VAPOR COMPRESSION CYCLE SCALING – MICROGRAVITY COLD STORAGE REFRIGERATOR SIZING

PREPARED BY:
AIR SQUARED INC, PURDUE UNIVERSITY, AND WHIRLPOOL CORPORATION

CONTACT INFORMATION:
AIR SQUARED INC
510 BURBANK STREET
BROOMFIELD, COLORADO – 80020
PHONE: (303) 466-2669
EMAIL: s.caskey@airsquared.com
WEBPAGE: https://airsquared.com/

PURDUE UNIVERSITY – HERRICK LABORATORIES
177 SOUTH RUSSELL STREET
WEST LAFAYETTE, INDIANA – 479007
PHONE: (765) 494-2132
EMAIL: groll@purdue.edu
WEBPAGE: https://engineering.purdue.edu/Herrick

WHIRLPOOL CORPORATION
2000 M-63
BENTON HARBOR, MICHIGAN – 49022
PHONE: (269) 923-5000
EMAIL: alberto_r_gomes@whirlpool.com
WEBPAGE: https://whirlpoolcorp.com/

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1. Vapor Compression Cycle Scaling – Refrigerator Yardstick

To go beyond the design of a Vapor Compression Cycle (VCC) refrigerator for an ISS double mid-deck locker, a scaling approach was taken to provide examples that could support future NASA requirements. The goal was to reach two system configurations covering different storage sizes to quantify significant parameters of the VCC cold storage system. By spanning two different sizes, a trend could be obtained to estimate VCC cold storage capabilities and requirements for different applications not covered directly here. While reducing effort on assessing new applications for the technology, system designers can more easily consider the benefits or tradeoffs with a reference.

1.1. Modular Refrigerator Approach

In a regular refrigeration system, the vapor compressor components, such as evaporator, condenser, compressor, and electronic boards are fully integrated with the refrigerator cabinet, meaning, components such as harness, refrigerant lines and other structure components are foamed in (inside of insulation). This approach is used since there is a specific size and configuration to be used at a consumer home. When it comes to space exploration, there are key requirements, such as weight, reliability, robustness to launch loads, and minimal/or no service of the unit that all become critical for the design of the product.

Based on key NASA requirements for cold storage temperature range, different storage sizes, reliability, weight and sustain launch loads, the team proposal is to design a modular architecture composed of a (1) cooling module and an (2) expandable cabinet, following a similar design approach used in this contract with ISS demonstration units. Figure 1 below shows the overall concept.

1.2. Cabinet & Door Architecture

The cabinet construction can be done using a “Lego approach”, have a determined base size (X vs Y footprint) and use different middle sections to define different heights. In this way the cabinet is formed by at least 2 base parts and potentially multiple center connections. The following descriptions are also shown in Figure 2.

- Top Section - Part connected with the cooling module with all required mechanical interfaces defined
- Bottom Section - the base of the product.
- Middle flexible section - attached between top and bottom section that expand the potential height of the product.

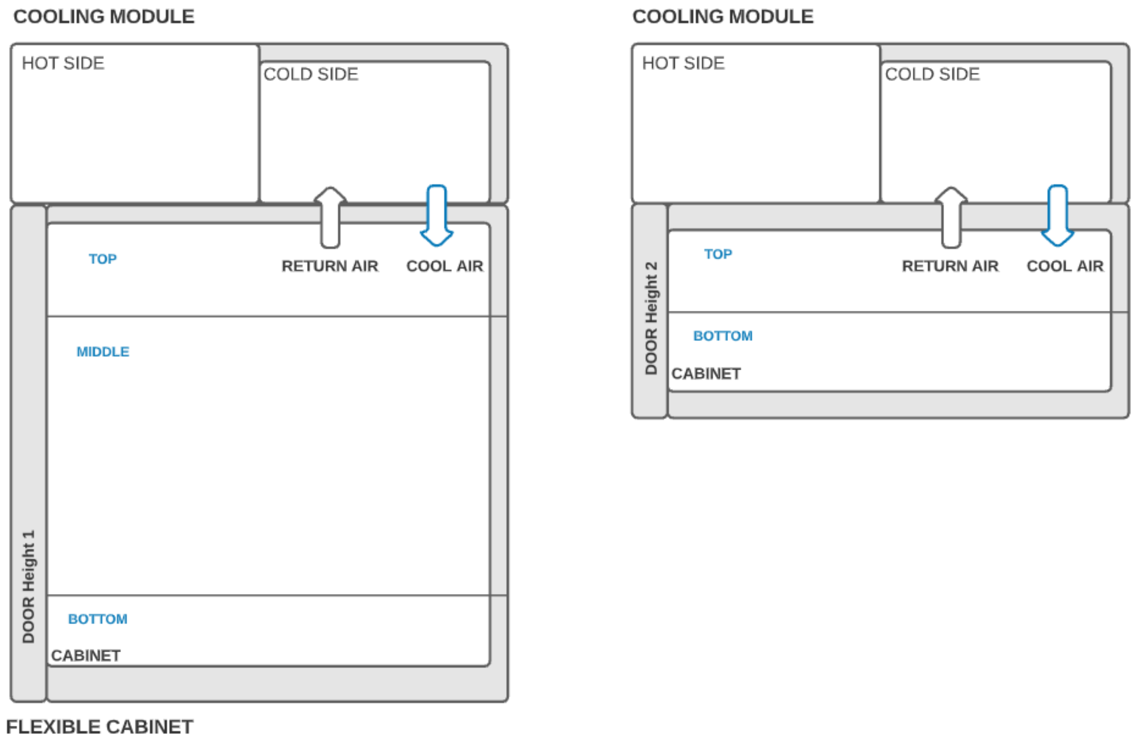

Figure 1: Modular Refrigerator Design Approach with Examples of Extending a Cabinet Volume (left) within Core Assemblies (right)

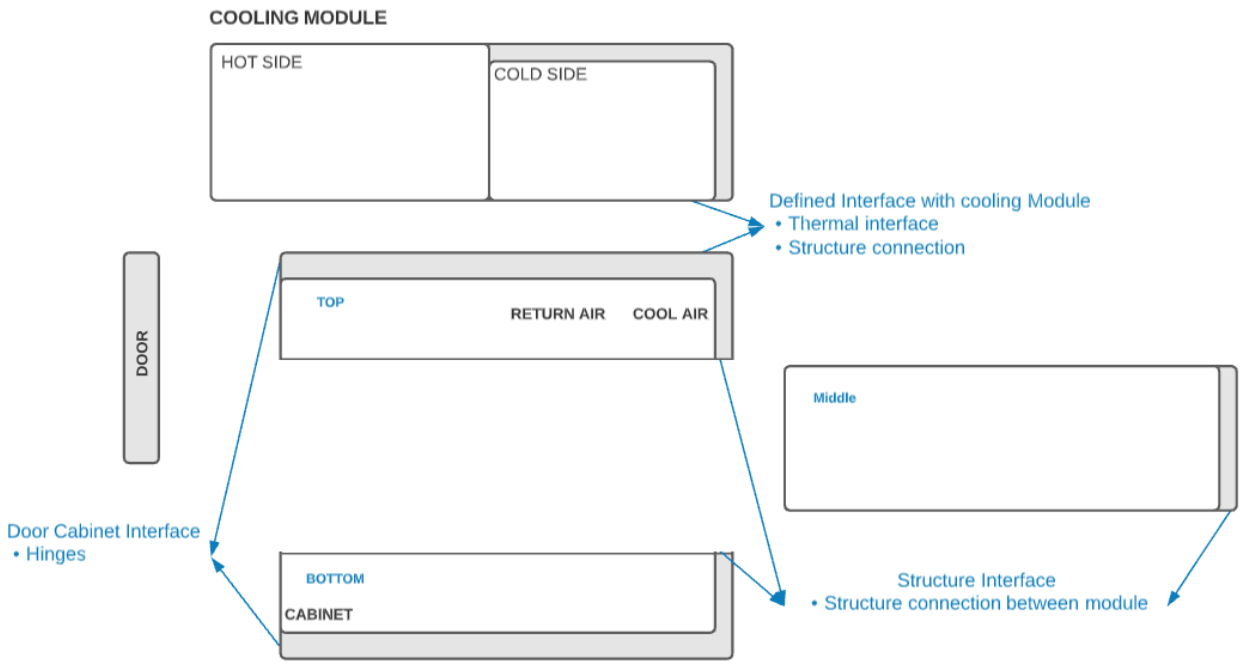

Figure 2: Identified Major Components and Interfacing Location of Modular Refrigerator Design

The door can be designed in a simple, flat approach and be sized to the total height required for cold storage volume. Figure 3 captures the simplified door concept. There would be 3 main sections of the door.

1. Door Top - reinforced to support the door hinge system and connects with the Top Section of the cabinet
2. Door Bottom - similar to Door Top and can be connected to the Bottom Section of the cabinet
3. Frame - contains the insulation and structural panels. The parts can be dimensioned to meet the product overall height.

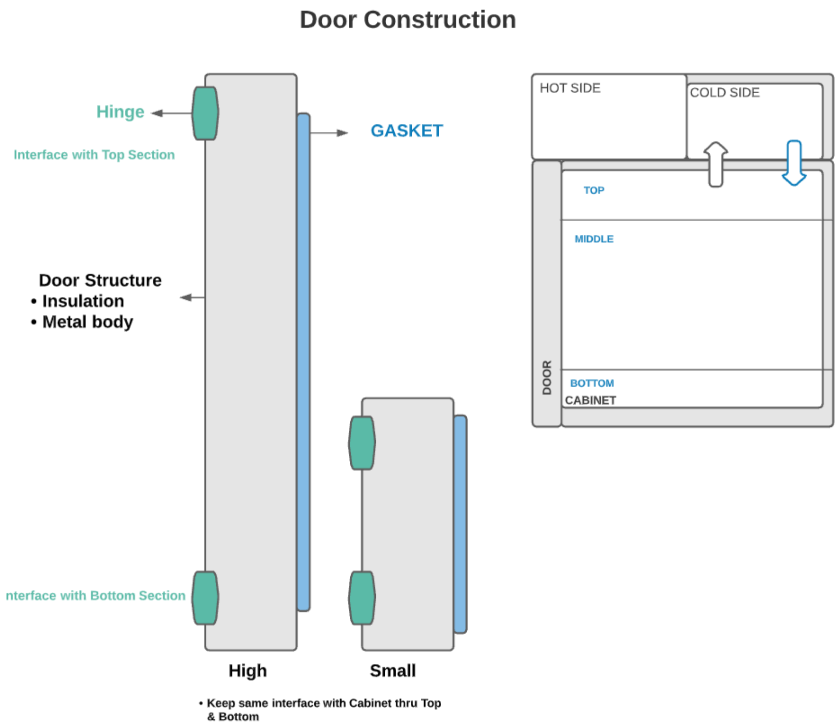

Figure 3: Example Door Construction to Increase Modular Refrigerator Storage Volume

The approach proposed here would be very similar to the one taken for the doors on the ISS demonstration cabinet, Figure 4.

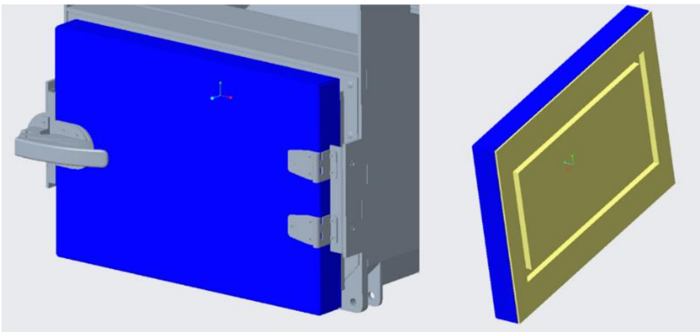

Figure 4: Revisit ISS Demonstration Unit Door Design as Example for Modular Refrigerator Approach

1.3. Oil-Free Scroll Compressor

To explore the requirements of an oil-free scroll compressor for a modular refrigerator, three fabricated units designed for refrigeration were compared at the freezer conditions (evaporation temperature of -30C and condensing temperature of 30C). The units had been developed as a part of this project across the three phases or from previous developments completed at Air Squared. The suction volume determined which units were selected for the study to provide a range of available cooling capacities. The three sizes were 4.33 cm^3/rev, 15.24 cm^3/rev, and 35.73 cm^3/rev. The volumetric efficiency was estimated based on the pressure differential calculated at the R134a saturation pressures for the required cabinet and heat rejection temperatures. Two speeds were evaluated to capture cooling capacity turndown and were also accounted for in the volumetric efficiency. The isentropic efficiencies listed are required targets of the compressor to achieve a COP levels of ~1.5 and ~2.0. The VCC efficiency is a significant parameter to its attractiveness as a cold storage system in space. The compressor as the dominate power consumer of the cycle needs to achieve a high performance to support those targets. Across the three compressor options, a wide range of cooling capacity between 60 W to 1.1 kW can be achieved, as shown in Table 1. As the compressor increases in suction volume, higher isentropic efficiencies are possible with a reduced ratio of mechanical losses to compression power requirements. Depending on the ultimate cabinet configuration sought, a larger compressor could provide efficiency benefits while using a combination of compressor speed and ON/OFF duty cycling to support reduced cooling capacity needs.

Table 1: Compare Oil-Free Scroll Compressor Requirements Across Three Suction Volume Sizes

Suction Vol. [cm3/rev]	Eta_isen [%]	Eta_vol [%]	Speed [RPM]	Cooling [W]	Power [W]	Heat Rej. [W]	COP [-]	Size [m3]	Weight [kg]
4.33	45%	70%	1800	62	43	105	1.43	0.0023	3.3
	50%	80%	3600	141	88	229	1.59		
	60%	70%	1800	62	32	94	1.91		
	65%	80%	3600	141	68	209	2.07		
15.24	45%	70%	1800	207	145	352	1.43	0.0023	2.9
	50%	80%	3600	474	298	771	1.59		
	60%	70%	1800	207	109	316	1.91		
	65%	80%	3600	474	229	703	2.07		
35.73	45%	70%	1800	486	339	825	1.43	0.0119	14.4
	50%	80%	3600	1110	698	1808	1.59		
	60%	70%	1800	486	254	740	1.91		
	65%	80%	3600	1110	537	1647	2.07		

1.4. Two Example Configurations

With a flexible cabinet and door design approach, it is possible to support two types of applications:

1. Ship all modules packaged and assemble at the final location. This can save significant space in the spacecraft by launching all modules in compact layout without making space for the cold storage volume. Any damage occurred in transient can be quickly replaced in the final location with spare modules.
2. Assemble at Earth, start up, and load with cold storage products for launch while maintaining designed cold storage conditions.

To maintain a high performance, COP, and meet all required cooling capacities, cooling modules can be designed in two or three different sizes ranges. Each size could meet a range of cooling capacities and range of cold storage temperatures. Sizes can be defined by the space requirements and application. Based on two of the oil-free compressors, two example cabinet configurations for a small or medium cabinet are shown in Figure 5.

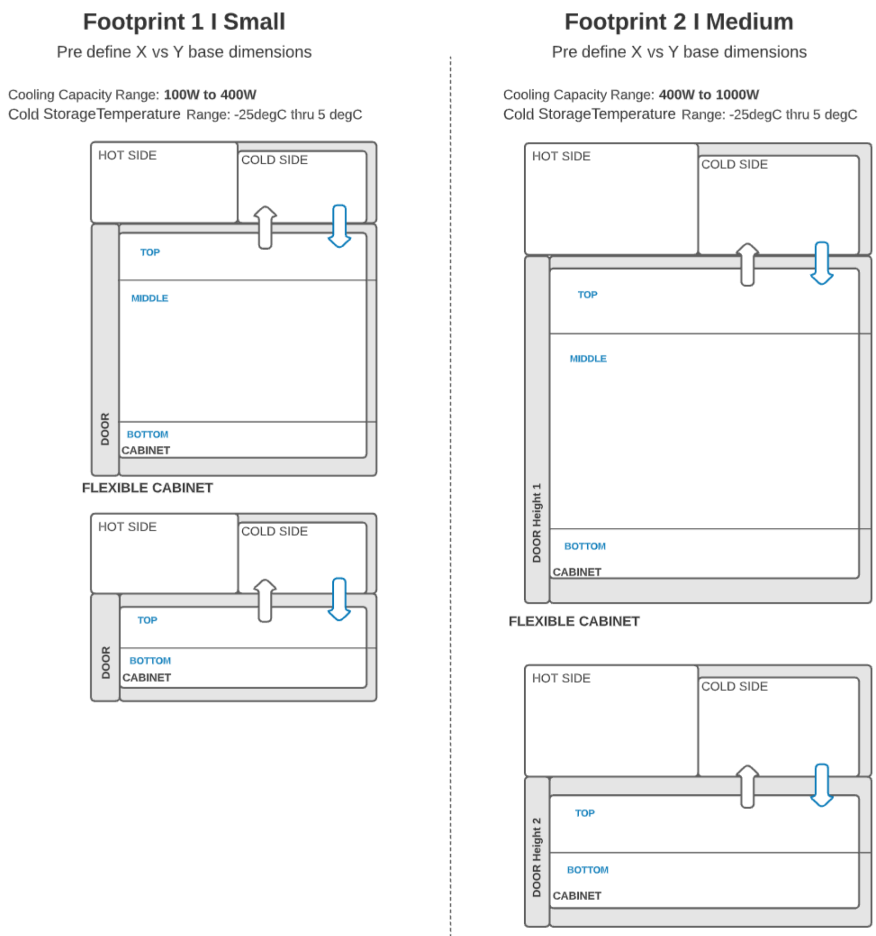

Figure 5: Two Size Cases of a Modular Refrigerator – Small (left) and Medium (right)

Once a range of cooling capacity and set point of each module is defined, it is possible to select key components that will be able to deliver the best performance point.

To make the refrigeration module adaptable to expanding or reducing the cabinet size, components that can modulate the cooling capacity are needed:

- Variable speed compressor: the BLDC driven, oil-free scroll compressor can achieve variable speed, delivering a range of mass flow rates thereby adjusting the cooling capacity to support a defined operation range
- Variable speed evaporator fan: modulate fan speed to control the cold air volumetric flow rate delivered to cold storage cabinet

All other components can be designed to deliver the maximum cooling capacity for the specific range.

Using a cooling approach with a simple cabinet can bring several advantages for application in space exploration:

- Simplified servicing: In case of a failure in the cooling module, the entire module can be replaced, avoiding the need of opening a sealed and pressurized, refrigeration system.

Additionally, the cooling module can be maintained without the need for removal of the refrigerated product.

- Reduced occupied volume for launch: All subassembly modules can be packaged into a tight footprint. Cooling modules can be shipped separately from the cabinet modules and stacked for compact packaging during launch.
- Separate, isolated cooling module. The refrigeration system is fabricated and checked on earth, all verification tests are completed without the need of the cabinet in question.

To illustrate the key system level dimensions, power draw, energy consumption, weight expected for this configuration, in Table 2, two examples are compared based on two different cold storage sizes: (1) 24 ft^3 and (2) 71 ft^3. Figure 5 highlights the minor differences between the two example sizes by leveraging a larger middle module for increased storage capacity. The original NASA topic requirements were revisited using the range of food densities, 250-500 kg/m^3, and applied to the two storage sizes estimated. A total weight of 170 to 1000 kg of food could be supported. Comparing the NASA mass and system efficiency targets of 0.2 kg of secondary mass per kg of food stored and 0.15 W of power consumption per kg of food stored, the larger storage volume of 71 ft^3 has more opportunity to hit these targets. Table 1 lists the required isentropic efficiency of the compressor to meet the power draw of the two cabinet examples presented.

Table 2: External Parameters of Two Modular Refrigerators with NASA Efficiency Targets Predicted

	Medium Size Unit		**Large Size Unit**	
Storage Temperature (°C / °F)	-25 to 5 / -13 to 41		-25 to 5 / -13 to 41	
Internal Cold Storage Volume (m^3 / ft^3)	0.68 / 24		2 / 71	
External Footprint Volume (m^3 / ft^3)	1.13 / 40		2.94 / 104	
External Footprint Base (cm x cm / in x in)	76 x 76 / 30 x 30		127 x 127 / 50 x 50	
Cabinet Height (cm / in)	183 / 72		183 / 72	
Cabinet Heat Gain (W)	110 to 170		285 to 350	
Total Weight (kg / lb)	45 to 82 / 100 to 180		91 to 168 / 200 to 370	
Power Draw (W)	60 to 100		140 to 230	
Energy Consumption per year (kWh/year)	525 to 875		1200 to 2000	
Steady State COP (W/W)	1.2 to 1.8		1.5 to 2	
Food Density (kg/m^3 / lb/ft^3)	250 / 16	500 / 31	250 / 16	500 / 31
Total Food Weight (kg / lbs)	170 / 375	340 / 750	500 / 1100	1000 / 2200
Mass Efficiency (kg/kg food low-high) *(0.2)*	0.27 - 0.48	0.13 - 0.24	0.18 - 0.34	0.09 - 0.17
System Efficiency (W / kg food low-high) *(0.15)*	0.35 - 0.59	0.18 - 0.29	0.28 - 0.46	0.14 - 0.23