AVOIDED EMISSIONS MODEL: METHODOLOGY REPORT

For Square Robot

Provided by Positive Scenarios Consulting

July 5, 2022

Contents

1. Introduction

In early spring of 2022, Positive Scenarios Consulting, LLC (herein, "PSC") engaged with Square Robot to develop a model for calculating greenhouse gas (GHG) emissions savings from their autonomous robot technology for inspection of aboveground liquid storage tanks.

PSC staff members previously performed a high-level analysis to calculate the potential greenhouse gas emissions, waste, and health benefit of Square Robot tank inspection technology compared to conventional manual cleaning and inspection processes in May of 2020. At the time, significant emissions savings were projected, because the Square Robot technology allows for closed-tank inspection, compared to the conventional process for manual inspections involving tank draining, cleaning, and forced ventilation of volatile gases, most of which are greenhouse gases and/or present health or air quality risks.

Now that Square Robot is a more mature operation, they sought to formalize the carbon emissions evaluation to better communicate to customers and with the possible future intent of generating carbon credits through the application of their novel technology.

To accomplish this objective, PSC developed a more precise model that can be used to calculate avoided emissions on a per-project basis, considering the specifications of each application. The stock liquids currently included in the model are diesel, kerosene, and jet fuel A, with the intention of expanding to other products as Square Robot expands their customer base. The model allows Square Robot to track the avoided emissions enabled by their technology, communicate the climate benefit to customers, and serve as the foundation for potentially developing a methodology for carbon credit generation in a future phase.

This report describes the methodology used for developing the model and calculating emissions, using project-specific parameters where possible and incorporating industry standard practices and best available scientific consensus. This report includes assumptions, limitations, and applicability conditions, and is intended to serve as a foundation for future iterations of the emissions model should Square Robot choose to expand operations to additional applications.

2. Definitions

- **Additional**: An activity or outcome that occurs as a result of the project scenario that would not occur in the baseline scenario.
- **Baseline scenario:** The set of activities and outcomes considered to be representative of business-as-usual methods for storage tank inspection and used as a comparative reference for the project scenario.
- **Direct emissions:** Greenhouse gas emissions that are directly released during the onsite inspection phase for the baseline or project scenarios.
- **Greenhouse gas emissions (GHGs)**: Emissions to the atmosphere that contribute to a climate warming effect, due to either direct or indirect radiative forcing activities.
- **Indirect emissions:** Greenhouse gas emissions that are released offsite as a result of onsite activities during the inspection phase, or as a result of upstream or downstream activities related to the inspection process.
- **Project scenario:** The set of activities and outcomes that occur during a Square Robot tank inspection project.
- **Stock liquid:** The product contained in the storage tank being inspected. This assessment currently includes diesel, kerosene, and jet fuel (A) as stock liquids.

3. Applicability

This methodology is intended to be used for estimating the avoided greenhouse gas emissions from aboveground storage tank inspection projects conducted by Square Robot autonomous robots as compared to conventional inspection processes. This methodology is not intended to be applied to projects conducted by a firm or technology other than Square Robot autonomous units.

In addition, this methodology and model are intended to be used only for aboveground vertical storage tanks under normal operating conditions and ambient temperature and pressure. This model does not accommodate underground tanks, horizontal tanks, heated or pressurized tanks, or tanks that are leaking or in a corroded or deteriorated condition. The model applies only to emissions resulting from cleaning and inspection of the storage tanks, and not to potential emissions due to other operating events or activities (e.g., routine losses, construction, decommissioning, or leakage).

The model considers only the case of direct replacement of the baseline scenario (conventional inspection) activities with the project scenario (Square Robot inspection) activities. It does not attempt to consider follow-on effects from inspection, including the need for tank shutdown and repair precipitated by inspection findings nor considerations related to possible lifetime extension of tanks due to robotic inspection.

In the current version, the model incorporates the following stock liquids: diesel, kerosene, and jet fuel (A), based on current applications of Square Robot's technology. Additional product types may be added in subsequent versions as Square Robot expands their operations.

This study does not address human health or safety considerations, beyond those indirectly influenced by the risks of climate change, nor does it consider performance or effectiveness criteria for the respective tank inspection techniques.

4. Background

4.1 Aboveground Storage Tanks

Refineries and industrial operations store hydrocarbon fuels in aboveground storage tanks typically constructed of steel. These tanks can vary in size, with a wide range of diameter, height, and storage capacity. Tanks may use different roof types and conditions, such as fixed roof, floating internal or external roofs, and cone- or dome-shape roofs. Tanks may store a range of liquids, from light distillate fuels to heavy crude oil. The type of liquid stored may necessitate certain tank parameters.

4.2 Tank Inspection

Regulations require that aboveground storage tanks are inspected periodically, typically every 10-30 years depending on the tank type, management conditions, and local requirements, for possible corrosion of the tank bottom or other issues that could result in compromised integrity of the tank. Conventionally, to conduct these inspections, storage tanks are drained, vented, and cleaned to allow inspectors to enter the tank and visually observe the tank for possible damage to the bottom. This manual process is resource-intensive, hazardous, costly, and time-consuming.

Square Robot was established in 2016 to autonomously inspect aboveground storage tanks with the purpose of reducing cost, improving safety, and minimizing hazardous vapor and chemical releases to the environment by keeping the tank in service (filled with product). By removing the necessity of draining, venting, and cleaning the storage tanks, there are indirect and direct GHG emissions benefits, in addition to reducing hazardous exposure for workers.

At the time of publication of this methodology, PSC understood that the vast majority of tank inspections are conducted through the conventional (manual) process and that robotic inspection such as Square Robot's approach represents a very small emerging market. As such, the manual tank inspection process (involving tank emptying, cleaning, manual inspection, and refilling) was taken as the baseline scenario for the emissions model.

4.3 Tank Emissions and Estimation Procedures

Due to changing ambient conditions or liquid levels inside the tank, volatilized vapors are released from the tank during normal operating conditions and during periodic events, such as emptying, refilling, and tank cleaning. Tanks may or may not have vapor control systems in place to reduce emissions vented to the atmosphere. In the case of the fuels considered as stock liquids in this model, these vapors typically consist of volatile organic compounds (VOCs) and air pollutants that could pose a risk to human health and the environment.

In addition to pollution and health concerns, released vapors from hydrocarbon fuels may have a direct or indirect greenhouse gas effect, depending on the type of fuel. If the vapors contain known greenhouse gases, such as methane, a direct global warming potential (GWP) can be applied. Other hydrocarbon vapors may have no or negligible direct GWP, however may result in indirect warming effects through reactions in the atmosphere and eventual breakdown to carbon dioxide, the most common manmade greenhouse gas in the atmosphere.

Because the released VOCs and other vapors released by the tanks are typically classified as regulated air pollutants, tank operators are typically required to estimate and/or monitor the quantity of annual air emissions to comply with regional or federal permitting requirements.

The industry standard estimation procedure in the United States is published by the U.S. EPA in their Compilation of Air Pollutant Emissions Factors (AP-42). While other methods exist for estimating emissions, typically through proprietary software programs or onsite monitoring, the AP-42 methods are commonly used by operators for determining anticipated emissions from different types of tank operations, including tank emptying, cleaning, and refilling.

In recent years, concerns have been raised on the accuracy of emissions estimation procedures and standard values used by AP-42 (Shankman & Kane, 2021). However, at the time of development no alternative approaches had been proposed or developed within the industry for theoretical estimation of emissions. (Maine Department of Environmental Protection, 2021). Thus, the following methodology is based on *AP-42, Fifth Edition, Volume I, Chapter 7: Liquid Storage Tanks* (rev. June 2020) as the current industry standard and most widely accepted calculation method. This model may be revised in future if other estimation methods are developed and validated through industry testing and peer review. The current approach is considered to be conservative and may underestimate actual emissions avoided.

5. Project Scenario

5.1 Overview

Square Robot currently works with a number of customers to conduct closed-tank robotic inspections using autonomous robots. Square Robot is based in Boston, MA with an office and field crews based in Houston, TX, and currently has five robots in operation. While most inspections currently occur in North America, Square Robot has intentions to expand operations to additional global locations.

Crew and Equipment

The Square Robot operation uses minimal personnel and equipment resources. A typical project consists of a 3-person crew, including robot operator, crew chief, and technician. Equipment primarily consists of the robotic unit and associated power and data transfer equipment, a generator-powered trailer for use by the crew, and transport equipment. Other equipment may be required on a per-project basis; frequently, Square Robot is able to use existing onsite equipment, such as a crane for hoisting the robot onto the tank roof.

Inspection Process

Once a project has been confirmed, Square Robot collects key information from the client including tank parameters and characteristics, product type, and location. To begin a project, Square Robot personnel and equipment are transported to the project site via truck. Upon arrival, the Square Robot crew coordinates with the onsite crew to arrange necessary permitting, training, and equipment setup.

Once project setup is complete and the inspection process can begin, a roof manway is opened temporarily to allow the robot to be lowered into the tank using a crane. Once the robot reaches a safe depth level, it powers on and begins recording readings. The robot navigates the tank bottom using a pre-planned program and sends real-time data to the operator via fiber optic cable. The tank remains in normal operation throughout the inspection.

On average, the robot will run for 5-7 hours per day depending on the viscosity in the tank. At the end of daily run, the robot is lifted out of the tank, cleaned, and charged using an existing onsite electricity source. This process is repeated each working day for the duration of the project. While the number of days required for inspection varies based on tank diameter, condition and client requirements, typical projects are expected to range from 3 to 5 days of in-tank inspection time (based on a 120 foot diameter tank).

In addition to providing detailed measurements of the tank bottom thickness, the robot acquires visual data and monitors other data points such as product temperature and bottom sediment conditions.

At the close of the project, equipment and personnel are transported offsite. The Square Robot team analyzes data collected by the robot during the inspection and reports findings to the client.

5.2 Emissions Sources

Potential greenhouse gas (GHG) emissions sources for the project scenario can be categorized as 'direct' or 'indirect' emissions. The following definitions are used in this model:

- **Direct emissions:** GHG (or GHG-forming) emissions generated and released directly during the inspection process.
- **Indirect emissions:** GHG emissions generated from upstream or downstream activities related to the project, or activities in the inspection phase that indirectly generate GHGs.

For the Square Robot case, potential emissions occur at three phases: Upstream, Inspection, and Downstream. The Inspection phase for the project case is defined as including the activities occurring while the Square Robot team is onsite and those required to analyze and deliver the results of the inspection.

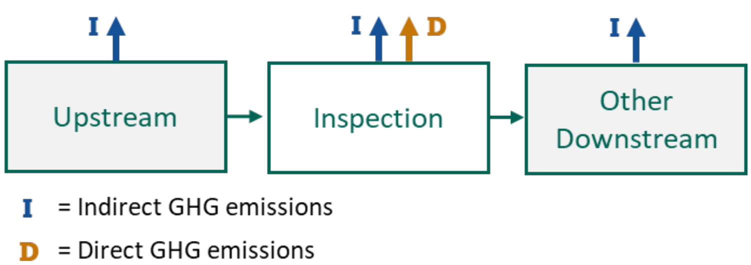

Figure 1: Potential GHG emissions sources for Square Robot inspection.

Upstream Emissions

Upstream activities generate **indirect** emissions prior to the inspection project occurring. Potential indirect upstream emissions sources include:

- Energy use and materials extraction required to produce the robot
- Transport of equipment and personnel to the project site

Emissions from these sources are expected to be minor when attributed to a single project instance.

Inspection Phase Emissions

Both indirect and direct emissions occur during the inspection phase.

Potential **direct** emissions include:

- Vapors released during opening of manways to move the robot in and out of the tank. These emissions are expected to be negligible given that the manways are relatively small and opened for only a short time each day.
- Evaporation from liquid fuel clinging to the robot when it is removed from the tank and cleaned. The amount of clingage is expected to be minimal and result in negligible emissions.
- Fuel combustion by a generator to power the crew's trailer. Energy is primarily used for climate control, with minimal usage for the operator's computer and monitoring equipment.

Potential **indirect** emissions sources include:

- Electricity use to recharge the robot following the daily inspection run. This is expected to require less than 15kWh per charge.
- Electricity use required to run any other ancillary equipment, such as lighting or cranes (these may also generate direct emissions depending on the energy source).
- Electricity required by the Square Robot team to analyze inspection data and generate the report of findings.

Emissions from these sources are expected to be minor.

Downstream Emissions

Downstream activities generate **indirect** emissions after the inspection project is complete. Potential indirect downstream emissions sources include:

- Transportation of equipment and personnel from the project site.
- Energy and materials required for ongoing maintenance, repairs, or upgrades of the robot throughout its lifetime.
- Ultimate disposal of the robot once it reaches the end of its useful life.

Emissions from these sources are expected to be minor when attributed to a single project instance.

6. Baseline Scenario

6.1 Overview

In the conventional inspection process, the stock liquid stored in above-ground storage tanks must be removed prior to inspection. The process can take many weeks and involves pumping the liquid out of the tank, venting volatile vapors, cleaning the tank, and finally performing the inspection. Repairs are made to the tank (if needed) prior to refilling with the stock liquid. Details on each phase are provided in the descriptions below. Information in this section was sourced from industry experts within the Square Robot team.

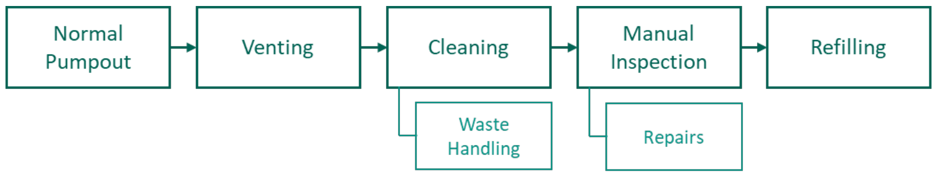

Figure 2: Summary of baseline scenario for storage tank inspections.

Pumpout

Liquid is pumped out of the storage tank directly to another tank via fixed pipework or by using a hose connected to a tank outlet and transferred to a tanker truck, which is then transported off-site. This process can take a few days to a few weeks, depending on the tank conditions and project timeline. Once the liquid level drops below the outlet height, a vacuum truck may be used to remove remaining freestanding liquid. Certain tank bottom conditions (e.g., drain-dry tanks) may allow for varying levels of complete liquid removal from the tank.

If the tank has a floating roof, the roof will be lowered during pumpout and 'landed' on legs once the liquid is drained to a certain height. After pumpout, the tank may remain idle for a short period of time (e.g., overnight or over a weekend) until forced ventilation begins.

Venting

Once the tank is emptied, the chamber must be vented to reduce the concentration of volatile vapors prior to personnel entering the tank.

Typically, forced rather than passive ventilation is used to reduce the time required to render the tank safe to enter. Fans or blowers are used to expel vapor out of the tank vents or manways. During this time, the vapor concentration can be monitored by the crew to determine the point at which the tank is safe for entry. At minimum, this safety threshold is determined by the Occupational Safety and Health Administration (OSHA) rule that flammable vapor concentration must be less than 10% of the lower explosive limit (LEL).

The initial venting period is typically conducted over a period of 24-48 hours before personnel can enter the tank. Continued venting often occurs throughout the cleaning process to ensure safety of the crews.

Cleaning

Emptied tanks must be thoroughly cleaned prior to inspection. Cleaning typically consists of manual removal of remaining liquid, sediment, and sludge from the tank bottom through the use of squeegees or vacuum houses. Cleaning may also involve the use of high-pressure water hoses to wash the tank bottom. Solid waste (sediment or sludge) removed from the tank is emptied into 55-gallon drums and transported offsite for disposal. Waste wash water can typically be handled in onsite wastewater treatment facilities, though may be transported offsite via truck.

The cleaning process typically involves a crew of 3-4 people and takes 5-7 days, depending on the tank conditions, stock liquid, and sediment buildup. Tanks with a coated bottom surface and containing lighter products with less sludge buildup are typically easier to clean and require less time.

Occasionally, depending on the tank's condition (e.g., if the coating has been compromised) and the preferences of the tank owner, the cleaning crew will also be asked to sand-blast the tank bottom to remove the coating for a more thorough inspection, which can take an additional 5-7 days.

Throughout this phase, cleaning equipment, lighting, and any crew accommodations (e.g., trailers) are powered through on-site generators.

Inspection

Once the tank has been thoroughly cleaned, an inspection crew of 2-3 people inspects the tank for corrosion, pitting, or other damage to the tank bottom and walls that could compromise the safety and integrity of the shell. This involves a visual inspection, often accompanied by a floor scanner. Equipment and lighting are run from an on-site generator. The inspection process generally takes approximately 2 days.

Repairs

Depending on the results of the inspection, repairs to the tank may be scheduled. The repair process can involve an additional 4-8 weeks of work, during which time the tank remains empty. Because the tank emptying and cleaning process is resource-intensive, tank owners often elect to conduct routine maintenance of the tank once it has been emptied regardless of inspection findings.

Refilling

After the inspection and repairs are complete, the tank is then refilled via a tanker or pipeline transferring product to the tank. Depending on the conditions of the storage tank (e.g., roof type), the speed of refilling may need to be moderated. During this process, there is commonly an open-air vent on top of the tank, through which vapors will escape as the liquid level rises in the tank.

6.2 Emissions Sources

The baseline scenario inspection process involves a significantly wider range of activities than the project case. While some emissions sources are expected to be similar, certain activities in the baseline scenario represent significant additional sources of GHGs. For the baseline scenario, the inspection phase is considered to include all activities associated with pumpout through refilling of the tank, rather than the physical tank inspection alone. Figure 3 illustrates the stages of emissions sources, described in more detail in the following section.

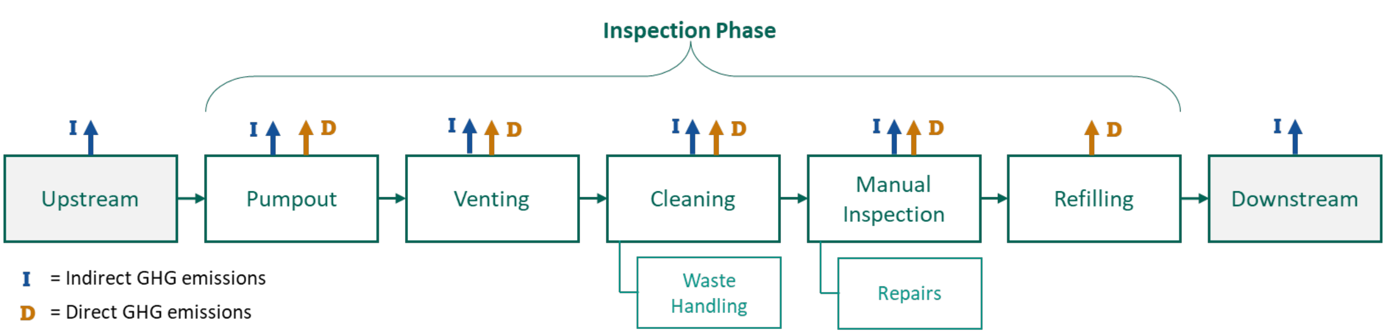

Figure 3: Summary of direct and indirect emissions sources for the baseline scenario.

Upstream Emissions

Upstream activities generate **indirect** emissions prior to the onset of the inspection project. Potential upstream emissions sources include:

- Energy use and materials extraction required to manufacture equipment used for the inspection phase. Equipment may include but is not limited to tanker trucks, vehicles, fans and blowers, generators, water hoses, sand blasters and repair equipment, such as welding equipment and cranes. Equipment needs are expected to be significantly greater than the resources required for the project case.
- Transport of equipment and personnel to the project site. Transportation emissions are expected to be greater than in the project case due to a greater quantity of equipment and personnel required for the baseline inspection process.

Although upstream emissions are expected to be greater for the baseline scenario than the project case, these indirect emissions are still expected to be small relative to other phases of the project.

Inspection Phase Emissions

All Stages

While each stage of the inspection phase contributes different activities and emissions sources, some activities are expected to occur throughout the entire inspection period. These include both direct and indirect emissions sources.

- **Direct** emissions sources include the combustion of fuel to power generators for trailers and other equipment throughout the inspection project. It is assumed that several climate-controlled trailers are onsite for the entire multi-week duration of the project for the comfort and convenience of the crew. Other equipment used throughout the inspection process may also run off generator power, such as fans and blowers, or may consume fuel directly such as crew vehicles or cranes.
- **Indirect** emissions sources include electricity use to power other equipment that may be used throughout the inspection process, such as monitoring equipment or computers.

Pumpout

Emissions generation during the pumpout of the tank stock liquid primarily results from direct vapor loss from the tank. For the stock liquids currently included in this model (diesel, kerosene, and jet fuel), vapors referenced in the following sections are assumed to be volatile hydrocarbons that ultimately form GHGs in the atmosphere (described further in Section 8). Because of this, vapor loss from the tank is considered a **direct** source of GHG emissions.

Vapor loss at the pumpout stage is dependent on the roof type of the storage tank. For fixed-roof tanks, some evaporation of the stock liquid will occur during pumpout; however, per the AP-42 methodology these losses are considered equivalent to 'breathing losses' that would occur under normal operating conditions and are not considered additional emissions specific to the inspection phase, so are not included in this model.

When floating-roof tanks are pumped out, as the liquid level lowers and the roof is landed a new vapor space is created between the roof and the liquid level. Often, forced air exchange is required at this stage to prevent a vacuum in the tank that could damage the roof. This vapor space does not occur under normal operating conditions and generates additional vapor loss due to evaporation of the remaining liquid heel in the tank and any product that clings to the interior tank surfaces. Vapor loss may be increased due to wind activity, depending on the type of floating roof (internal or external).

Venting

The venting phase is the primary source of emissions for the baseline scenario.

Direct emissions are generated through the release of the volatile vapors inside the tank through forced ventilation. After the stock liquid is pumped out, volatile vapors remain in the tank and must be vented for the safety of the cleaning and inspection crews. Additionally, a small amount of liquid is expected to remain in the tank through pooling on the tank bottom, clingage to interior surfaces, and mixed with any sludge or sediment on the tank bottom that cannot be pumped out. This remaining liquid will continue to evaporate and generate additional vapors.

Vapor control systems, if used for the tank system, can significantly reduce direct emissions from venting (and other stages resulting in direct vapor loss) through capture and storage of vapors. Vapor control systems that operate through combustion, however, effectively convert the released vapors to carbon dioxide and thus do not result in a reduction of GHG emissions.

Indirect emissions are generated from electricity used for fans/blowers and any monitoring or other equipment required for ventilation.

Cleaning

The cleaning stage is considered to occur separately from venting, although some ventilation likely continues throughout cleaning. No additional direct emissions are associated with the cleaning stage not already described in the *All Stages* or *Venting* stages.

Indirect emissions associated with tank cleaning result from several activities:

- Energy use associated with high-pressure water wash; this includes pumping water to the tank site and operating power sprayers.
- Energy and fuel use for removal of the resulting wastewater from the tank, pumping or other transport to a treatment facility, and treatment of the wastewater.
- Energy and emissions resulting from the transport and management of solid waste (sludge or sediment) removed from the tank.
- Electricity use to provide lighting for the cleaning personnel.

These emissions are expected to be small relative to emissions from other stages.

Manual Inspection

The manual inspection stage is not expected to generate any direct emissions not already described in other stages.

Indirect emissions sources may include:

- Energy use for lighting or floor scanners for the inspection crew (if not powered by onsite generators covered in *All stages* direct emissions).

- Potential activities associated with repairs precipitated by the inspection process, whether triggered due to inspection findings or scheduled as routine maintenance to take advantage of the empty and clean tank. Repair activities are not included in the scope of this assessment so have not been evaluated for additionality compared to the project case but may represent significant emissions-generating activities.

Refilling

During the refilling stage **direct** emissions are generated by the evaporation of incoming stock liquid as the tank is refilled. These vapors are forced out of the tank as the liquid level rises. The quantity of vapors released depends on the tank roof type, but both fixed and floating-roof tanks release vapors during the refilling stage.

Downstream Emissions

Downstream activities generate **indirect** emissions after the inspection project is complete. Potential indirect downstream emissions sources include:

- Transportation of equipment and personnel from the site.
- End-of-life impacts associated with any equipment or other materials used throughout the inspection process.

Emissions from these sources are expected to be minor when attributed to a single project instance.

7. Model Boundary

It is not feasible, or desirable, to calculate all possible emissions sources for the project and baseline scenarios considering the complexity and theoretical nature of the exercise. Therefore, a model boundary was established to include priority emissions sources in the calculations. The boundary was defined based on the following principles:

- **Materiality**: Focus on the activities expected to be the most material, i.e., significant, sources of GHG emissions.
- **Reduce uncertainty**: Include activities that are more certain to occur in the theoretical baseline scenario and that have lower uncertainty and variability in the quantity and type of emissions that could be generated.
- **Conservativeness**: Assumptions and boundary used will underestimate rather than overestimate emissions savings from the project scenario.

Figure 4 and **Table 1** summarize the stages selected for inclusion in the model boundary and the rationale for this selection.

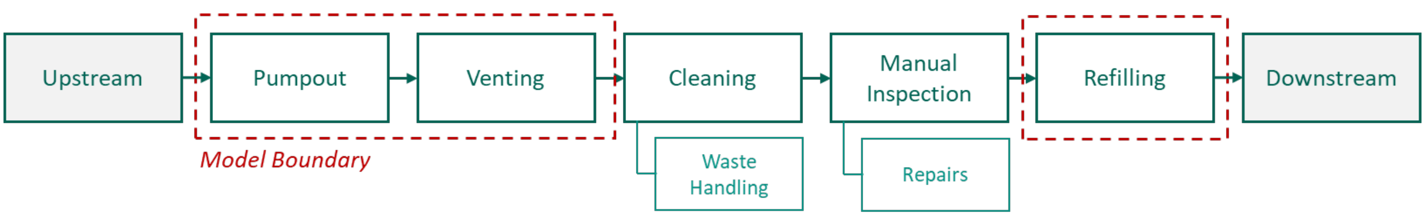

Figure 4: Summary of model boundary.

Table 1: Summary of stages included in model boundary and rationale.

Stage	Project Scenario	Baseline Scenario	Included in Boundary	Rationale
Upstream	Relevant	Relevant	No	Emissions are expected to be equivalent or greater in the baseline scenario than the project scenario. Exclusion of this stage is a conservative omission and is expected to underestimate actual emissions avoidance.
Pumpout	Not Relevant	Relevant	Yes	**Direct** emissions from tank pumpout are included in the model. These emissions are additional to the baseline scenario and do not occur in the project scenario. Any indirect emissions relevant to this stage are included in the *Inspection* portion of the baseline scenario.
Venting	Not Relevant	Relevant	Yes	**Direct** emissions from tank venting are included in the model. These emissions are additional to the baseline scenario and do not occur in the project scenario. **Indirect** emissions from this stage are not included. These are challenging to quantify and are expected to be minor compared to direct emissions; this is a conservative omission.
Cleaning	Not Relevant	Relevant	No	Emissions from this stage are challenging to quantify and may be highly variable project to project. This stage does not occur in the project scenario; exclusion of this stage is a conservative assumption and is expected to underestimate actual emissions avoidance.
Inspection	Relevant	Relevant	No	Emissions from this stage for the project scenario include all "Inspection Phase" emissions described in section **5.2.** Emissions for the baseline scenario are considered to include all emissions sources described in *All Stages* and the *Manual Inspection* sections of section **6.2**. Emissions from this stage are expected to be equivalent or greater in the baseline scenario than the project scenario. Exclusion of this stage is a conservative omission and is expected to underestimate actual emissions avoidance.
Repairs	Uncertain	Relevant	No	Repair activities are highly variable and challenging to quantify. Repairs may occur after the inspection process for both the project and baseline scenarios, but for the baseline scenario these activities are not necessarily directly attributable to the results of an inspection. Due to the complexity and theoretical nature of this stage, repair activities have not been explicitly evaluated in this assessment for additionality considerations and are excluded from the model.
Refilling	Not Relevant	Relevant	Yes	**Direct** emissions from tank refilling are included in the model. These emissions are additional to the baseline scenario and do not occur in the project scenario. Any indirect emissions relevant to this stage are included in the *Inspection* portion of the baseline scenario.
Downstream	Relevant	Relevant	No	Emissions are expected to be equivalent or greater in the baseline scenario than the project case. Exclusion of this stage

				is a conservative omission and is expected to underestimate actual emissions avoidance.

Many stages are excluded from the model that are expected to result in equivalent or higher emissions from the baseline scenario than the project scenario. Overall, this model is expected to be conservative and likely underestimates the total emissions savings from the Square Robot inspection process if assessed for the entire life cycle. In future, this model and associated emissions avoidance estimations could be improved by evaluating additional stages of the baseline inspection scenario.

8. Emissions Calculations

Calculations used in this model are based on best available established industry methodologies. The approach for quantifying vapor release from the storage tanks is sourced from the EPA's *AP-42, Fifth Edition, Volume I, Chapter 7: Liquid Storage Tanks* (rev. June 2020), and the approach for estimating global warming impact from hydrocarbon vapors aligns with the Intergovernmental Panel on Climate Change (IPCC) and literature approaches (Gillenwater, 2007, Murrells & Derwent, 2007). The methodologies and assumptions used are further defined in the following sections.

First, the total quantity (lb) of released vapors is calculated for each phase – Pumpout, Ventilation, and Refilling, as described in the following sections. All equations referenced in this section refer to those available in AP-42 Chapter 7.

Once the quantity of vapors is determined, the global warming impact is calculated in terms of carbon dioxide equivalents (CO2e).

8.1 Pumpout

Fixed Roof Tanks

For fixed roof tanks, the AP-42 methodology assumes that emissions during pumpout are equivalent to routine tank breathing losses and that no additional vapors are released that would not otherwise occur during normal operations. Working losses are attributed only to the refilling phase. Thus, for fixed roof tanks zero emissions are considered attributable to the pumpout phase.

Floating Roof Tanks

Floating roofs provide an emissions reduction benefit compared to fixed roof tanks by reducing the vapor space present in the tank at any particular time. However, during the pumpout and roof landing process a vapor space is created that generates additional emissions that do not occur under normal operating conditions. Per AP-42, these losses are known as **floating roof landing losses**.

During the pumpout phase, roof landing losses are calculated based on **standing idle** losses, which refer to evaporation that occurs while the roof is landed and some liquid remains in the tank, prior to forced ventilation begins. Standing idle losses result from breathing losses from the vapor space and continued evaporation of liquid remaining on the interior tank surfaces ("clingage losses"). For some exterior floating roof tanks, wind action can also increase the vapor release.

Breathing Losses

Breathing losses during the standing idle period are a function of the time the tank stands idle and the conditions to which the tank is subjected during that time. Variations in ambient temperature and/or temperature inside the tank can cause fluctuations in the vapor pressure of the stock vapor, leading to increased vapor release.

The standing idle loss can be calculated using equation **(3-7)**:

$$L_{SL} = n_d * K_e * \frac{P_{va} * V_v}{R * T_v} * M_v * K_s$$

Where:

- L_{SL} = Standing idle losses (lbs vapor)
- n_d = Number of days idle (days)
- K_e = Vapor space expansion factor, dependent on daily temperature variations, (per day), calculated from equation **(1-5):**

$$K_e = \frac{\Delta T_v}{T_{la}} + \frac{\Delta P_v}{P_a - P_{va}}$$

- T_{la} = Average daily liquid surface temperature (°R)
- ΔT_v = Range in daily temperature (°R)
- T_v = Average vapor temperature (°R)
- ΔP_v = Range in daily vapor pressure (psia)
- P_a = atmospheric pressure (psia)
- P_{va} = Average vapor pressure of the stock liquid (psia)
- V_v = Volume of the vapor space (ft^3)
- R = Ideal gas constant, 10.731 (psia-ft^3/lb-mole°R)
- M_v = Vapor molecular weight (lb/lb-mole)
- K_s = Standing idle saturation factor (dimensionless)

For this model, the following assumptions were used:

- **n_d** is set to 1 day. It is assumed that tanks typically stand idle overnight after pumpout before ventilation begins, but on occasion this idle time may be longer or shorter. One day is recommended as a minimum input.

- The inputs for average vapor temperature and daily temperature minimum and maximum used to calculate **K_e** are assumed to be equivalent to the average, minimum, and maximum ambient temperatures recorded by Square Robot throughout the project duration.
- **V_v** is calculated based on the roof leg height and diameter of the tank. Although the volume of the roof legs will reduce the vapor space volume, this is not considered to be significant relative to the overall tank dimensions.
- **K_s** is set equal to 0.5, or equivalent to the saturation factor recommended by AP-42 for a partial liquid heel. This is based on the assumption that the liquid in the tank is pumped out to the lowest level possible so that there is no freestanding liquid in the tank. It is assumed that some liquid remains due to

puddling, irregularities on the tank bottom, mixing with any sediment on the tank bottom, and pooling near the tank sump, thus the partial liquid heel is applied.

Wind Losses

For external floating roofs that are not domed, wind losses also play a role in the vapor loss during roof landing. Wind blowing across the landed roof can create pressure differentials that induce vapor flow out of the tank.

Equation **(3-10)** can be used to estimate wind losses for external floating roof tanks, based on an average wind speed of 10mph:

$$L_{SLWind} = 0.57 * n_d * D * P^* * M_v$$

Where:

- L_{SLWind} = Standing idle loss due to wind, per roof landing (lb)
- D = tank diameter (ft)
- P* = pressure function dependent on vapor and atmospheric pressure (dimensionless); see equation **(3-9)**
- M_v = stock vapor molecular weight (lb/lb-mole)

Similar to the breathing losses, it is assumed that n_d = 1, i.e., that the tank is idle for 1 day.

8.2 Ventilation

During the ventilation phase, prior to and during the manual cleaning process, vapors present in the tank are forced out through blowers or eductors. Because it is assumed that some stock liquid remains on the tank bottom and other interior surfaces at the onset of ventilation, it is also expected that evaporation continues to occur until the tank is fully clean.

While AP-42 presents a method for estimating ventilation emissions during an actual cleaning event based on blower speeds, duration, and in-tank measurements, this method is not appropriate for a theoretical model that cannot incorporate measured onsite values. Alternatively, PSC applied the assumption that any volatile materials present in the tank at the onset of ventilation are ultimately volatilized and expelled from the tank as vapors during ventilation and cleaning. Using this assumption, equation **(4-12)** is utilized to calculate the mass of remaining volatile liquid in the tank, equivalent to the ultimate vapor release from the tank:

$$L_{CV} = 7.48 * A * h_{le} * W_l * F_e$$

Where:

- L_{CV} = total emissions from ventilation (lbs)
- 7.48 = volume conversion factor (gal/ft^3)
- A = tank bottom area (ft2)
- h_{le} = effective depth of the stock liquid/sludge remaining in the tank (ft)
- W_l = density of the stock liquid (lbs/gal)
- F_e = fraction of sludge/liquid remaining that is volatile (%)

For this model, based on guidance provided in the AP-42 manual, the following assumptions were applied:

- Tank bottom area (A) is calculated based on the tank diameter and excludes any roof landing legs or other impediments. While these may reduce the tank bottom area, this is considered to be insignificant relative to the overall tank dimensions.
- Effective sludge depth (h_{le}) is assumed to be the average sediment depth observed during the Square Robot tank inspection and data collection. While variation is expected throughout the tank bottom, this measurement is considered the best available estimation to account for the pooling and sludge expected to remain on the tank bottom. In future, Square Robot may be able to improve this estimation through expanded data collection capacity to estimate total sediment volume rather than depth alone.
- The tank bottom is assumed to be flat, with no slope. While most tanks have sloped bottoms that could affect the calculation of sludge volume based on an average depth, per AP-42 guidance this slope is considered insignificant relative to the overall tank bottom dimensions.
- F_e is set to 20% for hydrocarbon fuels, the assumption provided by AP-42. This is expected to be a conservative estimate, particularly for highly volatile materials such as gasoline. Additionally, materials that generate low sedimentation may have a higher representation of volatile stock liquid in the effective depth assumed, or pooling on the tank bottom may increase the actual effective depth beyond the value assumed in the model.

8.3 Refilling

During refilling operations, vapors are generated by the incoming liquid and forced out of the tank by the rising liquid level. Emissions are calculated differently depending on the tank roof type.

Fixed Roof Tanks

Refilling losses in fixed roof tanks are considered 'working losses' and can be calculated using equation **(1-35):**

$$L_w = V_Q * K_N * K_P * W_v * K_B$$

Where:

- L_W = Working losses due to refilling (lbs)
- V_Q = volume throughput of stock liquid (ft^3)
- K_N = working loss saturation factor (dimensionless); set as 1 for a single refilling operation
- K_P = working loss product factor (dimensionless); set as 1 for all organic liquids other than crude oil (K_P for crude oil is set to 0.75)
- W_V = stock vapor density (lb/ft^3)
- K_B = vent setting correction factor (dimensionless)

In addition to the set parameters defined by AP-42 (K_N and K_P), the following assumptions were applied for refilling:

- Throughput volume, V_Q, is assumed to be equal to the liquid volume in the tank at the time of the Square Robot inspection. That is, it is assumed that if the tank were to be emptied it would be refilled to the same liquid height.
- The vent setting factor, K_B is assumed to be 1. Per AP-42, this assumption is used for all tanks with open vents or vents with pressure setting ranges ±0.3psig.

Floating Roof Tanks

Floating roof tanks minimize refilling emissions by decreasing the vapor space once the stock liquid reaches the landed roof height. Emissions from filling operations for floating roof tanks are characterized by equation **(3-18)**:

$$L_{FL} = \left(\frac{P_{VA} * V_v}{R * T_v}\right) * M_v * C_{sf} * S$$

Where:

- L_{FL} = filling loss for a landed roof (lb)
- P_{va} = true vapor pressure of the stock liquid (psia)
- V_v = volume of the vapor space (ft^3)
- R = ideal gas constant, 10.731 (psia-ft^3/lb-mole°R)
- M_v = vapor molecular weight (lb/lb-mole)
- C_{sf} = filling saturation factor for wind (dimensionless); set at 1 for clean tanks
- S = filling saturation factor (dimensionless); set at 0.15 for clean tanks

The vapor space volume is calculated based on the height under the landed roof and does not incorporate the space taken up by the landing legs; this is not expected to materially affect the calculations relative to the overall.

8.4 Global Warming Impact

Air emissions that have a global warming impact are referred to as greenhouse gases (GHGs) and characterized by their global warming potential (GWP) value. GWP provides a measure of the radiative forcing (i.e., heat capture) effect of a greenhouse gas, typically over a 100-year timeframe. GWP is presented relative to the radiative forcing effect of CO_2, thus GHGs typically measured in units of metric tons of CO_2e, or CO_2 equivalents.

Hydrocarbon vapors (also known as non-methane volatile organic compounds, or NMVOCs) have not historically been considered significant greenhouse gases and are expected to have a negligible direct radiative forcing effect. Vapors such as those from diesel fuel are often short-lived in the atmosphere (lifetime of hours to months) and are typically not accounted for in national or corporate greenhouse gas inventories (Gillenwater, 2007). However, these hydrocarbon vapors are understood to have indirect warming effects that do contribute to climate impacts (Gillenwater, 2007; Radunsky & Gillenwater, 2019).

Vapors contribute to warming impacts through two avenues: 1) intermediate reactions in the atmosphere to form other GHGs, such as ozone; and 2) ultimate breakdown of the hydrocarbon chains to CO_2. (Radunsky & Gillenwater, 2019)

For the first impact pathway, while some studies have attempted to characterize these intermediate reactions, this was done through complex atmospheric modeling and was shown to be highly dependent on localized conditions such as oxidizer concentration and mixing rates (Collins et al., 2002). In addition, it is expected that the speciation of the vapor would contribute to the rate and type of reactions that occur. Fuel vapors are complex mixtures of varying hydrocarbon chains, and the composition can be challenging to characterize as well as highly variable based on temperature or other conditions (Chin & Batterman, 2012; Greenfield & Rossi, 1999). For these reasons, intermediate reactions were considered too variable and uncertain to attempt to characterize in a simplified emissions model.

Instead, this model includes only the warming effect due to the ultimate degradation of vapors into CO_2 through oxidation of the carbon and hydrogen molecules. Per the method presented by Gillenwater (2007) and Murrells & Derwent (2007), it can reasonably be assumed that all carbon atoms originally present in the hydrocarbon vapor are oxidized to form CO2. Thus, if the initial overall mass ratio of carbon in the vapor is known, then a conversion to CO2 can be calculated based on the following equation:

$$GWP = mass\ \%\ C\ of\ NMVOC * \frac{44}{12}$$

Where 44 is the molecular weight of CO_2 and 12 is the molecular weight of carbon.

Although the vapor composition of the tank emissions may be unknown, and could vary over time throughout the project duration, it can be reasonably assumed that the overall carbon mass ratio for the entire vapor release period is equivalent to that of the original stock liquid. Overall, this estimation of GWP is expected to be somewhat conservative through the exclusion of any potential intermediate reactions.

References for fuel properties, including the assumed mass percentage of carbon, are included in the Excel model.

8.5 Total Avoided Emissions

Total avoided emissions for a particular Square Robot inspection project can be calculated in the Excel model using project inputs where available. Avoided emissions are calculated by summing the vapor mass quantities calculated for each stage (Pumpout, Ventilation, and Refilling) and multiplying the vapor mass by the relevant GWP for the stock liquid to result in emissions in terms of CO_2e.

As described in previous sections, this final value includes only a limited scope of emissions-generating activities. From a life-cycle perspective this total emissions value is expected to underestimate the overall avoided emissions benefit of the Square Robot process when all potential emissions sources are evaluated.

9. Discussion

This methodology and model described in this report is a theoretical approach that attempts to best characterize the material emissions from a tank inspection process based on best available data and industry methods. Given the limitations and uncertainty in estimating emissions from the baseline activities, and the inherent uncertainty in applying theoretical equations to a complex system, the scope and assumptions defined throughout this report were selected to provide a conservative approach. As such, it is expected that the results underestimate the life cycle GHG savings for the Square Robot inspection process compared to conventional tank inspection. This estimate could be improved by attempting to quantify the potential emissions excluded from the current scope of this model.

In the future, as Square Robot expands operations into different tank types and stock liquids, the model may need to be adjusted to incorporate differing baseline activities or assumptions that are not currently represented for the distillate fuels included. In addition, future enhancements to Square Robot's data collection capabilities may serve to improve the model and input parameters, such as through measurement of sludge or sediment volumes in the tank.

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