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Development of the Crew Dragon ECLSS

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SpaceX designed the Crew Dragon spacecraft to be the safest ever flown and to restore the ability of the United States to launch astronauts. One of the key systems required for human flight is the Environmental Control and Life Support System (ECLSS), which was designed to work in concert with the spacesuit and spacecraft. The tight coupling of many subsystems combined with an emphasis on simplicity and fault tolerance created unique challenges and opportunities for the design team. During the development of the crew ECLSS, the Dragon 1 cargo spacecraft flew with a simple ECLSS for animals, providing an opportunity for technology development and the early characterization of system-level behavior. As the ECLSS design matured a series of tests were conducted, including with humans in a prototype capsule in November 2016, the Demo-1 test flight to the ISS in March 2019, and human-in-the-loop ground testing in the Demo-2 capsule in January 2020 before the same vehicle performs a crewed test flight. This paper describes the design and operations of the ECLSS, the development process, and the lessons learned.

Nomenclature

AC = air conditioning
AQM = air quality monitor
AVV = active vent valve
CCiCap = Commercial Crew Integrated Capability
CCtCap = Commercial Crew Transportation Capability
CFD = computational fluid dynamics
conops = concept of operations
COPV = composite overwrapped pressure vessel
CRS = Commercial Resupply Services
ECLS = environmental control and life support
ECLSS = environmental control and life support system
FOD = foreign object debris
IPA = isopropyl alcohol
ISS = International Space Station
LEO = low Earth orbit
LiOH = lithium hydroxide
NASA = National Aeronautics and Space Administration
NPRV = negative pressure relief valve
PPRV = positive pressure relief valve
SLPM = standard liters per minute
TCS = thermal control system

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I. Introduction

HUMAN spaceflight is central to the mission of SpaceX – making humanity multiplanetary. The first astronauts the company will fly will be on the Crew Dragon spacecraft (Figure 1) to the International Space Station (ISS). A major development for this vehicle is the Environmental Control and Life Support System (ECLSS). While Crew Dragon's predecessor (Dragon 1) has a basic environmental control system sized for carrying mice, the demands of crew are far higher, and the list of potential faults and contingencies that the system must cope with is extensive. Additionally, the system must undergo rigorous testing in order to be considered qualified for human flight. In this paper, we review the requirements imposed on the ECLSS, how the design evolved to meet the requirements, and how its performance was tested.

II. Commercial Crew ECLSS Requirements

In a broad sense, the purpose of the ECLSS is to maintain a habitable environment for the crew within the pressurized cabin. Human metabolism consumes oxygen while producing carbon dioxide, water vapor, and waste. The ECLSS has to replenish the consumed oxygen, scrub carbon dioxide, and remove water vapor. It also regulates the pressure of the cabin atmosphere throughout all nominal phases of flight and during contingencies such as damaged sealing. It works in concert with the thermal control system (TCS) and air conditioner (AC) to keep the cabin in temperature ranges acceptable to crew and powered cargo. Finally, a gaseous nitrogen fire suppression system with fixed and portable flow paths is provided for emergency use.

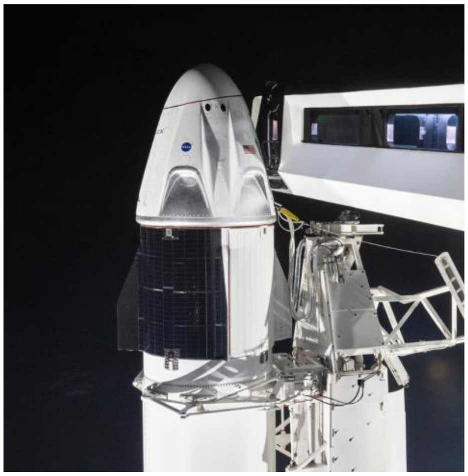

Figure 1: Crew Dragon on the launch pad. *Demo-1 mission, March 2018.*

A. Customer

The cabin environment requirements are given by CCT-REQ-1130 which specifies a cabin pressure of 96.5 kPa (14.0 psia) to 102.7 kPa (14.9 psia), ppO_2 of 19.4 kPa (2.82 psia) to 22.7 kPa (3.30 psia), $ppCO_2$ not to exceed 4 mmHg, temperature of 18.3 to 26.7 °C, and relative humidity of 25-75%. These requirements pertain to nominal unsuited operations. For the reentry phase of flight, the crew is supplied with air that has been cooled through the addition of cold nitrox, so the maximum permitted powered cargo inlet air temperature of 29.4 °C becomes the driving requirement for cabin air temperature.

The mission duration is not directly specified in the requirements documents but is the result of a collaborative process between SpaceX and NASA to define the conops for nominal missions and contingency scenarios. The derived requirement is approximately five days of free flight for the worst case. Given a crew size of four, this means that the ECLSS consumables must last for 20 person-days using conservatively high metabolic loads and conservatively low efficiency of utilizing each consumable. No additional safety factor is applied since each input to the consumables analysis is worst-case. Some consumables are sized for a worst-case scenario other than total mission duration; for example, nitrox quantity is driven by the vent and repress scenario (see page 4).

CCT-REQ-1130 specifies that systems used to control a catastrophic hazard shall be redundant, which includes the ECLSS. This means that the system must be robust to the failure of any single valve, fan, sensor, or other component. Redundancy adds substantial complexity to the system in order to protect against the multiple failure modes that components can have; for example, a single valve must become a quadrature of valves in order to be tolerant to any one of them failing either open or closed. Engineering judgement and requirements documents are used to assess which failure modes are considered credible. For example, per CCT-REQ-1130 3.2.3.1, pressure vessels are not required to be failure tolerant as long as the risk of their catastrophic failure can be adequately controlled through means other than redundancy.

B. Internal

SpaceX's internal posture on controlling catastrophic hazards is to incorporate two-fault tolerance wherever the impact of doing so (such as in complexity or mass) is not extreme, going beyond the customer requirement. To this end, most groups of sensors used in the ECLSS are triplicated, and most airflow requirements are met by a single fan out of a group of three.

Reusability is central to SpaceX's goal of lowering the cost of space transportation, so the Crew Dragon ECLSS is designed for rapid refurbishment to support multiple missions with the same vehicle. The focus on reusability motivated placing the entirety of the ECLSS, as well as all TCS components other than the radiator, within the reentry vehicle rather than the disposable trunk.

III. Subsystem Design Overview

Most of the ECLS subsystems on Crew Dragon are divided into two major groups: air revitalization and ox-nitrox. The former focuses on cleaning, decontaminating, and conditioning the cabin air while the latter contains, feeds, and releases pressurized gases. Most ECLSS components are located under the floor within the pressurized section since they directly interact with the cabin environment. Other components, primarily from the AC and TCS subsystems, are located where volume permits in the service section which is within the backshell of the capsule but not pressurized while on-orbit (Figure 2). The trunk is a separate module attached to the aft end of the capsule and jettisoned before reentry; its only function related to environmental control is to host the TCS radiator (covering the side of the trunk facing out of the page in Figure 2) to reject heat from the vehicle to space.

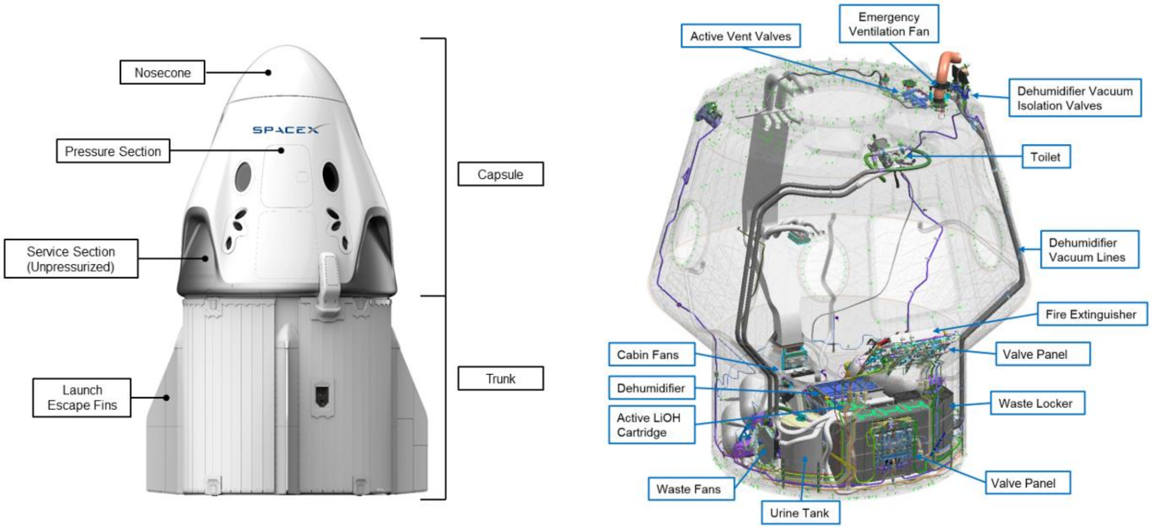

Figure 2. The Crew Dragon spacecraft and ECLSS. *Four crewmembers fly in the pressure section; the ECLSS is primarily located under the floor within this volume.*

A. Pressure Control

The Pressure Control system incorporates three major elements to maintain cabin pressure within the human and structural design requirements. These are the Active Vent Valves (AVVs), the Positive Pressure Relief Valve (PPRV), and the Negative Pressure Relief Valve (NPRV). Additionally, the spacecraft has a manual pressure equalization plug on each hatch to permit individuals outside the capsule (either astronauts on station or the recovery team) to manually equalize pressure. All valves and plugs typically remain uncapped throughout a mission, inclusive of the time on station, but caps are provided in case a leak is suspected.

The AVV quadrature, composed of four latching solenoid valves with manual overrides, is used for nominal cabin pressure control, automatic equalization with the ISS vestibule after docking and external atmosphere after landing, vestibule depressurization, and the nitrox entry purge. The AVVs prevent high cabin pressure by opening and venting the cabin to space when cabin pressure increases above a high pressure threshold. The only times when active cabin pressure control is expected to be needed is for the nitrox cooling purge during entry and possibly during suit leak checks (i.e. when gas is introduced into the cabin), detailed later in the paper. The quadrature of valves is single-fault tolerant in their primary role of cabin pressure regulation.

B. Oxygen and Nitrox System

Dragon stores gaseous oxygen for metabolic consumption and for use in the space suit during an emergency involving a depressurized cabin. It uses nitrox, a mixture of 23% oxygen and 77% nitrogen, for a variety of applications including suit leak checks, providing gas in a contaminated atmosphere scenario to breathing masks or the space suit, diluting a contaminated atmosphere, and feeding a cabin leak. A novel use of nitrox is also for cooling both the cabin and space suit air during reentry as the capsule thermal control system is limited during this phase of flight. Nitrox was selected over dedicated nitrogen tanks because it does not require mixing with oxygen and can feed the space suit directly. With a nitrox system, a leak of gas can never result in a hazardous oxygen concentration at nominal cabin pressure.

Under the floor of Dragon, oxygen and nitrox is stored in two packs of three composite overwrapped pressure vessels (COPVs), each with its own regulator. The tanks are based on the NASA X-38 crew return vehicle oxygen tanks and are designed and qualified per AIAA-S-081. Two tanks contain oxygen and four contain nitrox. Two bottle pack assemblies prepared for integration are shown in Figure 3.

1. *Oxygen and Nitrox Regulator*

The SpaceX-designed regulator assembly connected to each COPV contains a fill valve and motor-actuated ball valve in addition to providing pressure regulation capability. Key requirements for the regulator include operation under near-cryogenic temperatures (due to adiabatic expansion of the gas) and high-pressure oxygen compatibility. A commercially available copper-nickel-tin alloy called Toughmet is used for many parts of the regulator since it provides high strength and has passed promoted ignition testing at up to 69 MPa (10,000 psi) of oxygen. Toughmet also has good wear resistance and machinability.

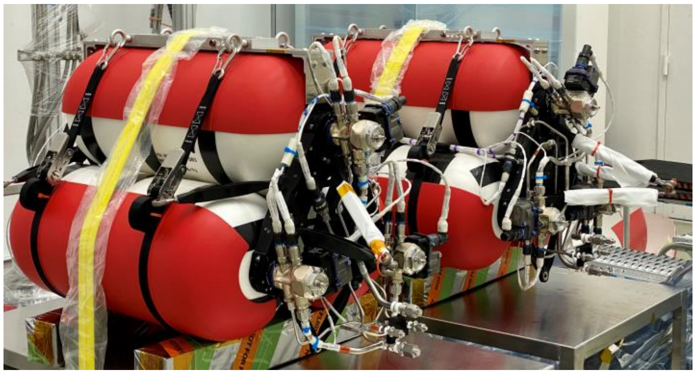

Figure 3: Oxygen and nitrox bottle packs.

The check valve within the regulator used for filling the COPV uses geometry and materials adapted from a pintletip design for a Mars Sample Analysis Solenoid Valve developed at Goddard Space Flight Center[1]. This provides a very low leak rate that improves over time as components burnish against each other.

2. *Oxygen and Nitrox Delivery*

Nitrox delivery to the cabin is controlled by a set of solenoid valves called cabin repress valves mounted on a distribution panel with downstream diffusers. These valves are nominally used to perform a nitrox cooling purge during reentry in which cold nitrox is purged through the cabin in order to cool the cabin air below 29.4 °C. The cabin purge is driven by latching open the outer AVV string and controlling cabin pressure with repress valve injections to keep it between the low and high cabin pressure thresholds.

A separate valve controls flow to the suit air duct upstream of the suit fans. This valve is used for cooling the suit air during reentry to maintain the suit inlet temperature between 12.8 and 26.7 °C by mixing nitrox chilled by adiabatic expansion into the fan airflow going to the suits.

In a contingency involving a depressurizing cabin, the two primary cabin repress valves are commanded open to feed the leak and attempt to maintain cabin pressure above 8 psia (55 kPa). For equivalent hole diameters of up to 0.6” (15 mm), the flow rate from two repress valves is more than that through the hole, and thus cabin pressure can be maintained above 8 psia for as long as nitrox consumables permit. There are sufficient consumables to feed a leak from a 0.25” (6 mm) hole for the worst-case emergency deorbit duration. For larger hole sizes, Dragon will stop feeding the leak when a nitrox reserve mass is reached and allow the cabin to depressurize, feeding oxygen to the suits. When reentering with a depressurized cabin, the repress valves flow nitrox into the cabin as the external pressure increases.

Another contingency in which the AVVs are used is a contaminated atmosphere resulting from a fire. If toxic combustion product levels are below a defined threshold, the cabin is purged with nitrox using the primary repress valves while the AVVs maintain a cabin pressure of 8.0-8.5 psia (55-59 kPa). If the atmosphere is even more contaminated, it can be vented to near-vacuum and replaced with clean nitrox using both cabin repress valve sets.

The single nitrox manifold has triplicated pressure transducers to monitor system status. If high manifold pressure is detected, the manifold is “burped” to relieve pressure by opening downstream primary repress valves briefly. If manifold pressure continues to rise, the system is safed and the tank isolation valves are closed. Should pressurization above 1.22 MPa occur, burst discs and relief valves passively open to keep pressure below the maximum design pressure of 1.72 MPa. Gas is vented out of the pressure section through two pass-throughs in the forward bulkhead to prevent damage to downstream components.

3. *Gas temperatures*

A challenge in high-pressure gas systems, particularly in space, is managing the cold temperatures during use. Initial low-temperature qualification bounds were set via flow testing with the tank in a hard vacuum environment. However, a paper about the Orion Consumables Storage Subsystem[2] described a lack of gravity-driven natural convection within the interior of the tank resulting in the possibility of temperatures near the isentropic theoretical limit and well below our ground test data. This motivated a new CFD model (Figure 4) and extensive testing to understand the true low temperature bound. The model was validated against both the Orion model and Falcon 9 Stage 2 data. The derived heat transfer coefficients were then incorporated into larger ECLSS models using a polytropic gamma that can reasonably predict tank temperatures throughout a variety of nominal and emergency operations. These models informed design changes to ensure that the tanks were correctly flow-balanced in zero-g. Orifices were added downstream of each regulator to ensure all four nitrox tanks flow in parallel during high-use scenarios such as a cabin depressurization. The flow-balancing orifices maximize the efficiency of extracting gas from the tanks and help ensure that gas temperatures remain within component capabilities.

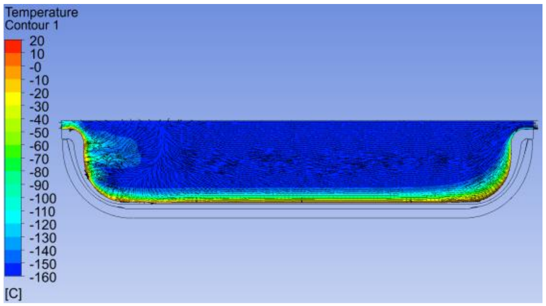

Figure 4: COPV microgravity CFD.

4. *Ground Support Equipment*

An important aspect of spacecraft development is ground support equipment and the checkout processes with which it is associated. Early in the development of the oxygen and nitrox system SpaceX created several automated carts that can supply vacuum as well as gases at up to 69 MPa (10,000 psi) such as the one shown in Figure 9. Temperature control using liquid nitrogen heat exchangers and electric heaters enable outlet temperature to be modulated down to -150 °C. Oxygen safety measures include chilling the gas into the boosters, slow-opening valves, and use of Monel 400 components.

By chilling the gas inlet to the COPVs such that the internal energy of the gas at the inlet equals the final enthalpy of the gas contained within the COPV at room temperature, the tanks can be pressurized in under one hour to their target densities while maintaining average internal gas temperatures near room temperature. Temperature stratification of up to 50 °C during rapid fills does occur; however, qualification testing showed that this is not a structural concern for the tank. Temperature readings of the tank gas using the flight sensor yield an accurate live measurement of bulk gas temperature during 1 g transient fill and drain cycles.

Figure 5: The Demo-2 crew in their suits.

With such a versatile pressure testing and automation platform, we can perform a variety of qualification, acceptance, and development testing with the same piece of equipment.

C. Space Suit Interfaces

Crew Dragon uses open loop, air-cooled, SpaceX-developed intravehicular pressure suits (Figure 5). The suit provides each crewmember with environmental protection, occupant protection, and emergency pressurization during contingency events, and is designed to remain as invisible as possible to the crew during nominal operations. The suit is a fully integrated garment that includes permanently attached boots, gloves, and a helmet. An umbilical is connected to each suit which distributes recirculated cabin air for suit cooling, delivers nitrox or oxygen for suit leak checks and contingency operations, and contains an electrical interface for pressure sensing and communications when the crew is suited.

The suit fluid module which feeds the umbilical is a small valve tray mounted inside the seat structure shell containing the main components of the suit fluid management system: a solenoid isolation valve with manual override, a regulator, flow control orifice, suit air check valve, and buddy breathe quick disconnect. The buddy breathe functionality permits a crewmember in a seat with a malfunctioning solenoid valve or regulator to receive gas from an adjacent seat.

D. Air Revitalization

The air revitalization system, composed of the air sanitation, dehumidifier, and air distribution subsystems, serves to circulate cabin air while removing carbon dioxide, trace contaminants, particulates, and humidity. The air sanitation box and dehumidifier are discrete subassemblies arranged in series under the floor of the spacecraft; cabin air is pulled through these assemblies and distributed throughout the cabin and to the suits through duct networks. Locating the fans downstream of these subassemblies reduces pressure drop through the manifolds surrounding the fans and minimizes the possibility of ingesting foreign object debris (FOD) into the fans.

1. Air Sanitation

Scrubbing crew metabolic waste products from the cabin is accomplished using four different types of air filters located in the air sanitation box, arranged so as to provide adequate flow to each filter while minimizing total pressure drop.


Figure 6: LiOH cartridge.

Lithium hydroxide (LiOH) cartridges are used for scrubbing crew-generated carbon dioxide (Figure 6). Each cartridge contains four LiOH cubes originally developed for submarines. The actively scrubbing cartridge can be replaced in flight as needed, with one swap required for a mission of nominal duration. The air sanitation box provides a storage location for three replacement cartridges.

Trace contaminants produced by human metabolism and material offgassing are scrubbed using a filter which has activated carbon media within fabric pleats. Immediately downstream of the trace contaminant filter is a high efficiency particulate air (HEPA) filter which removes particulates and mitigates any potential FOD produced by the trace contaminant filter. It is an off-the-shelf component with similar construction to the trace contaminant filter. Off-the-shelf as well as in-house components go through comprehensive qualification testing campaigns, which in the case of filters includes performance, pressure, shock, and vibration. Pressure drop throughout the life of the filter is especially important to quantify to ensure that the various elements in series or parallel will experience airflow rates within their required bounds.

Ammonia is scrubbed by a dedicated ion exchange resin filter on the downstream end of the air sanitation box. A filter medium with high efficiency and capacity for scrubbing ammonia is needed to protect the dehumidifier subsystem's Nafion membranes from chemical contamination; the susceptibility to performance degradation from ammonia exposure was discovered fortuitously during operation of the Dragon-1 ECLSS dehumidifier and subsequent testing of flown units, as detailed on page 8. The trace contaminant, HEPA, and ammonia filters are replaced on the ground between missions.

2. Dehumidifier

Humidity in Dragon is controlled by a dehumidifier system while on-orbit (Figure 7). The dehumidifier uses the vacuum of space to draw humidity across water-permeable (but air-impermeable) Nafion membranes. Control valves allow for selective enabling of four Nafion banks to autonomously control the rate of water vapor removal. Two vacuum lines allow for removed water to be vented to space. Each line has an isolation valve to turn off the system when the capsule is in the atmosphere or on-station.

Compared to a condensing heat exchanger, the Nafion dehumidifier is passive and does not require water phase separation and storage to successfully operate; instead, the water remains in the vapor phase on both the cabin side and vacuum side of the membrane and is rejected to space. This saves power or cooling that otherwise would be needed to condense the water during flight. Additionally, the mass of the water leaves the vehicle and does not need to be stored or dumped using another system. Validation of the system's driving physics during ground testing is relatively simple as the system operates identically in microgravity and 1-g. Modulation of water removal rate is facilitated by the fact that water flux through Nafion increases with higher humidity, such that the system finds a stable equilibrium humidity with a given number of control valves open at a certain humidity generation rate.

Dehumidifier sizing was dictated by crew metabolic water generation rate and target cabin humidity, the latter of which is based on the cabin air dew point required to preclude condensation on the pressure section interior. The large required membrane area led to an extensive manufacturing development campaign for the Nafion banks which resulted in setting up dedicated shop floor space, tooling, and test assets in an ammonia-controlled environment. In addition to manufacturing difficulty a disadvantage of this system architecture is its susceptibility to chemical degradation which is further described later in this paper. Overall, although this system design is well suited for the mission scope of Crew Dragon, its architecture is not directly applicable to long-duration ECLSS since it would be impractical to recover the rejected water. However, lessons learned from the design and production processes will nevertheless be useful to the development of future systems that use physically and chemically sensitive membranes.

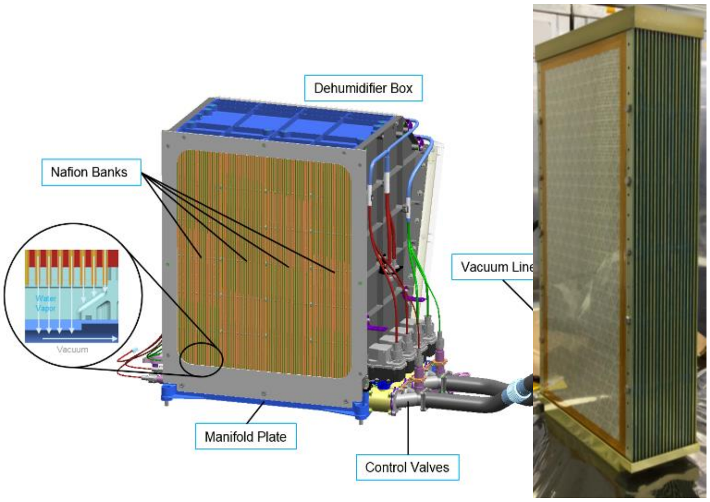

Figure 7: Dehumidifier box (left) and Nafion blade bank (right).

3. Air Distribution

Air which has been scrubbed of carbon dioxide, trace contaminants, particulates, and humidity, and has been thermally conditioned by passing through the TCS heat exchangers is directed through the main cabin ducting to provide adequate mixing of air in the habitable volume. An overview of the ducting layout can be seen in Figure 2.

Airflow through the air revitalization system and the cabin ducting is provided by cabin fans. To be two-fault tolerant to losing cabin airflow, there are three cabin fans, one of which runs at a time. Elimination of recirculation within the fan assembly is provided by a shuttle valve called the flapper box which also provides a streamlined duct downstream of the active fan to minimize pressure drop (Figure 8).

Figure 8: Flapper box. *Operating modes with center fan and left-hand fan active.*

An additional pressure source is required to push air into the suits during nominal suited operations due to their significantly higher flow impedance than the rest of the air distribution system. For this purpose, a triplicated set of suit fans is provided, one of which runs at a time. Fabric check valves serve to prevent recirculation at the low volumetric flowrate required by the spacesuits.

E. Air Conditioning

For phases of flight where the capsule is in space, the TCS radiator provides an efficient method of rejecting waste heat. The radiator is composed of aluminum panels mounted to the outside of the trunk through which coolant is pumped. For brief periods such as reentry, the thermal mass of the capsule, combined with sufficient insulation from the heatshield, ensures safe cabin temperatures. After reentry, however, a means for rejecting heat is again necessary as the capsule sits in the ocean. (While nominally expected to be recovered by a vessel in less than one hour, conditions have to remain safe for crew and powered cargo for two hours). Complicating the thermal story is the fact that the nominal splashdown zone for the capsule is the Atlantic Ocean off the coast of Florida, where the water is typically warm, so rejecting heat directly into the ocean is not possible. For this reason, Crew Dragon has a vapor compression cycle air conditioning system with a hydrofluorocarbon refrigerant that uses the external atmosphere as a heat reservoir to reject heat (both sensible and latent) from the cabin air via fans blowing air through a condenser. This system turns on once main parachutes have deployed and runs for up to two hours following splashdown. It is also used on the launch pad after hatch closure to control cabin humidity and temperature. The air conditioning system controls the cabin environment without the communication of any air across the pressure vessel boundary, which will keep the crew safe in the event that there are propellant vapors outside.

IV. Testing and Validation

Crew Dragon's ECLSS has been extensively tested at many levels of integration during the course of the program. Component operations have been demonstrated in flight testing on the Dragon 1 spacecraft as well as in formal qualification testing on the ground to meet the requirements of SMC-S-016. The full ECLSS has been tested in three capsules – the ECLSS Module, Demo-1, and finally the Demo-2 spacecraft which will be the first to fly crew.

A. Dragon 1

The Dragon 1 ECLSS was designed to accommodate an Animal Enclosure Module (AEM) and powered cargo for delivery to and from the ISS. This system met all operational requirements during Commercial Resupply Services (CRS) missions. Development and implementation of the Dragon 1 ECLSS provided flight heritage and lessons that were applicable to components and subsystems for Crew Dragon.

1. LiOH

The same off-the-shelf LiOH cube was used for the Dragon 1 ECLSS (in smaller quantities) that is now used for Crew Dragon. A particular design challenge of this component was structural constraint of the cubes in order to well-support them while permitting swelling as CO_2 is absorbed. Implementation on Dragon 1 allowed for validation of the design's functional operation in flight (including controlling humidity when the dehumidifier was not active), as well as structural validation of the cubes (specifically showing that dusting is not a problem) before they were implemented in the Crew architecture.

2. Dehumidifier

Dragon 1 ECLSS used a Nafion dehumidifier for humidity control, the first time such a system was used in a spacecraft. This system was schematically similar to the Crew Dragon dehumidifier (albeit with much less membrane area) and provided flight data that drove requirements changes to the Crew air sanitation system to mitigate Nafion contamination.

This system was first implemented on the CRS-4 mission and was found to be less effective than predicted, originally attributed to possible blockage in the vent path to vacuum. However, this cause was eventually exculpated. The recovered CRS-4 and -6 dehumidifiers were performance tested in a sealed chamber and found to be significantly less effective than newly manufactured assemblies. Samples of fresh, un-flown, and flown Nafion were taken for lab testing, the results of which suggested that the degradation was likely due to ammonia exposure during flight. Further testing was performed to determine the ambient ammonia concentration in various SpaceX facilities, and separately to characterize how ammonia is absorbed by Nafion.

Based on this conclusion, design and operational mitigations were implemented for the Crew Dragon dehumidifier so it can maintain its required performance margin throughout multiple missions. A dedicated ion exchange filter for ammonia was sized with capacity to maintain high efficiency while scrubbing the crew metabolic ammonia load plus the ammonia encountered when the cabin fan is operating while docked with ISS. Fan on-time constraints while the hatch is open on-station were implemented in part to minimize ammonia exposure.

3. Oxygen

To replenish metabolic oxygen consumed by the mice, a small high-pressure oxygen system was developed. It consisted of two COPVs feeding independent regulated manifolds. A relief system protected the downstream manifold from regulator failure. While this system was considerably smaller than that later used for crew, it shared the principal architectural elements.

B. Component Qualification

Component and subsystem qualification for Crew Dragon generally follows the process outlined in SMC-S-016 including proof, leak, performance, shock, vibration, thermal, electromagnetic interference, thermal vacuum, and static load testing as applicable.

Oxygen and nitrox COPV qualification per AIAA-S-081 (Figure 9) was an intensive process building on the original testing performed in the X-38 program in the 1990s. Fiber-optic strain gages were embedded within the overwrap to validate structural models. Vibration testing of a fully pressurized COPV was conducted with care given the large stored energy and safety concerns in addition to the magnitude of the levels. The aluminum liner plastically responds during proof and autofrettage so safe life was demonstrated via coupon testing instead of linear elastic fracture mechanics. Safe life testing involved cycling pre-cracked coupons while monitoring crack growth via electric potential drop. This testing motivated improvements to the tank inspection procedure to detect smaller flaws and also resulted in reducing the rated cycle life. Additional testing was performed to demonstrate thermal margin in the bond line, validate the fill process, and guarantee consumables quantities.

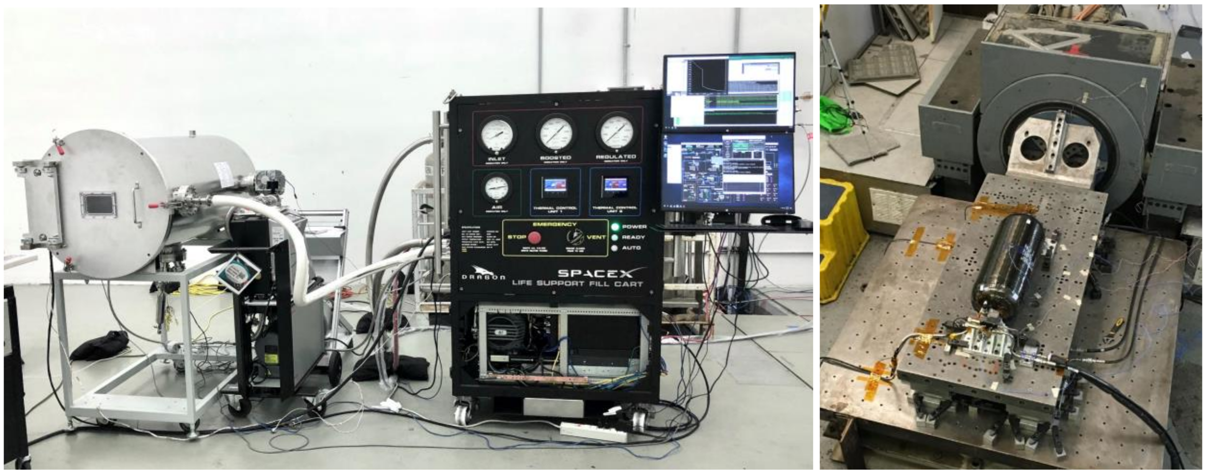

Figure 9: COPV testing. *Left: Proof and leak testing. Right: Vibration qualification testing.*

C. ECLSS Module

The first integrated demonstration of the Crew Dragon ECLSS was performed in November 2016. This four-hour test used the ECLSS Module which was composed of a Crew Dragon primary structure with the air revitalization system and ox-nitrox system installed (Figure 10). There were no seats or other interior hardware. The purposes of this test were to demonstrate ECLSS functionality under flight-like metabolic loading and to refine the design of conops and control schemes. Test participants conducted periods of exercise to create transients in the humidity and CO_2 loads.

Figure 10: ECLSS Module.

The ECLSS successfully maintained the cabin environment within the required parameters during the course of this testing. It was a valuable opportunity to practice integrating the full system into a flight-like primary structure. Follow-on tests were performed using this capsule to further investigate effects seen in the initial testing and to improve performance, such as adjusting the configuration of the dehumidifier control algorithm. In addition, the testing revealed idiosyncrasies of the cabin environment sensors based on the specifics of where they were placed (such as the airflow conditions surrounding them) which resulted in adjusting which sensor locations were used in assessing which environmental parameters.

The ECLSS Module is still used for development testing as of 2020.

D. Demo-1

In March 2019 Crew Dragon flew on its maiden uncrewed test flight, the Demo-1 mission to the ISS. Its primary objective was to demonstrate the capability to launch, rendezvous and dock with ISS, and return to Earth. A crew-capable ECLSS was flown on this mission and maintained the cabin environment to meet cargo requirements while demonstrating functionality under dynamic conditions. This mission provided a partial validation of subsystem performance and operational characteristics to the degree possible with no metabolic load. A brief overview of noteworthy data follows.

1. Trace Contaminant Filter

Slightly elevated isopropyl alcohol (IPA) levels in cabin air were detected during the ISS-docked phase of Demo-1. Post-flight, it was determined that the trace contaminant filter had likely adsorbed IPA vapor from capsule interior cleaning late in the integration process. As a result of this lesson learned, several operational constraints were put in place to mitigate IPA exposure and release by the trace contaminant filter for future flights. Production planning for filters has been updated to avoid the use of IPA for cleaning. For capsule cleaning shortly before launch, hydrogen peroxide is now used instead of IPA. Install of the filter for flight is required to be within this window so as to minimize exposure to IPA-based cleaning compounds.

2. Pressure Rebound and Temperature Effects

During Demo-1 free flight several venting events occurred due to cabin temperature changes. While temperature-induced pressure changes were expected, after cabin pressure was vented a small rebound in pressure occurred over the course of several seconds after the venting event. The rebound is suspected to be from air trapped inside volumes within the cabin that are partially sealed such as bins, foams, and other containers. The pressure control scheme was updated to anticipate this capacitance in future flights.

E. Human-in-the-Loop Testing

In January 2020, following checkouts of the ECLSS in the Demo-2 capsule, the team performed human-in-the-loop testing as the most high-fidelity demonstration of integrated life support functionality that could be undertaken before flight (Figure 11). This test was not a customer requirement, but was driven internally by engineering to better understand and validate the system as a whole. Human-in-the-loop testing exercised significantly more of the vehicle than the earlier ECLSS Module testing: it demonstrated both nominal and some contingency operations, handoffs between various subsystems, and the interaction of ECLSS hardware with avionics and flight software. Far more than a life support test, it was intended to be a demonstration of how many of the most important elements required for crew flight would interact.

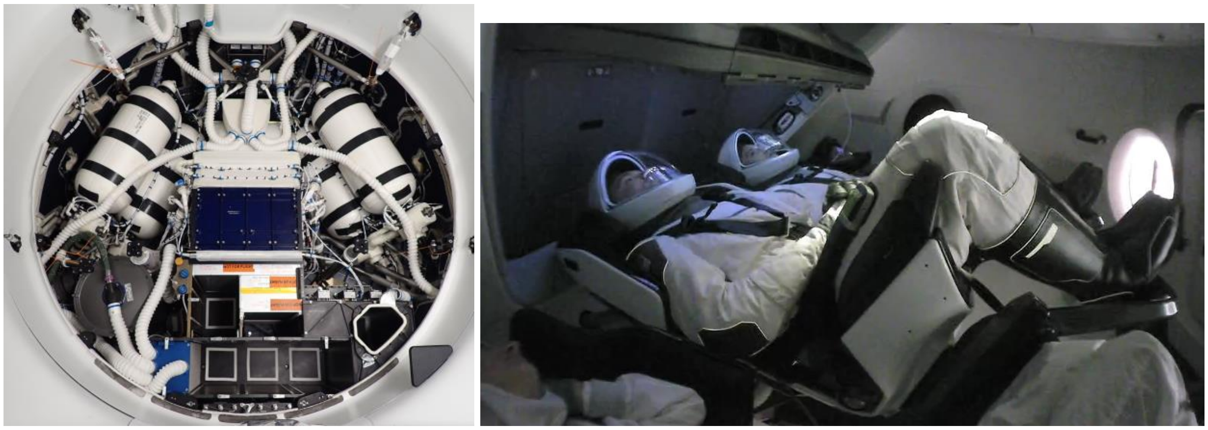

Figure 11: The Demo-2 spacecraft. *Left, the ECLSS under the floor; right, during human-in-the-loop testing.*

This testing in Hawthorne, California involved two separate cases, ascent and reentry, with four test participants (a full crew complement) providing a metabolic load and performing crew activities at the appropriate times. During the ascent case, the capsule was initially configured as if it was on the launch pad, with conditioned air blown through the hatch. The test participants entered and conducted leak checks on their spacesuits. The air revitalization, ox-nitrox, and air conditioning systems were enabled prior to hatch closure. Slightly less than two hours later, when the vehicle would nominally arrive on-orbit, a ground vacuum system was used to expose the pressure control and dehumidifier flow paths to vacuum so that they could be used for venting the cabin and controlling humidity. The ascent test also included the test participants doffing their suits in the cabin, a swap to an end-of-life LiOH cartridge to gather data on telemetry indications in that scenario, and a reduction in airflow to simulate a failure in the air distribution system.

The reentry case lasted two and a half hours and began with the ground vacuum system operational as if the capsule was docked to the ISS. The test participants entered the capsule and performed suit leak checks with the hatch closed. During this operation, the pressure control system vented the cabin due to the pressure increase caused by nitrox flowing to the suits; this did not cause any problems with the leak check success criteria and was a key objective of the test. Later, nitrox purges were used to cool the suits and cabin. The air conditioning system activated at the time of main parachute deployment. The hatch was opened and the test case ended after 25 minutes in the splashdown configuration.

Human-in-the-loop testing was treated with equal rigor to an actual crewed mission in how the software configurations were tested and how the data was reviewed. It provided a valuable dataset to help the team understand what telemetry should look like during nominal and off-nominal operations. During testing, all subsystems performed well and controlled the environment within requirements. Several opportunities to further optimize control parameters were identified relating to the AC system and the cabin pressure control system. The performance of the air revitalization system was more robust than expected when airflow was intentionally reduced below nominal, with only a very gradual drift of the cabin environmental parameters away from the centers of the intended bounds.

V. Conclusion

Over the past four years, an ECLSS for the Crew Dragon spacecraft has been designed and tested. Its hardware, software, and operations continually evolved with the larger vehicle. Critical to the success of the development process was the vertically integrated organizational structure of SpaceX in which teams developing components, subsystems, sensors, software, operations, and manufacturing processes work together closely and constantly. There was a tight feedback loop between system- and component-level design criteria for new products such as sensors and valves in which both requirements and capabilities were rapidly driven to convergence. The highly integrated nature of the teams makes it possible to iterate quickly through testing of components, subsystems, flight prototypes, and full flight systems. This philosophy of extreme ownership extends to the operational phase of the vehicle when ECLSS engineers act as specialists in Mission Control, ensuring that the individuals who best understand the hardware are available to rapidly assess its performance and advise the operational team.

The Crew Dragon ECLSS is prepared to support the return of American astronauts to space. The integrated nature of its development process and the rigor of its testing will serve as the model for similar systems in future SpaceX vehicles.

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