.n., December 8, 2009. TB 10-5430-253-13.

5. Schmitigal, J., Nielsen, S., Kline, T. Evaluation of Gauging Accuracy of Collapsible Fuel Tanks. s.l. : US Army Combat Capabilities Development Command Ground Vehicle Systems Center, 2019. CCDC GVSC Technical Report 29934.