

The Use of Clean Agent Systems to Protect Leaky Enclosures

*Fire Suppression and Detection Research and Applications - A Technical Working Conference
(SUPDET 2008) – March 11–13, 2008 – Orlando, FL*

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ABSTRACT

The use of a clean agent for fire protection requires a high degree of enclosure integrity to ensure that the required agent concentration will be achieved and maintained for sufficient time to preclude the re-occurrence of the fire event (notification and intervention by trained personnel, equipment shut-down and cooling). For enclosures where this degree of integrity cannot be obtained, extended discharge systems are required to maintain the concentration.

The agent requirements are not as straight forward for the extended discharge system as they are for the initial/standard discharge systems. Agent requirements for an initial discharge system are based upon the volume of the protected enclosure and the appropriate mixing equation. Agent requirements for the extended discharge system are based upon the make-up agent flows derived from an analysis of the leakage rates from the enclosure. This is further complicated by the inability to achieve a constant flow rate of agent into the enclosure during the system discharge time. During the discharge, the decreasing flow rate of agent from the cylinders results in a higher than necessary agent flow rate at the beginning of the discharge in order to have the necessary agent flow rate at the end of the discharge.

In this paper, the concepts utilized to estimate agent retention times are adapted to address the determination of the agent requirements of an extended discharge system. These concepts are combined with the Peng-Robinson Equation of State, in order to predict the agent concentration in a leaky enclosure over the course of a 10-plus minute extended discharge of two clean agents, Inergen™ (IG-541) and FM-200™ (HFC-227ea). The flow of agent into the enclosure was predicted with HAI's clean agent flow calculation software, modified to account for the effects of the longer discharge duration on agent temperature and non-equilibrium phase concentrations.

The developed enclosure model was applied to a tape storage silo, StorageTek Model 9310, to determine the agent requirements for an extended discharge system. A plywood mock-up of the silo was constructed incorporating the cooling vent openings, pass-through openings to adjacent storage silos, and openings between the silo and the connected tape drive enclosures. This constructed mock-up was utilized to verify the agent requirement predicted by the developed model.

The developed enclosure model was demonstrated to have successfully determined the agent requirements for the mocked-up tape storage silo to provide 11.5 minutes of protection, with good agreement between the predicted and measured agent concentrations. This process for determining the extended discharge requirements and design of the system can be extended to other enclosures that could require an extended discharge.

This project was accomplished with the help and support of Chemtura Corporation (formerly Great Lakes Chemical Corporation), Ansul Inc., a division of Tyco International Ltd., and Kidde-Fenwal, Inc. The project work was sponsored by the General Services Administration (GSA) of the US Government for the Social Security Administration, Head Quarters.

Approach

A three staged approach was taken to determine the agent requirements needed to protect the StorageTek enclosure.

1. A steady state flow model was developed which balanced the volumetric flow-rates into and out of the leaky enclosure during the application of the agent. This defined the minimum continuous agent flow required to maintain the agent design concentration in the enclosure.
2. A transient model was developed to confirm the results of the steady state model and to assess the impact of the non-constant application rate of the agent. The transient model was also used to predict the resulting temperature decrease in the enclosure and the potential for water vapor condensation. HAI's agent flow model used to design clean agent systems was modified to predict the longer duration flow-rates into the enclosure needed as an input to the developed transient model.
3. A plywood mock-up of the StorageTek unit was constructed, preserving the leakage flows and ventilation conditions, to allow for experimental verification of both the developed models and agent requirements needed to protect the enclosure. In-situ testing was not possible due to availability and access concerns for the StorageTek library storage module.

1.0 LEAKAGE ANALYSIS

The leaky enclosure to be protected is a cluster of StorageTek library storage modules. Adjacent silos in a cluster are able to pass tapes through 30 x 30 cm (1 x 1 ft) ports located near the floor. There are two or four of these ports in each silo, depending on the location of the silo in the cluster. Each tape storage silo is equipped with a mechanical arm that can automatically retrieve a tape and then insert it into a drive unit, pass it to an adjacent silo, or deliver it to a door for human retrieval. There is a 7.5 cm (6 in.) diameter mesh-covered hole in the center of the module floor. Measurements indicate the mesh reduces the area of this hole by 25%, yielding an open area of 137 cm² (21.2 in²). The mesh-covered hole is centered above a perforated floor tile with an open area of 558 cm² (86.5 in²). The bottom of the silo is 3.8 cm (1.5 in.) above the room floor tiles. There are also several mesh-covered vents in the silo walls located near the

ceiling and near the floor. The total vent areas near the ceiling and floor were 1,219 cm² (189.0 in²) and 534 cm² (82.7 in²), respectively.

Between one and four tape drive enclosures can be attached to the modules, with different silos potentially having different types of tape drives. The drive units are equipped with their own ventilation fans and get supply air from the silo enclosure and/or from the surrounding room. In either case, air is exhausted from the drive unit to the room and not into the silo. Since the tape drives are set back into the tape drive enclosure, the opening is larger than what would be calculated by subtracting the area of the tape drive from the opening area. It was estimated that the effective vent area around the tape drive was approximately 75% of the area of the opening. Measurements of a silo indicated that the open area around the drives was 69.7 cm² (10.8 in²) per drive; thus, for a silo with 20 drives connected the open area would be 1,394 cm² (216 in²). There are also large holes/vents in both the top and bottom of the drive unit enclosures. The total open areas in the top and bottom of the drive enclosure were measured as 1,313 cm² (203.5 in²) and 569 cm² (88.2 in²), respectively. Additional mesh-covered vents in the side of the drive enclosure, located near the bottom of the unit, provide an additional 63.2 cm² (9.8 in²) of vent area. The total vent area from the drive unit enclosure to the surrounding room is 1,945 cm² (301.5 in²).

Internal dividers within the tape drive enclosure reduce the effective leakage area to 1,105 cm² (171 in²). These internal dividers isolate an area that houses the ventilation fans at the top of the enclosure where two 20 cm (8 in.) diameter holes allow the fans to pull air from behind the tape drives and exhaust it out the larger exterior opening. An additional 7.5 cm (3 in) diameter hole allows the cables carrying power to the fans to pass into the chamber. The internal dividers also isolate two chambers at the bottom of the drive enclosures which house the power supplies for the tape drives and exhaust fans. Each of these power supply chambers has two 5 cm (2 in) diameter holes that allow for the power cables to pass to the tape drives and to the ventilation fans via a central plenum area. While the isolation of these areas reduces effective leakage area with respect to protecting the remaining areas of the tape drive enclosure and the tape storage silo connected to it, the ability to protect these isolated areas of the tape drive enclosure without direct agent introduction into them is doubtful.

Electric power is supplied to the drive units and the mechanical arm on different circuits. The system is configured such that power to the mechanical arm is secured prior to suppression system activation, but power to the drive units is not secured.

Ventilation for the silo is typically supplied from the pressurized sub-floor through the perforated floor tile and hole in the floor. With the sub-floor pressurized to 39.8 Pa (0.16 iwc), the flow rate of air into the silo from the sub-floor is estimated to be 4,021 LPM (142 CFM). Air is exhausted from the silo through louvered vents on the sides of the silo into the computer room. There are no ventilation fans inside the storage silo. The entire above ceiling area within the computer area is typically used as the return plenum for the ventilation system. Ventilation may not be secured during the alarm or suppression system activation sequence. Figure 1 summarizes the ventilation configuration of the typical computer area with tape storage silos.

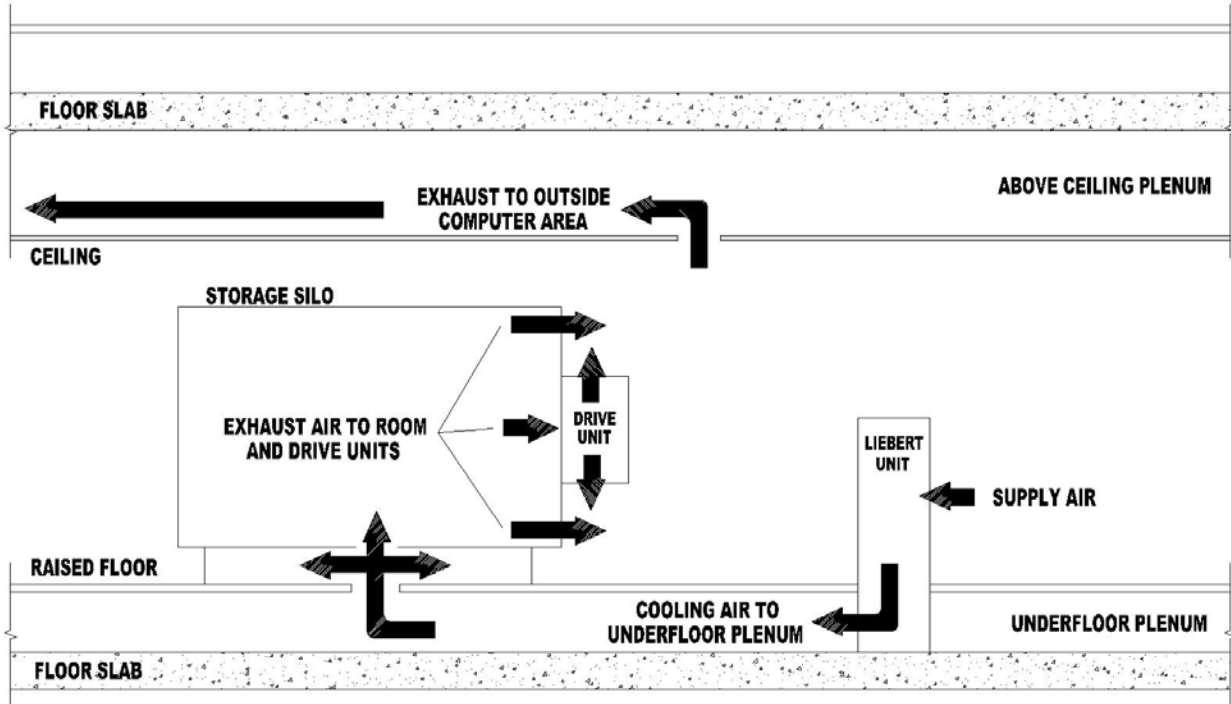


Figure 1 - Typical Ventilation Configuration

1.1 Steady State Leakage Analysis

In order to estimate the agent requirements for protecting the tape storage silos, a steady state flow analysis was performed utilizing a neutral plane concept [1, 2]. In utilizing this concept, the heavier than air, agent:air mixture flows from the silo to the room below the neutral plane and air flows into the silo above the neutral plane. The tape drive enclosures attached to the silo have their own neutral planes. The flow of either agent:air mixture or air between the silo and the tape drive depends on the relative heights of the two neutral planes and whether the agent is directly discharged in the tape drive enclosure to maintain the agent:air mixture throughout the tape drive enclosure.

The height of the neutral planes in the silo and the connected tape drive enclosures are determined through two interconnected volumetric flow balances for the case where agent is discharged into the tape drive enclosure as follows:

$$\begin{aligned}
 Q_{in,silo} + Q_{in, \text{ from drive}} + Q_{in,sub} + Q_{agent,silo} &= Q_{out,silo} + Q_{out, \text{ to drive}} \\
 Q_{in,silo} &= \sum_{leaks} C_d [2g (p_{mix}-p_{air})/p_{air}]^{0.5} \int h^{0.5} (dh/dA)_{leak} dA \\
 Q_{out,silo} &= \sum_{leaks} C_d [2g (p_{mix}-p_{air})/p_{mix}]^{0.5} \int h^{0.5} (dh/dA)_{leak} dA \\
 Q_{in,sub} &= C_d A_{sub} [2g (P_{sub}-\{(p_{mix}-p_{air})gh\})/(p_{air}g)]^{0.5} \\
 Q_{agent,silo} &= (Q_{in,silo} + Q_{in,sub}) [C_{agent}/(100-C_{agent})] \\
 Q_{in,drive} + Q_{in, \text{ from silo}} + Q_{agent,drive} &= Q_{out,drive} + Q_{out, \text{ to silo}} \\
 Q_{in,drive} &= \sum_{leaks} C_d [2g (p_{mix}-p_{air})/p_{air}]^{0.5} \int h^{0.5} (dh/dA)_{leak} dA \\
 Q_{out,drive} &= \sum_{leaks} C_d [2g (p_{mix}-p_{air})/p_{mix}]^{0.5} \int h^{0.5} (dh/dA)_{leak} dA \\
 Q_{agent,drive} &= Q_{in,drive} [C_{agent}/(100-C_{agent})] \\
 Q_{in, \text{ from drive}} &= Q_{out \text{ to silo}} = C_d A_{leak} [2g (p_{mix}-p_{air})/p_{mix}]^{0.5} [h_{drive}-h_{silo}]^{0.5}
 \end{aligned}$$

$$Q_{\text{out, to drive}} = Q_{\text{in, from silo}} = C_d A_{\text{leak}} [2g (p_{\text{mix}} - p_{\text{air}}) / p_{\text{mix}}]^{0.5} [h_{\text{silo}} - h_{\text{drive}}]^{0.5}$$

Where Q is the volumetric flow rate with the subscript identifying direction, C_d is the discharge coefficient for the vent/leak, g is the acceleration due to gravity, p_{mix} is the density of the agent:air mixture, p_{air} is the density of air, h is the height above or below the neutral plane, A is the area of the vent/leak and C_{agent} is the concentration of the agent to be maintained in the silo and drive. The agent:air mixture properties were evaluated at -6 °C (20 °F) when utilizing FM-200 and 15 °C (60 °F) when utilizing Inergen to account for the reduced temperature resulting from the discharge of the agent.

If the tape drive is not protected, then the analysis is more complex due to the tape drive only being partially filled with agent:air mixture and the potential for air flow through the tape drive enclosure into the silo. The changes in the model to deal with this complexity are as follows:

$$\begin{aligned} Q_{\text{in, from drive}} &= Q_{\text{out, to silo}} = (2/3) C_d A_{\text{leak}} [2g (p_{\text{mix}} - p_{\text{air}}) / p_{\text{air}}]^{0.5} [H_{\text{leak, top}}^{1.5} - h_{\text{leak}}^{1.5}] \\ Q_{\text{out, to drive}} &= Q_{\text{in, from silo}} = C_d A_{\text{leak}} [2g (p_{\text{mix}} - p_{\text{air}}) / p_{\text{mix}}]^{0.5} [(2/3)(h_{\text{leak}}^{1.5} - H_{\text{int}}^{1.5}) \\ &\quad + (H_{\text{int}} - H_{\text{leak, bottom}})(h_{\text{silo}} - h_{\text{drive}})^{0.5}] \\ h_{\text{leak}} &= H_{\text{int}} - h_{\text{drive}} + h_{\text{silo}} \\ H_{\text{int}} &= (h_{\text{silo}} + h_{\text{drive}}) / 2 \\ Q_{\text{agent, silo}} &= (Q_{\text{in, silo}} + Q_{\text{in, sub}} + Q_{\text{in, drive}}) [C_{\text{agent}} / (100 - C_{\text{agent}})] \\ Q_{\text{agent, drive}} &= 0 \end{aligned}$$

Where $H_{\text{leak, top}}$ is the height of the top of the vent/leak between the silo and the tape drive enclosure, $H_{\text{leak, bottom}}$ is the height of the bottom of the vent/leak between the silo and the tape drive enclosure, h_{leak} is the neutral plane height in the vent/leak between the silo and the tape drive enclosure, and H_{int} is the height of the interface between the agent:air mixture and the air above it in the tape drive enclosure. Note that the protection afforded to the drive box enclosure without discharging agent into the drive enclosure would not be complete. No protection would be provided above the interface height in the drive box and low concentration/reduced protection zone may exist between the neutral plane height in the drive box and the interface height.

As the discharge of either agent into the silo is not at a constant rate over the course of the discharge, a padding factor must be applied to determine the actual agent supply requirements so that the determined minimum agent flow rate is maintained or exceeded throughout the discharge. For FM-200, the padding factor was determined by comparing the average flow rate over the course of the discharge to the minimum flow rate occurring just before liquid run-out at the nozzle and was found to be approximately 1.26. For Inergen, the padding factor was determined by trial and error adjustment of the restrictor plate and nozzles to maintain the required flow rate for the longest time period. The padding factor for Inergen was found to be approximately 2.7. It should be noted that the padding factors would be system dependant and were determined with systems constructed of 6 mm (0.25 in) schedule 80 pipe, 12.3 m^3 (435 ft^3) delivered cylinders assembled with a 12 mm (0.5 in) manifold and restrictor plate for Inergen, and a cylinder rated for 272 kg (600 lb) with 231 kg (510 lb) of agent for FM-200. The agent requirements for the silo and drive enclosure protection are given in Figures 2 and 3.

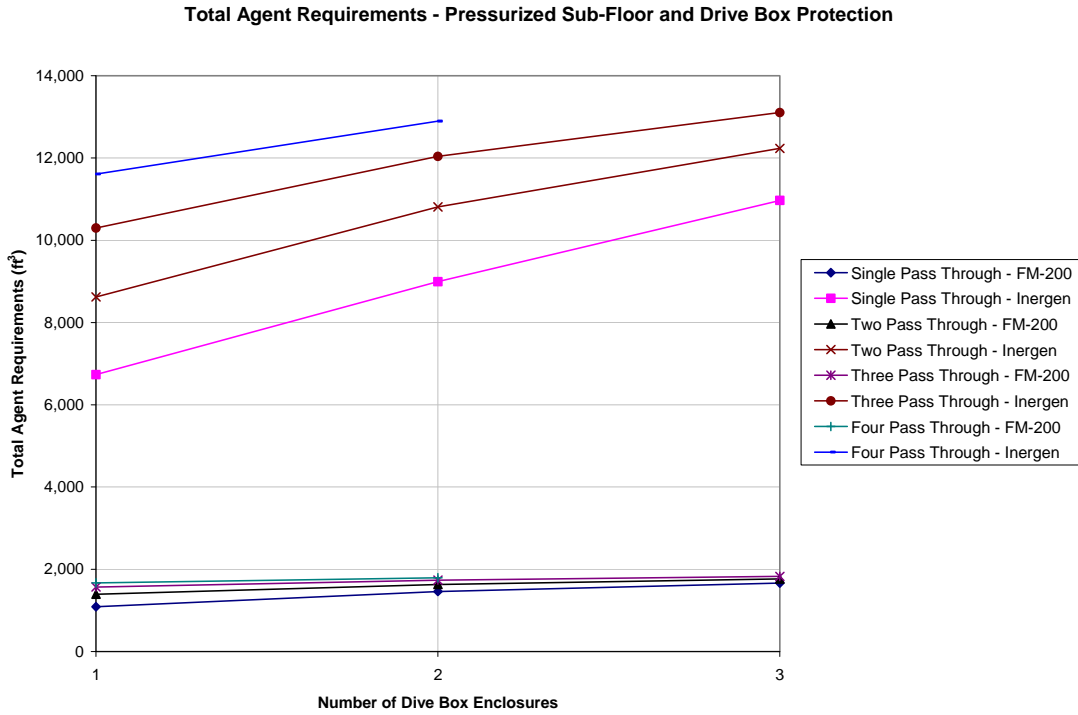


Figure 2 - Volumetric Agent Requirements for Silo and Drive Enclosure Protection

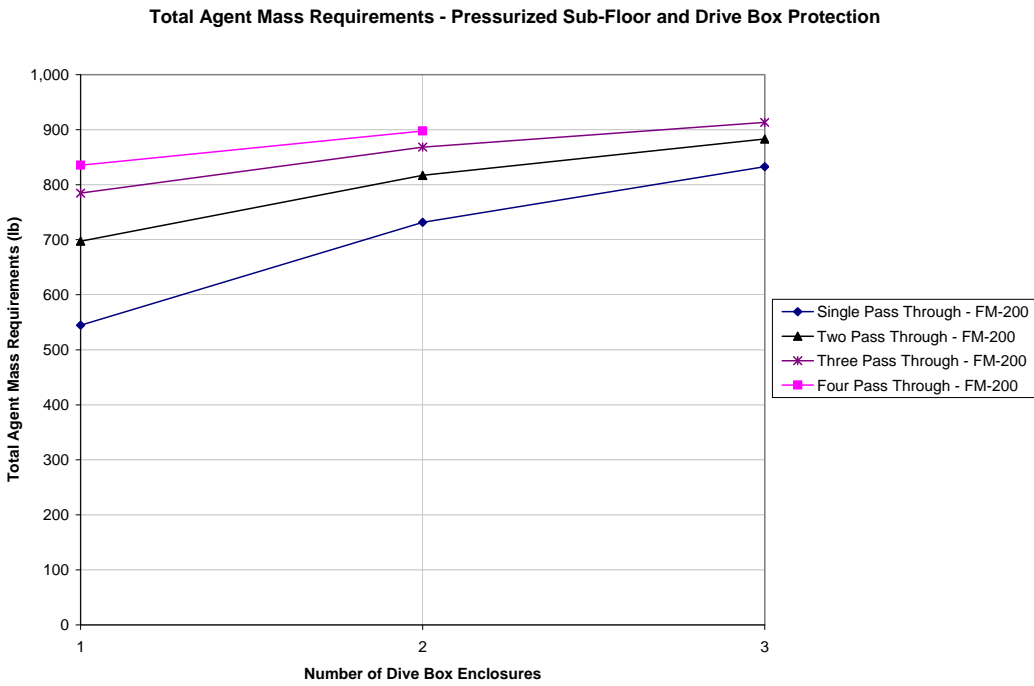


Figure 3 - Agent Mass Requirements for Silo and Drive Enclosure Protection

1.2 Quasi-Steady State Enclosure Analysis

A single enclosure single zone quasi-steady state model was also utilized during this project to aid in refining the agent requirements and to aid in the analysis of the test results. The model divides the duration of the flow into the enclosure into small time steps. The vent equations and flow balances described previously for the steady state model were solved for each time step. The flow of agent into the enclosure for each time step was based on the predicted nozzle flows utilizing HAI's agent flow software. An energy balance is performed to determine the temperature and density of the mixture inside the enclosure as follows [3]:

$$\Sigma m_{in}H_{in}-\Sigma m_{out}H_{out}=M\Delta U+Q_{walls}$$

where m_{in} is mass flow rate into the enclosure (air through vents or agent through the nozzles), H_{in} is the enthalpy of the fluid flowing into the enclosure (air or agent), m_{out} is mass flow rate of the agent:air mixture out of the enclosure, H_{out} is the enthalpy of the agent:air mixture flowing out of the enclosure, M is the mass of the agent:air mixture in the enclosure, ΔU is the change in the internal energy of the mixture in the enclosure and Q_{walls} is the heat transferred from the enclosure walls to the agent:air mixture.

The thermodynamic properties of the agent:air mixture, and the ambient air were determined with the Peng Robinson Equation of State as follows [4]:

$$\begin{aligned} Z^3-(1-B)Z^2+(A-2B-3B^2)Z-AB+B^2+B^3 &= 0 \\ Z &= PV/(nRT) \\ A &= \Sigma_i \Sigma_j Y_i Y_j (A_i A_j)^{0.5} \\ A_i &= 0.45724 a z_i (P/P_{c_i}) / (T/T_{c_i})^2 \\ a z_i &= [1 + z m_i (1 - (T/T_{c_i})^{0.5})]^2 \\ z m_i &= 0.37464 + 1.54226 w_i - 0.26992 w_i^2 \\ B &= \Sigma_i Y_i B_i \\ B_i &= 0.0778 (P/P_{c_i}) / (T/T_{c_i}) \\ H &= H^0 + RT \{ Z - 1 - (1/(8^{0.5} B)) \text{Log}_e [(Z+B(1+2^{0.5})) / (Z+(1-2^{0.5})B)] \\ &\quad \Sigma_i \Sigma_j Y_i Y_j (A_i A_j)^{0.5} [1 + z m_i (T/T_{c_i})^{0.5} / (2 a z_i^{0.5}) + z m_j (T/T_{c_j})^{0.5} / (2 a z_j^{0.5})] \} \end{aligned}$$

where Z is the compressibility factor for the phase or mixture it is solved for, R is the ideal gas constant, P_{c_i} is the critical pressure of species i in the mixture, T_{c_i} is the critical temperature of species i in the mixture, w_i is the Pitzer Accentric factor of species i in the mixture, H is the enthalpy of the phase or mixture and H^0 is the enthalpy of a corresponding ideal gas at temperature T . H^0 is determined from the ideal gas heat capacity correlation as follows:

$$H^0 = \Sigma_i Y_i \{ A_{cp,i} (T - T_{ref}) + B_{cp,i} (T^2 - T_{ref}^2) / 2 + C_{cp,i} (T^3 - T_{ref}^3) / 3 + D_{cp,i} (T^4 - T_{ref}^4) / 4 \}$$

where T_{ref} is a reference temperature defining the state from which the enthalpy is measured (-40 C, ideal gas for the developed model).

The thermodynamic properties of the agent are evaluated utilizing the same equations as that utilized by HAI's agent flow software.

As this model is a single enclosure model, only the agent concentrations in the silo are predicted. The tape drive enclosure is treated as a complex leak with the controlling area being the smallest flow area along the path from the silo through the tape drive to the outside.

2.0 APPARATUS

2.1 Simulated Tape Storage Silo

A simulated tape storage silo was constructed to mimic the leakage characteristics of the StorageTek Library Tape Storage Modules. The simulated silo was constructed of plywood over a 5 x 10 cm (2 x 4 in) stud frame. The simulated silo was 2.84 x 2.84 x 2.23 m (9.33 x 9.33 x 7.33 ft) giving the rectangular simulated silo the same cross-sectional area and height as the StorageTek silos. A simulated tape drive box was attached to the side of the silo to simulate a drive box with twenty tape drives. Two vertical slots cut into the side of the silo connecting to the drive box simulated the twenty smaller openings allowing for insertion of the pulled tapes into the drive by the robotic arm of the storage silo. A single 30 x 30 cm (12 x 12 in) opening simulated the pass-through opening to a connected silo. The simulated silo was set above a sub-floor section pressurized to 39.8 Pa (0.16 iwc). A perforated tile, 3.8 cm (1.5 in) underneath the 15 cm (6 in) diameter opening in the floor of the silo, matches the typical cooling air supply configuration. Figures 4 through 6 present views of the simulated tape storage silo.

A second pass-through opening was added to the simulated for two of the tests performed to assess the impact of the variation in silo configuration.

The simulated silo, with one pass-through opening and one tape drive enclosure, represents a simplified configuration as the silos can have as many as four pass-through openings and as many as four tape drive enclosures. This configuration was selected to enable verification of the design methods and validate the protection strategy, while providing enough information to adapt the developed design to be modified for the varied configurations.

The leakage area of the constructed simulated silo as configured with one pass-through opening and one drive box was measured with a door fan and found to have 0.466 m² (5.02 ft²) of leakage. In comparison to the intended leaks, this leaves 0.012 m² (0.13 ft²) of leakage unaccounted for and is the leakage area of the plywood joints in the simulated silo. In the subsequent analysis, this area is modeled as a vertical gap the height of the silo with the same area.

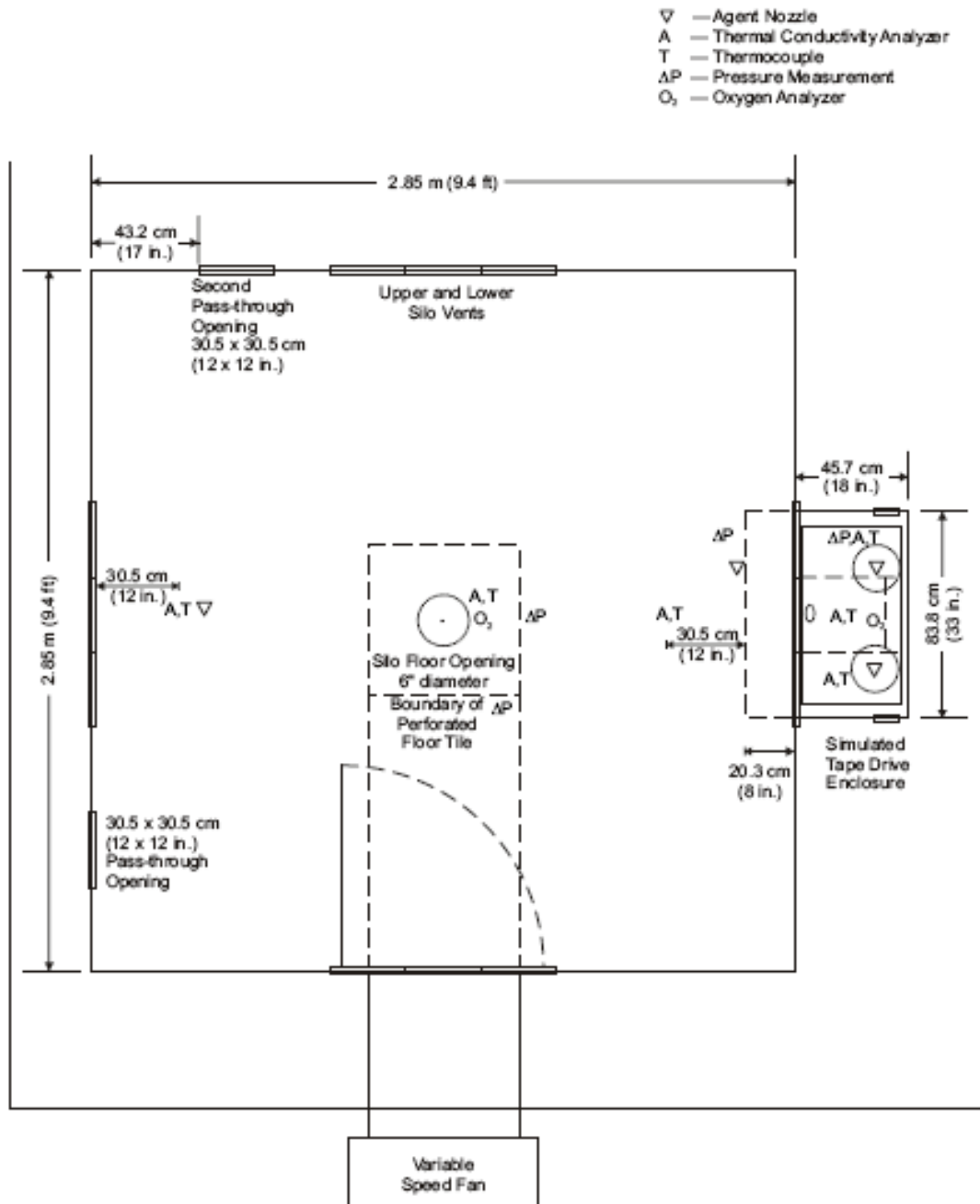


Figure 4 - Plan View of the Simulated Tape Storage Silo

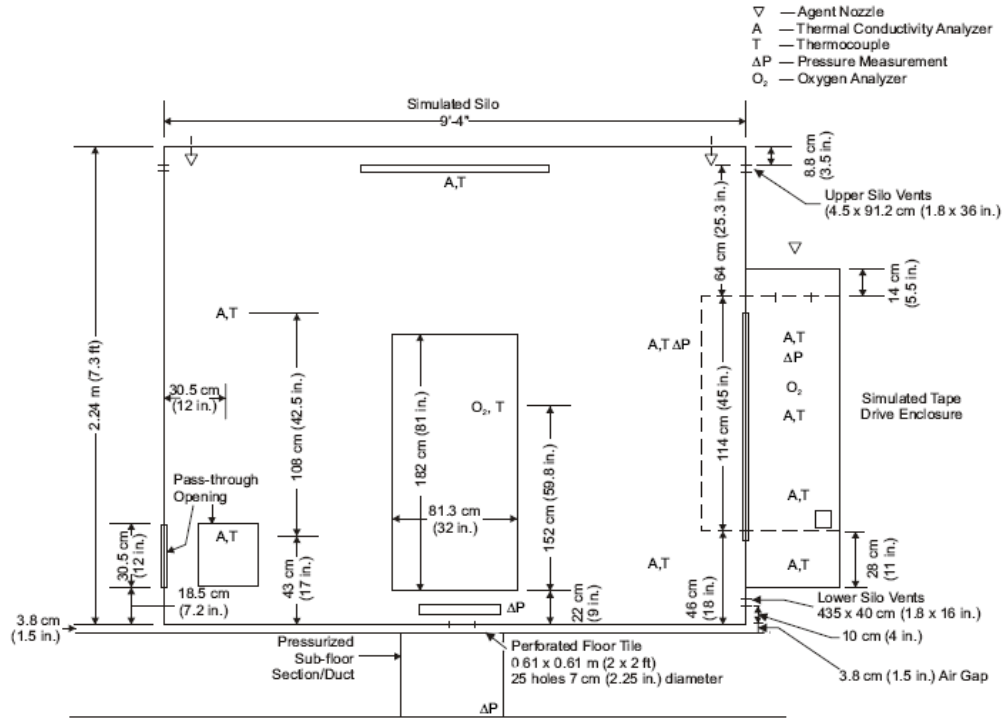


Figure 5 - Elevation View of Simulated Storage Silo

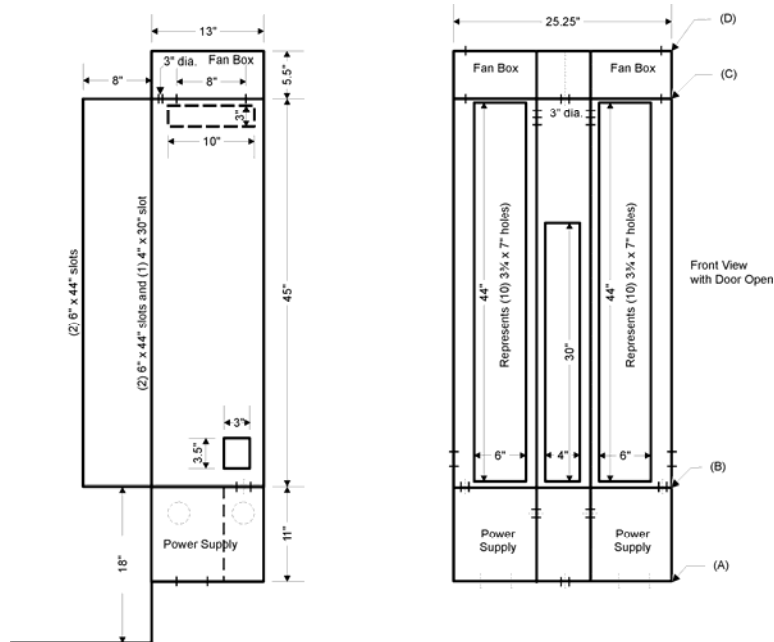


Figure 6 - Simulated Tape Drive Enclosure

2.2 Clean Agent Discharge Systems

Only the extended discharge systems were included in these tests. The initial discharge system, intended to quickly achieve the design concentration, can be designed utilizing standard methods and design tools. The effect of not including the initial discharge system in these tests is a longer build-up to the design concentration with no effect on the ability to maintain the concentration in the silo after the design concentration has been achieved.

The extended discharge systems were design to maintain the design concentration for a period of 15 minutes. Reduced duration tests, designed to maintain the design concentration for 3 to 5 minutes, were utilized to verify required flow-rates and to investigate the effects of a second pass through opening without involving the full 15 minute agent mass.

Two clean agents were utilized during these tests. The first of which was FM-200, HFC-227ea which is manufactured by Great Lakes Chemical Corporation (division of Chemtura). The extended discharge systems were designed to maintain an agent concentration of 8% in the silo and tape drive enclosure. The silo system utilized either a Kidde-Fenwal Cylinder rated for 272 kg (600 lb) of FM-200 for the full duration test, or a Kidde-Fenwal Cylinder rated for 90.7 kg (200 lb) of FM-200 for the reduced duration tests. The agent was discharged into the silo through two 180° 1.2 cm (0.5 in) nozzles. The pipe network for this system was constructed from 6 mm (0.25 in) schedule 80 steel pipe. The system parameters for the test systems employing FM-200 are given in Table 1.

The second agent utilized was Inergen, which is a blend nitrogen, argon and carbon dioxide, and manufactured by Ansul, Inc. The extended discharge system was designed to maintain an agent concentration of 42.8% in the tape storage silo and tape drive enclosure. The reduced duration tape storage silo extended discharge system utilized 4 Ansul 12.3 m³ (435 ft³) Inergen cylinders discharging into the silo through two horizontal single orifice nozzles and the full duration system utilized 17 Ansul 12.3 m³ (435 ft³) Inergen cylinders. An Inergen tape drive enclosure system was not tested. The cylinders were connected through a manifold constructed of 1.2 cm (0.5 in) schedule 80 steel pipe. The pipe system down stream of the pressure reducing orifice was that same as that utilized during the FM-200 tests. The system parameters for the test systems employing Inergen are given in Table 2.

Table 1 - FM-200 Silo System Parameters

Test Name	Cyl. Size [lb]	Agent Mass [lb]	Agent Volume [ft ³]	Number of Nozzles	Orifice Size [in]	Dis. Time [sec]	Nozzle Pressure [psig]			
							Max		Average	
							East	West	East	West
PSSA4	200	200	441.5	2	0.219	277	125	122	77	74
PSSA11 (Two Pass-through)	200	200	441.5	2	0.18	288	165	167	97	101
PSSA12 (Full Duration)	600	490	1082	2	0.125	689.1	277	277	121	123

Table 2 - Inergen Silo System Parameters

Test Name	Number of Cyl.	Cyl. Size [ft ³]	Agent Volume [ft ³]	Restrictor Plate [in]	Number of Nozzles	Orifice Size [in]	Dis. Time [Sec]	Nozzle Pressure [psig]			
								Max		Average	
		East	West	East		West					
PSSA8	4	435	1740	0.2134	2	0.18	508			270	271
PSSA10 (Two Pass-through)	4	435	1740	0.2134	2	0.18	452	1050	1048	277	284
PSSA13 (Full Duration)	17	435	7395	0.213	2	0.18	1744	1025	1026	285	291

2.3 Instrumentation

Four thermal conductivity meters, providing eleven measurement locations, were utilized to measure the agent concentration within the simulated tape storage silo and the drive box. Five of the sampling locations were inside the silo: two were located near the slots connecting to the drive box, one in the center of the silo near the ceiling, and the other two near the opposite wall of the silo from the drive box. The five sampling locations in the tape drive were located with four in the two sections where the tape drives would be located, one in the center plenum section of the enclosure and one in a lower power supply section. One of the sampling locations in the tape drive enclosure was relocated to the top portion of the tape drive enclosure normally occupied by two exhaust fans.

Continuous gas samples were withdrawn from the center of the silo and from the center of the drive box and analyzed for oxygen and carbon dioxide concentrations.

Five differential pressure transducers with a measurement range of ± 1245 Pa (± 5 iwc) were utilized to measure the pressures inside the pressurized sub-floor, inside the silo adjacent to the opening to the sub-floor, inside the silo adjacent to the drive box connection 1.1 m (3.7 ft) above the silo floor, inside the drive box at the same elevation, and within the gap between the floor of the simulated silo and the raised sub-floor. These pressure transducers were referenced to the ambient atmosphere inside the laboratory at the same elevation as the measurement point in the drive box.

Air temperature measurements were made at the same locations as the agent concentration and oxygen concentration measurements for a total of thirteen locations.

The temperature and pressure of the discharging agent was monitored upstream of the nozzles, upstream of the tees (Extended Discharge Systems), upstream of the pressure reducing orifice (Inergen systems), and in the agent cylinder (FM-200 systems).

2.4 Procedure

The agent analyzers were warmed-up and calibrated. The agent analyzers were connected to the sampling tubes pulling from the desired locations in the tape storage silo mock-up. The access door to the silo mock-up was secured. The exhaust system, exterior to the mock-up, was activated to prevent any buildup of agent outside of the mock-up and the variable speed fan was set to achieve the 39.8 Pa (0.16 iwc) pressurization level.

The data acquisition system was started. The sub-floor was pressurized 10 seconds after the data acquisition system was started. The agent cylinders were actuated 30 after the data acquisition system was started.

The data acquisition system was secured after the discharge of agent into the mock-up had ended and the agent concentration meters were reading less than 1% FM-200 or 10 % Inergen.

3.0 RESULTS AND DISCUSSION

3.1 FM-200 (HFC-227ea) Testing Results

The results from testing with FM-200 (HFC-227ea) are summarized in Table 3. Figures 7 through 10 present the agent system pressures and the agent concentrations measured during test PSSA4 in both the simulated tape drive enclosure and the simulated tape storage silo along with the predictions for these pressure and concentrations. HAI's flow software was modified to account for changes in the non-equilibrium behavior of the flowing agent:nitrogen mixture caused by the longer duration flow. As can be seen from these figures, the predictions and measured values are in good agreement with each other. The neutral plane in the tape drive enclosure predicted for the configuration of test PSSA4 was just below the level of the fan box near the top of the enclosure. This correlates to the sensitivity of the measured agent concentration at that location to minor disturbances in the air flows outside of the mock-up and the jumpy trace shown in Figure 10.

When the second pass-through opening was added for test PSSA11, the developed concentration high in the simulated tape drive enclosure was noticeably reduced. This is consistent with the steady state analysis that showed drops in the neutral plane height in the tape drive enclosure when either additional pass-through openings or additional tape drive enclosures were added to the tape storage silo. The agent concentrations in the simulated tape storage silo and tape drive enclosure are presented in Figures 11 and 12.

During the full duration test, PSSA12, the agent discharge rate was higher than initially anticipated which resulted in higher than desired agent concentrations. The agent concentrations in both the simulated tape storage silo and the simulated tape drive enclosure are presented in Figures 13 and 14. Note: five of the concentration traces shown in these two figures evidenced concentrations higher than the meters utilized could read (11%).

Table 3 - Results from Testing with FM-200 (HFC-227ea)

Test	Agent System Flow								Concentration in Silo			
	Discharge Time		Average Nozzle Press		Flow Rate Req. - S. S. Model	Flow-Rate (Pred.)		Pred. Time Above Req. Flow	Maximum Concentration		Duration Above Design	
	Act.	Pred.	Act.	Pred.		Max.	Average		Act.	Pred.	Act.	Pred.
	[sec]	[sec]	[psig]	[psig]	[lb/s]	[lb/s]	[lb/s]	[sec]	[%]	[%]	[sec]	[sec]
PSSA4	277	287	75	69	0.432	0.974	0.693	287	10.3	10.1	264	251
PSSA11 (Second Pass Through)	288	306	99	93	0.554	0.950	0.646	221	8.7	8.8	123	139
PSSA12 (Full Duration)	689	759	122	125	0.432	0.800	0.628	759	11.1	10.1	528	714

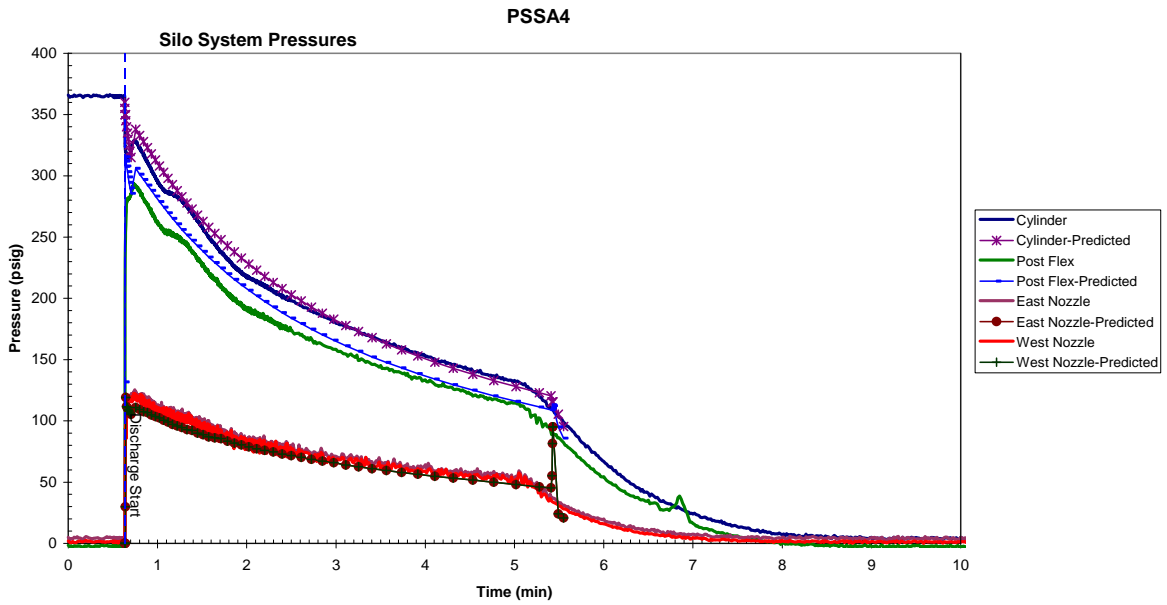


Figure 7 - Agent System Pressures during Silo System Test with Single Orifice Horizontal Discharge Nozzles - PSSA4

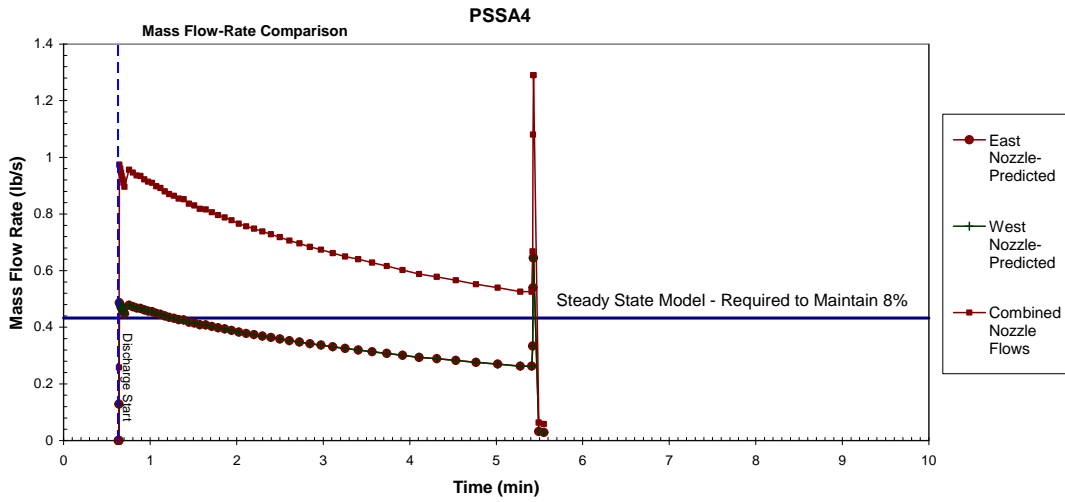


Figure 8 - Predicted System Flow Compared to Required Flow to Maintain 8 % by Volume Concentration - PSSA4

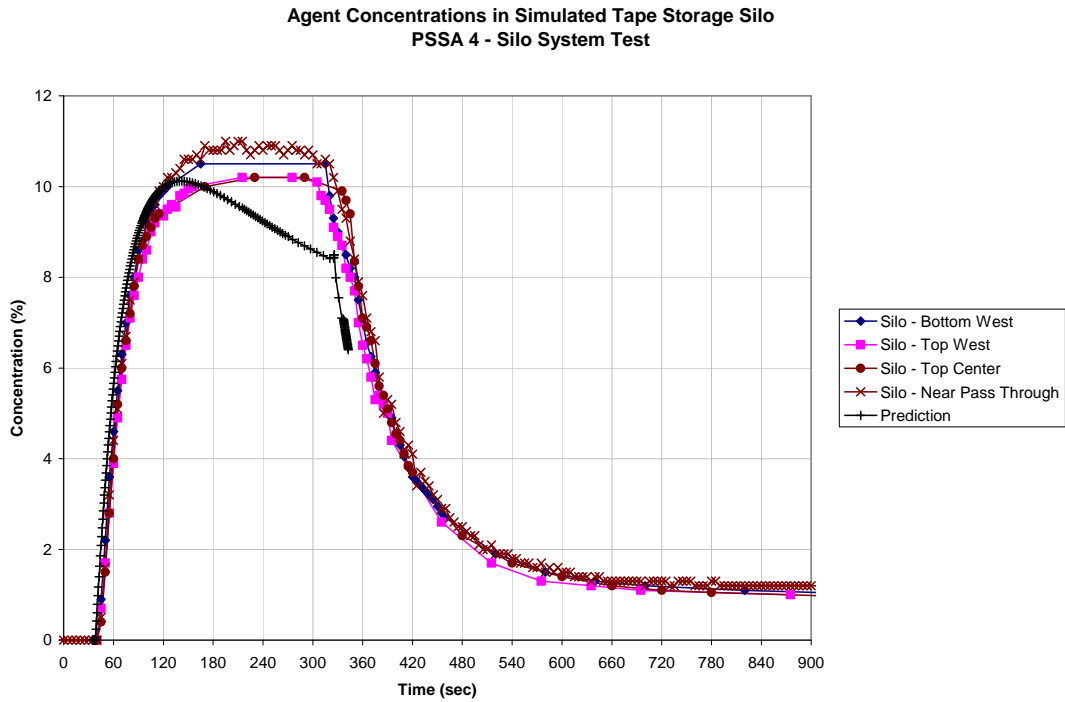


Figure 9 - Agent Concentration in Simulated Tape Storage Silo during Silo System Test with Single Orifice Horizontal Discharge Nozzles - PSSA4

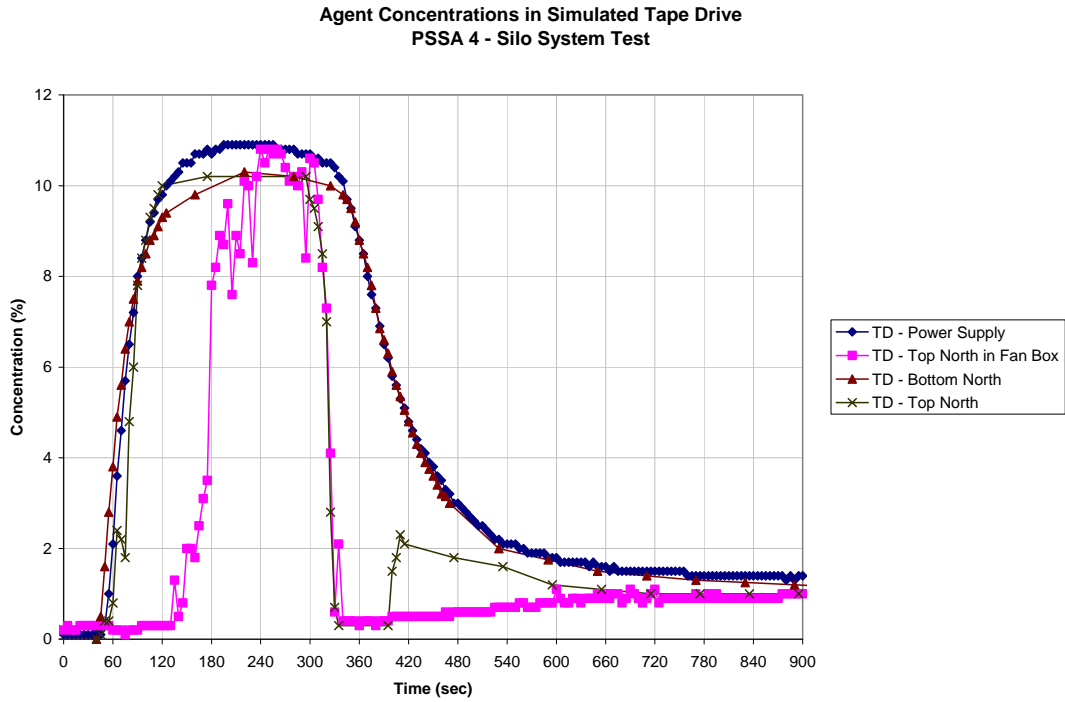


Figure 10 - Agent Concentration in Simulated Tape Drive Enclosure during Silo System Test with Single Orifice Horizontal Discharge Nozzles - PSSA4

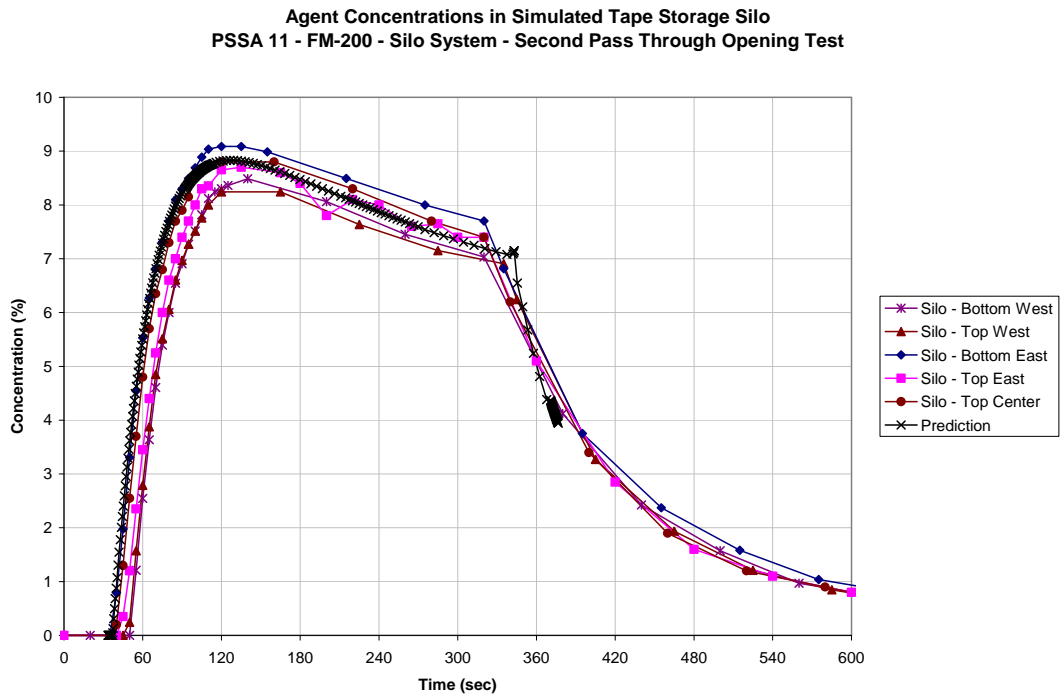


Figure 11 - Agent Concentration in Simulated Tape Storage Silo during Silo System Test with Second Pass-Through Opening - PSSA11

Agent Concentrations in Simulated Tape Drive
 PSSA 11 - FM-200 - Silo System - Second Pass Through Opening Test

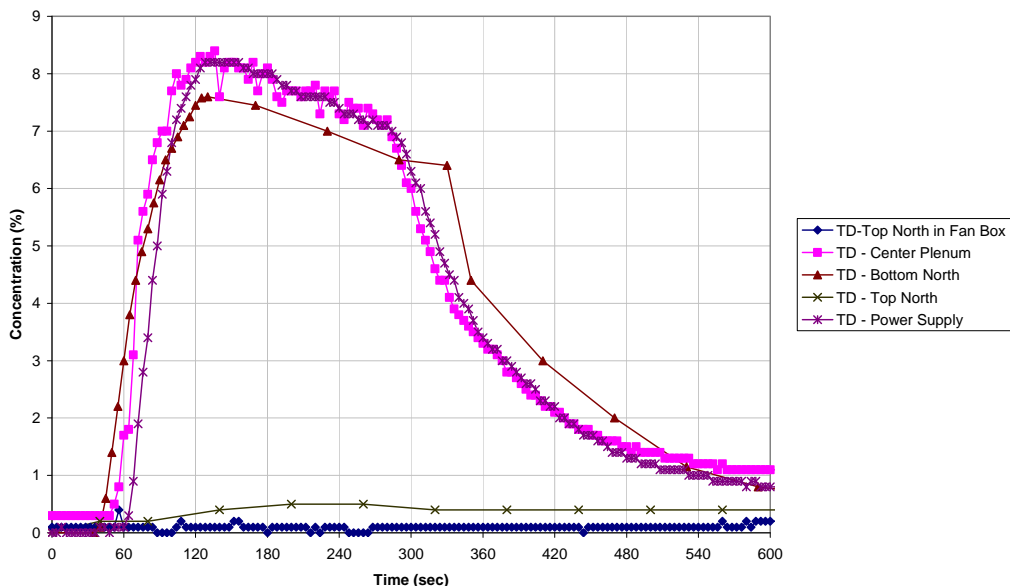


Figure 12 - Agent Concentration in Simulated Tape Drive Enclosure during Silo System Test with Second Pass-Through Opening - PSSA11

Agent Concentrations in Simulated Tape Storage Silo
 PSSA 12 - FM-200 - Silo System - Full Duration Extended Discharge Test

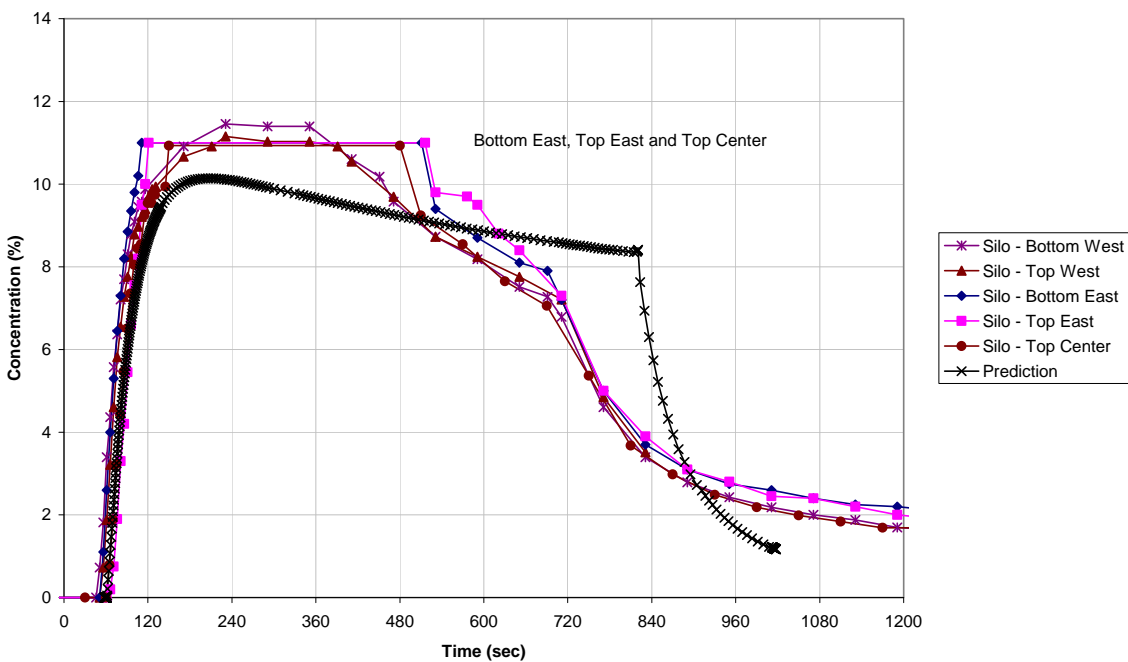


Figure 13 - Agent Concentration in Simulated Tape Storage Silo during Full Duration Silo System Test - PSSA12

Agent Concentrations in Simulated Tape Drive
PSSA 12 - FM-200 - Silo System - Full Duration Extended Discharge Test

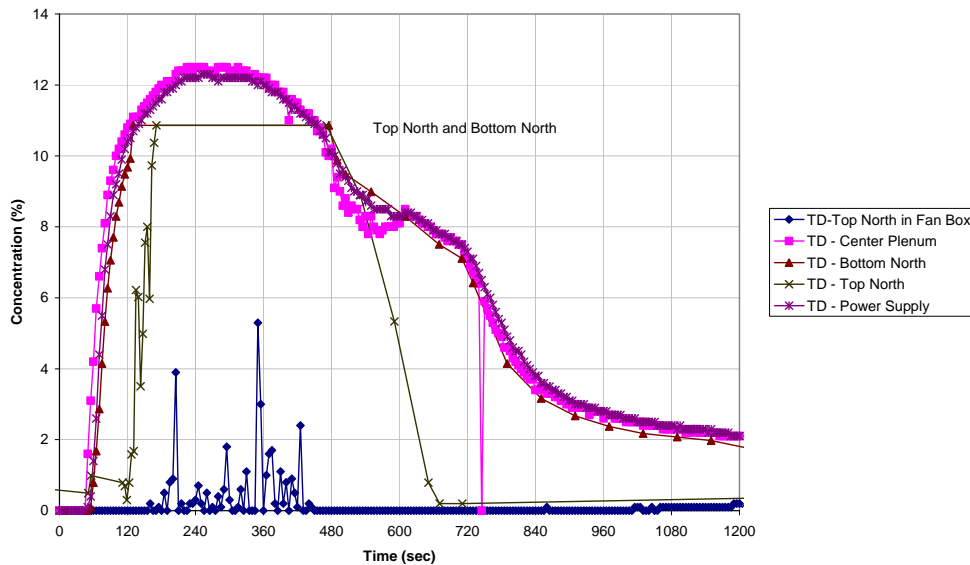


Figure 14 - Agent Concentration in Simulated Tape Drive Enclosure during Full Duration Silo System Test - PSSA12

3.2 Inergen Testing Results

The results from the testing with Inergen (IG-541) are summarized in Table 4. The Inergen system pressures and Inergen concentrations in the simulated tape storage silo and simulated tape drive enclosure are given in Figures 15 through 18 for the second of these tests PSSA8. HAI's flow software for Inergen was modified to account for the increased heat transfer associated with the longer duration flow in preparing these predictions and as the input to the quasi-steady state enclosure model. The jumpy agent concentration traces for high in the tape drive enclosure given in Figure 18 is evidence of the proximity to the neutral plane in the tape drive, which was predicted by the steady state model to be near the top of the tape drive enclosure (a little higher than was predicted for the corresponding test with FM-200).

The addition of the second pass-through opening did not have as dramatic an effect on the concentration in the tape drive enclosure during the Inergen test (PSSA10), as it did during the FM-200 test (PSSA11). The concentration in the tape drive was reduced, however. The difference between the measured and predicted duration that the agent concentration is maintained above the design concentration is exaggerated by the maximum concentration achieved being not much greater than the design concentration. The agent concentrations in both the simulated tape storage silo and the simulated tape drive enclosures are given in Figures 19 and 20.

The agent concentrations for the full duration tests are given in Figures 21 and 22. The agent concentration in the simulated tape drive enclosure was less than would have been expected based on the previous testing and may have resulted from slight differences in nozzle positioning due to the nozzle changes between this test and the previous tests.

Table 4 - Result Summary from Testing with Inergen (IG-541)

Test	Agent System Flow								Concentration in Silo			
	Discharge Time		Average Nozzle Press		Flow Rate Req. - Steady State Model	Flow-Rate (Pred.)		Pred Time Above Req Flow	Maximum Concentration		Duration Above Design	
	Act	Pred.	Act	Pred.		Max.	Average		Act	Pred.	Act	Pred
	[sec]	[sec]	[psig]	[psig]	[CFM]	[CFM]	[CFM]	[sec]	[%]	[%]	[sec]	[sec]
PSSA8	508	417.92	270	228	172	573.6	176.4	231.42	52.2	51.2	176	175
PSSA10 (Second Pass Through)	452	443	281	287	208	722	224.6	197.4	42.6	46.8	55	109.5
PSSA13 (Full Duration)	1744	2349	288	227	172	578	175.6	979.8	51.1	65.3	434	741.5

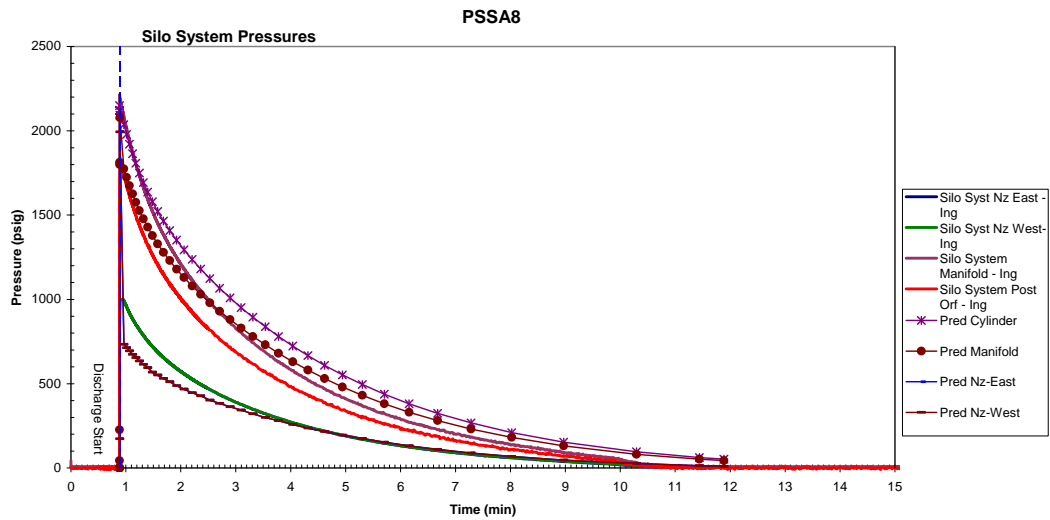


Figure 15 - Inergen System Pressures during Silo System Test with Increased Nozzle and Restrictor Plate Orifices and 60° Angle of Discharge from Near Wall - PSSA8

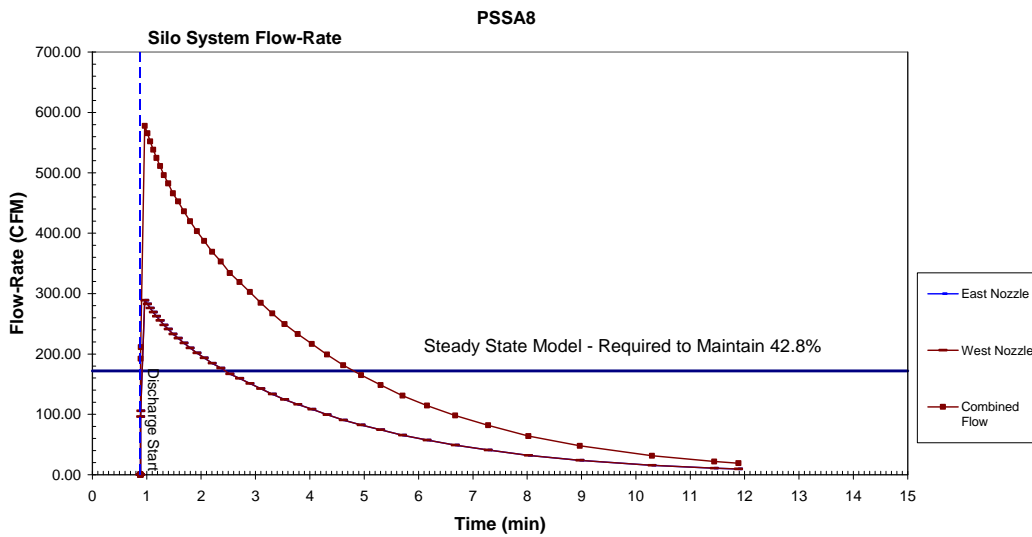


Figure 16 - Inergen System Flow-Rate Comparison - PSSA8

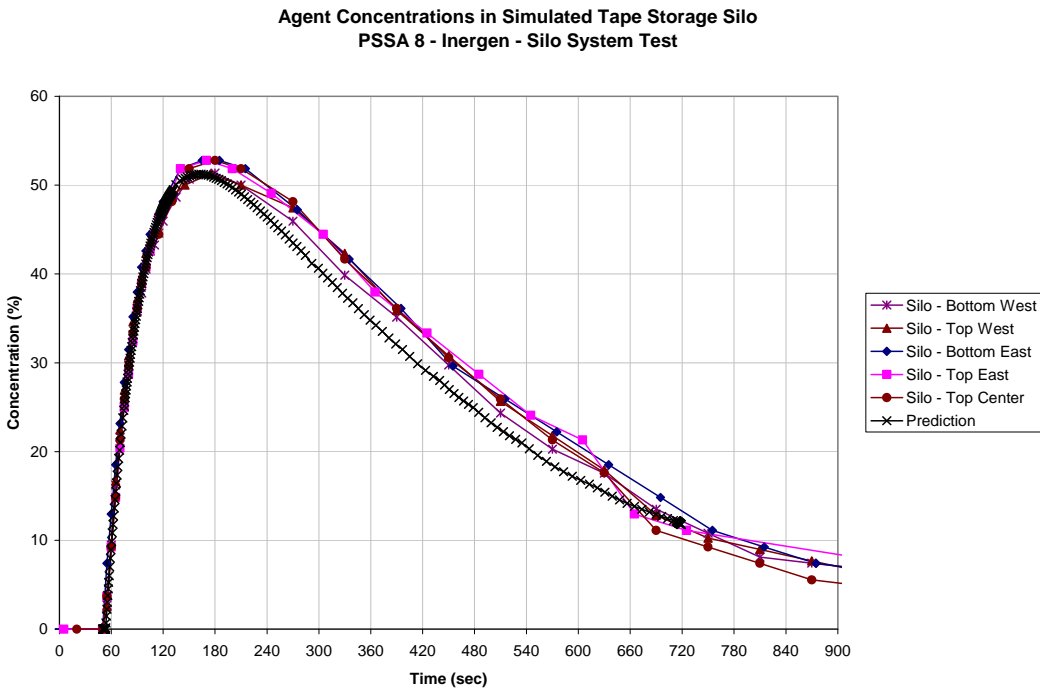


Figure 17 - Inergen Concentration in Simulated Tape Storage Silo during Silo System Test with Increased Nozzle and Restrictor Plate Orifices and 60° Angle of Discharge from Near Wall - PSSA8

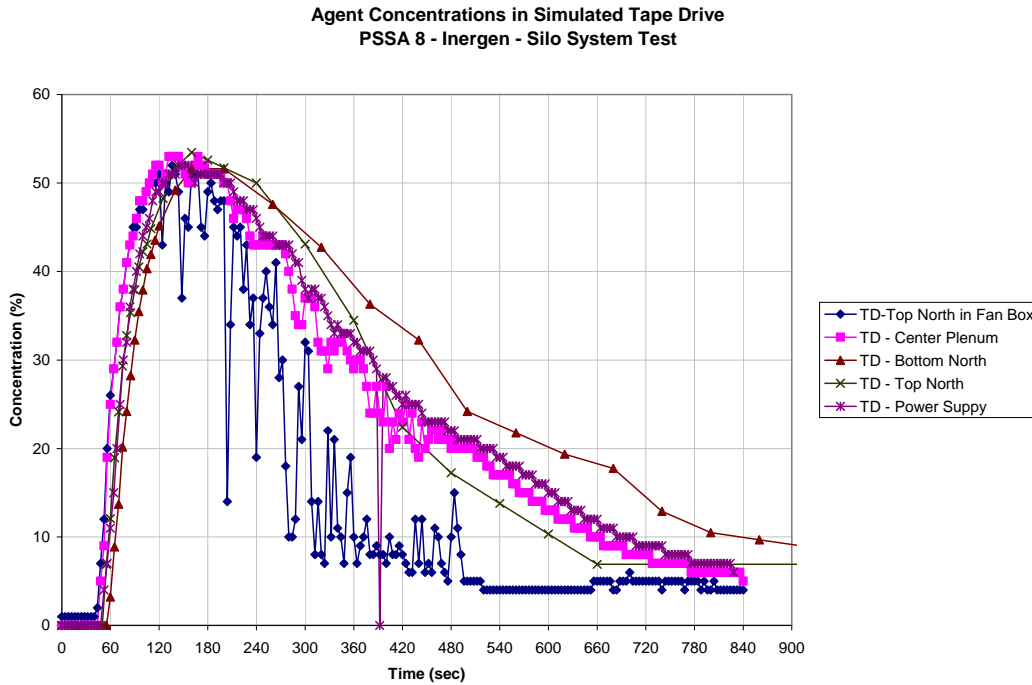


Figure 18 - Inergen Concentration in Simulated Tape Drive Enclosure during Silo System Test with Increased Nozzle and Restrictor Plate Orifices and 60° Angle of Discharge from Near Wall - PSSA8

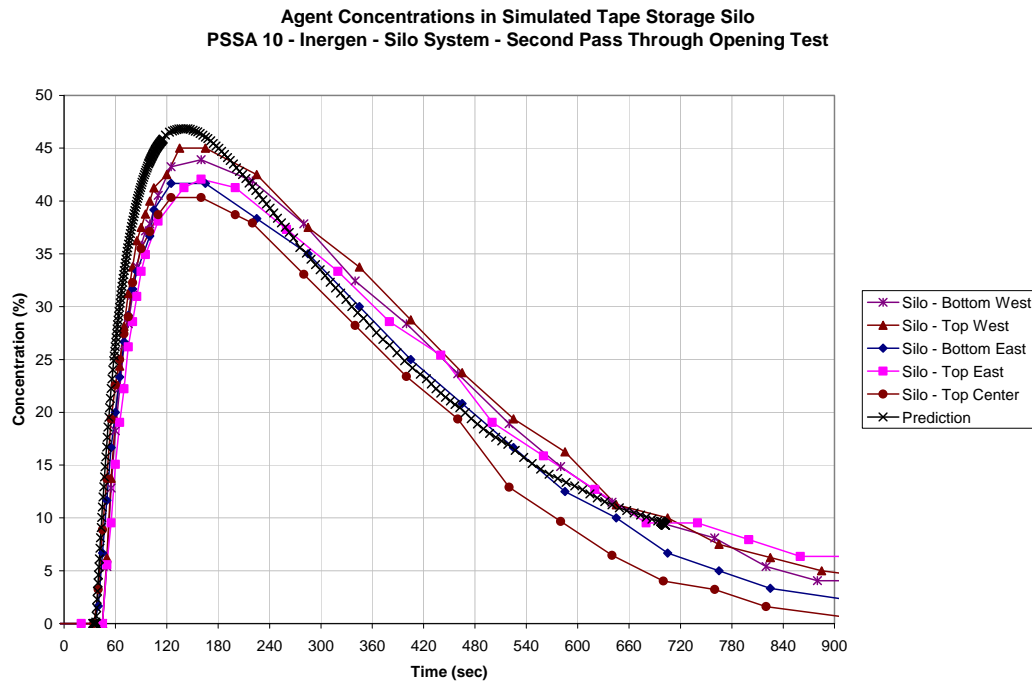


Figure 19 - Inergen Concentration in Simulated Tape Storage Silo during Silo System Test with Added Second Pass-Through Opening - PSSA10

**Agent Concentrations in Simulated Tape Drive
PSSA 10 - Inergen - Silo System - Second Pass Through Opening Test**

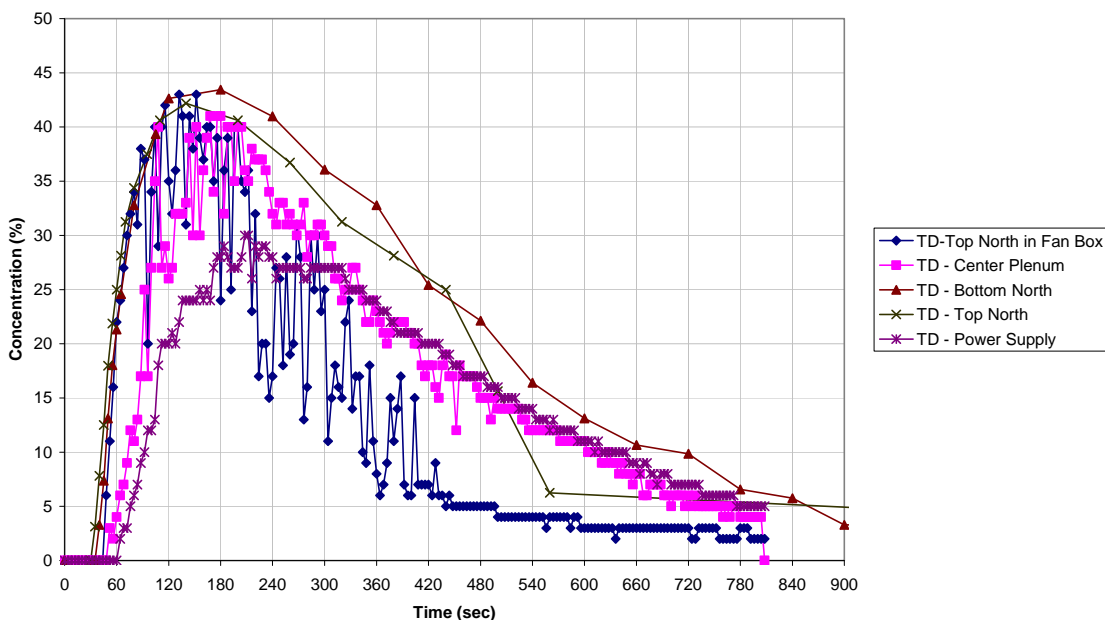


Figure 20 - Inergen Concentration in Simulated Tape Drive Enclosure during Silo System Test with Added Second Pass-Through Opening - PSSA10

**Agent Concentrations in Simulated Tape Storage Silo
PSSA 13 - Inergen - Silo System - Full Duration Extended Discharge Test**

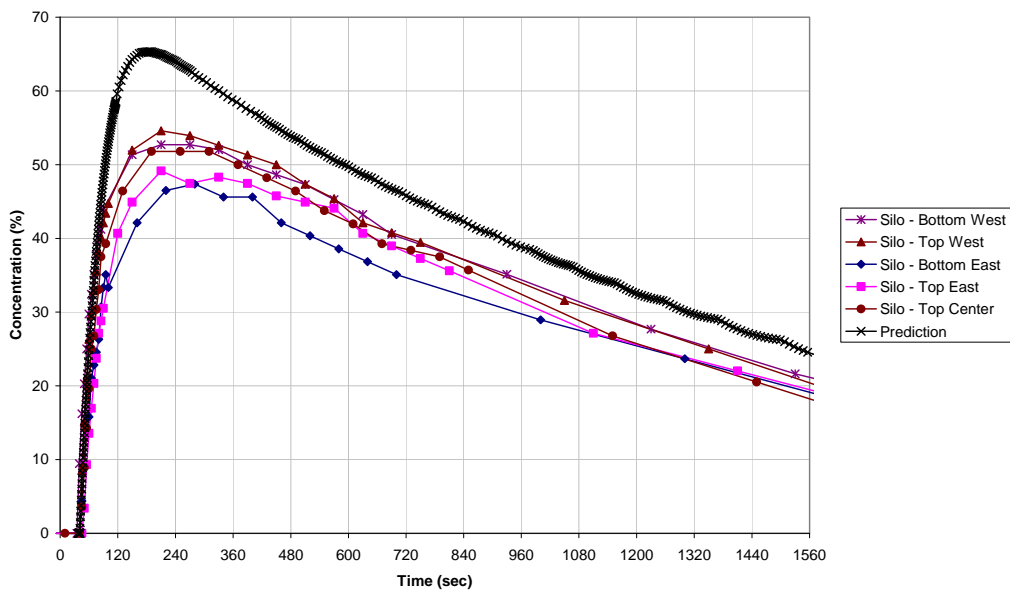


Figure 21 - Inergen Concentration in Simulated Tape Storage Silo during Full Duration Silo System Test - PSSA13

**Agent Concentrations in Simulated Tape Drive
PSSA 13 - Inergen - Silo System - Full Duration Extended Discharge Test**

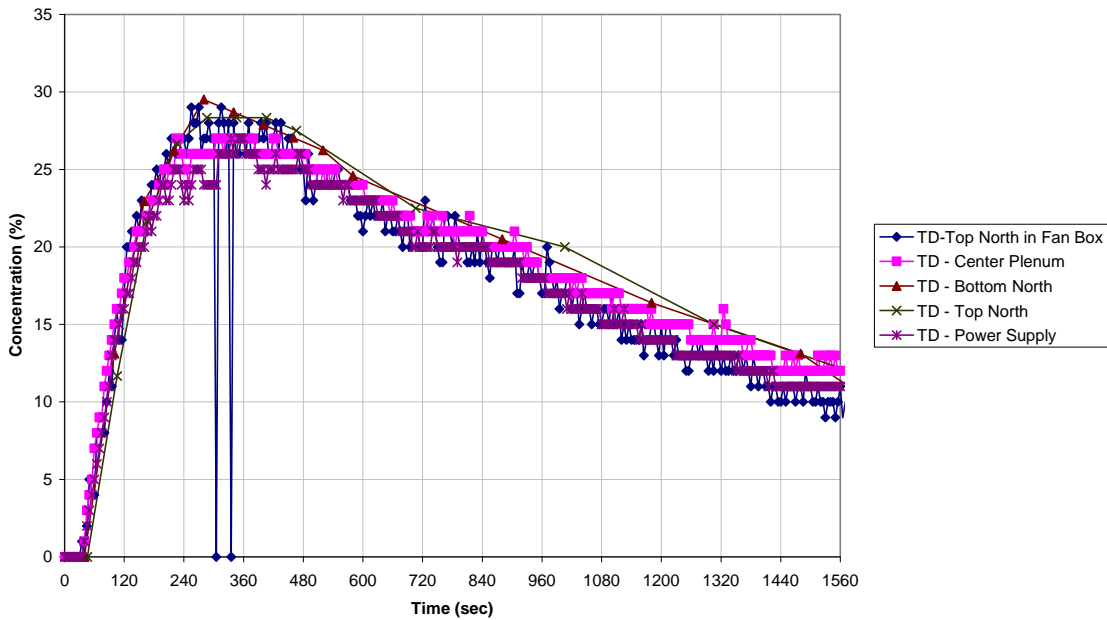


Figure 22 - Inergen Concentration in Simulated Tape Drive Enclosure during Full Duration Silo System Test - PSSA13

4.0 CONCLUSIONS

The developed enclosure model was applied to a tape storage silo, StorageTek Model 9310, to determine the agent requirements for an extended discharge system needed to provide protection for this leaky enclosure. A plywood mock-up of the silo was constructed incorporating the cooling vent openings, pass-through openings to adjacent storage silos, and openings between the silo and the connected tape drive enclosures. This constructed mock-up was utilized to verify the agent requirement predicted by the developed model.

The developed enclosure model was demonstrated to have successfully determined the agent requirements for the mocked-up tape storage silo to provide 11.5 minutes of protection, with good agreement between the predicted and measured agent concentrations. The model was able to produce reasonable results for both a halocarbon agent (FM200) and an inert gas (Inergen). The modifications to the HAI flow calculation model allowed for accurate predictions of the extended discharge system.

This process for determining the extended discharge requirements and design of the system can be extended to other enclosures that may require an extended discharge. NFPA 2001, Standard for Clean Agent Extinguishing Systems (2008 Edition), now essentially requires a 10 minute hold time for 85% of the design concentration at the highest level of combustibles in the enclosure. In order to meet the more demanding 10 minute requirement, more enclosures will

likely require extended discharge systems. This work demonstrates a process for developing the design of these extended discharge systems.

This project was accomplished with the help and support of Chemtura Corporation (formerly Great Lakes Chemical Corporation), Ansul Inc., a division of Tyco International Ltd., and Kidde-Fenwal, Inc. The project work was sponsored by the General Services Administration (GSA) of the US Government for the Social Security Administration, Head Quarters.

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