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Literature Review on Spaceport Fire Safety

FINAL REPORT BY:

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FOREWORD

Commercial space travel has developed in the United States to the point where multiple spaceports have been constructed or are under construction. Commercial space travel is projected to be a billion-dollar industry and there are currently no guidelines addressing the specific hazards presented by spaceports that go beyond what is anticipated at airports covered by the NFPA series of standards (e.g., NFPA 403, 407, 418). With plans for several more spaceports in the works, NFPA standards currently address model rockets, mid-sized rockets, and several aircraft, but that is where the NFPA coverage ends. There are several major companies that have invested heavily into space missions, launch facilities and become major providers of low orbit missions. They are looking for guidance covering the launch of satellites, unmanned as well as manned space missions, space planes, rockets, and capsules.

The goal of this project is to compile information that relates to the fire hazards associated with spaceports through a literature review. This project is comprised of the following tasks:

1. Literature review of any available standards or guidance for fire protection related to spaceports.
2. Summarize incidents (fires, explosions, etc.) which have occurred at spaceports or similar facilities.
3. Document the fire hazards related to these facilities and the knowledge gaps that exist.
4. Compile the information in a report.

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About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

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Executive Summary

A literature review of the fire protection and safety-related codes and standards applicable to commercial spaceports was performed under the auspices of the Fire Protection Research Foundation (FPRF). In compiling this report, codes and standards from the NFPA, NASA, ISO, FAA, the Air Force, and DoD were reviewed. Based on this review, key knowledge gaps were identified, and recommendations made. There are several NASA documents on astronaut safety and requirements, but these were not covered in the scope of the review.

Currently, there are no NFPA standards made specifically for spaceports, or in general for large-scale rocket launches. The NFPA series dealing with rockets, NFPA 1122-1127, deals mainly with model hobby rockets and not large commercial rocketry. Commercial spaceflight operations, specifically in spaceports, are subject to different oversight compared to a government launch site. For federal launch facilities, codes are typically custom-tailored to the launch site based on DoD standards and do not always apply to commercial entities operating on site. On non-federal sites, local Authorities Having Jurisdiction (AHJs) may not have the resources or experience to evaluate launch hazards. Storage of common rocket fuels, such as liquid oxygen (LOX), are covered in NFPA standards, however operating procedures for fueling (loading) are not. There are standard procedures used, such as removing all staff from the area while fueling, but these are not part of the public standards at this time.

Many other topics are relevant to spaceport fire safety. For instance, the need for specialized firefighter PPE and protection plans is noted for airports and certainly applies to spaceports, however the specific types of PPE required are not specified and left to local decision makers. Due to the nature of the hypergolic and toxic fuels that can be used, nonstandard PPE may be required for some firefighting response operations. A similar situation exists with firefighting requirements and tactics. Current standards require a site safety and security plan, notification of local authorities, etc., however details on the implementation of these measures is not specifically addressed. Overall, site considerations are more complex on a commercial platform compared to a controlled government facility and there are not many guidelines on how to address these issues.

Our conclusion is that additional resources should be provided for commercial spaceport operators and AHJ's to assess local hazards. Many of these guidelines exist in NASA or DoD standards or technical documents, however these need to be publicly accessible so that they can be adopted and used where needed. A new standard covering commercial spaceports which synthesizes this information, as well as more resources for local officials, could improve the process of safeguarding these new facilities.

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Background

Over the past two decades commercial space transportation has seen an incredible rate of growth around the world, especially in the United States. A number of commercial ventures have been working on commercial space launches, the most well-known include SpaceX, Virgin Galactic, and Blue Origin, while traditional ventures such as Orbital ATK and United Launch Alliance continue to conduct launches primarily for the U.S. Government. With the increase in entities planning to launch, there has been growing interest to develop commercial spaceports to facilitate launch and reentry of a variety of space vehicles. Commercial space travel is projected to be a billion-dollar industry and yet there are currently no public guidelines addressing the fire hazards presented specifically by spaceports.

This report reviews the current literature including available standards and guidance for fire protection in spaceports, accidents (fires, explosions, etc.) occurring at spaceports or similar facilities, and documents these fire hazards and the knowledge gaps that exist. While there are existing standards in the NPFA 400 series covering airports, many hazards go beyond what is anticipated at airports and may require additional protection schemes or multi-hazard analyses. Unlike the airport industry, much of the onus for safety is put on the vehicle operators. Of particular attention in this review will be what standards are available in public sources, e.g. NFPA, FAA, or ISO standards, vs. government regulations, e.g. from NASA or the Air Force, that do not apply to commercial installations or commercial operations on government facilities but are currently used to ensure the safety of staff, visitors, astronauts, and participants in the spaceflights at operational launch and/or reentry facilities. Note that the codes, standards and regulations presented throughout this report are the most current at the time of writing with all editions noted in the references at the end of the report.

Current Spaceports

The Office of Commercial Space Transportation, a division of the Federal Aviation Administration (FAA), oversees licensing of commercial spaceports. As of February 9, 2018, there were 10 active launch site operators with a current license, shown in Table 1. With growing interest in this area, there are dozens or more plans in the works for future commercial launch sites. 2017 was a record year, with 23 commercial launches. With additional launches of both manned and unmanned cargos for governments on top of commercial needs, there is a growing market for space travel. Spaceports may also provide operations beyond launches or reentries. For instance, in McGregor, Texas SpaceX performs a number of static rocket tests that may require similar safety measures to launches.

Table 1: Active launch site operators in the United States[1].

Operator	Site	Location
Virginia Commercial Space Flight Authority	Wallops Flight Facility	VA
Harris Corporation	California Spaceport	CA
Oklahoma Space Industry Development Authority	Burns Flat, Oklahoma	Oklahoma
Space Florida	Cape Canaveral Air Force Station	Florida
Houston Airport System	Ellington Airport	TX
Jacksonville Aviation Authority	Cecil Field	Florida
Midland International Airport	Midland International Airport	TX
Mojave Air & Spaceport	Mojave Air & Spaceport	CA
New Mexico Spaceflight Authority	Spaceport America	New Mexico
Alaska Aerospace Development Corporation	Pacific Spaceport Complex Alaska	Alaska

[1] https://www.faa.gov/data_research/commercial_space_data/licenses/#operatorLicenses

Each of the current spaceport sites in Table 1 currently has their own form of fire and other safety measures. However, except for those located on federal lands (e.g. Space Florida), there are no universal standards available to operators or AHJs to ensure safety.

Diversity of Propellants

While there are a variety of hazards on spaceports, the most commonly thought of relates to the storage and launch of rockets with highly combustible propellants (fuels). The processes of fueling, launch, and re-entry have long been the most dangerous operations in spaceflight. In terms of ground hazards, the process of storing propellants, fueling launch vehicles and, now with the advent of controlled return vehicles, ensuring safety during landing is critical. Protection of both life safety and minimizing potential damage to the vehicle, the launch site, and surrounding areas all plays a role in this process. With the advent of commercial space travel, the variety of launch vehicles being considered and used is drastically expanding. Similarly, the variety of propellants used is changing rapidly. This list is not considered to be exhaustive in terms of the diversity of currently used and potential future propellants or the hazards associated with them.

Standard rocket propellants include liquid mixtures of an oxidizer and fuel. The oxidizer is typically liquid oxygen (LOX) and a highly refined kerosene (RP-1). This formulation is used, for instance, by SpaceX on the Falcon rocket, United Launch Alliance's Atlas 5 and was used on the Saturn V rockets that took astronauts to the moon. Other variations have included LOX/liquid hydrogen and nitrogen tetroxide/hydrazine combinations. LOX/liquid hydrogen was used, for instance, on the space shuttle and is still in use on the Delta IV and Ariane 5. Certain rockets have recently been developed that use LOX and liquid methane, including Blue Origin's BE-4 engine and SpaceX's Raptor series of rockets. Liquid methane is being pursued due to its higher density and ability to be stored more easily in a smaller space. Current standards exist for the storage of liquid methane (e.g. NFPA 59A), however these have been developed for traditional liquefied natural (LNG) operations, which may differ from the processes used in current or future space vehicles (e.g. supercooling).

Another approach to liquid propellants is a monopropellant, e.g. a mixture which already has an oxidizer mixed into the fuel. Monopropellants, such as hydrogen peroxide, hydrazine, and nitrous oxide, are not used as commonly in launch vehicles due to safety concerns; however, they are still critical for attitude control in spacecraft in lower quantities. A variety of hazards are encountered with these monopropellants, therefore, during payload preparation, storage, transport, launch and recovery. Special considerations must be made for personnel safety around these fuels, however sometimes these can arise in conflict with traditional safety procedures.

Solid rocket propellants, while not commonly used at present due to their lower performance and lack of control after ignition, have been heavily used in the past as a rocket propellant primarily as a booster to larger liquid-fueled rockets (e.g. the space shuttle's two solid-rocket boosters (SRBs)). Solid propellants typically consist of a solid oxidizer in a polymer binder with flakes of energetic compounds intermixed. Many orbital launchers have used solid propellants as boosters. The space shuttle, for instance, used two solid rocket boosters to provide additional thrust during the first stage of launch. They may also be used in later stages of a rocket. The major disadvantage of a solid rocket fuel is that there is a lack of control once ignited, however new hybrid rocket designs, which feature a liquid or gas oxidizer flowing past a solid propellant, would alleviate some of these concerns and have been considered for future designs.

With the growth of the commercial space travel industry there has been increased focus on new propellant formulations such as supercooled propellants, hybrid engines, etc. With all the changes in propellant formulations emerging it is important to keep in mind that standards developed should be flexible enough to adapt to a rapidly changing market.

Hazards and Related Incidents

Almost half a dozen spacecraft accidents and failures have been reported in the news over the past few decades, however most of these reported failures have occurred during fueling, launch, or landing of space vehicles. While these activities are critical for safety, most fire and life safety hazards that occur on launch sites relate to more traditional issues such as storage of flammable materials, active and passive fire suppression, egress, etc. There are, of course, a wide variety of additional issues to be covered specifically in spaceports as well

Fire and life safety have always been a serious consideration in operation of spaceports. With the advent of commercial spaceports, including commercial use of government-owned launch sites, there is perhaps a greater risk for fires because of the changing composition and uses of volatile fuels, gaps in standards, and the infancy of the industry. For all spaceports, the presence of powerful ignition sources used during launch procedures combined with the surrounding highly combustible components of propellants create the possibility for significant losses in the case of accidental fires and explosions. Currently, there are no NFPA standards on fire and life safety procedures written specifically for spaceports, however, researching past incidents can provide us with a better understanding of regulations that should be implemented at spaceports to prevent the same incidents from happening in the future. Presented here are only a few noteworthy accidents, primarily occurring during fueling or launch, to highlight some safety hazards unique to spaceports. The focus on incidents solely where the launch vehicle was involved was not because other hazards do not exist at launch sites, but rather because documentation was widely available only for these major incidents. Later in the report we suggest the adoption for additional reporting and tracking of incidents and close calls.

Selected Incidents

On July 26, 2007 an explosion occurred on the test stand at the Mojave Air and Spaceport killing three Scaled Composites employees and injuring three others. They were performing an oxidizer cold-flow test meant to be part of Virgin Galactic's SpaceShipTwo rocket when the accident occurred. The cause of the accident was not clearly identified in the report following the accident, however this highlights the need for on-site safety measures during fueling, launch, and recovery[2]. Even though this was a cold-flow test where the Nitrous Oxide used was not supposed to ignite, for some unknown reason it ignited.

In October 2014 an Orbital ATK Antares rocket exploded soon after liftoff resulting in an explosion that caused significant damage to the area surrounding the launch site. The failure appeared to occur due to an explosion in a liquid oxygen turbopump in the rocket's first stage. The damage to the launch site at the Mid-Atlantic Regional Spaceport (MARS) on Wallops Island, Virginia was estimated to be $15 million[3].

In 2015, SpaceX's Falcon 9 exploded on the launch site at the Cape Canaveral Spaceport in Virginia. The spacecraft, intended to launch a satellite into space, exploded during a

[2] http://knightsarrow.com/wp-content/uploads/2012/12/Full-OSHA-report-of-60-pages-0003_rotated.pdf
[3] http://spacenews.com/report-finds-commercial-spaceports-confused-about-insurance-requirements/

static fire test of the rocket's engines while on the ground. It was determined that an issue with a pressure vessel in the second-stage liquid oxygen tank caused the explosion[4]. Due to safety procedures, no one was on site during the explosion and no injuries or fatalities were reported, *emphasizing the need for strict Standard Operating Procedures adhering to the qualifications for licensing*. One unique aspect of the Falcon 9 is that SpaceX uses oxygen cooled to lower temperatures than what is used in other rockets to increase its density and save space, however it is closer to the temperature at which oxygen solidifies. Many commercial companies have unique or proprietary techniques such as new propellant formulations and recoverable rockets that land back on earth, potentially bringing diverse safety concerns not faced before.

There are a number of more minor, non-newsworthy incidents such as small processing fires, most of which occur during fueling operations. It is difficult to find data for these incidents due to the commercial nature of the operations. While the FAA does require reporting of these accidents; the authors of this report were not able to find a database of these incidents. NASA, however, maintains a Lessons Learned section of their website for small incidents[5], which is useful to find incidents which occur on government launch sites. While some commercial spaceports have incident reports, and publishing such reports is beneficial to the company, there is no requirement for them. There is little information on minor incidents that happen at commercial spaceports available to the public.

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[4] https://www.spacex.com/news/2016/09/01/anomaly-updates
[5] https://llis.nasa.gov/

Codes and Standards Reviewed

In this section, we provide a bullet list of codes and standards which were reviewed during this study. Documents from the National Fire Protection Association (NFPA) and the National Aeronautics and Space Administration (NASA) are the primary sources used. NASA is a government organization that operates space launch vehicles and participates in the function of running launch sites, though these are usually officially part of a military or federal government facility. NFPA is a private, not for profit organization that writes safety standards which are used by local, state and national governments. They are created by a committee process with broad input from different groups. For this report, we reviewed NFPA 30, 55, 400, 403, 407, 418, 495, 600, 1125, and 1127 as well as documents from the International Standards Organization (ISO), the Federal Aviation Administration (FAA), the National Aeronautics and Space Administration (NASA), and the United States Air Force (USAF), part of the Department of Defense (DoD). A summary of these codes and standards and the topics they cover is given in Table 2.

- **NFPA 30** is the Flammable and Combustible Liquids Code. It applies to the storage, use, and handling of flammable or combustible liquids, including most common spacecraft fuels.
- **NFPA 55** is the Compressed Gases and Cryogenic Fluids Code. It applies to the storage, use, and handling of cryogenic fluids, including liquid oxygen.
- **NFPA 400** is the Hazardous Materials Code, which applies to the storage, use, and handling of cryogenic fluids, compressed gases, corrosive solids and liquids,

and a host of other hazardous properties. This covers 2 major fuels: LOX and hydrazine.

- **NFPA 403** is the standard for Aircraft Rescue and Fire-Fighting Services at Airports. It gives instructions as to the standards required by airport fire services, such as arrival time.
- **NFPA 407** is the standard for Aircraft Fuel Servicing, which applies to fuel servicing of all aircraft using liquid petroleum fuel. RP-1 technically falls under this category.
- **NFPA 418** is the standard for Heliports and applies to heliports and rooftop hangars. For the most part, it isn't particularly applicable to rockets.
- **NFPA 472** is the Standard for Competence of Responders to Hazardous Materials/Weapons of Mass Destruction Incidents. This applies to the response of firefighters to hypergolic propellants.
- **NFPA 495** is the Explosive Materials Code (2013 edition). It applies to the storage, use, and handling of explosive materials. However, it has a few exceptions: the code does not apply to high-powered rocketry or model rocketry, and instead tells the user to follow NFPA 1122, 1125, or 1125, depending on the situation. In addition, the code does not apply to the transportation and use of explosive materials by federal, state, or municipal agencies when engaged in normal or emergency activities. It covers hydrazine.
- **NFPA 1125** is the standard for the Manufacture of Model Rocket and High-Power Rocket Motors. This code is exclusively tailored to hobby model rockets, and has restrictions as to the maximum imparted impulse the rocket can have.

- **NFPA 1127** is the standard for High Power Rocketry. The code is tailored exclusively to large model rockets, and has restrictions as to the maximum imparted impulse the rocket can have.
- **NFPA 1620** is the Standard for Pre-Incident Planning. It is general and not specific to spaceports.
- **NFPA 1710** is the standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments.
- **NASA 8719.11** is the NASA fire safety code. This code outlines NASA minimum fire protection requirements and is enforced at all NASA spaceports. It should be noted that this code makes several references to the NFPA codes listed above.
- **ISO 14620** (Space Systems Safety Requirement) is the ISO standard for facilities that launch objects into space. The document covers measures designed to protect ground and air crews and the general public. All ISO codes come from and are used in Europe.
- **ISO 14624** is a 7-part document that covers several tests for the safety and compatibility of materials in space systems. These tests are designed to let engineers know the key qualities of materials they may use in the design of a spaceport.
- **ISO 17666** is the standard that describes risk management in space systems. The standard provides a skeleton framework for determining and managing the risks associated with the operation of a spaceport.

- **The Air Force Space Command Manual 91-710** covers the United States Air Force's safety procedures for the operation of facilities that launch objects into space. Topics covered include fuel storage and fire detection.
- **CFR: TITLE 14—Aeronautics and Space, Chapter 3 Part 400—Commercial Space Transportation**. The document covers the process for acquiring the permit and launch license from the FAA needed to operate a spaceport. Part 420 of the document discusses handling and storage of fuels in addition to safety plans for the site.
- **UFC 3-600-01** is the general fire protection code for DoD facilities. The code lays out criteria for fire protection systems including detection and suppression.

Of note is that human spaceflight requirements are considered beyond the scope of this report. The focus is solely on the launch site and regulations required for commercial operators which, for the most part, apply for both manned and unmanned launches. Certainly, human spaceflight considerations will this may be necessary as part of an overall safety approach. Readers are referred to Pelton et al., 2010 for more information on human spaceflight safety standards.

	NFPA Standards												ISO			DoD	Air Force	FAA	NASA
Topic	**30**	**55**	**400**	**403**	**407**	**418**	**472**	**495**	**1125**	**1127**	**1620**	**1710**	**14620**	**17666**	**14624**	**UFC Criteria**	**Manual**	**CFR-FAA**	**8719.11**
Fuel Storage and Fueling																			
Storage of Fuels (LOX)	■	■	■		■	■			■								■	■	■
Storage of Fuels (RP-1)	■		■		■				■								■	■	■
Storage of Fuels (hydrazine)			■		■			■	■								■	■	■
High energy fuels								■	■									■	■
Fueling			■		■			■											
Reinforced Materials						■		■											
Emergency Response and Planning																			
Spaceport Emergency Planning	■	■	■	■	■	■		■			■							■	■
communication	■	■	■										■					■	■
Firefighter PPE				■			■												
Firefighter tactics	■						■	■				■							■
Fire station location and capability			■	■		■						■							■
Training Requirements																			
Training requirements	■	■	■	■	■			■				■	■						■
Building Requirements																			
Electrical wiring and equipment	■	■	■		■				■				■		■		■		■
Rocket Hangars						■													■
Suppression																			
Extinguishing agents	■	■	■	■		■											■		
Hand Portable Fire Extinguishers	■				■	■		■											■
Launch Requirements																			
Manned vs Unmanned flights										■								■	
Launch and Recovery										■								■	
Risk Management																			
Saftey of visitors and employees											■		■	■				■	
Site security	■	■	■		■			■	■									■	
Brush management	■	■	■															■	

Table 2: Topics covered by relevant commercial spaceport safety standards and regulations. Applicable codes and standards to each topic are highlighted.

Emergency Response and Planning

Emergency protocols vary from spaceport to spaceport, but the majority of regulations involving the storage and use of common fuels and propellants require implementation of and training for an emergency action plan. NFPA 30, 55, 400, 403, 472, and 495 all independently require the implementation of an emergency action plan, with the exact requirements for the action plan differ depending on what fuel is being used or processed.

Emergency response teams must also be on hand and know what to expect with all the diverse hazards on site. This may include proper equipment and training to handle any emergency situation that may occur. Many of these emergency response protocols may overlap with current standards for airports, but there are many factors unique to spaceports that should be accounted for. A summary of what is covered in current regulations related to emergency response and planning is shown in Table 2.

Common aspects of emergency action plans include procedures to be followed in event of a spill, a drill schedule, and procedures to mitigate unintended release of liquid fuels, in addition to training requirements. In NFPA 400, the emergency planning protocol requires one or more staff members to act as a liaison to emergency response crews. “Responsible persons shall be designated and trained to be emergency response (ER) liaison personnel. (6.1.4.3.1) Emergency response liaison personnel shall do the following:

(1) Aid emergency responders in pre-planning responses to emergencies

(2) Identify locations where hazardous materials are located

(3) Have access to safety data sheets

(4) Be knowledgeable in the site emergency response procedures (6.1.4.3.2)."

In addition to emergency response personnel, all spaceport facilities should also have an emergency action plan. Chapter 7 of NFPA 400 offers a comprehensive list of all required parts of this emergency action plan. "A written emergency action plan that is consistent with the personnel and equipment employed shall be developed and implemented". (7.2.3.1). Despite some useful features, spaceports are not currently required to utilize NFPA 400. FAA regulations under CFR Title 14 also call for a launch operator to have identified all hazardous materials and systems as part of the ground safety plan (417.405).

Another potentially unique aspect of commercial spaceports is that the crews ensuring emergency response and security may be contracted and operate on a part-time basis. General guidelines for control of public access during launch site operations is covered by CFR Title 14 §420.53

Firefighting Response

Spaceports represent a unique challenge from a firefighting perspective, and the existing code that most fully addresses this challenge is the NASA-STD-8719.11. Government owned and operated spaceports usually have some permanent or contracted on-site resources, although they may also have agreements with local municipal or volunteer EMS and fire departments (12.3). Per NASA-STD-8719.11, a contracted on-site fire brigade must be given a firehouse to stay in and a site-specific code must be written for them that complies with federal regulations (12.4.2). These regulations, from agencies including NFPA and OSHA, require an adequate living space, a place to store appropriate PPE, appropriate training and a turnout time of no more than one minute (12.8, 12.9). The standard also allows for a combination of local and on-site fire fighters. A summary of regulations addressing firefighter response including tactics, fire stations, PPE, etc. is given in Table 2.

The NASA standard also addresses the added danger of hazardous materials. When responding to an event that involves hazardous materials that one would expect to encounter at a spaceport, such as hydrazine, firefighters are expected to contain the fire, but “recovery, neutralization, and clean-up” are to be handled by hazardous material experts trained for that material (12.1.4).

NFPA 403, the standard for airport fire rescue of aircraft, sets several standards for the emergency response organization that the NASA standard references. For example, the NASA standard references the requirement that firefighters be readily available during flight operations, there is a maximum response time between alarm and firefighter response, and provisions for a full set of PPE and relevant tools and equipment provided by the airport.

NFPA 1710, the Standard for the Organization and Deployment of Fire Suppression Operations, Emergency Medical Operations, and Special Operations to the Public by Career Fire Departments, also has several standards for managing career fire departments stationed on facilities. Like NFPA 403, it requires the facility to provide PPE for firefighters expected to enter fire zones, but it also requires emergency action plans, standard operating procedures, and periodic drills. Regarding appropriate PPE or tactics for firefighters, the hazards posed by toxic high energy fuels is unique and requires a HAZMAT response in compliance with NFPA 472.

Risk Management

The area surrounding a spaceport is just as important to protect as the spaceport itself. If a fire or explosion were to occur in a spaceport there is typically a large quantity of volatile fuels present that could cause a hazard to nearby populations. Designing the facility to separate different physical hazards and keeping any vulnerable populations at a far enough radius away from hazards is critical. Several existing codes and standards provide recommendations on storage and design of volatile fuels and even on brush management to prevent fire spread throughout the site.

Given the risks associated with launching objects into space, NFPA, FAA, and NASA regulations call for a certain level of preflight planning and site preparation. One element of this is brush clearing. NFPA 30 requires that ground areas around facilities where combustible liquids are stored are required to be kept free of weeds and brush. Additionally, NFPA 55 and 400 require a minimum separation distance of 15 feet from weeds and other combustible materials when fuels are stored outside. This effort is meant to reduce the risk of a fire starting near highly combustible fuels.

Regarding the design of the spaceport itself, CFR Title 14 Part 420 provides the necessary separation distance between the public and explosive hazard storage, and between the hazardous fuels themselves. The FAA Office of Commercial Space Transportation also provides a Safety Management System (SMS) policy for spaceports (FAA 2015).

There are also codes that describe the level and nature of training that employees are expected to receive. NASA-STD-8719.11 lays out several key points of basic fire safety training. Employees are required to be trained within their first 30 days on site that covers the operation of emergency protocols, evacuation planning, and any emergency procedures specific to their area of work (11.5.2.2). Buildings with 10 or more occupants are required to have annual fire drills conducted by experts in fire safety (11.5.1.1, 11.5.1.2). Additionally, personnel required to use fire extinguishers must be trained in their use, but not everyone needs to know how to use one (11.5.3). NASA standard also covers rules on smoking and basic housekeeping meant to reduce fire risk. Personnel are expected not to smoke in designated areas and to reduce clutter that could contribute to a fire in a building (11.4, 11.6).

ISO presents several standards specifically devoted to spaceport risk management. ISO 14620, section 5.2.3 provides a safety system order of precedence. Moreover, there is a hierarchy of important safety precaution measures when it comes to keeping an area safe. First is hazard elimination, where all unnecessary hazards are removed completely from the project or mission. Second is hazard minimization. All hazards that cannot be eliminated shall be carefully controlled and monitored to reduce their level of risk. This leads into the third step which is hazard control, where automatic safety devices are implemented as part of the design process. Along with hazard control are warning devices and special procedures. This section covers the needs for some type of detection and alarm system to be installed to alert people in the case of an emergency. Finally, when it is not possible to eliminate, minimize, or control existing hazards, special procedures will be put in place prior to any incident occurring. Some examples include, “Physical barriers, safe separation distances, minimal personnel allowance with access control, remote monitoring, tagout/lockout methods, and time-limited exposure shall be considered as means of hazard mitigation and risk reduction”. Though these procedures are the least effective of the risk management strategies listed above and should not be the primary method of ensuring operational safety, they are crucial to the safety plan of a launch or reentry facility.

ISO 17666 also provides a framework for setting up a risk management system similar in style to NFPA 400. ISO 17666 is never explicit about what the hazards or risks in a spaceport are. Instead, it lays out a process where risks must be identified by the people operating a spaceport and an appropriate risk management plan must be established to determine the level of caution needed for an action. Risks are to be rated by spaceport operators on a scale from “very low risk” to “very high risk” and then a risk trend will be drawn up.

Site Security and Safety

Security takes special precedence on launch sites not only because of hazardous propellants and payloads but also to protect the public during fueling, launch, and other spaceport operations. Most regulations have some sort of requirement with regards to general site security, securing buildings against unlawful entry, and protecting storage containers from tampering. Facilities where combustible liquids are stored or used require much stronger security measures to ensure the safety of people and property.

ISO 14620 covers spaceport site safety and security, stating trained and qualified security personnel must be present to ensure the safety of the spaceport and the people within it. These safety representatives much have a reporting line and access to top management at all times (4.2). To minimize the hazards to human safety, certain preventative measures like physical barriers, safe separation distances, and time-limited exposures should be put in place to visitors and employees. Further clarification such as the extent of training and qualifications is not provided. FAA CFR Title 14 § 420.53 also dictates that launch operators must prevent unauthorized access to launch sites by means of physical barriers, surveillance and/or security personnel, but the extent of these security measures are not defined within the document or appendices.

Hazardous materials storage, use, handling and dispensing areas must be secured against unauthorized entry and may require a security plan to restrict access to such facilities at the AHJ’s discretion. In addition, a security plan is required when hydrazine or Oxidizer Class 3 and 4 solids or liquids are stored. Cryogenic fluid storage requires security against unauthorized entry for the system and safeguards against accidental tampering.

Security measures are outlined in other standards with similar security concerns. For aircraft fuel servicing, access to fuel loading areas and fuel storage must be secured, as per NFPA 407 5.2.1. Explosive materials require a security plan in order to apply for the applicable licenses and permits, as per NFPA 495 4.2.5. NFPA 730 covers general premises security and details what a security plan entails. Notably, it requires securing the perimeter of the facility, securing important assets in the facility, and controlling who enters and leaves by screening or inspecting who comes in. Some of these may be applicable to spaceports, however differences may apply.

High Energy Propellants

Launch operations tend to rely on a variety of different types of liquid and solid propellants (fuels). These include Liquid Oxygen (LOX), Rocket-Propellant 1 (RP-1, essentially highly-refined kerosene), methane, hydrogen, monopropellants (e.g. hydrazine) and solid propellants. These fuels all have extremely different chemical properties, and all three could be used in different stages of a single launch. All of these fuels are volatile and extremely high energy, with the ability to cause potentially devastating fires if they ignite in an out of control manner. Beyond requiring specialized protective equipment, responding fire departments will need specialized training for responding to high energy fuel fires.

Liquid Oxygen is a cryogenic oxidizer that retains its liquid state between 54.56 and 90.19 K (-361.82 to -297.33 degrees Fahrenheit). It is typically used in the launch stages of spacecraft and is usually burned with RP-1 in order to generate thrust. Due to it needing to be kept in a range of very specific temperatures, it has stringent storage requirements that are primarily covered in NFPA 55, the Compressed Gases and Cryogenic Fluids standard. This covers both cryogenic fluids and bulk oxygen systems but does not cover bulk liquefied oxygen systems (it does, however, cover bulk liquefied hydrogen systems).

LOX also provides additional risk in certain configurations. For instance, SpaceX cools its LOX to near its freezing point in order to maximize its density, which means that it’s more at risk for solidifying, and has additional hazards added onto the launch if the oxygen warms up enough, raising its density. This “superchilling” was part of the cause of an explosion on a Falcon 9 rocket in September 2016; the liquid oxygen became too cold to retain its liquid state and solidified[6]. Liquid oxygen is classified as a cryogenic oxidizing fluid, and counts as high-hazard level 3 contents under NFPA 400 due to its status as a cryogenic oxidizer.

In some new configurations a hybrid rocket motor is used where a solid propellant fuel and liquid oxidizer are combined. In such an instance Nitrous Oxide (NOS) has been used as an oxidizer with a solid plastic fuel by Scaled Composites[7].

RP-1 is a flammable liquid and is mainly subject to NFPA 30, which covers flammable and combustible liquids. Of the 3 fuels noted here, it is the easiest to store or fuel without worry of it boiling or exploding, and its storage is subject to the fewest number and least stringent codes. It is a Class II combustible liquid as per NFPA 30 and, because of this, has relatively relaxed storage requirements (its storage is comparable to kerosene due to them sharing the same NFPA combustible liquid class). It is chemically similar to jet fuel due to them both being derived from kerosene, and because of this, fire codes intended for airports can potentially be repurposed for RP-1 storage.

Hydrazine is a hypergolic fluid that has been used for second stage launches and is now more commonly used for propulsion in low-earth orbit. However, it is extremely toxic, corrosive, and can react spontaneously and violently. Because of this, a number of various NFPA codes apply to its storage and handling, notably NFPA 400 (hazardous materials) and NFPA 495 (explosive materials). The local AHJ will likely use both of these

[6] https://www.popsci.com/spacex-fuel-falcon-9-with-astronauts-on-board
[7] http://www.knightsarrow.com/rockets/scaled-composites-accident/

codes and take the most stringent requirements for each when considering its storage, especially in conjunction with storage of other high-energy fuels. NFPA 704 fire diamond classifies hydrazine as 4/4/3, meaning that it is lethal, extremely flammable, and fairly unstable. It produces toxic nitrogen compounds during combustion and will auto ignite at room temperature (74 F) if it comes into contact with rust and may ignite when on porous materials[8]. A review of incidents involving hypergolic propellants for spacecraft propulsion documented by NASA is available by Nufer (2010).

Hydrazine presents a challenge for firefighters due to its explosive nature. The explosive materials code, NFPA 495, explicitly forbids attempting to fight fires that cannot be controlled or contained before they reach any explosive materials in section 4.1.1.1, and since hydrazine is rarely used in spaceport activities without the presence of RP-1 and Liquid Oxygen, a hydrazine fire can quickly get out of control. In addition, it presents a possible exposure hazard if the vapors are able to leak out of containment, necessitating full PPE and self-contained breathing apparatus (SCBA) during most operations around the substance. Storage and handling of hydrazine represents a specific challenge not only for use but also for design of the spaceport. *Specific conflicts with zoning and regulation may arise once hydrazine or other hypergolic fuels are loaded and sealed into a launch or re-entry vehicle.*

The Air Force Space Command Manual 91-710 can be seen as another reference to how codes address the issue of storing hypergolic fuels in spaceports. At Air Force

[8] https://cameochemicals.noaa.gov/chemical/5019

spaceports, hypergolic fuels are stored in bays in designated containment areas and these bays must be built to specifications for thickness and material (5.3.4.1). The code goes on to describe standards for storage facility ventilation, the process of transferring fuels, and the particular types of fire detection that shall be used in these areas (5.3.4.2, 5.3.4.4, 5.3.4.8.1).

While not specifically mentioning hypergolic fuels, CFR Title 14 Chapter 3 provides guidelines for the storage and handling of explosive liquid and solid fuels. The design of the spaceport must be such that explosive hazards such as propellants be a minimum distance from both public areas and incompatible fuels (420.63-420.69).

Liquid methane is now being considered as a more common propellant. In the presence of a pilot flame both liquid and gaseous methane will spontaneously ignite. It is also an asphyxiation risk due to it being odorless, colorless, and, while lighter than air at room temperature, when super cooled it can be denser than air and collect in low areas. It does not, however, present the type of serious health risks encountered with some hypergolic fuels. Like LOX, it must be stored at very low temperatures in order to retain its liquid form; due to this, it is classified as a cryogenic fluid, and its storage is primarily dictated by NFPA 55, The Compressed Gases and Cryogenic Fluids Code. It counts at High-Hazard Level 2 Contents under NFPA 400 due to its status as a flammable cryogenic fluid.

Liquid Hydrogen is a component of propellant mixtures and is used primarily in conjunction with LOX. To retain its liquid state, it must be stored between -259 and -252 C (14 and 20 K). Due to it being used in its liquid form, it classifies as a cryogenic fluid and its storage is primarily dictated by NFPA 55, The Compressed Gases and Cryogenic Fluids Code. Chapter 11 of NFPA 55 deals specifically with bulk liquefied hydrogen systems. It counts at High-Hazard Level 2 Contents under NFPA 400 due to its status as a flammable cryogenic fluid.

Extinguishing Agents

Extinguishing agents are mandated by several codes and standards for both potential automatic extinguishing agents and as airport firefighting extinguishing agents. Fire control systems are required to comply with NFPA 11, 12, 12A, 13, 15, 16, 17, 750 or 2001, depending on which system is being installed and if the facility is using combustible liquids. When using compressed gases or cryogenic fluids, the facility is required to be protected by an automatic fire sprinkler system following NFPA 13, except for rooms with noncombustible construction and noncombustible contents, though local AHJs may require sprinkler protection for the entire facility. Following the hazardous materials code, buildings required to comply with certain protection levels (1-4) must be protected by an automatic sprinkler system following section 55.3 of NFPA 5000. However, the 400 standard also prohibits using a dry-pipe system in an area where oxidizers are stored over the MAQ, as well as disallowing halon and halocarbon extinguishers. Building owners also have to install a sprinkler system in accordance with NFPA 5000 when storing over the MAQ of unstable or reactive solids or liquids required to comply with protection levels 1-4. NFPA 403 mandates specific primary extinguishing agents for on-site fire fighters when hydrocarbon fuels are involved: Aqueous film-forming foams (AFFF), Fluoroprotein foam (FP) or film-forming fluoroprotein foam (FFFP), Protein foam (P), or Fluorine-free synthetic foam. In addition, all airport fire fighting vehicles must carry either a clean agent or potassium-based dry chemical agent as a complementary agent.

Hand Portable Fire Extinguishers

One aspect of fire safety planning applicable to spaceports but not unique to them is the use of hand portable fire extinguishers. NASA's standard dictates that dry chemical fire extinguishers are to be primarily used unless the AHJ calls for something else to fit a certain situation or hazard (8.9.2). For instance, class K extinguishers should be used in cooking areas and class D extinguishers should be used with combustible metals (8.9.2.1, 8.9.2.5). A summary of regulations related to hand portable fire extinguishers is listed in Table 5, above.

NFPA 30 requires listed fire extinguishers to be provided specific to the hazards of operation and storage. NFPA 407 requires fire extinguishers to be made available on aircraft servicing ramps or aprons, in accordance with NFPA 410. In addition, it forbids ABC dry chemical extinguishers near aircraft operating areas and requires fuel servicing personnel to receive training on the extinguishers they would expect to use. Extinguishers are also required on each fuel vehicle loading position or rack.

NFPA 418 also requires extinguishers for each takeoff and landing areas, parking areas, and fuel storage areas. In addition, extinguishers that the facility cannot protect against tampering may be omitted with approval from the AHJ. NFPA 495 requires motor vehicles transporting fuel to have at least two fire extinguishers.

Launch and Building Requirements

There are specific issues which arise related to spacecraft launches. These are covered by several NFPA standards; however, these are more geared towards model rocket launches than commercial spaceports. FAA licensing specifically addresses launch and reentry procedures, site requirements, and launch operator responsibilities; however, the document leaves fire safety to the discretion of the AHJ and launch operator without specifying these requirements (CFR Title 14, Chapter 3, Part 400).

Spaceports may have unique building configurations such as vehicle assembly buildings, payload preparation areas, and launch sites, which require adjustments from standard building requirements. There are few regulations covering these scenarios. NFPA 418 and NASA STD 8719.11 do address some aspects of protecting rocket hangars. More specific information for the protection of high-energy fuels is provided in the previous sections.

Conclusions and Knowledge Gaps

General Conclusions

Currently, there are no NFPA standards available specifically for spaceports, or for large-scale rocket launches. The NFPA series dealing with rockets, NFPA 1122-1127, deals mainly with model hobby rockets and not large commercial rocketry. A number of ISO standards are available that address aspects of spacecraft launch and spaceport operations, however these do not cover all aspects required to fully define safety requirements for a commercial spaceport. FAA licensing specifically addresses launch and reentry procedures, site requirements, and launch operator responsibilities; however, the document leaves fire safety to the discretion of the AHJ and launch operator without specifying these requirements (CFR Title 14, Chapter 3, Part 400).

The addition of more commercial entities adds a new dimension to this safety issue, since site standards have previously been tailor-made by the government for the government's use by professionals in the field. There are a number of NASA and DoD regulations which do cover many of the requirements for spaceports, however they are specially designed for government entities and there is no mechanism for their application and adoption by local AHJ's for commercial spaceports. Allowing commercial sites to set their own standards or rely on AHJs who are not familiar with rocket launches is not recommended.

Commercial spaceflight operations, specifically spaceports, are subject to different oversight compared to a government launch site. Local AHJs may not have the resources or experience to evaluate launch hazards, since spaceports are often located in less populated areas due to FAA licensing or local government regulation. *An AHJ assigned to a spaceport may be used to working with similar occupancies, or not have experience with more energetic materials, such as hypergolic fuels.*

Our conclusion is that additional resources should be provided for commercial spaceport operators and local authorities to assess hazards. Many of these guidelines exist in NASA or DoD standards or technical documents, however these need to be publicly accessible so that they can be adopted and used where needed. A new standard covering commercial spaceports which synthesizes this information alongside more resources for local officials could improve the process of safeguarding these new facilities.

Specific Gaps

There are a number of gaps in publicly available regulation which could be addressed to improve fire safety at commercial spaceports.

Emergency Risk Management

For emergency risk management, ISO 17666 and NFPA 1620 provide a skeleton format for the idea of risk management but does not provide particulars on how to fit it into a spaceport. This is an issue when an AHJ without prior expertise on spaceports is in charge of safety and enforcement for a site. While a site plan should still be custom-tailored to specific hazards at a location, more details are recommended to be included in materials that AHJs and site operators can use. This could include reference to specific NFPA standards or other relevant regulations.

Firefighter PPE and Tactics

Firefighter PPE required to respond to launch facility emergencies, often includes a HAZMAT level response. For example, hydrazine is an explosive fire hazard that is also toxic in even minute quantities. With the advent of new propellant formulations, hazards to emergency personnel must be continually updated to address the changing hazards posed by the propellants and methods of fueling, storage, launch, etc. Currently, launch site operators are responsible for ensuring that adequate PPE and firefighter tactics are properly addressed; however, AHJs at the local level may not have the proper expertise to determine if requirements are met. Current firefighter tactics treat fuels as a combination of explosives and toxins for the purposes of emergency response. A document specific to spaceports would help instruct a response unique to propellants rather than a general category of explosives. As some commercial sites may not have permanent operations staff, concerns related to contracted or mutual-aid emergency personnel arise due to the specific nature of the hazards. Specialized training will be required to ensure competency for any contracted or mutual-aid personnel that could be outlined in a synthesized document.

Propellant Storage, Handling and Usage

There are specific hazards associated with common rocket propellant formulations. NFPA and FAA regulations cover storage of those fuels; however, fire safety requirements for the process of fueling (fuel loading) are left to the judgement of the launch site operator. With new propellant formulations (e.g. supercooled LOX, hybrid rockets, etc.) coming to market these hazards could increase in the future. Development of regulations covering these hazards for commercial operators would help establish a common procedure for safe handling that local AHJs unfamiliar with spaceflight operations may adopt. For instance, NFPA 55 does not cover the use of oxygen detection that may be appropriate for a potential LOX or inert substance leak.

Hypergolic fuels are especially dangerous; for instance, hydrazine is colorless, odorless, tasteless and highly toxic. As such, it presents a health safety hazard both to spaceflight personnel and first responders. Conflicts may arise in locations where transport of sealed containers (often in the payload) occurs between assembly and launch and when determining appropriate tactics for firefighter response.

Recently, ASTM International Subcommittee F47.04 on Spaceports has convened a work item (ASTM WK59169) to develop a “New Guide for Storage, Use, and Handling of Liquid Rocket Propellants”[9]. This may cover many of the items recommended for propellant storage, handling and use once it is completed; however, it will not address other concerns such as emergency risk management, firefighter response, etc.

[9] https://www.astm.org/DATABASE.CART/WORKITEMS/WK59169.htm

Crewed vs. Un-crewed Flights

While human safety plays a factor in any mission, the safety requirements and protocol for crewed spaceflight require more scrutiny. It is important to define different preparations and response protocols for these separate types of missions. While most of this would be covered by NASA's standards governing safety requirements for launching astronauts into space (NASA Standard 3001), there is the potential for changes at the launch site, for fueling procedures, etc., which should also be considered. Most current standards focus on launch systems, the safety of the public during launch, and crew safety during spaceflight. Site-specific concerns are not well-covered for crewed spaceflight and may have to be addressed as commercial launch of crewed vehicles begins.

Safety Reporting

Unlike government spaceports, there is not a public reporting system for both accidents and close calls. The systems by NASA and the FAA are excellent resources for constant improvement of safety procedures, available at https://llis.nasa.gov and https://www.faa.gov/data_research/accident_incident, however reporting requirements for commercial spaceports to the FAA do not necessarily require public disclosure and do not require close call reporting, which could also be useful for constant improvements in safety.

Site Security

While current FAA regulations require a site safety and security plan, there are no specific public guidelines for the creation of such a plan. There are many elements of site safety and security at a commercial spaceport that would be unique compared to other occupancies, e.g. a high density of propellants, potentially toxic payloads, etc.

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