NASA/TM–20210013869
NESC-RP-14-01012

Risk Reduction of Orion Multi-Purpose Crew Vehicle (MPCV) Program Government-Furnished Equipment for Environmental Control and Life Support (ECLS)

Clinton H. Cragg/NESC
Langley Research Center, Hampton, Virginia

John C. Graf
Johnson Space Center, Houston, Texas

Alan Hobbs
Ames Research Center, Moffett Field, California

April 2021

NASA STI Program Report Series

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counterpart of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- Help desk contact information:

https://www.sti.nasa.gov/sti-contact-form/
and select the "General" help request type.

NASA/TM–20210013869
NESC-RP-14-01012

Risk Reduction of Orion Multi-Purpose Crew Vehicle (MPCV) Program Government-Furnished Equipment for Environmental Control and Life Support (ECLS)

Clinton H. Cragg/NESC
Langley Research Center, Hampton, Virginia

John C. Graf
Johnson Space Center, Houston, Texas

Alan Hobbs
Ames Research Center, Moffett Field, California

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

April 2021

Acknowledgments

The following individuals are recognized for their expertise, technical insight, and generosity in teaching members of the assessment team the fine points of their disciplines:

- Harold Beeson (NASA White Sands Test Facility (WSTF), retired): oxygen safety, test design, flammability.
- Gus Sarkos (Federal Aviation Administration (FAA)): fire safety, methods development for standard performance tests.
- Neil Scholes (United Kingdom (UK) Royal Navy – retired): emergency response systems in submarines.
- Rich Stein (formerly United States (US) Bureau of Mines): contingency breathing system design and test.
- Joel Stolzfus (NASA WSTF, retired): oxygen safety, test design, flammability.
- Frank Tittel (Rice University, retired): laser spectroscopy, methods of gas monitoring.

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

NASA Engineering and Safety Center
Technical Assessment Report

Risk Reduction of Orion Multi-Purpose Crew Vehicle (MPCV) Program Government-Furnished Equipment for Environmental Control and Life Support (ECLS)

March 25, 2021

Report Approval and Revision History

NOTE: This document was approved at the March 25, 2021, NRB. This document was submitted to the NESC Director on March 30, 2021, for configuration control.

Approved:	*Original Signature on File*	4/1/21
	NESC Director	Date

Version	Description of Revision	Office of Primary Responsibility	Effective Date
1.0	Initial Release	Clinton H. Cragg, NESC Principal Engineer, LaRC	3/25/2021

Table of Contents

Technical Assessment Report

List of Figures

List of Tables

Technical Assessment Report

1.0 Notification and Authorization

The NASA Engineering and Safety Center (NESC) was requested to conduct technical risk-reduction activities for safety-critical government-furnished environmental control and life support (ECLS) equipment for the Multi-Purpose Crew Vehicle (MPCV) Program. These items include the post-landing anomaly gas monitor, the in-flight anomaly gas monitor, the emergency breathing mask, the 144-hour in-suit survival capability, the portable fire extinguisher, the smoke eater, and the post-landing carbon dioxide (CO_2) control system.

The key stakeholders for this assessment include:

- MPCV: the Orion ECLS System Manager and the Orion Functional Area Manager.
- The International Space Station (ISS) Program: the ISS Vehicle Manager; the ISS ECLS System Manager and the ISS Gas Monitoring System Manager.
- Safety and Mission Assurance (S&MA): the Johnson Space Center (JSC) ECLS S&MA.

2.0 Signature Page

Submitted by:

Team Signature Page on File – 4/12/21

Mr. Clinton H. Cragg Date

Significant Contributors:

Dr. John C. Graf Date

Dr. Alan Hobbs Date

Signatories declare the findings, observations, and NESC recommendations compiled in the report are factually based from data extracted from program/project documents, contractor reports, and open literature, and/or generated from independently conducted tests, analyses, and inspections.

3.0 Team List

Name	Discipline	Organization
Core Team		
Clint Cragg	NESC Lead	LaRC
Hank Rotter	Former NESC Lead	JSC (retired)
John Graf	Technical Task Point of Contact (POC)	JSC
Alan Hobbs	Human Factors	ARC
Mary Kaiser	Human Factors	ARC
Chris Nagel	Technical Task POC	JSC
Jeff Sweterlitsch	Technical Task POC	JSC
Mary Coan Skow	Technical Task POC	JSC
Consultants		
Nik Adam	Technical Expert: Water Chemistry	JSC
Wade Bostick	S&MA	JSC
Grant Bue	Technical Expert: Thermal Systems	JSC
Colin Campbell	Technical Expert: Spacesuit Sensors	JSC
Cinda Chullen	Technical Expert: Spacesuit Sensors	JSC
Paul Greenberg	Technical Expert: Particulates	GRC
Susana Harper	Technical Expert: Fire Testing	WSTF
Mark McClure	Technical Expert: Chemical Analysis	WSTF
Paul Mudgett	Technical Expert: Gas Monitoring	JSC
Moses Navarro	Technical Expert: Computational Fluid Dynamics Analysis	JSC
Mike Pedley	Technical Expert: Materials and Processes	JSC
Gary Ruff	Technical Expert: Fire Safety	GRC
Gene Ungar	Technical Expert: Thermal Systems	JSC
Business Management		
Linda Moore	Program Analyst	LaRC/MTSO
Assessment Support		
Linda Burgess	Planning and Control Analyst	LaRC/AMA
Jonay Campbell	Technical Editor	LaRC/KBR
Kylene Kramer	Project Coordinator	LaRC/AMA

3.1 Acknowledgments

The following individuals are recognized for their expertise, technical insight, and generosity in teaching members of the assessment team the fine points of their disciplines:

- Harold Beeson (NASA White Sands Test Facility (WSTF), retired): oxygen safety, test design, flammability.
- Gus Sarkos (Federal Aviation Administration (FAA)): fire safety, methods development for standard performance tests.
- Neil Scholes (United Kingdom (UK) Royal Navy – retired): emergency response systems in submarines.
- Rich Stein (formerly United States (US) Bureau of Mines): contingency breathing system design and test.
- Joel Stolzfus (NASA WSTF, retired): oxygen safety, test design, flammability.
- Frank Tittel (Rice University, retired): laser spectroscopy, methods of gas monitoring.

4.0 Executive Summary

This is an assessment of Environmental Control and Life Support (ECLS) equipment that is being developed and supplied to the Orion Multi-Purpose Crew Vehicle (MPCV) Program[1] as Government Furnished Equipment (GFE). This equipment is being designed, developed, and qualified for flight by the Johnson Space Center (JSC) in compliance with EA-WI-023 [ref. 1]. This report focuses on three pieces of equipment that support the Orion Fire Safety System: the Contingency Breathing Apparatus (CBA); the Orion Portable Fire Extinguisher (OPFE); and the Orion Smoke Eater Filter (OSEF). Information about the Laser Air Monitor, the Anomaly Gas Analyzer, the Post-Landing Lithium Hydroxide (LiOH) system, and the Collapsible Contingency Urinal is provided in Orion Program design review documentation.

This assessment evaluates the CBA, the OPFE, and the OSEF from three perspectives: 1) physical aspects of the hardware; 2) organizational and process controls that structure the development activities; and 3) human-systems integration (HSI). The key findings for each of these three perspectives are listed below.

Physical assessment key findings:

- The Orion Program is using the appropriate type of fire safety equipment. NASA is developing unique GFE rather than purchasing commercially available equipment or recertifying Space Shuttle Program (SSP) or International Space Station (ISS) hardware. This is correct and appropriate; Orion fire safety needs are unique and specific.
- The CBA, OPFE, and OSEF designs meet the technical requirements and address the key operational risks of the Orion Program. Fire safety equipment intended for use in a confined space should avoid components with stored energy or potentially hazardous chemicals and should be safe to use in a small, confined space. They should be effective. Compared with other candidate technologies, the CBA, the OPFE, and the OSEF are simple, safe, and effective.
- Fire safety systems should be simple and easy to operate. Fire safety systems are used in unstructured, time-critical, emergency conditions; it is especially important that fire safety systems are intuitive and easy to operate. The CBA, OPFE, and OSEF are intuitive and easy to use.

Organizational and process controls key findings:

- NASA hardware development processes work for systems that are regularly used but do not necessarily work for seldom-used contingency systems such as fire safety equipment. NASA processes allow fire safety equipment to be qualified by analysis only (i.e., without testing). The possibility exists that the first time fire safety equipment is operated is during an on-orbit fire emergency.
- NASA currently has no process that requires fire safety equipment to be exercised regularly as part of a proficiency/proving ground-test program. NASA processes require training, but these training requirements can be met with classroom training that does not provide the trainee with the opportunity to use the equipment. Fire safety system equipment is not regularly used and when it is used it is used in an uncontrolled, time-critical emergency

[1] The Orion MPCV Program will be referred to in this report as the “Orion Program.”

situation. Training and operational proficiency are especially important in these circumstances.

HIS key findings:

- NASA uses Likelihood × Consequences matrices to identify key risk challenges (indicated by the red cells in Figure 4.0-1). Managers are trained to identify key challenges and to direct efforts and focus resources on these key challenges. This directs efforts away from mitigation of low-probability risks. However, given the limited data on which likelihood estimates are based, there is uncertainty regarding cell assignment.

This decision-making conflict between risk factors of perceived moderate likelihood and those with perceived extremely low likelihood is graphically described in Figure 4.0-1.

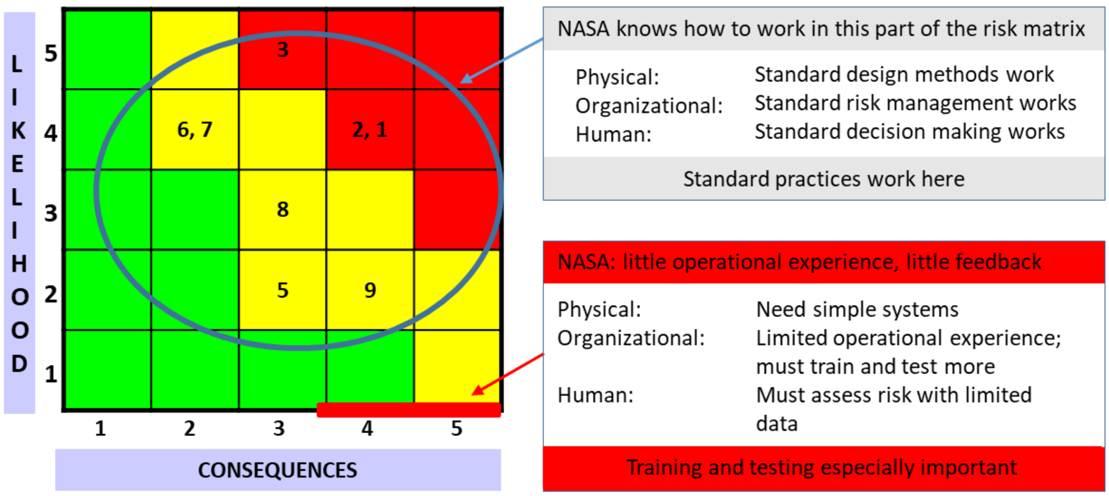


Figure 4.0-1. Graphical Description of Fire Safety System Risks, compared with other Competing Program Risks

- The CBA, OPFE, and OSEF systems have benefitted from considerable development testing. The CBA, OPFE, and OSEF project management plans specify that key performance requirements will be qualified by test, but there are no current plans for human-in-the-loop (HITL) evaluations in operational environments. Further, there are no plans to regularly exercise this hardware once it is qualified or provide realistic proficiency training (e.g., a simulated laptop fire). Note that the Orion Program has plans for maintenance, inspection, and limited-life management.

- The NASA Chief Engineer, the Chief of Safety and Mission Assurance (S&MA), and the Chief of Health and Medical should require that realistic training and proficiency testing of fire safety systems be required for the Orion Program and for other human spaceflight (HSF) programs (e.g., ISS and Gateway).

- The Orion Program should look to other programs within NASA and other "analog" organizations (e.g., military, aviation) for insight into fire safety systems. Many of these organizations have come to recognize the value of hands-on training in operational environments. The Orion Program should also consider whether a single-strand response capability (i.e., a single fire extinguisher with no other extinguishing/containment equipment onboard) is a sufficiently robust system. Most critical systems require double or triple redundancy.

5.0 Assessment Plan

The original scope of the assessment plan was to assess Orion GFE hardware development risks and conduct risk reduction activities to increase the technical maturity of key items to meet Orion Program schedules. The disengagement criterion was having the Orion Program stand up projects to develop GFE systems. The plan for this assessment evolved and changed over time, as technology matured and program structure changed. When this activity was originally planned and approved, this assessment addressed an issue of organizational prioritization. The Orion Program was just beginning, and it needed to prioritize which elements would be funded immediately and which would be postponed. The Orion Program placed priority on elements that were highly integrated and required systems-integration testing. As standalone equipment, the development of Orion ECLS systems would be postponed for several years. This NESC risk-reduction activity was focused on starting this development early so designs would have sufficient time to reach technical maturity. Seven hardware elements were identified in the initial plan:

- Post-landing anomaly gas monitor
- In-flight anomaly gas monitor
- Emergency breathing mask
- 144-hour in-suit survival capability
- Portable fire extinguisher
- Smoke-eater
- Post-landing carbon dioxide (CO_2) control

NESC-sponsored risk-reduction work was initiated for each of these elements. The Orion Program sponsored hardware development for each of these items at different times, with some changes to configuration and interfaces as the Orion vehicle design evolved. The work related to space suit aspects of the 144-hour in-suit survival capability risk was started in fiscal year 2016 (FY16), and contingency urine collection in a pressurized vehicle environment was postponed until FY19. The Anomaly Gas Analyzer (AGA), CBA, OPFE, OSEF, and Post-Landing LiOH projects were started in FY17. The Laser Air Monitor (LAM) was started in FY18. In FY17, the Orion Program split urine collection in the space suit and contingency urine collection in the event of a failure of the toilet system into two separate systems with two separate pieces of equipment. The Orion Program started the Collapsible Contingency Urinal (CCU) project in FY19.

At the time of writing this report, the Orion Program sponsored work controls and documents the design, development, and qualification of GFE ECLS items. The Preliminary Design Review (PDR) and Critical Design Review (CDR) documentation for these GFE items is the most current and the best documented record of these hardware items. A review of the PDR and CDR packages confirms that NESC-sponsored activities have benefited the Orion Program. Key elements for each of the systems were first developed as part of this NESC-sponsored effort:

- The AGA design uses a photoacoustic method of gas detection that was developed and evaluated as a part of this assessment.
- Laser screening and quality control processes planned for the LAM were initiated as part of this assessment.

- CBA prefilter development was started as part of this assessment.
- Low-weight internal bladder designs used by OPFE are based on designs developed for this NESC assessment.
- Performance tests of sorbent beds operating under OSEF flow conditions were first performed as part of this NESC assessment.
- The first tests of reactive plastic LiOH integrated with a portable fan were performed as part of this NESC assessment.
- The first prototypes of the CCU were produced as part of this NESC assessment.

In FY18 and FY19, the NESC assessment focused on the organizational and process aspects of GFE flight hardware development and on the human aspects of decision-making and risk management. The assessment focused on fire safety equipment, in particular the CBA, the OPFE, and the OSEF. This final report focuses on these three pieces of equipment, particularly the organizational and process aspects of their development and the human decisions that impact overall fire safety system performance. The other GFE items, the LAM and the AGA, and the Post-Landing LiOH and CCU are proceeding through nominal GFE development processes, benefitting from the early assistance provided by the NESC and documented in accordance with EA-023 [ref. 1].

6.0 Structure of this Assessment: Physical, Organizational, Human

This assessment and this report intentionally structure the work into three interacting factors. These factors are graphically described in Figure 6.0-1.

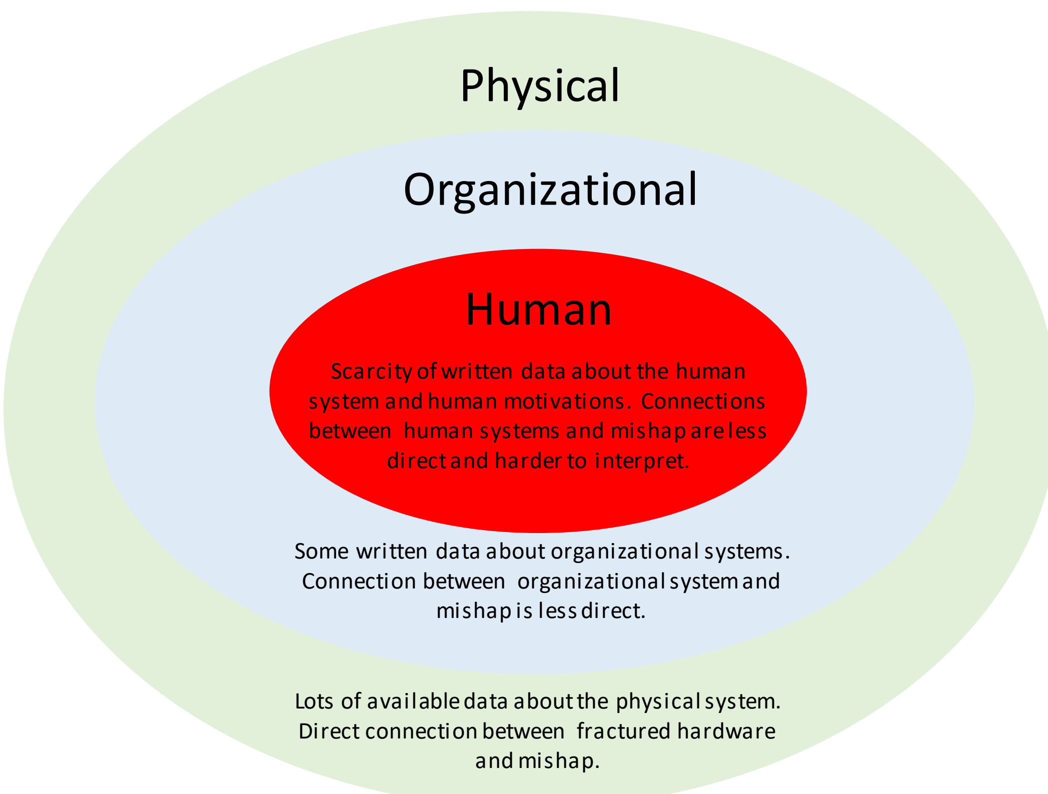


Figure 6.0-1. Structure of this Assessment and the Nature of Complex Systems

The physical aspects of a complex system (i.e., system hardware, configuration, materials, engineering drawings, test equipment, measurements of performance) are the best documented and the easiest to review. Many assessments only consider the physical aspects of a system. When there is a safety mishap, physical elements of the system will be damaged and the failure-analysis efforts will likely, but not exclusively, focus on the physical hardware.

Interacting with the physical system is the organizational system. The organizational and process aspects of a system are partially documented. Organizational and process aspects of a complex system can be found in budgets, qualification process documents, organizational charts, and test standards. There are strong connections between the physical and the organizational aspects of a system. One common example of an organizational problem at the heart of a system failure is "stove piping." A complex system that is managed by a large and distributed organization will distribute system control to many distinct organizational groups. Each of these organizational groups has limited knowledge of the overall system, and each of these organizational groups has limited control. Organizational stove piping can result in a failure of the physical component. Understanding the organizational problem at the heart of a component failure can facilitate proper corrective action. Failure to understand the organizational problem can result in fixing an individual component problem, failing to fix the organizational issue, and having a different component fail for the same underlying reason. Large and complex technical organizations rely on Systems Engineering and Integration to address organizational issues like stove piping.

Human aspects of a complex system are highly critical to system success yet are often the least considered. There are multiple reasons for this neglect. Often, managers may be unaware of the disciplines that address these aspects (i.e., HSI and Human Factors). Alternatively, managers may feel that human aspects can be addressed downstream in the design cycle (e.g., through training or selection of adaptive users). The fact is, human values, behaviors (e.g., abilities and limitations), and motivations must inform the entire design cycle to ensure system success.

The current assessment began with a single organizational issue: new GFE ECLS hardware needs time to develop and validate but the Orion Program Office was postponing the start of this work. The original plan was to focus entirely on the physical aspects of the ECLS hardware and develop prototype equipment. As the assessment progressed, it became clear that the assessment scope should not be restricted to only the physical aspects but should also consider organizational/process aspects and human behavior/decision-making aspects. Physical systems cannot be successful without proper organizational and human support. In the course of this assessment, it became clear that seldom-used, contingency systems present a unique set of physical, organizational, and HSI challenges.

This assessment explains and interprets three elements of the Orion Fire Safety System: the CBA, the OPFE, and the OSEF. These three pieces of equipment are intentionally assessed regarding all three factors—the physical aspects of the systems, the organizational and process aspects, and the HSI aspects of the system. The CBA, the OPFE, and the OSEF are described individually in separate sections of the report, but these three items are part of an integrated system. These three elements work together as a system in which the performance of each item affects the performance of the other items. These three elements must work together; thus, they must be evaluated together (as they are in the "Supertest," which is described in Section 10.9 and Appendix D). Further, the suite of equipment will need to be evaluated with the intended users in a realistic operational environment.

7.0 Comparative Analysis of Shuttle, ISS, and Orion Fire Safety Systems

7.1 Fire Safety Hardware Components and Fire Safety Systems

The primary focus of this assessment is the three specific hardware devices (i.e., CBA, OPFE, and OSEF). These three pieces of hardware are part of a larger fire safety system. The Orion Fire Safety System is defined by fire safety processes, vehicle architecture, vehicle geometry, fire detection systems, operational procedures performed by the crew, operational procedures performed by ground support personnel, orbital trajectories, mission timelines, fire safety hardware (e.g., CBA, OPFE, and OSEF), and environmental control and life support system (ECLSS) hardware.

The Orion Fire Safety System is not like the fire safety system on either the Shuttle or the US Segment of the ISS. Unique aspects of the integrated system drive the need for unique pieces of hardware. Orion cannot use hardware developed for other programs—the reasons for this are described in the remainder of this section.

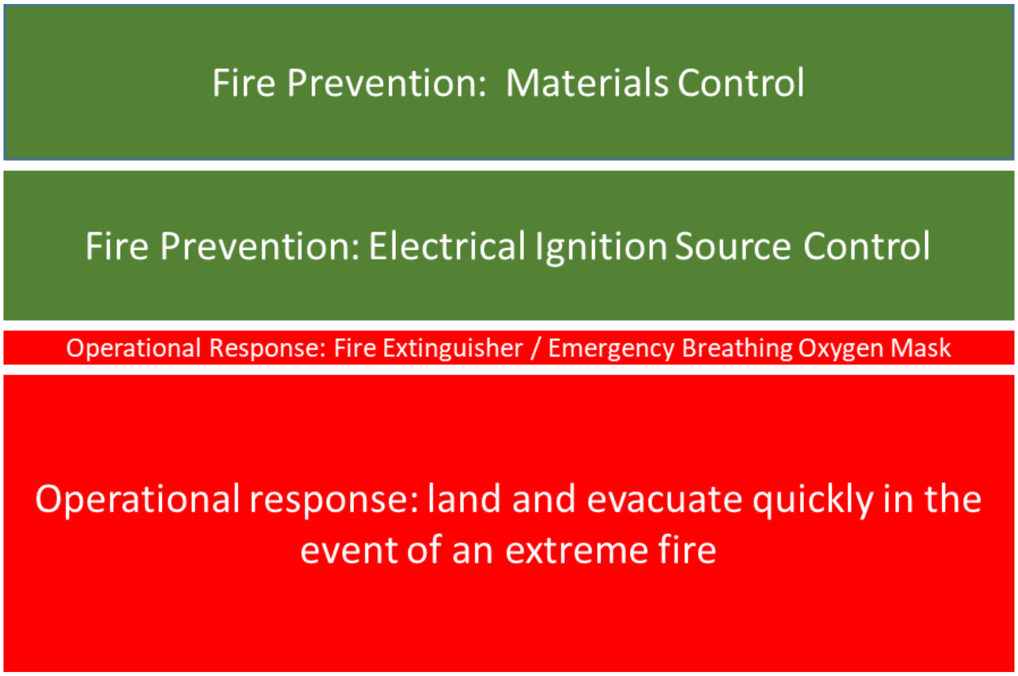
The Orion Fire Safety System can be most easily described through comparison with the SSP and ISS Program fire safety systems. A comparative analysis can highlight the key design drivers and the most critical fire safety needs. Therefore, the following sections describe and compare the SSP, ISS Program, and Orion fire safety systems.

7.1.1 Shuttle Fire Safety System

Like other human-rated spacecraft, the elements of the Space Shuttle fire safety system included both fire prevention processes and physical hardware to detect and suppress fire. The Shuttle had a system for fire detection, a system for fire suppression, a contingency breathing system for the crew, a system for purifying the spacecraft environment after a fire, and a system for emergency egress from the vehicle (i.e., land and evacuate), if needed.

A subjective assessment of the relative importance of key fire safety subsystems is shown graphically in Figure 7.1-1. The primary elements of the Shuttle fire safety system were: 1) fire prevention through materials control and 2) fire prevention through ignition source control. In the event that a significant fire occurred, a central part of the fire-response system was the ability to quickly land the shuttle and give the crew the opportunity to egress the vehicle. Fire extinguishers were part of the Shuttle fire safety system, but the primary methods of control of fire hazard were fire prevention through materials control and ignition source control rather than the ability to extinguish fires.

Program-level configuration can influence component design. For example, the Shuttle crew had the capability to land the vehicle in less than 90 minutes in the event of an emergency, and the vehicle ECLS system could purge cabin air for the 90-minute emergency landing duration. These attributes enabled the Shuttle to use a Halon fire-extinguishing medium. Halon is an effective fire-extinguishing medium, but it cannot be easily filtered from spacecraft air and Halon decomposition products can be toxic. Halon was an acceptable design solution for the Shuttle because the cabin atmosphere could be vented and the crew could egress from the vehicle after an emergency landing. Halon is not acceptable for the ISS because the habitable volume of the ISS is too large for a cabin purge. Halon is not acceptable for Orion because the Orion vehicle cannot quickly land and Halon decomposition products can be toxic. Venting the Orion vehicle is technically possible: the Orion vehicle has the capability of a cabin purge. Astronauts can don spacesuits, and the contaminated atmosphere can be vented to vacuum. There are provisions to vent and repressurize the cabin once, but there are many severe operational risks involved in putting astronauts in spacesuits and taking the cabin to vacuum conditions. From an overall risk perspective, Halon is not acceptable for Orion.



Items shown in green are preventative measures intended to prevent fires, and items shown in red are operational controls intended to mitigate a fire that has occurred. The thickness of the block represents the relative importance to the overall fire safety system.

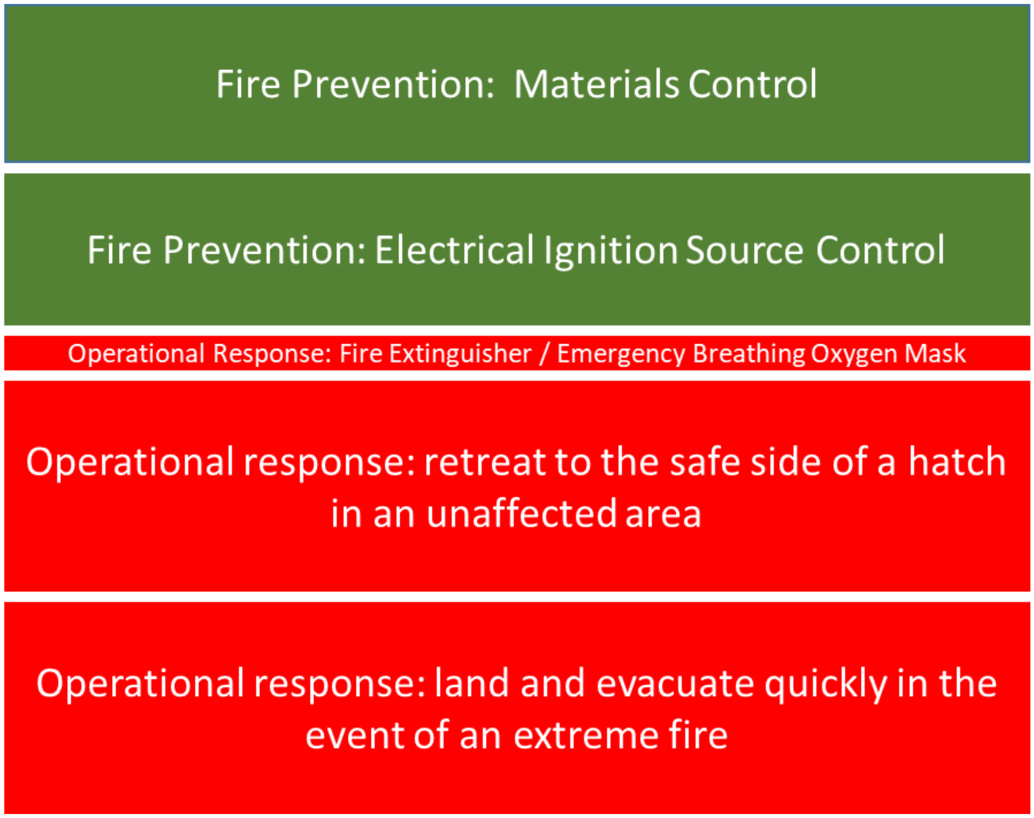
Figure 7.1-1. Graphical Representation of Space Shuttle Fire Safety System

7.1.2 ISS Fire Safety System

The US Segment of the ISS has a complex and multifaceted fire safety system that has a system for fire detection, a system for fire suppression, a contingency breathing system for the crew, a system for purifying the spacecraft environment after a fire, and a system for emergency egress from the vehicle if needed.

A subjective assessment of the relative importance of key fire safety subsystems is shown graphically in Figure 7.1-2. The primary elements of the ISS fire safety system are identical to those of the SSP: 1) fire prevention through materials control and 2) fire prevention through ignition source control. In the event that a significant fire occurs, a central part of the fire response system is the ability to retreat to a module unaffected by the fire, close the hatch, and isolate the fire from the rest of the vehicle. For particularly severe fire events, the ISS maintains an emergency egress capability. The fire extinguisher/emergency breathing system hardware is part of the overall ISS fire safety system, but fire prevention is the primary method of control of the hazard of fire on ISS.

The ISS has some examples where Program-level configuration drives component design. CO_2 was selected as the fire-extinguishing agent, in part because the ISS had systems that could scrub CO_2 from the atmosphere and because the volume of the vehicle was too large to practically vent.



Items shown in green are preventative measures intended to prevent fires, and items shown in red are operational controls intended to mitigate a fire that has occurred. The thickness of the block represents the relative importance to the overall fire safety system.

Figure 7.1-2. Graphical Representation of the ISS Fire Safety System

7.1.3 Orion Fire Safety System

Orion has a complex and multifaceted fire safety system that has a system for fire detection, a system for fire suppression, a contingency breathing system for the crew, and a system for purifying the spacecraft environment after a fire. Again, the primary elements of the Orion Fire Safety System are fire prevention through materials control, and fire prevention through ignition source control.

A subjective assessment of the relative importance of key fire safety subsystems is shown graphically in Figure 7.1-3. Note the absence of two key safety attributes: the Orion crew cannot quickly land and egress the vehicle in the event of a serious fire emergency, nor can the crew retreat to the safe side of a hatch.

Items shown in green are preventative measures intended to prevent fire, and items shown in red are operational controls intended to mitigate a fire that has occurred. Items outlined but not colored are missing. The thickness of the block represents the relative importance to the overall fire safety system.

Figure 7.1-3. Graphical Representation of Orion Fire Safety System

This lack of an onboard safe haven and the lack of an emergency egress capability places Orion in a uniquely severe fire safety posture, which dramatically increases the importance of the Operational Response Option. Compared with the Shuttle and the ISS, the CBA/OPFE/OSEF hardware system has a more critical role in fire hazard control; thus, the system must be demonstrated to be reliable and robust. Further, the Orion Program should recognize the inherent risk of single-strand failure in the system. Likewise, the program should recognize that if system resources are exhausted in responding to a fire incident, then the crew will be without resources to address an additional fire or reignition (the latter being a common occurrence with lithium-ion battery fires).

7.2 Comparative Analysis Summary

Findings:

F-1. Halon decomposition products are toxic, but the SSP could use Halon fire extinguishers because the Shuttle Orbiter had the capability to land quickly in the event of an emergency, Shuttle astronauts could egress the vehicle, and Shuttle ECLS systems could purge the cabin atmosphere during an emergency landing.

F-2. In the event of a fire on the ISS, procedures specify that NASA astronauts are to don an oxygen breathing mask.

F-3. In the event of a fire, the Orion crew cannot quickly land and egress, nor can they retreat to an unaffected compartment. This increases the criticality of a reliable and robust onboard fire safety system, as it will be the sole fire mitigation option available to the crew.

8.0 Assessment of Physical Aspects of Orion Fire Safety Hardware

This assessment addresses the CBA, the OPFE, and the OSEF from three different perspectives: physical, organizational/process, and human aspects that drive decisions and behavior affecting the hardware. This section focuses on the physical aspects of the hardware.

Details about the concept of operations, functional requirements, physical requirements, system interfaces, hardware design, hardware configuration, and qualification processes are summarized in three appendices. Appendix A describes the CBA, Appendix B describes the OPFE, and Appendix C describes the OSEF.

Key details of the physical configuration that impact safety and performance are described in the following three subsections.

8.1 Assessment of Physical Aspects of the Contingency Breathing Apparatus (CBA)

8.1.1 Concept of Operations

The CBA devices are stowed in a wall-mounted locker in sealed bags. In the event of a fire or other event that causes the air to become contaminated, each crewmember will don a CBA. The CBAs are designed to be "one size fits any crewmember," so individual CBAs are not assigned to specific crewmembers. To don a CBA, the vacuum-sealed bag is opened (there is a tearaway slit), and the CBA is removed from the bag. When removed from the bag, the CBA is unfolded; otherwise, it is in a fully assembled configuration, ready to be worn. The crewmember unfolds the CBA and pulls it over their head. Next, the crewmember cinches the straps to secure the mouthpiece and prevent exhaled breath from fogging the visor. The CBA is worn until readings from the AGA confirm that it is safe to doff the mask. If the OSEF is performing nominally and the fire is similar in size to the challenge fire in the Supertests, then the CBA can be doffed without any cartridge replacement. If cabin contamination continues for an extended period, the CBA system has replaceable cartridges. With two sets of replacement cartridges, the system can provide breathing protection for up to 8 hours. When CBA use is complete, the hardware is placed in a bag and stowed. The bag is designed to prevent off-gassing of captured contaminants.

8.1.2 Key Functional Requirements

Key functional requirements include:

- Demonstrate performance in a test that is complex, multicomponent, and realistic.
- Demonstrate performance in a test that is repeatable, controllable, and single component.
- Pass leakage test, including users who have long hair or beards.
- Rebreathing exhaled breath, less than 1.3%.
- Pass system pressure drop test (70 mm water column at 42.5 lpm).

8.1.3 Key Performance, Human Systems, and Environmental Requirements

Key performance, human systems, and environmental requirements include:

- System can be accessed and donned in less than 30 seconds, achieving a proper seal in a micro-G environment (note that the FAA requirement is 15 seconds).
- Pass communication test (hearing and speaking).
- Exposed materials shall pass flame impingement and molten drip tests.
- One size fits every astronaut.
- Five-year shelf life.
- Operating temperature range: 37 to 133 ºF.
- Operating pressure range: 9.5 to 15.55 psi.

8.1.4 Hardware Configuration

A description of terminology can introduce the main components of the CBA and place it in context with emergency breathing systems developed for ISS. The Emergency Mask (EM) is a hooded device that includes a neck dam, nose cup, face shield, and hood. In the image on the left side of Figure 8.1-1, the EM is the item that is black in color. Figure 8.1-1 identifies the main components of the EM. There are minor changes to the EM due to component obsolescence, but the Orion and ISS EMs are equivalent parts. The Fire Cartridge (FC) is the red filtering respirator cartridge that contains the P100 particulate filter, the activated carbon, and the carbon monoxide (CO) oxidation catalyst. The CO oxidation catalyst is not a commercial product; it is developed by TDA Research specifically for NASA. Each batch is subjected to a rigorous set of acceptance tests before it is used. The CO oxidation catalyst used in the CBA is the same as the CO-oxidation catalyst used in OSEF. Compared with commercially available oxidation catalysts, this catalyst performs well at low temperatures, in high-humidity environments, and under high space velocity conditions. A cross-sectional view of the fire cartridge is shown in Figure 8.1-3. There are minor changes to the FC due to component obsolescence, but the Orion and ISS FCs are equivalent parts. The Orion Fire Cartridge (OFC) consists of a FC with a removable prefilter. A CBA Assembly consists of one EM with two OFCs attached, ready to wear, folded and stowed in a sealed bag.

Figure 8.1-1. Prototype CBA (use configuration (left), respirator cartridge (right))

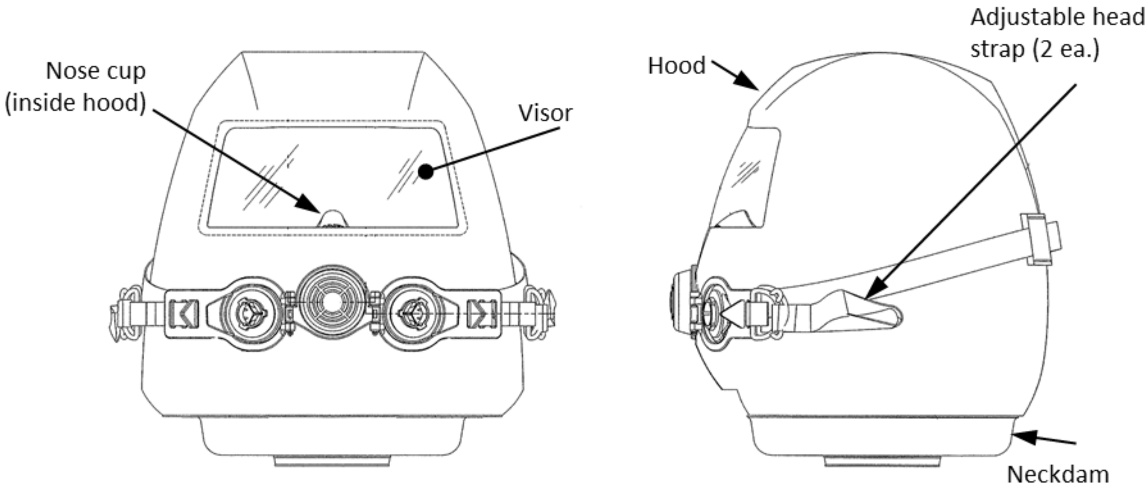


Figure 8.1-2. EM Configuration and Components

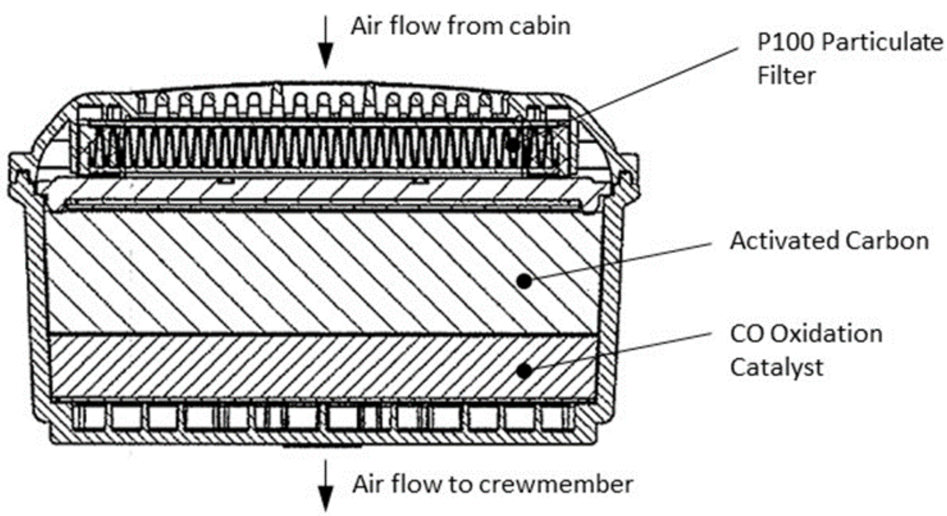


Figure 8.1-3. Orion Program Fire Cartridge Cross-sectional View

8.1.5 CBA Issues

The central issues for CBA performance relate to 1) breathing resistance, and 2) catalyst poisoning.

8.1.5.1 Assessment of Breathing Resistance

The CBA must filter gaseous contaminants, smoke-sized particulates, and water discharged from the OPFE. The CBA must also meet pressure drop requirements; it must be sufficiently easy to breathe through. Continued use of CBA in a contaminated environment makes filter loading, filter capacity, and pressure drop issues more severe. The performance requirement to filter contaminants while meeting pressure drop requirements is key to the CBA; however, verifying performance is challenging because it requires extensive testing.

The issue of capacity/filtering efficiency/pressure drop was recognized at the earliest stages of development of NASA's first filtering respirator systems (i.e., the ISS Ammonia Respirator and the ISS FC), but greater scrutiny was placed on this issue after a test of a FC clogged and exceeded pressure drop requirements in less than 15 minutes. A special review board was convened to evaluate the test results and recommend corrective action. A post-test review recognized that the test conditions were inadvertently severe: the cartridge was placed a few centimeters from the combustion products generator, and the P100 filter was exposed to molten material. The review board also recognized that the pleated P100 filter used in the FC has great performance characteristics for filtering efficiency but a relatively low capacity (i.e., a relatively small amount of soot or molten aerosols can clog the filter). The review board accepted the project team's recommendation that the cartridge configuration shown in Figure 8.1-3 was safe for use on ISS. One of the major reasons for this determination was a comparison between the test conditions and the expected conditions in the ISS. ISS crewmembers are instructed to retreat from the area affected by fire and get to the safe side of a hatch. ISS crewmembers have replacement filter cartridges (i.e., if cartridges become clogged, then the crewmembers can replace them with fresh cartridges).

Conditions in the Orion vehicle are more severe, as there is no safe space or safe side of a hatch. For launch-mass reasons, the number of replacement cartridges is expected to be substantially less than on the ISS. One of the central activities for this NESC risk reduction assessment was to develop and test a removable prefilter for the CBA cartridge. The concept is to incorporate a two-filter system: first, a prefilter with a high capacity that removes most of the load; and second, a P100 high-efficiency particulate air (HEPA) filter that has high removal efficiency but low capacity. If the prefilter is removed, then the P100 HEPA filter can meet crew protection requirements (the P100 filter rating establishes that requirements are met, but this will be verified by test). The removable prefilter works as a system with the OSEF. The job of the OSEF is to quickly remove particulates and water from the cabin. If, for instance, the OSEF can remove >90% of the particulates and water from the cabin in 30 minutes, then the CBA might be worn as a two-filter system for 30 minutes, the prefilter can be removed, and the CBA filter can operate without a prefilter in the mostly clean cabin for another 60 minutes.

A substantial amount of prefilter development work has been performed in the past five years—with much of it conducted as part of this NESC assessment. Prefilter development and prefilter testing has been performed at NASA JSC and through contracts with Gentex, TDA Research, Jacobs Engineering, and Serionix. Prefilter tests are done as side-by-side comparison tests because environmental conditions in a smoke/soot/aerosol/water environment are difficult to reproduce experimentally. Two respirator cartridges are placed side-by-side in a test chamber; one has a prefilter and one does not. Prefilter performance is evaluated by how much longer the filter operates below pressure drop limits than the unprotected baseline. Some of these prefilter tests are done in extremely severe environments. Figure 8.1-4 shows an example of one prefilter test; visibility in the test chamber is less than 50 cm.

Figure 8.1-4. Example of a Prefilter Challenge Test

The August 2019 configuration of the prefilter prototype is shown in Figures 8.1-5 and 8.1-6. The CBA CDR, conducted in August 2019, presents a configuration of the CBA that includes a prefilter. At PDR, the CBA configuration did not include a removable prefilter for reasons of technical maturity. The addition of a removable prefilter substantially mitigates the clogging/pressure drop risk issue.

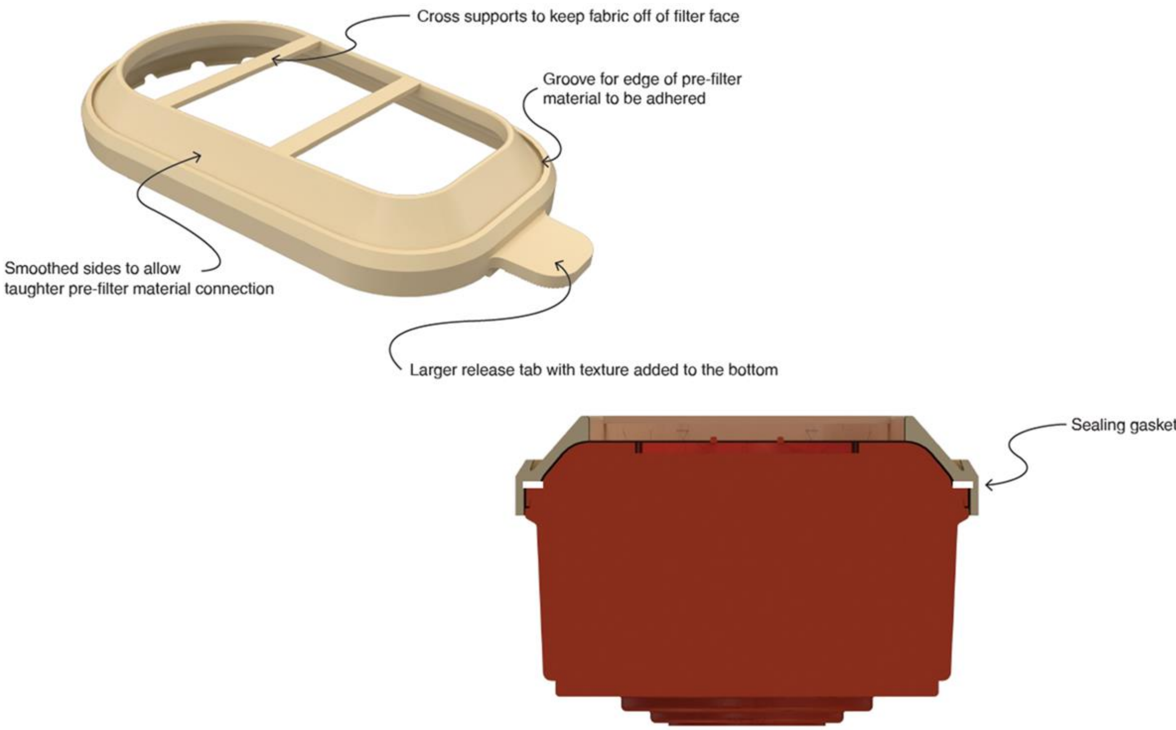


Figure 8.1-5. CAD Model of Removable Prefilter Frame

Figure 8.1-6. Removable Prefilter Prototype

8.1.5.2 Assessment of Catalyst Poisoning

There have been two build lots of the ISS Fire Cartridge. The first lot was built in 2010 and the second in 2015. The performance of the 2010 lot was nominal at the time of qualification and acceptance, and performance was essentially identical when retested in 2015 and 2018 as part of surveillance test activities. The 2015 build lot had nominal performance at the time of flight acceptance, but 2018 surveillance tests measured a degradation in performance. One key performance test measures CO oxidation: the cartridge is challenged with 1,000 ppm of CO in challenging temperature/humidity/flow environments. The performance requirement is to maintain the outlet concentration less than 50 ppm. All tests of the 2010 build lot cartridges maintain outlet concentrations <10 ppm. The 2015 build-lot acceptance test results were all <5 ppm, but when the 2015 build lot cartridges were retested in 2018, one cartridge had CO outlet concentrations >50 ppm.

The 50-ppm exceedance triggered an operational response to tag the hardware on ISS as not for use. It also initiated an extensive investigation. Root cause has not been definitively determined, but all available evidence suggests that during the 2015 build, activated carbon was exposed to contaminated air during the assembly process. Records indicate that cartridges were kept in temporary storage bags while a technical issue with the vacuum heat-sealing equipment was resolved. The results of the investigation suggest that the carbon adsorbed and held the contaminants in 2015, and CO oxidation catalyst was not exposed to any contaminants that could poison the catalyst. Over time, with changes in temperature, some of the contaminants desorbed from the carbon, diffused, and came in contact with the catalyst. This likely caused a partial poisoning of the CO catalyst, resulting in a 90 to 95% conversion rather than >99% conversion.

The ISS Program Office has sponsored an effort to make corrective actions to the manufacturing and surveillance processes. The Orion Program plans to adopt these corrective measures.

8.1.6 Summary

A filtering respirator is the type of emergency breathing device that best meets the technical requirements and operational risks of the Orion Program: it must be simple and intuitive to use and have the least amount of stored energy and reactive chemicals compared with other types of contingency breathing devices. The design aspects of the CBA meet the Orion Program requirements. The one-size-fits-every-astronaut design improves operational simplicity. The addition of a prefilter significantly improves the robustness of the system. Direct fire challenge testing increases the likelihood that the system will perform as expected in an emergency situation.

8.2 Assessment of Physical Aspects of the Orion Portable Fire Extinguisher (OPFE)

8.2.1 Concept of Operations

The OPFE is mounted on the wall of the Orion vehicle (i.e., the ECLSS Wall). Prior to launch, the OPFE is secured with a strap designed to withstand emergency launch and landing loads. When this strap is secured and pinned, the crew cannot deploy the OPFE as quickly. In the event of a fire on the pad, the crew is instructed to egress the vehicle. If a fire occurs during ascent, the crew will wait until orbit or emergency landing before using the OPFE. Once on orbit, the pip (quick-release) pin is released, and the OPFE is in a mounting configuration that enables fast use in an emergency situation. If a fire occurs in orbit, the crew will first don a CBA, then discharge the OPFE to extinguish the fire, and then monitor the cabin atmosphere using the AGA. The OPFE is designed for a single use. If the fire is a battery fire, the crew is instructed to extinguish the fire, wait 15 seconds, and then discharge the remaining contents. The operations follow the familiar fire extinguisher convention of "pull the pin and squeeze the trigger." The OPFE can be used in a shirtsleeve environment (with bare hands) or in a spacesuit with pressurized gloved hands. After the fire is extinguished and the condition of the cabin atmosphere is determined, the crew may deploy the OSEF to clear the cabin atmosphere of smoke and water from the OPFE. There is no planned on-orbit maintenance or on-orbit refilling.

8.2.2 Key Functional Requirements

Key functional requirements and the verification method of the OPFE include:

- Must extinguish a reference battery fire, verified by test.
- Must extinguish a reference open cabin fire, verified by test.

8.2.3 Key Performance, Human Systems, and Environmental Requirements

Key performance, human systems, and environmental requirements include:

- Once removed from the bracket, the time to pull the pin and discharge shall take no more than 5 seconds.
- PFE shall be capable of being removed from the bracket in less than 10 seconds when in the launch and landing configuration.
- PFE can be removed from the bracket and operated with either bare or pressurized-gloved hands.

- The discharge time of a fully loaded OPFE shall be a minimum of 25 seconds.
- The total mass of the entire OPFE system shall be less than 18.4 lb.
- Battery fire test shall be performed in an environment with >30% oxygen.
- One-year service life.
- OPFE shall be capable of being operated by a pressurized gloved hand with a 4.4 psid (pounds per square inch differential).
- Shall operate in a cabin with pressures ranging between 2.9 and 21.6 psia.
- Single fire extinguisher may not be adequate to address a reignition or second fire event.

8.2.4 Hardware Configuration

The configuration and key design aspects of the OPFE are highlighted in the following three figures: Figure 8.2-1 shows the OPFE and the mounting bracket configuration. The mounting bracket is especially large because the Orion contingency shock loads are severe. Figure 8.2-2 illustrates the configuration of the bladder and other internal components. The bladder is secured to the tank at both ends of the tank to accommodate shock loads. Figure 8.2-3 describes the sequence of the cradle mount opening. This cradle mount system is relatively large, but it satisfies the timeline requirements to access the fire extinguisher quickly while meeting structural loads requirements.

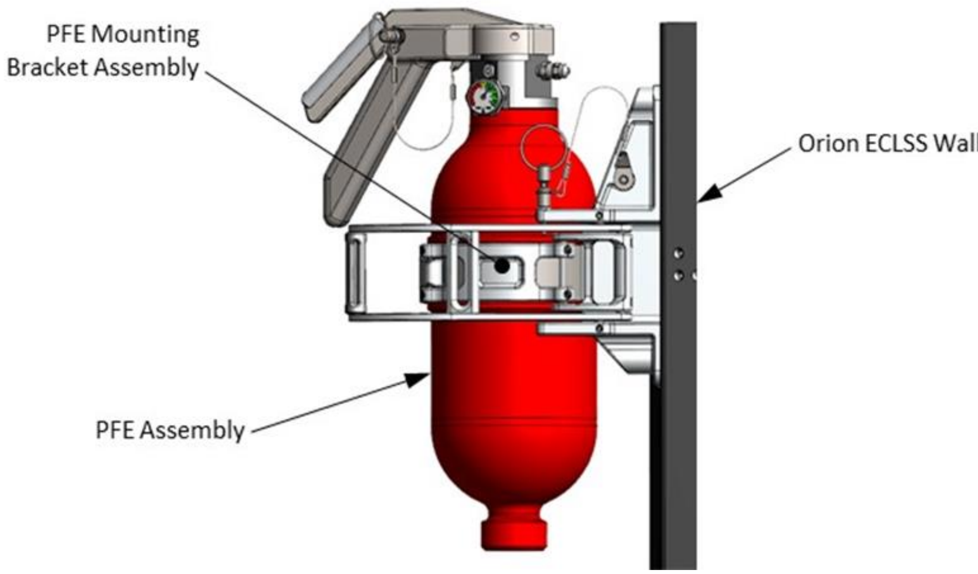


Figure 8.2-1. OPFE and Mounting Bracket Configuration

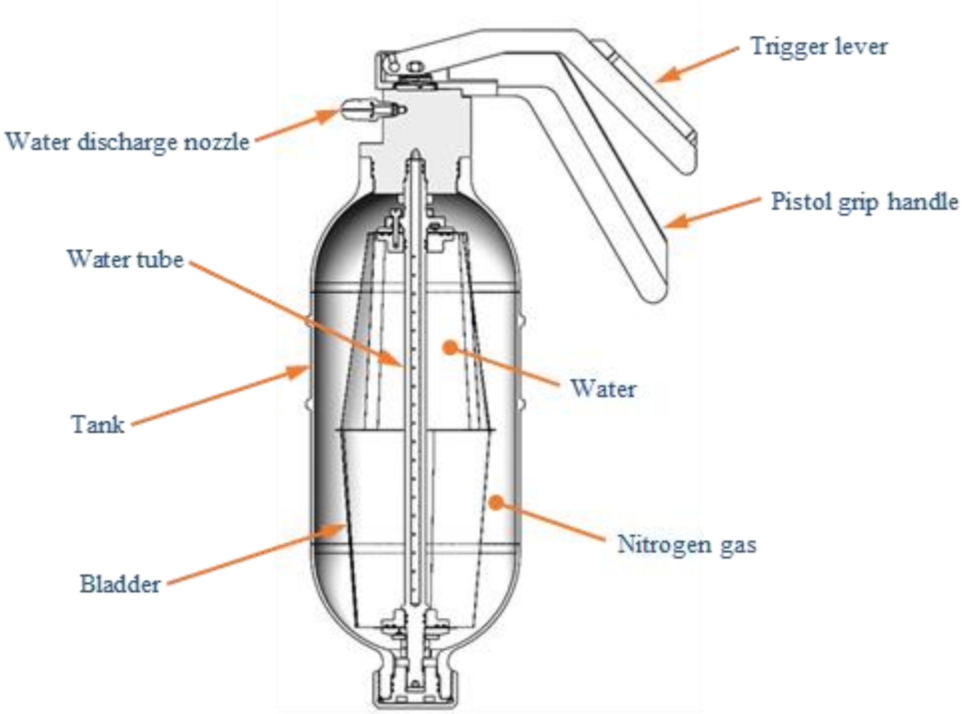


Figure 8.2-2. OPFE Cross-sectional View

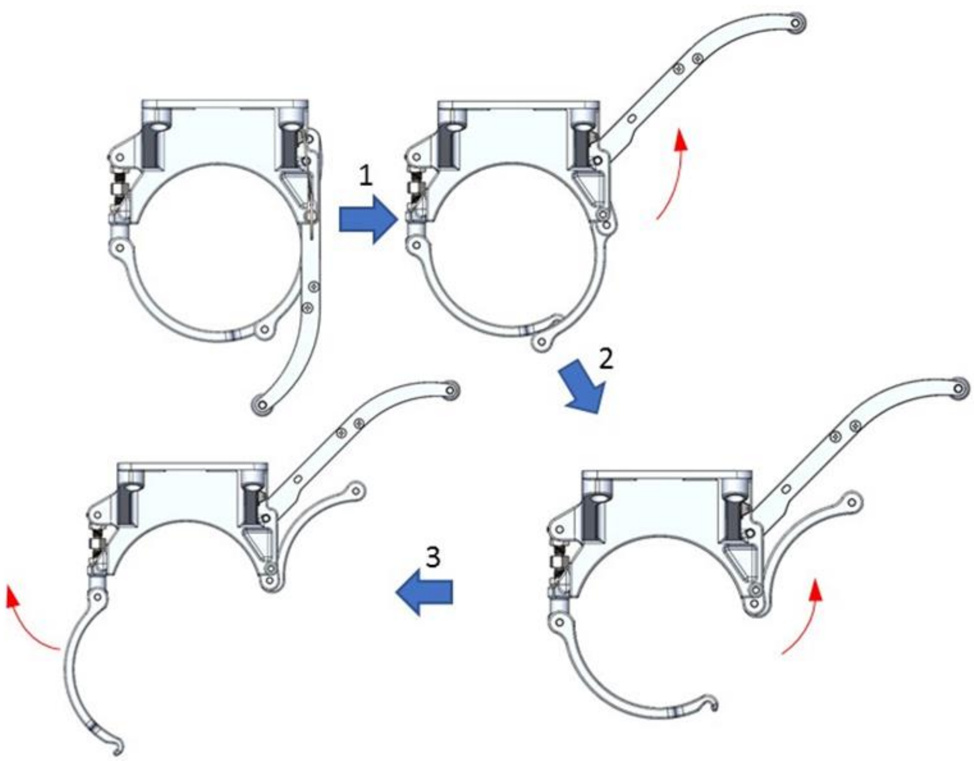


Figure 8.2-3. Cradle Mount Opening Sequence

8.2.5 OPFE Issues

The central issues related to OPFE performance relate to (1) the internal bladder and (2) the discharge spray pattern.

8.2.6 Assessment of Internal Bladder

The internal bladder of the OPFE is substantially different from that of the ISS fine water mist portable fire extinguisher. The primary design driver of the ISS bladder was service life. The service life was specified to last from 2010 (when the design was established) to substantially later than 2025 (2025 was the stated end of the ISS Program in 2010, but ISS personnel wanted to protect for the possibility of a program extension). The ISS portable fire extinguisher can be delivered to the ISS in a non-operable soft stowed configuration, and once on ISS the acceleration loads are small. There were effectively no weight constraints placed on the ISS portable fire extinguisher. There was a volume constraint (i.e., the system had to fit inside existing lockers), but any realistic design that fit within the locker could be effectively launched to ISS. The design drivers for the OPFE are substantially different (i.e., the service life is 1 year, with a challenge to establish a 6-year service life, and the acceleration loads are substantial). The OPFE has a severe system-level weight constraint (i.e., the entire system must weigh less than 18.4 lb (fully charged). The Orion system needs drive the bladder design to be anchored at both ends of the tank and to be constructed primarily of lightweight, nonmetallic materials. By comparison, the ISS bladder is entirely metal and anchored at one end.

The structural needs of the bladder make completely discharging the contents of the bladder more difficult. Following several design/test/evaluate/redesign iterations, the performance of this new subsystem has been outstanding. The available test data indicate that the bladder meets all requirements; however, the bladder is a new design and uses a large number of nonmetallic materials that are in contact with water, and must satisfy leak, service life, and structural requirements. New designs, and those involving nonmetallic materials in contact with water, should be flagged as having additional technical risk.

8.2.7 Assessment of Spray Discharge System

The spray discharge system merits special focus because it is a new design to meet Orion Program requirements. The spray pattern needs of the OPFE are unique, largely due to the size of the vehicle. The Orion vehicle is small compared with the ISS, so the planned distance from the fire is closer (i.e., the specified distance between nozzle and the fire for both Orion performance tests is 2 ft). Nozzle spray pattern and discharge rates must be selected with a specific concept of operations in mind: if the expected fire-fighting distance is relatively great, then the nozzle should have a narrow discharge pattern and should discharge water with more momentum. If the fire-fighting distance is relatively small, then the nozzle should have a broader discharge pattern and should discharge water with less momentum. Discharge time must be selected with a concept of operations in mind. If the discharge time is too long, then the delivery rate is so small that it cannot extinguish large fires. If the discharge time is too short, then an operator can “waste” a large portion of the fire extinguisher contents simply by pointing the extinguisher at the wrong target for a few seconds. The OPFE has a requirement that discharge time shall be greater than 25 seconds.

The nozzle, tank pressure, and overall system design is well suited to performance fire tests, with a 2-ft distance between the nozzle and the fire and a requirement to discharge contents for longer than 25 seconds. If the system is tested against a broader range of fire challenge conditions, then system robustness can be better assessed. Tests should also validate that intended users can properly aim and direct the spray in operational conditions (i.e., micro- or 1-G, with bare or gloved hands).

8.2.8 Summary

The Orion Program has a set of technical requirements and operational risks that are better met with water spray than any other kind of fire extinguisher. A water spray system is simple and intuitive to use, and it is the safest possible system to discharge into a confined space. Discharging causes the least amount of pressure increase, and it discharges the safest and most benign extinguishing agent. Water spray is an effective way to extinguish a battery fire, considered the most severe Orion fire scenario. The design aspects of OPFE match the needs of Orion. The system meets the weight and structural requirements. Performance tests using development hardware indicate that the OPFE will meet every requirement published in the OPFE Project Technical Requirements Specification.

8.3 Assessment of Physical Aspects of the Orion Smoke Eater Filter (OSEF)

8.3.1 Concept of Operations

The OSEF is stored in OASIS (Orion Aft Storage Intravehicular Activity (IVA) System) locker F1. Nominally, it is never removed from its stored configuration. In the event of a fire, the OSEF is the central hardware element for post fire cleanup. During a fire emergency, the crew dons the CBA and discharges an OPFE if necessary. After the fire is fully extinguished, the AGA is used to assess the quality of the air and establish a post-fire cleanup baseline. The OSEF filter is retrieved, the nominal cabin particulate filter is removed, and the OSEF filter is installed in the HPC1 filter housing. After the OSEF is installed, the cabin fan is turned on and the system is monitored. The AGA is checked to monitor contaminant decay rates and air-quality levels. Cabin fan condition levels are monitored for system pressure drop and cabin fan motor temperature. If the cabin fan diagnostics show signs of increasing the system pressure drop, then the fan can operate at a lower flow/higher torque setting. If cabin fan diagnostics continue to show signs of increased pressure drop, then the OSEF can be reconfigured and the OSEF prefilter can be removed. When AGA readings indicate that air-quality levels have reached "mask off" conditions, the OSEF is removed and placed in a post-use storage bag. The particulate filter is reinstalled in HPC1.

8.3.2 Key Functional Requirements

Key functional requirements and the verification method of the OSEF include:

- Demonstrate performance in a test that is complex, multicomponent, and realistic.
- Demonstrate performance in a test that is repeatable, controllable, and single component.
- Remove 500 ml of water, verified by test.
- Remove particulates (0.5 to 100 microns), verified by test.

8.3.3 Key Performance, Human Systems, and Environmental Requirements

Key performance, human systems, and environmental requirements include:

- Operate with a nominal cabin fan flow rate of 122 cubic feet per minute (cfm).

- Delta pressure shall be less than 4.7 inches of water gauge pressure (IWG) at 122 cfm. Capable of being extracted and installed in less than 6 minutes.
- Capable of being removed and placed in post-use bag in less than 5 minutes.
- Total mass of the entire OSEF system shall be less than 9.6 lb (as-built weight is currently greater).
- Does not require the use of tools.
- Five-year shelf life.
- Operating pressure range of 9.5 to 16.9 psia.

8.3.4 Hardware Configuration

Figures 8.3-1 through 8.3-3 illustrate different aspects of the OSEF. Figure 8.3-1 shows the exterior dimensions and the shape of the hardware. Figure 8.3-2 provides an exploded view that shows the orientation of the internal components, and Figure 8.3-3 shows the configuration of the prefilter in relation to the main filter.

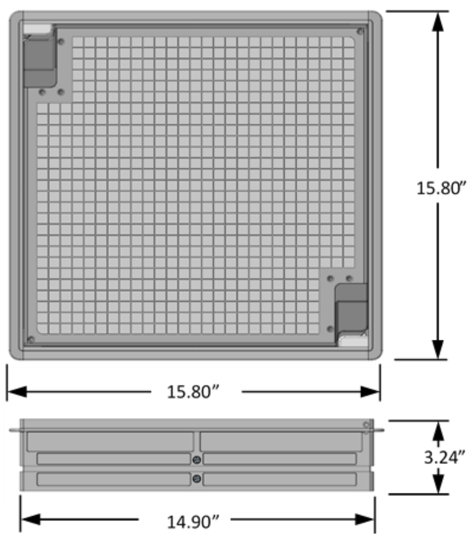


Figure 8.3-1. OSEF Exterior Configuration and Exterior Dimensions

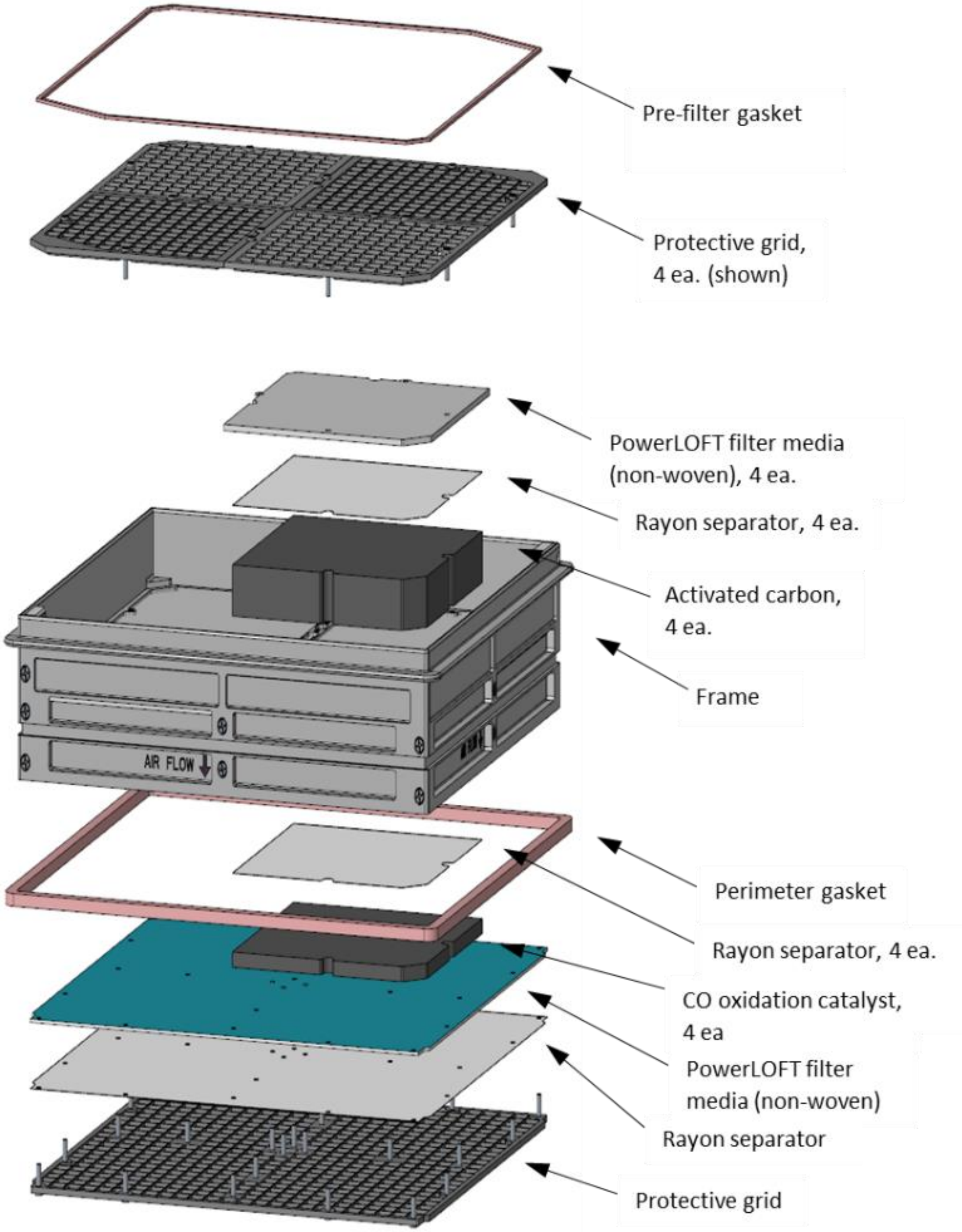


Figure 8.3-2. Exploded View of OSEF Components

Figure 8.3-3. Removal of OSEF Prefilter from OSEF Main Unit while Installed in HPC1

8.3.5 OSEF Issues

The central issues related to OSEF performance relate to 1) air flow rate and 2) meeting the conflicting requirements to capture and contain large amounts of soot and water while keeping system pressure drop low. These two issues are described in the following sections.

8.3.6 Assessment of OSEF Airflow Rate

The OSEF is relatively flat and small to meet HPC1 interfaces. The cabin fan flow rate is fairly fast to mix the air, prevent CO_2 pocketing, and maintain temperature. For fast cabin cleanup, it is beneficial to have a fast cabin fan. The nominal cabin fan flow velocity is 122 cfm, and the internal volume (depending on the number and size of the items that displace cabin air) is on the order of 350 cubic feet (ft^3). The cabin fan exchanges one entire cabin volume every 3 minutes. There is a cleanup rate estimate that three complete volume exchanges reduce the initial concentration of a contaminant by 90%. If the cabin fan is operating nominally, the OSEF has a 100% removal efficiency, and gas mixing is sufficiently uniform, then the cabin air concentrations should be reduced by more than 90% from their original concentrations in approximately 10 minutes. Test data are necessary to confirm this because of gas mixing effects, but this simple sizing estimate shows the benefit the OSEF can provide to a fire safety system.

From a sorbent system design perspective, the fast flow conditions, combined with the limited filter volume, pose a technical challenge. Sorbents, like the activated carbon used in the OSEF, remove volatile contaminants with a greater efficiency when gas velocity is low. Catalysts, like the CO oxidation catalyst, convert CO to CO_2 with a greater efficiency when gas velocity is low. Compared with other spacecraft air-quality systems, the gas velocity flowing through the OSEF is extremely high.

One aspect of OSEF mitigates this issue: unlike most filtering systems that protect a downstream component, the OSEF can meet performance requirements even if there is partial breakthrough. There is no immediate safety impact to less-than-perfect removal efficiency; the CBA is protecting the air quality for the crew. The most important requirement for CBA is to provide clean air to the crew. As a result, the CBA filter bed is thicker than test data indicate is necessary. The thicker bed means that the most important requirement is met with margin, but the thicker bed also increases pressure drop. The most important requirement for the OSEF is fast cabin cleanup. A thinner bed, with less pressure drop and faster airflow, can clean the cabin quickly even if the removal efficiency is less than 100%.

The OSEF has tested catalyst performance and sorbent performance in fast-flow conditions. Available test data indicate that the fast-flow issue has been successfully addressed, and sorbent and catalysts are working well even in fast-flow conditions.

8.3.7 Meeting Soot and Water Capture Requirements while Keeping Pressure Drop Low

Catalysts and sorbents do not work well if they are coated with water. Water from the fire extinguisher needs to be removed from the process airflow upstream of the sorbent and catalyst beds. Prefilter beds for soot and water removal must have a high capacity for soot and water, have a removal efficiency of close to 100%, and maintain low system pressure drop. The OSEF uses three different design approaches to minimize pressure drop in a clogging environment:

- Pleated prefilter configurations and material selection.
- Design that enables removal of the prefilter if the system pressure drop increases.
- Sufficient filter size. System volume is critical to sorbent and catalyst design, but prefilters need surface area. The cross-sectional dimensions and surface area of the prefilter are favorable for capturing water while meeting system pressure drop requirements.

Available prototype test data and Supertest performance data indicate that water/soot removal requirements can be met while maintaining system pressure drop. (The "Supertest" was an integrated test conducted by JSC WSTF personnel on the CBA, OSEF, OPFE, and AGA exposed to an energetic laptop fire. The test is described in greater detail in Appendix D.)

There is an additional issue that affects system design and qualification, which is that gravity profoundly affects filter performance and filter test results. In a gravity environment, water pools at the bottom of a pleated filter, and soot-containing air is introduced through the top of the filter. In microgravity conditions, the water and the soot will be exposed to all parts of the filter. Candidate filter materials cannot be tested in a 1-g environment in a way that represents actual performance in a microgravity environment. System performance cannot be fully verified during qualification tests. The Orion Program team is testing existing filter designs as rigorously as gravity tests allow, but pleated filters cannot be subjected to "fly what you test and test what you fly" test conditions in a gravity environment.

8.3.8 Summary

The OSEF meets Orion Program requirements. Because the cabin volume is relatively small and the cabin fan operates at a relatively fast flow, fast cabin cleanup is possible. The OSEF has no high-pressure components, no stored energy, and no reactive chemicals. Available performance test data indicate that performance test requirements can be met. The challenges of testing a pleated filter in a gravity environment make OSEF test data for water and soot removal indirect.

8.4 Assessment of Physical Systems

8.4.1 Assessment of Physical Systems: Findings

F-4. A filtering respirator has greater simplicity and fewer potential hazards than any other contingency breathing system.

F-5. CBA cartridges without any prefilter have clogged during testing.

F-6. CBA prefilters have been developed by testing prototype prefilters in challenging and realistic test environments.

F-7. A water-spray fire extinguisher discharges an expellant with fewer hazards that any other fire extinguishing system.

F-8. The OPFE internal bladder carries additional technical risk; because it is a new design, it has nonmetallic materials in contact with water and severe structural load requirements.

F-9. A sorbent/catalyst cleanup filter has greater simplicity and fewer hazards than any other cabin atmosphere cleanup system.

F-10. The OSEF CO catalyst, sorbent, and flow distribution systems carry additional technical risk because OSEF flow rates are fast and linear gas velocities are high.

F-11. The OSEF prefilter cannot be fully tested on the ground in a gravity environment.

8.4.2 Assessment of Physical Systems: Recommendations

R-2. When selecting fire safety technology for HSF missions, design simplicity should be a key selection criterion.

R-3. When selecting fire safety technology for HSF missions, minimizing hazards associated with elevated oxygen, toxic chemicals, and high-pressure systems should be a key selection criterion.

R-4. When selecting fire safety technology for HSF missions, there should be HITL demonstration of fire safety equipment in end-to-end tests that demonstrate the usability and effectiveness of equipment and procedures under realistic conditions, including reduced visibility and communication intelligibility.

R-5. Fire safety equipment should be developed and qualified by test whenever possible.

R-6. If fire safety equipment is qualified by analysis, then the additional risk of qualification without test should be documented and tracked.

9.0 Assessment of Organizational and Process Aspects of Orion Fire Safety Hardware

This assessment addresses the CBA, the OPFE, and the OSEF from the perspectives of physical, organizational/process, and human aspects that drive decisions and behavior affecting hardware. This section focuses on the process and organizational aspects of the hardware.

Details about the NASA standards for flight hardware development and qualification, standards for S&MA, organizational structures, and Center- and Agency-level processes are assessed in this section. This process assessment is split into three sections: CBA, OPFE, and OSEF. Note that this section is intentionally short and repetitive to emphasize some key aspects of process controls and their effects on the resulting NASA fire safety hardware.

9.1 Assessment of Organizational and Process Aspects of CBA

9.1.1 Comparison of Processes for Shuttle, ISS, and Orion Contingency Breathing Devices

9.1.1.1 Shuttle

The Shuttle used a supplied-oxygen method of contingency breathing. Supplied gas systems can be qualified by analysis. It is assumed that the quality of the air supplied to the crewmember is independent of the cabin atmosphere condition.

Subsystems were qualified by test. Fitting leakage was verified by system-level test. Regulators were tested for design qualification and individual serial number acceptance.

No Shuttle astronaut ever wore an oxygen mask as part of a training event that involved fire. The SSP had no requirement or process standard that dictated the need for testing a portable breathing apparatus (PBA) in an environment with fire.

Figure 9.1-1. Elements of PBA and Portable Hose Assembly, used by both Space Shuttle and ISS Programs

9.1.1.2 ISS

The ISS initially developed and qualified a supplied-oxygen method of contingency breathing. Supplied gas systems can be qualified by analysis; it is assumed that the quality of the air supplied to the crewmember is independent of the cabin atmosphere condition.

Subsystems were qualified by test; fitting leakage, for example, was verified by system-level test. Regulators were well tested both for design qualification and for individual serial number acceptance.

Some ISS supplied-oxygen PBA systems were reconfigured to supplied-air PBA systems to give the crew the opportunity to directly experience the feeling of breathing through a PBA without the hazards of working with an elevated oxygen system.

No ISS astronaut ever wore an oxygen mask as part of a training event that involved fire. The ISS Program had no requirement or process standard that dictated the need for testing PBA in an environment with fire. The ISS Program had no requirement or process standard that dictated the need for training astronauts with a PBA in an environment with fire.

In 2005, the ISS Program developed a filtering respirator to protect the crew from an ammonia leak. In 2010, a FC was developed to mate to the hooded respirator to protect the ISS crew from post-fire combustion products. The ammonia respirator and the FC were tested using ammonia challenges and fire challenges, respectively. The hooded respirator was tested with test subjects for fit; the protection factor was measured by comparing the levels of candle smoke inside and outside the hooded respirator. Material permeability tests were performed at the US Army Center for Chemical and Biological Warfare. Materials were tested with flame impingement and molten drip challenge tests.

No ISS astronaut ever wore a respirator-based contingency breathing device while training in an environment with fire. ISS astronauts receive a considerable amount of training on the systems and the hardware, but do not wear a respirator while extinguishing a fire.

9.1.1.3 Orion

Orion CBA is qualified using a two-tiered test approach:

1. The CBA is tested in environments that are complex, dynamic, and realistic. These kinds of environments are hard to reproduce in a controllable, systematic way, so these kinds of tests are realistic but not reproducible. The Supertests, described in Section 10.2 and Appendix D, are the best examples of realistic tests.
2. The CBA is tested using reproducible, single-component, chemical challenges. These single-component chemical challenges do not represent realistic fire conditions, but test results can be compared with analytical predictions.

The Orion CBA has no associated requirements to exercise the hardware once it is qualified:

- There are no NASA process standards requiring that hardware be exercised once qualification is complete.
- There are no NASA process standards requiring that hardware be exercised in test conditions other than those used in qualification tests.
- There are no NASA process standards requiring that flight crew be trained to use fire safety hardware in actual fire conditions.
- There are no NASA process standards requiring that fire safety hardware must demonstrate performance by test.

9.2 Assessment of Organizational and Process Aspects of OPFE

9.2.1 Comparison of the Processes for Shuttle, ISS, and Fire Extinguishers

9.2.1.1 Shuttle

The Shuttle used a system with both fixed and portable system of fire extinguishers, shown in Figure 9.2-1. Both used Halon 1301 as the fire extinguishing agent. Flooding gaseous fire extinguisher systems can be qualified by analysis. It was assumed that fire could not be sustained when a critical concentration of extinguishing media was reached.

Subsystems were qualified by test (e.g., discharge rates were verified by test).

No Shuttle astronaut ever extinguished a fire using the Shuttle portable Halon fire extinguisher. There was no standard fire challenge test and no requirement to conduct a training event that involved live fire. The SSP had no requirement or process standard that dictated the need for testing the Halon fire extinguishers in an environment with fire. The SSP had no requirement or process standard that dictated the need for training astronauts with the fire extinguisher to actually extinguish a fire.

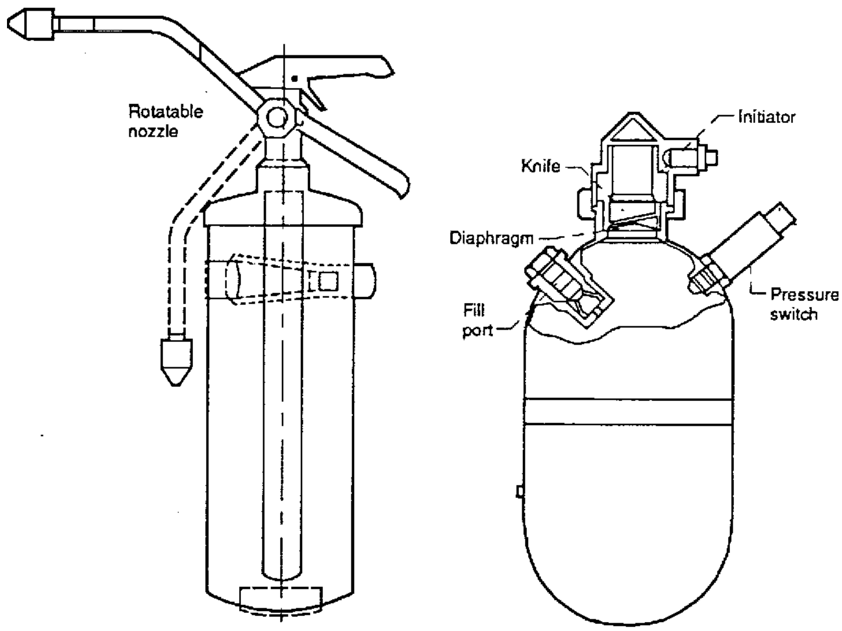


Figure 9.2-1. Schematics of Portable (left) and Fixed (right) Shuttle Fire Extinguishers

9.2.1.1 ISS

The ISS initially developed a portable CO_2 fire extinguisher (Figure 9.2-2). Flooding-gas fire extinguishing systems can be qualified by analysis; it is assumed that fire cannot be sustained when a critical concentration of extinguishing medium is reached.

Subsystems were qualified by test; for example, discharge rates were verified by test. It is interesting to note that during a discharge rate test, developers realized that the rapid discharge of pressurized CO_2 caused rapid cooling, and touch temperatures were lower than human standards. The insulating cover was added to the system late in the development, after a gas discharge rate test identified the previously unrecognized touch temperature issue.

No ISS astronaut has extinguished a fire using the ISS CO_2 portable fire extinguisher. There was no standard fire challenge test and no requirement to conduct a training event that involved live fire. The ISS Program had no requirement or process standard that dictated the need for testing the CO_2 fire extinguishers in an environment with fire. The ISS Program had no requirement or process standard that dictated the need for training astronauts with a fire extinguisher to extinguish a fire. ISS crews are trained on the use of the fire extinguisher, but this training does not involve discharging CO_2 from the fire extinguisher or extinguishing a fire.

Figure 9.2-2. ISS CO_2 Portable Fire Extinguisher

In 2009, the ISS Program developed a fine water mist fire extinguisher. Currently, the ISS has two types of fire extinguishers: CO_2 fire extinguishers for fires in hidden areas inside the rack, and water mist fire extinguishers for open cabin fires and fires involving a battery. The water mist extinguisher was developed using actual performance tests where the extinguisher was tested in severe fire conditions. The water mist extinguisher was qualified using a series of performance tests where the fire extinguisher had to be able of extinguishing a series of realistic but severe fires. NASA had no process standard that required that the water mist to be qualified by performance test, but the ISS Program elected to qualify by performance test.

9.2.1.3 Orion

The OPFE is qualified using a two-tiered test approach:

1. The OPFE is tested in environments that are complex, dynamic, and realistic. These kinds of environments are hard to reproduce in a controllable, systematic way, so these kinds of tests are realistic but not reproducible. The Supertests, described in Section 10.2 and Appendix D, are good examples of realistic development tests.
2. OPFE development hardware is tested using reproducible simple tests (e.g., tests to verify discharge rate and spray pattern). These simple tests do not directly assess the PFE’s ability to extinguish a complex and dynamic fire, but simple reproducible tests can verify subsystem function.

The OPFE has no associated requirements to exercise the hardware once it is qualified:

- There are no NASA process standards requiring that hardware be exercised once qualification is complete.
- There are no NASA process standards requiring that hardware be exercised in test conditions other than those used in qualification tests.
- There are no NASA process standards requiring that flight crews be trained to use fire safety hardware in actual fire conditions.

- There are no NASA process standards requiring that a fire extinguisher must demonstrate that it can extinguish a fire.

9.3 Assessment of Organizational and Process Aspects of OSEF

9.3.1 Comparison of the Processes for Shuttle, ISS, and Cabin Cleanup Devices

9.3.1.1 Shuttle

The Shuttle used a repurposed LiOH canister packed with a granular catalyst of 2% platinum on activated carbon. The canister was called an Ambient Temperature Catalytic Oxidizer (ATCO), shown in Figure 9.3-1. The canister was designed to be installed instead of a LiOH canister. The activated carbon was designed to remove volatile organic contaminants, and the platinum catalyst was designed to oxidize CO to CO_2. The ATCO was partially qualified by test. A CO removal test was conducted as a single component challenge test; the challenge gas consisted of CO in air. There was no smoke, acid gases, or other combustion products in the challenge gas stream.

There was a concern that smoke would clog the ATCO filter material and block airflow, but no smoke challenge test was performed. There was a concern that acid gases would poison the ATCO catalyst. This issue was addressed with a subscale, two-component test.

The SSP had no requirement or process standard that dictated the need for testing ATCO canisters in a representative post-fire environment. The SSP had no requirement or process standard that dictated the need for training astronauts in the use of ATCO canisters in a contaminated environment. Astronauts were provided classroom training and had the opportunity to handle hardware in a classroom environment.

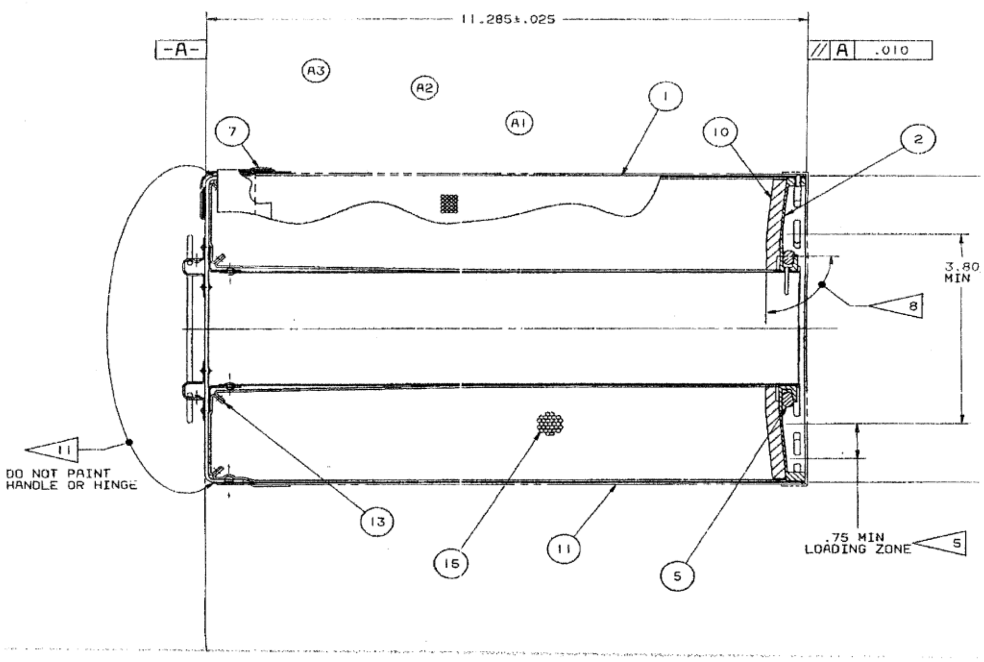


Figure 9.3-1. Engineering Drawing of ATCO Canister used on Space Shuttle and ISS

9.3.1.2 ISS

The ISS also uses the repurposed LiOH canister packed with a granular catalyst of 2% platinum on activated carbon (i.e., the ATCO). This canister was designed to be used with a portable fan assembly (PFA). The activated carbon was designed to remove volatile organic contaminants, and the platinum catalyst was designed to oxidize CO to CO_2. The ATCO was partially qualified by test. A CO removal test was conducted. The CO removal test was performed as a single component challenge test; the challenge gas consisted of CO in air. There was no smoke in the challenge gas stream and no acid gases. There were no other combustion products in the challenge gas stream.

There was a concern that smoke would clog the ATCO filter material and block airflow, but no smoke challenge test was performed. There was a concern that acid gases would poison the ATCO catalyst—this issue was addressed with a subscale, two-component test.

The ISS Program has no requirement or process standard that dictates the need for testing ATCO canisters in a realistic post-fire environment. ISS has no requirement or process standard that dictates the need for training astronauts the use of ATCO canisters in a contaminated environment.

9.3.1.3 Orion

The OSEF is qualified using a two-tiered test approach:

1. The OSEF is tested in environments that are complex, dynamic, and realistic. These kinds of environments are hard to reproduce in a controllable, systematic way, so these kinds of tests are realistic but not reproducible. The Supertests, described in Section 10.2 and Appendix D, are good examples of realistic development tests.
2. OSEF development hardware is tested using single-component chemical challenge tests. These simple tests do not directly measure the OSEF's ability to quickly purify the post-fire cabin environment, but simple reproducible tests can verify subsystem function.

OSEF has no requirements to exercise the hardware once it is qualified:

- There are no NASA process standards requiring that hardware be exercised once qualification is complete.
- There are no NASA process standards requiring that hardware be exercised in test conditions other than those used in qualification tests.
- There are no NASA process standards requiring the flight crew to be trained to use fire safety hardware in actual fire conditions.
- There are no NASA process standards requiring that the OSEF demonstrate by test that it can clean a cabin after a fire.

9.4 Assessment of Organizational and Process Aspects

9.4.1 Assessment of Organizational and Process Aspects: Findings

F-12. The performance of the Shuttle fire safety equipment was qualified by analysis.

F-13. Shuttle flight procedures specify that in the event of a fire, astronauts don a PBA oxygen mask.

F-14. No Shuttle astronaut ever wore a PBA oxygen mask in an environment with fire as part of a training exercise.

F-15. The performance of the ISS PBA and the ISS CO_2 PFE were qualified by analysis.

F-16. ISS flight procedures specify that in the event of a fire, astronauts don a PBA oxygen mask.

F-17. No ISS astronaut wore a PBA oxygen mask in an environment with fire as part of a training exercise.

F-18. The development and qualification of Orion fire safety equipment uses testing. Orion has a two-tiered test approach: some tests are dynamic and realistic, and some are repeatable.

F-19. The Orion Program does not plan to exercise fire safety equipment once it is qualified.

F-20. NASA has no requirement mandating that astronauts have the opportunity to use flight configuration fire safety hardware in an environment with fire. With respect to fire safety procedures, NASA has no requirement to "train like you fly and fly like you train."

9.4.2 Assessment of Organizational and Process Aspects: Observations

O-1. Hardware that is regularly exercised is more likely to perform as expected. One form of regular exercise is "proving ground" testing. Proving ground activities test hardware in complex and variable environments.

O-2. Many successful operational organizations use a system of rigorous proficiency training. One intent of this training is to make all operators and stakeholders familiar with the systems, and another is to identify previously overlooked issues. One example of the successful use of proficiency training is the submarine drills conducted by the US Navy, discussed in Section 10.

O-3. Qualification test programs are limited in scope; they do not include every operational scenario and do not test in every environmental condition.

9.4.3 Assessment of Organizational and Process Aspects of Fire Safety Systems: Recommendations

R-7. NASA processes should mandate that the performance of safety critical equipment must be demonstrated by test.

R-8. NASA processes should mandate that astronauts have the opportunity to use flight configuration fire safety equipment in an environment with fire as part of their proficiency training, similar to Title 14 of the Code of Federal Regulations (14 CFR) 121.417, which requires that all airline crewmembers extinguish a real fire during training.

R-9. Fire safety hardware should be regularly exercised by the intended users.

10.0 Assessment of HSI Aspects of Orion Fire Safety System

Humans are critical components of complex systems, from initial design through manufacture, use, and maintenance; through repair and system upgrade; and, finally, to system retirement. Clearly, humans will play a major role throughout the Orion Fire Safety System lifespan. Human decision-making determines the level of risk posed by fire and the level of resources dedicated to mitigating the risk. However, given the current assessment focus on fire safety hardware, the emphasis of this section will be on the human role as a system user.

As described in the previous section, it is critical that the individual hardware pieces of fire safety equipment be evaluated as an integrated suite, demonstrating operational efficacy. More to the point, it is critical that additional tests be conducted with the intended users functioning in the intended operational environment (or a realistic simulation). This latter domain of evaluation and testing falls under the purview of HSI.

Given the costs and potential risks of iterative, integrated testing, HSI practitioners draw on other knowledge sources to hone and direct empirical tests. In this section, three of these sources (i.e., relevant research findings, case studies, and analogs) are explored, followed by a summary of already completed and suggested tests to validate the Orion Fire Safety System.

10.1 Relevant Research Findings

There is robust research literature dealing with how individuals and organizations perceive risk. Perceived (subjective) risk does not always correspond with objective risk. This is especially true when the objective risk is small or difficult to define. NASA management has adopted a risk assessment approach based on evaluating the likelihood and consequences of off-nominal events. By plotting programmatic risks in these Likelihood × Consequences matrices, risks can be prioritized for optimal distribution of limited resolution resources.

The human decision-making conflict between risk factors of moderate likelihood and those with extremely low likelihood is graphically described in Figure 10.1-1.

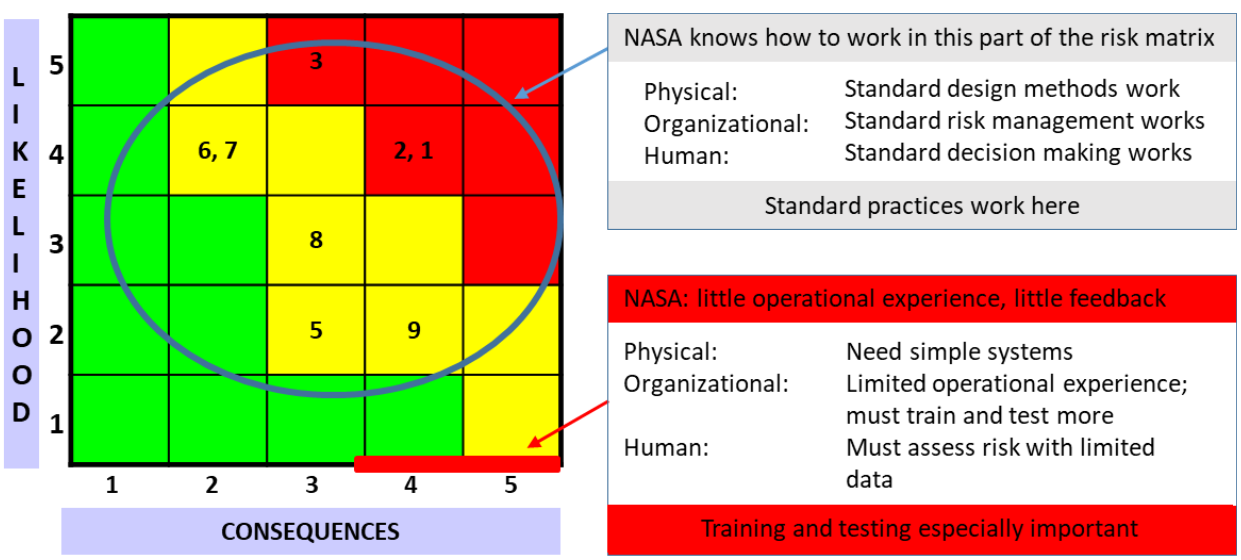


Figure 10.1-1. Graphical Description of Fire Safety System Risks, compared with other Competing Program Risks

Program managers have the responsibility to identify key issues/risks and direct limited resources toward their mitigation. Because the risk of fire is perceived to be extremely low, program managers direct resources for testing and training away from fire safety to issues/risks identified as high priority.

Unfortunately, given the novelty and uniqueness of many NASA systems, likelihood estimates can vary dramatically and evolve over time. For example, at the time of the Space Shuttle's first launch in 1981, the risk of loss of crew was estimated to be between 1:1,000 and 1:10,000. At the completion of the Space Shuttle Program (2011) after 135 flights, the revised risk for the first flight (employing modified estimation tools) was 1:9. In light of such likelihood uncertainty, managers may want to ensure that adequate resources are addressed to mitigate high-consequence events, such as an onboard fire.

At the operational level, it is critical to the evaluation of the Orion Fire Safety System to establish whether the crew can effectively use the proposed equipment suite to extinguish a fire in the mission environment with minimal injury, damage, or threat to mission success. HITL testing should be performed using a realistic operational environment and two representative fire scenarios (i.e., a laptop fire and a post-abort open cabin fire).

There is rich literature examining how humans respond to rare emergency events. The key findings are summarized here. The general findings are that people respond best if given hands-on training regarding their required roles and duties, as well as how each individual functions within the teamed response. Such training is especially critical if the response is time critical, as is the case with a fire igniting in a closed environment.

10.1.1 Human Performance and Emergency Response

Experience from safety-critical environments (e.g., maritime industry, aviation, and military settings) indicates that the stress of an emergency situation can reduce crew performance, particularly if task performance is reliant on conscious thought and problem solving. Stress can increase error rate [refs. 20, 22, 24], lead to the omission of tasks steps ([ref. 15] and result in "tunnel vision," in which the person may become focused on one aspect of the situation, sometimes to the exclusion of critical information [refs. 16, 25].

During initial learning of a complex procedure, the performer relies on conscious thought and attention to perform the necessary actions. With practice, automatic skill routines develop, enabling the crewmember to perform certain task steps in a rapid and consistent manner [ref. 19]. Compared with conscious mental processes, well-developed automatic skill routines are generally more resistant to stress. This is one reason why military drills are used to ensure that personnel can continue to perform under extreme stress.

Although classroom training can provide the necessary declarative knowledge relevant to an emergency response, the development of automatic procedural skills requires practical training, preferably in an environment as close as possible to the situation in which those skills will be needed. Furthermore, if the emergency requires a team response, training should occur at a team level and should include the necessary communication, coordination, and leadership skills [ref. 13]. In light of the research on stress and performance, the NASA Human Integration Design Handbook [ref. 23, p. 177] recommends that "emergency procedures should be extensively trained."

10.1.2 Skill Decay and Need for Recurrent Training

Emergency procedure skills are known to decay with time. In a review of emergency response training in military, offshore oil rig, maritime, and medical settings, Sanli and Carnahan [ref. 27] found that skills decayed in 6 months or less without refresher training. An early study of simulated lunar landing skills by test pilots found that skilled performance of critical tasks for long-duration space missions could be expected to deteriorate if the task had not been practiced within the previous 2 months [ref. 14].

10.1.3 User-Centered Design

For safety equipment to be useable and effective in real-world conditions, it must be designed with the physical and cognitive capabilities of the user in mind. NASA STD 3001, Volume 2 (Revision B) [ref. 26], contains physical and cognitive ergonomics requirements for equipment to be used in conjunction with design requirements published by the FAA [ref. 17]. These requirements are intended to ensure that equipment is compatible with the body dimensions, strength, reach, and range of motion of crewmembers, "taking into account factors such as gravity environments, clothing, pressurization, and deconditioning related to mission duration" [ref. 26, p. 18]. The standard covers considerations such as:

- Is equipment reachable by the crewmember in his/her working posture, using the most encumbering equipment and clothing anticipated?
- Will the weakest crewmember have the strength to perform the tasks required in an emergency?

Reference 26 requires designers to ensure that equipment is compatible with the cognitive capabilities and expected limitations of crewmembers. Among the issues considered in the standard are:

- Will crewmembers be able to perform their tasks in a timely and accurate manner for all anticipated levels of crew capability?
- Will the crewmembers have access to the information needed to perform the emergency tasks (e.g., visual information)?
- Will crewmembers be able to communicate effectively when using emergency equipment during an emergency?

Compliance with the intent of NASA STD 3001 can be partly evaluated by analysis; however, experience has shown that HITL evaluations are the most effective way to ensure that systems are useable and effective. Realistic training exercises with the user population can provide one of the most effective HITL evaluations, as performance difficulties encountered during training frequently point to system design deficiencies.

The effectiveness of emergency equipment is sometimes impaired by usability deficiencies that were not apparent to system designers but became evident only when users performed the task during training or under real-world conditions. For example, Fairbanks et al. [ref. 18] found that a commonly available defibrillator suffered from poor interface design that made it difficult to use even by trained emergency medical technicians (EMTs). Although the intent of training is to impart the necessary competencies to users, realistic training also provides a valuable opportunity to identify usability deficiencies in equipment and procedures.

10.1.4 User-Centered Design Requires an Understanding of Task to be Performed

For equipment and procedures to be genuinely user-centered, it is necessary to understand the tasks that must be accomplished by the crew and the environment in which they must be performed. Task analysis achieves this by identifying the sources of information required by the crew, the required actions, and the necessary cognitive activities, including decisions and communication requirements. NASA STD 3001 [ref. 26, Section 3.2.1] requires that each HSF program or project shall perform a task analysis to support hardware and operations design.

Some of the questions that would be asked in the course of a task analysis of the crew use of fire safety equipment would include the following:

- What sources of information are relied on by the crew (e.g., alarms, direct sensory information, and documentation)?
- Is the crew expected to perform steps from memory or would a checklist be used?
- What communication is required between team members, and how would communication be affected by a breathing mask?
- What physical actions are required?

10.1.5 Crew Resource Management

A team response to an emergency requires not only individual technical proficiency but also non-technical teamwork skills, also referred to as "crew resource management (CRM)" skills [ref. 21]. The value of CRM skills has been recognized within virtually all safety-critical industries, as well as within NASA. These competencies include effective communication, task delegation, and crew coordination. In the absence of these skills, even individuals with a high level of individual technical competency, may fail to perform a task effectively when working as a team. These skills must be developed and exercised through practice. In the case of emergency procedures, this can only occur via specialized practical training, including the performance of emergency tasks in a realistic team context.

10.2 Case Studies

While lacking the empirical strength of research studies, case studies can help inform the HSI community of specific examples of a system performing well or poorly in a particular instance. As a result, HSI researchers can identify important issues to study further, and HSI practitioners can glean important "lessons learned" either from the event itself or from subsequent investigation and analysis. It is important that case studies be used as only one tool in the HSI toolbox to avoid practices based on isolated, anecdotal evidence. This subsection presents four case studies relevant to fires in enclosed vehicles, and lessons learned that can inform the Orion Space Safety System.

10.2.1 Case Study 1: Fires on US Aircraft Carriers *Oriskany*, *Forrestal*, and *Enterprise*

Three serious fires occurred on board US Navy aircraft carriers in the 1960s. On May 26, 1966, a fire occurred on the *USS Oriskany* that killed 44 crew and injured another 156. On July 1967, a fire occurred on the *USS Forrestal* that killed 134 crew and injured another 161. On January 14, 1969, a fire occurred on the *USS Enterprise* that killed 28 crew and injured another 314. These incidents can be assessed from the perspective of initiating event, incident response, training, post incident analysis of root cause, and corrective actions. The fire onboard the *USS Forrestal* will be the main focus of this case study because the post incident investigation and corrective actions offer especially instructive lessons regarding human spaceflight fire safety [refs. 28–31]. The fires that occurred on the *USS Oriskany* and *USS Enterprise* will be briefly described for reasons of context.

The *USS Oriskany* fire started when a flare was accidentally actuated and then placed inside a locker containing a large number of magnesium flares. The door to the locker was jammed and could not be opened, so the firefighting team bravely tried to cool the area around the locker by spraying large amounts of water onto the outside of the locker. The cooling efforts were unsuccessful; about 10 minutes after the initial flare actuation, several flares inside the locker ignited and the locker blew apart. Firefighting teams tried to remove fuels and munitions from the area, but the locker blast triggered a substantially larger fire. After the fire, a Navy investigation determined that the magnesium flares involved in the initiation of the fire could inadvertently ignite.

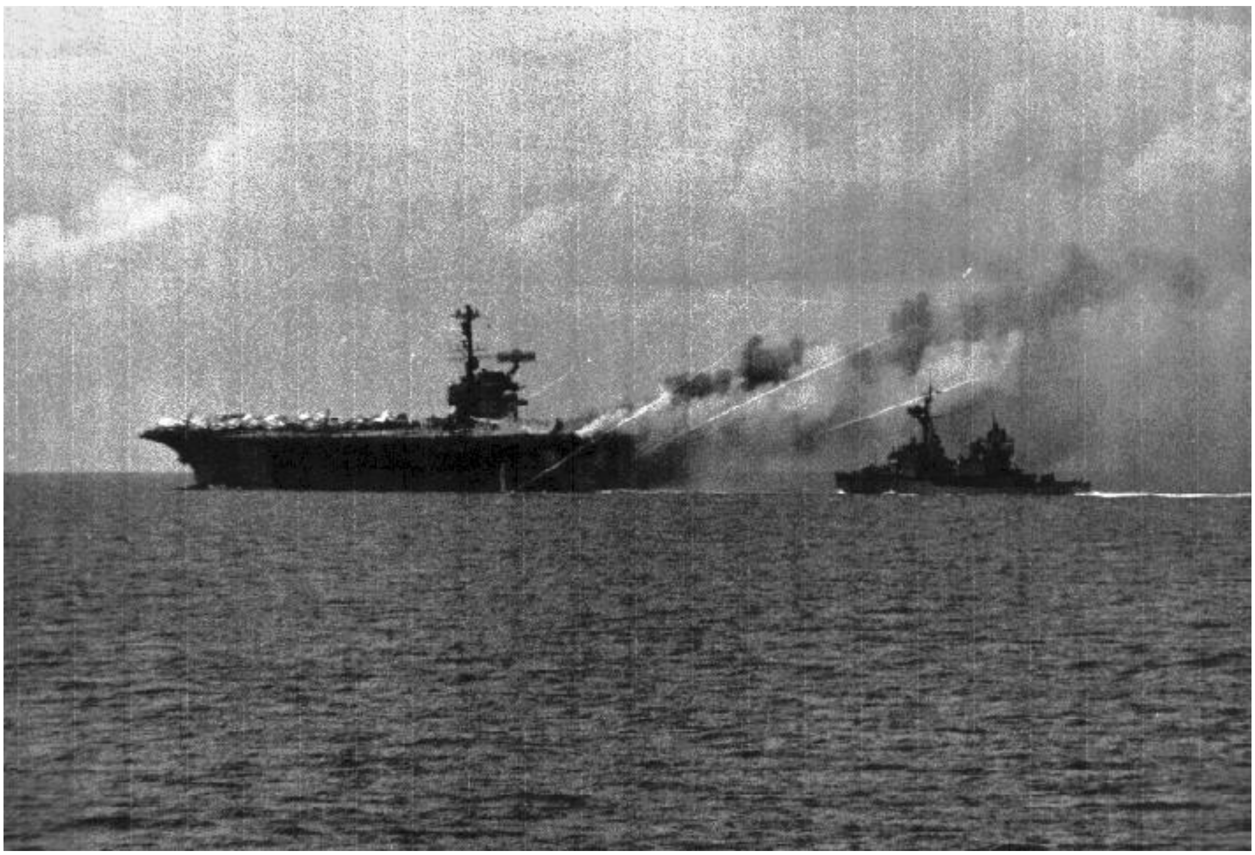


Figure 10.2-1. Photo of 1967 Fire Onboard USS Forrestal, with USS Rupertus in Foreground [US Navy photo reprinted from ref. 32]

The fire onboard the *USS Forrestal* started when an anomaly caused a Zuni rocket mounted to an F-4B Phantom aircraft to inadvertently fire. The rocket struck the fuel tank of an A-4 Skyhawk aircraft, which was in line to take off. The flight line had a large number of items that contained fuel or munitions, so the risk of an extremely large fire was immediately apparent. The damage control team quickly approached the fire and began spraying down the affected area. The damage control team had been shown a training film that indicated munitions could be exposed to a jet fuel fire for up to 10 minutes before "cooking off" and detonating. Unfortunately, the munitions on the *USS Forrestal* were more sensitive to external heating, and the munitions “cooked off” and detonated 1 minute and 36 seconds after the start of the fire. An expanding progression of explosions and fires ensued despite efforts by personnel to extinguish fires and remove munitions from the area.

After the fire, the US Navy conducted a series of after-incident reviews and made three main corrective actions:

- Triple Ejector Rack (TER) electrical safety pins designed to prevent the Zuni rocket from inadvertently firing were modified and subjected to a series of procedural changes.
- The US Navy initiated an Aircraft and Ordnance Safety Program to delay munition cook-off. These efforts resulted in a whole class of “insensitive munitions.”
- The US Navy implemented additional firefighting training. The detonation of the first explosion killed nearly all of the trained firefighters onboard, so most firefighting efforts after the initial detonation were improvised by crew who were untrained in firefighting. In response, the US Navy adopted a week-long firefighting training program. All sailors are instructed in fire behavior and must demonstrate the ability to actively use portable fire extinguishers and hoses and the ability to egress from confined spaces filled with smoke.

Like the *USS Forrestal* fire, the fire that broke out onboard the *USS Enterprise* started when a Zuni rocket inadvertently detonated. Like the *Forrestal* fire, there were munitions in the area that were sensitive to detonation caused by “cooking off” when externally heated. Corrective actions related to the TER safety pins and insensitive munitions had not been implemented; the *Enterprise* fire occurred less than 18 months after the *Forrestal* fire. The after-incident report praised the firefighting actions taken by the *Enterprise* crew. The investigation report notes that on the *Forrestal*, only half of the ship’s crew and none of the air wing had attended firefighting school. When the fire on the Enterprise broke out, 96% of ship’s crew and 86% of the air wing had completed firefighter training.

10.2.2 Case Study 2: Apollo 1 Fire

On January 27, 1967, NASA was conducting a “plugs out” simulation of the Apollo spacecraft to test whether the spacecraft could operate on (simulated) internal power (i.e., disconnected from all cables and umbilicals). This test was a critical milestone on the path to a planned launch on February 21. Because neither the launch vehicle nor the spacecraft was loaded with fuel or cryogenics, the test was considered nonhazardous.

The test was not proceeding well. There were delays due to an unidentified odor and communication issues, the latter leading Commander Gus Grissom to comment: “How are we going to get to the Moon if we can’t talk between two or three buildings?” At 6:30 p.m., 5.5 hours after the exercise began, the countdown remained on hold at T minus 10 minutes.

While the crewmembers used the delay to run through their checklist once more, there was a momentary increase in the AC Bus 2 voltage. Nine seconds later (6:31:06) there was an exclamation of alarm (believed to be uttered by Commander Grissom), followed by 2 seconds of scuffling sounds through Grissom’s open microphone. At 6:31:06, another crewmember (believed to be Ed Chaffee) reported: “[I’ve or We’ve] got a fire in the cockpit.” This was followed, after 6.8 seconds, by another badly garbled transmission that referred to fire and getting out; the transmission ended with a cry of pain.

Fed by the spacecraft’s pure-oxygen environment, the raging fire raised the internal pressure to 29 psi, which ruptured the command module’s inner wall at 6:31:18, allowing flames and gases to rush through open access panels to two levels of the pad's service structure (see Figure 10.2-2). The intense heat, dense smoke, and ineffectual gas masks (designed for toxic fumes rather than heavy smoke) hampered rescue attempts. It took 5 minutes for the pad workers to open the three hatch layers. As the dense smoke cleared in the cabin, it was obvious that all three crewmembers were dead [ref. 11].

Figure 10.2-2. Interior of Apollo 1 Spacecraft after Fire

NASA conducted an internal investigation of the accident; the Apollo 204 Review Board released its final report on April 5, 1967. There were obviously many factors that contributed to the fire and its grim outcome. For the purpose of this report, it is instructive to compare the conditions in place during the Apollo 1 test with the fire safety systems illustrated in Figures 7.1-1 through 7.1-3 (note that none of the fire safety subsystems employed in subsequent spacecraft systems were in place that day).

In terms of preventative measures, the Apollo 1 spacecraft failed to control either the flammable materials or the ignition sources, and the crew cabin's pure-oxygen environment provided an abundance of the third element of the fire triangle. As for operational responses to the fire, there was no fire extinguisher present in the crew cabin (fire extinguishers were included as a Mission Operational Aid beginning with Apollo 7). Tragically, there was also no viable provision for evaluation. The mechanism to open the hatch door was multi-phase and cumbersome, and there was not adequate fire equipment for rescuers to aid in a timely manner.

Lessons Learned

- Nonflammable materials should be selected for the spacecraft interior design.
- The spacecraft should be kept clean of any flammable vapors or debris.
- There should be no electrical ignition sources in the spacecraft.
- Fire safety equipment should be provided to the crew.
- A safe and timely egress system should be provided.
- Rescue crews should have safe and timely access to the scene.

- Fire emergencies are dynamic and time critical.

10.2.3 Case Study 3: *Mir* Fire

Four Russian cosmonauts, Valeri Korzun, Alexander Kaleri, Vasily Tsibliev, and Aleksandr Lazutkin; one German astronaut, Reinhold Ewald; and one NASA astronaut, Jerry Linenger, were on board the *Mir* spacecraft on February 24, 1997. Because of the large crew size, chemical oxygen generators were used to supplement the oxygen provided by the Elektron water electrolysis system.

Astronaut Jerry Linenger reports that while he went to the Spektr module to do some work, Aleksandr Lazutkin went to the Kvant-1 module to activate another oxygen generator. In a complete surprise, the normally slowly reacting chemicals erupted into searing flame. The flame shot out about 2 to 3 ft, with bright bits of molten metal "flying across and splattering on the other bulkhead."

The crew immediately began putting on oxygen masks. Linenger's first mask failed to activate, so he used another one. While trying to operate the potassium superoxide (KO_2) rebreather units, smoke quickly filled the cabin. Linenger reports, "I did not inhale anything, and I don't think anyone else did because the thickness of the smoke told you that you could not breathe."

Valerie Korzun, who was in charge of the station, began to deploy fire extinguishers to fight the fire. Korzun later said, "When I started spraying foam on the hot canister, the foam didn't stick and had little effect. So I switched to water, and started using that." The water turned to steam and added to the smoke. Linenger stayed with Korzun and passed fresh fire extinguishers to him. The fire eventually burned itself out, but smoke remained everywhere, even in the distant modules. It was now hotter than body temperature inside the Kvant-1 module, and the smoke and soot was so thick that Lazutkin reported, "We even thought someone had switched the lights out in Kvant. That's how black it was."

The fire consumed most of the canister (see Figure 10.2-3) and the panel that covered the device.

Figure 10.2-3. Remains of Oxygen Generator involved in 1997 Mir Fire

Neither German astronaut Reinhold Ewald nor NASA astronaut Jerry Linenger had ever activated the KO_2 chemical rebreather before the emergency on the *Mir*. They had obtained classroom training on the device, but KO_2 chemical rebreathers are complex devices with three different chemical reactions that must occur in sequence before they are fully operational.

Initially, the moisture from the exhaled breath starts a chemical reaction, then the hydrated chemical reacts with exhaled CO_2 and oxygen is released. Some of these chemical reactions are exothermic and produce amounts of heat that are easily noticeable to the wearer. It is likely that the first chemical rebreather that Linenger activated was operating nominally but he perceived the system to be faulty, so he held his breath (in a contaminated environment with dense smoke) and tried a second device. Valerie Korzun had never extinguished an oxygen candle fire before the on-orbit fire. He was developing firefighting techniques in real time during an on-orbit fire emergency.

Lessons Learned

- All crewmembers must be trained in the use of fire safety equipment.
- Fire safety equipment must be appropriate for the operational environment.
- All fire safety equipment must be maintained in good operating condition.
- Emergency response roles and procedures must be established and understood by all crewmembers.
- Onboard fire emergencies are dynamic and time-critical, leaving little time for problem solving or consultation with Ground Control.

10.2.4 Case Study 4: Fire On Board Submarine *HMS Tireless*

On March 21, 2007, 130 submariners were on board the UK Royal Navy submarine *HMS Tireless*. The *HMS Tireless* was in Artic waters, north of Alaska, participating in US Navy/UK Royal Navy joint training exercises. An explosion occurred in the forward escape compartment, resulting in two fatalities and a serious injury (see Figure 10.2-4). The explosion was caused by a chemical oxygen generator, similar to the chemical oxygen generator involved in the *Mir* fire. Normally, chemical oxygen generators onboard submarines undergo a high-temperature chemical decomposition that releases hot oxygen into the submarine atmosphere. Available evidence indicates that the oxygen generator that exploded was dropped, and the chemical briquette was fractured. Additionally, there was a breach of the seal on the lid of the canister. The canister was stored in an environment that contained oil and other flammable liquids, and forensic evidence suggests that oil leaked into the canister and soaked into the chemical briquette.

Figure 10.2-4. Photo of HMS Tireless Shortly after Explosion and Fire during Rescue Activities

There were two types of emergency breathing devices on board the *HMS Tireless* at the time of the explosion: 1) chemical rebreathers, which are self-contained and allow for free movement, and 2) a supplied-air breathing system (referred to by submariners as “ship’s air”). The supplied air breathing systems are plugged in to fittings mounted on the compressed air lines. The compressed air lines are located throughout the ship.

At the time of the explosion, there were approximately 30 submariners sleeping in the forward area. These submariners retreated from the explosion to the center area of the ship because there was a possibility that an isolation hatch would need to be closed. Each of the submariners retreating from the forward area passed a bank of chemical rebreathers. No one used any of the rebreathers. Each of the submariners leaving the forward area searched for ship’s air masks. All of the available fittings were used, and there were submariners without access to ship’s air. Submariners assisted each other and shared the ship’s air systems.

While this assessment focuses on fire response systems, two aspects of the chemical oxygen generator operational processes should be noted because they are relevant to operational processes for fire safety system:

1. There was a tragic lack of shared understanding of hazards and use environments: the people with an understanding that the chemical oxygen generators would be stored in an oily contaminated environment did not recognize the chemical hazards. The people with an understanding of the chemical hazards did not know that chemical oxygen generators would be stored in a contaminated environment.
2. The oxygen generators were occasionally used, but there was no systematic method of inspection or record keeping of anomalies. Some units hissed when initiated, some units had burn-through spots on parts of the can, and some units had lids that were not fully sealed, but this evidence was not collected in a systematic way before the fire, so it could not be acted upon.

The Captain focused training efforts on the nuclear reactor, the nuclear weapons, high-voltage electrical lines, and other systems perceived to present the greatest hazards on the ship. This allowed a lesser hazard (i.e., the chemical oxygen generator) to be neglected and mishandled.

With respect to emergency breathing systems, the lack of shared understanding and training resulted in too few breathing systems and a sharing of masks. The emergency systems subject matter experts considered rebreathers to have superior engineering specifications but did not realize that the crew did not understand or trust the rebreather systems. The Captain and the US Navy senior leaders had competing demands for their attention and limited resources. The limited training resources were directed to other systems, so submariners did not get a chance to use rebreathers as part of their training.

Lessons Learned

- Flammable material must be properly contained and stored away from ignition sources.
- All high-risk equipment (e.g., oxygen generators) must be regularly inspected and maintained in good operating condition.
- All crewmembers must be trained in the use of fire safety equipment.
- Emergency response roles and procedures must be established and understood by all crewmembers.

10.3 Analog Studies

Despite 60+ years of HSF, the absolute number of missions flown (and onboard emergencies encountered) is relatively small. Thus, in addition to examining previous NASA programs for guidance, it is also useful to seek guidance from other organizations that face similar challenges (albeit with larger scales of operations). In the field of HSI, NASA experts frequently examine analog programs from the military, aviation, medicine, high-risk industries (e.g., nuclear plants, off-shore oil platforms), and remote research outposts for evidence of effective design, evaluation, and training for complex systems.

This subsection considers three analogs relevant to the Orion Fire Safety System. From within NASA, a natural analog is the selection and qualification of the ISS's original fire safety equipment. From the military, the US Navy's SUBSAFE program provides an excellent demonstration of how to implement effective safety training and evaluation. Finally, from the aviation community, the FAA's response to the fire risk introduced by new battery technology demonstrates the development and testing of effective fire-suppression procedures, with an emphasis on disseminating this information and training flight crews.

10.3.1 Analog 1: Selection and Qualification of Original ISS Fire Safety Equipment

In March 2009, fire safety subject matter experts met at WSTF to develop performance test standards for a prototype water mist fire extinguisher. Included in this group were Mike Pedley, M&P System Manager for ISS, Harold Beeson, Chief of Labs at WSTF, and John Graf, Technical Lead for the Water Mist Fire Extinguisher Development. Mike Pedley and Harold Beeson have served as fire safety subject matter experts since the late 1980s. They had direct knowledge regarding the selection and qualification processes for the CO_2 fire extinguisher and PBA supplied oxygen contingency breathing system for the ISS.

Development and qualification of a fine water mist fire extinguisher would require new processes and new test techniques. The Halon fire extinguisher for the Space Shuttle was qualified by analysis to demonstrate that that a gaseous flooding system would create a Halon concentration sufficient to extinguish any fire. There was no "standard fire" for the SSP, and no standard performance test to demonstrate the ability to extinguish a fire. Similarly, the CO_2 fire extinguisher for ISS was qualified by analysis. There was no standard performance test to demonstrate that the CO_2 fire extinguisher could actually extinguish a fire. Water mist fire extinguishers cannot be credibly qualified by analysis; water mist systems must be qualified by test. The performance of the water mist fire extinguisher depends on the size and temperature profile of the fire, the distance from the fire, the discharge rate, and operator technique. Because the performance of a water mist fire extinguisher must be demonstrated by test and because NASA had no preexisting performance test standard for fire extinguishers, NASA needed to develop a performance test standard for water mist qualification. Previously, fire extinguishers qualified by NASA did not demonstrate by test that they could extinguish fires.

Similarly, the supplied oxygen breathing systems for the Space Shuttle and the ISS were qualified by analysis. It was not required to test the PBA in a contaminated atmosphere. Positive pressure inside the mask created a condition where analysts could show that contaminated air could not realistically be inhaled, which allowed the PBA to be qualified by analysis. Filtering respirators (Figure 10.3-1) must be qualified by test. The performance of the filtering respirator depends on the levels of contamination, the temperature and humidity of the air, and the rates of breathing. NASA had no preexisting performance test standard for contingency breathing devices, so there was a need to develop a performance test standard for the EM systems.

Mike Pedley has well-established concerns about the use of the CO_2 fire extinguisher. M&P evidence suggests that microgravity fires starve themselves of oxygen because of the lack of free convection. Discharging a CO_2 fire extinguisher in an open cabin environment causes air to mix and circulate in unpredictable ways. Mike Pedley has indicated in ISS Program control boards that the safest thing to do in the event of an open cabin fire is to turn off ventilation and not use the CO_2 fire extinguisher. The rationale for this suggestion is that in microgravity, the most effective and reliable way to control the growth of a fire is to limit the supply of fresh oxygen. Without buoyant convection, microgravity fires will self-extinguish in still air. Discharging a CO_2 fire extinguisher may extinguish a fire, but it may also circulate the air and resupply the fire with more oxygen. Harold Beeson has well-established concerns about the use of CO_2 fire extinguishers because there is a chance of discharging the fire extinguisher into an area where crewmembers do not have a source of contingency breathing. Harold Beeson tells students in his oxygen safety classes that "the concentration of CO_2 that extinguishes fires is the concentration of CO_2 that kills astronauts." He also has concerns about wearing an oxygen mask in a fire on-board ISS, for reasons of increased flammability in the elevated oxygen environment surrounding the wearer of the mask.

Figure 10.3-1. ISS Fire Safety Training Exercise (filtering respirator on left, supplied oxygen system in center)

The heritage of the CO_2 fire extinguisher and oxygen-based breathing system was re-reviewed in light of their safety hazards and the possibility of using less hazardous alternatives (e.g., a filtering respirator or a water-based fire extinguisher). Pedley and Beeson report that the system was selected and specified by the ISS Vehicle Manager. The fact that the CO_2 fire extinguisher and the oxygen mask could be qualified by analysis meant that qualification costs would be significantly less than developing and qualifying new technology that required qualification by analysis. Water-based fire extinguishers were not developed, as selecting a water-based fire extinguisher would introduce schedule risk.

The human decision-making aspects of selecting a fire extinguisher that could harm the crew and make microgravity fires larger, and of wearing an oxygen mask in a fire emergency, should be assessed. This project attempts to understand the human decision-making aspects that lead to the selection of a fire extinguisher that could harm the crew and wearing an oxygen mask in a fire emergency. One explanation is that from the vehicle manager's perspective, the risk of missing program schedule/budget requirements is a high likelihood risk that must be prioritized. The risk resulting from wearing an oxygen mask in a fire is low because the likelihood of a fire is low. The rational decision for the vehicle manager was to select equipment that could be qualified by analysis (to address the schedule and budget risk) and to address the fire safety risk by preventing fires through a rigorous program of materials control and ignition control. Subject matter experts focused efforts on ignition source control and fire prevention.

It is important to note that the rigorous process of material controls established by the M&P System Manager and the rigorous process of ignition controls established by the Oxygen Safety Group at WSTF have been effective. To date, no NASA fire extinguisher has been discharged on the ISS.

The ISS Program Managers had competing priorities and a low-likelihood risk item like use of a fire extinguisher, which resulted in fire response systems being placed low on the list of priorities. Fire safety subject matter experts emphasized fire prevention. ISS system trainers conducted classroom training on the fire safety hardware, but the training did not involve using the hardware in an environment with fire. The astronauts are motivated to learn as much as they can from training in any form.

10.3.2 Analog 2: Admiral Rickover's Program of Rigorous Sea Trials

The previous analog example presented a situation where organizational processes were structured in a way that there was little or no proficiency training, and little or no exercising of emergency equipment. The present analog example presents a case where organizational processes are structured to exercise hardware and to build operational proficiency through mandated drills in realistic conditions. The people who developed these processes recognized the unique aspects of mitigating low-probability risks. The organizations and processes put the emphasis on the tests and training, not on the predicted probability.

Admiral Hyman Rickover served as director of the US Naval Reactors Office and directed the original development of naval nuclear propulsion and operations. The United States Nuclear Navy has a continuing record of zero reactor accidents involving the uncontrolled release of fission products. This accident-free record stands in stark contrast to that of the Soviet Union, which has 14 known reactor accidents. After two US Navy nuclear submarines sank in the 1960s with all hands (the *USS Thresher* and the *USS Scorpion*), the Submarine Safety Program (SUBSAFE) was established. The loss of both ships was not due to a reactor accident. Since the establishment of SUBSAFE, no US submarines have been lost, while the Soviet Union/Russian Federation has continued to lose submarines due to non-nuclear reasons.

There are several tenets to a successful reactor safety program and a successful SUBSAFE program. Both involve well-educated and trained crews. Additionally, a central part of both was a rigorous initial sea trials program. Successful completion of sea trials verifies that the crew is well trained, the equipment is functioning as it should, and the processes important to controlling a reactor accident are being followed. Admiral Rickover made it a point to be aboard during the initial sea trials of every nuclear submarine completing its new construction period (see Figure 10.3-2).

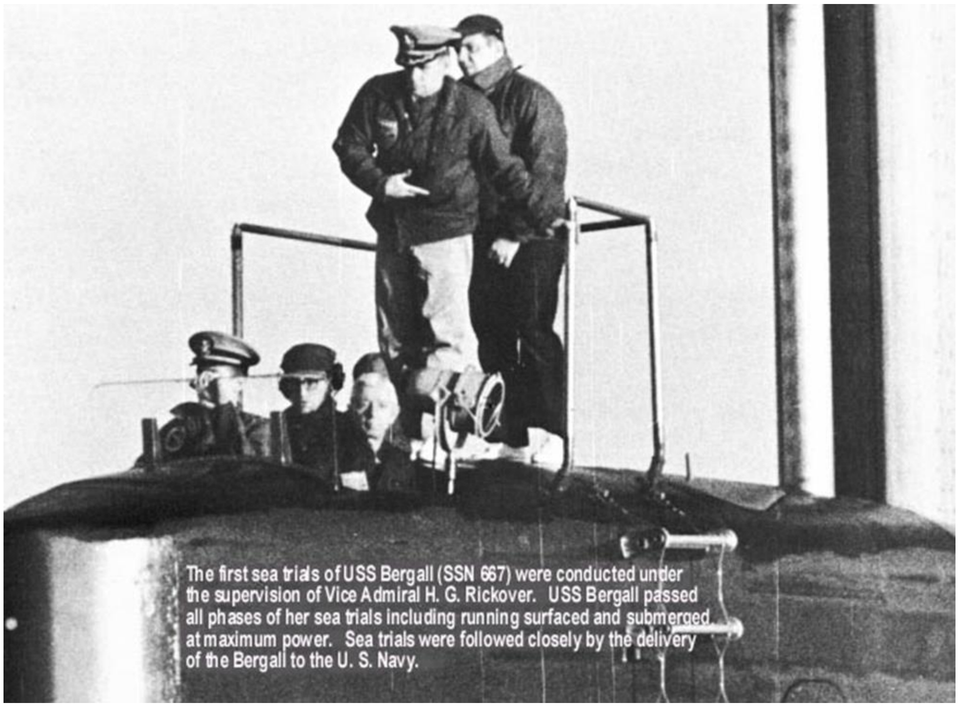


Figure 10.3-2. Then Vice Admiral Rickover aboard the USS Bergall during Initial Sea Trials

Admiral Rickover developed a safety culture that used a sea trials program, thus ensuring that everyone holds a shared belief that the crew should be fully trained and the equipment should be working nominally, both for the successful completion of sea trials and for controlling the unlikely chance of a reactor accident. Everyone had a shared understanding of the physical aspects and technical details of the system. Admiral Rickover personally participated in the sea trials to learn about the issues directly.

10.3.3 Analog 3: FAA Development of Laptop Fire Challenge Test

On September 15, 2006, at Los Angeles International Airport in Los Angeles, California, an IBM ThinkPad battery suffered a cell pressure release and started a fire in the airport terminal. The owner of the laptop was able to get the flaming laptop off the plane by running up the jet bridge in the opposite direction from the boarding passengers, successfully getting the burning device off the plane and the jet bridge and into the larger terminal. In the terminal, the fire burned vigorously for about 1 minute, then high intensity flaring began and the fire grew to a larger scale while issuing a thick cloud of white smoke. Eventually, an airport employee extinguished the fire using a fire extinguisher.

This incident was an early example of the risk laptop computers and other electronic devices powered by lithium-ion batteries pose to commercial flights. Between March 20, 1991, and August 1, 2019, the FAA recorded 265 air/airport incidents involving lithium batteries carried as cargo or baggage (both carried on and checked). While many of these incidents occurred at cargo-processing facilities or airport terminals, a considerable number occurred during what could be considered an “in flight” analog (i.e., onboard the aircraft with cabin doors secured, thus requiring the flight crew to resolve the emergency).

The FAA responded to these incidents in a timely manner. The Agency initiated a rigorous and extensive testing program to evaluate fire suppression procedures. Several types of laptops were used as test articles, several different configurations were tried, and several different methods of initiating the fire test were developed. After many iterations of methods development testing, a standard test method was developed and several fire-extinguishing methods were directly tested. Three examples of these direct fire challenge tests are shown in Figures 10.3-3 through 10.3-5.

Figure 10.3-3 shows the results from an FAA laptop fire test using a Halon fire extinguisher. The Halon extinguisher initially extinguishes the fire (left), but the remaining residual heat and stored chemical energy in the battery causes the laptop fire to reignite (right).

Figure 10.3-3. FAA Laptop Test using Halon Fire Extinguisher

Figure 10.3-4 shows results of an FAA laptop fire test using ice as the fire extinguishing agent. As in the Halon test, the ice initially extinguishes the fire, but like the Halon test, the remaining residual heat and stored chemical energy in the battery causes the laptop to reignite (right).

Figure 10.3-4. FAA Laptop Test using Ice as Extinguishing Agent

Figure 10.3-5 shows results of an FAA laptop fire test using water as the fire-extinguishing agent. Unlike the Halon or ice tests, the water fully extinguishes the laptop fire. Test results were presented to flight attendants and other flight crew.

Figure 10.3-5. FAA Laptop Test using Water as Extinguishing Agent

The FAA determined other effective methods for fire suppression and containment. First, if the device's battery has not yet burst into flame, it is often sufficient to place the device in fire bag. Second, containment in a fire bag (preferably with the device flooded with water or other non-alcoholic fluid) serves as an excellent deterrent to reignition (a significant danger with lithium-ion batteries).

The FAA did not dismiss the risk of laptop fire by (correctly) noting that the likelihood of a laptop fire on an aircraft is relatively small because they recognized the consequences are potentially quite severe. Instead, the FAA focused on the need for effective testing to better understand which firefighting strategies were most effective. Compare the FAA program to the fire response strategy on *Mir*. There had been a series of mishaps involving chemical oxygen generators prior to the 1997 *Mir* fire, but there was no corresponding test program to evaluate different firefighting strategies. Valerie Korzun had to develop a firefighting strategy on the fly, in real time, during the *Mir* fire. First, he tried foam, and later switched to water. The FAA test program tried many different extinguishing methods on several different test configurations, and then shared the test results with flight attendants and other flight crew (e.g., SAFCO 09013 [ref. 12] and an accompanying training video).

10.4 System-level Testing and HITL Testing

Although the scope of the current assessment focuses on three pieces of hardware (i.e., the CBA, the OPFE, and the OSEF), it must be recognized that these are critical components of the Orion Fire Safety System and that is it the system whose performance must be validated to ensure mission success. The logical first step in this validation process is to test and evaluate the hardware as an integrated suite. This is covered in the Supertest discussion.

However, while the Supertest step is necessary, it is not sufficient. To validate the Orion Fire Safety System for flight, HITL testing and evaluation is necessary to verify that the crew can successfully deploy the system as intended in the operational environment.

10.4.1 NASA's Supertests of Orion Fire Safety Equipment

Although NASA's Supertests are not actual HITL evaluations, they represent an important step in that direction by testing the three critical hardware components being evaluated (i.e., the PFE, the OSEF, and the CBA) as an integrated system.

As of June 2019, WSTF personnel have conducted two multi-component, systems-level tests of Orion prototype fire response hardware. These tests are informally referred to as the Supertests. The first of these tests (i.e., Supertest 1) was conducted in 2018, and the second (i.e., Supertest 2) was conducted in 2019. A pretest configuration of key test articles for Supertest 2 is shown in Figure 10.4-1.

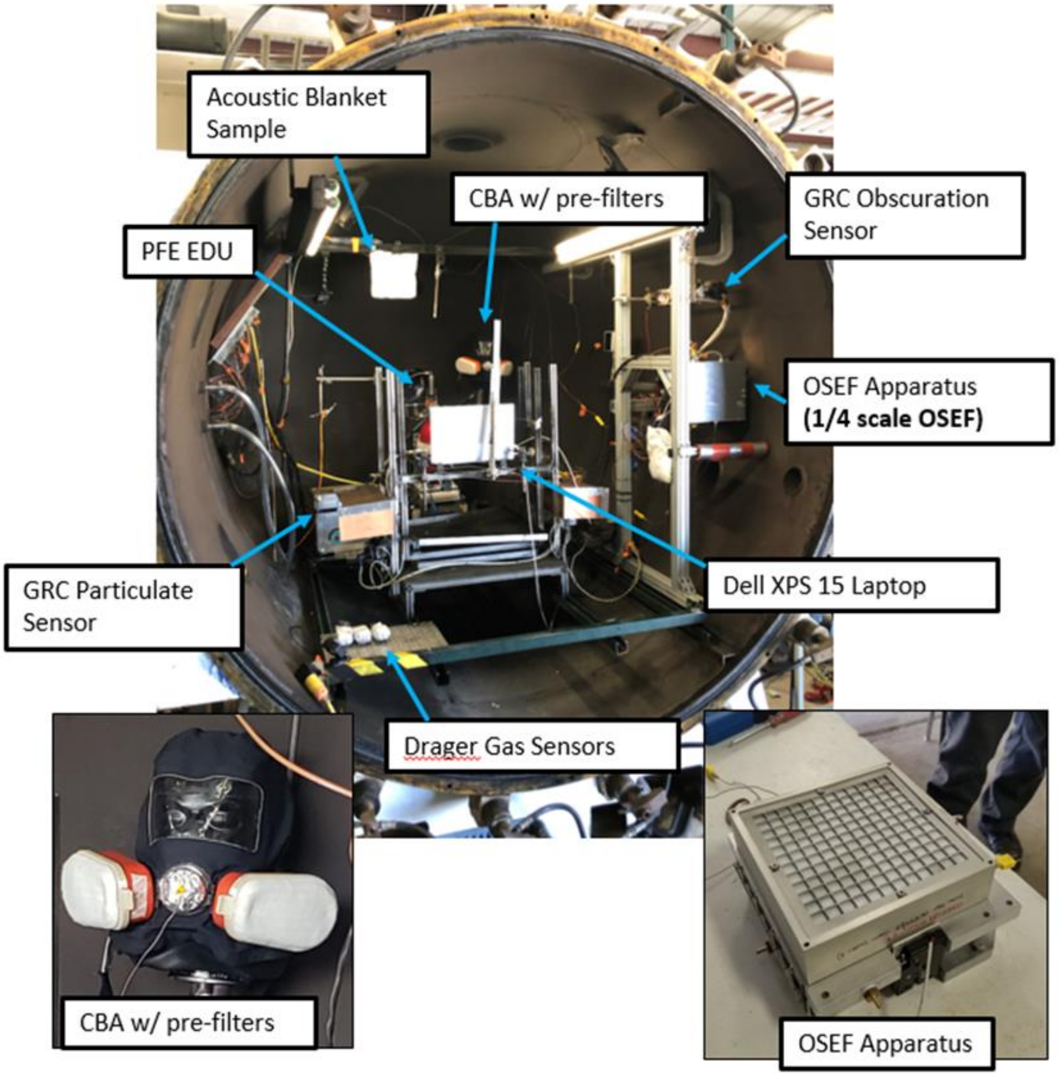


Figure 10.4-1. Photograph showing Configuration of Supertest 2, Conducted in June 2019

The Supertests were not required by any NASA standard. The Supertest costs were shared by several different programs. Results of the Supertests directly support qualification of the PFE, the OSEF, and the CBA. Test data inform engineering analyses that are used to verify (by analysis) that flight hardware requirements have been met. Additionally, the Supertests provided large-scale, realistic fires to measure the rate of fire growth and heat release. Smoke detector performance was measured for a complex and realistic fire and compared with several analytical measures of air quality. OSEF filters were challenged with large and realistic amounts of smoke, soot, water droplets, and steam. The OSEF and CBA work together as a system, and the

Supertests enabled a direct measure of system interactions and system-level performance. More detailed descriptions of the Supertests are given in Appendix D.

Note that the Supertests performed to date have only dealt with the laptop fire scenario. An additional system-level hardware test should be performed for the "post-abort open cabin fire" scenario.

10.4.2 Additional HITL Testing and Evaluation Needed

The Orion Program has already established important operational requirements and concepts of operation for the Orion Fire Safety System. Some of these are specific to individual components but logically must be extensible to the entire system. In terms of designing HITL evaluation, the critical operational requirements include:

- Extinguishing a battery fire (assumes shirt sleeves/bare hands, micro-G environment).
- Extinguishing a post-abort open cabin fire (assumes flight suit/gloved hands, 1-G environment).

Testing and evaluation should be conducted in a constrained volume matching the Orion's dimensions, with the equipment placed as it is planned to be located during the phase-of-flight of the fire scenario. The crew's initial locations and positions (e.g., seated and strapped in for post-abort) should likewise reflect the fire scenario.

In addition to providing additional validation of the hardware suite, HITL tests can evaluate whether components meet Program requirements (e.g., time to don the CBA). The tests can also identify ergonomic and workflow issues that delay time-critical crew actions. After testing is completed, the results can be used to develop operational procedures (e.g., individual roles, action and communication flow, crew coordination) that can be used later for training and proficiency testing.

While HITL tests should ideally involve full end-to-end simulations in the actual operational environment, the uniqueness of the space environment (e.g., micro-G) often requires additional evaluation in part-task tests. Thus, for example, it may be necessary to validate CBA donning on the ISS or in parabolic flight to ensure the time requirement can be met. Similarly, an immersive display (i.e., virtual reality (VR) headset) might be worn to ensure users can properly employ the OPFE in micro-G, where flame and water flow dynamics differ from 1-G). Often, techniques developed for HITL testing and evaluation can be repurposed for onboard recurrent training.

Thus, a VR system can simulate the fire and extinguisher behavior without danger or depletion of fire-extinguisher resources. Similarly, a "dummy" mask can be used to practice donning without compromising the operational mask air filters. Both initial and recurrent training help ensure that the crew is able to respond quickly and correctly to an actual emergency.

10.5 HSI Assessment: Findings, Observations, and Recommendations

10.5.1 HSI Assessment: Findings

F-21. Estimating the likelihood of emergency events is difficult, especially in domains with limited operational experiences (e.g., spaceflight hours versus commercial aircraft flight hours).

F-22. Complex systems need to be evaluated with HITL tests, employing realistic operational environments and scenarios.

F-23. Humans deal best with emergency events when they have been well-trained and have had the opportunity to practice in a realistic environment. Current training efforts reinforce procedures, operational sequences, and spatial relationships, but a lack of fire-safe training facilities and operational hardware creates a situation in which astronauts do not have the opportunity to discharge a fire extinguisher on a representative fire.

F-24. When the Apollo 1 fire occurred, none of the preventative measures were properly practiced, nor were operational controls intended to mitigate a fire in place. Improved fire safety practices were implemented afterward in response to the Apollo 1 fire.

F-25. When the *Mir* fire occurred, neither visiting astronaut had ever used the KO_2 emergency breathing system hardware; furthermore, the efficacy of fire extinguishing agents in the space environment was not understood, requiring "on the fly" development of fire-fighting procedures.

F-26. When the *HMS Tireless* fire occurred, submariners elected to share the "ship's-air" masks they trusted rather than use a KO_2 rebreather.

F-27. Oxygen breathing masks and CO_2 fire extinguishers were selected for use on the ISS, in part because they could be qualified by analysis.

F-28. The US Navy submarine fleet has never had a reactor accident that resulted in a nuclear release, and it has not lost a submarine since establishing the SUBSAFE program in the 1960s.

F-29. Rigorous sea trials and extensive proficiency training are central elements of US Navy safety efforts; many other organizations likewise stress emergency preparedness and drills.

F-30. The FAA tested many different fire-control strategies after a laptop battery fire occurred, and the FAA shared test results with commercial airline employees so they could be better prepared if a laptop (or other electronic device) fire occurs during a flight.

F-31. The Orion Program conducted a systems-level fire safety test, placing the CBA, the OPFE, the OSEF, and other systems in a closed chamber with a laptop fire.

10.5.2 HSI Assessment: Observations

O-4. NASA managers are trained to identify key challenges using Likelihood × Consequences matrices, and to direct efforts and focus resources on these key challenges. This directs efforts away from mitigating low-probability risks, even those with potentially catastrophic consequences.

O-5. The Orion Program has yet to conduct a systems-level fire safety test for the second fire scenario (post-abort open cabin fire).

O-6. The Orion Program has yet to conduct HITL fire safety system test to demonstrate usability and effectiveness in the intended operational environments under realistic conditions.

10.5.3 HSI Assessment: Recommendations

R-10. NASA should address the challenge of mitigating high-consequence/low-likelihood risks by establishing low-consequence/high-likelihood proficiency/proving-ground tests patterned after US Navy submarine sea trials and emergency-response drills practiced by other organizations.

R-11. The Orion Fire Safety System should be evaluated with HITL tests involving intended users and realistic operational scenarios. The results of these evaluations can then form the basis for the development of initial and recurrent crew training programs.

11.0 Conclusions

The key findings for this assessment are shown in the order they are discussed in this assessment report: conclusions regarding the physical aspects of the systems are given first, then conclusions regarding the organizational and process aspects, followed by the human behavior and human decision-making aspects. One summary recommendation is given.

Physical assessment key findings:

- The Orion Program is using the right kind of fire safety equipment. NASA is developing unique GFE rather than purchasing commercially available equipment or recertifying SSP or ISS hardware. This is correct and appropriate; Orion fire safety needs are unique and specific.
- The CBA, OPFE, and OSEF designs meet the technical requirements and address the key operational risks of the Orion Program. Fire safety equipment intended for use in a confined space should be simple and easy to use. The systems should avoid components with stored energy or potentially hazardous chemicals, and these should be safe to use in a small, confined space. The equipment should be effective. Compared with other candidate technologies, the CBA, OPFE, and OSEF are simple, safe, and effective.
- Fire safety systems should be easy to operate. Fire safety systems are used in unstructured, emergency conditions; it is especially important that fire safety systems are intuitive and easy to operate. The CBA, the OPFE, and the OSEF are intuitive and easy.

Organizational and process controls key findings:

- NASA hardware development processes work for systems that are regularly used but do not necessarily work for seldom-used contingency systems such as fire safety equipment. NASA processes allow fire safety equipment to be qualified by analysis only (without testing). The possibility exists that the first time fire safety equipment is operated is during an on-orbit fire emergency.
- NASA currently has no process that requires fire safety equipment to be exercised regularly as part of a proficiency/proving-ground test program. NASA processes require training, but these training requirements can be met with classroom training that does not provide the

trainee the opportunity to use the equipment. Fire safety system equipment is not regularly used, and when it is used, it is in an uncontrolled emergency situation. Training and operational proficiency are especially important in these circumstances.

HSI key findings:

- NASA managers are trained to use Likelihood × Consequence risk evaluation to identify key challenges, and to direct efforts and focus resources on these key challenges. This directs efforts away from mitigating low-probability risks, even those with potentially catastrophic consequences.
- The NASA Chief Engineer, the Chief of S&MA, and the Chief of Health and Medical should require that realistic proficiency testing of fire safety equipment be required for the Orion Program and other HSF programs (e.g., ISS and Gateway).
- The NASA Chief Engineer, the Chief of S&MA, and the Chief of Health and Medical should require that the Orion Fire Safety System be evaluated with HITL tests involving intended users and realistic operational scenarios. The results of these evaluations should be incorporated into initial and recurrent crew training programs.

12.0 Findings, Observations, and NESC Recommendations

12.1 Findings

The following findings were identified:

F-1. Halon decomposition products are toxic, but the SSP could use Halon fire extinguishers because the Shuttle Orbiter had the capability to land quickly in the event of an emergency, Shuttle astronauts could egress the vehicle, and Shuttle ECLS systems could purge the cabin atmosphere during an emergency landing.

F-2. In the event of a fire on the ISS, procedures specify that NASA astronauts are to don an oxygen breathing mask.

F-3. In the event of a fire, the Orion crew cannot quickly land and egress, nor can they retreat to an unaffected compartment. This increases the criticality of a reliable and robust onboard fire safety system, as it will be the sole fire mitigation option available to the crew.

F-4. A filtering respirator has greater simplicity and fewer potential hazards than any other contingency breathing system.

F-5. CBA cartridges without any prefilter have clogged during testing.

F-6. CBA prefilters have been developed by testing prototype prefilters in challenging and realistic test environments.

F-7. A water-spray fire extinguisher discharges an expellant with fewer hazards that any other fire extinguishing system.

F-8. The OPFE internal bladder carries additional technical risk; because it is a new design, it has non-metallic materials in contact with water and has severe structural load requirements.

F-9. A sorbent/catalyst cleanup filter has greater simplicity and fewer hazards than any other cabin atmosphere cleanup system.

F-10. The OSEF CO catalyst, sorbent, and flow distribution systems carry additional technical risk because OSEF flow rates are fast and linear gas velocities are high.

F-11. The OSEF prefilter cannot be fully tested on the ground in a gravity environment.

F-12. The performance of the Shuttle fire safety equipment was qualified by analysis.

F-13. Shuttle flight procedures specify that in the event of a fire, astronauts don a PBA oxygen mask.

F-14. No Shuttle astronaut ever wore a PBA oxygen mask in an environment with fire as part of a training exercise.

F-15. The performance of the ISS PBA and the ISS CO_2 PFE were qualified by analysis.

F-16. ISS flight procedures specify that in the event of a fire, astronauts don a PBA oxygen mask.

F-17. No ISS astronaut wore a PBA oxygen mask in an environment with fire as part of a training exercise.

F-18. The development and qualification of Orion fire safety equipment uses testing. Orion has a two-tiered test approach: some tests are dynamic and realistic, and some are repeatable.

F-19. The Orion Program does not plan to exercise fire safety equipment once it is qualified.

F-20. NASA has no requirement mandating that astronauts have the opportunity to use flight configuration fire safety hardware in an environment with fire. With respect to fire safety procedures, NASA has no requirement to "train like you fly and fly like you train."

F-21. Estimating the likelihood of emergency events is difficult, especially in domains with limited operational experience (e.g., spaceflight hours versus commercial aircraft flight hours).

F-22. Complex systems need to be evaluated with HITL tests, employing realistic operational environments and scenarios.

F-23. Humans deal best with emergency events when they have been well-trained and have had the opportunity to practice in a realistic environment. Current training efforts reinforce procedures, operational sequences, and spatial relationships, but a lack of fire-safe training facilities and operational hardware creates a situation in which astronauts do not have the opportunity to discharge a fire extinguisher on a representative fire.

F-24. When the Apollo 1 fire occurred, none of the preventative measures were properly practiced, nor were operational controls intended to mitigate a fire in place. Improved fire safety practices were implemented afterward in response to the Apollo 1 fire.

F-25. When the *Mir* fire occurred, neither visiting astronaut had ever used the KO_2 emergency breathing system hardware; furthermore, the efficacy of fire extinguishing agents in the space environment was not understood, requiring "on the fly" development of fire-fighting procedures.

F-26. When the *HMS Tireless* fire occurred, submariners elected to share the "ship's-air" masks they trusted rather than use a KO_2 rebreather.

F-27. Oxygen breathing masks and CO_2 fire extinguishers were selected for use on the ISS, in part because they could be qualified by analysis.

F-28. The US Navy submarine fleet has never had a reactor accident that resulted in a nuclear release, and it has not lost a submarine since establishing the SUBSAFE program in the 1960s.

F-29. Rigorous sea trials and extensive proficiency training are central elements of US Navy safety efforts; many other organizations likewise stress emergency preparedness and drills.

F-30. The FAA tested many different fire-control strategies after a laptop battery fire occurred, and the FAA shared test results with commercial airline employees so they could be better prepared if a laptop (or other electronic device) fire occurs during a flight.

F-31. The Orion Program conducted a systems-level fire safety test, placing the CBA, the OPFE, the OSEF, and other systems in a closed chamber with a laptop fire.

F-32. The Orion Program development of fire safety components (e.g., CBA, OPFE, and OSEF) follow best practices for safety equipment development: development includes system-level performance tests in a relevant environment, pressure vessel components conform to best practice standards, sorbent beds and catalyst beds are rigorously tested, and qualification of nonmetallic materials conforms to best practice standards.

12.2 Observations

The following observations were identified:

O-1. Hardware that is regularly exercised is more likely to perform as expected. One form of regular exercise is "proving ground" testing. Proving ground activities test hardware in complex and variable environments.

O-2. Many successful operational organizations use a system of rigorous proficiency training. One intent of this training is to make all operators and stakeholders familiar with the systems, and another is to identify previously overlooked issues. One example of the successful use of proficiency training is the submarine drills conducted by the US Navy, discussed in Section 10.

O-3. Qualification test programs are limited in scope; they do not include every operational scenario and do not test in every environmental condition.

O-4. NASA managers are trained to identify key challenges using Likelihood × Consequences matrices, and to direct efforts and focus resources on these key challenges. This directs efforts away from mitigating low-probability risks, even those with potentially catastrophic consequences.

O-5. The Orion Program has yet to conduct a systems-level fire safety test for the second fire scenario (post-abort open cabin fire).

O-6. The Orion Program has yet to conduct HITL fire safety system test to demonstrate usability and effectiveness in the intended operational environments under realistic conditions.

12.3 NESC Recommendations

12.3.1 Key NESC Recommendation

R-1. The NASA Chief Engineer, the Chief of S&MA, and the Chief of Health and Medical should require that realistic training and proficiency testing of fire safety systems and equipment be regularly conducted for all HSF Programs (e.g., ISS, Orion, Gateway, Artemis, and future programs). ***(F-12, F-15, F-18, F-19, F-20, F-22 through F-26, F-29, F-31)***

12.3.2 Secondary NESC Recommendations

The following NESC recommendations are directed toward the NASA Office of Safety and Mission Assurance:

R-2. When selecting fire safety technology for HSF missions, design simplicity should be a key selection criterion. ***(F-4, F-7, F-9, F-25, F-26)***

R-3. When selecting fire safety technology for HSF missions, minimizing hazards associated with elevated oxygen, toxic chemicals, and high-pressure systems should be a key selection criterion. ***(F-1, F-3, F-7, F-13, F-14)***

R-4. When selecting fire safety technology for HSF missions, there should be HITL demonstration of fire safety equipment in end-to-end tests that demonstrate the usability and effectiveness of equipment and procedures under realistic conditions, including reduced visibility and communication intelligibility. ***(F-12, F-13, F-22, F-23, F-24, F-29, F-31)***

R-5. Fire safety equipment should be developed and qualified by test whenever possible. ***(F-5, F-6, F-12, F-15, F-18, F-30, F-31)***

R-6. If fire safety equipment is qualified by analysis, then the additional risk of qualification without test should be documented and tracked. ***(F-5, F-11, F-12, F-15, F-25, F-26, F-27)***

R-7. NASA processes should mandate that the performance of safety critical equipment must be demonstrated by test. ***(F-3, F-5, F-28 through F-31)***

R-8. NASA processes should mandate that astronauts have the opportunity to use flight configuration fire safety equipment in an environment with fire as part of their proficiency training, similar to 14 CFR 121.417, which requires that all airline crewmembers extinguish a real fire during training. ***(F-2, F-13, F-14, F-16, F-17, F-20, F-22, F-23, F-25, F-26, F-29)***

R-9. Fire safety hardware should be regularly exercised by the intended users. ***(F-5, F-6, F-8, F-10, F-19)***

R-10. NASA should address the challenge of mitigating high-consequence/low-likelihood risks by establishing low-consequence/high-likelihood proficiency/proving ground tests, patterned after US Navy submarine sea trials and emergency-response drills practiced by other organizations. ***(F-21, F-23, F-28 through F-31)***

R-11. The Orion Fire Safety System should be evaluated with HITL tests involving intended users and realistic operational scenarios. The results of these evaluations can then form the basis for the development of initial and recurrent crew training programs. ***(F-20, F-22, F-23, F-25, F-26)***

13.0 Alternative Viewpoint(s)

There were no alternative viewpoints identified during the course of this assessment by the NESC team or the NRB quorum.

14.0 Other Deliverables

No unique hardware, software, or data packages, outside those contained in this report, were disseminated to other parties outside this assessment.

15.0 Lessons Learned

No lessons learned were identified for inclusion in the NASA Lessons Learned Information System (LLIS).

16.0 Recommendations for NASA Standards and Specifications

The NASA Chief Engineer, the Chief of S&MA, and the Chief of Health and Medical should require that realistic simulated proficiency testing for fire safety be required for Orion Program and for other HSF programs (e.g., ISS and Gateway).

17.0 Definition of Terms

Finding	A relevant factual conclusion and/or issue that is within the assessment scope and that the team has rigorously based on data from their independent analyses, tests, inspections, and/or reviews of technical documentation.
Observation	A noteworthy fact, issue, and/or risk, which may not be directly within the assessment scope, but could generate a separate issue or concern if not addressed. Alternatively, an observation can be a positive acknowledgement of a Center/Program/Project/Organization’s operational structure, tools, and/or support provided.
Problem	The subject of the independent technical assessment.
Recommendation	A proposed measurable stakeholder action directly supported by specific Finding(s) and/or Observation(s) that will correct or mitigate an identified issue or risk.
Supporting Narrative	A paragraph, or section, in an NESC final report that provides the detailed explanation of a succinctly worded finding or observation. For example, the logical deduction that led to a finding or observation; descriptions of assumptions, exceptions, clarifications, and boundary conditions.

18.0 Acronyms and Nomenclature List

ºF	degrees Fahrenheit
ºC	degrees Celsius
AGA	Anomaly Gas Analyzer
ATCO	Ambient Temperature Catalytic Oxidizer
CBA	Contingency Breathing Apparatus
CCU	Collapsible Contingency Urinal
CDR	Critical Design Review
CFE	Contractor-furnished Equipment
cfm	cubic feet per minute
CFR	Code of Federal Regulations
CH_2O	Formaldehyde
C_3H_4O	Acrolein
cm	centimeter
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRM	Crew Resource Management
dB	decibel
DOT	Department of Transportation
ECLS	Environmental Control and Life Support
ECLSS	Environmental Control and Life Support System
EM	Emergency Mask
FAA	Federal Aviation Administration
FC	Fire Cartridge
ft	feet
FY	Fiscal Year
GCAR	Government Certification Approval Request
GEMCB	GFE Executive Management Control Board
GFE	Government-furnished Equipment
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HEPA	High-efficiency Particulate Air
HF	Hydrogen Fluoride
HITL	Human-in-the-Loop
HPC1	Orion Cabin Particulate Control Assembly
HSF	Human Spaceflight
HSI	Human-Systems Integration
ISS	International Space Station
IVA	Intravehicular Activity
IWG	inches of water gauge pressure
JSC	Johnson Space Center
kg	kilogram
kPa	kilopascal
LAM	Laser Air Monitor
lb	pound
LiOH	Lithium Hydroxide

lpm	liters per minute
MICD	Mechanical Interface Control Document
mm	millimeters
mmHg	millimeters of mercury
MPCV	Multi-Purpose Crew Vehicle
NESC	NASA Engineering and Safety Center
NFPA	National Fire Protection Association
NH_3	Ammonia
N_2H_4	Hydrazine
O_2	Oxygen
OASIS	Orion Aft Stowage IVA System
OFC	Orion Fire Cartridge
OPFE	Orion Portable Fire Extinguisher
OSEF	Orion Smoke Eater Filter
PBA	Portable Breathing Apparatus
PDA	Pre-Delivery Acceptance
PDR	Preliminary Design Review
PET	Polyethylene Terephthalate
PIA	Pre-Installation Acceptance
PMMA	Polymethyl Methacrylate
POC	Points of Contact
POU	Point of Use
PPE	Personal Protective Equipment
ppm	parts per million
psia	pounds per square inch absolute
psid	pounds per square inch differential
psig	pounds per square inch gauge
S&MA	Safety and Mission Assurance
SMAC	Spacecraft Maximum Allowable Concentration
SSP	Space Shuttle Program
UK	United Kingdom
US	United States
V&VD	Verification and Validation Document
VR	Virtual Reality
VTL	Verification Tracking Log
WSTF	White Sands Test Facility

19.0 References

1. "Project Management of GFE Flight Projects," NASA JSC Engineering Directorate, EA-WI-023C (Rev. C), January 17, 2002.
2. "Orion MPCV Human-Systems Integration Requirements," MPCV 70024, HS3017A.
3. National Fire Protection Association (NFPA), 1994.
4. "Orion Multi-Purpose Crew Vehicle Program Anthropometry Data Book," MPCV 72585.

5. “Orion Multi-Purpose Crew Vehicle (MPCV) Program Operational Concepts (OpsCon) Document,” MPCV 72093.
6. “Orion Multi-Purpose Crew Vehicle (MPCV) Systems Requirements Document,” MPCV 72000.
7. “Cross Program Procurement and Use Control Specification,” MPCV 70156.
8. “Fire Extinguisher Mechanical Interface Control Document (MICD),” 948CA7348027.
9. “Orion Multi-Purpose Crew Vehicle (MPCV) Program: Crew Interface Labeling Standard,” MPCV 70152.
10. “Interface Control Document (ICD) for the Orion Smoke Eater Filter (OSEF) to the Multi-Purpose Crew Vehicle (MPCV),” JSC 67243.
11. Orloff, Richard W., “Apollo 1 – The Fire: 27 January 1967,” NASA History Series NASA SP-2000-4029, (2000/2004).
12. DOT/FAA, “Safety Alert for Operators (SAFO 09013),” Washington, D. C.: Flight Standards Service, 2009.
13. Berman, J., “Design and Support for Abnormal Situations,” In F. Redmill & J. Rajan (Eds.), Human Factors in Safety-Critical Systems, Butterworth, Boston, MA, 1997, pp. 203-227.
14. Cotterman, T., and Wood, M., “Retention of Simulated Lunar Landing Mission Skills: A Test of Pilot Reliability,” AMRL-TR-66-222, Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, 1967.
15. Dismukes, R. K., and Nowinski, J., “Prospective Memory, Concurrent Task Management, and Pilot Error,” In A. F. Kramer, D. A. Wiegmann, & A. Kirlik (Eds.), *Attention: From Theory to Practice*, Oxford University Press, 2007, pp. 225-236.
16. Easterbrook, J. A., “The Effect of Emotion on Cue Utilization and the Organization of Behavior,” *Psychological Review*, Vol. 66, No. 3, 1959, p. 183.
17. “Human Factors Design Standard,” HF-STD-001B, Atlantic City: Federal Aviation Administration, 2016.
18. Fairbanks, Bishop, Marks, and Shar, “The Practice of Emergency Medicine/Original Research Usability Study of Two Common Defibrillators Reveals Hazards,” *Annals of Emergency Medicine*, Vol 50, No. 4, 2007, pp. 424-432.
19. Fisk, A. D., Ackerman, P. L., and Schneider, W., “Automatic and Controlled Processing Theory and its Applications to Human Factors Problems,” *Advances in Psychology*, Vol. 47, North-Holland, 1987, pp. 159-197.
20. Hockey, G. R. J., “Changes in Operator Efficiency as a Function of Environmental Stress, Fatigue, and Circadian Rhythms,” In K. R. Boff, L. Kaufman, & J. P. Thomas (eds.), *Handbook of Perception and Human Performance*, Wiley/Interscience, New York, NY, 1986.
21. *Crew Resource Management*, Kanki, B. G., Anca, J., and Chidester, T. R. (eds.), Academic Press, 2019.

22. Mandler, G., Stress and Thought Processes," In L. Goldberger & S. Breznitz (eds.), *Handbook of Stress: Theoretical and Clinical Aspects*, Free Press, New York, NY, 1982.

23. "Human Integration Design Handbook," NASA/SP-2010-3407, 2010.

24. Wallace, D. F., Anderson, N. S., and Shneiderman, B., "Time Stress Effects on Two Menu Selection Systems," In B. Shneiderman (ed.), *Sparks of Innovation in Human–Computer Interaction*, Ablex Publishing, Norwood, NJ, 1982, pp. 89–97.

25. Wickens, C. D., Hollands, J. G., Banbury, S., and Parasuraman, R., Engineering Psychology and Human Performance. Psychology Press, 2015.

26. "NASA Space Flight Human-System Standard - Volume 2: Human Factors, Habitability, and Environmental Health," NASA STD-3001, Revision B, January 1, 2015.

27. Sanli and Carnahan, 2018.

28. Gilbert, K., "Fire in Hangar Bay One!" *All Hands Magazine*, February 1967.

29. Burlage, J. D., *The Forrestal Fire*, Navy News Service, 2017.

30. Stewart, H. P., "*The Impact of the USS Forrestal's 1967 Fire on US Navy Shipboard Damage Control*," Master's Thesis, US Army Command and General Staff College, 2004.

31. Carlin, M. J., *Trial: Ordeal of the USS Enterprise – 14 January 1969*, Tuscara Press, West Grove PA, 1993.

32. "The USS Forrestal (CVA-59) Fire and Munition Explosions," URL: http://www.insensitivemunitions.org/history/the-uss-forrestal-cva-59-fire-and-munition-explosions/, last accessed February 8, 2021.

Appendix A. Orion Contingency Breathing Apparatus (CBA)

A.1 Purpose

A cabin fire on board Orion presents a potentially catastrophic emergency for the crew, vehicle, and mission. Products of combustion contaminate the cabin atmosphere in the form of smoke particulates and harmful gases, and water spray released into the cabin from the PFE system during firefighting is present in the environment.

The Orion CBA is a one-size-fits-all emergency device worn on the head, consisting of a protective mask and two OFCs. The CBA provides head and respiratory protection for Orion crewmembers in the event of a suspected or known cabin fire. The CBA is a first-response emergency mask designed to provide crewmembers with up to 8 hours of protection. This protection includes two replacements of its pair of OFCs during the 8-hour period.

A.2 Overview

The CBA, with two pre-installed OFCs, is stowed in a vacuum-sealed bag prior to use. Because the CBA seals around the crewmember's neck, it protects the head and eyes. The integral nose cup seals against the mouth, to route exhaled breath out of the mask, minimize rebreathing, minimize mask fogging, and serve as a second seal to protect the wearer from environmental contaminants.   The CBA mask is identical to the ISS Emergency Mask and is equipped with respirator cartridges based on the ISS FC design. Serving as the crewmember's PPE, the CBA is donned during a cabin fire event. The crewmember subsequently resolves the fire event and monitors the AGA to confirm safe contaminant concentrations before doffing the CBA.

The life of a CBA Assembly (consisting of a mask and two OFCs) is expended after exposure to a fire event. In addition, a mask's life is expended after a total of seven don/doff cycles in uncontaminated environments. However, an OFC cannot be reused even if exposed to a non-contaminated environment. During an event, the OFCs may be replaced to allow for prolonged use of a CBA mask. The opening of the CBA is stretched over the crewmember's head and pulled down such that the neck dam is sealed against the neck. Once retrieved from its stowage location, the CBA is designed to be donned within 30 seconds. Only one crewmember is required when donning or doffing the CBA. However, a second crewmember may verify the mask's neck dam is properly seated against the neck.

Four CBA Assemblies are individually packaged in vacuum-sealed bags and soft-stowed within an ECLSS wall box, to be retrieved when a fire event is annunciated. Eight pairs of OFCs are stowed in the OASIS Locker F1. Ties to constrain long hair above the neck prior to donning the CBA Assembly are available but not a necessity when using the CBA. Reading goggles donned external to the CBA Assembly, are available in the Contamination Cleanup Kit. Contaminated CBAs are placed in sealable Point-of-Use (POU) Trash Bags.

The CBA is designed to fit crewmembers within the minimum/maximum range of relevant anthropometric measurements found in the Orion MPCV Human-Systems Integration Requirements [ref. 2]. It is made of a self-extinguishing fabric that meets the National Fire Protection Association (NFPA) 1994 standard [ref. 3] and includes a neck dam and transparent visor. The neck dam provides a seal around the neck to prevent the crewmember from further exposure to contaminated environments. Figure A-1 shows the CBA Assembly and an OFC.

Figure A-1. CBA (left) shown with Two Respirator Cartridges Installed and Cartridge (right) (in both images, ISS Fire Cartridges are shown representing an OFC)

Once a CBA and/or a set of OFCs have reached their end of life, they are placed in individual POU Trash Bags to prevent off-gassing of the captured contaminates. The POU Trash Bags are stowed for the remainder of the mission.

A.3 Concept of Operations

The CBA Assembly is a first-response emergency device designed to provide respiratory and head protection from contaminated cabin air arising from smoke or fire. The crew may perceive a fire event by smell or sight or by smoke alarm annunciation and will immediately don the CBA Assemblies. A CBA concept of operations flow diagram is shown in Figure A-2.

During the event, if the OFCs have been used for 90 minutes, or if it becomes difficult to breathe through the cartridge due to restricted flow, the crewmember will remove and replace the cartridges to continue operation of the CBA Assembly. This requires a maximum of 30 seconds after removal from its packaging. Two additional pairs of OFCs per crewmember will be stowed onboard in an OASIS locker.

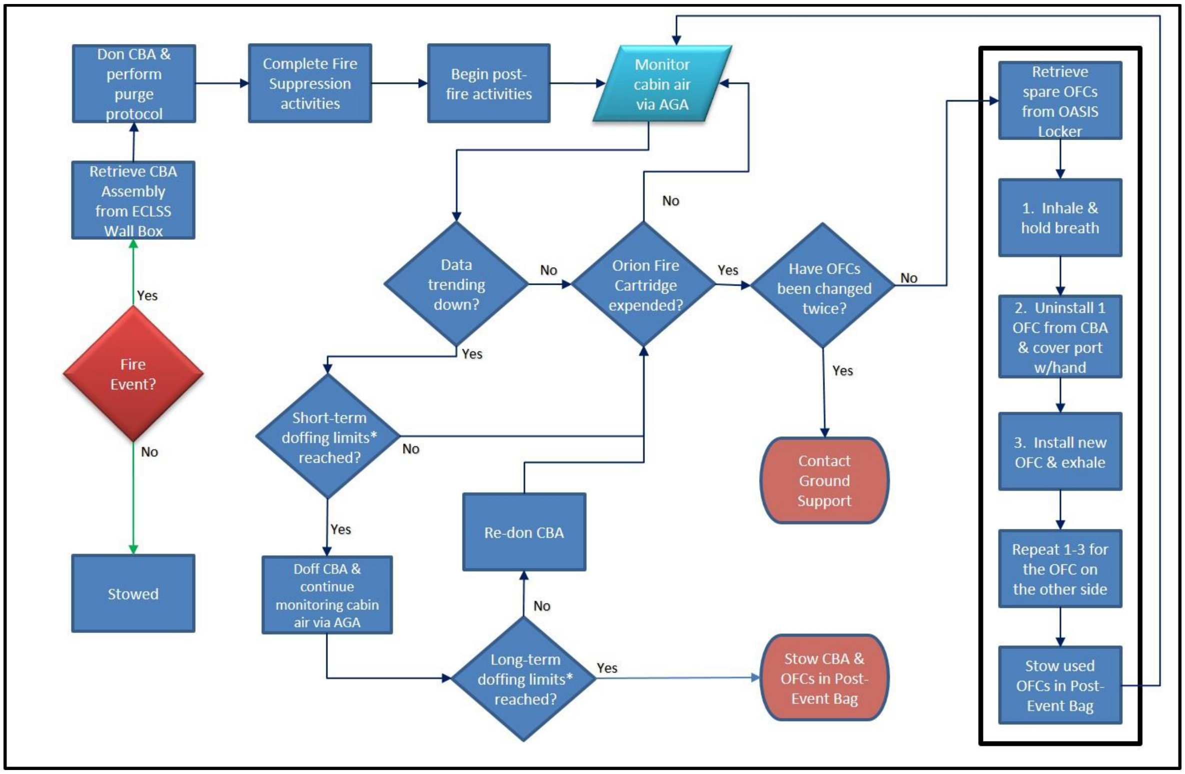


Figure A-2. CBA Concept of Operations Flow Diagram (prefilter is not shown in the operations flow due to its on-going product development activity)

The CBA Assembly concept of operations in response to a fire event while unsuited is as follows:

1. Upon notification of the fire event, the crew locates the CBA Assemblies in the ECLSS Wall Box and performs the following:
   a. Each crewmember retrieves a single CBA Assembly (with two OFCs pre-installed), removes it from its sealed bag, and returns the bag to the ECLSS Wall Box.
   b. Each crewmember dons the CBA Assembly, purges the CBA hood space per trained protocol, and then breathes normally.
   c. Another crewmember verifies that the two cartridges are properly installed and the neck dam seals properly around the neck.
   d. Crewmember initiates a countdown timer to track the time when the OFCs should be replaced, per training protocol.
2. The crew monitor the AGA to quantify the concentrations of the contaminants during the event. If concentrations of the constituents listed in Table A-1 have reached the 1-hour SMAC threshold as confirmed by the AGA, then the crew may doff the CBA Assembly.

Table A-1. Constituent Doff Limits

Constituent	1-hour SMAC (ppm (mg/m^3))
CO	425 (485)
Hydrogen chloride (HCl)	5 (8)
Hydrogen cyanide (HCN)	8 (9)
Hydrogen fluoride (HF)	5 (4)

3. During the event, should the operation time of the OFCs exceed the defined operational life or breathing become sufficiently impeded, the OFCs will be replaced with an unused pair per the following:
    a. The crew locates and retrieves two OFCs located in the Orion Fire Cartridge Transport Bag stowed in OASIS locker F1 and a POU Trash Bag.
    b. The crew opens the packaging of one OFC.
    c. The crew removes one OFC from the CBA Assembly, while holding their breath, and replaces it with the new OFC.
    d. The crew places the used OFC into a POU Trash Bag.
    e. The crew repeats these steps for the other OFC.
    f. The crew seals the used OFCs in the POU Trash Bag and stows it in the OASIS along with the empty OFC packaging.

The CBA Assembly is a single-use item and is considered contaminated if removed from its sealed packaging in a contaminated environment. However, if the crew dons the CBA Assembly in the event of a false alarm, the CBA may be reused during the mission if its operational lifetime has not yet been exceeded. In this case, the installed OFCs will be replaced should an actual fire event take place during the remainder of the mission. The CBA is limited to a contaminated environment exposure for no longer than 8 hours, including OFC change-outs.

During the post-fire event activities, the used CBA Assemblies and OFCs will be re-stowed in a safe configuration to limit crew exposure to contaminants that may remain on the mask and in the OFC media per the following steps:

4. The crew locates a designated POU Trash Bag.
5. The crew seals the CBA and expended OFCs in the POU Trash Bag and stows it in the ECLSS Wall Box.

Assumptions

The following are assumptions and operational notes regarding the CBA Assembly:

- The CBA Assembly is for IVA use only. It is intended for fire response activities within the MPCV cabin.
- The CBA Assembly is a passive device. It does not serve as an oxygen gas source.
- The CBA Assembly does not provide an interface for food or drink packages.
- The CBA Assembly does not provide a means to enhance verbal communication through the mask.

- The CBA Assembly is not used by suited crewmembers.
- The CBA Assembly may be used before, during, and after use of the PFE.
- During a fire event, the CBA Assembly will be donned in a contaminated environment and, therefore, requires a purge of the hood space (i.e., the air between the hood's interior surface and the crewmember's head) immediately after donning. Purging reduces the concentration of contaminants around the crewmember's head and eyes. Filtered air inhaled through the OFCs is used to force contaminated hood space air out of the CBA Assembly through the exhalation port.
- The CBA Assembly will not protect crewmembers who cannot breathe on their own. However, a crewmember with shallow breathing will not experience any greater hazard by wearing the CBA Assembly.

A.4 System Interfaces

The Orion CBA Assembly interfaces with the Orion vehicle and the flight crew are illustrated in Figure A-3.

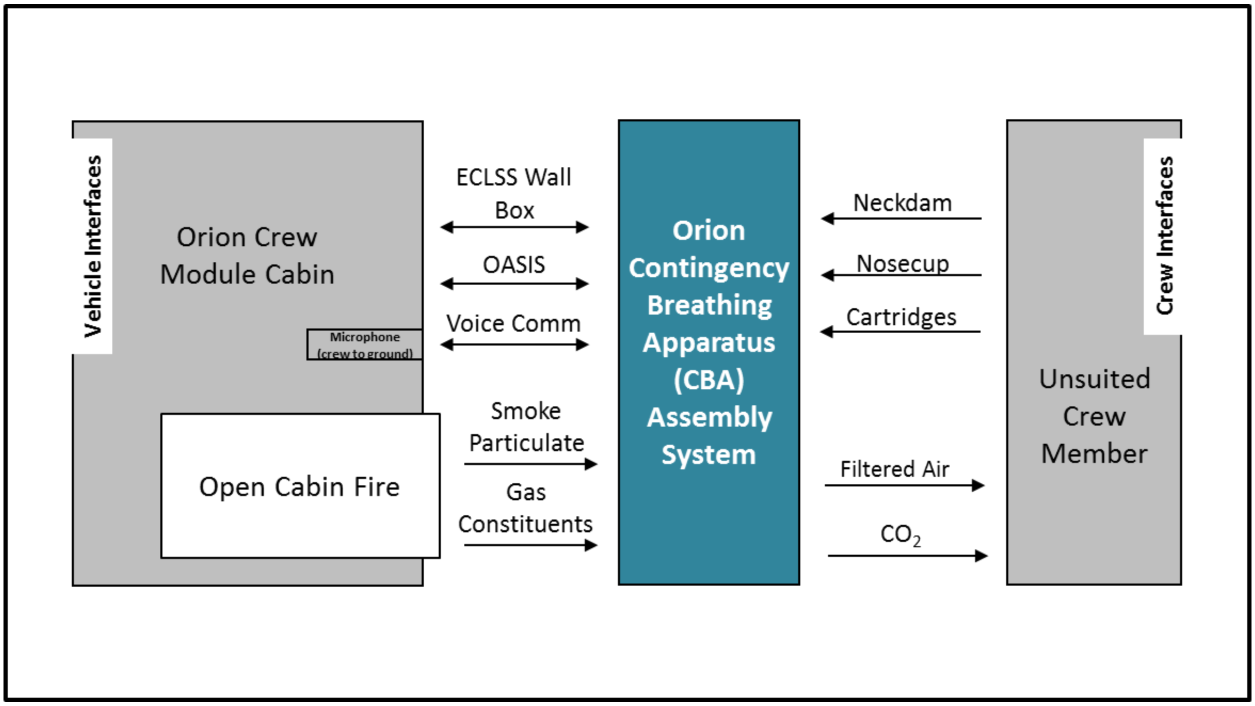


Figure A-3. Orion CBA Assembly Functional Interface Diagram

A.4.1 Vehicle Interfaces

The Orion MPCV provides defined interface locations for stowage for the CBA Assembly and spare OFCs. Except for stowed configurations, the CBA Assembly and OFCs do not directly interface with the MPCV. Four CBA Assemblies will be soft-stowed within the ECLSS Wall Box (see Figure A-4) and can be retrieved within 30 seconds of a fire event annunciation. An additional eight pairs of OFCs (two extra sets per crewmember) are stowed in the OASIS Locker F (see Figure A-5). POU Trash Bags will be used to reseal contaminated CBA Assemblies and OFCs. There is no direct interface with the Orion Communication System.

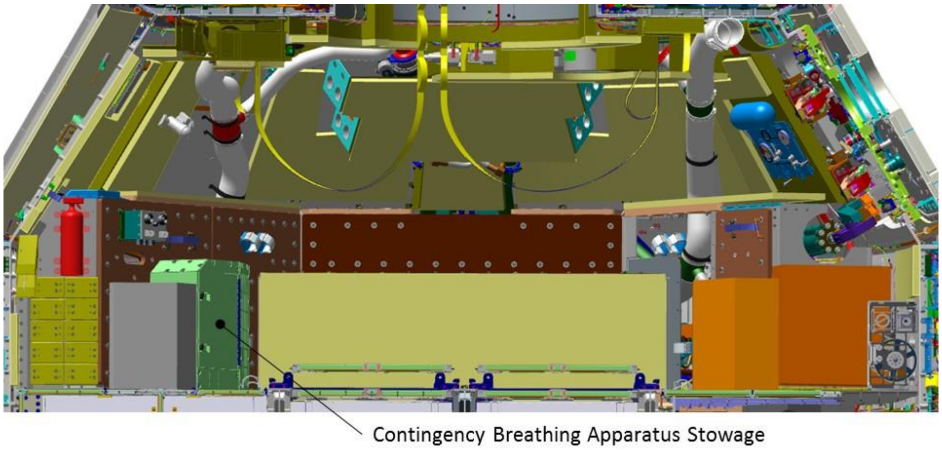


Figure A-4. Orion Crew Module ECLSS Wall (reference starboard is left side of image)

Figure A-5. Orion Crew Module OASIS Locker Configuration
(view looking from tunnel hatch; crew seats not shown for clarity)

A.4.2 Crew Interfaces

The opening of the CBA is stretched over the crewmember's head and pulled down such that the neck dam is sealed against the crewmember's neck. The mask includes a nose cup, which limits the inhalation of contaminants that may be present in the hood space. There is a transparent visor at the front of the mask with a fog-resistant coating. The visor allows the crewmember to see while wearing the mask and protects the crewmember's eyes from contaminants.

An interior nose cup fits around the nose and mouth. It is adjusted with two straps that tighten the nose cup against the crewmember's face for a proper seal to minimize rebreathing and visor fogging.

The OFCs are replaceable, which allows for full operational life of the CBA. If the OFC becomes spent during a fire, crewmembers must remove the two OFCs from the CBA inhalation ports and install new cartridges.

Once retrieved from its stowage location, the CBA Assembly can be donned within 30 seconds. Only one crewmember is required when donning or doffing the CBA Assembly. However, a second crewmember can verify proper cartridge and neck dam installation.

A.4.3 Ground Systems Operations

The CBA Assembly and spare OFCs will have physical and maintenance interfaces with the following ground systems:

- Quality inspection during shipping and receiving of hardware and confirmation of hardware condition and configuration (e.g., damage, part number, serial number, cage code).
- Ground Transportation Crew for transporting to and from Orion MPCV.
- Ground Installation Crew for installing and removing the CBA Assemblies and spare OFCs into and from the Orion MPCV.

A.5 Functional and Physical Requirements

The key technical requirements for the CBA Assembly are discussed.

CBA Mask/Hood

- The CBA shall have a transparent and colorless viewport. The visor shall be designed to prevent fogging or the condensation of water vapor, which causes vision impairment. Imperfections in the visor shall not reduce clarity and sharpness of vision more than the user's normal eyesight.
- The CBA shall meet functional and performance requirements for a minimum of 8 hours. The CBA must sustain the crew during fire event containment and environmental cleanup activities. The mask must withstand permeation of the environment during this period, without considering the number of cartridge changeouts necessary to sustain crew for this duration.
- The CBA shall connect with the OFC bayonet fitting.
- The CBA shall not have any after-flame longer than 5 seconds, drip, melt, or develop a hole that is visible to the unaided eye after exposure to molten drips, as specified in ANSI/ISEA 110-2009, "American National Standard for Air-Purifying Respiratory Protective Smoke Escape Devices," Sections 9.12.1 and 9.12.3.
- The CBA shall not drip, melt, or develop a hole that is visible to the unaided eye after exposure to a flame or heat source, as specified in Attachment A of the "NIOSH Statement of Standard for CBRN Air-Purifying Escape Respirator," Section 3.5.
- The CBA shall not have any after-flame longer than 5 seconds after exposure to and removal from a flame source, as specified in Attachment A of the "NIOSH Statement of Standard for CBRN Air-Purifying Escape Respirator," Section 3.5.
- The exhalation airflow resistance of the CBA shall not exceed 20 mm (millimeter) water column above ambient pressure at a minimum airflow rate of 42.5 liters per minute (lpm).
- The CBA shall not exceed 1.5 pounds (lb) (0.68 kilograms (kg)), not including OFCs.

OFC

- Two OFCs, while attached to the CBA, shall be capable of removal and replacement by a single crewmember in 30 seconds or less after removing the new OFCs from their packaging.
- Particulate filtration efficiency shall be ≥99.97% efficiency (P100) with a particle size of 0.3 microns when tested in accordance with Title 42 Code of Federal Regulations (CFR) Part 84, "Approval of Respiratory Protective Devices."

- The initial inhalation airflow resistance of an individual OFC shall not exceed 70 mm water column below ambient pressure at an airflow rate of 21.25 lpm in smoke-free air (pre-fire event) at an ambient temperature of 22 degrees Celsius (ºC) (i.e., 71 degrees Fahrenheit (ºF)) and an ambient pressure of 101.4 kilopascals (kPa) (i.e., 14.7 pounds per square inch absolute (psia)).
- The inhalation airflow resistance of the OFC shall not exceed 127 mm water column below ambient pressure at an airflow rate of 21.25 lpm after exposure to 50 milligrams per cubic meter (mg/m^3) particulate concentration in an environment with an ambient temperature of 22 ºC (71 ºF) and ambient pressure of 101.4 kPa (14.7 psia), for a period of 90 minutes.
- The OFC shall prevent liquid water and visible droplets of water from entering and disrupting airflow through the granular bed.
- The initial inhalation airflow resistance of the OFC shall decrease by less than 25 percent after exposure to molten drips when tested in accordance with ANSI/ISEA 110-2009, “American National Standard for Air-Purifying Respiratory Protective Smoke Escape Devices,” Section 9.12.
- The OFC shall not drip, melt, or develop a hole that is visible to the unaided eye (per JPR 5322.1G) after exposure to a flame or heat source, as specified in Attachment A of the “NIOSH Statement of Standard for CBRN Air-Purifying Escape Respirator,” Section 3.5.
- The OFC shall not have any after-flame longer than 5 seconds after exposure to and removal from a flame source, as specified in Attachment A of the “NIOSH Statement of Standard for CBRN Air-Purifying Escape Respirator,” Section 3.5.
- The OFC shall meet all functional and performance requirements after exposure to a molten drip, flame or heat source, as specified in such requirements levied on the CBA.
- The OFC shall meet functional and performance requirements for up to and including 90 minutes, while operating at 37 to 133 ^{o}F and 9.5 to 15.55 psia.
- When the OFC is exposed to an environment containing the maximum concentration of the constituents listed in Table A-2, the effluent shall not contain any of the constituents with concentrations higher than the 24-hour SMAC limit per Table A-2, at an airflow rate of 21.25 lpm for a minimum of 90 minutes.
- The volume of each OFC shall not exceed the dimensions of 4 × 4 × 7 inches (10.16 × 10.16 × 17.78 cm) in the packaged configuration.
- The OFC shall not exceed 1 lb (0.45 kg) including its packaging.

Table A-2. Constituent Concentrations Post-Don for OFC

Constituent	Cabin: Max Concentration (ppm (mg/m^3))	Cartridge Effluent: 24-hour SMAC (ppm (mg/m^3))
2-Methylpropenal	0.36 (1.04)	0.35 (1.0)
Acetaldehyde	8.44 (15.21)	6.0 (10.0)
Acrolein (C_3H_4O)	1.7 (3.8)	0.035 (0.08)
Acrylonitrile	2.6 (5.65)	1.52 (3.3)
Benzene (C_6H_6)	15.34 (49.0)	3.0 (10.0)
CO	588.34 (674.0)	100.0 (114.0)
Formaldehyde (CH_2O)	1.19 (1.46)	0.5 (0.6)
HCl	0.27 (0.4)	2.0 (3.0)
HCN	0.49 (0.54)	4.0 (4.5)
HF	1.86 (1.52)	2.5 (2.0)[†]
Methyl nitrite	14.36 (35.86)	7.0 (17.0)

†: Source: Temporary Spacecraft Allowable Concentrations on Hydrogen Fluoride (Lam, 2015)

Integrated Assembly

- The CBA Assembly shall meet the intent of MPCV 70024, "Orion MPCV Program: Human-Systems Integration Requirements," HS3017A [ref. 2], by providing a means for the crew to breathe while in a contaminated cabin environment.
- The CBA Assembly shall meet all functional and performance requirements after exposure to a molten drip, flame, or heat source, as specified in requirements levied individually on the CBA and OFC.
- The CBA Assembly, in its ready-to-use configuration, shall have the capability of being donned in 30 seconds or less, assuming the OFCs are preinstalled and the CBA is still in its packaging. This requirement refers to the time necessary to don only the CBA Assembly and not to doff other equipment.
- The CBA Assembly shall meet a minimum fit factor requirement of 500 when used by a crewmember with facial hair growth no longer than 1.27 cm (0.5 inch).
- The CBA Assembly should allow masked users to communicate face-to-face at a separation distance of 3 ft with a word recognition rate of 70% in the expected ambient noise environment with a speech level of 66 dB SPL ±5 dB at the listeners head location.
- The CBA Assembly should allow users to communicate with ground support personnel with a word recognition rate of 70% in the expected ambient noise environment with a speech level of 66 dB SPL ±5 dB at the listener's head location.
- The inhalation air flow resistance of the CBA Assembly shall not exceed 70 mm water column below ambient pressure at a minimum air flow rate of 42.5 lpm in smoke-free air at an ambient temperature of 22 °C (71 °F) and ambient pressure of 101.4 kPa (14.7 psia).
- The CBA Assembly shall limit CO_2 rebreathing to less than 1.3% by volume at a 42.5 lpm minimum breathing rate.

- The CBA Assembly, subsequent to purging, shall reduce the maximum concentration of constituents listed in Table A-3 to a concentration inside the mask of less than the 24-hour SMAC values listed in Table A-3 over a range of breathing rates of 42.5 lpm for a minimum of 8 hours with cartridge swap out.

Table A-3. Constituent Concentrations Post Mask Donning

	Cabin	**Within Mask Hood-Space**
Constituent	**Max Concentration (ppm (mg/m^3))**	**24-hour SMAC (ppm (mg/m^3))**
2-Methylpropenal	0.36 (1.04)	0.35 (1.0)
Acetaldehyde	8.44 (15.21)	6.0 (10.0)
C_3H_4O	1.7 (3.8)	0.035 (0.08)
Acrylonitrile	2.6 (5.65)	1.52 (3.3)
C_6H_6	15.34 (49.0)	3.0 (10.0)
CM	588.34 (674.0)	100.0 (114.0)
CH_2O	1.19 (1.46)	0.5 (0.6)
HCl	0.27 (0.4)	2.0 (3.0)
HCN	0.49 (0.54)	4.0 (4.5)
HF	1.86 (1.52)	2.5 (2.0) †
Methyl Nitrite	14.36 (35.86)	7.0 (17.0)

†: Source: Temporary Spacecraft Allowable Concentrations on Hydrogen Fluoride (Lam, 2015).

- The OFC shall minimize obstruction into the CBA Assembly user's field of view.
- The volume of each CBA Assembly shall not exceed 0.43 ft^3 (0.012 m^3) in the packaged configuration with two OFCs installed.
- The CBA Assembly shall not exceed 3.5 lb (1.6 kg).
- The volume of each CBA shall not exceed 0.33 ft^3 (0.01 m^3) in the packaged configuration.
- The CBA Assembly shall be designed such that when the cartridge interface experiences structural failure, the mask and the mask's cartridge interface are not rendered unusable.
- Following a false alarm, the visor of the CBA should be wiped down, along with the interior of the nose cup, and allowed to dry for up to 24 hours.
- The CBA Assembly shall meet the size requirements in Table A-4 for unsuited crewmembers as defined in MPCV 72585, "Orion Multi-Purpose Crew Vehicle Program Anthropometry Data Book," [ref. 4], Table 3-1: Anthropometric Dimensional Data for American Female and Male.

Table A-4. Anthropometric Dimensions for CBA

No.	Dimension	Minimum (cm, inch)	Maximum (cm, inch)
639	Neck circumference	27.8 (10.9)	43.4 (17.1)
165	Bizgomatic (face) breadth	12.0 (4.7)	15.5 (6.1)
427	Head breadth	13.3 (5.2)	16.5 (6.5)
441	Head length	17.3 (6.8)	21.6 (8.5)
430	Head circumference	51.3 (20.2)	61.0 (24.0)
586	Menton-sellion (face) length	9.9 (3.9)	14.0 (5.5)

- The CBA Assembly shall not require the use of tools to operate the assembly, including mating/de-mating the OFCs.
- The CBA Assembly shall have a field of view as determined by American National Standards Institute/International Safety Equipment Association (ANSI/ISEA) 110-2009, "American National Standard for Air-Purifying Respiratory Protective Smoke Escape Devices," Section 9.6.2, as performed per NIOSH Procedure CET-APRS-STP-CBRN-0312.
- The CBA Assembly should provide post-exposure containment of the OFC media to limit the release of captured contaminants into the habitable volume to a value that does not exceed the 7-day SMAC limits in Table A-5, as a time-weighted average, and does not exceed the 1-hour SMAC limits in Table A-5 at any time, for a period of no less than 7 days.

Table A-5. Hazard Containment SMAC Values

Contaminant	1 Hour SMAC (ppm (mg/m^3))	7 Day SMAC (ppm (mg/m^3))
2-Methylpropenal	0.35 (1.0)	0.14 (0.4)
Acetaldehyde	10.0 (18.0)	2.0 (4.0)
C_3H_4O	0.075 (0.17)	0.015 (0.03)
Acrylonitrile	1.7 (3.69)	0.46 (1.0)
C_6H_6	10.0 (35.0)	0.5 (1.5)
CO	425.0 (485.0)	55.0 (63.0)
Cyanogen	8.0 (17.0)	1.0 (2.1)
Fluorotrimethylsilane	4.77 (18.0)	1.01 (3.8)
CH_2O	0.8 (1.0)	0.1 (0.12)
Furan	3.95 (11.0)	0.025 (0.07)
HCl	5.0 (8.0)	1.0 (1.5)
HCN	8.0 (9.0)	1.0 (1.1)
HF	5.0 (4.0)†	1.0 (0.8)
Methyl acrylate	0.43 (1.5)	6.0 (21.13)
Methyl nitrite	20.03 (50.0)	3.0 (7.5)
Sulfur dioxide	10.0 (26.0)	0.4 (1.0)

† Source: Temporary Spacecraft Allowable Concentrations on Hydrogen Fluoride (Lam, 2015)

- The CBA Assembly shall add less than 10 ^{o}C (18 ^{o}F) to the breathable air at any time during its 90-minute use time when challenged with less than or equal to 1,000 ppm CO.

- The CBA shall have a shelf life of 5 years.
- The OFC shall have a shelf life of 5 years.
- The CBA shall meet functional and performance requirements for a maximum of seven don/doff cycles within an uncontaminated environment.
- OFCs shall be single use only starting at the time of packaging removal.
- The OFC will be limited to one launch and one landing cycle.
- Table A-6 provides environmental requirements for the CBA and the OFC.

Table A-6. Environmental Requirements for the CBA and OFC

Environment	Range
Operating thermal environment	2.78 °C to 56.1 °C (37 °F to 133 °F)
Non-operating thermal environment	2.2 °C to 56.1 °C (36 °F to 133 °F)
Relative humidity	25% to 75% at 2.78 °C to 56.1 °C (37 °F to 133 °F)
Operating pressure environment	65.5 to 107.2 kPa (9.5 to 15.55 psia)
Non-operating pressure environment	65.5 to 116.5 kPa (9.5 to 16.9 psia), stowed and deployed
Pressure environment, safety	0.0 to 148.9 kPa (0.0 to 21.6 psia), stowed and deployed

A.6 Hardware Design

The CBA mask is made of self-extinguishing fabric and a butyl rubber neck dam, providing fire and contaminant protection for the crewmember’s head. It also includes a transparent visor made of polyethylene terephthalate (PET) polyester film and interfaces for two OFCs. Inside the hood is a nose cup made primarily of platinum-cured silicone. See Figures A-6, A-7, and A-8 for mask configuration details.

Figure A-6. CBA Mask (front view, shown without cartridges)

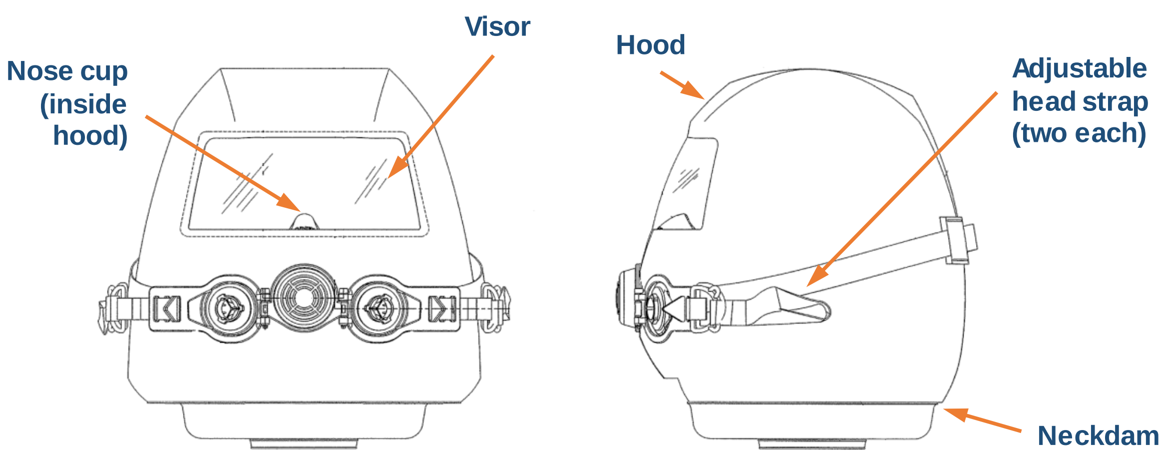


Figure A-7. CBA Mask Features (front and side views, shown without cartridges)

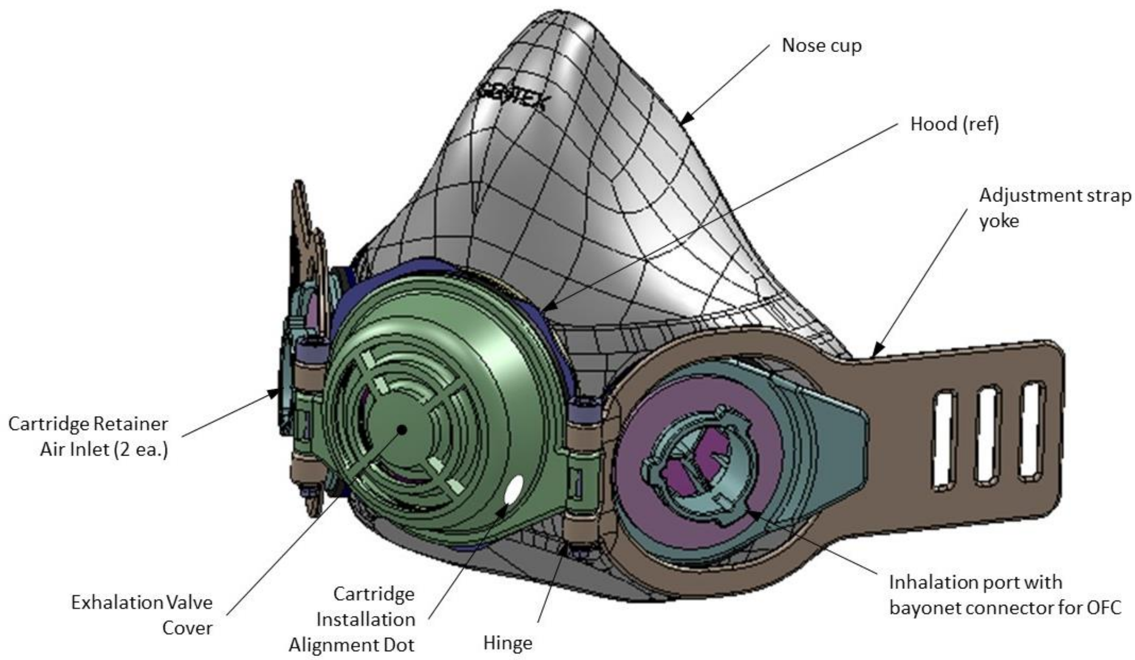


Figure A-8. CBA Mask Nose Cup Integrated with Respiratory Interfaces (OFCs and complete hood not shown for clarity)

OFCs are multi-layered respirator cartridges consisting of an internal NIOSH P100 particulate filter, a granular activated carbon layer, and a granular CO oxidation catalyst layer (see Figures A-9 and A-10). Functionally, the layers of the OFC operate as follows:

- The internal filter mechanically traps particulates from fire and water expelled from the PFE.
- Activated carbon adsorbs combustion gases.
- The catalyst, with ambient oxygen, oxidizes CO into CO_2 in an exothermic reaction.

Due to the historical experiences that ISS respirator cartridges prematurely restrict flow during testing, an OFC prefilter was developed to prolong the life of the cartridge. Figure A-11 shows the OFC prefilter installed on the cartridge body.

The major design goals for the prefilter are that it does not initially restrict airflow by more than 5 mm water column at 21.25 lpm and that it traps particulates and water mist. The prefilter is replaceable by the crew and has a shelf life of at least 5 years.

The prefilter element is made of wool fibers that are flame retardant and has a low pressure drop at typical respiration flow rates. The filtration media is mounted on a frame that clips onto the filter cover of the OFC. When the prefilter becomes loaded with particulates and water mist, it can be removed by the crewmember by prying the assembly off using the release tab. A new prefilter may be installed onto the OFC, or the crewmember can continue to use the OFC without a prefilter. Like the OFC, the prefilter has a shelf life of greater than 5 years.

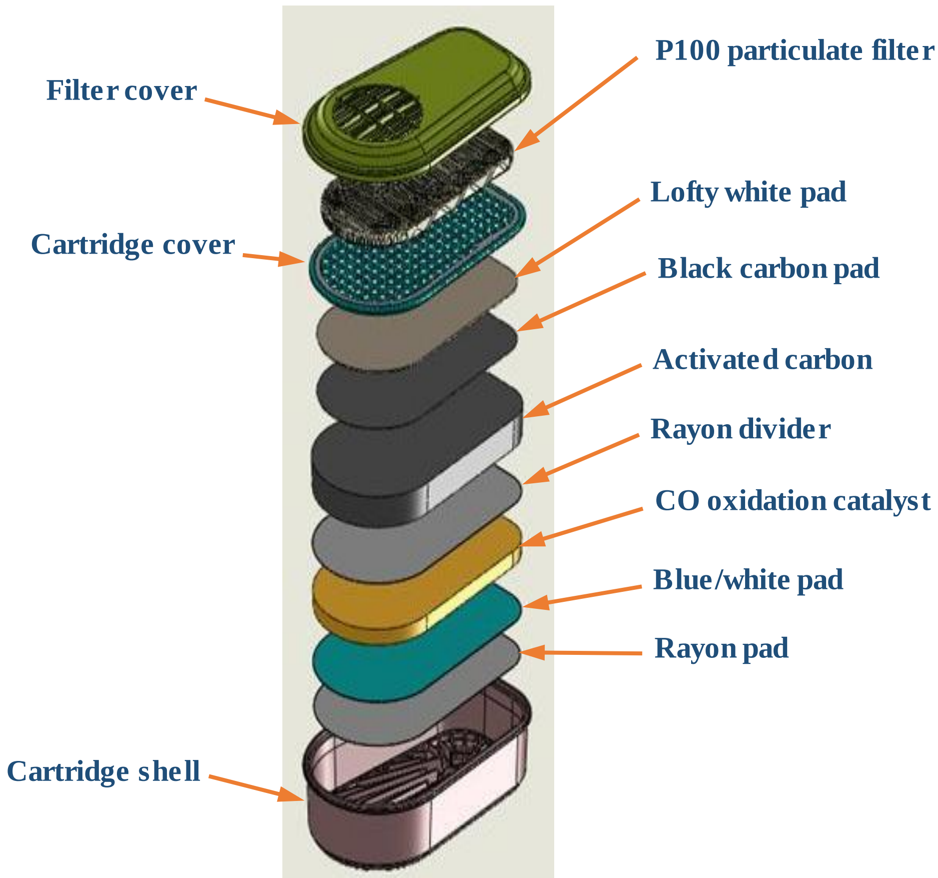


Figure A-9. Orion Fire Cartridge, Exploded View (external prefilter assembly not shown)

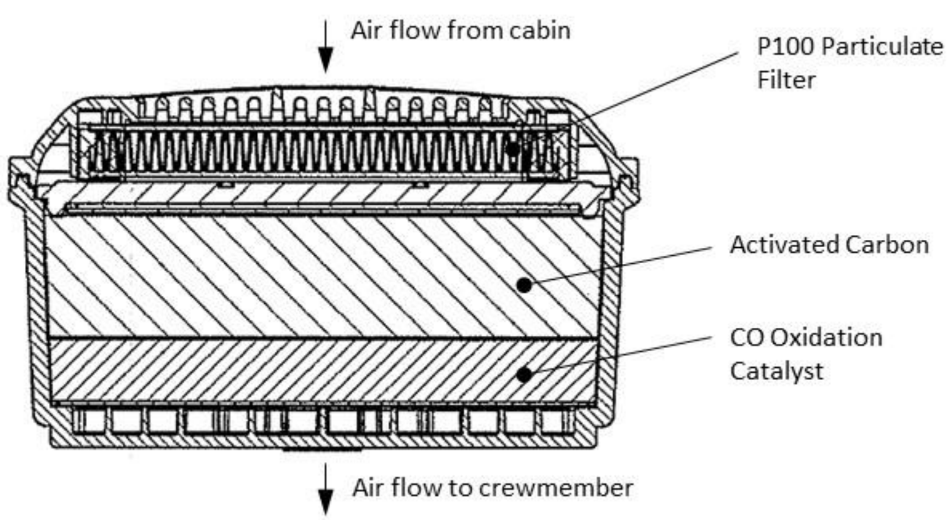


Figure A-10. Orion Fire Cartridge, Section View (prefilter not shown)

Figure A-11. OFC with Prototype Prefilter Assembly Installed

A.7 Certification Process

The CBA Assembly is certified through a series of qualification and acceptance activities. These activities are made of up tests, analyses, inspections, and demonstrations that ensure the hardware meets all performance requirements. These activities confirm that the CBA Assembly end items comply with their specifications, function properly, and are ready for use as a part of the flight system. A Verification and Validation document (V&VD) specifies success criteria for each requirement. A Verification Tracking Log (VTL) is used to track the status of verifications and the documentation provided as evidence for the completion of the verifications. The number of verification activities for the CBA Assembly are as follows:

- 44 tests
- 78 analyses
- 37 inspections
- 9 demonstrations

Four CBA qualification units and 13 OFC qualification units are used for requirement verification. Figures A-12 and A-13 show the qualification and acceptance flow for the CBA mask and OFC. There are two types of contaminant reduction performance tests:

1. Real fire challenge – realistic but not controllable/repeatable.
2. Single-component flow bench challenge – controllable/repeatable but not realistic.

3. For subsequent builds of the OFC, each lot will be re-qualified. Ten cartridges will be randomly selected from every build lot. All cartridges will complete airflow resistance test and PDA/PIA.

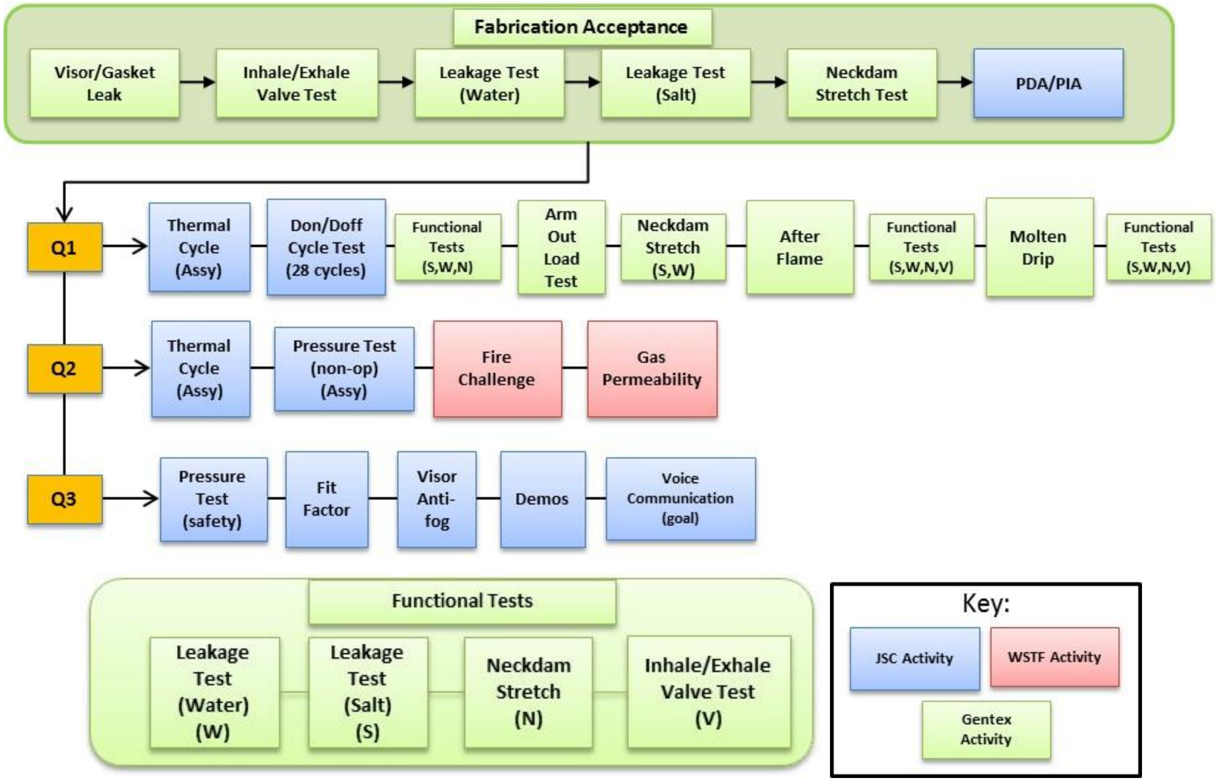


Figure A-12. CBA Qualification and Acceptance Test Flow

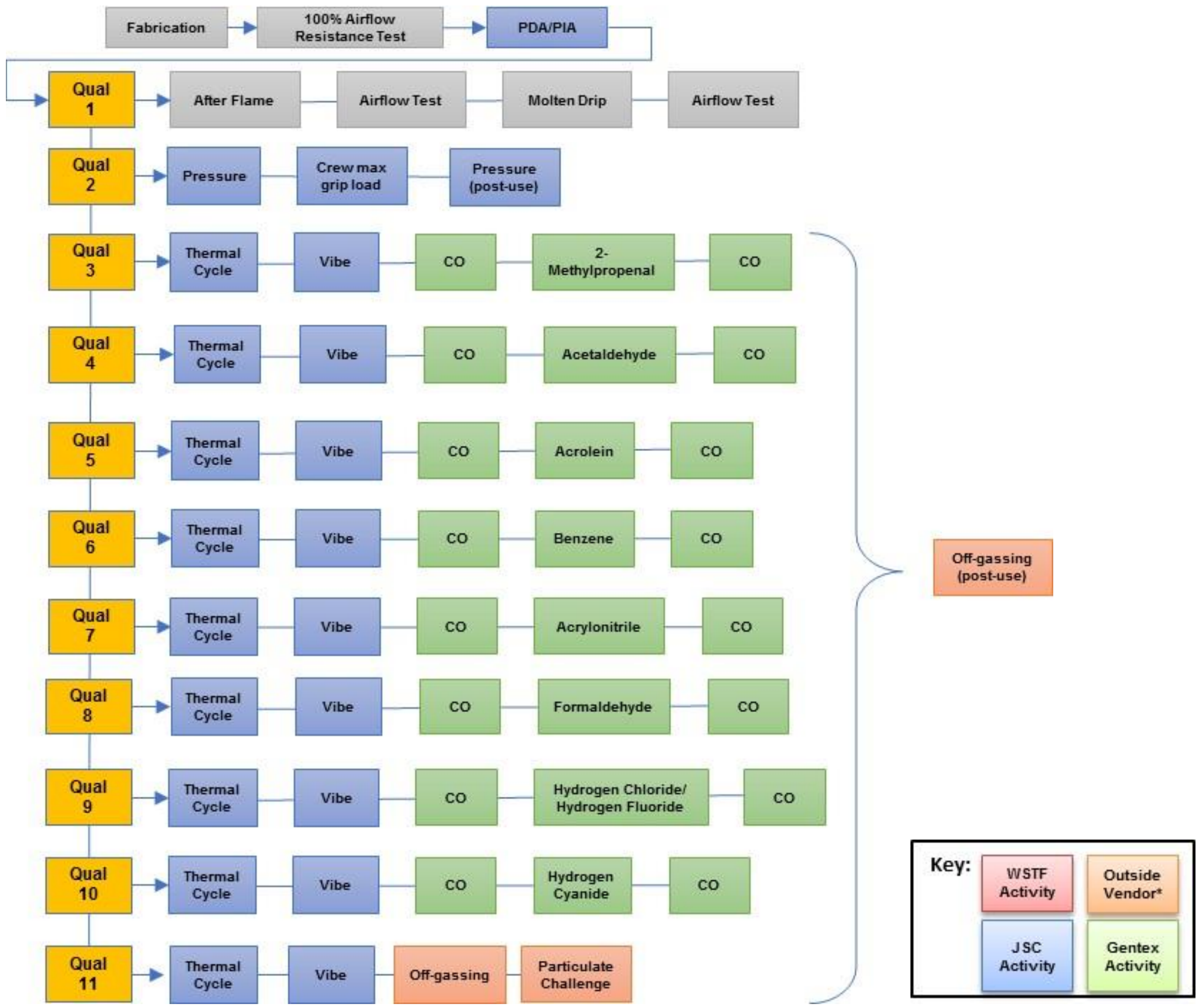


Figure A-13. CBA Qualification and Acceptance Test Flow

For the CBA mask, each build lot will undergo a reduced qualification test plan for subsequent builds. Four masks will be used for verifying qualification requirements. Two masks from each build lot will be randomly selected and subjected to the following:

- Thermal cycle (masks 1 and 2)
- Don/doff cycle (masks 1 and 2)
- After flame/molten drip (mask 1)
- Fire challenge (mask 1)
- Crew-induced loads testing (mask 2)

All masks will complete inhalation/exhalation resistance testing, water leak, salt fog, neckdam stretch, and PDA/PIA.

Surveillance testing of the OFC activated carbon will be conducted to verify a minimum 5-year shelf life. This is performed each year after manufacture. Additional units will be built at the time of manufacture to ensure the same lot of media is used for surveillance testing. Single chemical exposure and WSTF Fire Challenge B testing verify performance.

For the CBA mask, surveillance testing is conducted to show performance compliance beyond the current 5-year certification. Ammonia challenge testing shows permeability resistance. Inhalation port gasket compression analysis is conducted separately to prove performance beyond 5 years.

There are extensive verification activities outside testing that are used to certify the CBA Assembly for flightworthiness. Table A-7 shows the activity and the types of requirements that are verified.

Table A-7. CBA Assembly Non-test Verification Activities

Verification Activity	Requirement Type
Analyses	– Various functional/performance requirements – Reliability, availability, maintainability and testability – Environments – Stress – Thermal – Fracture control – Materials – Lifetime – Human integration assessments
Inspections	– Various functional/performance requirements – Product marking and labeling – Sharp edges – Pinch points – Holes – Cleanliness
Demonstrations	– Various functional/performance requirements – Hardware interfaces – Human integration assessments – Packaging breach

Appendix B. Orion Portable Fire Extinguisher (OPFE)

B.1 Introduction

A cabin fire onboard Orion presents a potentially catastrophic emergency for the crew, vehicle, and mission. Products of combustion contaminate the cabin atmosphere in the form of smoke particulates and harmful gases. Therefore, the capability to extinguish cabin fires is imperative. The OPFE system is designed to provide this function for the crew. The OPFE system includes the OPFE Assembly and the OPFE Mounting Bracket Assembly.

The purpose of the OPFE Assembly is to generate a plume of water to extinguish a fire within the crew cabin habitable space. However, the OPFE is not intended to extinguish fires within inaccessible avionics compartments. The extinguisher comprises a pressurized tank of nitrogen gas and liquid water, a hand-operated trigger valve, and a fixed Nozzle Assembly. The OPFE Assembly is serviced after each Orion mission and reused for up to five Orion missions with no on-orbit maintenance or repair. The planned service life of the OPFE is 1 year. However, the technology is being developed with the understanding that future long-duration missions will require a service life of at least 6 years.

The purpose of the OPFE Mounting Bracket Assembly is to provide adequate restraint of the OPFE through all mission phases, while providing access to the OPFE for emergency firefighting scenarios. The OPFE Mounting Bracket Assembly is hard-mounted to the Orion ECLSS wall inside the habitable volume of the vehicle. The OPFE Mounting Bracket Assembly is inspected after each Orion mission and reused for up to five Orion missions. Nominally, the OPFE Mounting Bracket Assembly should remain in the Orion vehicle for use on future missions. However, if the Orion vehicle will not be reused, the OPFE Mounting Bracket Assembly is removed from the vehicle, inspected, and installed in another vehicle for future missions.

B.2 Overview

The OPFE Assembly is shown in Figure B-1. The OPFE Assembly provides a portable fire suppression capability for Orion using water expellant. Fire suppression is achieved by removal of heat by water vaporization. Additionally, there are other suppression mechanisms, including dilution of oxygen in the immediate vicinity of the fire by the evolving water vapor and wetting of fuel surfaces adjacent to the combustion zone.

There are two primary system elements of the OPFE Assembly:

- Tank assembly
- Nozzle assembly

The Tank Assembly maintains the contents of the extinguisher at pressure until the OPFE is activated. The tank is a metal shell containing pressurized gas that surrounds a water-filled bladder. The bladder will be removed and replaced between Orion missions. The tank is red, which signifies that the PFE is emergency-use equipment.

The Nozzle Assembly controls the flow of the water from the tank. To activate the Nozzle Assembly, the operator is trained themselves to counteract momentum forces. The safety pin is removed prior to squeezing the handle. This allows water to discharge from the nozzle.

Releasing the handle stops the flow of water from the OPFE. The OPFE Assembly is designed to extinguish a laptop battery fire. This fire scenario is discussed later in this appendix.

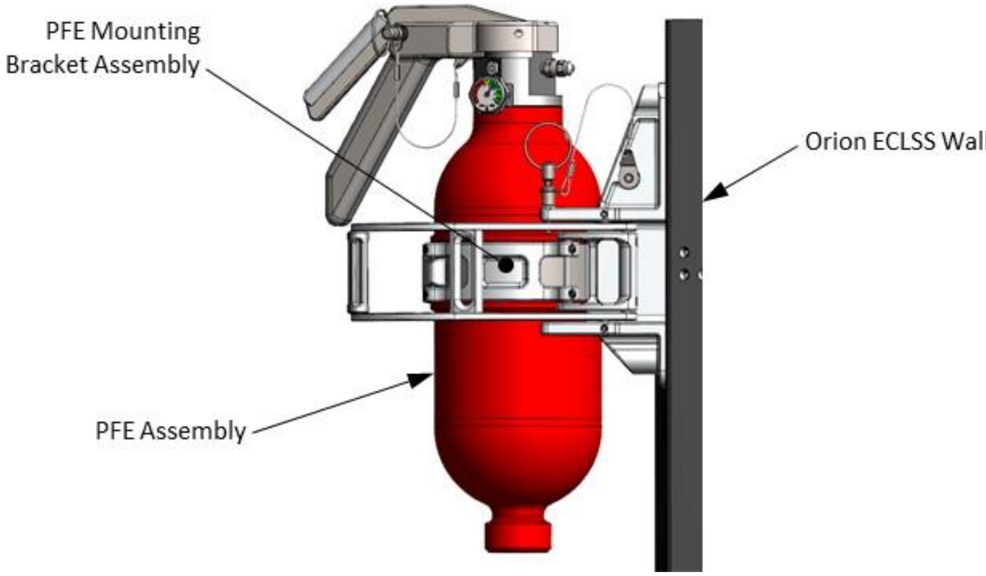


Figure B-1. OPFE Assembly and PFE Mounting Bracket Assembly

The OPFE Mounting Bracket Assembly is designed to securely restrain the OPFE Assembly during all mission phases. The Mounting Bracket Assembly has two configurations for restraining the OPFE Assembly: one configuration for launch/landing/abort and a second configuration for on-orbit operations. The launch/landing/abort configuration employs additional hardware to dampen vibration and shock loads imparted on the OPFE Assembly during these mission phases. In this configuration, the OPFE Assembly is less accessible than in the on-orbit configuration. While on-orbit, the PFE is restrained in a manner that provides quick access to the unit for use in an emergency fire scenario. In both mounting configurations, the PFE is accessible without the use of tools.

B.3 Concept of Operations

The OPFE mounting location within the crew module is shown below in Figures B-2 and B-3.

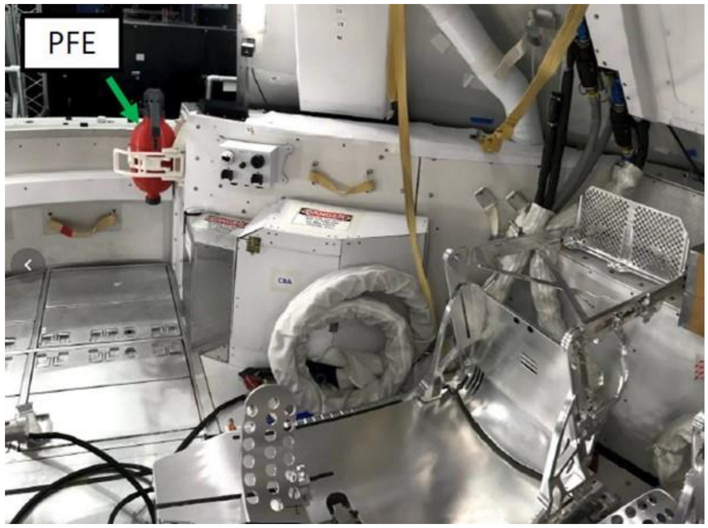


Figure B-2. OPFE Location in Crew Module (PFE, upper left of image; crew seat, lower right)

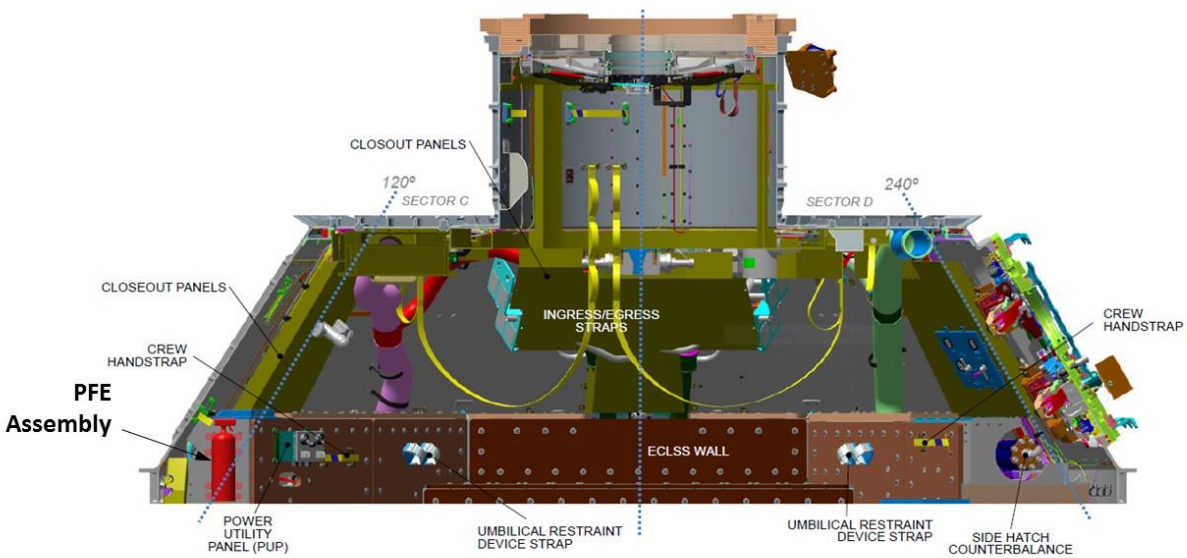


Figure B-3. OPFE Location in Crew Module on ECLSS Wall (starboard direction to left of image)

Operational guidelines, capabilities, and constraints that have been derived from MPCV 72093, "Orion Multi-Purpose Crew Vehicle (MPCV) Program Operational Concepts (OpsCon) Document" [ref. 5] and MPCV 72000, "Orion Multi-Purpose Crew Vehicle (MPCV) Systems Requirements Document" [ref. 6]. These concepts are applicable to this document where the operations intersect with fire response operation. An overview of the concept of operations is shown in Figure B-4.

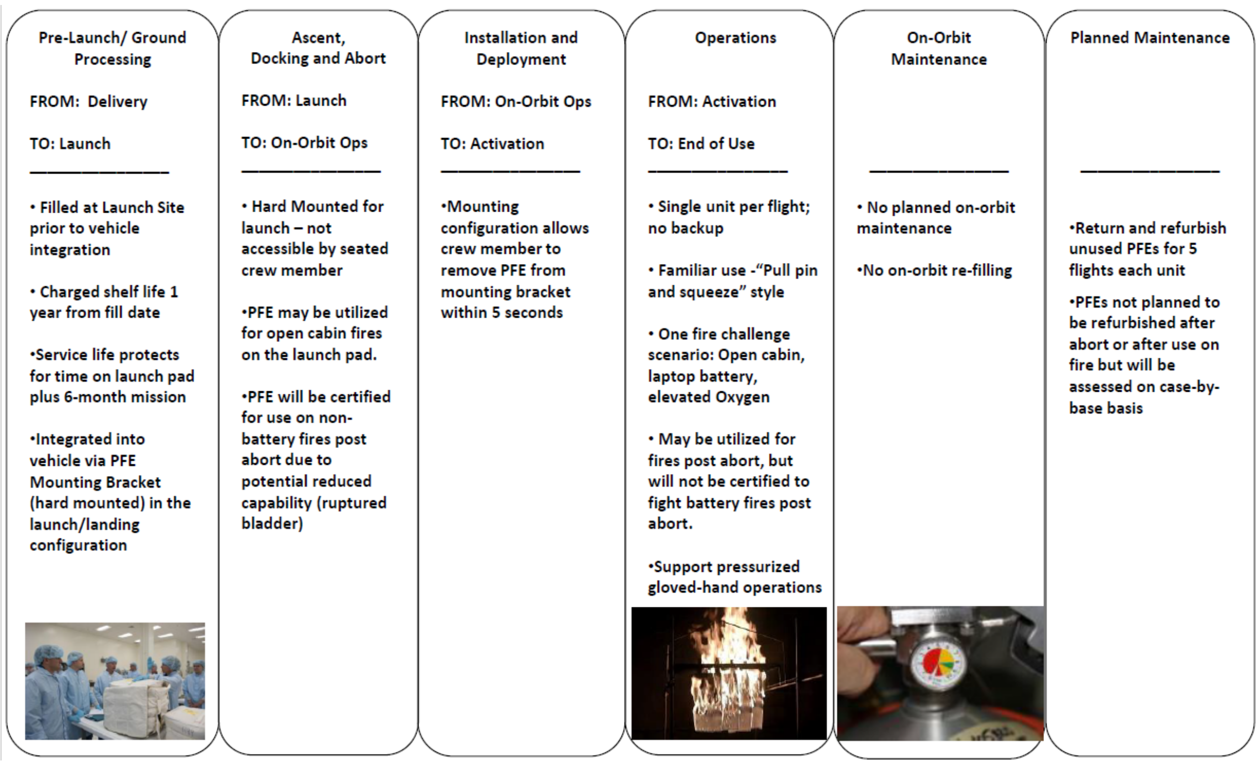


Figure B-4. OPFE Life Cycle Concept of Operations

B.3.1 Emergency Operations

In the event of a fire, an alarm will be triggered by a smoke detector or the crew will trigger the fire alarm when they smell or see smoke or flames. The crew response to a fire event will vary depending on the mission phase. If the fire event occurs on the launch pad, the crew will egress the vehicle and not use the OPFE, unless they deem it is necessary to use it to evacuate the vehicle. If the fire event occurs during ascent, entry, or abort, the crew will trigger the fire alarm and wait until orbit or post-landing to respond to the scenario. During an on-orbit or post-landing fire scenario, the crewmembers will perform the following tasks:

1. Don a CBA.
2. Discharge the PFE to extinguish the fire.
3. Monitor the AGA for cabin air constituents.

After a fire event, the crew will use the OSEF to clean the cabin atmosphere.

The OPFE is used on combustible materials and electrically energized surfaces. To use the OPFE, the crew will remove the OPFE Assembly from the OPFE Mounting Bracket Assembly, brace themselves, remove the safety pin, and squeeze the handle while pointing the nozzle of the OPFE at the flame source. When using the OPFE, the crewmember must use at least one handhold or foothold for restraint to counteract the propulsive discharge force of the PFE. The direction of spray is controlled by the operator, and proper fire suppression technique is required for efficient fire suppression.

In a typical fire-fighting operation, the operator will sweep the water plume from the PFE around the fire until the flames are extinguished. When flames are no longer visible, the operator will release the handle to halt OPFE discharge and visually inspect the fuel source to confirm that the fire has been extinguished. If any signs of combustion exist, the crewmember will discharge the PFE again by squeezing the handle and aiming the water plume at the fuel source. In the case of a battery fire, after no reignition of flames has occurred for approximately 30 seconds, the crewmember will discharge the remainder of the PFE contents to ensure the fire is fully extinguished to prevent reignition. This provides further heat removal and prevents potential thermal runaway, as the battery may remain warm after the fire is initially extinguished.

The OPFE can be discharged multiple times during a mission if water remains in the tank after its initial use. However, the PFE will not be certified to extinguish multiple fire events. The operator may pulse the spray of the extinguisher, as needed, for improved fire-suppression performance as well as for conservation of the water during fire-fighting activities. The colored index of the OPFE pressure gauge will indicate the tank's approximate expellant quantity. After extinguishing the fire, the safety pin is reinserted to prevent inadvertent discharge of the remaining contents.

B.3.2 Ground Processing and Prelaunch

The OPFE Mounting Bracket will be delivered to the Orion Program for installation into the Orion vehicle. The OPFE will be filled and pressurized at KSC prior to integration into the Orion vehicle. The OPFE will not be Department of Transportation (DOT) certified for pressurized shipment.

The OPFE Mounting Bracket installation will be performed by the Orion prime contractor. The Mounting Bracket will be secured to the Orion ECLSS wall with bolts provided by the Orion Program or the Orion prime contractor.

The OPFE Assembly will be integrated into the Orion vehicle after processed at KSC. The OPFE will be installed in the OPFE Mounting Bracket in the launch/landing/abort configuration.

B.3.3 Nominal Flight Operations

The OPFE will be stowed in the launch/landing/abort configuration in the OPFE Mounting Bracket during launch and ascent. The OPFE will not be used to extinguish a fire during launch and ascent.

The OPFE will be stowed in the on-orbit configuration in the OPFE Mounting Bracket Assembly during the on-orbit mission phase. In any open cabin fire scenario, the crew can use the OPFE Assembly to extinguish the fire. The OPFE is certified for use in extinguishing a laptop battery fire. This ensures that the most challenging, enveloping case is used for certification. However, the OPFE is intended for use in any open cabin fire event during the on-orbit mission phase.

Prior to entry, the OPFE is reconfigured to the launch/landing/abort configuration in the OPFE Mounting Bracket. The OPFE will not be used to extinguish a fire during entry.

The OPFE will be stowed in the launch/landing/abort configuration in the OPFE Mounting Bracket during landing. The OPFE will not be used to extinguish a fire during landing.

The OPFE will be stowed in the launch/landing/abort configuration in the OPFE Mounting Bracket during the post-landing mission phase. In an open cabin fire event, the OPFE will be used to extinguish the fire.

The OPFE will be returned to the PFE Sustaining Engineering team for refurbishment after each Orion mission. Because the PFE tank is not certified per DOT regulations for shipment, it is necessary to discharge the PFE prior to shipment.

B.3.4 Off-nominal Flight Operations

The OPFE can be used with or without suits. If unsuited during a fire event, the crew is instructed to first don a CBA. After PFE use, the crew will install the OSEF, which reduces cabin contaminants and ultimately allow the crew to remove their CBA and don their suits.

However, there are contingency events within the cabin that may affect OPFE operations. The OPFE will remain stowed during a cabin depressurization during launch or reentry. The OPFE is certified to not create a hazard during a cabin depressurization event. The OPFE Assembly will remain stowed during a cabin contamination event, other than a fire scenario. There is no impact to OPFE functionality from cabin contamination. The OPFE will remain stowed during a cabin leak or depressurization event.

The OPFE Assembly will remain stowed during an in-flight abort. The OPFE is certified not to create a hazard during or after exposure to abort loads. The OPFE Assembly will remain stowed during a contingency reentry. Loads for a contingency reentry are not expected to be outside the range of nominal reentry loads. The OPFE Assembly will be stowed in the launch/landing/abort configuration during reentry phase.

The OPFE Assembly will remain stowed during a contingency landing and recovery. Loads for a contingency landing and recovery are not expected to be outside the range of nominal loads. The OPFE Assembly will be stowed in the launch/landing/abort configuration during the landing and recovery phase.

The OPFE Assembly will be designed to support a charged (filled with water and gas pressurized) service life of one year. The OPFE will be refurbished between Orion missions by replacing the internal bladder and inspecting the hardware.

B.4 System Interfaces

OPFE System interfaces are depicted in Figure B-5.

The OPFE System is mounted inside the cabin area where it can be quickly accessed by the crew during an emergency. The OPFE Mounting Bracket Assembly is attached to the Orion vehicle ECLSS wall via fasteners. The OPFE Assembly is secured in place by the Mounting Bracket Assembly. The details of the mounting location are provided in Mechanical Interface Control Document (MICD), 948CA7305027.

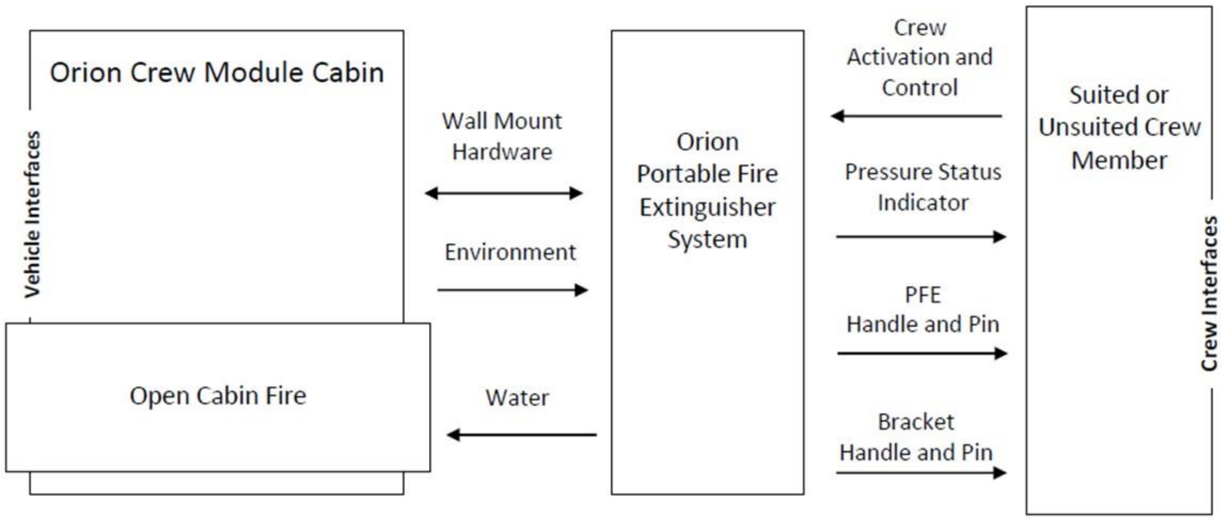


Figure B-5. OPFE Functional Interface Diagram

A pressure gauge on the tank enables the crew to verify PFE pressure before and during use. In the event of a fire, the OPFE Assembly will be retrieved by a crewmember from the Mounting Bracket Assembly without the use of tools. The crewmembers will brace themselves, pull the safety pin, and squeeze the handle to discharge the water spray. The crew interface is designed to allow use by a suited (fully pressurized) or non-suited crewmember. A fire could arise immediately following an EVA when crewmembers are in pressurized suits. Additionally, a fully suited/pressurized crewmember may need to reconfigure the stowage of the OPFE mounting bracket following a cabin depressurization event.

The allocated mass for the OPFE System (OPFE Assembly and Mounting Bracket Assembly) is 18.38 lb. The allocated mass is defined in the OPFE Project Technical Requirements Specification, JSC-47147.

B.5 Standard Fire Extinguishing Cases

The OPFE must extinguish two types of standard test fires:

- Battery fire
- Post-abort open cabin fire

Both fire tests are described here.

B.5.1 Battery Fire Test Standard

- The battery fire test shall be configured according to Figure B-6.

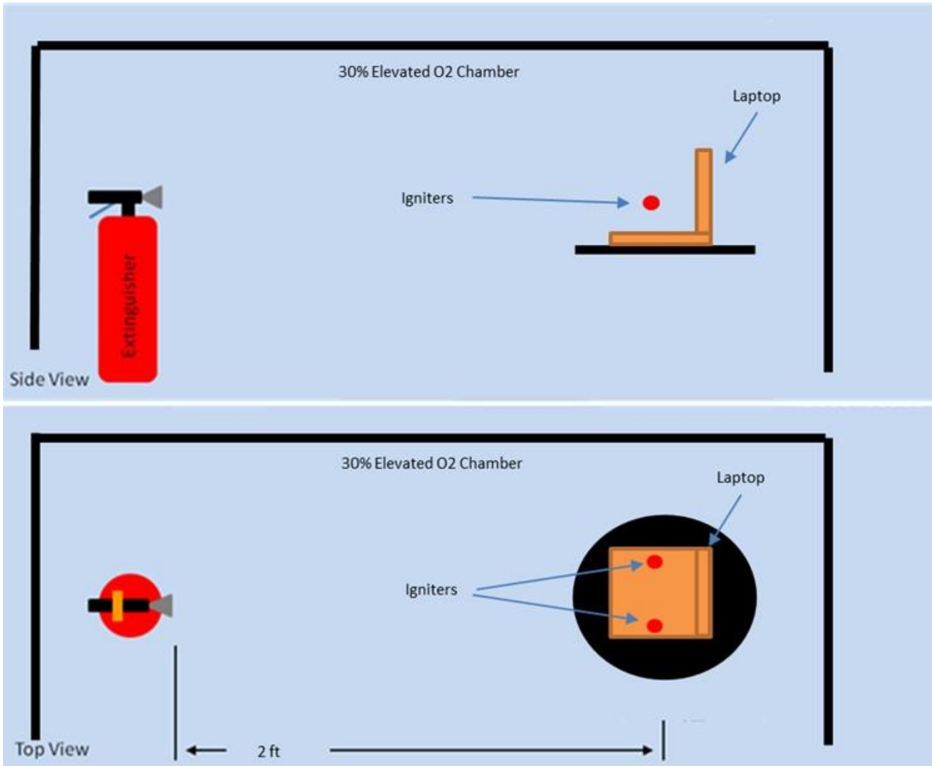


Figure B-6. Battery Fire Test Configuration (side view (above) and top view (below))

- The fire extinguisher nozzle shall be no closer than 2.0 ft from the fire through the duration of the test.
- The fire extinguisher shall be fully discharged during the test.
- Testing shall be performed when initial, pre-ignition, chamber conditions have stabilized as follows:
  - Oxygen concentration: Minimum 30%
  - Pressure: 527.5 millimeters of mercury (mmHg) ±51.7 mmHg (10.2 psia ±1 psia)
  - Temperature: 23.9 °C (+5.5 °C/–5.6 °C) (75 °F (±10 °F))
- The following environmental conditions shall be documented prior to the start of the test:
  - Oxygen concentration
  - Pressure
  - Temperature
  - Humidity
- The fuel shall consist of a laptop with equivalent battery characteristics to the HP Zbook Elite battery, fully charged.
- The test operator shall wait for ready test signal. This is determined to be 30 seconds after full battery engulfment (visible thermal runaway from the battery pack).
- Each test shall be video recorded.
- The following performance criteria shall be used for the Battery Fire Test:
  - A test fire is considered to be extinguished when flames are no longer visible and no reignition occurs within a 15-minute observation period.

    - The number of times the test must be performed will be defined in the OPFE Certification and Acceptance Test Plan.
- The laptop battery will be ignited from below using the hot plate. Once flaming ignition has occurred, the hot plate will be turned off. Following the determination that the fire has met the ready test criteria (i.e., battery has reached full engulfment and 30 seconds have passed), the test operator will attempt to extinguish the fire.
- The test operator will engage the fire and then evaluate continuing fires and smoking, pulsing the fire extinguisher per discretion until the extinguisher is fully discharged.
- Following full discharge of the OPFE, the test article will continue to be monitored for at least 15 minutes to ensure no reignition occurs.
- Spacecraft contain many sources of stored energy. Design and materials reviews are employed to mitigate any inherent risks posed by stored energy sources. Considering the quantity and overall potential energy content contained on Orion, it is prudent to understand the efficacy of the water-based OPFE against a stored-energy fire incident. For this specific scenario, a representative laptop was selected.
- When engaging a stored-energy fire, the crewmember will spray the vicinity of the fire, which will extinguish the fire. A secondary objective of this test includes demonstrating the PFE's cooling capability and ability to mitigate reignition and propagation. The stored-energy fire has a greater potential to re-ignite if the heat has not been removed from the stored-energy component. It is important that the crewmember monitor an "extinguished" fire for extended duration to ensure no reignition.
- A stored energy fire has a great potential for a significant release of energy in a short duration during the fire event. Characteristics of a stored energy fire include rapid venting and ignition of released gases, projectiles, and toxic byproducts. The distances defined in this test standard are not intended to reflect an assessment of safe fire-fighting distance, but are instead focused on a performance standard.

B.5.2 Post-Abort Open Cabin Fire

- An open cabin, non-battery related fire in 1G environment occurring post abort. The OPFE post abort may have limited functionality due to potential damage due to abort loads. In this scenario, mixing may occur between the water and nitrogen inside the tank due to a potential damage of the internal water/gas separator. This scenario will engage a less challenging fire than Fire Scenario 1.0 and assuming water and nitrogen have mixed inside the tank prior to use.
- The open cabin fire test shall be configured according to Figure B-7.

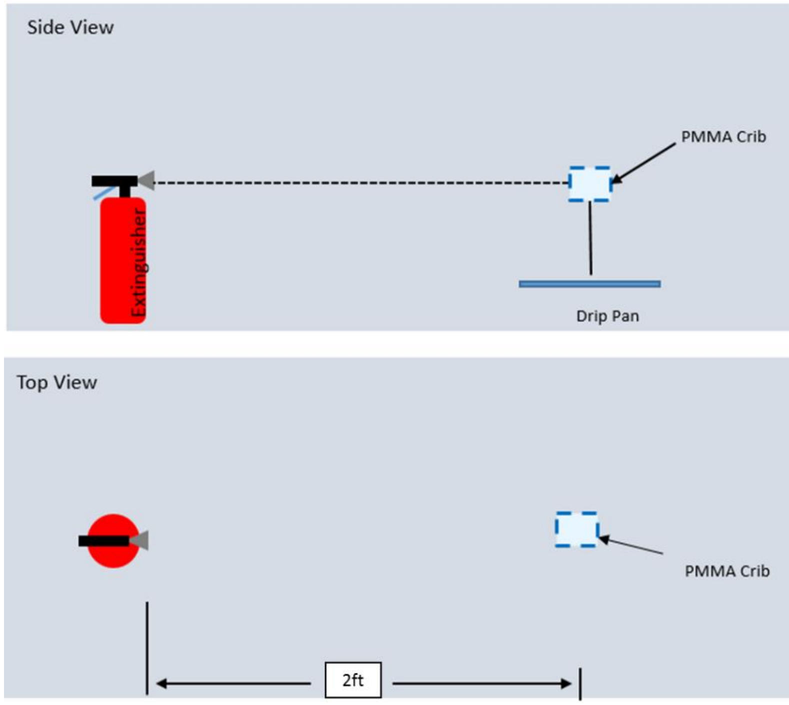


Figure B-7. Open Cabin Fire Test Configuration (side view (above) and top view (below))

- The fire fighter shall hold the nozzle of the extinguisher no closer than 2 ft from the fire through the duration of the test. The minimum distance of 2 ft is based on the small internal cabin volume of the Orion vehicle.
- The fire fighter shall be allowed to use any fire-fighting technique (e.g., sweep, burst, etc.); however, their feet are required to remain in a stationary position.
- The following environmental conditions shall be documented prior to the start of the test:
  - Oxygen concentration
  - Pressure
  - Temperature
  - Humidity
- The fuel shall consist of 700 grams ±35 grams (1.54 lb ± 0.08 lb) of polymethyl methacrylate (PMMA) sheets.
- The PMMA fuel shall be configured as shown in Figure B-8 and constructed per the following indications:
  - Quantity of 15 7 × 1 × 0.25-inch thick strips and quantity of 12 6 × 1 × 0.25-inch thick strips of PMMA shall be used. Modify the lengths of the strips to achieve total crib mass of 700 grams ±35 grams.
  - Each strip shall be notched 3/32 inch of the height at 1-inch intervals on the intersecting side to achieve a 3/16-inch height interlock between each intersecting PMMA strip. A four-flute end mill shall be used to achieve ~0.05-inch oversized width notches.
  - Loctite brand gel-type super glue shall be used to hold the structure together at each intersection of PMMA strips.

  This fuel configuration was shown to provide structural stability and repeatability of fire propagation and fuel consumption during development testing and provides a targeted energy output of approximately 75kW for the fire. The fuel configuration enables air and oxygen flow completely around the PMMA strips during propagation for consistent fire growth patterns. The structural stability provided by the configuration ensures accurate mass loss measurements prior to activation of the test article.

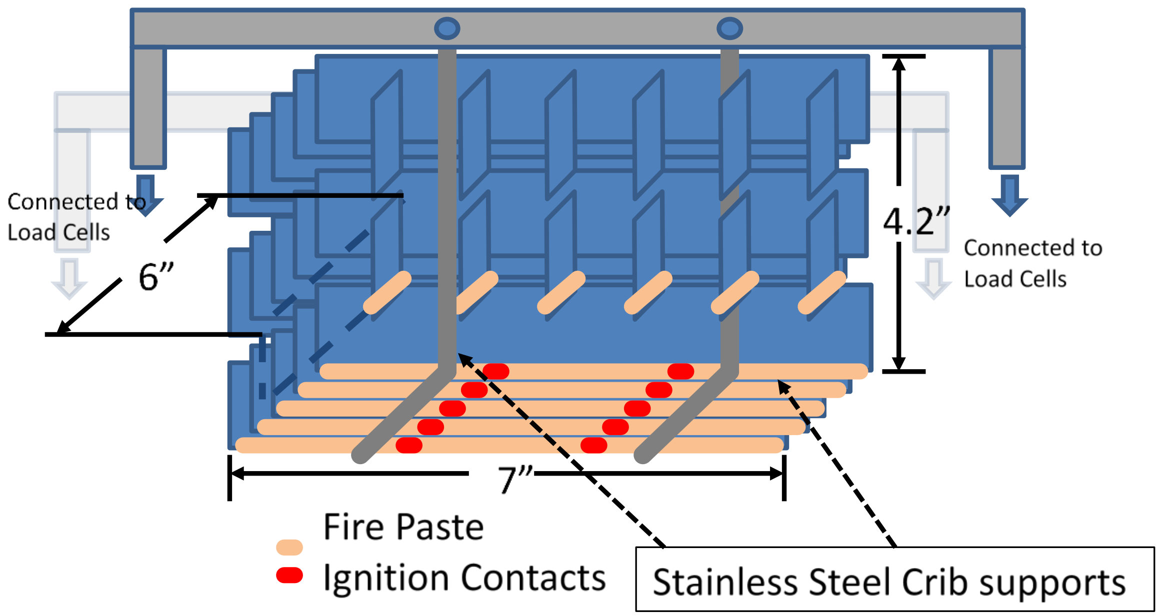


Figure B-8. PMMA Crib Configuration and Support, Fire Paste Application, and Ignition Points

- The fuel crib configuration shall be lined with a total of 10 grams ±1 gram (0.35 ounces ± 0.04 ounces) of fire paste accelerant. Specifically controlling the quantity and application of fire paste accelerant to the PMMA crib ensures the fire develops in a repeatable manner.
- The fuel crib configuration shall be ignited from the bottom of the PMMA crib at the points lined with fire paste accelerant using a pyrofuse wire.
- The fuel configuration shall be attached to a strain gauge that provides real-time insight into the amount of fuel that is consumed during the fire test.
- The test article shall be activated when all of the following test criteria are met:
  - All PMMA strips are fully involved in the flames as determined by visual observation.
  - There is no structural failure of the PMMA crib resulting in loss of fuel.
  - 30% (+0%/–0.5%) oxygen near fuel configuration
  - Minimum of 90 grams ±5 grams (3.17 ounces ± 0.18 ounces) of weight loss is actively measured during fire growth.
- Each test shall be video recorded. Video recording is necessary to ensure all data are accurate and to allow for review and confirmation of specific timeline events.
- A post-test visual inspection shall be performed to ensure that a minimum of 85% of the PMMA crib was involved in the fire. The crib consists of 177 double-sided 1-inch squares. Divide the number of burned double-sided 1-inch squares in the crib by 177. Involvement of 85% of the PMMA crib is an indicator of an adequately developed fire and serves as a quantifiable means of validating the test from a repeatability perspective.
- The following performance criteria shall be used for the Open Cabin Fire Test:

    - A test fire is considered to be extinguished when flames are no longer visible.
    - Number of times the test must be performed will be defined in the Certification and Acceptance Test Plan.
- The fuel crib will be ignited along the bottom of the PMMA strips, and the fire will be allowed to grow until the fire is fully involved. Once the fire is fully involved, the PFE is discharged, with operator discretion determining horizontal sweep if necessary. The discharge will be continuous until flames are visibly extinguished, and additional pulses will be allowed as required. The crib will then be inspected by counting the number of double-sided 1-inch squares that have been burned to determine that 85% or greater of the crib was involved in the fire.
- Spacecraft atmospheres have two different environments with respect to fire control: open cabin environment, and enclosed volumes. The open cabin is where the crew resides—it is a larger volume, and in a fire scenario, the crew will have access and/or line of sight to the fire. When engaging an open cabin fire, the crewmember will spray the vicinity of the fire, which will prevent the fire from spreading and reduce the fire size. This will allow the crewmember to get closer to the fire, thereby allowing better access to the fire, which will ultimately lead to extinguishment from a close distance. The distances defined in this test standard are not intended to reflect an assessment of safe fire-fighting distance but are instead focused on a performance standard.

B.6 System Requirements

The OPFE must also meet numerous functional, physical, environmental, reliability, maintainability, structural, human engineering, safety, and lifetime requirements. Key OPFE requirements are:

- The OPFE shall be portable.
- The continuous discharge time of a fully charged PFE shall be a minimum of 25 seconds.
- The maximum time to initiate discharge of the suppressant of a fully charged OPFE from the time of activation shall be 1 second.
- The OPFE shall cease dispensing suppressant in less than 1 second after the activation mechanism is released.
- The OPFE shall be capable of discharging unused suppressant at any time within 24 hours of initial actuation.
- The suppressant used in the OPFE shall preclude electrical shock hazard to the crew during use on electrically energized systems operating in the Orion environment.
- The OPFE shall be filled with water per JSC-SPEC-C-20D, Grade A, and filled through a 0.2-micron particle filter.
- The OPFE shall be filled with nitrogen (N2) gas with Grade B quality in accordance with MPCV 70156, "Cross Program Procurement and Use Control Specification," [ref. 7], Table 3.5-24.
- External leakage from the OPFE shall be less than 1% mass of remaining contents 24 hours after initial use.
- The OPFE fill ports shall be designed so that they can be capped prior to flight.
- The OPFE shall provide containment of the nitrogen gas.

- The OPFE shall provide containment of the water until actuation is initiated.
- The OPFE shall provide a visual indication of system pressure that:
  - Is visible through all mission phases.
  - Indicates sufficient quantity to fight the challenge fire scenario.
  - Indicates when the PFE is empty.
- The time to remove a safety pin and any other actions required after the OPFE is removed from the bracket until the OPFE is ready for content discharge shall take no more than 5 seconds.
- The mass for the OPFE System in the flight configuration shall be less than 8.34 kg (18.38 lb).
- The OPFE System shall fit within the volume shown in "Fire Extinguisher Mechanical Interface Control Document (MICD)," 948CA7348027 [ref. 8].
- The exterior of the PFE tank shall be a red color.
- The OPFE shall provide a 3 × 5-inch location to adhere an Operations Label.
- The OPFE shall limit the maximum A-weighted overall SPL at the crewmember's head location caused by known noise sources, including voice communications and alarms, to less than 85 dBA during all mission phases except launch and entry.
- The OPFE shall limit impulse noise, measured at the crewmember's head location to less than 140 dB peak SPL during all mission phases except launch and entry. This requirement is a flow down from MPCV 70024, HS3078 [ref. 2]. The impulse noise limit is applicable to any noise portion less than 1 second.
- On-orbit maintenance is not required for the OPFE system.
- The OPFE system labels shall be in accordance with MPCV 70152, "Orion Multi-Purpose Crew Vehicle (MPCV) Program: Crew Interface Labeling Standard" [ref. 9].
- Text shall be written in the American English language, based on Webster's New World Dictionary of American English.
- The OPFE system shall provide fit, access, reach, view, and operation of the OPFE system for unsuited crewmembers as defined in MPCV 72585, "Orion Multi-Purpose Crew Vehicle Anthropometry Data Book" [ref. 4].
- The OPFE system shall withstand the following forces without sustaining damage:
  - 449 N (101 lbf) pull on the bracket handle to open the bracket.
  - 783 N (176 lbf) grip on the PFE handle to actuate the OPFE.
- The OPFE system shall require forces no greater than the following for operation:
  - 111 N (25 lbf) pull on the bracket handle to open the bracket.
  - 49 N (11 lbf) grip on the PFE handle to actuate the OPFE.
- The OPFE shall be provided with handles or other means for grasping, tethering, handling, or carrying by flight crew (and, where appropriate, by an unpressurized or pressurized gloved hand).
- The system shall provide fit, access, reach, view, and operation of human-systems interfaces in crew functional areas for suited crewmembers as defined in MPCV 72585, "Orion Multi-Purpose Crew Vehicle Anthropometry Data Book" [ref. 4].

- The OPFE system shall be operable by a pressurized gloved hand at 4.4 psid.
- The OPFE system shall be operable by an unpressurized gloved hand.
- The OPFE bracket shall be operable without the use of tools.
- The OPFE shall be capable of being removed from the bracket when in the on-orbit configuration in less than 5 seconds.
- The OPFE shall be capable of being removed from the bracket when in the launch and landing configuration in less than 10 seconds.
- The OPFE system shall be restrained to prevent it from coming loose during all mission phases, including launch, entry, and abort.
- OPFE system components and equipment that are intended to be operated by suited crew should require forces no greater than the following:
  - 56N (13 lbf) to pull on the bracket handle to open the bracket.
  - 25N (6 lbf) grip on the PFE handle to actuate the OPFE.
- The OPFE shall protect against inadvertent activation.
- The OPFE shall meet a 1-year charged service life.
- The OPFE should meet a 6-year charged service life.
- The OPFE system shall be reusable for five flights.
- Significant environmental OPFE requirements are listed in Table B-1.

Table B-1. Significant Environmental OPFE Requirements

Requirement Type	Requirement Description
Operating thermal environment	2.2 to 49.4 °C (36 to 121 °F)
Non-operating thermal environment	2.2 to 49.4 °C (36 to 121 °F)
Operating pressure environment	19.7 to 148.9 kPa (2.86 to 21.6 psia)
Non-operating pressure environment	0 to 148.9 kPa (0 to 21.6 psia)
Pressure rate of change	–207 kPa (–30.0 psi)/min and +93.1 kPa (+13.5 psi)/min
Humidity	0 to 100%

B.7 Hardware Design

Figure B-9 shows a section view of the OPFE.

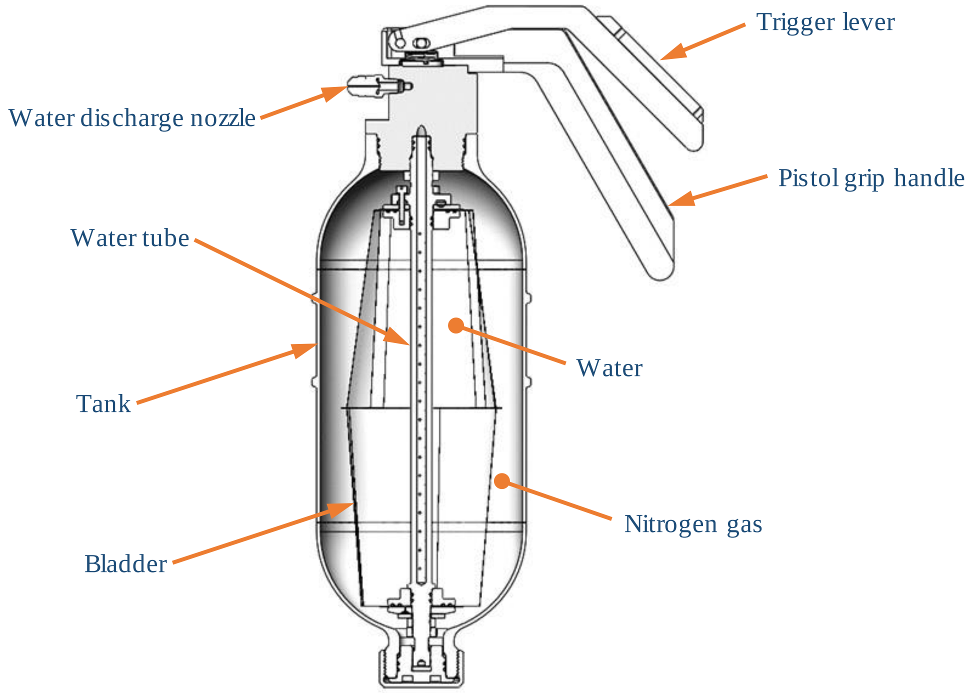


Figure B-9. OPFE Assembly Section View

Nitrogen gas, charged to 300 psig, places a load on a bladder filled with 3 lb of water. The bladder is made of polyurethane and retrained with a textile layer. When the trigger lever is depressed, water is forced up through the water tube and out the discharge nozzle. A plume of water spray is expelled from the nozzle. Figure B-10 shows a prototype OPFE nozzle discharge test. The nozzle is optimized for a spray range of 2 ft. With a fully charged OPFE, the spray duration is 25 seconds.

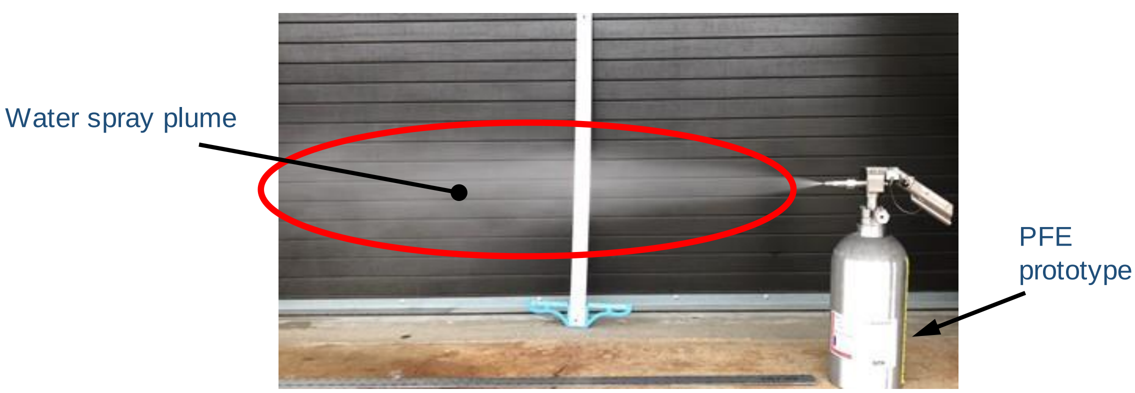


Figure B-10. OPFE Spray Plume Test

Trigger lever actuation force ranges from 3.4 to 4.8 lb. During a complete discharge of water, the nitrogen pressure falls to 196 psig. Ports used to charge water and nitrogen gas into the OPFE are shown in Figure B-11. These ports interface with ground support equipment (GSE) when servicing the OPFE prior to flight.

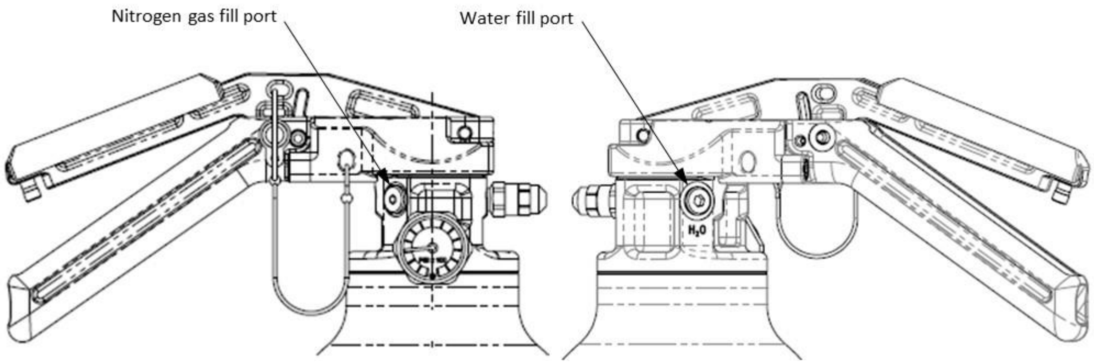


Figure B-11. OPFE Gas and Water Fill Port Locations

Other OPFE features include a pressure gauge that monitors the internal nitrogen gas pressure and a tethered trigger PIP pin that prevents inadvertent discharge. The pressure gauge ranges from
0 to 1,500 psig. These nozzle assembly features are shown in Figure B-12.

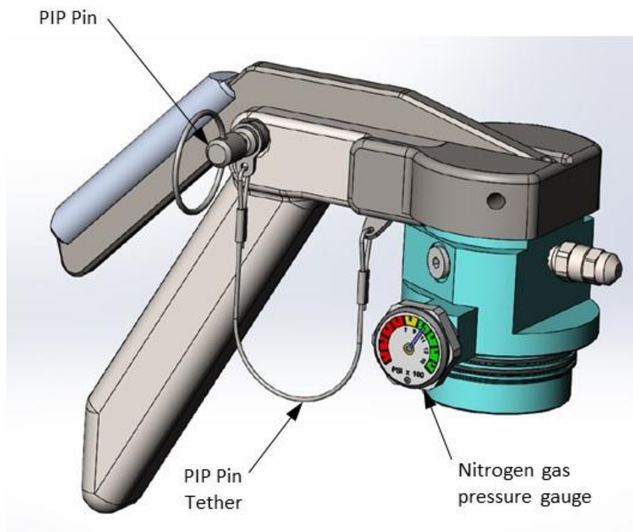


Figure B-12. OPFE Nozzle Assembly Features

The OPFE is secured in the Orion crew cabin by a rigid multi-link cradle (see Figure B-13). To remove the OPFE from the cradle, the PIP pin is removed and the cradle handle is rotated outward. The two cradle clamps are subsequently swung open to remove the OPFE from the mount. See Figure B-14 for a sequence of steps for opening the OPFE cradle mount.

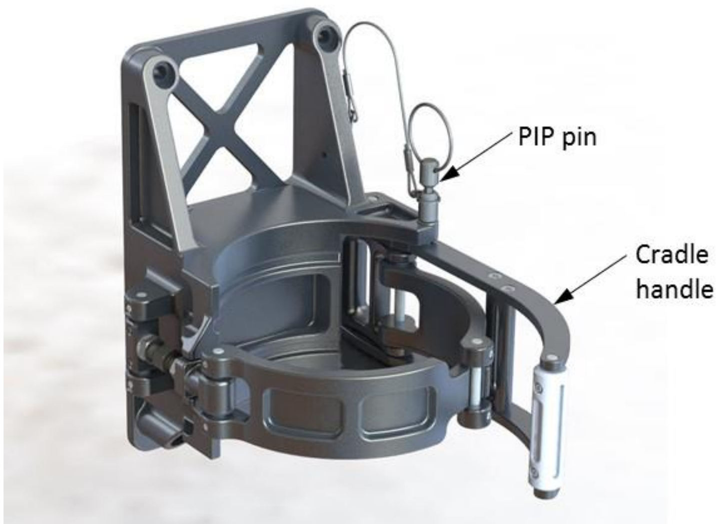


Figure B-13. OPFE Cradle Mount

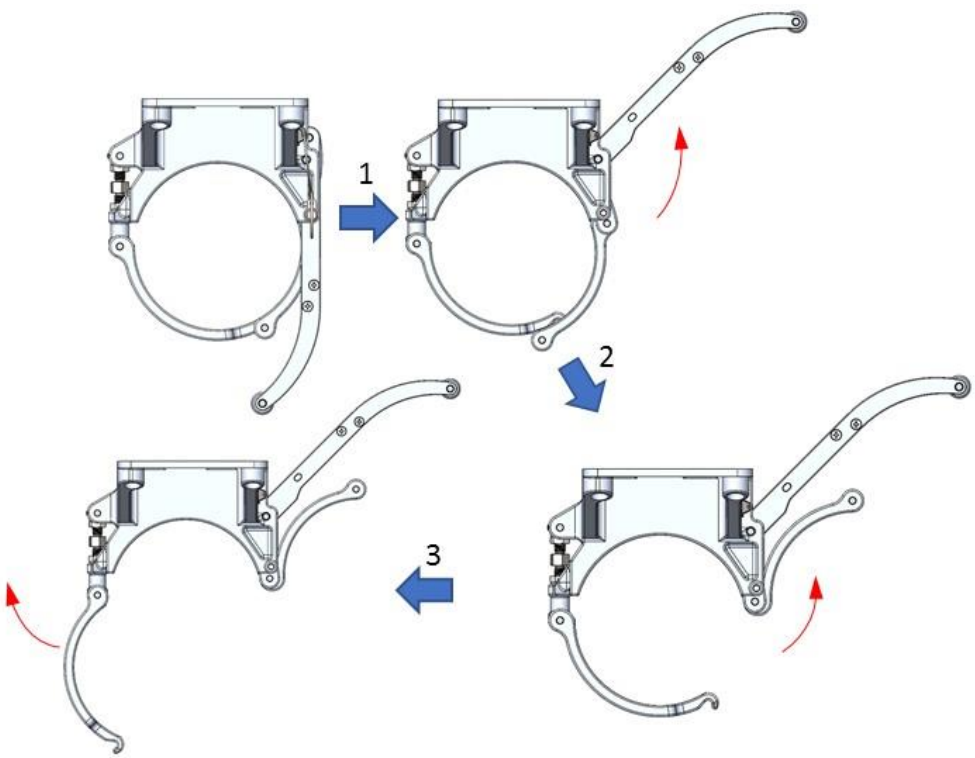


Figure B-14. OPFE Cradle Mount Opening Sequence (top view)

The OPFE tank rests in the cradle between two retainer rings that are part of the tank's external structure. A tensioner feature on the cradle provides an adjustable restraint force for the tank. Figure B-15 shows the PFE mounted in the cradle.

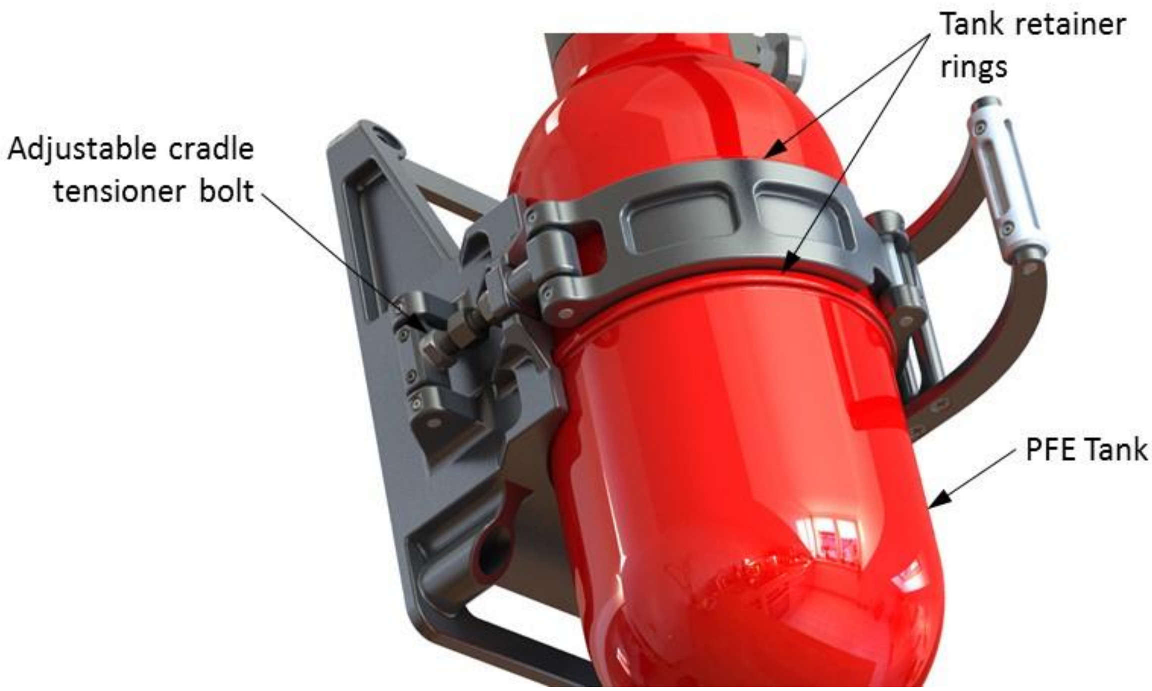


Figure B-15. OPFE in Cradle Mount

B.8 System Certification

The OPFE project will provide evidence to the S&MA personnel and the GEMCB that the OPFE system satisfies all performance and design requirements. Certification is based on the provided verification products and may be supplemented with any validation product(s). Based on this evidence, S&MA and the GEMCB approves the request for certification and signs off on the Government Certification Approval Request (GCAR). This process is an audit of how the project has verified each project requirement.

Qualification testing is performed on qualification units that are identical to the flight articles but are not intended for flight. The purpose of qualification tests is to ensure the design of the project's deliverables meet the environmental requirements imposed on the deliverable. These tests may exceed the expected induced environment levels. Qualification testing proves that an end item's design is adequate to meet the environment specification requirements. This testing will include functional tests before and after exposure to the test environment to determine the success or failure of the test. Depending on the project requirements, this may also include functional and performance tests being conducted during the environment tests.

Acceptance testing is used to prove the flight units have replicated the certified design. These flight units are tracked by serial number. Acceptance testing is performed on each deliverable end item. In addition to proving the functionality of each unit at a selected subset of specification values, this testing also is intended to screen out manufacturing defects, workmanship errors, incipient failures, and other performance anomalies not readily detectable by inspection.

The OPFE product verification methodology is shown in Figure B-16.

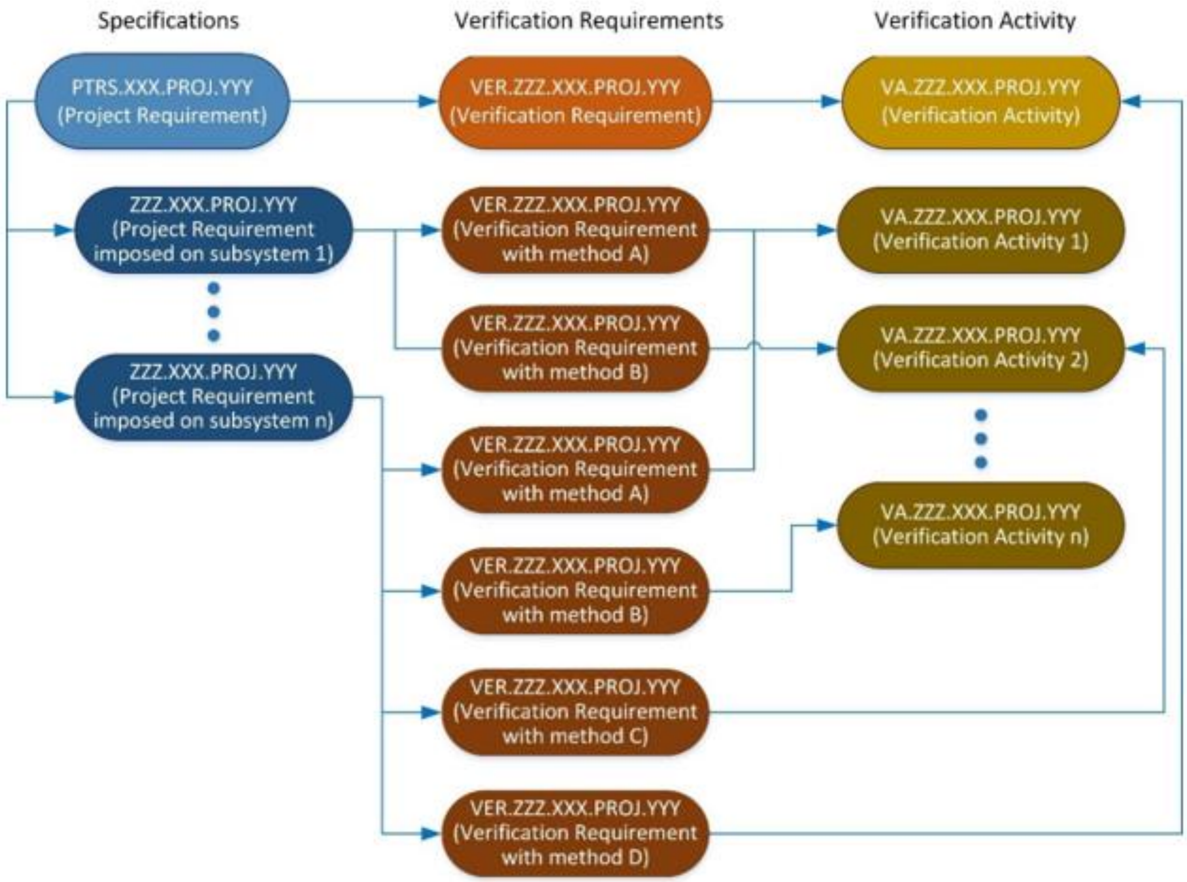


Figure B-16. OPFE Product Verification Methodology

The OPFE qualification test flow is described in Table B-2.

Table B-2. OPFE Qualification Test Flow

Test No.	Qualification Test Description
1	1.5 × MDP proof pressure and 1.0 × MDP leak test
2	Initial full functional/minimum discharge duration
3	Multi-use/cease discharge/start discharge
4	Acoustic measurement
5	Helium leak pre-environment testing
6	SRS shock
7	Random vibration nominal ascent
8	Random vibration abort
9	Thermal cycle: eight cold and eight hot discharge cycles
10	Helium leak post-environment testing
11	Post qualification disassembly/inspection

Other OPFE qualification tests that are not a part of the primary test flow are as follows:

- Tank-only pressure cycle test
- Tank-only burst test

- Cartridge valve life test (400 cycles)

The OPFE acceptance test flow is described in Table B-3.

Table B-3. OPFE Acceptance Test Flow

Test No.	Acceptance Test Description
1	1.5 × MDP proof pressure and 1.0 × MDP leak test
2	Initial full functional/minimum discharge duration
3	Multi-use/cease discharge/start discharge
4	Helium leak pre-environment testing
5	Random vibration nominal ascent
6	Random vibration abort
7	Thermal cycle (four cold and four hot discharge cycles)
8	Helium leak post-environment testing

Options for testing required to accept post-flight refurbished PFE units are:

- Option 1: Initial functional, helium leak, random vibration, helium leak.
- Option 2: Initial functional, helium leak.

Appendix C. Orion Smoke Eater Filter (OSEF)

C.1 Introduction

A cabin fire onboard Orion presents a potentially catastrophic emergency for the crew, vehicle, and mission. Products of combustion contaminate the cabin atmosphere in the form of smoke particulates and harmful gases. In addition, water spray released into the cabin from the PFE system during firefighting is also present in the environment.

As a first response, crewmembers don a CBA for protection against contaminants while responding to the fire event. After the fire is extinguished, the OSEF is an emergency response device that removes post-fire particulates and harmful gases. The OSEF is installed into the Orion cabin particulate control assembly, HPC1. It temporarily replaces the cabin HEPA filter. The cabin recirculation fan pulls air through the OSEF, and ambient contaminants are subsequently reduced to safe levels.

The OSEF is composed of two major elements:

4. Prefilter: a detachable element designed to capture particulates and water mist.
5. Primary filter: an element consisting of an activated carbon adsorbent and CO oxidation catalyst that remove contaminant gases.

The prefilter extends the operational duration of the OSEF by decreasing the likelihood of clogging the primary filter.

C.2 Overview

The Orion spacecraft supports long-duration missions. It serves as the exploration vehicle that carries the crew to space, provides emergency abort capability, sustains astronauts during their mission, and provides safe reentry from deep space return velocities.

The crew module seats four crewmembers who face a tunnel hatch that is in the forward position of the module. Refer to Figure C-1 for the Orion crew module reference frames. Under nominal operations, air is circulated throughout the habitable volume of the module from several cabin ventilation ports. Air is returned to ECLSS air revitalization system through HPC1, which houses the cabin HEPA filter. Figure C-2 shows the HPC1 in the crew module.

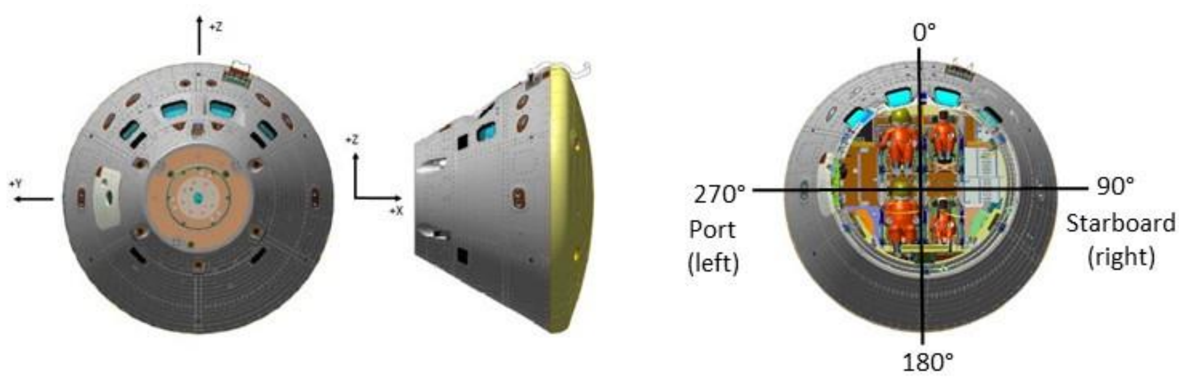


Figure C-1. Orion Crew Module Coordinate Frame of References (tunnel hatch not shown)

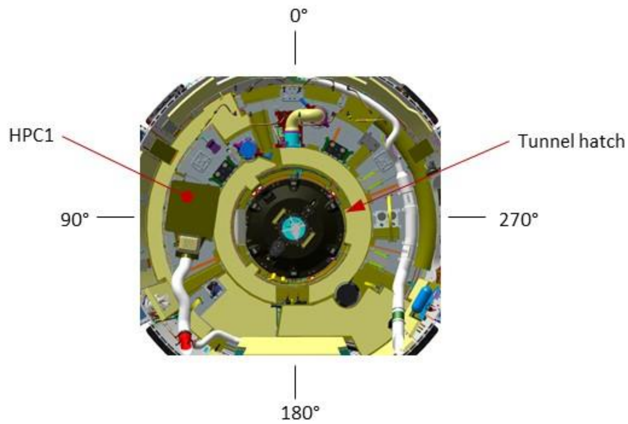


Figure C-2. HPC1 Location within Orion Crew Module (view looking forward toward tunnel hatch)

Figure C-3 depicts the OSEF assembly. Cabin air is drawn into the prefilter, which protects the primary filter from particulates and moisture. During post-fire cleanup operations, the OSEF is installed into HPC1. Cabin air flows through OSEF, and the air recirculates back to the cabin. If the prefilter becomes restrictive to flow, it can be detached from the primary filter (see Figure C-4) and cabin air cleanup operations resumed.

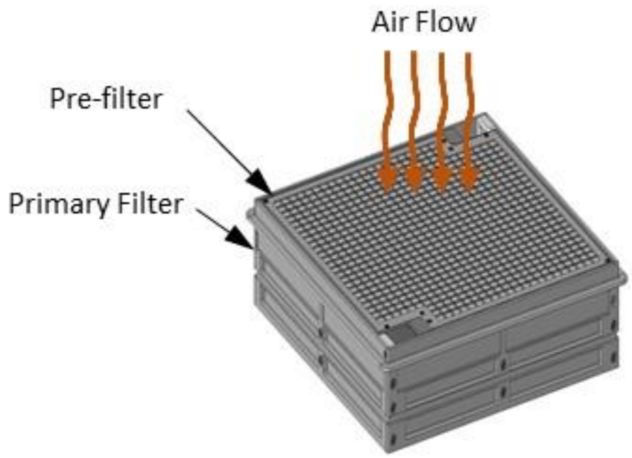


Figure C-3. OSEF Assembly

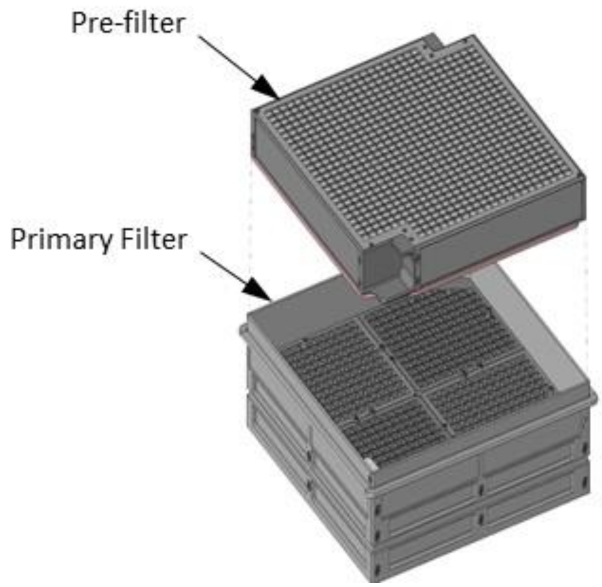


Figure C-4. OSEF Assembly, Filter Elements Shown Separated

C.3 Concept of Operations

During launch and ascent phases of the mission, two OSEF units are stowed in the OASIS Locker F1 of the crew module. Should there be an onboard fire during the mission, the crew will perform procedures to extinguish the fire. Subsequently, during post-fire cleanup operations, the crew will verify that the cabin fan is powered off and will remove the HEPA filter from HPC1. One OSEF unit will be unstowed from its OASIS locker and installed into the HPC1. Figure C-5 depicts the OASIS locker location.

Figure C-5. Orion Crew Module OASIS Locker Configuration (view looking from tunnel hatch – crew seats not shown for clarity)

The cabin fan will be activated to provide airflow through the OSEF. At this point, the OSEF is operational. The crew will monitor the cabin fan current draw, temperature, and rotational speed to detect degradation in performance, which may indicate that the OSEF is restricting air flow. The crew will also monitor the AGA. The AGA measures concentrations of cabin gas constituents, including CO_2, CO, oxygen, HCl, HF, HCN, and ammonia. Figure C-6 shows the location of the AGA in the crew module.

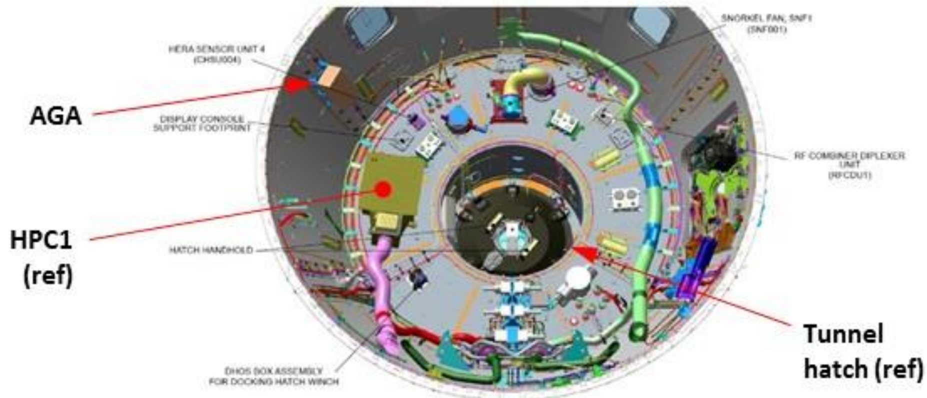


Figure C-6. AGA Location in Orion CM (viewed from crew seating area)

If there is degradation in cabin fan performance, the crew will detach the prefilter from the primary filter and continue monitoring the fan performance. If necessary, during post-fire cleanup, the Crew may replace the entire OSEF with the second stowed unit. Prior to replacing the OSEF, the cabin fan will be de-energized to prevent the system from ingesting loose items into the ducting.

OSEF operations end when the crew determines that either of the following has occurred:

6. The cabin atmosphere has become safe to breathe based on AGA air constituent measurements.
7. The OSEF's life has been expended and other actions are required to reduce air contaminant concentrations.

For reference, the OSEF concept of operations is depicted graphically in Figure C-7. After use, the OSEF is sealed in a post-use bag (see Figure C-8) and restowed in OASIS. The cabin HEPA filter is reinstalled in the HPC1.

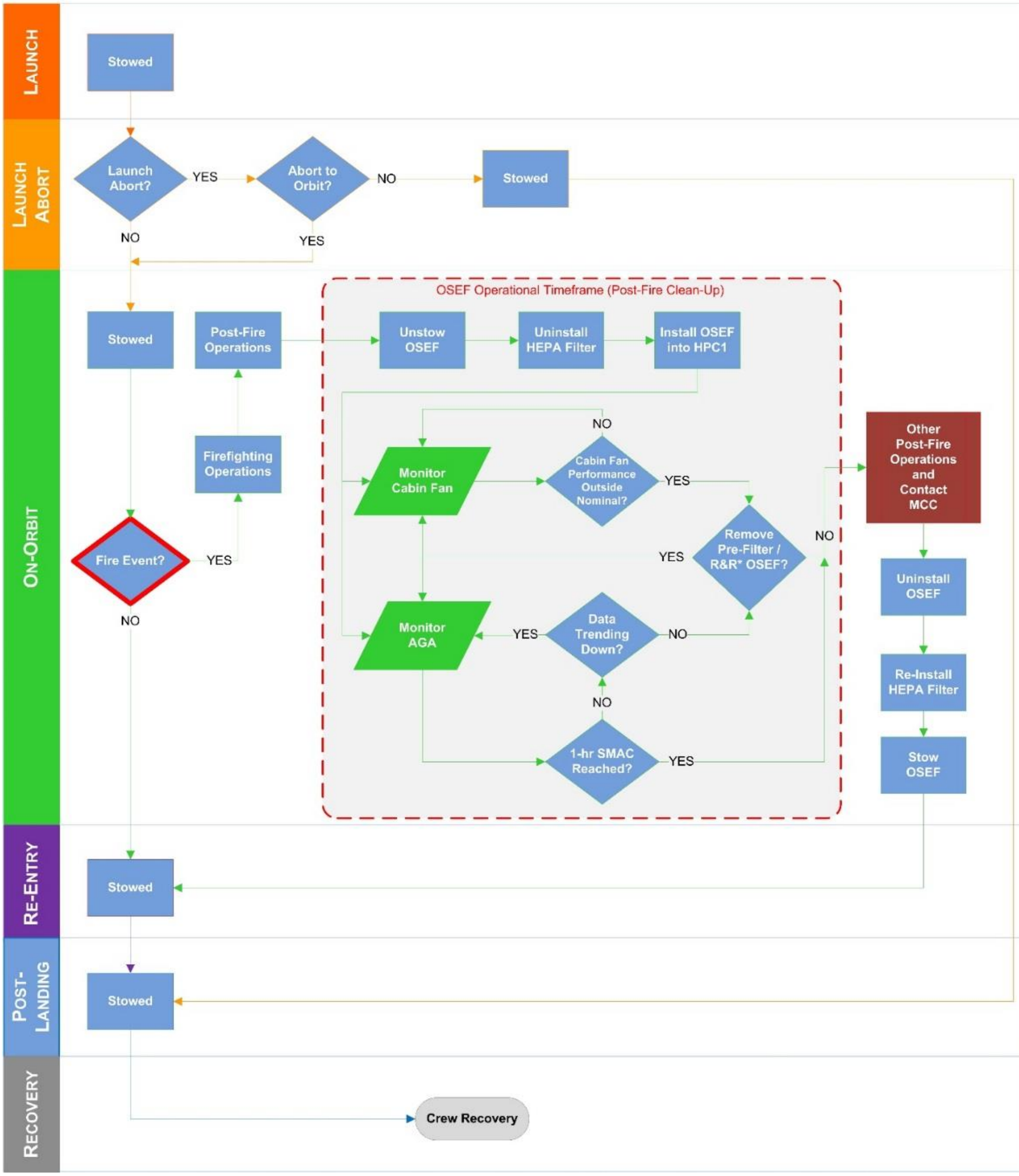


Figure C-7. OSEF Concept of Operations Flow Diagram

Figure C-8. OSEF Post-use Stowage Bag Front View (left) and Rear View (right)

C.4 System Interfaces

The OSEF is a passive device that has two major system interfaces: with personnel and with the vehicle. The functional interface diagram for OSEF is shown in Figure C-9.

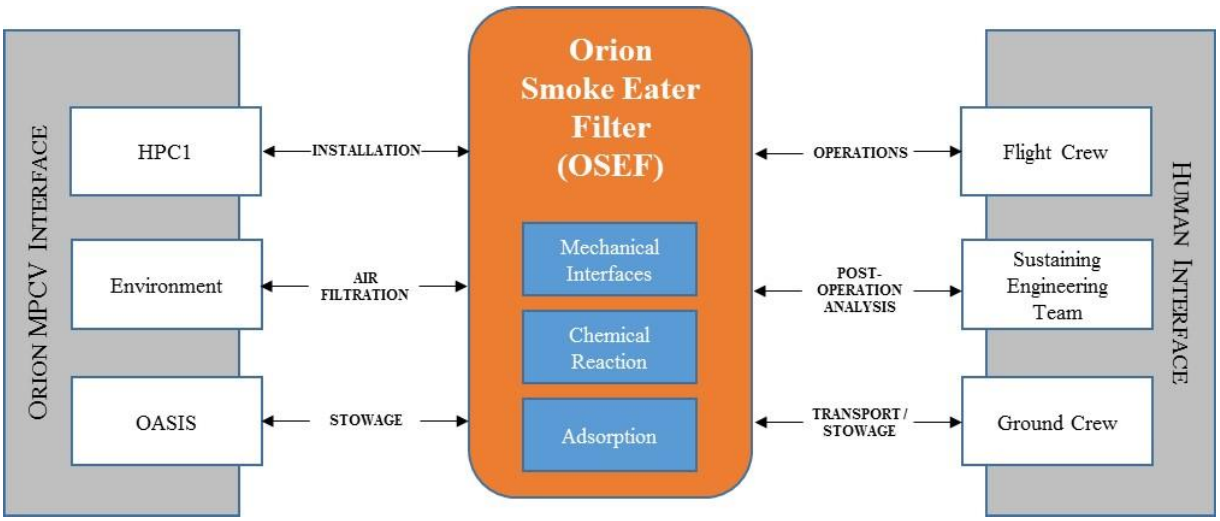


Figure C-9. OSEF Functional Interface Diagram

During operation, when installed in HPC1, the OSEF is required to meet pressure differential limitations set by the vehicle cabin air system in the nominal and contingency vehicle power cases, as shown in Tables C-1 and C-2.

Personnel interfaces include operations with ground support and sustaining engineering personnel, as well as the in-flight crew. Vehicle interfaces include pre- and post-use stowage accommodations, HPC1 interfaces, and operational air cleanup functions. A list of each interface condition is shown in Table C-3.

Table C-1. Pressure Differential across OSEF for Nominal Vehicle Power Case

Fan Speed (RPM)	Flow Rate (ACFM)	OSEF ΔP (IWG)
15000	122	4.64
15100	92	7.40
14470	62	8.30

NOTE: Orion Bus Voltage = 110 V, Air Stream Temperature: 70 °F

Table C-2. Pressure Differential across OSEF for Contingency Vehicle Power Case

Fan Speed (RPM)	Flow Rate (ACFM)	OSEF ΔP (IWG)
13150	92	4.76
13200	62	6.68

NOTE: Orion Bus Voltage = 98 V, Air Stream Temperature: 70 °F

Table C-3. OSEF Interface Descriptions

Interface Condition	Type	System Interfaces	Interface Category
Stowage (prelaunch)	Physical	OASIS	Volume
Stowage (prelaunch)	Environmental	OASIS	Thermal, pressure
Stowage (launch)	Environmental	Launch loads	Loads spectrum, thermal, pressure
Stowage (non-use, abort)	Environmental	Abort loads	Loads spectrum, thermal, pressure
Stowage (in flight)	Environmental	In-flight loads	Loads spectrum, thermal, pressure
Stowage (in flight)*	Physical	OASIS	Volume (dimensions)
Fire event (hardware access and retrieval)	Operational	OASIS, human factors	Access time
Fire event (hardware access and retrieval)	Physical	OASIS, human factors	Ergonomic
Hardware installation	Operational	HPC1, human factors	Installation time
Hardware installation	Physical	HPC1, human factors	Ergonomic
Air filtration (hardware use)	Environmental	ECLSS	Thermal, pressure, humidity
Air filtration (hardware use)	Operational	ECLSS	Flowrate, ΔP

Interface Condition	Type	System Interfaces	Interface Category
Hardware removal (prefilter and primary filter)	Operational	HPC1, human factors	R&R time
Hardware removal (prefilter and primary filter)	Physical	HPC1, human factors	Ergonomic
Hardware removal (prefilter only)	Operational	HPC1, human factors	Removal time
Hardware removal (prefilter only)	Physical	HPC1, human factors	Ergonomic
Post-event containment (temporary)	Operational	Human factors	Temporary stowage volume
Post-event containment (temporary)	Physical	Internal vehicle volume, human factors	Volume, ergonomic
Post-event containment (final)	Operational	Human factors	Installation time (into containment packaging)
Stowage (post-event)	Physical	OASIS, human factors	Ergonomic
Stowage (post-event, landing)	Environmental	OASIS, landing loads	Loads spectrum
* Same as prelaunch stowage			

C.5 Physical and Functional Requirements

One of the primary functional requirements of the OSEF is to reduce post-fire cabin air contaminants to below the 1-hour Spacecraft Maximum Allowable Concentration (SMAC) level so that the crew may safely don their spacesuits. Table C-4 specifies the maximum expected contaminant concentrations and their associated 1-hour SMAC limit.

The OSEF lowers contaminant concentration levels to below the 1-hour SMAC limit in less than 4 hours. It operates when exposed to atmospheric particulate concentration of 0.05 mg/m^3 (100,000 particles per cubic foot) to 50 mg/m^3 (100 million particles per cubic foot) for particles of 0.5 microns to 100 microns in aerodynamic diameter. The OSEF will reduce the particulate concentration to the 1-hour SMAC limit of 5 mg/m^3 to allow the crew to safely don their suits.

After 4 hours of exposure to the conditions of WSTF Fire Challenge B, the OSEF effluent will not contain any compound released during the fire challenge with a concentration higher than its 1-hour SMAC limit.

Because the post-fire cabin air environment will contain water mist expelled from the fire extinguisher, the OSEF is designed to capture water. The current capture volume requirement is 500 ml of water.

Table C-4. Orion Post-fire Contaminants

Contaminant	Max Concentrations†	1-Hour SMAC Limit
C_3H_4O	1.7 ppm (3.8 mg/m^3)	0.075 ppm (0.17 mg/m^3)
C_6H_6	15.34 ppm (49.0 mg/m^3)	10 ppm (35 mg/m^3)
CO	588.34 ppm (674.0 mg/m^3)	425 ppm (485 mg/m^3)
CH_2O	1.19 ppm (1.46 mg/m^3)	0.8 ppm (1.0 mg/m^3)
HCl	0.27 ppm (0.4 mg/m^3) ††	5 ppm (8 mg/m^3)
HCN	7 ppm (7.82 mg/m^3)	8 ppm (9 mg/m^3)
HF	1.86 ppm (1.52 mg/m^3) ††	5 ppm (4 mg/m^3) †††

† Except where noted, maximum concentrations are based on the MPCV's habitable volume of 325 ft^3 as of February 13, 2018. These concentrations are peak values found in WSTF Laptop Fire Test results.

†† These concentrations are values found in WSTF fire test results prior to laptop testing. The values are conservative compared with those found during laptop testing.

††† Source: Temporary Spacecraft Allowable Concentrations on hydrogen fluoride, dated December 2015.

Chemicals used in the manufacture of OSEF and chemical reaction products produced by these chemicals, if released into the habitable volume, shall not decompose into hazardous compounds that threaten crew health.

After cleanup operations, the OSEF will be repackaged to provide containment that limits the release of captured contaminants into the cabin to a daily value of no more than the quantities listed in Table C-5 for a period of no less than 6 days.

Table C-5. Contaminant Hazard Containment SMAC Values

Contaminant	7-Day SMAC
C_3H_4O	0.015 ppm (0.03 mg/m^3)
C_6H_6	0.5 ppm (1.5 mg/m^3)
CO	55 ppm (63 mg/m^3)
CH_2O	0.1 ppm (0.12 mg/m^3)
HCl	1 ppm (1.5 mg/m^3)
HCN	1 ppm (1.1 mg/m^3)
HF	1.0 ppm (0.8 mg/m^3)†

†Source: "Temporary Spacecraft Allowable Concentrations on Hydrogen Fluoride," December 2015.

Environmental conditions met by OSEF are found in Table C-6. For load environments imposed by the vehicle during all launch phases, abort phases, and landing, refer to JSC-67243, "Interface Control Document (ICD) for the Orion Smoke Eater Filter (OSEF) to the Multi-Purpose Crew Vehicle (MPCV)" [ref. 10].

Table C-6. Significant Environmental OSEF Requirements

Requirement Type	Requirement Description
Operating thermal environment	2.8 to 36.1 °C (37 to 97 °F)
Non-operating thermal environment	2.2 to 49.4 °C (36 to 121 °F)
Operating pressure environment	65.5 to 107.2 kPa (9.5 to 15.55 psia)
Non-operating pressure environment	65.5 to 116.5 kPa (9.5 to 16.9 psia) in packaging
Pressure environment - safety	0 to 148.9 kPa (0 to 21.6 psia) in packaging.
Pressure rate of change	–207 kPa (–30.0 psi) per minute and +93.1 kPa (+13.5 psi) per minute in packaging
Humidity	0% and 75% relative humidity at 97 °F

Other OSEF functional and physical requirements are as follows:

- The total mass of OSEF does not exceed 9.6 lb.
- The total volume of OSEF does not exceed 1910 in^3.
- Manipulation, removal, and replacement of the OSEF does not require the use of tools.
- OSEF provides crew interfaces that, together with off-nominal crew tasks, result in a Bedford Workload Scale rating of 6 or less.
- The OSEF can be extracted from its packaging and installed into its operating location within 6 minutes.
- The OSEF can be removed from the HPC1 placed within the post-fire event containment packaging within 5 minutes.
- The OSEF does not require on-orbit maintenance.
- OSEF assemblies have a one-mission life, whether or not used for post fire cleanup.
- The OSEF has a shelf life of 5 years.

C.6 Hardware Design

The function of the OSEF prefilter is to delay the clogging of the primary filter by capturing particulates. Pleated media mechanically traps the contaminants, allowing smaller contaminants, including gases, to pass through to the primary filter. Figure C-10 shows the OSEF exterior dimensions.

The primary filter assembly is a two-layered granular bed that contains an adsorbent and a catalyst. The principal function of the adsorbent is to trap contaminant compounds in highly porous activated carbon having an exceptionally large surface-area-to-volume ratio. It also protects the catalyst below it from poisoning. Subsequently, the catalyst oxidizes CO into CO_2 in an exothermic reaction.

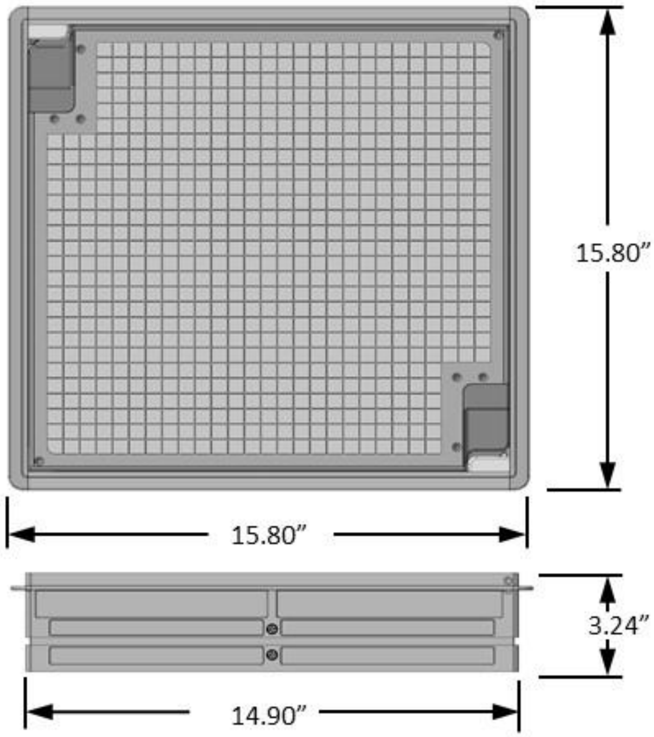


Figure C-10. OSEF Exterior Dimensions

The hinged lid of the HPC1 opens for removal of the cabin HEPA filter and installation of the OSEF (see Figure C-11). The OSEF has a perimeter gasket that prevents air bypass around the assembly. It seals against an internal ledge in the HPC1 (see Figure C-12).

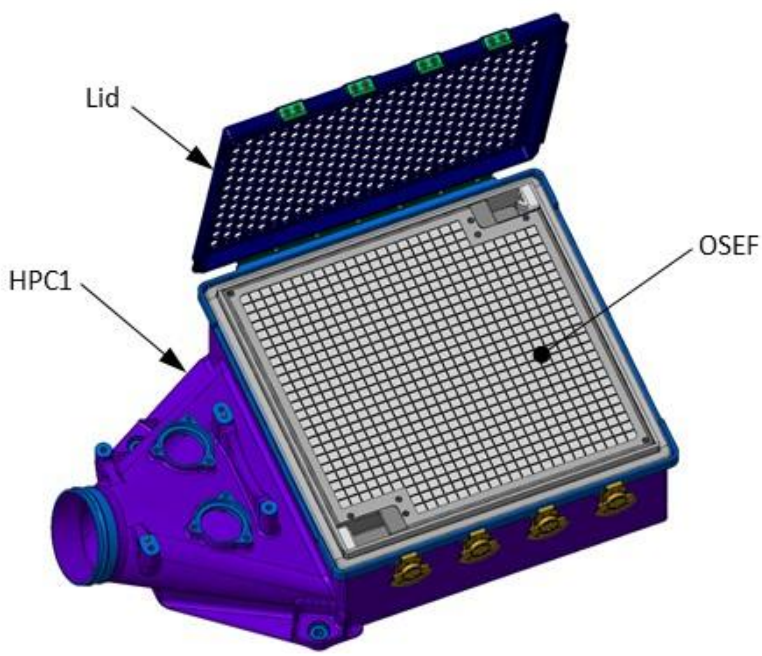


Figure C-11. OSEF Installed in Orion HPC1 (lid in open position)

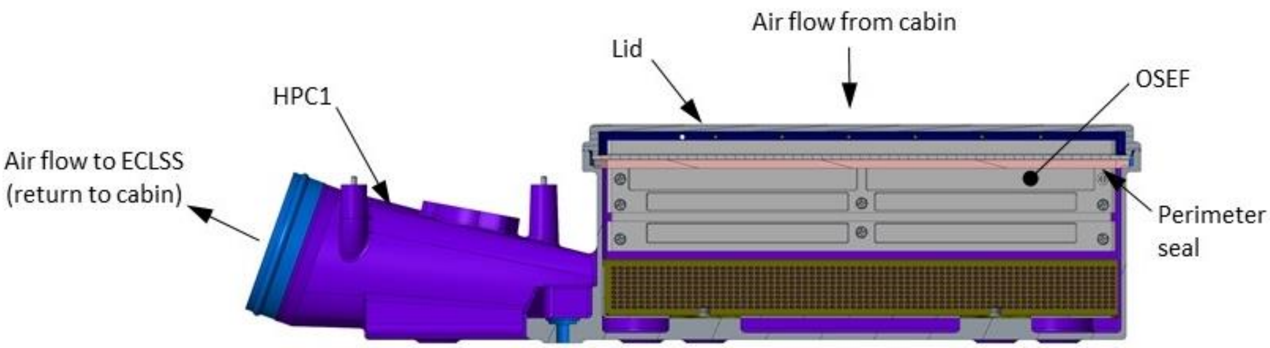


Figure C-12. OSEF Installed in Orion HPC1 (cross-sectional view)

The OSEF prefilter is a framed, pleated particulate filter that has a protective grid at the flow entrance. Figure C-13 shows an exploded view of the prefilter assembly.

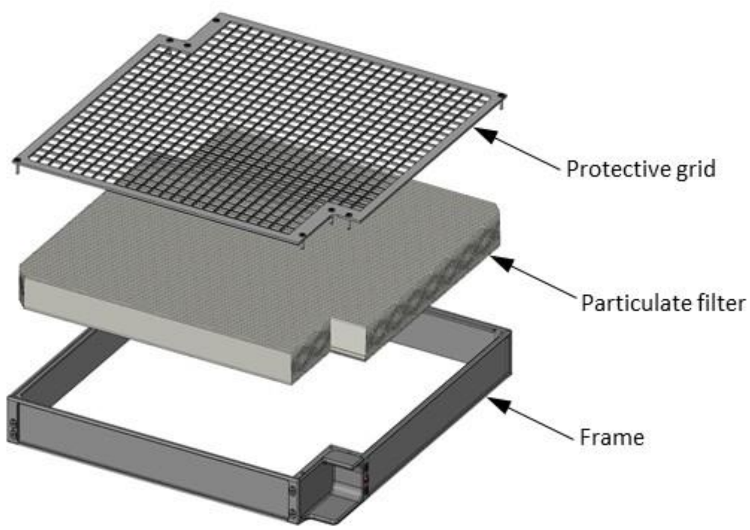


Figure C-13. OSEF Prefilter Assembly, Exploded View

The OSEF primary filter is a four-compartment assembly. The bottom of the assembly has a protective grid that is covered by two non-woven filtration elements. The main frame is attached to the grid; together they sandwich the filtration elements in place. CO oxidation catalyst is packed into each compartment, on top of which a rayon separator is placed. Activated carbon is loaded into each compartment onto the separator pads and covered by two non-woven filtration elements. Each compartment has an entrance grid that is attached to the main frame. A gasket keeps the primary filter frame sealed against the prefilter frame. The perimeter gasket (shown earlier) attaches to the exterior lip of the frame. Figure C-14 shows an exploded view of the OSEF Primary filter.

To secure its position in the frame and facilitate its removal from the primary filter, the prefilter has two spring-loaded detents. They engage with a small indented feature on the inside of the primary filter frame (see Figure C-15).

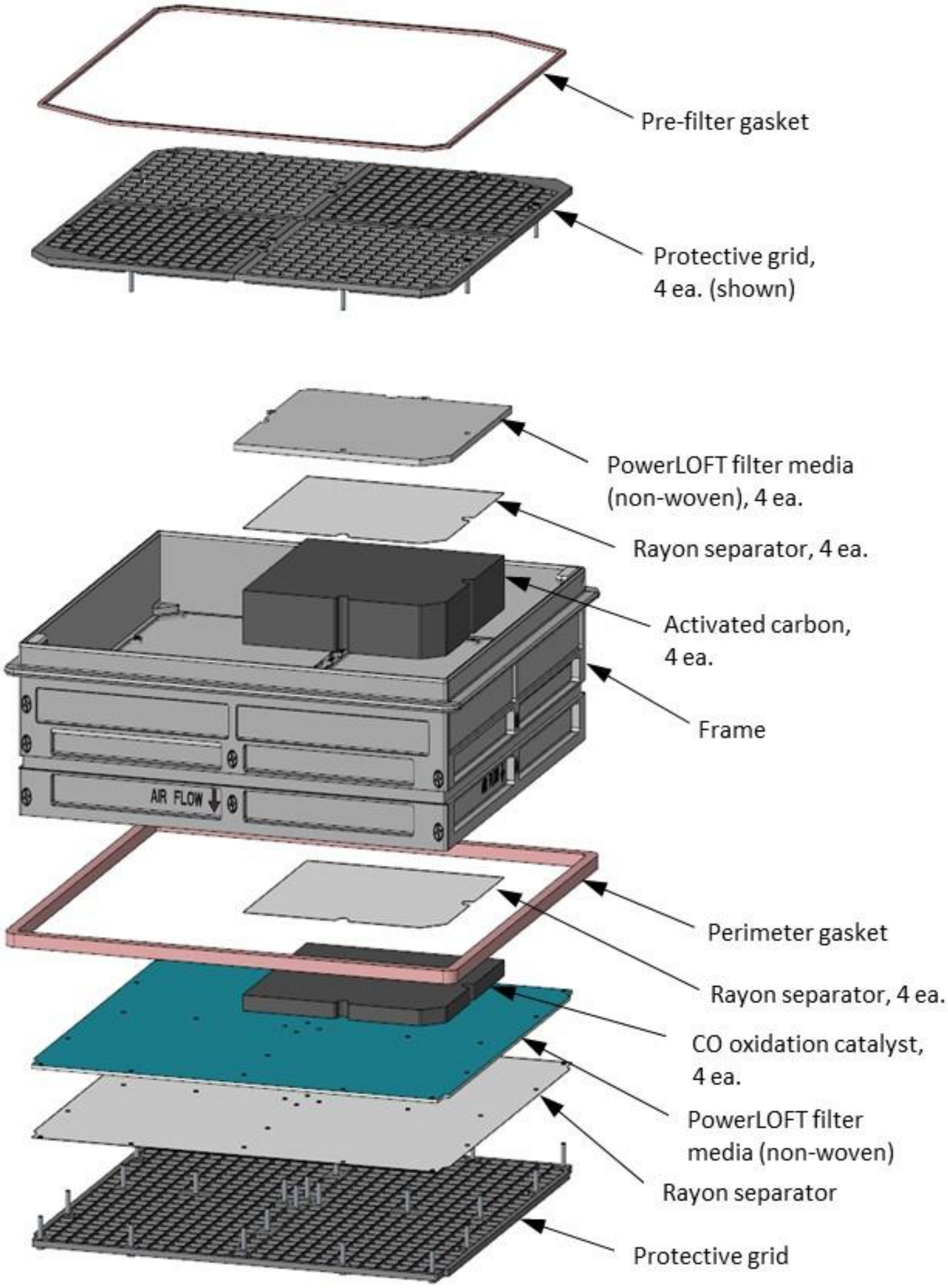


Figure C-14. OSEF Primary Filter Assembly, Exploded View

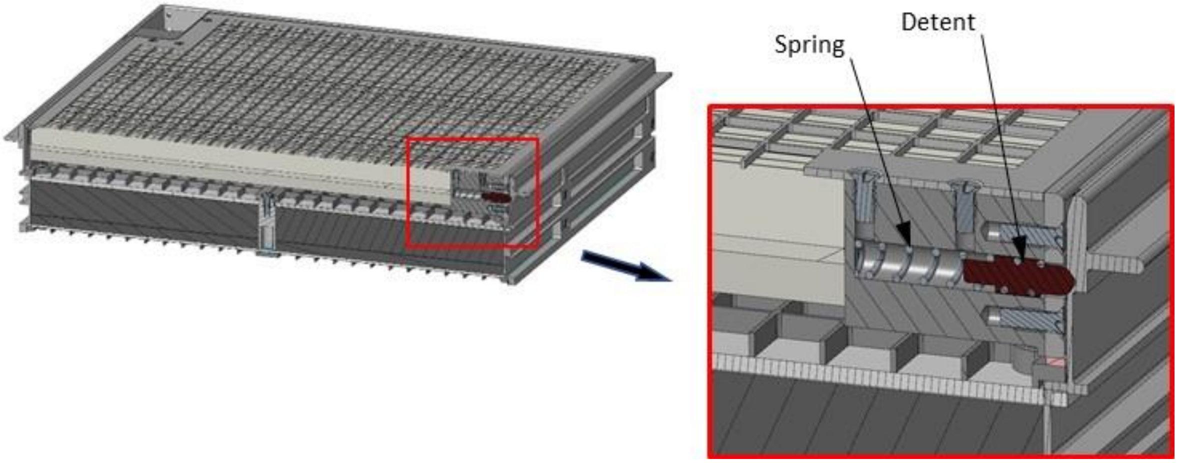


Figure C-15. OSEF Assembly Section View (left) and Prefilter Detent Detail

The OSEF assembly has finger-pull features that aid in removing the prefilter from the primary filter and to assist in removing the primary filter from the HPC1 (refer to Figure C-16).

Figures C-17 and C-18 demonstrate the use of the finger pull features. Figure C-17 shows the OSEF being pulled from the HPC1. Figure C-18 shows the prefilter pulled from the primary filter. This allows the primary filter to continue cleanup operations if the prefilter becomes restrictive to flow.

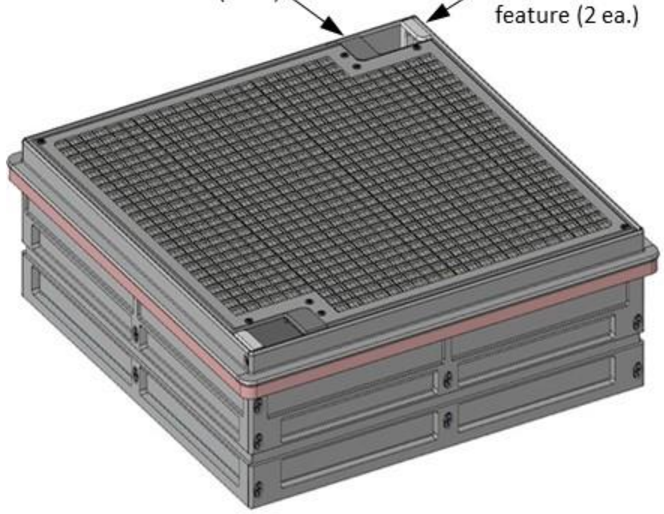


Figure C-16. OSEF Assembly Finger Pull Features

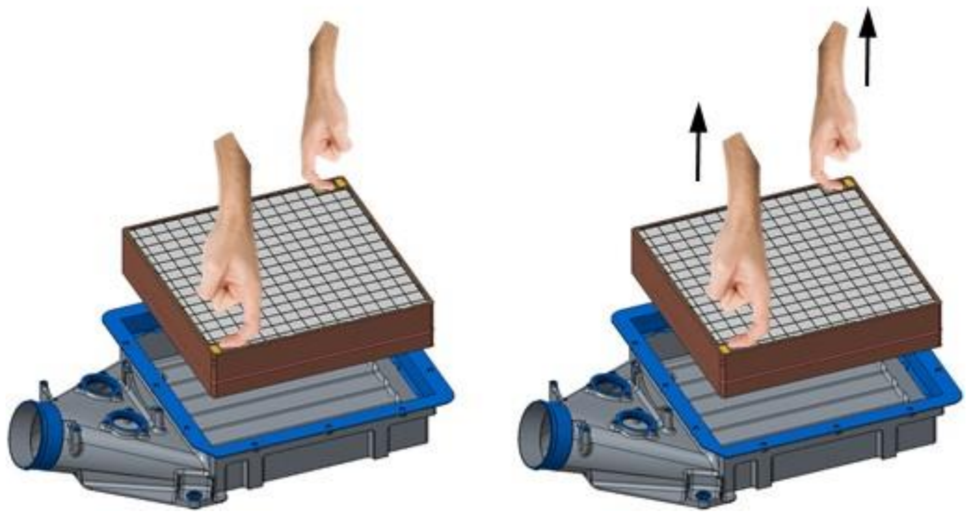


Figure C-17. OSEF Removal from HPC1

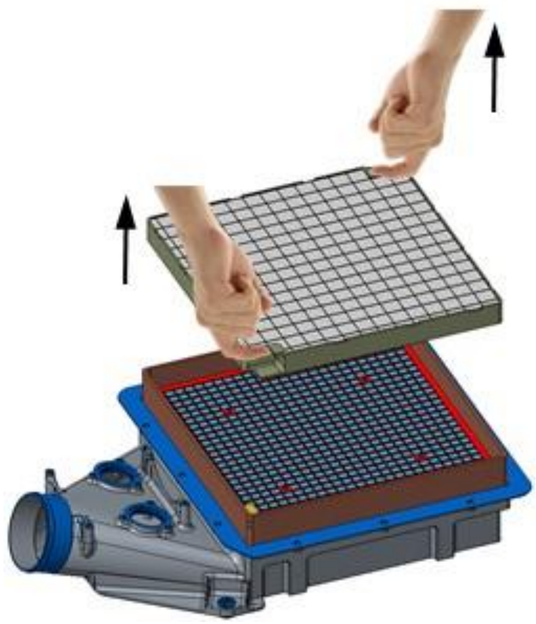


Figure C-18. OSEF Prefilter Removal from Primary Filter while installed in HPC1

C.7 System Certification

The following section outlines the qualification and acceptance tests and the associated high-level test procedures for OSEF flight hardware. Qualification tests are performed on one full-scale unit and several mini-scale units, while nondestructive acceptance tests are performed on all flight units. See Figures C-19 and C-20 for the test flow approach for OSEF qualification testing. The numbering in these figures represents the units randomly selected from the entire lot production run and does not represent a sequential production or selection. Each manufactured lot will undergo qualification testing.

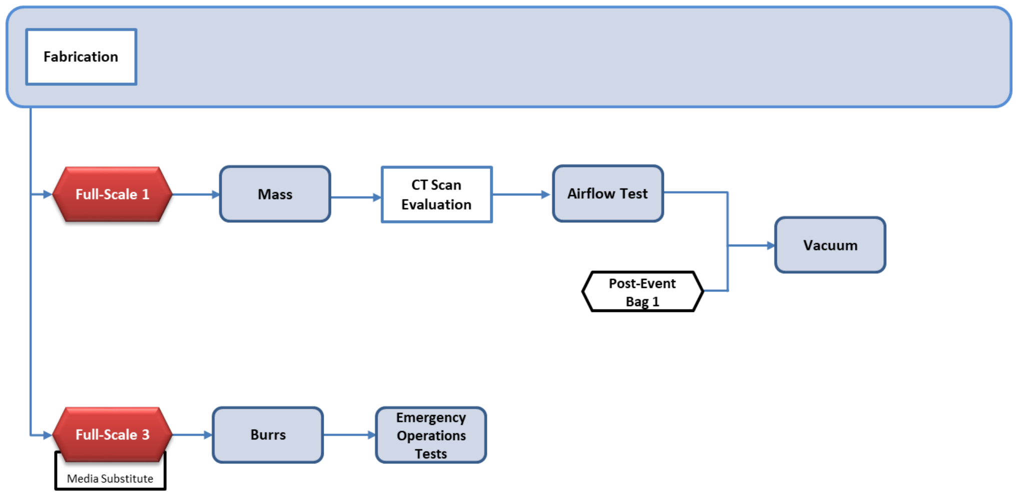


Figure C-19. OSEF Qualification Full-scale Unit Test Flow Diagram

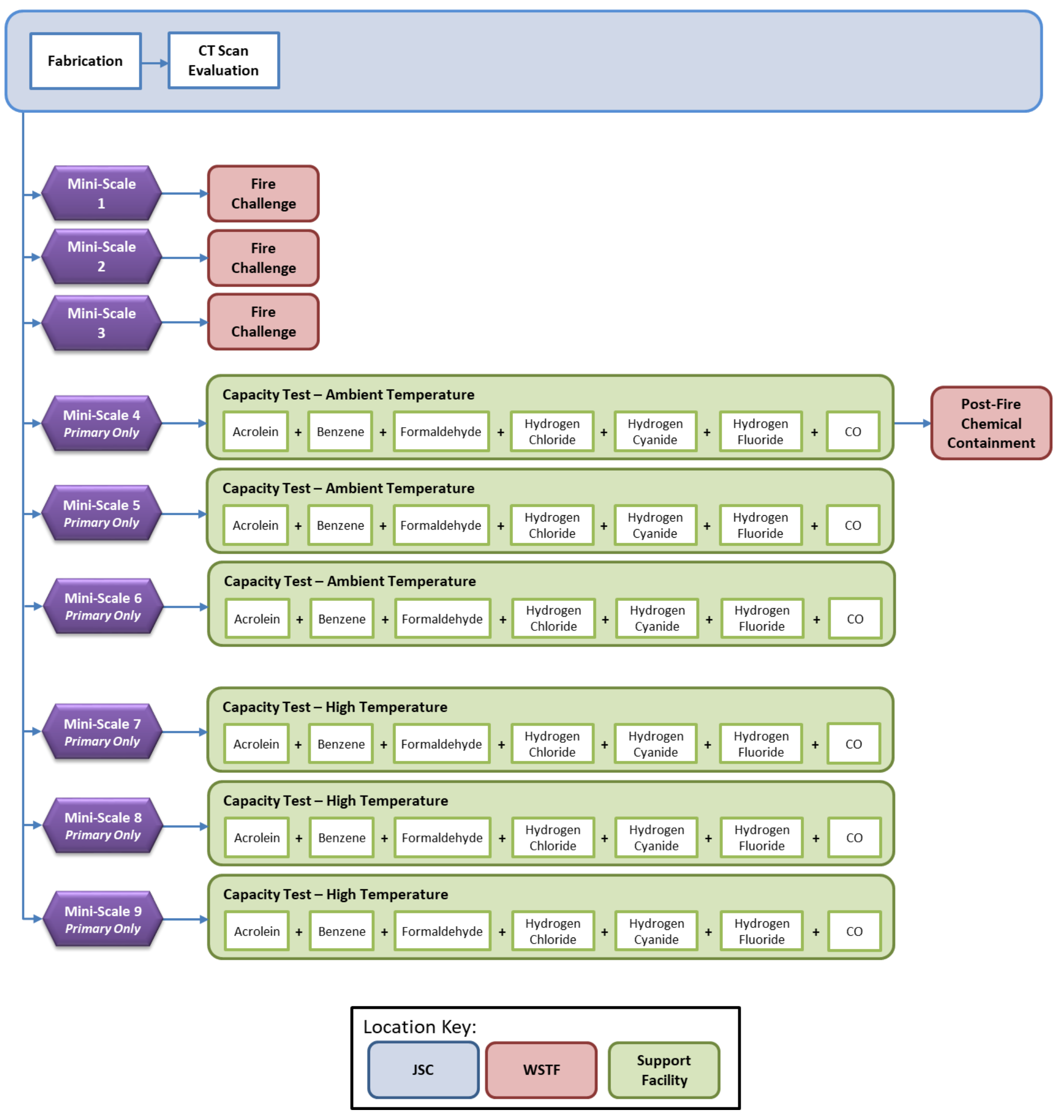


Figure C-20. OSEF Qualification Mini-scale Unit Test Flow Diagram

Qualification testing consists of subjecting the OSEF to airflow, pressure, particulate, and multiple chemical flow challenges, as well as crew operations. The particulate and multiple chemical flow challenges are intended to represent a laptop fire onboard Orion, as a result of thermal runaway with extremes of all potential fire cases. The particulate concentrations and selected contaminants used in the tests are representative of those found resulting from laptops purposely ignited in a controlled chamber at WSTF. Unlike performing laptop combustion tests, the test configurations and profiles for qualification of the OSEF were chosen for the ability to control the chemicals, thus providing reproducibility of results.

Acceptance testing will be performed on all OSEF flight units prior to delivery. Two criteria must be met for successful acceptance: (1) mass, and (2) burrs.

Verification activities will be documented on formal Task Performance Sheets. The certification process will also include analysis, memorandums, and reports. The OSEF project will document all analyses via reports or engineering memorandums. Furthermore, Certificates of Conformity and/or reports of tests performed by the vendor will be used as evidence of compliance with requirements as applicable. Verification activities and subsequent results will be approved by the appropriate stakeholder. Figure C-21 depicts the OSEF verification flow processes.

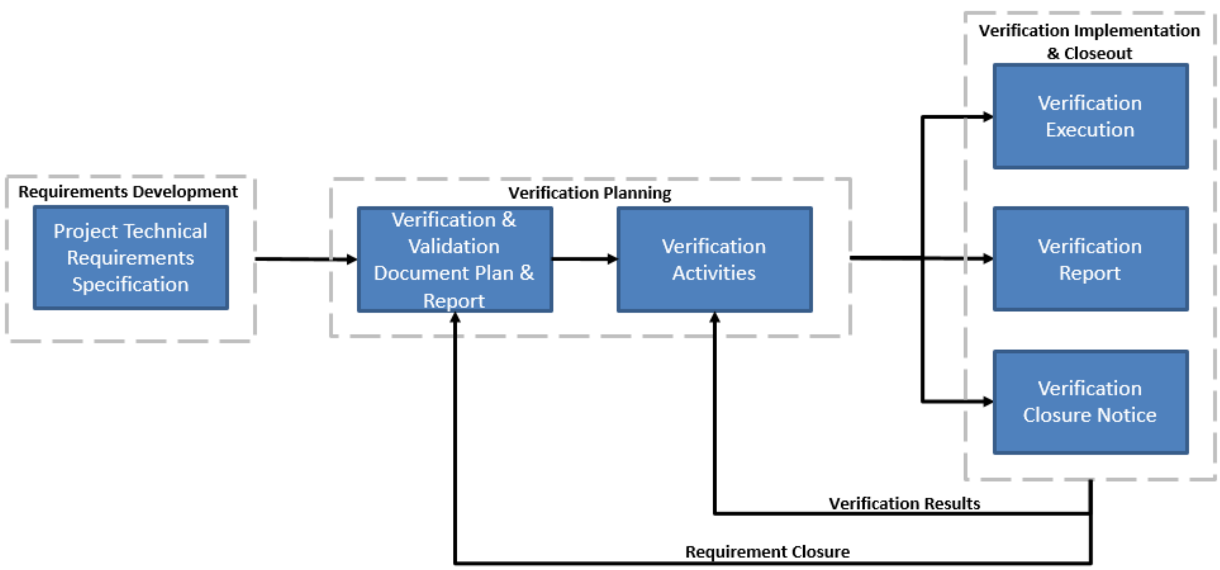


Figure C-21. OSEF Verification Flow

Appendix D. Orion Fire Scenario Supertests

D.1 Introduction

Evaluating fire safety equipment in worst-case scenarios is essential to understanding performance capacities and deficiencies. For Orion, a laptop computer fire in an open cabin configuration was identified as having the greatest released energy and, therefore, capable of producing the most challenging fire onboard the spacecraft. This fire source is likely the most thermally active and greatest producer of combustion gases and particulates. As such, a series tests were conducted to characterize the environment and evaluate the performance of fire protection hardware.

D.2 Laptop Computer Fires

To characterize the cabin environment during a laptop computer fire, a series of tests were conducted to collect data in the following technical areas:

- Particulate concentration
- Oxygen depletion
- Evolved toxic gas constituents
- Thermal energy modeling

During a cabin fire, the combustion process produces particulates known as an aerosol mass. These particulates can cause harm to the crew and obscure their field of vision. Laptops (see Figure D-1) were burned in a 55-ft^3 test chamber by heating the battery packs. Aerosol mass concentration measurements were taken with TSI DustTrak DRX, as shown in Figure D-2. During testing, visible smoke was typically noted 1 to 2 minutes after the start of the test. Smoke began streaming in the 2- to 3-minute timeframe, and the computer laptop was no longer visible at the 4- to 5-minute mark. Figure D-3 shows particulate test data gathered during one of the laptop fire tests.

Figure D-1. Laptop Computer in WSTF Test Chamber

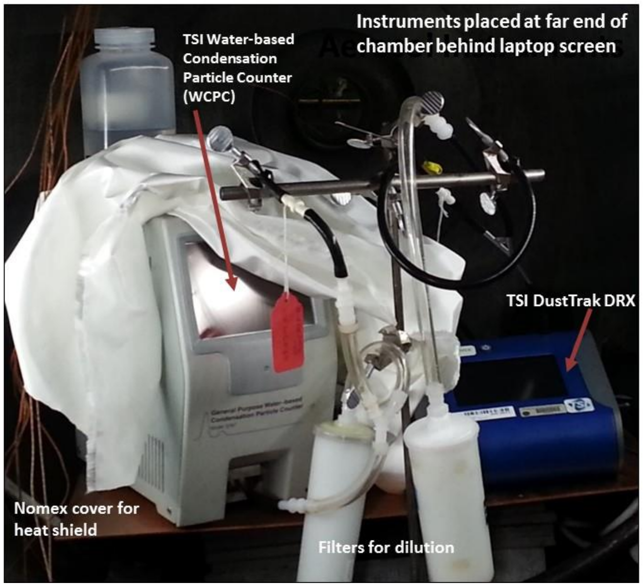


Figure D-2. TSI DustTrak DRX Test Equipment

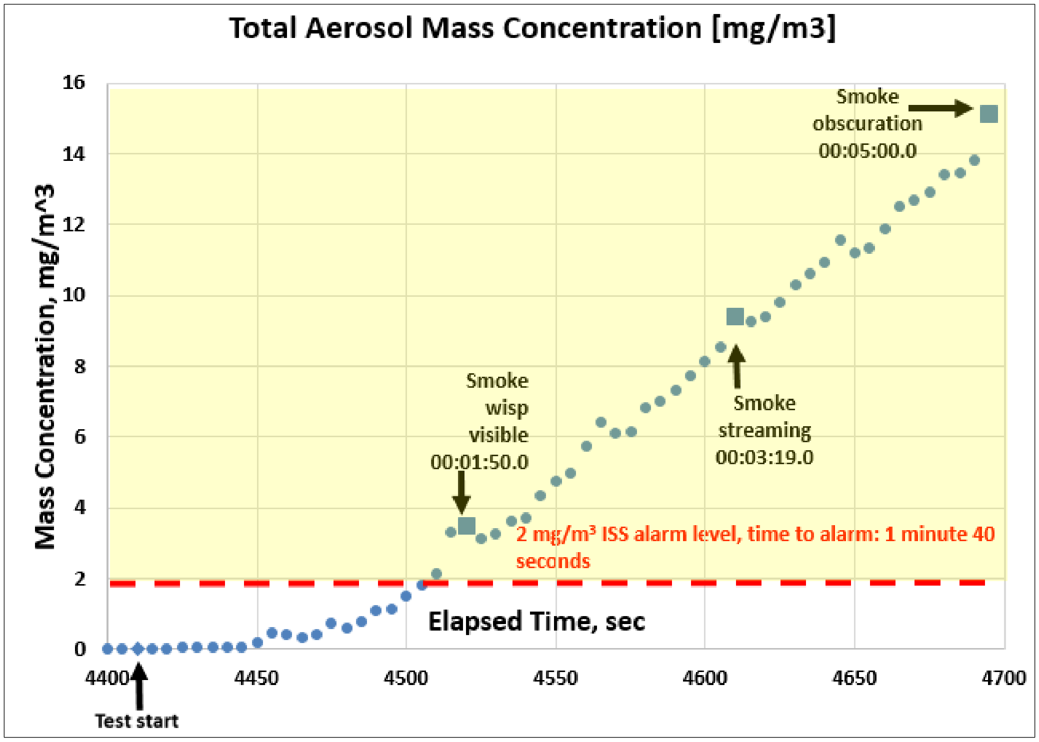


Figure D-3. Aerosol Mass Concentration Test Data, Adjusted for Orion Cabin Volume of 325 ft³

This testing was conducted primarily to understand the relationship between crew mobilization to fight the fire and the state of the particulate concentration environment during that time. Based on an estimated crew timeline starting during their sleep period, the crew would be ready to fight the fire 3 minutes after annunciation of the smoke alarm. This includes a wakeup period, donning of the CBAs, and preparing the OPFE for discharge. During this period, the mass concentration of particulates was less than 16 mg/m^3. To be conservative, the CBA and OSEF hardware is certified for a 50-mg/m^3 particulate environment. Maintaining a concentration of particulates greater than 50 mg/m^3 is achieved by conducting WSTF fire challenge test B, which simulates a moderate avionics fire. Oxygen concentration data from four laptop fires were collected to assess the impact the fire had on oxygen levels in the Orion cabin. Table D-1 shows the results.

Table D-1. Oxygen Concentration during Laptop Fire Tests

Test	Pre-test O_2	Post-test O_2
1	30.12%	27.1%
2	21.25%	20.4%

The conclusion from these tests is that the drop in oxygen concentration during a laptop fire will not impede crewmembers' breathing.

Toxic gas constituent concentrations were measured during computer laptop fires to characterize the cabin environment. These concentrations are important in specifying requirements for the development of fire protection hardware. Three specific concentration profiles are of interest:

1. Hoodspace volume within the CBA mask
2. OFC influent
3. OSEF influent

The cabin environment will drive the permeation of toxic gases through the mask material. The mask must prevent permeation rates such that concentrations of toxic gases in the hoodspace do not rise above specified levels during an 8-hour period. This provides adequate protection for a crewmember's eyes and head.

The OFC must reduce levels of toxic gases below the 24-hour SMAC level for a minimum of 90 minutes per cartridge at a nominal flow rate when exposed to the cabin fire environment. This allows the crew to breathe safely through the OFCs during the fire and during the post-fire cleanup period.

The OSEF must reduce concentrations of toxic gases in the cabin to below the 1-hour SMAC limit in less than 4 hours. When the 1-hour SMAC limit is reached, the crew can doff their CBAs and don their suits.

Analysis of the laptop fire compounds uncovered a specific concern regarding the concentration of C_3H_4O. The testing showed a maximum cabin C_3H_4O concentration arising from a laptop computer fire to be 3.8 mg/m^3. However, the 1-hour SMAC limit for this compound is 0.17 mg/m^3. A potential danger occurs during the period when the crew is unprotected and is in the process of donning the CBA. The JSC Toxicology Group assessed that a brief (i.e., a single breath) exposure to C_3H_4O at a concentration of 4.6 mg/m^3 will not produce any toxicological effects in the human lung. Therefore, the crew likely will not be harmed during the donning of the CBA.

An assessment of the thermal environment was conducted to determine maximum temperature exposures the fire protection equipment may encounter during a fire event. A combination of actual laptop fire test measurements, combined with the development of thermal models, provided insight into the thermal conditions during a fire. The analytical results for the CBA are shown in Figure D-4.

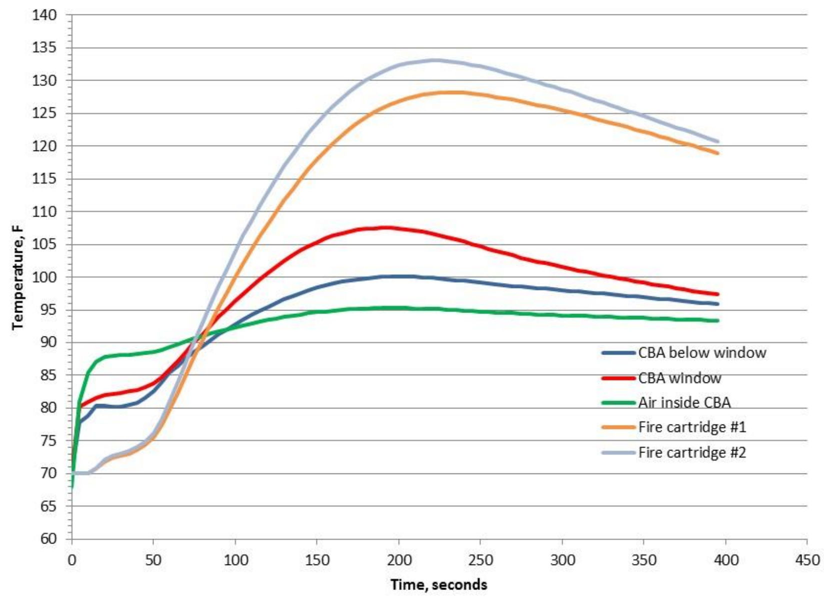


Figure D-4. Analytical Thermal Profile of CBA Exposure Temperatures during Laptop Computer Fire

Similar studies were also performed for the PFE and OSEF. Certification requirements were determined for upper temperature exposure limits during operation as follows:

- CBA: 133 °F
- PFE: 121 °F
- OSEF: 97 °F

Early developmental testing was conducted with the OPFE to determine its efficacy against laptop computer fires (see Figure D-5). Multiple configurations were tested using both water mist and water spray designs. Both technologies successfully extinguished laptop fires in open- and closed-lid configurations. All tests used ~2 lb of water to extinguish the fire. Oxygen environments of 21% and 30% were evaluated.

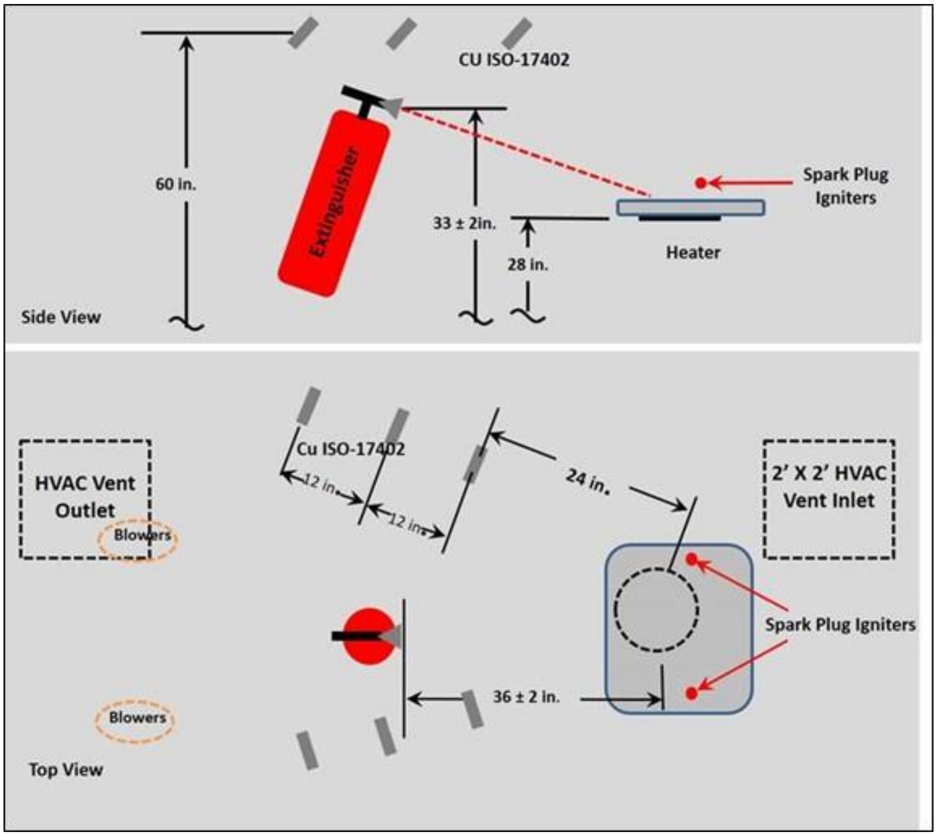


Figure D-5. OPFE Fire Extinguisher Laptop Computer Fire Test Setup at WSTF

D.3 Supertest #1

In September 2018, the Orion GFE hardware development team conducted the first series of integrated tests of emergency equipment for an Orion fire scenario. Included in the test were the following:

- Orion water spray OPFE
- Orion CBA (including OFCs)

Figure D-6 shows the OPFE and the CBA. The purpose of the test was to assess the performance of this hardware when exposed to a laptop computer fire. The configuration of the key hardware for the test is shown in Figure D-7.

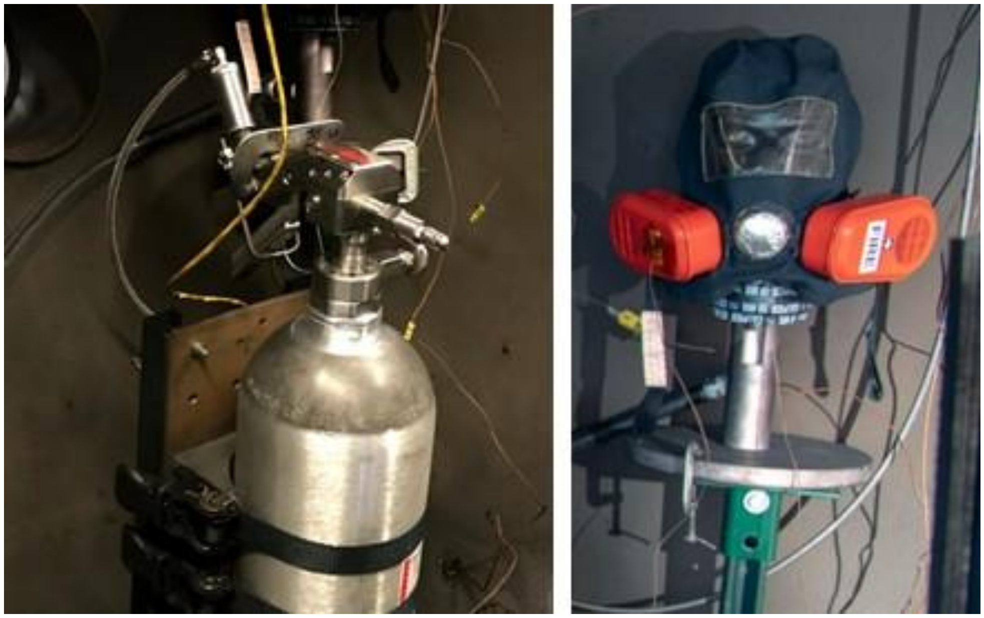


Figure D-6. Supertest #1 Test Articles (left, remote activation PFE; right, CBA headform)

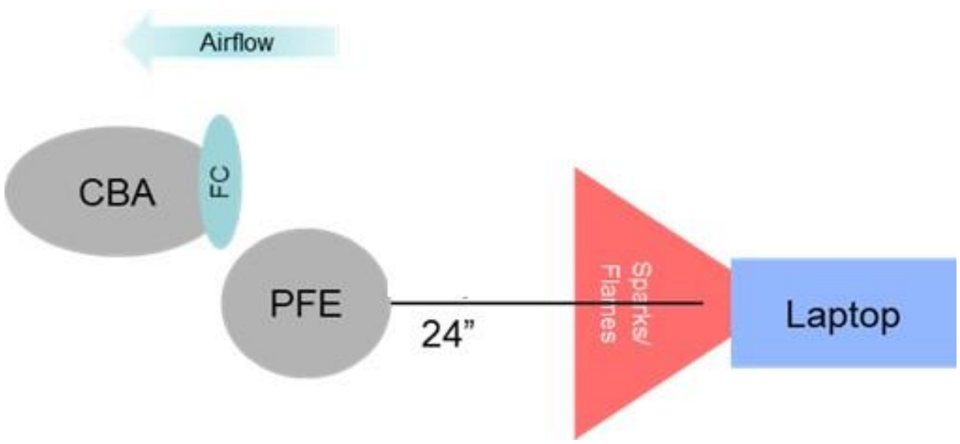


Figure D-7. General Configuration of Test Articles in Supertest #1

The key findings for this test series were:

- The OPFE was able to extinguish all laptop fires.
- Introduction of OPFE water spray into the environment caused CBA FC clogging with both tested laptops. Airflow restriction was observed 6 to 7 minutes after simulated CBA donning.
- The Dell XPS laptop produced significantly more particulate and quantities of toxic gases than the Surface Pro laptop.

D.4 Supertest #2

In June 2019, a second test series was undertaken to conduct integrated testing with a larger complement of Orion emergency equipment. Included in the test were:

- OPFE
- Emergency mask with FCs
- FC prefilters
- OSEF

The testing was conducted in a closed chamber at WSTF. The FC prefilters and the OSEF were not part of Supertest #1. The chamber was configured with the hardware as shown in Figure D-8.

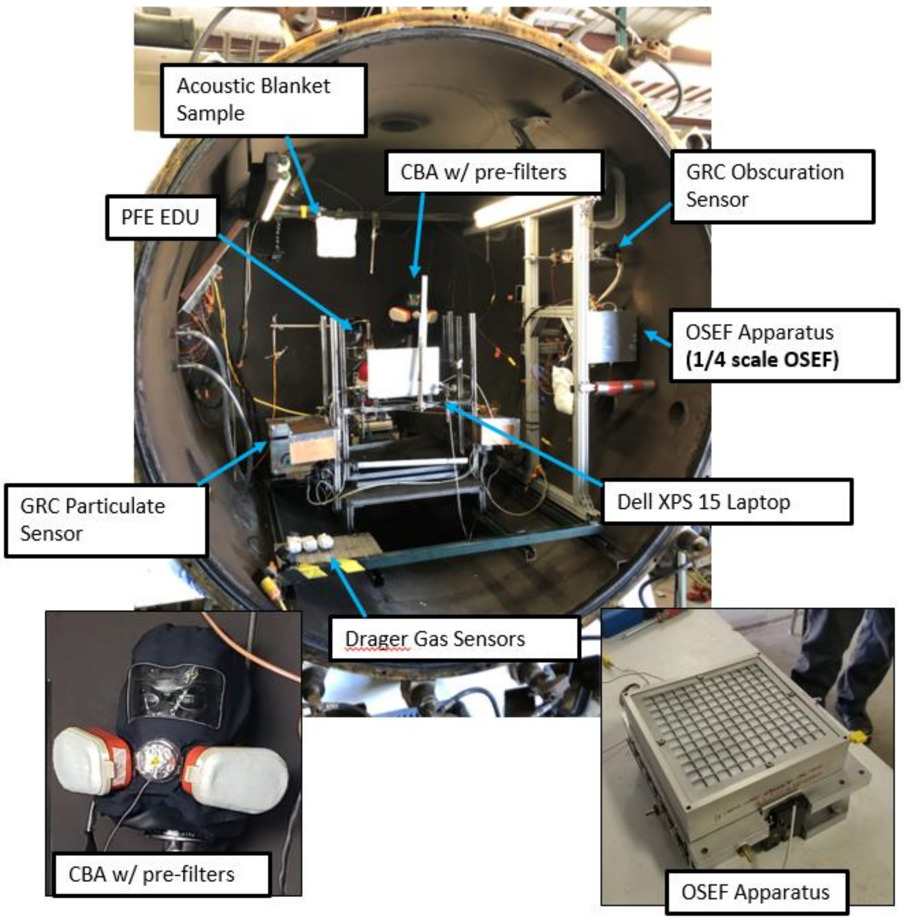


Figure D-8. Supertest #2 Test Configuration at WSTF

A prefilter for the OFC was developed based on the results of Supertest #1. The function of the prefilter is to extend the life of the OFC. One of the objectives of the Supertest #2 was to assess the effectiveness of the prefilter.

The six key test configurations are shown in Table D-2. A ¼-scale OSEF was used in place of a full-scale unit. Performance results were assessed accordingly. The Orion Program is considering flying one of two different laptop models, a Surface Pro or a Dell XPS 15. Both were tested during this test series. Sealed and unsealed OFC prefilters also were tested (see Figure D-9).

Table D-2. Supertest #2 Key Test Configurations

Test	Laptop	Ignition Method	PFE Used?	Prefilter Seal?
1	Surface Pro	Patch heater	Yes	No
2	Surface Pro	Burner	Yes	No
3	Dell XPS	Burner	Yes	Yes
4	Dell XPS	Patch heater	Yes	Yes
5	Surface Pro	Burner	No	Yes
6	Dell XPS	Burner	No	Yes

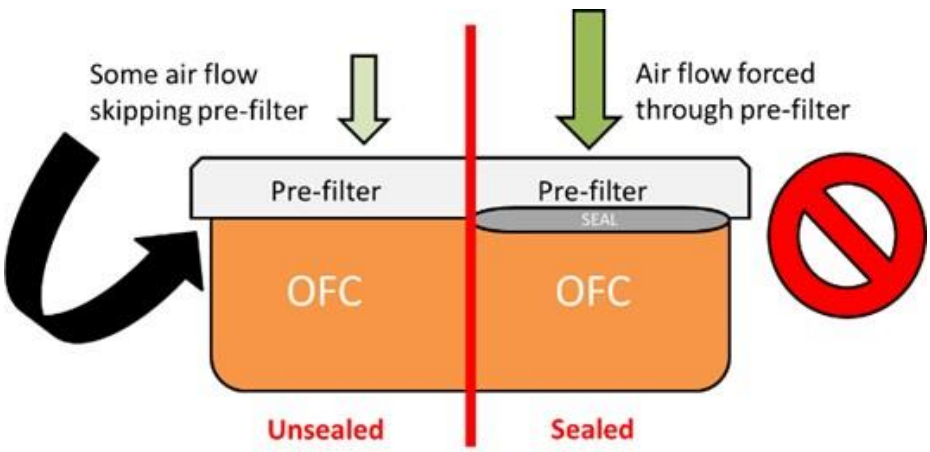


Figure D-9. Two OFC Prefilter Test Configurations

For each test performed, the test operations were conducted per the timeline shown in Table D-3.

Table D-3. Supertest #2 Operations Timeline

Operation	Time
Begin laptop battery heating	–
Open flame observed	0
CBA and/or PFE initiation	Open flame +30 sec
PFE depletion start	PFE initiation +40 sec
PFE operations complete	PFE depletion start +30 sec
OSEF operations start	PFE operations complete +30 sec
Test end	OSEF start operations +120 min

A fire that is not extinguished with an OPFE creates a significantly worse environment for particulate and some toxic gases due to the uninterrupted combustion process (see Table D-4). The OSEF must work harder to scrub more CO and particulate, while suffering from catalyst poisoning occur due to the higher ammonia concentration. Temperatures in the environment are higher without using a PFE, as thermal runaway is not hindered and more battery cells are able to ignite. The notable increase in CO_2 concentration is mostly attributed to laptop combustion, as levels sharply increase at combustion and only rise slightly as the test continues. These results demonstrate how the presence of a PFE affects particulate and toxic gases evolving from a Dell XPS 15 laptop battery fire.

Table D-4. Results Comparing PFE Use versus no PFE Use

Data Type	**With PFE** 19-47720 D – 3/6	**Without PFE** 19-47724 D – 6/6	**Delta**	**Ratio (No PFE/PFE)**
CO	148 ppm	740 ppm	592	5.00
HCN	3.4 ppm	3.0 ppm	–0.4	0.88
HCl	5.0 ppm	1.2 ppm	–3.8	0.24
Ammonia	35 ppm	77 ppm	42	2.2
CO_2	0.43%	1.58%	1.15	3.67
O_2 (min)	19.6%	18.2%	–1.4	0.93
Particulate	384 mg/m^3	1016 mg/m^3	632	2.65
CBA temp	100.25 °F	103.85 °F	3.6	1.04
Env. temp	170.45 °F	257.49 °F	87.04	1.51

The OSEF toxic compound scrubbing performance was evaluated in four of the six test runs. Toxic compound concentrations did not tend to reach 1-hour SMAC values (see Table D-5). A ¼-scale OSEF test successfully scrubbed compounds below their 1-hour SMAC when a PFE was used. However, the OSEF failed to scrub the cabin of CO (see Figure D-10) below its 1-hour SMAC when the OPFE was not used and the Dell XPS 15 experienced full thermal runaway (i.e., 6 out of 6 (6/6) battery cells igniting). This was likely due to catalyst poisoning from an approximately twofold increase in ammonia concentration.

Table D-5. OSEF Total SMAC Performance

Test No.	Ignition	PFE	SMAC	CO	HCN	HCL
19-44720	D – 3/6	YES	1 hour	-	-	<1
			24 hour	15	-	1
			7 day	47	120+	1
19-47722	S – 1/4	YES	1 hour	-	-	-
			24 hour	-	-	-
			7 day	22	15	-
19-47724	D – 6/6	NO	1 hour	120+	-	-
			24 hour	120+	-	-
			7 day	120+	120+	7
19-47725	D – 1/6	YES	1 hour	-	-	-
			24 hour	19	-	-
			7 day	68	99	-

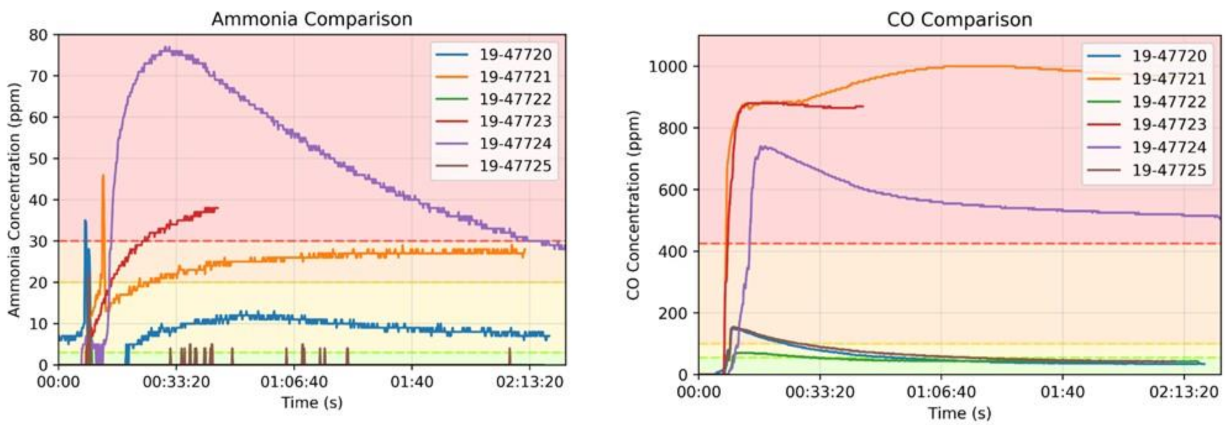


Figure D-10. OSEF CO Scrubbing Performance

The OSEF filter assembly, when configured with the primary filter and prefilter C, had the following average performance parameters when an OPFE was used:

- Particulate scrubbing: ~10 mg/m^3/min (max. 330 mg/m^3)
- 50 mg/m^3 scrubbing time: ~25 minutes

Figure D-11 shows the particulate scrubbing profile when the OSEF was challenged with cleanup from a Dell XPS 15 fire.

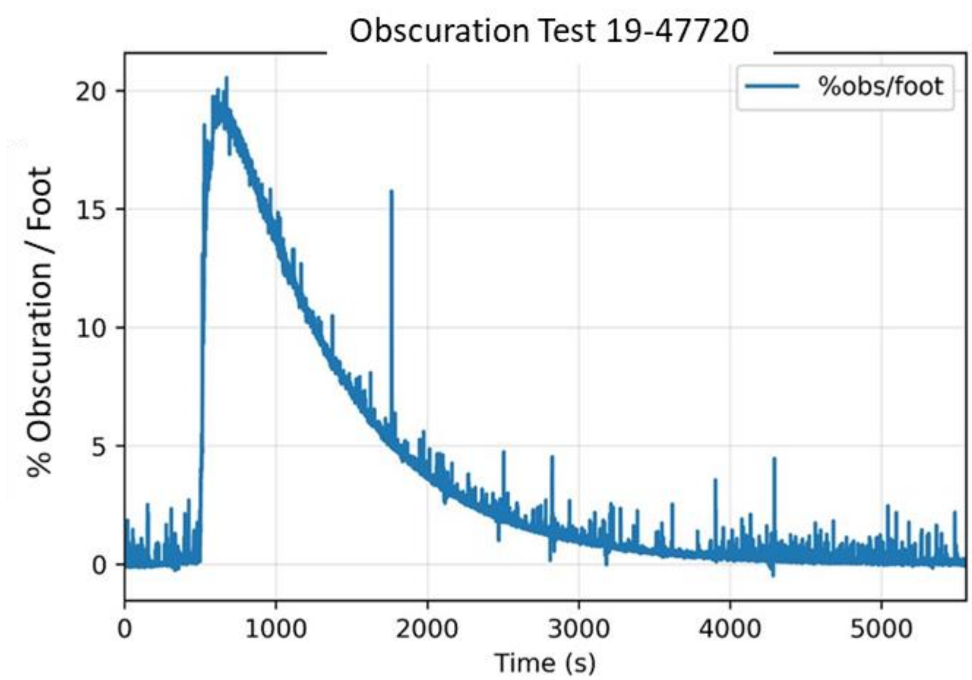


Figure D-11. OSEF Particulate Scrubbing Profile

The FC prefilter was first tested without a gasket or "seal" between the FC and the prefilter interface and did not clog in the baseline test 19-47722, but did clog in test 19-47721, which produced more RH% (see Table D-6). Particulate data were not captured for this test.

After a seal was added to the prefilters, no clogging was observed for the remainder of the tests, except for a single cartridge clog in an extreme ignition test where one cartridge was exposed to a larger concentration of smoke and flames. In this test, the pressure differential lingered slightly below the 150-mm H_2O clog value, and the flow rate dropped to about 30 to 40 lpm.

Table D-6. Summary of CBA Performance

Test No.	Ignition	FC Config.	OSEF	PFE	Max. Particulate (mg/m3)	Max. (RH%)	Clog Time (min)
19-47720	D – 3/6	Class III, Pre: Seal	Prim, Pre: C	YES	384.0	-	None
19-47721*	S – 4/4	Class III, Pre: No seal	Pre: Graf	YES	-	88.9	16.5 min*
19-47722	S – 1/4	EDU, Pre: No seal	Prim, Pre: C	YES	-	69.8	None
19-47723**	S – 4/4	Class III, Pre: Seal	Pre: P100	NO	1134.8	35.9	None**
19-47724	D – 6/6	Class III, Pre: Seal	Prim, Pre: C	NO	1016.4	50.7	None
19-47725	D – 1/6	EDU, Pre: Seal	Prim: Pre: C	YES	268.0	88.2	None

**No flame, only white smoke*
***Extreme ignition; one cartridge clogged*

Permeability of the CBA hood was evaluated. No indications of toxic gas breakthrough were observed beyond the 7-day SMAC in a 90-minute toxicity sample analysis. Table D-7 shows the results of the CBA hood permeability testing.

Table D-7. CBA Hood Permeability Test Results

Gas	Environment (mg/m3)	Inside CBA (mg/m^3)	SMAC (mg/m^3)
2-Methylpropenal	-	0	0.4
Acetaldehyde	-	0	4
Acrolein	-	0	0.03
Acrylonitrile	-	0.006	0.4
Benzene	-	0.005	1.5
Carbon monoxide	54.7	0	63
Formaldehyde	-	0	0.12
Hydrogen cyanide	1.2	0	1.1
Methyl nitrite	-	0	7.5

The thermal environment during the testing was evaluated. Figure D-12 shows the proximity of thermocouples in relation to the laptop and the CBA.

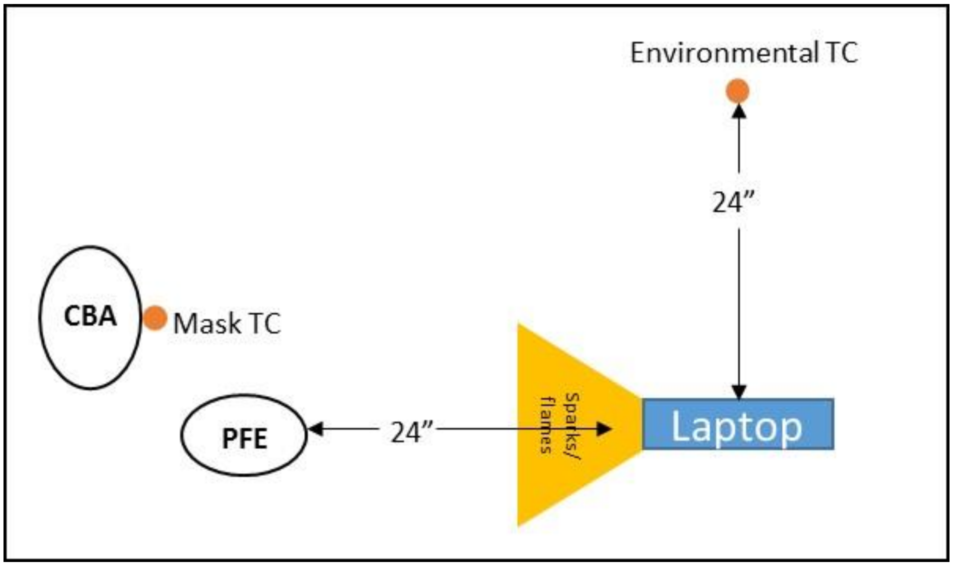


Figure D-12. Thermocouple Test Configuration

Testing revealed that the rise in temperature is directly related to the number of cells ignited. Maximum temperature rise inside the CBA during a Dell XPS 15 fire was 22 °F. The maximum temperature rise inside the CBA during a Surface Pro fire was 7 °F. Figure D-13 shows the relative temperature rises for several tests.

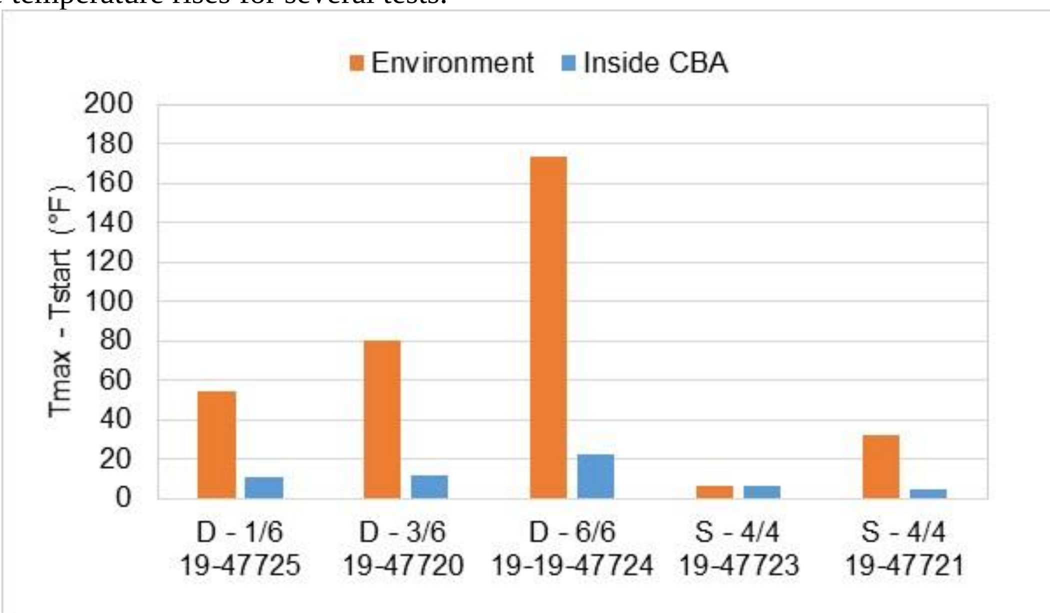


Figure D-13. Internal CBA Temperatures

Key conclusions drawn from the Supertest #2 campaign were:

- The OPFE successfully extinguished all fires.
- An external FC prefilter with a sealed interface substantially increased the life of the FC. No clogging was observed in the FC for 120 minutes in all tests where a sealed prefilter was used.
- An external prefilter and OFC with no seal lasted 120 minutes in the baseline environment without clogging.

- When larger numbers of laptop cells were ignited, higher concentrations of toxic gases, increased particulate densities, and greater production of thermal energy were observed.
- The larger the number of laptop battery cells ignited, the more likely the ammonia concentration was to reach levels capable of potentially poisoning the OSEF CO oxidation catalyst.
- The CBA FC cartridge showed no indications of toxic gas breakthrough exceeding the 7-day SMAC in a 90-minute toxicity sample analysis.
- Baseline test conditions did not tend to produce CO, HCN, and HCl quantities above the 1-hour SMAC.
- The OSEF successfully scrubbed gases down to the 24-hour SMAC for CO, HCN, and HCl in most tested cases, significantly below the 1-hour SMAC. However, there was one test case of suspected CO oxidation catalyst poisoning due to the presence of up to 70 ppm of ammonia.

REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
04/16/2021	Technical Memorandum	

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Risk Reduction of Orion Multi-Purpose Crew Vehicle (MPCV) Program Government-Furnished Equipment for Environmental Control and Life Support (ECLS)	
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	**5d. PROJECT NUMBER**
Cragg, Clinton H.; Graf, John C.; Hobbs, Alan	
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
	869021.01.23.01.01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
NASA Langley Research Center Hampton, VA 23681-2199	NESC-RP-14-01012
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
National Aeronautics and Space Administration Washington, DC 20546-0001	NASA
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	NASA/TM-20210013869

12. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category Space Transportation and Safety
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The NASA Engineering and Safety Center (NESC) was requested to conduct technical risk-reduction activities for safety-critical government-furnished environmental control and life support (ECLS) equipment for the Multi-Purpose Crew Vehicle Program. These items include the post-landing anomaly gas monitor, the in-flight anomaly gas monitor, the emergency breathing mask, the 144-hour in-suit survival capability, the portable fire extinguisher, the smoke eater, and the post-landing carbon dioxide control system. This document contains the outcome of the NESC assessment.

15. SUBJECT TERMS

Environmental Control and Life Support; NASA Engineering and Safety Center; Multi-Purpose Crew Vehicle; Government Furnished Equipment

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	UU	146	(443) 757-5802