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Research Article
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Cargo Compartment Fire Extinguishing System

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Abstract

In all large passenger transport airplanes, halon fire bottles are used to extinguish fire in the cargo compartments. Halon as a fire-extinguishing agent, contributes to the destruction of stratospheric ozone in the atmosphere and it is banned in many countries. FAA considers halon 1301 as an effective firefighting agent due to its low toxicity and noncorrosive properties but because it damages the ozone layer, it has been phased out of production. However, it is still widely used on commercial aircraft until a suitable replacement is found. In this paper we will present an alternative approach to using halon 1301 as a fire fighting paradigm. In the proposed method, nitrogen is first extracted from the atmosphere by using the onboard air separator module it is then cooled, and pressurized into the cargo compartments to suppress any fire. Several methodologies can be used to increase the flow rate from the air separator module, to extinguish fire in cargo compartment.

Keywords: Fire; Cargo

Nomenclature

A/C = Aircraft

ADIRUS = Air Data Inertial Reference Unit

ASM = Air Separator Module

AVEC = Avionic Equipment Ventilation Computer

CMD = Command

ISO = Isolation

FCV = Flow Control Valve

FWC = Flight Warning Computer

FWD = Forward

LGCIU = Landing Gear Control Interface Unit

OBIGGS = Onboard Inert Gas Generation System

OVBD = Overboard

Pr. SNR = Pressure Sensor

P/B = Pushbutton

PSCU = Proximity Switch Control Unit

PRV = Pressure Relief Valve

SNR = Sensor

SOV = Shut-Off Valve

S/W = Switch

SDCU = Smoke Detector Control Unit

VLV = Valve

VC = Ventilation Controller

T SNR = Temperature Sensor

Introduction

In recent years, environmental concerns have moved towards removing halon as a fire extinguishing agent in transport airplanes. The European commission ruled that halon 1301 and 1211, must not be installed onboard new airplanes by 2018 and by 2040 halon must be removed and replaced in all operating aircraft. The International Civil Aviation Organization (ICAO) adapted a resolution that requires a halon replacement agent for lavatory extinguishers, and hand held halon extinguishers by 2011 and 2016, respectively. There is however an increasing concern for aircraft manufacturers, to find an effective halon replacement. Nitrogen is in fact suitable to suppress class A - petroleum products, cellulosic materials, and polymers – class B – flammable or combustible liquids – and class C - energized electrical equipment – fires [1]. A possible alternative to halon is nitrogen due its inertness and its suitability to suppress fires [2].

Pressurization with nitrogen has been proposed and tested as a technique for suppressing fires in gastight spaces. Laboratory fires of several representative class A and B fuels in a 270-litre confined combustion chamber have been extinguished by 0.5 atm pressure of nitrogen [3]. The approach proposed in this paper, it requires nitrogen to be extracted from the air supply by using the air separator module (ASM). High-pressure air fed into the separator; where some gas molecules such as oxygen and carbon dioxide travel more quickly through the hollow fibers; while nitrogen cannot pass through the fibers and is extracted from a different output port.

The Onboard Inert Gas Generation System (OBIGGS) generates nitrogen-enriched air, which is currently used to inert the air inside the center fuel tank to reduce any fire risk. As civil aviation authorities require all airplanes that carry more than thirty passengers, to have an OBIGGS installed nitrogen extracted from the OBIGGS could be used to extinguish fire in cargo compartment. The main challenge with this approach is the low flow rate and hence the long time it may take to inert the cargo compartment of a large transport airplane [1]. In the

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proposed approach, we will describe different methodologies that can be used to increase the flow rate from the ASM and hence overcome this limitation. Nitrogen from ASM could also be used as a backup if the nominal fire extinguishing system onboard the aircraft is not sufficient to extinguish the fire. Several experiments to determine the effectiveness of nitrogen to extinguishing fire in confined and ventilated spaces were performed. The purpose of experiments was to assess the suitability of nitrogen as a fire suppressant agent and to determine the necessary pressure, time and size of fire that can be extinguished.

Current Cargo Fire Extinguishing System

In Airbus A330 series, each cargo compartment has four smoke detectors when two smoke detectors sense smoke, the Smoke Detection Control Unit (SDCU) generate warnings (master warning light and continuous repetitive chimes) and in case of smoke detection in forward cargo compartment, the smoke legend on forward agent pushbutton illuminate. Pilot as soon as he selects FWD Agent pushbutton, the fire bottle 1 supplies halon to forward cargo. If the fire has not extinguished then pilot select AFT agent pushbutton and halon from fire bottle 2 discharge via a flow metering unit which restrict the agent flow, so that the agent is slowly discharged into cargo bay and it takes 240 minutes to completely discharge the agent. This causes a slow and continuous flow of halon into the cargo compartment to keep the fire out. When pressure in the bottle decreases, the bottle pressure switch causes advisory message to show in the cockpit.

One of the disadvantage with current cargo fire extinguishing system in airplanes is that spurious cargo smoke warning results in pilot to discharge the halon fire bottles unnecessary, and result in depletion of extinguishing agent. In addition, in case of genuine fire, then there is no or not enough extinguishing agent left to use.

Other disadvantage with current system is that the fire bottle can automatically discharge outside aircraft, due to thermal expansion due to high internal temperature rise. In such condition when the fire bottle discharge their agent overboard during the flight than there will be no halon agent left to extinguish the fire or smoke in the cargo compartments so in proposed technique, inert gas nitrogen can be generated at any time and for any duration used to extinguish the fire. In addition, to discharge the content of a halon bottle, it requires an explosive cartridge to be fired. The fire bottle cartridge is a life item, and normally has a five years life. In case of defective cartridge or expired cartridge, then the halon agent cannot flow to extinguish fire. As shown in Figure 1, fire bottles have a thermal relief valve to discharge the agent overboard in case excessive internal pressure due to temperature rises.

FAA considers Halon 1301 as an effective firefighting agent with low toxicity, noncorrosive but because it damages the ozone layer, it is phased out of production however widely used on commercial aircrafts until a suitable replacement is developed [4]. The U.S Army conducted investigation of combustion properties of fuel containing halon 1301 in engines, and the result showed that the combustion products derived from halon were so corrosive that it severely damaged the engine in less than 50 hours of operation [5]. Currently, on all transport airplanes, halon agent during fire is applied to outside the engine and not to inside of the engine because it is corrosive. Halon 1301decomposes to form hydrogen fluoride and hydrogen bromide which if it does not get diluted in air, then 15 minutes' exposure becomes lethal also even small concentration can produce corrosion on metals, therefore halon should not be used on metal fires because of exothermic reactions between halons and metals [6].

Spurious Smoke Warnings

Spurious cargo smoke warnings are false warnings, and can result in flight crew to discharge the cargo fire bottle, extinguishing agent unnecessary. This situation reduces the flight safety, that in case of real fire during flight, then there is no or not enough fire extinguishing agent left to extinguish the real fire. Consequently, fire increases its intensity, thus produce more toxic fumes that can enter the cockpit. Fumes can impair judgment and affect performance of the flight crew.

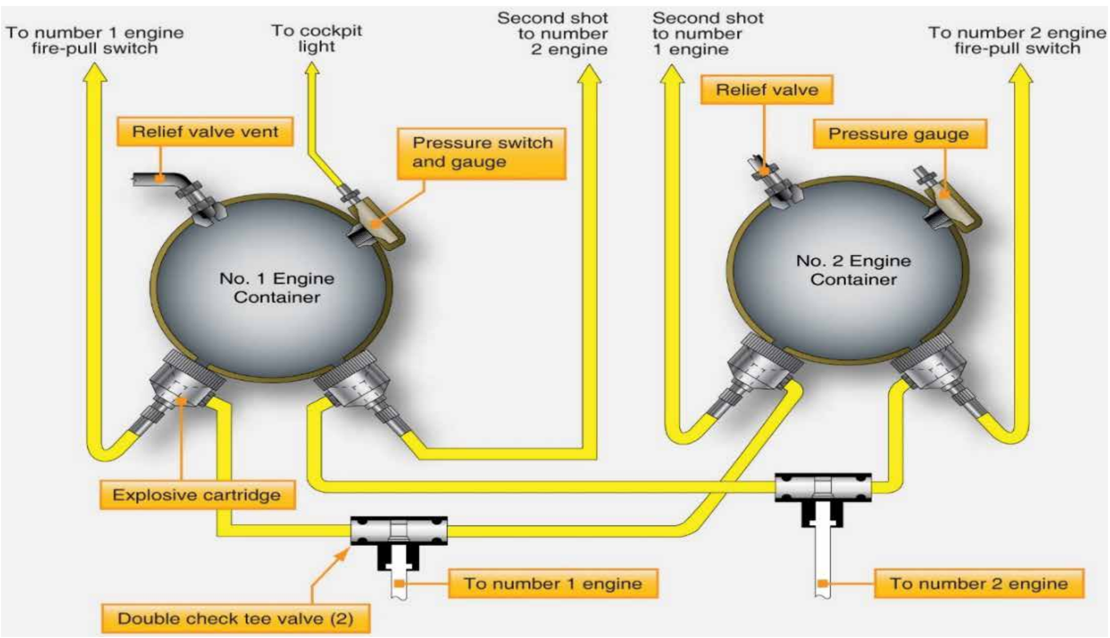

Figure 1: Figure showing current halon engine fire bottle extinguishing system [4].

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However, in proposed design, nitrogen is available all the time during the flight, and can be used to extinguish fire.

Spurious cargo smoke warning can be triggered by contaminated air circulation from various sources. For example, smoke warning can be triggered by extreme condensation in the cargo compartment. Cargo smoke warning can be generated by cargos such as tropical fruits, and vegetables etc. These cargos cause humidity levels to increase in unventilated compartments with the result that large quantity of condensation can form, the droplets of which appear to the smoke detector to be like smoke particles. In addition, cargo smoke warning can be triggered when aircraft operating in hot and humid conditions. Cargo smoke warning can be triggered fumes from ground equipment operating in the near vicinity of the cargo-loading door. Smoke warning can be triggered by oil vapor in the bleed air. The oil vapor appears to the detector to be smoke particles and thus generate alarm. The oil vapor is typically the result of oil spillage in the bleed air ducts from the APU. Smoke warnings can be triggered by ingestion of anti-ice/de-ice fluids into the intakes of either the engines or APU. Smoke warning can be triggered by ingestion of engine cleaning agent into the air conditioning system. Most of the smoke warnings been reported by airlines to Airbus, have been due to spurious smoke warnings. Only on very rare occasions, some of the cargo warning were triggered by a real fire [7].

One source of contamination is the APU; the APU bleed-air supply contamination can be due to either APU internal oil leakage or re-ingestion of oil, hydraulic or de-icing fluids. External fumes near the APU air intake, from exhaust gas fumes of main engines of any aircraft nearby or ground power units, can be ingested by the APU, and lead to smell in cabin degraded. Hydraulic fluid leaks from the aircraft main landing gear bay, can be directed along outside of the aircraft fuselage, up to the APU air intake. Hydraulic fluid can be ingested, while APU is running, and causes the aircraft air condition system contamination, and result in associated smell in the cabin. APU external fuel or oil leakage may be re-ingested if the APU inlet seal or APU doors seal degraded [8].

Current Cargo Fire/Ventilation Systems

In modern airplanes such as Airbus A330/340 series, the cargo fire extinguishing system, each cargo compartment has four smoke detectors and when two smoke detectors sense smoke, SDCU generate cargo smoke warnings in the cockpit. In case of smoke warning in forward cargo compartment, pilot selects FWD Agent pushbutton, and the circuit fires the halon-extinguishing bottle number one and halon flow into forward cargo. If the fire has not extinguished then pilot select AFT agent pushbutton and halon from fire bottle number two discharges via a flow metering unit which restrict the agent flow so that the agent is slowly discharged in the compartment, and takes 240 minutes to completely discharge the agent in the second bottle.

In addition, forward and AFT cargo compartments are ventilated and heated, as shown in Figure 2. Air from air condition system (cabin air) enters the cargo compartment through inlet isolation valve, then the extract fan, extract air from the compartment through the outlet isolation valve, and dump it overboard. Cargo ventilation controller controls the cargo ventilation system. Ventilation controller stops the extractor fan if the isolation valve is not open [9].

Some aircraft have cargo heating as well as cargo ventilation system, as shown in Figure 2. The cargo heating system is optional and it is to be selected manually by pilot. For example, in Airbus A320 series,

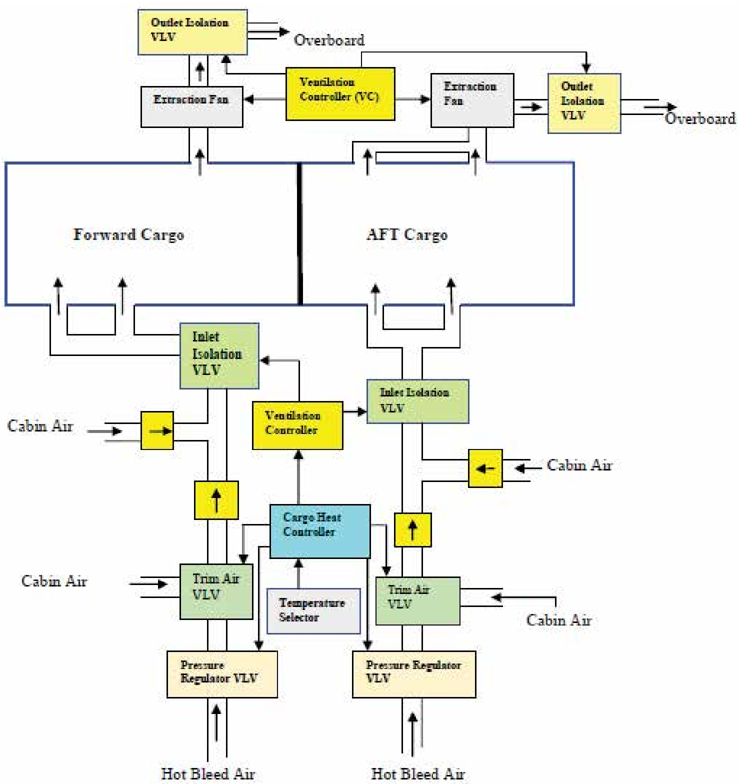


Figure 2: Figure showing current cargo compartment ventilation and heating system.

the cargo heat controller controls the trim air valve and the pressure regulating valve. The trim valve is a stepper motor which modulate the amount of hot air going to the cargo according to temperature selection by pilot. Hot bleed air enters the pressure regulator valve, where its pressure regulated to the required value then mixed with cool cabin air by trim air valve, to achieve required temperature. Heat controller send signal to ventilation controller to open the isolation valves for heated air to enter the cargo compartment. Cargo heat controller controls the pressure regulator valve and trim air valve. The cargo heating stops; if the isolation valves are closed, or ventilation extract fan stopped or in case of duct overheat [10]. In some aircrafts such as Airbus A330/340 series, avionics equipment cooling air, after passing through the equipment, it gets warm, and during flight, it is routed to forward cargo compartment through under-floor valve. The avionics equipment cooling controlled by AVEC. On the ground, the avionics equipment cooling is dumped overboard via overboard extract valve.

Proposed Cargo Fire Extinguishing System

In the proposed designed, the components are nitrogen processor, shut-off valves, a flow control valve, air compressor, heater, three air separator modules in parallel, nitrogen and standby pump, a heat exchanger (cooler 1), and the sensors to measure pressure, temperature, and flow rate. Nitrogen processor contains the logic, and gives command to increase the amount of air supply to ASMs and to pressurize nitrogen to higher values because experiment shows the increasing the nitrogen pressure result in quicker time to extinguish fire. Nitrogen processor send a signal to cargo ventilation and cargo heating system to stop supplying conditioned airflow to the cargo, in order to stop fresh oxygen reaching the fire. Nitrogen processor can be programmed to supply nitrogen automatically to the cargo when the smoke detectors sense smoke in particular cargo bay, or it can be programmed that pilot manual selection required (by selecting a pushbutton). Air compressor used to increase the pressure of air supply to ASM inlet, in order to increase the nitrogen flow rate. Three ASMs used to increase the nitrogen flow rate to the cargo compartment. Cooler 1 is a heat exchanger, bleed air supply to the ASM is maintained to 180F plus or minus 10F, hence the nitrogen flow from ASMs will be at the same temperature, it is cooled in order to increase the nitrogen density, and reduce the temperature of the fire.

With reference to Figures 3 and 4, the smoke detectors sense smoke in the FWD cargo compartment and send warning signal to SDCU, which in turn send signal to FWC in order to generate oral and visual warnings to the pilots. SDCU send signal to ventilation controller, which causes the FWD cargo inlet and outlet isolation valves to close and the extractor fan to stop. When the cargo ventilation isolation valves are closed, the ventilation controller send such data to nitrogen processor and used as part of the logics. The processor will send signal to AVEC to close under floor valve to stop avionics equipment cooling air to be discharged in the FWD cargo compartment, and to open the overboard extract valve so that the avionics equipment cooling air is dumped overboard during FWD cargo smoke/fire condition. This action will prevent oxygen supply to reach the fire inside cargo compartment while nitrogen supplied into the cargo compartment. Nitrogen processor send signal to the cargo heat controller to stop the cargo heating system. The FCV opens more (high flow mode), in order to increase the bleed-air supply inlet to ASMs and consequently increase the nitrogen output.

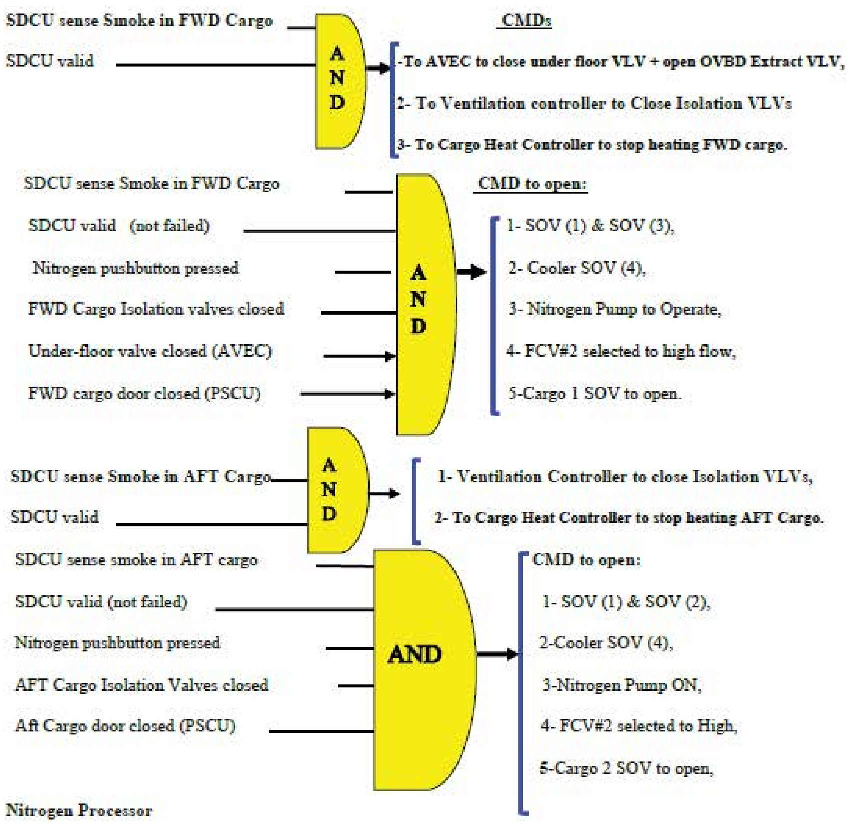


Figure 3: Proposed design of cargo fire extinguishing system for forward and AFT compartments.

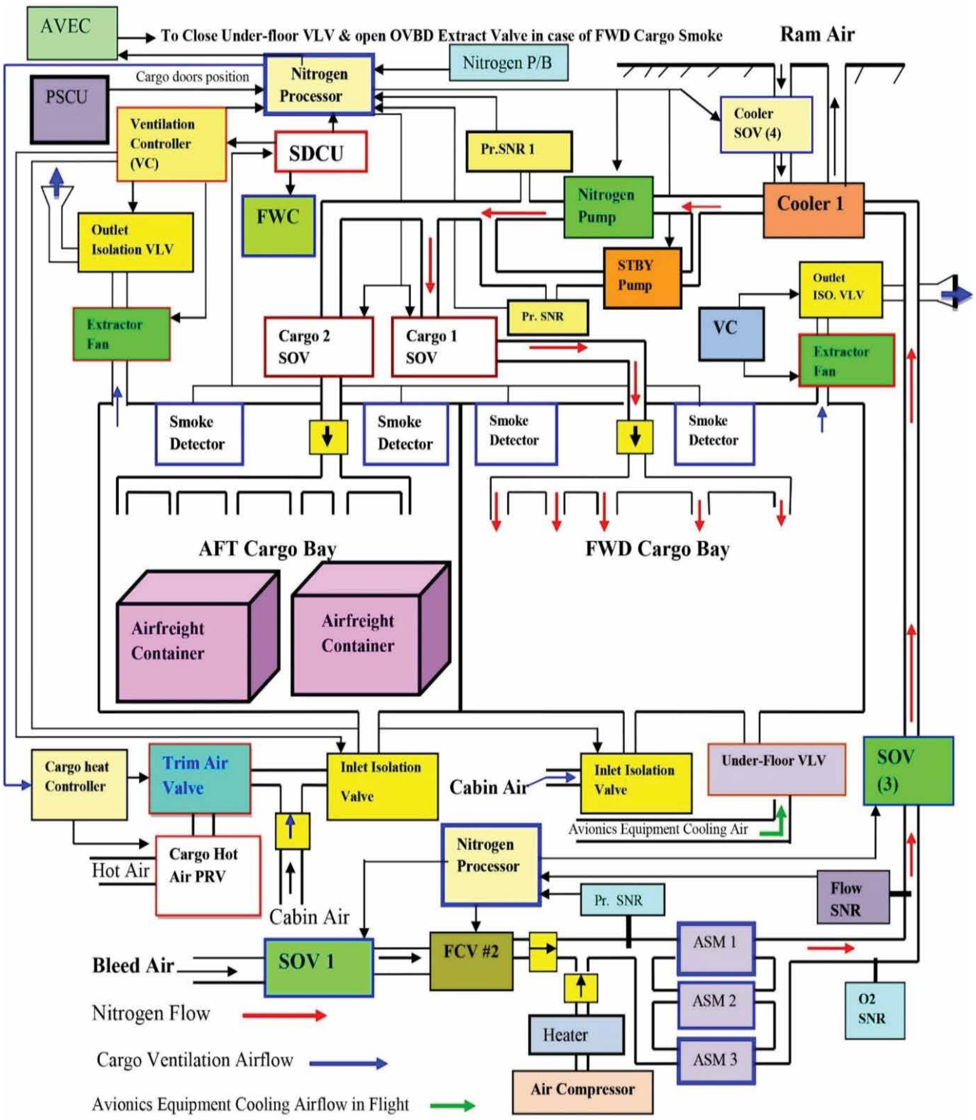


Figure 4: Proposed design of cargo fire extinguishing system.

Moreover, the SOV (3) opens to allow nitrogen flow to the nitrogen pump. The nitrogen pump operates to increase the pressure of nitrogen, in order to extinguish fire quicker, and then routed to forward-cargo, via cargo 1 SOV. Cooler SOV (4) opens to cool the nitrogen in order to increase its density, and to reduce nitrogen temperature because nitrogen output from ASMs regulated to 94C for better operational performance of ASM's. When nitrogen cooled, it can reduce the temperature of the fire in the affected area. The Cooler SOV (4) uses ram air to cool nitrogen. Nitrogen processor allow nitrogen to flow into FWD cargo, in order, to quickly extinguish the fire and or smoke. When Smoke detectors sense no smoke condition, SDCU send no smoke condition signal to the nitrogen processor, and a message appears in the cockpit. Pilot can de-select nitrogen pushbutton to stop nitrogen flow into the compartment.

In the proposed technique, nitrogen processor can be programmed to supply nitrogen to affected cargo compartment automatically when at least two smoke detectors sense smoke in the cargo compartment. When the system is de-selected, nitrogen processor closes, cargo 1 SOV, SOV (3), Cooler SOV (4) and stop nitrogen pump. Nitrogen processor command AVEC to re-open under floor valve (if aircraft in flight mode) and to close overboard extract valve. It also send signal to ventilation controller to re-open the applicable isolation valves.

In case of AFT cargo smoke detection, similar actions to forward cargo condition, except nitrogen processor command cargo 2 SOV to open to direct nitrogen from ASMs to AFT cargo as shown in Figure 4. When the SDCU receives no smoke signal from the associated smoke detectors, no message will be shown in cockpit. At the same time, it send signal to nitrogen processor. If pilot, de-select the nitrogen pushbutton, then nitrogen flow to affected cargo compartment stops. In the proposed approach, in order to extinguish fire in the cargo compartments, the cargo ventilation inlet and outlet isolation valves in aft cargo compartment, commanded to close position in order to prevent oxygen flow to reach the fire in the affected compartment. Nitrogen processor send signal to the cargo heat controller to stop the aft cargo heating system, if it was selected on.

PSCU senses FWD and AFT cargo doors positions and send such data to nitrogen processor, and used as part logic in the proposed design for cargo smoke extinguishing system. Nitrogen applied to extinguish fire in forward cargo bay, when the FWD cargo door is close, similarly in aft cargo compartment, the aft cargo door have to be closed. This is to ensure that aircraft is in flight mode, and to isolate the fire with fresh oxygen supply from ambient atmosphere.

Challenges

The main challenge with the proposed approach is the limited flow rate from the ASM, and hence the long time it may take for the cargo compartment to be rendered inert. Different approaches can be used to increase the nitrogen flow rate from the ASM. Increasing the pressure of the bleed air supply to the ASM, will increase the nitrogen flow output and decrease oxygen concentration. As shown in tests carried out by FAA and Airbus [11]. Higher bleed air pressure can be supplied to ASM either by taking the bleed air supply from the high pressure compressor stage of the engine, or using a compressor to pressurize the airflow to ASM. If engine compressor bleed air is not readily available, then an alternative could be to use an air compressor to increase pressure supply to the ASM inlet. The compressor type can be rotating either impellers or positive displacement.

An alternative approach that does not require pressurization of nitrogen would be to reduce the size of the cargo compartment, by diving it into smaller sections. This can be achieved by using airfreight containers in the cargo compartments. Cargo compartment can be of different sizes. Air cargo containers are usually made from light aluminum, as shown in Figure 5, however, lightweight carbon reinforced fiber and polypropylene containers have recently become. In either case, the airfreight container is to be installed with a smoke detector, a nitrogen port, and a mechanical pressure relief valve.

In the proposed technique, when the airfreight container is placed inside the cargo compartment, it will have to be connected to a nitrogen flexible hose, and electrical receptacle, to power the smoke detector inside the container. Should the smoke be detected; then the nitrogen processor energizes the associated container solenoid valve, and nitrogen from the ASMs will be routed to the effected container. When the pressure inside the container reaches a predetermined threshold of 30 psi depending upon the size and type of the container, the relief valve opens to vent excess nitrogen and to prevent over pressurization of the container. As safety feature, if the container is not electrically to the aircraft, then a message will appear in the cockpit to alert the crew. This is done by means of a proximity sensor in the nitrogen hose connector.

Figure 5: Figure showing light aluminium air-freight container.

Nitrogen is used in some trucks and ships to transport fresh fruit, vegetables, flowers, plants etc. Nitrogen preserves freshness and increases the fruits and vegetable storage life.

ASM performance can be increased if the ASM fibers are made from nanoparticles materials. Several experiment tests conducted involving membranes based gas separation, involving the hollow-fiber membranes made from three different types of fibers, such as pure polycarbonate, polypropylene, and polycarbonate added with silica nanoparticles. Gas permeabilities of O_2, N_2 and CO_2 were measured to determine the gas separation properties of obtained hollow fibers, and the test results showed that nanoparticles increased the absorption of gas separation, and improved selectivity [13].

For ASM efficiency, the inlet air pressure has to be high (typically 40 psi or more). It is possible to operate at lower pressures but more ASMs are required and this increases weight with each ASM weighting approximately 27kg. For illustration, if the air-supply inlet pressure to ASM is at 15psi, then ten ASMs are required, but if the inlet air pressure is at 56psi, then only two ASMs required to provide the required NEA capacity [12]. A single ASM at altitude of 32,000 feet, if the ASM inlet pressure is 32 psi, then ASM nitrogen flow rate will be equal to 8 cubic feet per minute (SCFM). At 40,000 feet, if ASM inlet pressure is 40 psi, then ASM nitrogen flow rate will increase to 10 cubic feet per minute [13]. In proposed design, air compressor used to increase the pressure of air supply inlet to 65 psi to ASMs.

The proposed design, as shown in Figure 6, allows the airfreight containers to be cooled by means of the aircraft air condition system, in order to meet critical storage needs of the temperature sensitive cargo such as medical or fresh produce. Should smoke be detected, the air supply to the container is stopped so to ensure a higher effectiveness of the nitrogen.

The proposed airfreight containers can be filled with inert nitrogen gas, to 2 to 3 psi. In such case, each container will be inerted with nitrogen, one at a time, when certain conditions fulfilled (cargo door closed and engine operation). It means that as soon as aircraft starts moving, during taxi phase, the containers will be inerted slightly with nitrogen, the containers will be installed with a pressure sensor, which send data to the N2 processor. The proposed containers will be installed with a pressure relief valve, to dump excessive pressure. Experiments conducted and result showed that nitrogen of 2-psi extinguishes fire effectively. In the proposed technique, nitrogen temperature from ASM is controlled to suitable values.

By increasing the number of ASMs, it will increase the nitrogen flow rate. Experiments have been conducted, result showed that nitrogen flow of ASM approximately doubled for the two-membrane configuration [1]. In addition, increasing the size of the Air Separator Module, the nitrogen flow increases.

Another technique, which can be used, is that storing nitrogen from ASM in a cylinder, as a backup source, which can be used in case of fire/smoke, to increase the nitrogen flow to the affected area. The cylinder pressure continuously monitored, and if it falls below certain value, sensed by the pressure sensor, and the system, supply air to ASM to generate nitrogen, then pressurized and stored in the cylinder bottle. Once the pressure in the cylinder reaches the limit, the N2 SOV closes by command from N2 processor, as shown in Figure 7, the refilling of the nitrogen bottle done automatically, if bleed air supply is not available, the air compressor operates to supply pressurized air inlet to the ASMs.

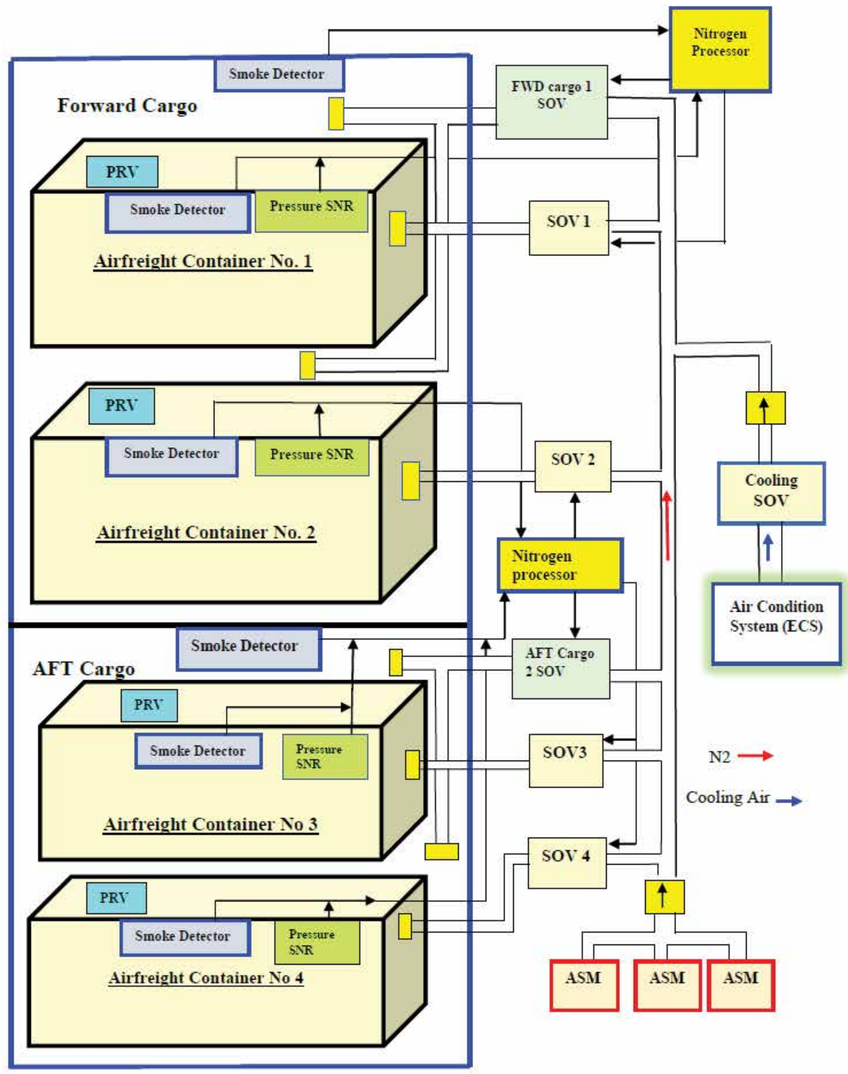


Figure 6: Proposed technique of using individual containers with nitrogen connection.

Nitrogen Experiments

Experiments were performed to evaluate the effectiveness of nitrogen in extinguishing fire in a compartment determine if the size of fire affects the nitrogen fire extinguishing ability, thirdly, determine the time it takes for the fire to be extinguished and determine the minimum pressure for nitrogen to be effective in extinguishing the fire. The first experiment was performed using a transparent, 50 cm, cubic box. The top side of the box his equipped with a port for the nitrogen input connection, as shown in Figure 8.

The experiment is at first performed with only one candle and carried out using one lit candle, and then the number of candles was increased. Experiment conducted initially with the test box having no ventilation. The nitrogen shut-off valve was opened manually, in order to allow nitrogen stored in the bottle to flow to the nitrogen pressure regulator, and then the pressure regulator was manually adjusted in order to control the nitrogen pressure. Experiment was first conducted with the test box having no ventilation to atmosphere, in order to analysis the effectiveness of nitrogen. Then the same experiments conducted with the test box having a ventilation port of 12.73 mm, this is done in order to establish if nitrogen can effectively extinguish fire in ventilated container (test box), as shown in Figures 9-12.

A series of experiments conducted, aimed at gathering information by using dry nitrogen under different pressure values to extinguish different size of fire. Table 1 shows the nitrogen pressure and time taken to extinguish different sizes of fire inside the test box during the experiments. The analysis of the experiment research showed that increasing nitrogen pressure, resulted in quicker extinguishing time. Figure 13 shows increasing nitrogen pressure, results in extinguishing the fire of the same intensity quicker. This is because nitrogen under higher pressure, quickly decrease the oxygen concentration in the air for the fire already in the process of combustion. In principle, there are two approaches to fire suppression: either decreasing the oxygen concentration or inerting the combustible environment. For fire to occur, it requires oxygen, and by supplying nitrogen at higher pressure, nitrogen pushed away the oxygen from fire at faster rate, hence inhibited combustion process sooner. However, increasing the fire size, it took slightly few seconds longer time. For illustration, five lit candles were extinguished in 0.51 seconds by using nitrogen at 10 psi, however, increasing fire size to 30-lit candles took 2.54 seconds to extinguish

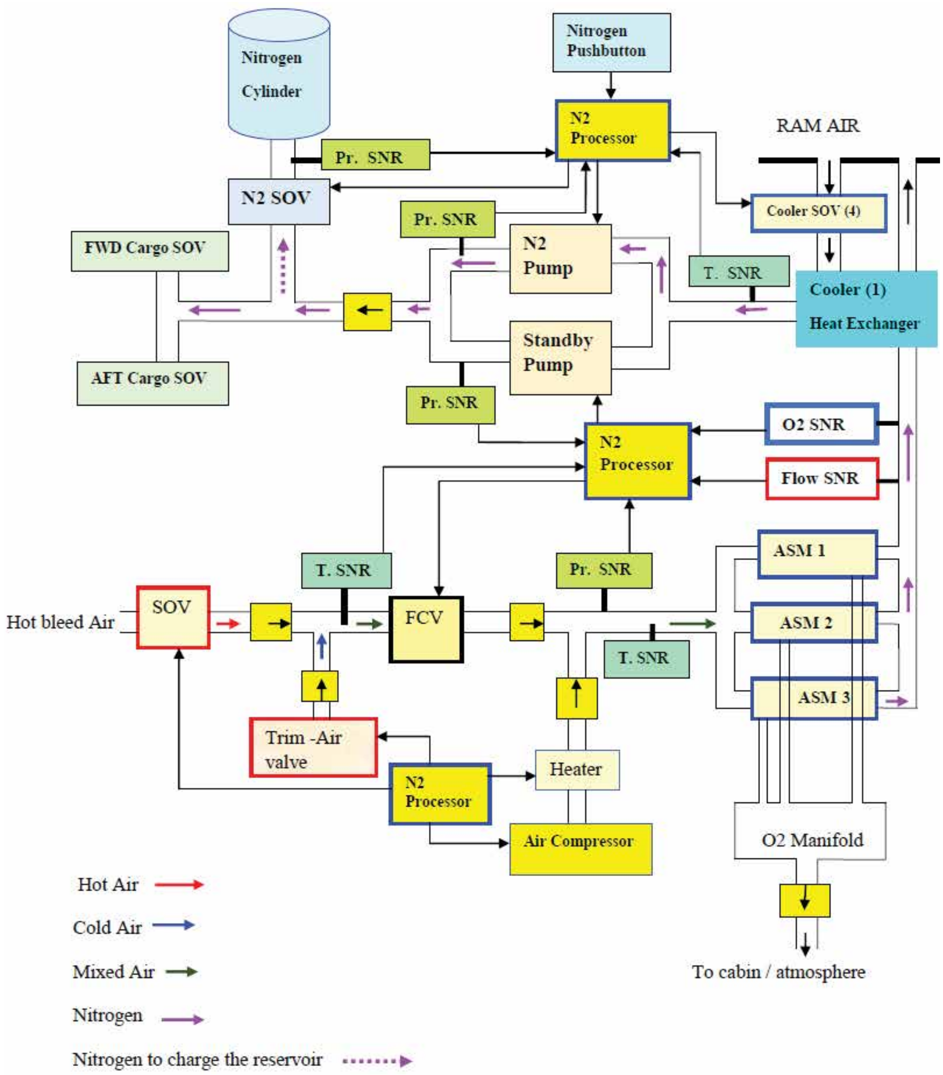


Figure 7: Nitrogen from ASMs stored in the cylinder, and used as backup during cargo fire.

when nitrogen supplied at 10 psi, as shown in Figure 14.

The experimental study of this research shows that nitrogen did not require a cleanup after the fire event experiment, as the result of gas release. Nitrogen discharge did not create a fogging effect hence vision wasn't compromised or obscured, unlike most fire-extinguishing agents. Nitrogen did not damage protected sensitive equipment. It can be concluded that dry nitrogen is non-conductive and can be used in environments where sensitive electronic devices are present.

Figure 11 shows one to five lit candles were extinguished in the same time when supplied with same nitrogen pressure (5 psi). Figure 14 shows dry nitrogen was used at different pressure to extinguish different size of fire, and time to extinguish fire was recorded. Based upon the experimental research, the analysis showed that minimum of 2 psi was sufficient to extinguish fire effectively, but it took few seconds more time. In addition, fire size, did not have effect on nitrogen to extinguish the fire. The experiment had limitation due to difficulties in building a transparent test box to represent actual aircraft cargo size.

Future Work

Although, FAA have conducted extensive ground and flight tests on using nitrogen from ASM to inert center fuel tank compartment on Airbus A320, as published in FAA document: DOT/FAA/AR-03/58. It states that the results of the tests indicated that the concept of the using nitrogen from ASM found effective to inert fuel tank compartment, except bleed air consumption was greater than expected. Therefore, it would be advantageous, to perform an experimental study using dry nitrogen from ASM to extinguish fire in a typical cargo size compartment, which is beyond the scope of this dissertation. The actual aircraft cargo compartment can vary from one aircraft type to another. The experiment had limitation due to difficulties in building a transparent test box to represent actual aircraft cargo size. The theoretical and practical achievement of this research can certainly be considered as an important milestone in the road-map to perform more research in future.

Conclusion

The experimental study and theoretical achievement of this research shows that nitrogen of 2 psi was sufficient to extinguish fire (57 lit-candles) in less than five seconds. In addition, the experimental

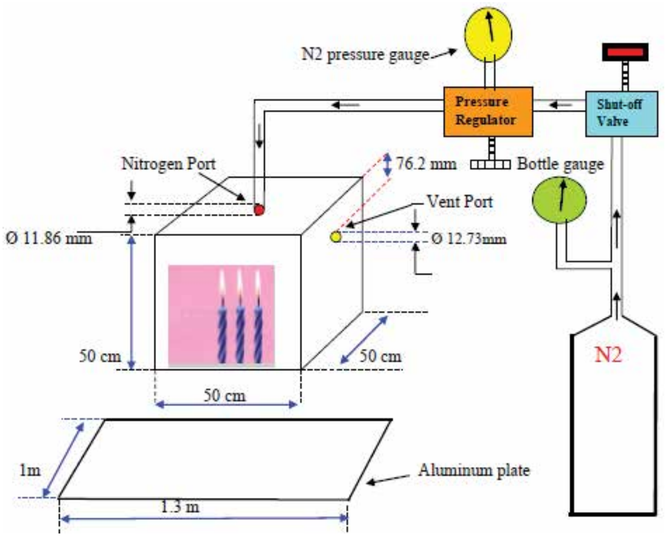


Figure 8: Experimental setup.

Figure 9: Figure showing lit candles during experiment setup.

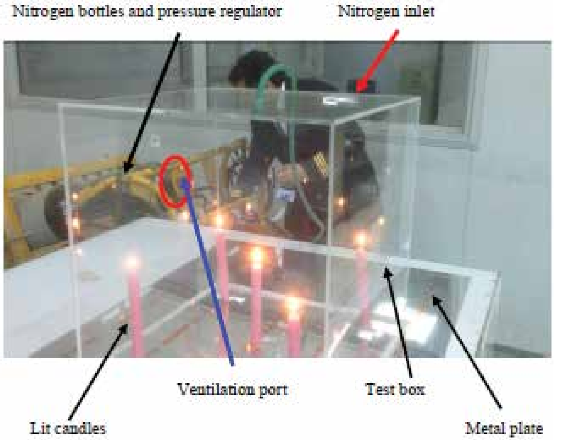


Figure 10: Experiment using five lit candles position at each corner, away from nitrogen direct source.

research showed that increasing the nitrogen pressure, resulted in faster fire extinguishing time because nitrogen at higher pressure, depleted the fire from oxygen at faster rate, and inhibited combustion process quicker. Nitrogen discharge did not require cleanup after extinguishing the fire during experiment, unlike halon or other extinguishing agent if the affected area is not cleaned, it can result into metal corrosion or damage sensitive electronic devices. In addition, it can be concluded from the experiment research that nitrogen is non-conductive and

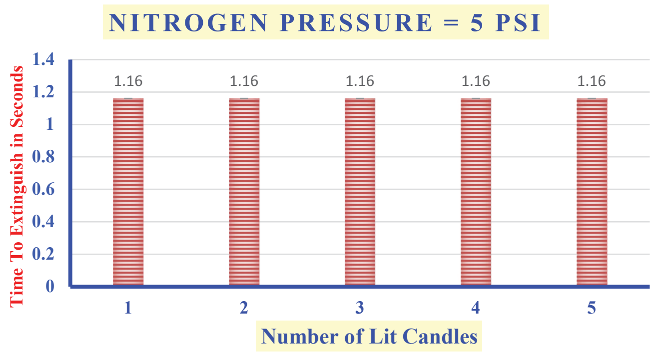


Figure 11: Figure showing usage of nitrogen pressure of (5 psi) to extinguish candles from one to five lit candles.

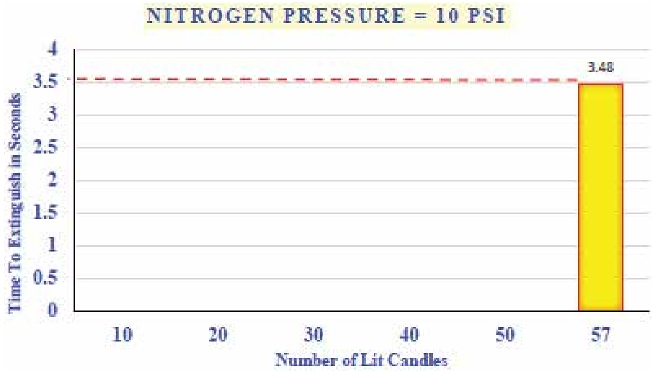


Figure 12: Figure showing the chart for using nitrogen pressure of (10 psi) to extinguish fifty-seven lit candles.

Number of lit candles	Nitrogen pressure (psi)	Extinguishing time (sec)
1 to 5	5	1.16
5	2	3.73
5	4	3.20
5	5	2.70
5	6	2.60
5	8	1.80
5	10	0.51
10	2	4.22
10	5	1.32
10	10	1.28
20	2	4.32
20	5	2.30
20	10	2.22
30	2	4.50
30	5	3.35
30	10	2.54
50	5	3.45
57	10	3.48

Table 1: Table showing the nitrogen pressure and time taken to extinguish different fire intensity inside the test box.

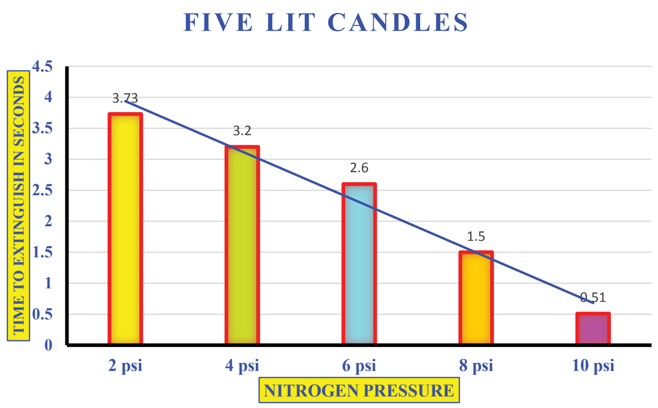
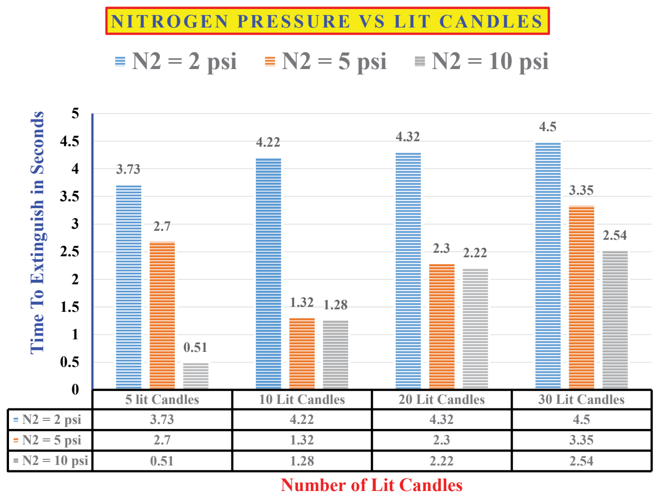


Figure 13: Figure showing the chart for using different nitrogen pressures to extinguish five lit candles.



	5 lit Candles	10 Lit Candles	20 Lit Candles	30 Lit Candles
N2 = 2 psi	3.73	4.22	4.32	4.5
N2 = 5 psi	2.7	1.32	2.3	3.35
N2 = 10 psi	0.51	1.28	2.22	2.54

Figure 14: The chart shows that using nitrogen at higher pressures, it extinguish fire quicker.

therefore, it can be used on aircraft environment where sensitive devices are present. Therefore, such research can certainly be considered as important milestone in the road to carry out further experiments in larger space, using dry nitrogen. Many technical challenges have been faced; and overcame in the proposed approach. This is starting point, that some new research paths can be opened, as regard to increasing flow rate from gas separation modules. The final goal will be to generate nitrogen from atmosphere at increased flow rate to extinguish fire in cargo compartment on commercial airplanes.

How the proposed design is going to affect the relevant stakeholders? The aircraft manufacturing company and the shareholders will want the best return on their investments. In the competitive market, and fluctuating oil prices, most airlines forced to reduce fares; however, safety concepts are at very core of any organization. The proposed technique have advantage over the existing cargo fire extinguishing cargo using halon, because nitrogen is noncorrosive when it reacts with moisture and it does not poses threat to the environment (zero ozone layer depletion/zero global warning). Nitrogen effectively extinguish fire, and FAA considers nitrogen inert gas as a suitable alternate to halon. The proposed design increases flight safety, and consequently reduces future aircraft accidents. This in turn, enhance the image of the airline, and wins more customers thus result in business growth and increases profitability.

How the proposed design is could be implemented in practice? Using dry nitrogen from gas separation modules is already approved by civil aviation authorities such FAA and EASA for use on all commercial airplanes, and meets the civil aviation airworthiness requirements. Nitrogen is used to inert center fuel tank known as On Board Inert Gas Generating System (OBIGGS). FAA requires a decrease in the flammability of center fuel tanks, and the 2008 ruling affects all future fixed-wing airplane design with (passenger capacity greater than 30). All new Airbus and Boeing aircrafts with center fuel tanks are required to have OBIGGS. In order to implement the proposed design, it requires a processor, several shut-off valves, and sensors, additional ASMs to be accommodated in existing OBIGGS. Alternatively, nitrogen from existing OBIGGS, instead of inerting center fuel tank, is diverted to extinguish cargo compartment. In such scenario, priority is given to extinguish fire onboard of airplane. This arrangement can be done by reprogramming the OBIGGS processor, and bears no additional cost.

The main challenge of flow rate limitation of using nitrogen from ASM to extinguish fire in cargo compartment can be overcome by using several methodologies. The ASM flow rate can be increased by several methodology. The flow rate of ASM can be increased by increasing the size of ASM or increasing the number of ASMs. In addition, the ASM flow rate can be increased by increasing the bleed air pressure supply inlet to the ASM. This can be achieved by taking bleed air of higher pressure, from engine high compressor stage, instead of intermediate compressor stage. In addition, the bleed air pressure can be increased by using an air compressor, which can be driven by engine accessory gearbox or an electrical motor or Ram Air Turbine (RAT).

Other methods include using airfreight containers, which are installed by a smoke detector, a PRV, and nitrogen supply connection. Most airlines use airfreight containers. In such arrangement, nitrogen from ASMs can be directed, only to the affected container under fire. The advantages of using airfreight containers are that small pieces of cargo can be wrapped into a single unit, so it saves time to load/off-load items, and reduce turn-around-time. On long haul flights, using more than one airline, the containers could be transported from plane to plane with amazing speed and ease. In addition, it minimizes the aircraft center of gravity to shift during flight. Another technique is to inert each airfreight container with nitrogen, one at a time, when certain conditions fulfilled (cargo door closed and engine operation). Nitrogen temperature can be controlled to desired temperatures; this will help to carry temperature sensitive items. In such arrangement, reduces the risk of ignition/fire, because for fire to occur, it requires oxygen. Nitrogen used in some trucks and ships to transport fresh fruit, vegetables, flowers, plants etc. Nitrogen preserves freshness and increases the fruits and vegetable storage life.

Alternate method, includes storing nitrogen from ASM in a cylinder bottle, which can be used in case of cargo fire/smoke, to increase the nitrogen flow to the affected area. In proposed technique, the nitrogen cylinder pressure is continuously monitored, and if it falls below certain value, sensed by the pressure sensor, the system automatically top it up, hence, no need for personnel to fill the cylinder.

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