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Building a 21st Century Multi-User Commercial Spaceport: Development and Application of the Spaceport Readiness Level Scale

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Acronyms

AFSS – Autonomous Flight Safety System

CCAFS – Cape Canaveral Air Force Station

CONOPS – Concept of Operations

KSC – Kennedy Space Center

LOC – Launch Operations Center

NASA – National Aeronautics and Space Administration

SLS – Space Launch System

SRL – Spaceport Readiness Level

STS – Space Transportation System

TRL – Technology Readiness Level

USAF – United States Air Force

Abstract

Commercial spaceports have arisen over the last decade and a half to support a growing commercial space marketplace. The introduction of expected suborbital launch capabilities for tourism and for orbital launch operations at an increased cadence has demonstrated a need for more capability at the spaceport level to support airport-like operational fluidity. Despite these advancements, a measure has yet to be developed to demonstrate a spaceport's support capabilities in a straightforward and rapid manner.

Based on this need, the Technology Reading Level scale, utilized in many industries as a means for procurement and technological development measurement, has been used as a baseline to develop the proposed Spaceport Readiness Level (SRL) scale. This proposed scale measures a spaceport's progression from ideation, to development, and through maturity at a system of systems level. From this point, the scale can be used either as a means of demonstrating current support capabilities or as a roadmap for achieving future maturity in space launch operations. Necessarily general in nature, the SRL provides a tool for spaceports ranging from those under consideration to those with storied histories of space launch efforts. The adoption of the SRL scale will aid the process by which rapidly evolving space launch companies transition to locations with the capabilities to support their required efforts and support requirements. It may also provide a more effective means for companies to communicate with current spaceport locations to guide modifications that would benefit both the needs of the company and the launch site.

1.0 Introduction

The launch of Yuri Gagarin into Earth orbit marked the first steps of mankind into outer space and launched expansion into a new frontier of exploration throughout the world. The Space Race between the Soviet Union and the United States of America exemplified this new spirit with both countries innovating rapidly to develop new and exceptional capabilities to carry men further and further from the Earth's surface. This concentrated application of political willpower and industrial might saw the development of the first spaceports capable of launching crewed spacecraft. Further, the creation of test ranges throughout the world were constructed and used for similar civil and military purposes. These newly built spaceports were the bulwark of every future spaceflight program, serving as both industrial bases and engineering headquarters for current and developing programs.

At the same time as spaceflight accelerated, both nations of the space race identified the immense investments required to continue their developments. As a result, both concentrated their efforts into a central launch location which could be further developed to suit the needs of evolving spacecraft requirements. The United States, through the National Aeronautics and Space Administration (NASA), prepared their Launch Operations Center (LOC), which would eventually be designated Kennedy Space Center (KSC) in honor of the late president, for the largest rocket man has yet launched, the Saturn V. The Saturn V launched every manned mission beyond Earth orbit and remains one of the greatest engineering marvels mankind has yet to develop. Yet the Saturn V, and the infrastructure required to launch it, were not the beginning of KSC's launch program. Rather, they were the evolution of years of experience launching a variety of test vehicles and other less capable flight vehicles.

All major spaceflight programs in the United States would begin and end at KSC, starting with the Mercury Program which launched America's first astronaut into space. Mercury was followed by the Gemini Program, which developed the capabilities needed to reliably remain in space for longer periods of time. Finally, the Apollo program, flying on the massive Saturn V, would carry American astronauts beyond Earth orbit. Throughout this period, new launch infrastructure was rapidly developed, improved, and replaced as spaceflight became more routine. Evolving program requirements would see the addition of everything from new launch pads to towering strongbacks which would serve as the bases for every future launch from KSC. Further, the co-located Cape Canaveral Air Force Station (CCAFS), would host a multitude of dedicated launch complexes supporting test missions for both the military and NASA.

Foresight allowed NASA to follow this program with the Space Transportation System (STS), otherwise known as the Space Shuttle. As a Low-Earth-Orbit launch vehicle, the Space Shuttle was designed as a means for launching astronauts into orbit for a variety of missions, returning them, then rapidly (in relative terms to spaceflight) relaunching. The different requirements of this new vehicle saw further investment in KSC and the development of a truly multi-vehicle spaceport wherein different mature launch vehicles serving different purposes began to co-inhabit a single launch range. Different requirements for different vehicles allowed the variety of capabilities hosted by a mature spaceport to shine. The eventual end of the shuttle program and the growth of commercial launch capabilities has further proven the value of mature spaceports wherein existing capabilities are leveraged to develop new launch vehicles alongside the implementation of modern infrastructure improvements.

With this backdrop, it is clear that there is a recognized need to modernize infrastructure and operations at legacy spaceports, but also provide guidance to newly licensed, proposed, or developing spaceports on the same. As such, this thesis serves to fill that lacuna and quantify and qualify the capabilities that need to be developed to transform legacy ranges operating with a small number of launch vehicles and spacecraft with limited launch capabilities to spaceports that can support multiple launch vehicles at a rapid rate. Further, this research serves to aid the development and transformations of newly licensed or proposed spaceports into fully operational spaceports that meet the challenges of the growing industry. Using the Technology Readiness Level (TRL) scale as a point of departure, the author proposes a Spaceport Readiness Level (SRL) method for measuring the advancement of a spaceport from an initial status to a multi-user commercial spaceport

Section 2 of this thesis therefore will lay the groundwork for spaceport development in the past, present, and future. The rapid growth of commercial space will be discussed along with its application to a growing number of spaceports in the United States. Spaceports themselves will be examined, with a focus on their support capabilities and their history. Finally, Section 2 will highlight the future vision of modern spaceports and the expected requirements to achieve these long-term goals. Based on the analysis provided throughout Section 2, Section 3 will provide a rationalization of further research.

Section 3 of this thesis will focus on the foundation of the SRL, that is, the Technology Readiness Level (TRL) scale which has served as a measure of the maturity of a certain technology. This scale is discussed along with several different definitions of its use. A breakdown of the scale is included to depict the different levels of capability. The author then shows how the scale has been revised and modified into the proposed SRL. The SRL will enable spaceports to depict their current capabilities in a consistently measured scale. Just as the TRL is widely used for procurement and technology development measurement, the SRL can be used similarly for determining launch sites that are suitable for various launch activities. Further, the SRL can serve as a general guideline providing guidance on how to develop a spaceport's capabilities to meet commercial launch requirements.

Section 4 of this thesis applies the SRL scale to two test cases, specifically addressing CCAFS/KSC and Cecil Spaceport in Jacksonville, Florida. Both spaceports currently can be measured against the SRL scale at different levels of development. CCAFS/KSC is an example of a Federal Launch Site with multiple commercial users. Further, CCAFS/KSC has a long history of successful operation as a launch facility. On the other hand, Cecil Spaceport is an FAA-licensed commercial spaceport with a developing user base. Cecil is a new commercial spaceport without a launch history, but with several commercial customers. Both spaceports are advancing according to the SRL scale and will be measured to show the scale's effectiveness.

Based on the application of the SRL scale in Sections 3 and 4, Section 5 discusses recommendations developed from the test cases. Specifically, the SRL scale is examined as a means of providing a generalized guideline for spaceport development over the course of a spaceport's growth. Specific emphasis is placed on methodology for generalizing the SRL scale to enable easy application to the spaceport growth process. Next, an examination of cross-range capabilities is examined comparing federally operated ranges to limitations existing with commercial spaceports. Finally, an examination of limitations existing within this study is reviewed. Section 6 provides concluding remarks.

2.0 Background

2.1 Commercial Space

The rise of the commercial space industry has seemingly occurred overnight. The early 2000's saw the founding of multiple new commercial firms dedicated to reaching into space for a new reason: to make a profit. Commercial space in and of itself is not a new invention; commercial satellites have been flying for decades and commercial companies had been competing within the space industry for even longer. Yet the advent of commercial companies which no longer depended on, or sought to profit from, national space activities represents a fairly modern development. These companies have gone on to prove suborbital launch capabilities, reusable rockets, and massive launch cost reductions that are far outside the expected performance of entrenched legacy space operators.

Commercial space as a launch service therefore represents the newest development of spaceflight and has been, in part, catalyzed by the end of the Shuttle program and the transition to the Commercial Crew and Commercial Cargo Programs. While not the beginning of commercial spaceflight, this transition has proven to be a vital source of funding, technological exchange, and infrastructure development from the public to private sector. As dictated in his testimony to the House of Representatives Subcommittee on Aviation, Dr. Gerald Dillingham indicates that the Commercial Crew and Commercial Cargo Programs have led to an increase in commercial launches (Dillingham, 2016).

Other commercial launch capabilities have begun to grow at the same time to serve various sectors: Virgin Galactic for tourism and Blue Origin as a commercial launch competitor for example. These two example companies both seek to compete for portions of the commercial space economy, but neither have launched a commercial payload thus far. While launch services represent a growing economic force, they represent only $7.49 billion of the $383.5 billion space economy (Space Foundation, 2018). Worth noting is that this number does not represent launch services procured for the government, estimated at $5 billion, and does not account for launch capabilities taking place at a governmental level (such as the development and eventual launch of the Space Launch System [SLS]). As seen by the overall number of competitors within the industry, the launch portion of the space economy has yet to achieve maturity.

In many ways, the lack of maturity in the launch portion of the space industry has enabled the ongoing operation of a number of small research firms dedicated to developing capabilities designed to reduce the cost of entering space, yet without the dedicated funding to be able to achieve this goal. As a result, despite the prevalence of launch operators in development, the primary source of funding for many launch ventures remains the public coffers. While the government's presence is powerful, the overall commercial sector of the space economy is expected to grow at roughly a 7% rate (George, 2019). As the commercial sector continues to expand, the supporting industries required to enable successful launches, along with operational successes, will necessarily expand to match.

Commercial space operators cannot be inherently separated from the launch facilities they require. Indeed, the launch of the vast majority of commercial vehicle launches continues to occur from CCAFS/KSC due to its status as a long-operating and well-established launch range, with testing and operational launches at other locations remaining a minority of major operations. As the launch service industry expands, a number of other spaceports have achieved licensing in anticipation of future vehicle operations. While other locations are available, with the majority of non-test launch operations taking place at CCAFS/KSC, it stands as a perfect example point for the transition into modern spaceport ideology.

2.2 Spaceports

As the crucial path to space, spaceports serve as the primary conjunction of the outer space industry with its economic realization. The use of spaceports has changed rapidly over the last two decades, with the evolution of the commercial space industry demonstrating a need for increased flexibility in launch location combined with an increased launch tempo. Further, established launch ranges like CCAFS/KSC have had to adopt to the radically different demands of a commercial range user compared to established government actors. As a result, a slightly increased willingness to accept risk and an evolving desire to demonstrate commercial flexibility has been evidenced by existing spaceports throughout the United States. At the same time, the licensing of multiple commercial spaceports without a government launch heritage has seen an uptick in competition for launch providers, particularly in the suborbital launch category. With the progressive development of spaceport capabilities, new range users are being provided with flexibility in implementation of their launch programs.

The growth of commercial space may have spurred the development of new spaceports, but it is not the only driver of increased capability. Existing government spaceports have faced the need to upgrade their internal support capabilities to match the developments of new government vehicles (such as SLS) and military customers (such as modernized military launch systems). The influx of commercial customers occurring at the same time has led to innovation within the launch capability process wherein efforts have been focused on process improvement efficiency rather than solely on capability growth. As a result, the resources required to conduct launch operations have decreased while the capabilities evidenced throughout these launches has increased, as can be expected with a traditional technology improvement curve. With increased capability in evidence, launch providers have focused their efforts on existing ranges rather than embracing the growing number of solely commercial spaceports. A notable exception to the trend of existing spaceport use remains within the suborbital launch community.

While much of the growth of commercial space launch capability has occurred at existing spaceports, the entrenched government users and operators has required commercial users to be incorporated into the extensive, and expensive, rules and procedures implemented at those facilities (Handberg, 2014). These ranges, primarily at CCAFS/KSC but also Vandenburg Air Force Base (VAFB), have been making efforts to streamline their processes but still face commercial customers with increasing needs for flexibility and growing opportunities to achieve this flexibility at other locations. One example of this competition is the private development of a spaceport on the Texas coast by SpaceX, which seeks to remove itself from the regulatory burden imposed by government operated spaceports (Handberg, 2014).

While many newer commercial spaceflight companies (often termed "NewSpace") see the value in distancing themselves from government launch sites, this is not the case for all launch providers. More specifically, many of the legacy launch providers and established aerospace companies have operated within the government restrictions on established launch sites for many years and do not see an immediate need to distance themselves from regulations. These companies (one example being United Launch Alliance or ULA) have sunk large sums into the fixed infrastructure and extensive testing/demonstration required for government launch contracts and do not stand to benefit as completely as their more commercially focused competitors. An emphasis can be placed on the investments made into logistics infrastructure at this point, where it can be seen that legacy launch operators have significantly less flexibility in adapting to market changes as compared to NewSpace companies, which are not constrained by existing investments.

Yet the infrastructure capabilities of existing launch ranges are often, at least in part, funded by government operations rather than directly through the launch operators. While decreasing direct costs, this places the burden for improvements on the government, which does not necessarily invest as much as required gauged across economic expenditures of equal scale (Snead, 2008). As such, the existing infrastructure serves as both an advantage and disadvantage in the newly competitive commercial launch arena. The dichotomy evidenced by spaceport user needs and the capabilities which spaceports provide indicates that a further growth of commercial spaceports can be expected while entrenched legacy operators are likely to continue utilizing existing investments.

The growth of commercial spaceports and the ongoing development of existing launch ranges has been a focal point of an industry which has only recently become commercially competitive. As the competition between NewSpace companies and legacy launch providers continues to grow, spaceports will become a focal point of both cost and capability management. Infrastructure improvements on existing ranges have increased their capability and allowed for more flexibility in working with commercial launch providers, yet commercial spaceports continue to be licensed as they present other opportunities for launch providers to achieve optimal operations with increased flexibility. Despite these developments, many spaceports remain at low levels of capability and development without an easy method of determining their exact readiness for use. As such, their published plans for future developments serve as the primary indicator of future capabilities across the industry.

2.3 Future Vision

Potential and existing spaceports often prepare master plans which indicate their intended long and short-term goals and can be used as indicators of spaceport maturity. This is not a full-proof measure of determining the potential of a spaceport to support a specific launch capability but can be used as a generic scale of development. As more commercial launch operators achieve successful operations, commercially licensed spaceports will begin to operate for their intended purposes, with many conducting suborbital launch operations which have not yet achieved demonstrable commercial success.

Despite the lack of user, a “build it and they will come” mentality has led to the licensure of multiple spaceports throughout the United States and abroad which are theoretically capable of supporting suborbital flight missions, but which are not directly intended for orbital launches. At the same time as commercial spaceports evolve, existing government-operated ranges are seeking to demonstrate an improved ability to work with commercial users by increasing their operational flexibility while also increasing the efficiency of their process flows. As both forms of spaceports move conjointly to mature commercial launch operations and competition for users, a scale of maturity will be required as a measure of overall capability.

As a whole, spaceports and their operators have recognized the growing commercial launch industry and sought to capitalize on its development. The focus on suborbital launches for tourism especially has seen a focus on the transition of airports into spaceports, with the use of horizontal take-off and landing being seen as the typical launch profile of associated space vehicles. At the same time, multiple commercial companies have focused on orbital-class rockets which have demonstrated, or have the potential for, reusability through vertical take-off and landing. As such, spaceports have had to shift from launch ranges to airport-like launch and landing facilities. This mentality change is not completely revolutionary as the Space Shuttle landed at KSC, but its adaptation to more traditional rocket bodies is a new development. With spaceports pursuing both forms of launch vehicles, many are developing plans for capturing multiple launch operators which may operate at different levels of capability and sophistication.

Existing launch ranges have already demonstrated the ability to work with multiple launch vehicles, often with different capabilities and uses. CCAFS/KSC has launched every type of vehicle currently being utilized for orbital launches and also has demonstrated the capability for many suborbital launch platforms. While these capabilities have been demonstrated for government launch procurements, at a commercial level, CCAFS/KSC remains a vertical-launch (now also vertical-landing) site. With the identified trend towards multi-user (and multi-class) spaceports, CCAFS/KSC has sought to develop the capability to support all forms of commercial and government launch vehicle. As noted in the Cape Canaveral Spaceport Master Plan, CCAFS/KSC remains one of two spaceports in the world capable of supporting all vehicle classes (Space Florida, 2017)[1]. Further, with an entrenched government launch customer, CCAFS/KSC remains a readily accessible launch facility with existing infrastructure and a long history of successful launch operations. As such, the development of commercial spaceports for orbital launches is likely to be a slow process due to the level of competition and capability present currently. As a counterpoint, economics alone does not necessarily determine the need for commercial spaceports as can be seen by SpaceX's development of a private orbital-class facility on the coast of Texas.

As commercial companies begin to compete more aggressively, they are likely to occupy similar locations and operate on similar launch cadences, else they will fall to the wayside. As such, NASA has already recognized the need for the ability to safely support multi-user spaceports wherein multiple vehicle types are in evidence. As discussed in research prepared by NASA Langley, KSC has already accepted additional risks associated with commercial launch activity and has sought to better organize itself to promote those partnerships (Dacko, Ketterer, & Meade, 2016). With governmental focus already present, a general outline for the development of multi-user spaceports can be

[1] Cape Canaveral Spaceport (CCS) is a Space Florida term covering CCAFS, KSC, and attached properties owned by Space Florida. Space Florida is a governmental organization based around encouraging and enabling investment by commercial companies into Florida's space economy. Space Florida is not responsible for the Federally operated CCAFS/KSC but plays a part in capturing new business to the launch centers. Additionally, parts of CCAFS/KSC are managed and operated by Space Florida.

developed. Vandenburg Air Force Base (VAFB) and Wallops Flight Facility have also provided launch experience with multiple users, further allowing for government experience in the launch realm. While the NASA research focused specifically on KSC, its conceptual approach to safety requirements development and operational considerations lays a groundwork for future multi-user spaceports but fails to address when these components are needed in the maturation process.

A final important component to note in comparing growing commercial spaceports to their commercial counterparts is the difference in level of supportable capabilities. Commercial spaceports are often tailored to support a limited range of vehicle classes while larger established facilities such as CCAFS/KSC are capable of supporting a full spectrum of future and existing vehicles (Space Florida, 2018). As discussed by Space Florida, a comparison can be drawn to the airport network which supports flights around the world. As spaceports continue to develop, eventual frameworks for categorizing their capabilities will need to be developed as human transportation by space vehicles increases.

Licensed spaceports vary widely in their capabilities to support vehicle launches across the spectrum of vehicle classes. With the introduction of commercial spaceports that are now competing to attract launch providers, spaceport classifications will need to be developed to assist in easily assessing spaceport capabilities. Over the short-term, established launch facilities can be expected to out-compete the growing network of solely commercial spaceports due to their mature infrastructure and demonstrated capabilities, but this dominance may be at risk as more modern facilities become available. With commercial launch companies seeking to disrupt the industry with innovative capabilities, similar results may evolve from competition between spaceports. A scale will be needed to easily identify the capabilities of spaceports as they grow and evolve to match the needs of industry.

3.0 Technology Readiness Level

3.1 Definitions

The TRL scale was developed by NASA in the 1970's and refined into its 9-level scale used today in the 1990's (Banke, 2010). Initially developed as a means for determining the maturity of technologies, it has morphed into a widespread scale accepted throughout industry and governmental organizations for purposes ranging from acquisition to applied research. The scale's adoption by multiple organizations has led to modifications from its original format which have allowed for tailored use in different industries and for different forms of projects, with larger changes being made for topics such as software development.

Despite these modifications, all scales trend back to the original scale developed by NASA which is still in use with a focus on spaceflight applications. As a general rule, the scale can be efficiently utilized to determine the useful capability of a technology compared against a series of standardized baseline, Table 1 below, displays the current TRL definitions utilized by NASA as referenced in their procedural requirements (National Aeronautics and Space Administration, 2013).

TRL	Definition	Hardware Description	Exit Criteria
1	Basic principles observed and reported	Scientific knowledge generated underpinning hardware technology concepts/applications.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated	Invention begins, practical applications is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof-of-concept	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Documented analytical/experimental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to final operating environment.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrate overall performance in critical areas. Performance predictions are made for subsequent development phases.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in a relevant environment.	A high-fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Documented test performance demonstrating agreement with analytical predictions.
7	System prototype demonstration in an operational environment.	A high-fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	Documented mission operational results.

Table 1: NASA TRL Scale[2]

[2] Source: (National Aeronautics and Space Administration, 2013)

NASA's TRL scale as depicted in Table 1 demonstrates its ability to be applied to generic technologies as needed while evidencing its focus on a system's level approach to engineering development and progression from science to application. At a high level, this generality makes it easier to apply the scale to singular technologies and systems but limits its application to higher orders of capability involving integrations of systems and processes. Further, the generality of the scale means that for specific usage within an industry, lower level modifications are useful for tailoring the scale to fit its use. An application of this tailoring can be seen in Table 2 which depicts TRL levels as defined by the Defense Acquisition Guidebook (Defense Acquisition University, 2010).

TRL	Definition	Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.
5	Component and/or breadboard validation in relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7	System prototype demonstration in an operational environment.	Prototype near, or at, planned operational system. Represents a major step up from TRL 6, requiring demonstration of an actual system prototype in an operational environment such as an aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft.
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions.

Table 2: DoD TRL Scale[3]

[3] Source: (Defense Acquisition University, 2010).

A number of differences can be noted between Tables 1 and 2, namely in their intended applications. Table 1 includes exit criteria which can be used to determine the progression of a technology throughout its lifetime. These criteria, absent from the DoD scale, formalize the advancement process between TRL numbers allowing for a more accurate assessments of a technology's true position on the scale.

In a similar vein, the NASA version is far more generalized as to what the technology utilizing the scale may be. The DoD frame of reference is primarily based around weapons technology and includes examples for testing of said technology at each level on the scale. These minor differences tailored to each user are helpful in allowing the scale to serve as a general guideline of technological maturity for nearly every industry with only minor corrections.

3.2 Proposed Spaceport Modification

As seen by modifications by other users, adopting the TRL scale to a specific user or industry can help to refine its use. In this example, the TRL scale has been modified based on the NASA and DoD utilizations of the scale to focus specifically on the commercial spaceport industry. In order to accomplish this refinement, specific changes needed to be made targeted at measuring the maturity of a spaceport throughout its development process. While the TRL scale is typically focused on a single system or technology, it has been adapted in this circumstance to be a measure of development for a system of systems. At this level, the adapted scale measures development in aggregate rather than singularly. As such, the proposed SRL scale features more significant modifications as compared against similar efforts for other industries. Worth noting is the inclusion of Exit Criteria which had been excluded from the DoD scale. Table 3, below, depicts the proposed SRL Scale.

SRL	Adapted Definition (Spaceport)	Adapted Description (Spaceport)	Adapted Exit Criteria
1	Basic Spaceport area defined with general operational concepts considered	Basic airport/spaceport operations knowledge utilized to generate underlying concept	Documentation of basic CONOPS
2	Basics CONOPS incorporates specialized knowledge. Publication of spaceport proposals or research created.	Practical application of operations planning utilized to develop CONOPS without supporting analysis	Initial capabilities achieved through license application and equipment purchases
3	Analysis of CONOPS and establishment of limited capability (license, storage, etc.)[4]	Historical and simulated data/concepts utilized to develop initial operations with supporting analysis	Initial user establishes presence including components for testing and/or staffing of offices. License achieved
4	Limited single-user operations capability established with the ability to support user test operations	Limited operational capability utilized to demonstrate operations and capabilities	Successful limited launch operations undertaken
5	Initial proven operational capability of a single user's system, capability for additional users undertaking test operations	Operational capability of a single user utilized to demonstrate capabilities of spaceport in real-time operation with future performance estimates driven by data	Additional users establish presence or single user demonstrates multiple vehicles AND initial vehicle demonstrates mature capability
6	Mature operational capability of a single user/vehicle class, initial operational capability of additional users or vehicle classes	Mature experience utilized to improve operations as adaptations are made to overall capabilities to address changes to user base	Operational capability of multiple users or multiple vehicles
7	Initial rapid launch capability demonstrated with at least one user/vehicle class or rapid recycle proven across multiple users or vehicle classes	Increase in launch cadence demonstrated with use of mature technologies and processes outside of a test environment	Ability to launch a single vehicle class rapidly OR ability to rapidly cycle between vehicles demonstrated
8	Multiple vehicle class launch capability demonstrated with multiple mature flight operations capability proven	Initial ability to operate multiple launch operations conjointly demonstrated	Ability to conduct launch operations for multiple vehicles demonstrated on a test basis
9	Ongoing mature and rapid operation of multiple vehicle classes through launch capability	Mature ability to operate multiple launch operations including rapid recycle proven	Ability to conduct launch operations for multiple vehicles demonstrated on a repeatable mature process.

Table 3: Proposed SRL Scale for Spaceports

[4] Designation as a Federal Launch Range (operated by USAF or NASA) serves as the government equivalent of a Launch Site Operator License. FAA launch requirements must still be met, but procedures and safety rules may exceed FAA requirements.

As depicted in Table 3, the scale has been strongly tailored to be used for spaceports. While the changes are very specific, they have been made around the concept that they match the appropriate level of effort demonstrated at the general level utilized by other TRL modifications. Further, the use of a system of systems view for this adaptation has led to combining multiple factors into single steps to enable an accurate representation of the system of system's capability to support its intended use.

TRL 1 focuses on the application of basic scientific principles to a technology. As such, SRL 1 focuses on the use of basic operational principles to the spaceport system. At this level, the spaceport (not yet licensed) has demonstrated a desire to achieve licensing and is developing a general operational background. Knowledge in aviation and operations has been applied, but detailed analysis has not taken place. In order to advance to SRL 2, the equivalency exists as shown; the creation of a Concept of Operations (CONOPS) represents the most basic intended utilization of a spaceport's use in the same way as basic scientific knowledge provides the background development for technological development.

Achieving SRL 2 through the development of a CONOPS, enables a potential spaceport to begin further planning and development based on their background intended utilization. At this stage, background knowledge has been condensed to develop an actual plan of operations, but detailed analysis and refinement has not yet taken place. This is equivalent to other scales which at this stage focus on the development of a technology concept. In the wider approach of the SRL, this is shown through an operational concept. To graduate from the general scale to TRL 3, documentation is required to demonstrate analysis. In the SRL scale, analysis is shown through the submittal of a spaceport license (or equivalent federal designation) which denotes the significant analysis required for issuance.

SRL 3 focuses on the establishment of limited operational capability and is achieved through the issuance of a spaceport license (or designation as a Federal Launch Site) and demonstration of limited operational use. At this stage, analytics have been applied to provide mathematical backing to intended operations and historical data has been incorporated for efficiency purposes. Compared against the general scale, TRL 3 is established by demonstrating a proof of concept. In order to move to the next stage, limited user presence at the spaceport must be demonstrated. This is equivalent to the general exit criteria of validation of key parameters in that the establishment of a spaceport user validates the general concept of the spaceport.

SRL 4 transitions the use of the spaceport from concept proofing to capability development, representing a significant progressive leap. At this stage, the spaceport has established the ability to support a single user conducting test operations and demonstrated their ability to support such operations. This is similar to the equivalent position of validating a low-fidelity system to demonstrate basic functionality as espoused by the general TRL scale. The establishment of limited capability therefore indicates test operations but does not include the use of a space vehicle in an operational sense. In order to achieve SRL 5, the spaceport must demonstrate the ability to undertake a successful launch operation at their intended level of support. This is equivalent to demonstrating test performances with analytical data.

SRL 5 requires the demonstrated ability to support launch operations at an initial stage. Initial operational capability is defined as operations beyond testing, but which have not yet reached maturity. With demonstrated initial capability, SRL 5 shows equivalency to the requirement of component validation in a relevant environment. The data gathered at SRL 5 enables spaceports to improve their processes driven by data developed during actual operational use. To achieve the next SRL level, the spaceport must now demonstrate the ability to scale up their operations to support multiple vehicle types or users while maturing their support of the initial user, similar to the general requirement of documenting the needs for scaling the technology.

SRL 6 demonstrates the ability to support a mature launch vehicle while providing initial support capabilities to other vehicle classes. Mature support levels are defined at the point where process support for a vehicle has been optimized and significant efficiencies exist within the spaceport for the established vehicle type. These may include dedicated support teams for the identified vehicle or streamlined documentation requirements. At this stage in the general model, the technology has achieved a system prototype that has been demonstrated operationally. As a comparison, the use of the spaceport for a single vehicle serves as a prototype for eventual scaling. SRL 6 demonstrates the end of the spaceport development phase, transitioning to spaceport maturity with SRL 7. SRL 7 can be reached by demonstrating operational maturity with multiple users.

At SRL 7, a spaceport has developed the capabilities to support multiple users and/or multiple vehicle classes and is now maturing their combined support capabilities. As such, at this level, the spaceport has begun developing rapid launch capabilities that demonstrate processes that are utilizing historical performance as an improvement measure. This compares to the general concept of utilizing prototypes in an operational environment with the purpose of achieving overall improvements. In order to graduate to SRL 8, a spaceport must therefore demonstrate the ability to rapidly launch a single vehicle class or to cycle between multiple vehicles, but not to conduct these operations simultaneously.

SRL 8 utilizes the increased launch cadence achieved at the spaceport maturity level and focuses on the ability of enabling the initial capability to support multiple launch operations simultaneously. At this stage, the spaceport has demonstrated an ability to rapidly shift priorities and is now developing the ability to maintain these priorities simultaneously. This connects to the generalized TRL model wherein systems are “flight-qualified”. As the spaceport’s capability to support multiple launches matures, SRL 9 can be achieved with the accomplishment of an efficient process for multiple launch operations.

SRL 9 represents a spaceport that has completed maturation and is now capable of supporting nearly all needs of a user without significant alterations. At this stage, all systems within the system of system’s have been repeatedly utilized for successful operations and the processes required for new users have been refined. Historical data on previous operations has been gathered and future capability needs are tracked for changes. This compares well to the generalized TRL wherein the system has been proven through successful mission operations. With the achievement of SRL 9, a spaceport can be seen to have achieved the ability to simultaneously conduct launch operations with multiple vehicles and vehicle types with mature and thoroughly tested processes. While further efficiencies may be possible, they do not significantly alter current operational capabilities.

The SRL Scale enables a possible spaceport user to measure the currently demonstrated capabilities of a spaceport against other possible launch locations. This standardized measure can be useful for determining future needs and can also be utilized as a predictor for general spaceport development. As compared against the traditional TRL scale, the SRL Scale focuses on process and capability improvements at the system of systems level, enabling the precedent for future adaptations to the scale for other industries that may benefit from similar modifications.

4.0 Application

4.1 Process

With an SRL scale now available to be applied to a generic spaceport, test cases must be undertaken to ensure its applicability. These test cases will focus on demonstrated capabilities, meaning that planned and future operations will not be considered for current SRL assessments but may feature as a discussion point for future projected utilizations. It must be noted that the application of the SRL scale must be utilized linearly, despite the outside possibility that certain capabilities may be achieved at an earlier point in the spaceport's development period. This restriction is due in part to the process change efforts that must occur to demonstrate the maturity of a process, meaning that while a capability may be demonstrated, it is unlikely to be repeatable efficiently without further development following the appropriate scaling.

Limitations exist with the application of the SRL scale. The scale is focused on capabilities evidenced at the system of systems level and cannot be accurately assessed at a lower level within the system (though generalization higher is possible). Further, the scale is developed for spaceports seeking to achieve multi-user commercial launch capabilities that are intended for profit. As such, solely government ranges (such as military test sites) and those used primarily for testing purposes (such as Mojave Air and Spaceport) cannot be as accurately assessed in the maturity of their processes and capabilities as commercial spaceports. The scale is also based on the United States concept of commercial spaceports, meaning that international spaceport development may be measured at a lower fidelity. Finally, the scale does not account for the difficulty of achieving each SRL, meaning that a spaceport's location on the scale does not measure the investment of time and cost required to achieve each level.

4.2 Test Cases

Two test cases have been selected for testing of the SRL Scale. Specifically, Cecil Spaceport and CCAFS/KSC represent two spaceports operating with commercial customers that provide examples for the scale. They operate within the assigned limitations, being United States launch facilities with a focus on commercial operation. Worth noting is CCAFS/KSC's government heritage and current operation despite the fact that is increasingly used for commercial launches. Further differences will be discussed following application of the scale.

4.2.1 Cecil Spaceport

Cecil Spaceport is a FAA Licensed Non-Federal Launch Site located near Jacksonville, Florida (FAA AST, 2018). Cecil has been licensed as a Launch Site Operator (LSO) to allow for the use of horizontally launched commercial space vehicles (Jacksonville Aviation Authority, 2014). Cecil has never been intended as a launch site for traditional vertical-launch orbital rocket systems but has been envisioned as an airport analogue serving the horizontal launch market. Specifically, the use of suborbital horizontal launchers for tourism purposes is a targeted market in addition to horizontally launched air-dropped small orbital vehicles (such as the GOLauncher 1). Based on this background, Cecil serves as a good example for a developing spaceport.

An application of the SRL scale can be used to determine the current development level of Cecil Spaceport. Specifically, an analysis of each level of the scale can be used to determine the current position of Cecil Spaceport, while an examination of the Cecil Spaceport Master Plan can be used as a guide to the intended final capabilities intended to be developed. Cecil Spaceport has achieved SRL 1 as demonstrated by its basic definition and designation of Cecil Airfield as Cecil Spaceport (showing a defined area and general background definition).

SRL 2 achievement requires the development of a CONOPS based off of a general background concept. As depicted in the Cecil Spaceport Master Plan, a CONOPS has been developed and published (Jacksonville Aviation Authority, 2012). To graduate to SRL 3, an LSO License (granted by the FAA) is required. Cecil Spaceport was granted a license, LSO-09-012, showing they have refined their CONOPS and demonstrated the intention or capability to support a launch operator.

At this stage, Cecil has graduated from a concept spaceport to a developing spaceport, meaning that its capabilities are growing and that actual improvements are being made rather than simple planning. In June of 2018, Cecil Spaceport hosted an engine test for Generation Orbit, demonstrating a test operation. With this, Cecil has achieved SRL 4 by proving its ability to support operations. SRL 5 requires the support of successful launch operations. Cecil Spaceport has not yet demonstrated support capabilities for operations outside of a test environment, showing that it can be identified at SRL 4 effectively.

Cecil Spaceport is one of a number of small spaceports which have recently achieved LSO Licenses, but which are only beginning to develop true support capabilities for possible users. The granting of a license shows that a spaceport has achieved or planned for all necessary requirements as considered by the FAA and is a significant accomplishment. Once granted, spaceports are able to focus on developing the infrastructure required to support the launch of payloads as granted by their LSO License.

As Cecil is in this stage, its growing capabilities can be compared to the SRL scale to shows the effectiveness of the scale in measuring the growth of a Spaceport's support capability.

4.2.2 Cape Canaveral Air Force Station/Kennedy Space Center

Cape Canaveral is an amalgamation of the federally operated launch sites of KSC and CCAFS, operated by NASA and the USAF respectively. CCAFS/KSC has served for decades as America's premier orbital launch facility, launching rockets to the moon and beyond. In the last two decades, CCAFS/KSC has seen an influx of commercial launch operators as its government launch programs wind down. While new government programs are in development, they have yet to progress beyond the test stage while commercial launchers have rapidly advanced.

With a growing focus on commercial launch, CCAFS/KSC has sought to refine its processes and achieve cost efficiencies to remain a competitive spaceport with the newfound growth of commercially operated spaceports. It stands as a useful example for the application of the SRL scale to an established and well-developed spaceport. Due to swings in political direction and changes in commercial launchers, CCAFS/KSC has seen a significant range in operating activity throughout its lifetime. As the SRL scale is intended for use based on currently evidenced capabilities, CCAFS/KSC will be assessed throughout the Post-Shuttle era.

As described in the CCS Master Plan, Cape Canaveral has a defined spaceport area covering CCAFS and KSC (Space Florida, 2017)[5]. This satisfies the intents of SRL

[5] While Space Florida is not responsible for CCAFS and KSC, it is a stakeholder in operations there and plays a part in any commercial operations. As such, its Master Plan for the Cape Canaveral area serves as a legitimate resource for the planning requirements espoused by the first three levels of the SRL.

1. A defined CONOPS exists in the same document, fulfilling the evolution to SRL 2. As a Federally Operated Launch Site, CCAFS/KSC does not have an LSO License but its operation by the government fulfills the same purpose. This fulfills the requirement for SRL 3. Worth noting at this point is that Space Florida does control portions of CCAFS/KSC and has an active LSO, but these areas are not directly under consideration for this study. As expected, CCAFS/KSC has already completed the requirements for spaceport planning and can now be assessed in the spaceport development stage.

SRL 4 requires the capability to support test operations in a limited capacity. CCAFS/KSC has supported test operations in support of the Commercial Crew, Commercial Cargo, and Artemis Program, in addition to support for other military users. These test operations can be highlighted by the AA-2 launch test for the Orion Ascent-Abort test. This launch tested the abort capabilities of the Orion capsule and demonstrated the capability of CCAFS/KSC to support test operations. SRL 5 requires operational support capability of a single launch system and the capability to support test operations for others. CCAFS/KSC has supported long running operations of the Atlas V launch system, demonstrating the capability to support ongoing launch operations of a single system. At the same time, CCAFS/KSC has supported test development of the Falcon 9 launch system, demonstrating its repeated ability to support vertical landing operations.

SRL 6 requires mature operational support of a single launch system and initial support capability of others. As seen by the support of SpaceX Falcon 9 launches from CCAFS/KSC, the spaceport is capable of supporting repeated launch operations of the Falcon rocket over a relatively short period. This has been made possible by a concerted effort to refine documentation and support requirements to enable faster launch operations. The implementation of the Automated Flight Safety System has significantly reduced manning requirements for CCAFS/KSC support of future launches and has served to delineate future requirements efficiency. While supporting this mature process, CCAFS/KSC has also supported launches of the Delta and Atlas programs, evidencing the ability to support multiple users. SRL 6 marks the end of the development phase for a spaceport, with SRL 7 measuring growing spaceport maturity.

SRL 7 focuses on the ability to rapidly recycle between launch systems or to launch a single system rapidly. CCAFS/KSC has demonstrated the ability to rapidly recycle between launch systems, recycling between a Falcon 9 and Atlas 5 in less than 36 hours. This follows the announcement that the 45th Space Wing could accommodate two launches in 24 hours. This demonstrated rapid launch capability provides evidence to support the maturing processes of CCAFS/KSC.

SRL 8 focuses on the capability to operate multiple launch operations simultaneously. At this stage, a launch center must be able to support operations of different launch vehicles over the course of a single period as opposed to rapidly cycling between launch systems. This capability is fundamentally different from rapid cycling as it requires either larger personnel commitments to perform simultaneous operations, or significant technical sophistication enabling launch support personnel to juggle two operations. At this stage, a spaceport is approaching airport-like operational cadences and support capabilities. CCAFS/KSC are not yet at this stage of rapid launch but are moving in this direction rapidly. With next generation launch vehicles espousing rapid reuse capabilities without significant refurbishment, CCAFS/KSC have invested in modernizing their launch support infrastructure and procedural requirements. CCAFS/KSC are likely to be the first federally operated, and likely only operational, spaceport to achieve SRL 8 in the near term.

The transition into SRL 7-9 demonstrates a spaceport that has proven its capability to support all intended launch types and is now progressing in the maturity of its processes. These phases focus on increasing efficiency and launch cadences, which correlate well with the true support capability of a spaceport. CCAFS/KSC has a long history of launch performance and is now working to demonstrate rapid-launch capability. The application of the SRL scale again shows that the measure of a spaceport's ability to operate with commercial launch customers and to meet their needs can be accurately assessed.

5.0 Implications and Considerations

5.1 Development Guidelines

The SRL scale was developed with the intent of providing a generalizable measure of spaceport readiness across the spaceport industry. As such, its application to both a federally operated launch range and a commercial spaceport can be seen as a proof of concept of its effectiveness in this regard. While the scale on its own provides a guideline for the current operational support capabilities of a spaceport, it can also be used as a planning guideline for a spaceport seeking to advance in its capabilities in a measured way. By providing an expectation of support readiness, the SRL provides a new guideline in an area of business only vaguely explored currently.

An important consideration in the application of the SRL for planning or examination purposes, is the timeline for achieving an increased SRL level. As noted earlier while discussing limitations, the SRL itself does not account for differing degrees of time and resources required to advance between SRL levels. Figure 1, below, breaks down the notional SRL scale in a timetable format for easy discussion. Figure 1 is focused on the stages of progression of a new spaceport specifically in regard to the levels of the SRL. On the left of the figure, the Ideation component of spaceport development provides a point of focus. At this stage, a spaceport does not yet exist on paper, but planning is actively occurring to achieve the licensing/designation requirements to make official recognition occur. This stage of development represents a climb in resource requirements and time commitments as each SRL level is achieved. As a generic guide to development, the SRL can be used at this stage to provide a simplistic direction for a spaceport seeking official recognition.

The middle of

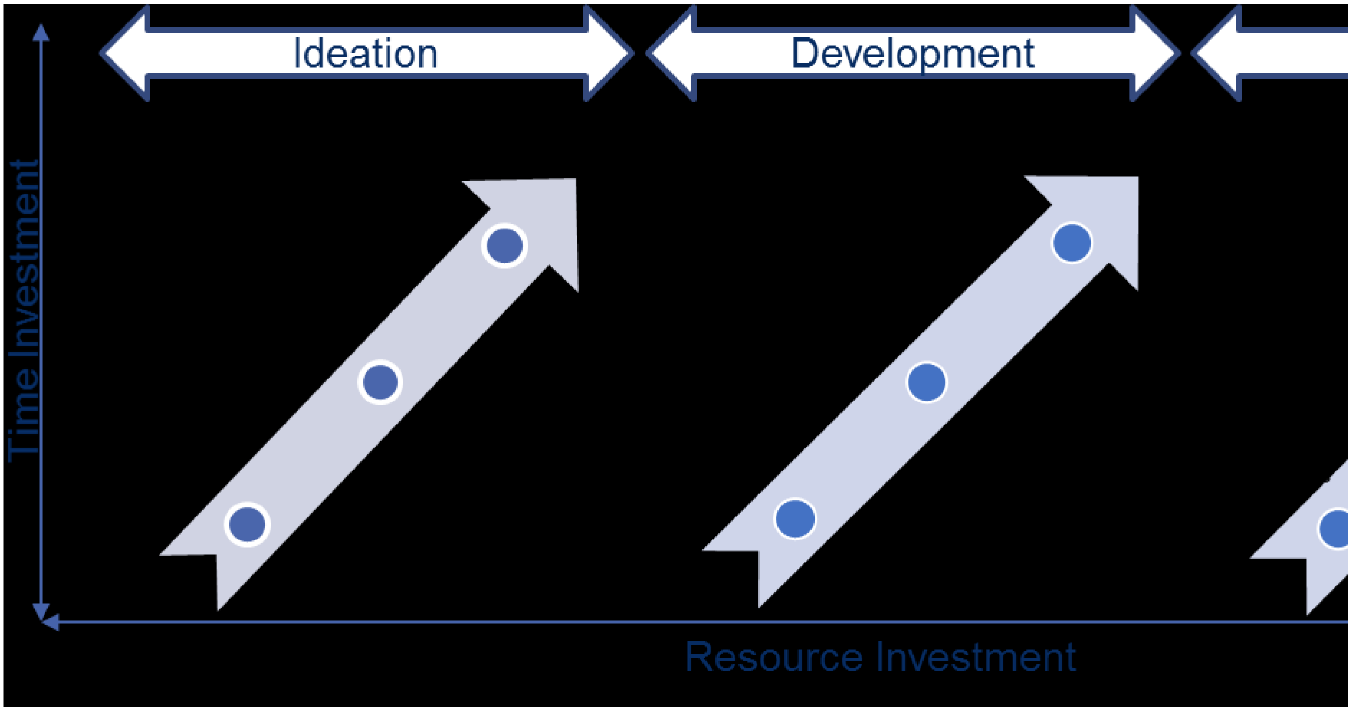

Figure 1, focused on spaceport development, focuses on infrastructure. Given that a spaceport has now achieved recognition, it can be expected that the spaceport will now seek to advance their capabilities such that they are able to support their expected consumer base. This effort can take many forms but will likely primarily focus on infrastructure development and risk mitigation. The goal of SRL 4-6 is to enable a spaceport to effectively provide the capabilities required for successful launch operations, and to begin developing those capabilities beyond initial capacities.

As discussed previously, spaceport development again proceeds non-linearly with increasing difficulty with each SRL achievement. With progression beyond SRL 3, a spaceport has completed ideation and is actively developing capabilities. At this stage, the focus for a spaceport is to test and prove out their initial assertions in SRL 4. With different spaceports seeking to capture different components of the marketplace, the exact scaling models are likely to differ. As such, the SRL scale remains generalized at this level to capture differences in infrastructure requirements.

At SRL 5, a developing spaceport is seeking to refine their processes with a user. With SRL 6, a spaceport is now maturing their processes with this user and entering true operational status. The development stage of a spaceport will see significant monetary investments along with revisions and refinements to the initial spaceport operations model. Utilizing the SRL, a spaceport can follow a generalized growth process that clearly shows their current capabilities and measures the maturity of their processes within their specified launch field. The final stage of the SRL scale focuses on the maturation of spaceport support processes.

Progressing beyond SRL 6, the spaceport has been established as an operational concept and possesses all of the required infrastructure to carry out launch operations. It is now incumbent that the spaceport begins to develop efficient and effective processes that are able to keep pace with the rapidly maturing commercial launch field. Specifically, the introduction of rapidly reusable launch vehicles has necessitated an ability to provide significantly more agile support capabilities for commercial launch providers. This is especially true when compared against government launch operators who typically schedule launches months or years in advance. Legacy operations such as these have required significant adjustments at federally operated launch sites that have performed to government schedules for decades whereas new commercial spaceports are able to enter the market with procedures more adept at answering modern launch requirements.

With a focus on process maturation established, Figure 1, shows a simplified development process for SRL 7-9. At this phase of development, a spaceport is now focusing on maturing their support processes to enable more airport-like operation. The desire end goal, achieved at SRL 9, is the capability to operate with multiple vehicles on an as-needed launch capability[6]. Before this capability is achieved, a spaceport must first exemplify an ability to improve their response capability based on existing launch operations. For this reason, the SRL scale must be approached linearly as a spaceport may be able to demonstrate rapid launch capability on a unique mission capability without demonstrating an evolved process.

The same process of testing, refinement, and maturation is applied to SRL levels 7-9 as was applied at SRL levels 4-6. This simplification enables an easy to recognize process which can be adapted to meet the needs of any spaceport without a tailored approach. By enabling a generalized system throughout development, this approach to the SRL scale allows for active use throughout a spaceports development operation. Further, the simplification enables a proactive approach to use, allowing for planning ahead of a spaceport's current SRL level by leveraging the same processes that were initially used to achieve the currently designated SRL level.

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[6] For the purposes of this study, it is not expected that a spaceport will be able to achieve airport-like operational cadences in the near term. A spaceport reaching SRL 9 is exemplified by a range user requesting a launch slot and the range being able to then support this requirement without significant process or operational changes. Operations at this cadence are inherently limited currently by the time required to prepare a launch vehicle for a mission, though this may change as launch vehicles become more capable of rapid response operations.

The SRL scale presents a new capability for measuring spaceport readiness throughout the development and growth of both commercial and federal spaceports. While research exists currently on safety, economic, and operational constraints of growing spaceports, the SRL scale provides a proactive approach to spaceport development. Effective application of the SRL scale in the opening stages of a spaceport's conceptualization will provide a straightforward path to actualization of a spaceport development plan. Further, use of the SRL scale will enable commercial and government launch organizations to easily comprehend the support capabilities of a spaceport and thus eases difficulties associated with determining operational launch sites for specific launches. The SRL scale can also be used effectively by spaceports already in operation by providing a guideline to achieve optimization.

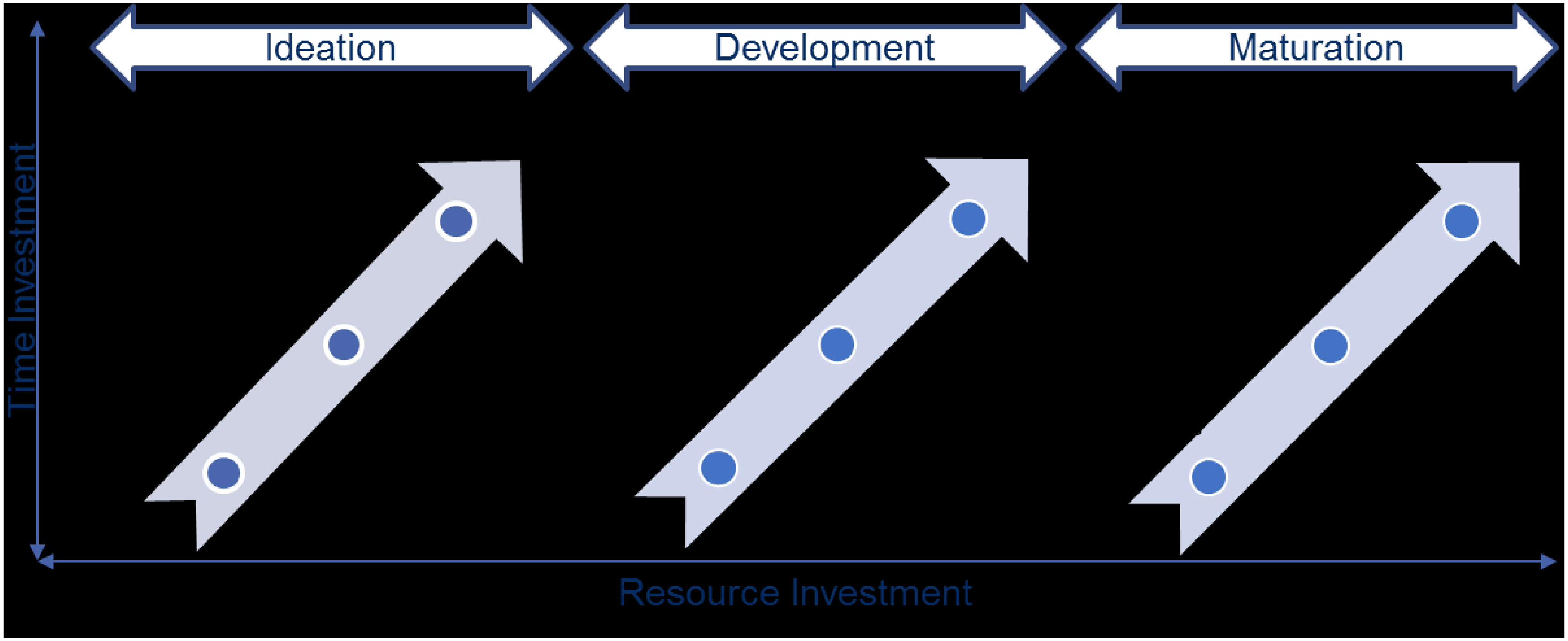

Figure 1: Proposed SRL Investment Scale

5.2 Cross-Range Operations

An important component of federally operated launch ranges is their ability to perform functions as support ranges. This means that the instrumentation and general capabilities of one launch facility are able to actively network and support launch operations at other facilities. Networking is prominent in military launch operations, but also features very importantly for NASA launch architecture. Notably, network operations are able to link tracking and command facilities across many of the different NASA operations and launch centers. This network capability serves as a strong force multiplier for federally operated launch centers. This capability is especially important for mission support following the launch phase of a space vehicle deployment, but still features importantly (primarily for safety reasons) during launch operations.

While cross-range capability remains a component of governmental launches, the introduction of Autonomous Flight Safety Systems (AFSS) has decreased the need for active participation in the tracking and command-destruct functions of many launch vehicles[7]. While the need for support capability is reducing, it is likely that many government launch operations are likely to require significant spaceport support operations that may not otherwise be provided to commercial operators utilizing AFSS systems. Therefore, federal launch sites are likely to remain the only ranges possessing the full-support capacity (telemetry and radar tracking, command-destruct, meteorological systems, down-range integration) traditionally utilized during space

[7] Currently, the Falcon series of launch vehicles operated by SpaceX is the only operable AFSS system. The majority of commercial companies have expressed a desire to implement similar systems in the future as other next generation launch vehicles enter service. The US military has stated that AFSS will not be implemented on current generation launch systems, expected to remain in service for several decades. As such, command-destruct and other supporting capabilities will remain a requirement for federal launch sites.

launch operations. This is due in large part to the significant infrastructure investments required to demonstrate these capabilities that are unlikely to be required by many commercial users.

As cross-range utilization becomes more focused on government customers, the increased costs of operating at federal launch sites are likely to drive a portion of commercial launch operations to commercially operated spaceports more in line with the launching company's support requirements. Despite this, governmental users are unlikely to accept any decreased factor of safety that would evolve from decreased support capabilities. Based on this expectation, both federally operated launch sites and commercially operated spaceports may develop further to support their own niche markets, leading to specialization that may not otherwise occur.

5.3 Limitations

The SRL scale is designed around allowing a rapid and simple assessment of a spaceports current capabilities at supporting a launch operator. As such, the scale has focused on the generally expected support capabilities based on historical needs of launch customers without focusing on projected future operations (such as point-to-point space operations). The SRL also provides a means for guiding growing spaceports towards achieving maturity in the spaceport sector without focusing entirely on a single launch system or operational concept. Given its generality when applied to the spaceport field, the SRL faces a number of current limitations.

The SRL was developed based on the American concept of spaceport operations. This focuses largely on capabilities to support multiple launch vehicles across differing operational concepts. Spaceports outside of America (especially in countries with less focus on launch operations outside of LEO) may be constructed and operated with significantly different expectations of support requirements. Further, these spaceports may operate with operational concepts not considered by American spaceport operators. Further limiting the SRL is the focus on a system of systems view. While the traditional TRL scale is focused on technology development at the system or subsystem level, the broader approach of the SRL focuses on capabilities at a lower fidelity. This limitation means that individual components of a spaceport (which may be more or less advanced than the aggregate capabilities of the entire facility) cannot be accounted for.

Further limitations exist in the inability to narrowly apply the SRL to a specific launch concept. Spaceports have grown to support different customers with different launch needs, but the SRL is intended to paint these different operations with a wide brush. While not able to dive into the exact specifics of a spaceports intended support use, the SRL can still be applied at a high level to identify the maturity of a spaceports processes for supporting a commercial launch. While the SRL maintains a number of limitations, it still can be accurately and effectively applied to spaceports to assess their maturity. As such, it can contribute largely to the growing spaceport industry as a means of maturity assessment and developmental guidance.

6.0 Conclusions

The introduction of commercial spaceports over the last decade and a half has seen the growth of a new industry often considered to be the boundaries of science fiction. The growth of commercial space launch vehicles has rapidly filled the expanding need for access to space while spaceports have begun to be licensed and operated to free commercial companies from the burden of operating within the strict confines of federally operated launch ranges. Despite these restrictions, federally operated ranges continue to espouse significant launch support capabilities not yet found in the commercial spaceport sector. As the launch industry grows, spaceports can be expected to rapidly invest in infrastructure and process improvement to meet the needs of the expanding space launch industry. As such, a method of measuring this growth and development is required to enable accurate assessments over the long term.

Development of the SRL scale has utilized the existing TRL scale framework and applied it to the rapidly growing spaceport sector. The TRL scale has traditionally been applied to individual sectors of the economy utilizing a tailored approach that enables the scale to accurately assess the specific requirements of a given sector without diluting the intent of the original scale. The SRL scale operates under a similar concept but features significant tailoring of the original scale to encompass operations occurring at a high level, with a significant focus on process and operational maturity rather than technological development. As such, the application of the SRL scale provides a new perspective to an area of research only now beginning to grow.

Further use of the SRL scale is worth noting in its role of a developmental framework for growing spaceports. The TRL scale is largely focused around procurement and technology advancement; while the SRL scale can be used in these roles, it also allows for measurement and planning of a spaceport's future capabilities without significant departure from current planning processes. This agile use of the SRL scale allows for use on spaceports only just beginning to be conceptualized to those which have launch space vehicles across the solar system. Also, worth noting is the ability of the scale to be applied despite rapid changes in operational concepts and launch system technology.

This study focused on the initial development of the SRL scale. Future research has the potential to significantly expand and further tailor the SRL scale to apply it to different forms of spaceports with higher specificity. The development of a derivate SRL scale focused on suborbital spaceflight may help to further define this component of space launch operations. Further, a focus on logistical and infrastructural considerations may enable a development of the SRL which enables analysis at the systems level in the same manner as the TRL scale. Finally, as spaceport development paths become clearer outside of the planning environment, future adjustments to the SRL will increase the scale accuracy and analytical capacity.

The generality of the SRL scale enables its use as next generation launch systems become operational and many spaceports grow to support their use. Armed with a new method appraising their growing capabilities and past successes, spaceports can use the SRL scale to prove out their present achievements and future accomplishments.

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