MODELING INERT GAS DISTRIBUTION IN COMMERCIAL TRANSPORT AIRCRAFT FUEL TANKS

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Abstract

Full-scale fuel tank inerting testing is being conducted on a ground based Boeing 747SP by the Federal Aviation Administration. Several methods of modeling inert gas distribution, in terms of oxygen concentration evolution, are being studied in an attempt to develop inexpensive tools for designing efficient inert gas deposit systems for commercial transport airplane fuel tanks. Results showed that an inexpensive scale test article and a simple engineering computational model were effective at predicting the inert gas distribution of the 747SP compartmentalized center wing fuel tank with highly localized inert gas deposit. The limited Computational Fluid Dynamics data available illustrates this method of predicting inert gas evolution through the tank has some limitations. The engineering model was less accurate when predicting trends of the inerting process for multiple-bay deposit points when compared with the scale tank test results.

Introduction

More emphasis has been placed on fuel tank safety since the TWA flight 800 accident in July 1996. The National Transportation Safety Board concluded that a center wing fuel tank explosion was the probable cause of the accident. Since the accident, the Federal Aviation Administration (FAA) has conducted a considerable amount of research into methods that could eliminate or significantly reduce the exposure of transport airplanes to flammable vapors. This includes research on fuel tank inerting which is commonly utilized by the military. Fuel tank inerting could prove to be more cost-effective if it were focused on center wing or body style tanks, which tend to be hotter during ground operation. Inerting of heated center wing tanks could reduce the average fleet exposure time to flammable vapors from approximately 35 percent to as little as 2 percent depending on fleet wide methods established [1].

To provide for a cost-effective implementation of inerting systems, efficient distribution of inert gas is critical, whether it be from an onboard inert gas generator (OBIGG) or from ground supplied inert gas. Traditional military systems distribute inert gas via a plumbing system in the fuel tank ullage that essentially ensures relatively uniform distribution of inert gas throughout. It would be advantageous to inert the relatively complex geometric space of a commercial transport center wing fuel tank with as little internal plumbing as possible to reduce cost and weight and to simplify the installation. Optimizing and validating the method of depositing inert gas has traditionally been an expensive and time-consuming process of computational fluid dynamics (CFD) and/or full-scale testing.

The goal of this research was to determine if small-scale testing and simple engineering models could be used to successfully determine the best method of depositing inert gas. The best method can be defined as the simplest deposit scheme that requires the least amount of inert gas to reach a given oxygen concentration. This research was centered on a fully operational, ground test 747SP that would be used to validate the best-determined deposit method. This method was also analyzed with a CFD model in an attempt to gauge the ability of more complex analysis tools to predict inerting conditions in a commercial transport fuel tank.

Previous FAA experiments focused on inerting of simple rectangular spaces, with a single deposit nozzle and exterior vent, with nitrogen-enriched air (NEA). NEA is the term used to describe relatively impure nitrogen (99% to 92% nitrogen by volume) which is usually generated by a gas separation process. This data illustrated that a volumetric tank exchange (VTE) of 1.5 to 1.6 was required to inert an ullage (empty space above the fuel) to 8% oxygen concentration using NEA 95 (95% nitrogen, 5% oxygen) [2]. This is to say that to inert a

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tank to 8% oxygen by volume you need 1.5 to 1.6 times the volume of the ullage of NEA 95. Most commercial transport fuel tanks are more complex and compartmentalized into separate bays by the primary structures of the wing (spars, ribs, etc.). Full-scale testing of a Boeing 737-700, that used a relatively thorough and complex distribution system, required a VTE of 1.7 to 1.8 to inert the tank to 8% with NEA 95 [3]. This brings into question the ability of simple experiments to model the inerting of a more complex geometric space. In another set of experiments, a plywood model of a 747SP center wing tank (CWT) was employed to determine the most efficient and cost-effective method of inerting the empty tank. These experiments illustrated that inerting the tank was most efficient (required the least amount of NEA) when inert gas was deposited in a single bay, far from the vent exits, given the tank vent system was modified to prevent cross flow [4]. Some airplane CWTs vent to both wing tip vents, which can cause ventilation of the CWT, due to cross flow, during some wind and flight conditions. Blocking half the vent system prevents this and allows for CWT inerting to be more predictable.

Equipment and Procedures

Full-Scale Test Article

A decommissioned Boeing 747SP was purchased to perform full-scale inerting testing on a commercial transport airplane. It has a maximum gross takeoff weight of 696,000 lbs with an empty dry weight of approximately 330,000 lbs. The aircraft has four under-wing engines and an auxiliary power unit (APU) with a wing span of 196 feet and an overall aircraft length of 185 feet.

The 747SP has four main wing fuel tanks, four wing tip reserve fuel tanks, and a large CWT. The CWT is approximately 242 inches long and 255 inches wide with height varying from 78 inches to 48 inches. As shown in figure 1, it has six bays. Two of the bays are the full width of the fuselage, and four bays are formed from two full-length bays, dissected mid-way with a partial rib. Forward of the first two full-width bays, but aft of the forward spar, is a large dry bay. Fuel and vapor flow between bays through small holes in the bottom and top of each spanwise beam and the midspar, and through penetrations made for wiring and tubing that pass from bay to bay. The CWT is vented to both wing tip surge/vent tanks via a vent channel in the wings with venting tubing contained within the tank. One vent channel travels along the top of bays 3 and 4, while the other travels along the top of bays 5 and 6. These channels vent crosswise to the exterior of the tank so that the vent channel plumbed on the right side of the tank (bays 5 and 6) is vented to the left side of the aircraft and vise-versa. Each vent channel is plumbed to a length of aluminum tubing on each side of the tank that travels forward perpendicular to the spanwise beams and midspar across the bays. A smaller tube travels aft within the vent channel bay. This plumbing configuration allows the CWT to vent pressure in various rolling and climb/dive scenarios. The vent channels from the CWT and all other fuel tanks terminate in one or both of the surge/vent tanks located near each wing tip. These act to catch fuel and prevent overflow, and are connected to the aircraft exterior via a NACA scoop located on the bottom surface of each wing. Figure 2 is a plan view of the 747SP CWT illustrating the bay layout and numbering convention.

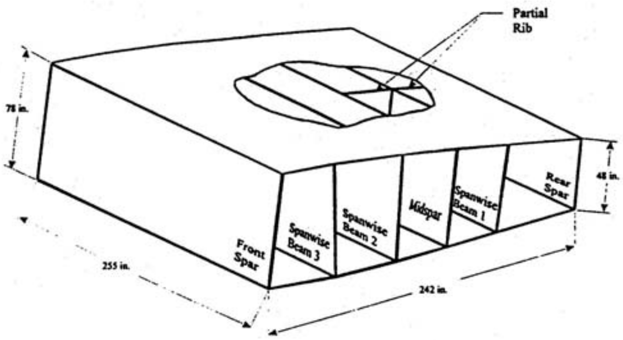

Figure 1. Center Wing Tank Off-Axis View

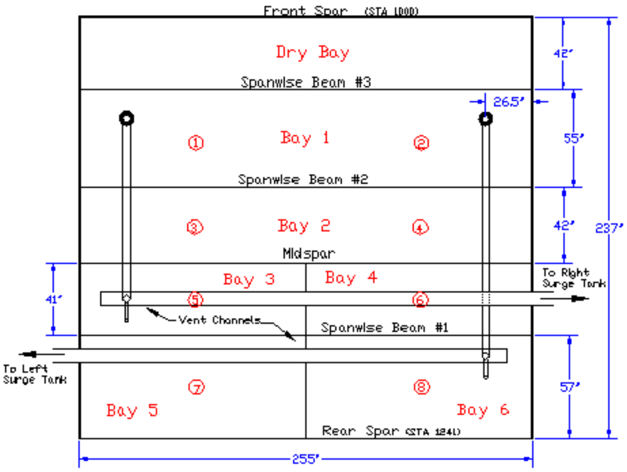

Figure 2. Top Diagram of Center Wing Tank with Eight Oxygen Sample Port Locations and Bay Numbering Convention

The test article was supplied with inert gas produced by an industrial NEA generator that can generate varying purities (residual oxygen concentrations) of NEA at flow rates capable of inerting the tank in less then 20 minutes. The NEA is supplied to a cart designed to meter the appropriate flow at the desired pressure to the aircraft NEA deposit manifold, which is plumbed to deposit all the NEA into bay 3. This method was established in scale testing as an efficient (least amount of NEA) method of inerting the tank, while still providing acceptable gas distribution from bay to bay [4]. This distribution method also allows for easy retrofit into an existing operation aircraft, as it requires very little modification of the tank.

The test article is supplied with independent ground power for instrumentation and climate control, as well as equipment and accessories to allow for complete operation of the instrumentation independent of the operation of the aircraft.

The 747SP full-scale test article was instrumented with gas sample plumbing and thermocouples in the CWT to allow for the measurement of inerting and flammability parameters within the aircraft fuel tank during normal operational conditions. The gas sampling system was installed within the test article, using pumps, plumbing, and a system of soleniod valves, to allow for gas analysis at eight locations (illustrated in figure 2) within the CWT.

Each gas sample is passed through a remote, flow-through oxygen sensor that uses an electrolytic cell to determine the partial pressure of oxygen and is connected to an analyzer that presents a calibrated volumetric oxygen concentration based on sample pressure. This type of analyzer has been successfully applied in ground and flight test to acquire oxygen concentration data in aircraft fuel tanks in the past [3]. It has a design that maximizes separation of the gas sample and signal and minimizes the energy required to operate, providing a significant level of protection against ignition of the flammable gas sample. The analyzers are calibrated by supplying each sensor with five calibration gases and fitting a second-order polynomial through the data. Although the analyzers are designed to have a linear response, this method allows for better adherence of the analyzer output to the calibration gas values and is presumed to improve the accuracy of the analyzers. Two of the eight gas samples can also be analyzed for hydrocarbon content by two total hydrocarbon analyzers. Four additional oxygen analyzers sample gas from the surge tank, the dry bay, and two user-specified locations.

24% Scale Tank

To model inert gas distribution in the 747SP CWT, a scale CWT model was constructed of plywood based on drawings from a National Transportation Safety Board (NTSB) report detailing work done on scale modeling of a 747-100 CWT [5]. The tank was built to 24% length scale (1.38% volume). Each spanwise beam, spar, and partial rib was also scaled as well, with all penetration holes being scaled in terms of relative area. The tank has an inert gas deposit nozzle in the bottom of each bay that can be independently supplied with NEA of varying purity, through a manifold of flow meters that allow for inert gas deposit in each bay at any desired flow rate. Reference 4 gives a complete description of the scale tank test apparatus with diagrams and photographs and includes the drawings of the tank profile with accompanying spars, spanwise beams, and ribs.

The scale tank uses the same bay numbering convention as the full-scale aircraft but has only one gas sample port in the center of each bay plumbed through a remote galvanic cell type oxygen sensor with an analyzer similar to what is used on the 747SP test article. The sample system is plumbed in a unique drafting manner that allows for rapid response time while still maintaining the advertised accuracy of ±2% of the analyzer reading. This requires calibration of the sensors by washing the tank with a known oxygen concentration gas until each sensor is stable, to allow for upscale spanning of the instrument to the desired oxygen concentration. Nonlinear calibration curves were developed for each analyzer/sensor to correct the discrepancies this method caused on the higher measured oxygen concentrations (16% to 21%). Each bay has a thermocouple to ensure static temperature conditions. It is critical that atmospheric pressure remain constant during the testing to maintain the accuracy of the oxygen analyzer reading during testing [4].

Test Procedures

Full-Scale Test Article

The test procedures for inerting the full-scale test article CWT initially involved obtaining ambient quiescent conditions in and around the tank. To perform an inerting test, the tank was first purged with air to ensure an ambient oxygen concentration in the tank, and the correct fuel load was obtained while the aircraft systems were off to give ambient, quiescent conditions on the aircraft. The NEA generator was then started, warmed up, and set to produce the desired conditions at the deposit cart while the flow was diverted away from the tank deposit manifold. The data acquisition system was then started and the aircraft and instrumentation were allowed to stabilize for a brief period of time providing a testing baseline. Next, the NEA was diverted into the tank for the desired amount of time. Lastly, the tank was allowed to settle for a few minutes, and the APU and air cycle machines (ACMs) were run to simulate actual aircraft operation. The ACMs created heating of the bottom surface of the CWT, which improved mixing in the tank. This mixing after heating of the tank during the tests illustrated the effect of vertical oxygen concentration stratification/gradient in the quiescent tank.

Scale Tank

To perform an inerting test in the scale tank model, the correct flow conditions were first set on the deposit flow meter manifold and the inert gas flow was then diverted away from the manifold. The tank was then purged with air until the oxygen analyzers stabilized, indicating that the test article has reached ambient oxygen concentration. The data acquisition system was started and 1 minute was allowed to elapse before diverting the inert gas into the tank. After the desired inerting time had elapsed, the inert gas was diverted away from the test article and the data acquisition was run 1 minute before ending the test.

Analysis and Modeling

Data Reduction Methods

It is advantageous to present the data in a manner which is easily applied to all fuel tanks and all NEA flow rates. It can be hypothesized that the volume of NEA deposited within the tank dictates how quickly or slowly a vented fuel tank becomes inert, given the assumption that the tank is homogenous and stores no gas (100% mixing, flow in = flow out). It also follows that this volume of gas, divided by the total volume of the tank, would be constant for a desired inerting level and given a fixed NEA percentage (percentage of N_2) of gas deposited. The time scale of the data was nondimensionalized by applying the flow rate and fuel tank volume, which is defined as the volumetric tank exchange (VTE).

$$Volumetric\ Tank\ Exchange = \frac{Time * Volume\ Flow\ Rate}{Fuel\ Tank\ Volume} \quad (1)$$

When comparing different methodologies of inerting the tank, it is convenient to be able to express the oxygen concentration of the tank as a whole, even though the concentrations of the individual bays often vary. To achieve this, a weighted average by volume was calculated at each point in time. This average weighed the oxygen concentration of each bay with the volume percentage of each bay.

$$\begin{aligned} Average[O_2] = {} & .31[O_2\,Bay1] + 0.23[O_2\,Bay2] + 0.10[O_2\,Bay3] \\ & + 0.10[O_2\,Bay4] + 0.13[O_2\,Bay5] + 0.13[O_2\,Bay6] \end{aligned} \quad (2)$$

Engineering Model

An engineering model was developed to predict the transient oxygen concentration evolution during uneven inert gas deposit in a fuel tank with multiple compartments. It was based on an inerting model developed by the FAA to predict the change in oxygen concentration in a simple box (single bay) with a single exit (one vent), given a volume flow of inert gas into the tank. The model tracks the volume of oxygen in the tank and calculates the volume fraction given the total tank volume. This principal can be represented by the following equation.

$$\begin{aligned} V_{O_2}(t) = {} & V_{O_2}(t-1) + \dot{Q}_{NEA} * IGOF * \Delta t \\ & - \dot{Q}_{NEA} * V_{O_2}(t-1) * \Delta t / V_{Tank} \end{aligned} \quad (3)$$

Where: $V_{O_2}(t)$ = Volume of Oxygen in Tank at Time *t*

$\dot{Q}_{NEA}$ = Flow Rate of Inerting Gas into Tank

IGOF = Fraction of Oxygen in Inerting Gas

V_{Tank} = Volume of Tank Ullage

Δt = Time Step

Equation 3 states that the amount of oxygen in the ullage at any time, *t,* is equal to the amount of oxygen at *t-1*, plus the amount of oxygen added during the time step, minus the amount of oxygen vented during the time step. This model assumes a homogenous ullage with good mixing at every time step. The oxygen concentration in the ullage at any time is equal to the calculated volume of oxygen divided by the volume of the ullage. The model is in a spreadsheet format and runs instantaneously. This methodology proved to be effective at modeling the inerting of a simple rectangular box with a single deposit and a single vent, provided that care is taken to ensure good mixing of the deposit gas before venting [2].

To apply this principal to inerting of a multiple-bay tank, assumptions must be made about the path of the flow. The focus of the modeling effort was to model the inert gas distribution in the full-scale 747SP. The test article has a single deposit of gas in bay 3 (see figure 2) and a vent exit port on the right side in bay 1 (looking forward) and in bay 6. The left side of the vent system (to right wing tip) was blocked to simulate a potential fleet modification previously discussed. The inert gas flow pattern was assumed using this information and can be seen in figure 3.

The multiple-bay inerting engineering model uses the same principal as the single bay model but uses the assumed flow pattern given in figure 3 to determine the input and output of each bay at each time step. All places where flow is split between multiple bays, the ratio of the cross-sectional flow areas between the different bays is used to weight the amount of flow to each bay. For example, if 30% of the total outflow area of bay 3 is to bay 2, 40% is to bay 4, and 30% is to bay 5, then 30% of the volume flow into bay 3 will flow to bay 2, 40% to bay 4, and 30% to bay 5. The multiple-bay model calculates the volume of oxygen in each bay as a function of time using the principals expressed in equation 4.

$$\begin{aligned} V_{O_2}(t) &= V_{O_2}(t-1) + \dot{Q}_{NEA} * \Delta t * IGOF \\ &\quad + \dot{Q}_{Bayn} * \Delta t * V_{O_2Bayn}(t-1) / V_{Bayn} \qquad (4) \\ &\quad - \dot{Q}_{sum} * \Delta t * V_{O_2}(t-1) / V_{Bay} \end{aligned}$$

Where: $V_{O_2}(t)$ = Volume of oxygen in a bay at time t

$V_{O_2Bayn}(t-1)$ = Volume of oxygen in surrounding bay n at time t

$\dot{Q}_{Bayn}$ = Flow rate from surrounding bay n

$\dot{Q}_{sum}$ = Sum of all the flow rates into a bay

$IGOF$ = Fraction of oxygen in inerting gas

V_{Bay} = Volume of a given bay

$V_{Bay\,n}$ = Volume of surrounding bay n

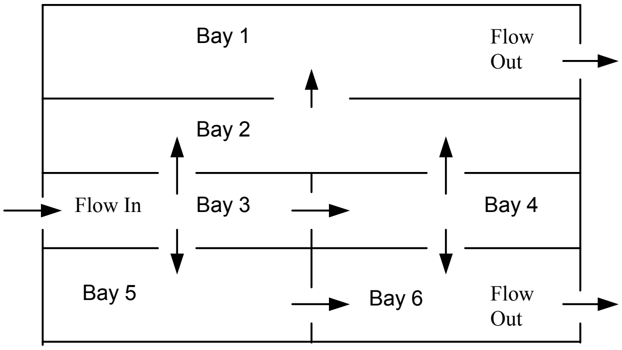

Figure 3. Diagram of Engineering Model Flow Pattern

This equation states that the volume of oxygen in a bay at time, *t*, is equal to the volume of oxygen in the bay at time *t-1*, plus the volume of the oxygen added to the bay in the inert gas, plus the volume of oxygen that flows into the bay from surrounding bays, minus the volume of oxygen that exits the bay. For the case illustrated in figure 3, the second term of the equation would be zero for all bays except bay 3, while the third term would be zero for bay 3, as no other bays flow into it.

Computational Work

To gauge the ability of complex analysis tools to accurately simulate oxygen concentration evolution during uneven inert gas deposit in a fuel tank with multiple compartments, a CFD model was developed with the CFD analysis package FLUENT. This modeling tool has the ability to track fluid species, such as oxygen concentration, at given locations. The data was generated using the Fluent CFD solver which uses a finite volume method where the general conservation (transport) equation, which includes mass, momentum, energy, diffusion, etc., is solved for each finite volume cell. The model was solved using a laminar flow throughout so that oxygen evolution is based entirely on diffusion of the different gas species. The model developed had approximately 700K cells and ran on a PC in 120 hours of computational time. More detailed information on the tool is available on line to registered users.

Results

Model Data Comparison

Inerting results from 747SP full-scale testing were compared with the scale tank data as well as the engineering model developed to simulate the distribution of inert gas in a six-bay, compartmentalized tank. Limited dimensionless results from the CFD analysis were also compared with the full-scale data, even though the computations were for the scale tank, to illustrate the effectiveness of the method.

Figure 4 compares the results from inerting the full-scale test article with the scale plywood tank in terms of VTE. The data compares very well illustrating the ability of a scale tank to simulate global flow behavior in a large confined tank given low-pressure flows and good mixing. This is possible because the velocities and pressures in the scale tank allow for inerting gas volume flow ratios from bay to bay to duplicate the full-scale test article. Since volume flow from bay to bay is the primary driver of oxygen concentration change in each bay, the scale tank duplicates the inerting gas distribution of the aircraft well. This is contrary to the belief that flow area scaling, to ensure equivalent pressure drops throughout the tank (Reynolds number matching), would be necessary to ensure that flow volumes split between the bays in a similar manner.

The oxygen concentration sample system in the full-scale test article exhibited a bias when averaged data was compared with theoretically and empirically averaged data. This bias manifested itself in the form of apparent initial efficient inerting of the tank that became less profound as the tank became more inert. After inerting was complete and the aircraft ACMs were operated, some bays exhibited a sharp increase in oxygen concentration. This was presumed to be caused by the sampling system reading a lower oxygen concentration than was representative of the bay or half-bay area being sampled and then mixing together quickly, due to the heating of the bottom of the tank by the ACMs. Since the sample system is located at the top of the bay and the deposited NEA tended to be warmer than the tank, oxygen concentration readings at the top of the CWT tended to be biased high. This was confirmed during a test with a gas sample probe located near the bottom in bay 2. This sample bias can be virtually eliminated by running the ACMs just before and during the inerting process as would be expected when inerting an in-service airplane between flights, or when it is being prepared for the first flight of the day. The full-scale test data presented was acquired in this manner.

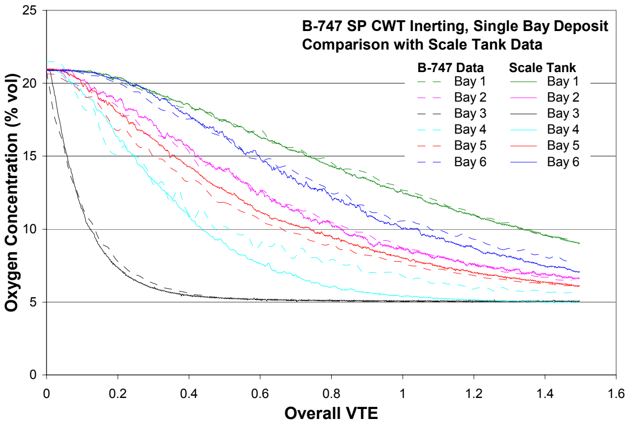

Figure 4. Comparison of Full-Scale 747SP CWT Inerting Data with Scale Tank Results

The results from the engineering model were also compared with the full-scale inerting data which is shown in figure 5. This illustrates the ability of a simple spreadsheet simulation to duplicate the inerting flow distribution in a compartmentalized tank. The data compares fair although some bays are considerably different. It is counter-intuitive that bay 1 models fairly well while bay 6 models relatively poorly. All inert gas flow passes through bays 1 or 6 before exiting so, by the model design, inert gas can either flow to bay 1 or 6. If bay 1 gets the correct amount of inert gas flow to reduce the oxygen concentration in the same manner as the full-scale test article, bay 6 should also. This discrepancy is most likely due to the sensitivity of the model for bay 6 inerting, which is a small bay compared to bay 1, which is the largest bay. A relatively small difference in the amount of inert gas traveling toward bay 1 (as opposed to 6) when comparing the model with the full-scale data would result in a greater change in oxygen concentration of a small bay then a large bay over the length of the test. The agreement of the model with the full-scale test data illustrates that individual bay mixing (while the ACMs are running) is generally good as the model assumes perfect mixing in each bay.

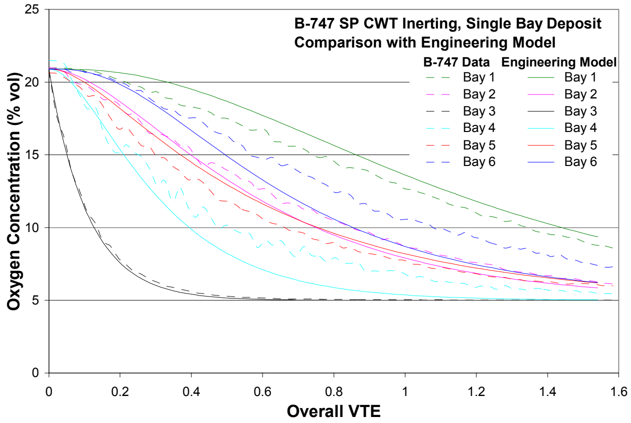

Figure 5. Comparison of Full-Scale 747SP CWT Inerting Data with the Engineering Model

Figure 6 compares the results of the CFD analysis with the full-scale test data. The CFD analysis was actually designed to model the scale CWT, but is compared to the full-scale test article to illustrate the point. Due to a lack of time and computer resources, the CFD analysis was not run to simulate the full length of the test. Like the engineering model, the CFD model bay oxygen concentration comparisons vary widely from bay to bay. Intuitively one would expect better adherence with oxygen evolution from bay to bay then the data illustrates when compared with the engineering model. Refining the model for the full-scale test article and completing the run in time is essential to understanding why the CFD analysis does not duplicate better results measured on the 747SP. However, limitations in the modeling method, as it pertains to mixing and distribution, are expected to create discrepancies even in a more refined model.

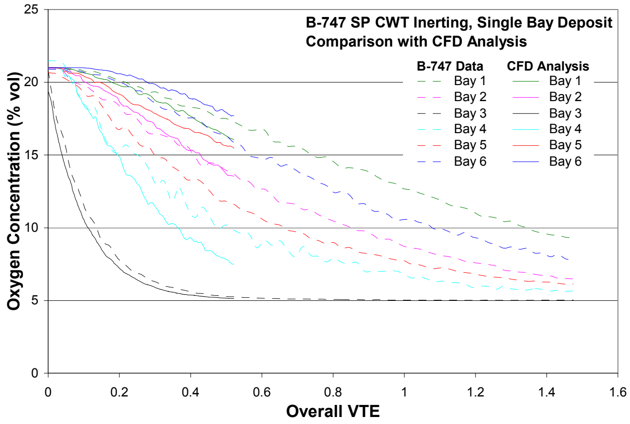

Figure 6. Comparison of Full-Scale 747SP CWT Inerting Data with the Results of a CFD Analysis

Figure 7 gives the volume weighted average oxygen concentration of the tank ullage for each modeling method discussed compared with the full-scale test article data. The results compare very well, illustrating that all modeling methods predict the same amount of inert gas required to obtain an 8% oxygen concentration (global average) as measured in the full-scale test article. Although, as previously mentioned, the CFD data only models one-third of the comparison data, it appears that the data would be very close to predicting the same result as the other two modeling methods.

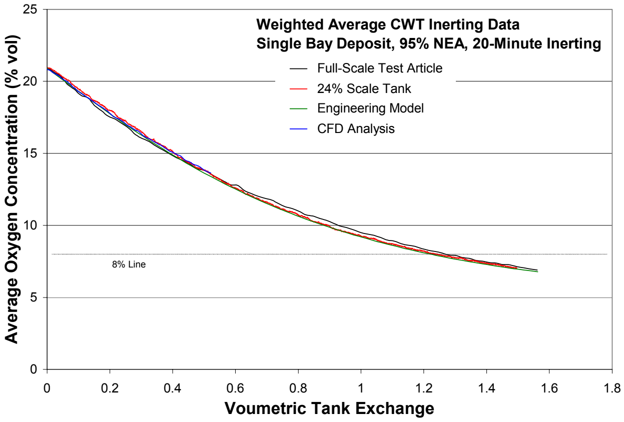

Figure 7. Comparison of Weighted Average Ullage Oxygen Concentration Data for the Scale Tank and Engineering Model with the Full-Scale Test Article

Mock-Trade Study Data

To validate the ability of both scale testing and engineering models to predict inert gas distribution in a compartmentalized tank, the results from scale testing of several different deposit methods were compared with predictions from the engineering model. The focus of this exercise is to compare results and analyze trends, in the manner a designer would, to gauge the ability of both modeling techniques to determine the best deposit method.

Figure 8 gives the results from inerting the scale tank with a single deposit in bay 3 as discussed in the previous section with predictions from the engineering model. Both modeling methods compare well, as expected, since both sets of data compare well to the full-scale data acquired for this case. As previously stated, the engineering model is expected to model this case well because it is the specific case it was designed to model. The engineering model relies heavily on the “cascading effect” of inert gas distribution, which states that as one bay becomes inert, it spills to another bay which becomes inert, which spills to yet another bay, and so on, until the inert gas flow exits the tank.

Figures 9 and 10 compare the engineering model predictions with scale tank inerting data for cases with multiple-deposit locations (four and two respectively), but venting in the same configuration as the single deposit case. The locations and ratios of NEA deposit were arbitrary and the data is presented for the sake of comparison of the two modeling methods. Figure 9 compares both modeling methods for four deposit locations and illustrates good agreement between the two methods with the exception of bay 4. Note that bay 1 and 2 model results in figure 9 give virtually the same oxygen concentration and appear as one magenta line. Figure 10, however, compares both methods for a test with two deposit locations and has less favorable agreement. This seems unusual, because the distribution method illustrated in figure 10 is more of a cascading flow as opposed to more of an equal distribution. Regardless, the engineering model reasonably represents the data trends measured in the scale tank, implying that the modeling methodology is founded on sound principles.

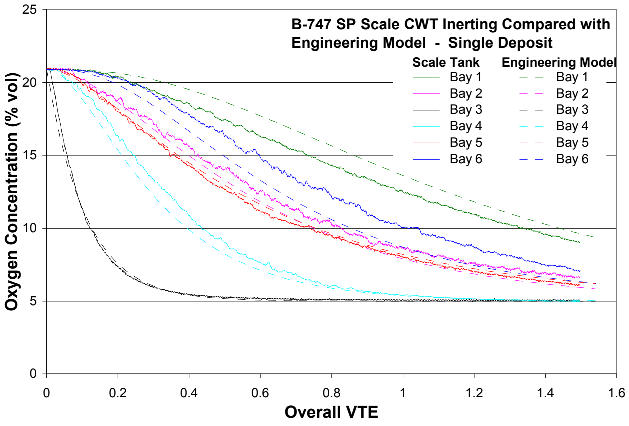

Figure 8. Comparison of Scale Tank Inerting Data with Engineering Model Predictions for the Single Deposit Case

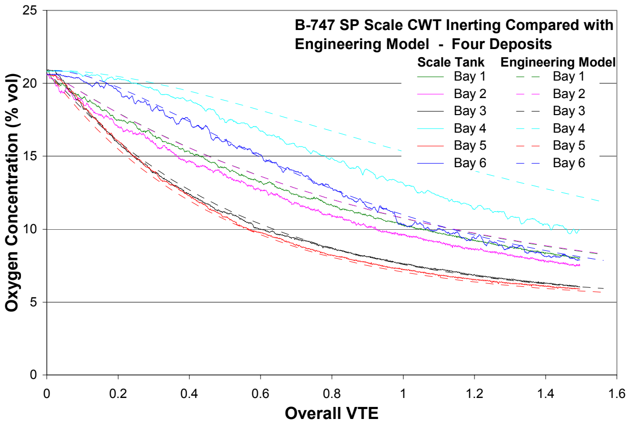

Figure 9. Comparison of Scale Tank Inerting Data with Engineering Model Predictions for the Four Deposit Case

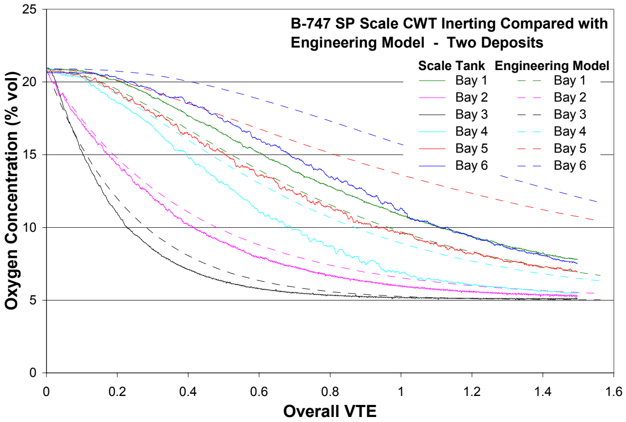

Figure 10. Comparison of Scale Tank Inerting Data with Engineering Model Predictions for the Two Deposit Case

Figure 11 compares the overall weighted average oxygen concentration data from the scale tank with the results of the engineering model. The results show a consistent bias of the engineering model to report less efficient inerting except for the single deposit case. This means there is a discrepancy between the modeling methods to predict which deposit scheme requires the least amount of inert gas to reach 8%, assuming this data represent a group of cases being analyzed for implementation. It may be that the "all roads lead out" philosophy of the model is overly simplistic. When depositing inert gas in bays with or near the tank vent exits, some flow may travel away from the vent, increasing the efficiency of the inerting process. The possibility remains that the methodology of the engineering model to split inert gas flow from bay to bay by the ratio of the flow cross-sectional areas is flawed, and it is only by fate that the single-deposit case has good agreement with full-scale measurements. Model modifications and additional comparisons with test data are required to validate the ability and limitations of this modeling methodology.

Summary

In summary, inexpensive scale representations and simple engineering models have been shown to be effective at predicting the inerting behavior of the 747SP compartmentalized CWT with highly localized inert gas deposits. The scale tank method data had good agreement with full-scale data illustrating the effectiveness of the modeling method. The limited CFD data available illustrates this method of predicting inert gas evolution through compartmentalized tanks has limitations and is cumbersome and resource intensive by its nature. The simple engineering model developed to predict inert gas distribution in a multiple-bay tank with a single deposit illustrated good agreement with the full-scale data. Although the engineering model appears to have some trouble predicting trends of the inerting process when performing a mock-trade study side-by-side with the scale tank, with improvement, the tool could prove effective at determining an efficient method of inert gas deposit in a very rapid, inexpensive manner.

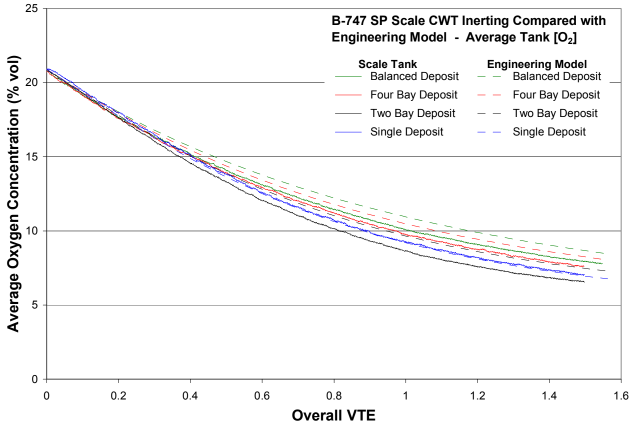

Figure 11. Comparison of Weighted Average Ullage Oxygen Concentration Data for the Scale Tank and Engineering Model for Different Deposit Methods

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