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Dormavac—Long Term Storage of Perishable Commodities

R. E. Alloca

Grumman Aerospace Corp.,
Bethpage, N.Y.

The application of the Dormavac process, involving vacuum storage of perishable commodities under controlled environmental conditions, is described. The biological basis and the results of verification laboratory tests are presented. The details of the system design of the intermodal container is presented, including highlights of each of the subsystems: thermal control, pressure regulation, humidification and power supply. The structural design configuration of the 12-meter flat-sided intermodal container is also presented, including the thermal isolation and insulation and the pressure integrity aspects.

INTRODUCTION

As educational levels rise and affluence grows throughout the world so does the desire for more nutritional fresh foods in ever increasing quantities and varieties. In addition, as the developing countries increase agricultural productivity beyond local demand, new markets are sought. A clear cut need has therefore arisen for a means to transport perishable commodities from distant lands to the market place. Conventional refrigeration transport, and even the modern controlled atmosphere refrigerated storage at reduced oxygen partial pressures, in most cases, are not able to prevent spoilage for the extended periods required. Air freight is limited on a cost and volume basis. A viable alternative to air transportation which has demonstrated long term storage capability is the subject of this paper, namely, the Dormavac® system and its applications (1).

The Dormavac system involves hypobaric or low pressure storage of the commodity in a continuously ventilated space under conditions of low, but above freezing, controlled, uniform temperature and near-saturated humidity levels. The purposes of this paper are to briefly explain the biological basis for the success of the Dormavac process, to report upon conceptual laboratory demonstrations, and to present an overview of the application of thermal control techniques and commercially available environmental systems hardware to configure a practical commercial product, a forty foot commodity transport intermodal container.

BIOLOGICAL BASIS

The principle of Dormavac storage was first explained and verified by laboratory test by Dr. Stanley Burg while at the University of Miami in the early 1960s (2). All living perishables consume oxygen and generate gases such as carbon dioxide or other volatile gases whose effects, as shown in Table 1 for some commodities, prevent long term storage. Removal of the generated gases is in accordance with the following equation: (3)

$$\dot{m} = k\,D\,(C_{int} - C_{ext})\,A_p$$

where: $\dot{m}$ is the rate of gas transport out of the commodity; D is the diffusivity in air; C_{int} and C_{ext} are the gas concentrations internal and external of the commodity; A_p is that portion of the commodities surface area perforated by air filled spaces; and k is a constant for the particular commodity related to internal structure and skin properties. The diffusivity D, is inversely proportional to pressure, and A_p is a function of relative humidity. In the Dormavac system, the low pressure results in a high D, and together with continuous ventilation which reduces C_{ext}, has, as an end result a reduction in C_{int}. The continuously maintained high humidity level, in addition to preventing commodity dessication, causes enlargement of the surface intercellular spaces and increased pore area, A_p, available for gas movement.

The reduction in pressure also proportionately reduces the partial pressure of oxygen which in itself has many beneficial effects on storage capability. In particular, the respiration rate is slowed in living commodities and bacteria growth is inhibited in meats and fish. The internal generation of the harmful gases is directly related to the respiration rate.

Temperature reduction has always been used to prevent spoilage. The benefit of reduced temperature, reflected in reduced rate of bacteria growth

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is exponential when within a few degrees of the optimum. If the temperature is more than a degree below optimum, the commodity may suffer cold damage; if it is a few degrees higher, the life expectancy of the product is severely diminished. Naturally, when specific temperature level is important, uniformity of temperature within the container is also important. The Dormavac system, with its liquid cooled cold plate walls and its ability to cool primarily by evaporation, coupled with the reduction in the internal heat load due to reduced respiration rates, provides quite uniform temperature gradients (approximately ±0.5°C).

Table 1 Volatile substances produced within perishable commodities and their effects (4)

VOLATILE SUBSTANCE	PRODUCED BY	EFFECT
CARBON DIOXIDE	ALL PRODUCTS	2% CAUSES BROWN STAIN OF LETTUCE; 2–10% CAUSES SCALD OF FRUITS, VEGETABLES AND FLOWERS
EHTYLENE	PLANT MATTER AND PATHOGENIC MOLDS	0.00001 – 0.00005% CAUSES FLOWER FADING; 0.00003 – 0.001% CAUSES FRUIT RIPENING, ABSCISSION OF LEAVES, FRUITS AND FLOWERS, RUSSET SPOT IN LETTUCE, DECAY IN CITRUS AND OTHER PRODUCTS. IN ADDITION, THE GAS INFLUENCES DORMANCY, RESPIRATION, BUD GROWTH AND RETENTION OF GREEN COLOR
ACETALDEHYDE, ETHYL ALCOHOL	PLANT MATTER, ESPECIALLY AT VERY LOW OXYGEN CONCENTRATIONS; AND PATHOGENS	LOW CONCENTRATIONS ENHANCE CHILLING DAMAGE AND CAUSE PHYSIOLOGICAL DAMAGE IN FRUIT, VEGETABLES, AND FLOWERS
FARNESCENE	APPLE	CAUSES CHILLING DAMAGE
OFF-ODORS, SUCH AS RANCID FAT	MEATS, PLANT MATTER (ALSO PRODUCED BY PATHOGENS ON THESE PRODUCTS)	PRODUCES OBJECTIONABLE QUALITY IN MEATS, FRUITS AND VEGETABLES
AMINE-OXIDE	BACTERIA WHICH GROW ON SALT WATER FISH AND SHRIMP	ODOR OF SPOILED FISH AND SHRIMP

LABORATORY VERIFICATION

To establish Dormavac capability, as well as optimum storage conditions in terms of pressure and temperature, numerous test and demonstrations have been conducted in the laboratory. In the interest of brevity, only the highlights of some of these tests are presented below; more extensive data can be found in Refs (4) and (5).

Pork Loins

Pork was stored under Dormavac conditions for 28 days at 10 mmHg absolute, 0°C (32°F), and 95% relative humidity and was compared with samples stored under conventional refrigeration. Figure 1, a summary of the bacteria data, shows that the Dormavac pork was well below the spoilage level at 28 days, a point considerable beyond that achieved by the conventionally refrigerated pork.

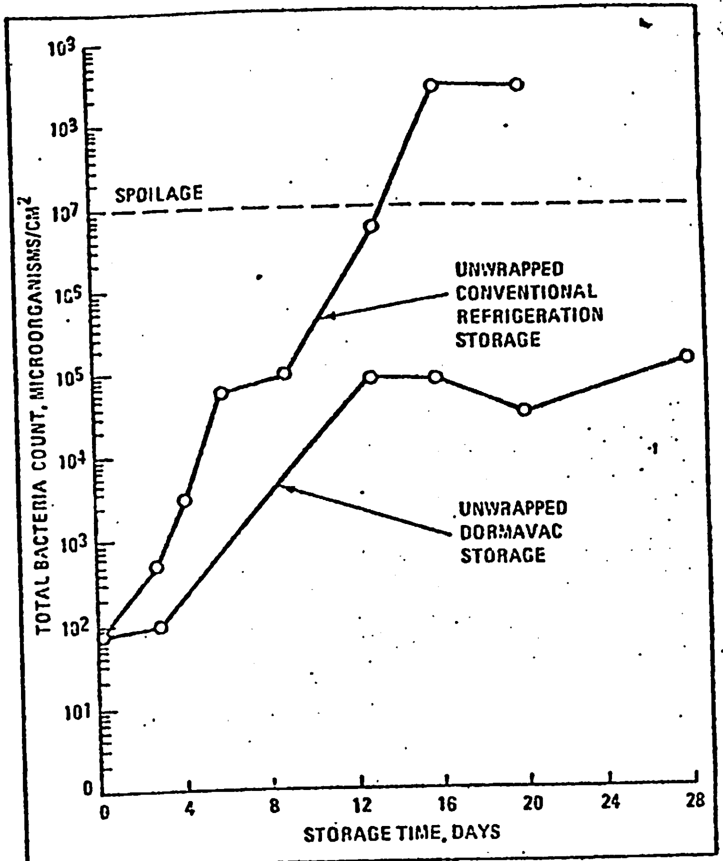

Fig. 1 Total bacteria count per square centimeter of pork loin surfaces

Strawberries

Strawberries, which are now transported by air to market, due to extremely limited storage life, survived 21 days of storage at a pressure and temperature of 20 mmHg absolute and 1.1°C (34°F).

Papaya

Tests were conducted at pressure ranging from 10 to 120 mmHg absolute to establish optimum Dormavac conditions. The tests show that more than 21 days of storage life was achieved for the test samples stored at 20 mmHg absolute and 10°C (50°F).

Limes

Chambers were set up at 20, 40 and 80 mmHg absolute and 10°C (50°F) to investigate storage life for limes under Dormavac conditions. After 71 days of storage, the limes at 80 mmHg scored the highest in all categories (color, texture, structure, decay and fungal growth) and were all marketable.

HARDWARE DEVELOPMENT

In parallel with the above noted tests, Grumman Allied Industries undertook the task of developing the laboratory phenomenon into a practical application for the commercial food transport market.

Design Requirements

The environmental control system design requirements were to provide, without manual readjustment, a precontainer controlled internal environment with a preset temperature and pressure within the range of -2°C (28°F) to 13°C (56°F) and 10 to 80 mmHg absolute, respectively, while maintaining 95% relative humidity with continuous ventilation at a rate of over two lumetric changes per hour. Transient requirements included 90 minutes to reduce the pressure of the 45 ubic meters volume (1600 cubic ft.) from normal tmosphere to 10 mmHg absolute and 48 hours to cool he commodity 13,000 kilograms of meat, by 11°C 20°F) if necessary (most commodities are prechilled hen loaded). The internal requirements had to be atisfied with external temperatures ranging from 29°C (-20°F) to 49°C (120°F) and with an altitude p to 3,000 meters. Self-contained diesel generator ower had to be provided for in transit over the oad.

Structural design requirements were to provide, ithout compromising the thermodynamic and pressure integrity aspects, a rectangular box structure capable of withstanding the enormous compressive forces when the interior was at full vacuum. The outer dimensions were fixed by international standards at 12 x 2.4 x 2.4 meters (40 x 8 x 8 ft.). Differential expansions associated with up to 65°C (150°F) outside (including solar effects) and -18°C (0°F) inside had to be considered in the design. Complete thermal insulation between the inner and outer wall was required. Air leakage requirements were, on a square foot basis, as severe as that of the Grumman designed and built Lunar Module, i.e., with the system shut down at vacuum the allowable pressure rise was to be no greater than 2.5 mmHg per hour.

Container Structural Configuration

The basic structural element is a 0.22 meter (9 in.) wide "I" beam which consists of inner and outer flanges of 6061 aluminum and an inner web of fiberglass (pultrusion). Fifty-four of these beams were welded together to form a complete 12 m (40 ft.) wall with no metal to metal contact between the inner and outer walls. As shown in Fig. 2, the container is assembled from eight sub-assemblies consisting of four longitudinal sections forming the side walls, ceiling and floor, two end frames, a bulkhead and a door. The assemblies are fastened together mechanically with inner and outer longerons forming the corners. The open wall assemblies are filled with foam-in-place, polyurethane insulation. The inner skin provides the pressure seal. Two steel end frames with standard corner castings are fastened to the basic container with strips of fiberglass providing the interface to avoid violation of the thermal isolation. The resultant overall coefficient of heat transfer per unit of wall area for the complete assembly is approximately 5.68×15^{-5} watts/cm^2 °C (0.1 Btu/Hr. Ft.^{2} °F). To facilitate fork lift loading, a liftable panel is added to the floor consisting of extruded aluminum T sections longitudinally welded together. Glycol cooling fluid passages are welded integral to the sidewalls, roof and fork lift floor. As shown in Fig. 3, there are four lines per wall. Each glycol line is an aluminum extrusion running the length of the wall, with a cross section consisting of two rectangular passages, such that the cooling fluid flows down the length of the container and back - all within the same welded extrusion, thereby minimizing temperature gradients.

Environmental System Configuration

The equipment section of the container, shown in Fig. 4, occupies a volume of 0.9 x 2.3 x 2.3 meters (37 x 90 x 90 in.) and consists of the following subsystems: power supply; cooling; pressure control; and humidification.

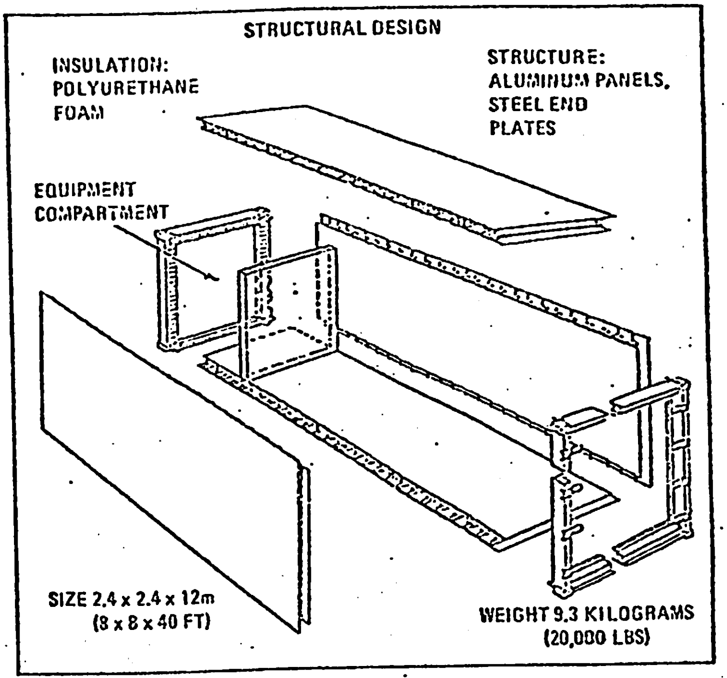

Fig. 2 Major structural segments of Dormavac intermodal container

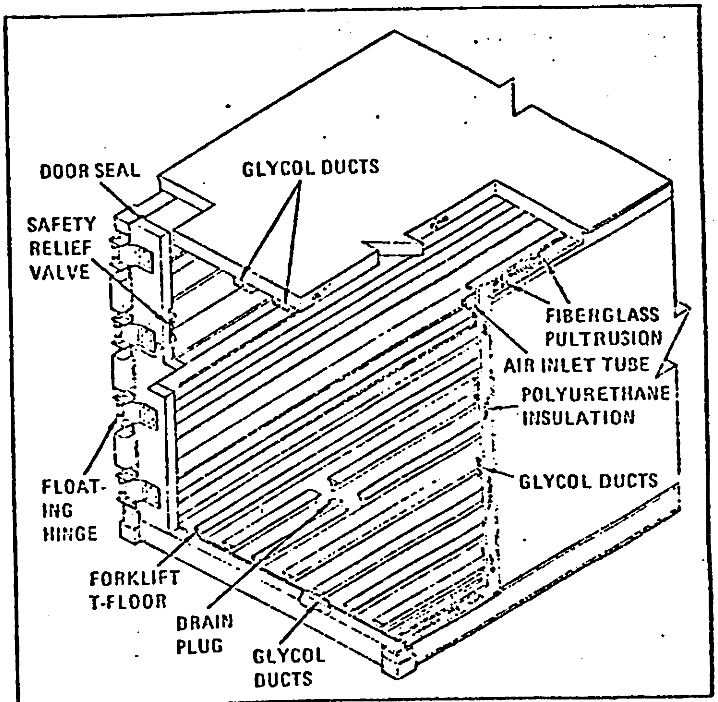

Fig. 3 Cutaway view of container showing integral coolant lines and thermal isolation between inner pressure shell and outer wall

The power supply subsystem includes a 28 KW (38 horsepower) diesel engine driving a generator which supplies 20 KW of 230 volt electric power. Sufficient diesel fuel is stored in the equipment bay for twenty-four hours of operation. The electric controls automatically sequence the startup of the major motor driven components to avoid stalling the diesel/generator with the required starting surge. A facility power cable is provided for connection to 230 VAC, 3 phase shipboard or ground power. The electrical controls automatically sense and correct for different phase connections. Since the container is to be used world wide it was necessary to install a 440/230 volt stepdown transformer for operation with higher voltage utility supply.

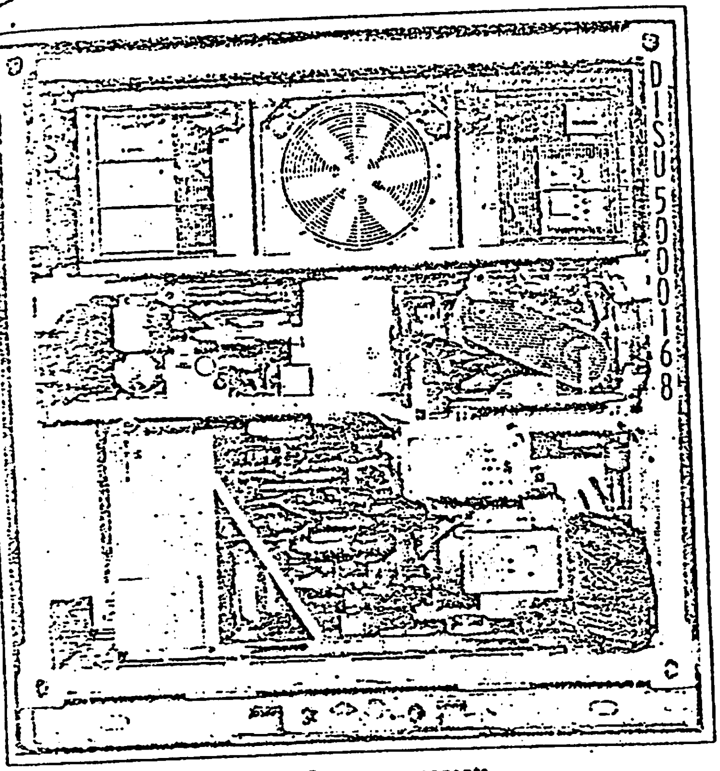

Fig. 4 System components

The cooling subsystem removes the wall heat leak, absorbs the commodity heat of respiration and cools the vacuum pump while maintaining a preset temperature within the container. The cooling fluid is a 50/50 mixture of inhibited ethylene glycol and water, with a freezing point of -37°C (-34°F) and a specific gravity of 1.07 at 15.6°C (60°F). As shown in Fig. 5, the glycol flows from the expansion tank through a tygon inspection tube to a circulating pump which has a capacity of 1.3×10^{-3} m^3/S (20 gallons per minute) at differential pressure of 1.4×10^5 N/M^2 (20 psid). The flow rate was set to limit the temperature rise of the coolant within the container to less than 0.6°C (1°F). The pump drives the fluid through parallel glycol to freon (R12) chillers within the refrigeration package, wherein the heat is rejected. The refrigeration unit is sized to provide 3.25 W/S (40,000 Btu/Hr.) cooling at a container temperature of 1.1°C (30°F) and an ambient of 49°C (120°F). It consists of two independent 3.7 KW (5 HP) refrigeration heat rejection freon loops, with the ultimate heat sink, outside air, driven by a single fan through the dual freon condensers. The refrigeration unit is capable of providing -18°C (0°F) glycol for those backhauls involving atmospheric transport of frozen food. The glycol flows from the refrigeration unit directly to the cooling lines within the container. An immersed thermister located at the point at which the glycol exits the container provides the intelligence

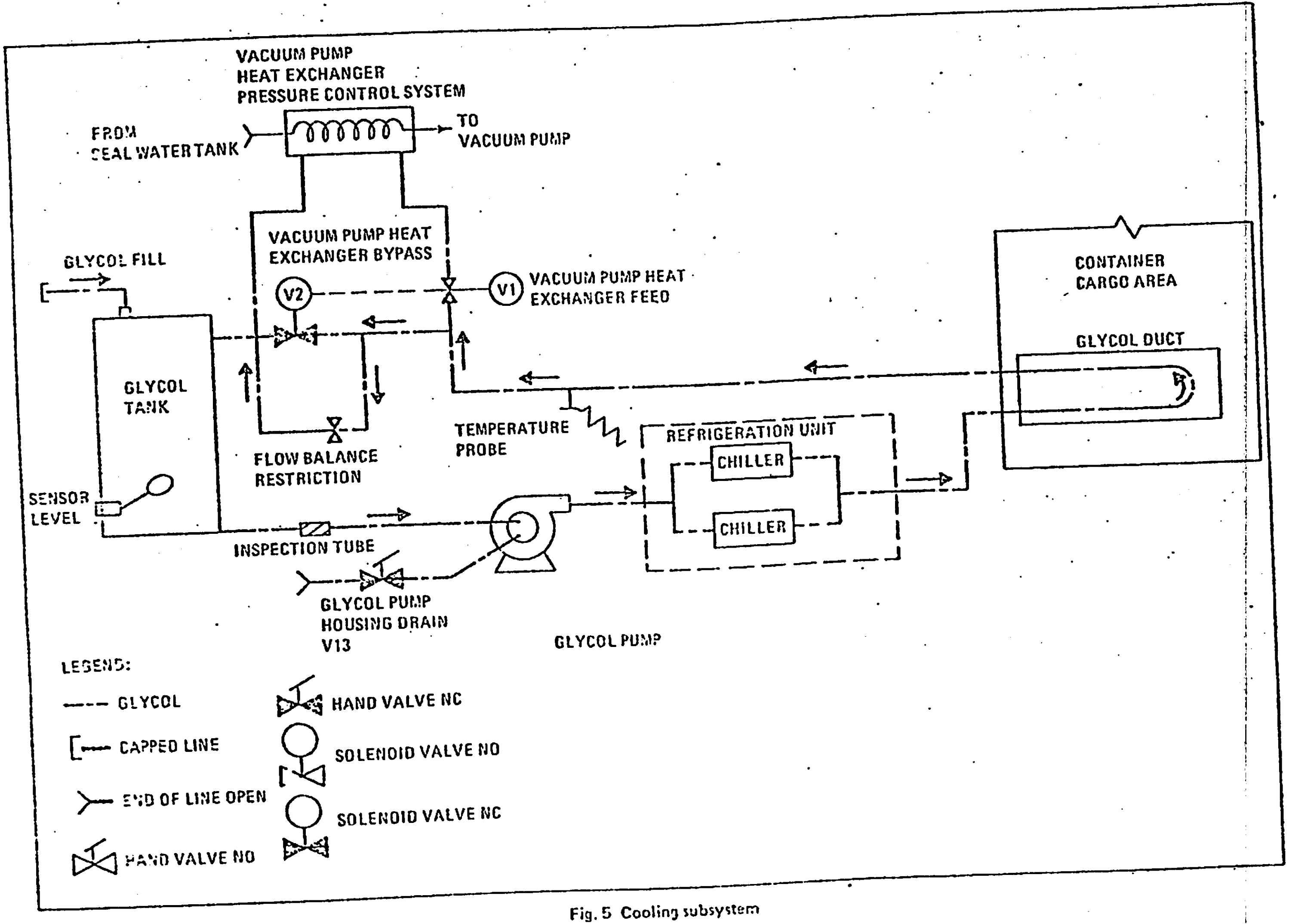

Fig. 5 Cooling subsystem

solid state temperature control. The tem- ature control automatically energizes or de- ergizes the two compressors sequentially depend- g upon the difference between the sensed and set perature. Modulating compressor control is ini- ated when the sensed temperature is within 0.8°C .5°F) of the set point.

From the container the glycol takes one of ree paths. Under Dormavac conditions, approxi- tely 4.4 x 10^{-4} m3/S (7 gpm) flows through the cuum pump heat exchanger and removes 1.3 W/S 6,000 Btu/Hr.) from the vacuum pump cooling water, th the remaining glycol flowing through a par- lel line with a reduced diameter section which tablishes the flow split to the vacuum pump, ereby minimizing the total system pressure drop. third parallel leg is provided which is used ly when the non-vacuum frozen food operating ode is in effect. By simply setting frozen food emperatures, the solenoid valve in the feed to acuum pump automatically closes and the solenoid alve in the third parallel leg opens to facilitate ypass of the non-operating vacuum pump. The auto- atic bypass of the vacuum pump heat exchanger is ecessary at frozen food conditions to prevent reeze-up of the vacuum pump cooling water. The glycol returns from the vacuum pump to the glycol ank reservoir. Since glycol is toxic and colorless, a trace dye has been added to ensure knowledge of points of leakage if they occur. If a refrigeration malfunction occurs and the temperature is more than 6°C (10°F) above set point with a non-operating compressor, then the vacuum pump automatically shuts down to avoid throwing its waste heat into the glycol loop, and hence, into the commodity.

The pressure control subsystem schematically shown in Fig. 6 consists of a 5.6 KW (7 1/2 horsepower) 5.7 x 10^{-2} m3/S (120 cfm) two stage vacuum pump assembly, a pressure regulator and a vacuum breaker.

The continuously operating vacuum pump assembly consists of a three lobe rotary positive displacement blower connected to the motor with a non-slip pulley, a liquid ring second stage close coupled to the double ended motor, a water cooling fluid heat exchanger, a motor and a two gallon seal water reservoir. The liquid ring second stage was chosen to facilitate recovery by condensation of the water vapor supplied to the container to maintain the high internal relative humidity. Without water recovery, a 700 gallon water tank would be required for a design duration trip of six weeks, rather than the 50 gallon reservoir provided. During pulldown, a portion of the first stage discharge is by-passed back to the container air supply line to minimize the pressure ratio across the first stage and thereby maintain total power requirements within the 5.6 KW (7 1/2 horsepower) motor capability. When the pressure drops below 120 mmHg absolute a pressure switch activates a solenoid valve which closes the bypass. Without the bypass line, the vacuum pump would draw a peak of 9 KW (12 horsepower) during pulldown.

The absolute pressure within the container is controlled by the amount of air which is metered into the air inlet by the vacuum breaker. The vacuum breaker modulates the induced air flow by comparing the container's pressure sensed at the vacuum pump inlet, against a set pressure signal from the pressure regulator. The pressure regulator is a pilot operated, adjustable absolute pressure type which provides a static selected "reference" pressure to the upper chamber of the vacuum breaker. The entire pressure control system can be isolated from the container for malfunction investigation or parts replacement by simply closing the supply and return vacuum tight ball valves. Included in the pressure control subsystem is an inlet replaceable cartridge air filter and a set of pressure gages.

The humidification subsystem shown schematically in Fig. 7 includes a humidifier, a water supply tank, a water feed purifier and the associated electrical controls. The humidifier is simply an electrically heated boiler which operates at low temperature due to the reduced pressure (water boils at 12°C (53°F) at 10 mmHg absolute). The heater wattage is modulated below its 3 KW rating by a sophisticated solid state controller which very rapidly pulses the heater to achieve the desired duty cycle and which automatically compensates for voltage changes. The required wattage is preset in accordance with the commodity set temperature and the desired humidity level (usually 95%) and is based on test devised vacuum pump flow rates as a function of pressure. As noted previously, most of the water boiled into the container is recovered in the vacuum pump second stage and recycled back to the water tank. Min./max. water levels are maintained in the humidifier by means of high and low level sensors. The water flows into the boiler when the level sensors signal the solenoid feed valve to open. The flow occurs as a result of the pressure differential between the boiler at container pressure and the supply tank at normal atmosphere. It should be noted that all water lines are traced with heater tape which is automatically energized if the outside temperature falls below 4°C (40°F).

System Performance

Although laboratory tests demonstrated the benefits of the Dormavac process, questions arose during the development phase as to whether the same performance could be extrapolated to a practical commercial application many times greater in size than any laboratory test. One question was whether an entire commodity load of approximately 13,000 kilograms (30,000 pounds) could be cooled down in a reasonable period to a uniform temperature (less than a 1°C variation). There was also a need for a better understanding of the internal modes of heat transfer. This was especially true since the laboratory tests indicated excellent heat transfer cooling capability, greater than that at atmospheric pressure, whereas analysis indicated a convective film coefficient of only 5.68 x 10^{-5} watt/cm^2 °C (0.1 Btu/Hr. $Ft.^2$ °F) at a pressure of 10 mmHg absolute. Various heat transfer mechanisms were postulated to explain the phenomena: evaporative cooling of the commodity with its own moisture or with moisture which condensed on the overhead and fell upon the commodity; a strong flow, due to pressure gradients associated with differential temperatures/water vapor partial pressures, giving significant convective cooling; or high radiant heat transfer from the cargo to cold walls since in a lab test (unlike a full scale container) the heat source/heat sink surface area ratio is nearly unity. A series of tests were conducted in a full size trailer and in a small bell jar with accurate environmental control capability.

The tests were quite successful with the following conclusions:

- Condensate did not "rain down" from the overhead
- A strong forced convective cooling flow did not exist

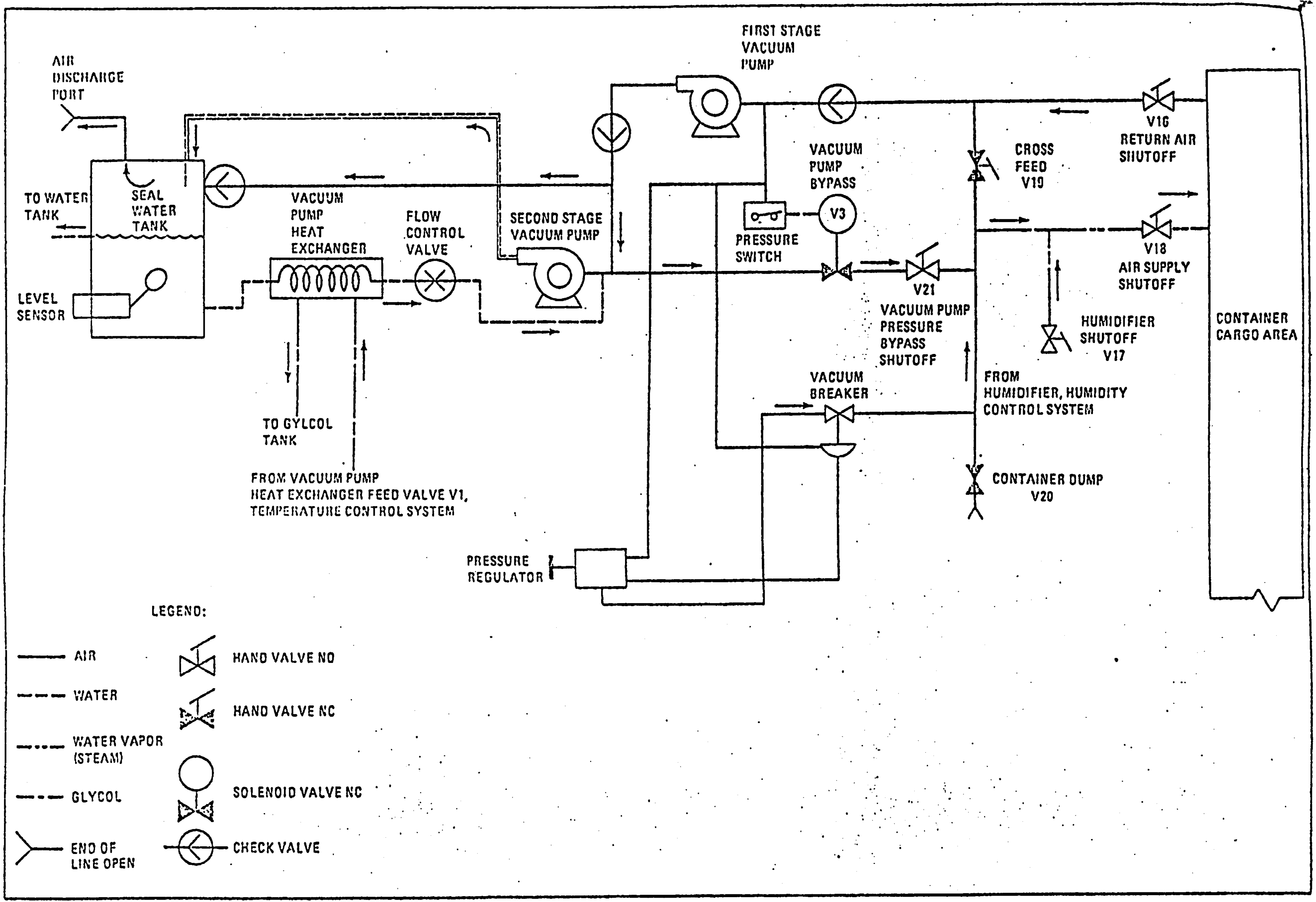

Fig. 6 Pressure control subsystem

- Radiation, depending upon the packing density, is significant
- Convected heat transfer was two to three times greater than analytically predicted but still insufficient to explain rapid chilldown
- Cooling by evaporation of the commodities' own moisture is by far the predominant mode of heat transfer.

The latter, most important, revelation emphasized the need to carefully determine proper wrapping, stacking and packing configurations and stressed the importance of maintaining uniform wall temperatures.

Today, with marketing of production containers, fully loaded container demonstrations are becoming the norm. Recently, an extensively instrumented static test using a production Dormavac container was conducted by the Australian meat authorities to confirm the Dormavac capabilities relative to the transport of lamb. Most of the 12,300 kilograms (28,000 pounds) of lamb cooled down to within 0.5°C (0.9°F) of the desired range within two days. At the end of the 40 day storage period, the lamb was judged to be excellent.

Other fully loaded demonstrations have been conducted successfully, some of which are noted below:

- 11,800 kilograms (26,000 pounds) of mangoes were shipped from Mexico to Japan - a 22 day voyage - and were sold at premium prices.
- Potted tropical plants were shipped from Hilo, Hawaii to Oakland, California and arrived in perfect conditions after 12 days.
- Papaya, picked one quarter ripe, were shipped from Hawaii to both the east and west coasts of the United States and upon removal from Dormavac condition, ripened with good color and taste.
- A 9,500 kilogram (21,000 pound) load of pork was shipped from Huron, S. Dakota to Hawaii and was declared to be the freshest meat ever shipped there by surface shipment.

CONCLUSION

This paper has presented the theoretical basis for the Dormavac process, documented test results, described the environmental system configuration and reviewed full scale verification demonstrations. The successful application of aerospace expertise to develop a laboratory phenomenon into a commercial product has been demonstrated. Obviously, system improvements, many of which will surface after further field service, can and will be made. But the completion of the development of the first generation production Dormavac container has initiated marketing of a product and a process that will probably alter significantly the existing world trade patterns. This potential has been recognized by the food industry with the joint award of the 1979 Food Technology Industrial Achievement Award to Armour Research Center and the Grumman Corporation for the "significant advance" in food technology achieved with the "hypobaric transport and storage of fresh meats and produce" (6).

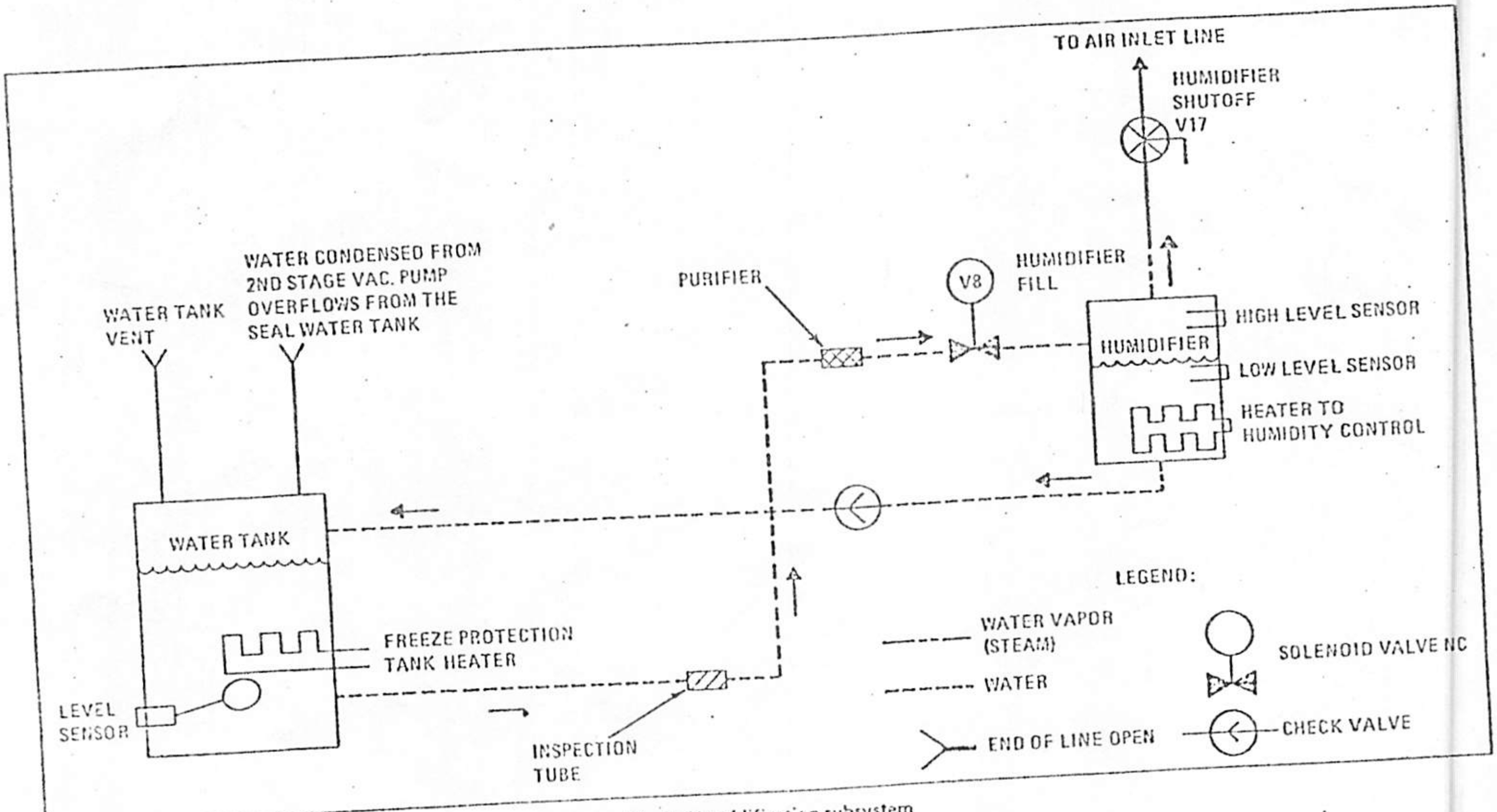

Fig. 7 Humidification subsystem

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