Federal Aviation Administration
Center of Excellence for
Commercial Space Transportation

Research Roadmap Report

December 2011

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1. Executive Summary

The Federal Aviation Administration's Office of Commercial Space Transportation (FAA AST) has established a Center of Excellence for Commercial Space Transportation (COE CST) in order to identify solutions for existing and anticipated commercial space transportation problems. This COE CST is a cost sharing partnership of academia, industry, and government that focuses on research areas of primary interest to the FAA and the U.S. commercial space transportation industry as a whole (Figure 1).

Developing a roadmap for future research was identified among the COE CST's first round of research tasks. To complete this, workshops were held where representatives from industry, academia, and government gathered to discuss what they saw as priority research objectives and the underlying organizational structure. The results from these workshops are presented in this document, and represent a near consensus opinion from these representatives of disparate fields. It is our conviction that these COE CST research goals and objectives will find broad application and relevance to the entire commercial space enterprise.

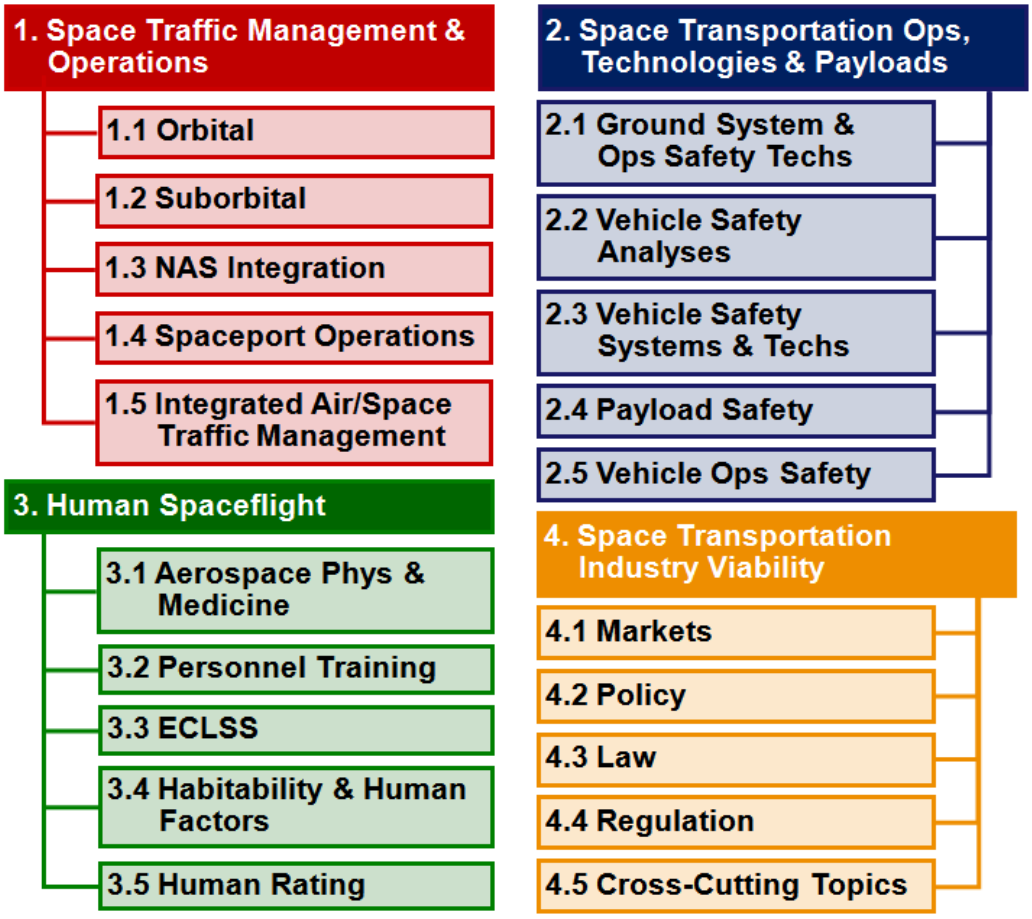

Figure 1: Research Theme Structure

For each of the four research themes, a key recommendation or high-priority research item was identified:

Theme 1 - Space Traffic Management (STM) & Operations

The first research theme focuses on the traffic management and operations of vehicles from the ground, through suborbital flight, to orbit. More specifically, this includes orbital STM, the integration of air and space traffic, and spaceport operations.

High-Priority Research: In order to reduce the imposition made on the National Airspace System and facilitate the integration of air and space vehicle traffic, a minimum safe corridor for launches and re-entries must be identified.

Theme 2 - Space Transportation Operations, Technologies & Payloads

The second theme is made up of a wide range of research areas. Ground system and operations safety technologies, vehicle safety analyses, vehicle safety systems and technologies, payload safety, and vehicle operations safety are all part of this theme.

Recommendation: Further effort is required to identify top research objectives from the technological landscape. This will require iterative effort between this theme and the other three themes.

Theme 3 - Human Spaceflight

The third research theme is concerned with the medicine, technology and training that is needed for both crew and spaceflight participants. This includes aerospace physiology and medicine, personnel training, ECLSS, habitability and human factors, and the human rating of vehicles.

High-Priority Research: Verifiable guidelines are needed for all spaceflight participants. To develop these, extensive data on the risks of various medications and conditions in the space environment are required.

Theme 4 - Space Transportation Industry Viability

The last research theme is focused on the business and government related aspects of CST. This includes markets, policies, laws, and regulations.

High-Priority Research: What “the market” is remains an open question to the CST industries. Identifying and verifying the suborbital and orbital microgravity commerce and research opportunities are highly important.

While the structure and prioritization presented in this report were developed with COE CST in mind, the results need not be limited to this scope. The representatives that attended the workshops and whose input is codified here captured the ideas and demands of the entire industry.

2. Overview of the Study

The results presented in this report were generated through a pair of workshops where numerous companies, agencies, research centers, universities, NASA, and the Department of Defense (DoD) were contacted and invited to send representatives. For each of the two workshops, approximately 60 people were in attendance.

The first was held at Stanford University in Palo Alto, CA, April 6-7 2011 and the second was at the Lockheed Martin Global Vision Center in Arlington, VA, August 16-17. The two locations and times allowed us to capture the views of a broad range of researchers with difficult schedules and travel availabilities.

At the workshops, the attendees were presented with several overviews on the different research themes. In addition, presentations from General Jay Santee of the Office of the Secretary of Defense - Policy, Professor John Logsdon of George Washington University, Faith Chandler of NASA's Office of the Chief Technologist (OCT), and Jeff Foust of Futron all gave input from their perspective on the landscape of CST.

For roughly 8 hours at each workshop there were breakout discussions where the large group broke into 4 smaller groups centered on each research theme. Some spent time in several different themes' discussions, while others focused on a single discussion group. The tasks set for them were:

- Finding an organizational principle or mission statement
- Correcting (if needed) the structure of the theme as defined by FAA AST
- Documenting the main research sub-areas
- Identifying important next-steps
- Prioritizing research topics

The groups were not necessarily able to complete all these tasks, but all made considerable progress towards the goals. After the breakout discussions, their work was summarized in a set of presentations given to the plenary group and accompanied by group discussion.

Chairs for each breakout group were chosen in advance as experts in their fields (Table 1).

	Workshop 1	**Workshop 2**
Theme 1	Kelvin Coleman (FAA AST) & Karl Bilimoria (NASA Ames)	Mike McElligott (FAA AST)
Theme 2	Dr. Dan Rasky (NASA Ames) & Dr. Juan Alonso (Stanford U.)	Nick Demidovich (FAA AST)
Theme 3	Dr. Jon Clark (Baylor College of Medicine)	Dr. Mark Weyland (NASA JSC)
Theme 4	Ken Davidian (FAA AST)	René Rey (FAA AST)

Table 1: Breakout Group Chairs

The research theme breakdown structure (Figure 1) was one of the results of these discussions. It began with a structure provided by FAA AST, but was revised to various degrees during both workshops. In addition, deeper levels of substructure were identified, in some cases down to the level of individual research tasks.

Workshop presentations are available at http://coe-cst.stanford.edu, while additional information on the COE and this report is available at http://www.coe-cst.org.

3. Commercial Space Transportation: A Strategic Overview

Overview of the Industry

The commercial space transportation industry has many sectors: orbital and suborbital launch vehicles, space tourism, spaceports, and numerous subsectors that support them including everything from pressure vessel manufacturers to software developers.

Much of the industry is driven by the end-customer. For orbital launches this is often the communications industry or the military, which uses satellites for surveillance, communications, and sensing applications. NASA and universities use orbiting platforms for Earth sensing and astronomy, but they also use the vehicles to launch probes out of Earth orbit to the moon, sun, and other planets in the solar system.

There are very few manufacturers of orbital launch vehicles due to the massive development and operational costs associated. Currently United Launch Alliance, Orbital Sciences, and SpaceX are the only companies who are offering orbital launch services in the USA. With the notable exception of SpaceX, all of these vehicles were developed with close partnership with government agencies or the DoD.

The suborbital launch industry has traditionally been limited to small sounding rockets used for microgravity, atmospheric, and astronomical research. However there are several companies currently developing vehicles which would also (or primarily) be used for suborbital tourism. These companies include Virgin Galactic, Sierra Nevada Corporation, XCOR, Blue Origin, Armadillo Aerospace, and Masten Space Systems.

These demands for suborbital and orbital launch vehicles drive the development of the vehicles themselves, which in turn drives the development of subsystems and support systems.

The Role of FAA AST

The FAA's Office of Commercial Space Transportation (FAA AST) has mandates to both regulate and encourage the commercial space transportation (CST) industry. AST regulates the operation of both spaceports and vehicles. AST does not regulate launches by and for the US government (for example, a Delta IV launching an NRO payload or NASA launching a science mission).

Reusable suborbital vehicles may obtain an experimental permit instead of a license. Permits have the advantage of fewer vehicle specification and safety requirements, but they are much more limited in scope; the operations must be for the non-commercial purpose of research & development, gathering data for a license, or crew training.

Licenses are required by all other vehicle launches in the US that exceed the limits for amateur rocketry, and are applicable either to a specific launch or can be used for up to 5 years, depending on the specifics of the license. US companies launching payloads anywhere in the world and foreign companies launching within the US are all regulated by the FAA AST. This requirement stems from the 1967 United Nations International Outer Space Treaty whereby the nationality of the launch operator and the nation in which the launch occurs are responsible for any subsequent damage that occurs.

Obtaining a vehicle license or permit requires five steps: policy review (national security and foreign policy), payload review (payload safety issues), maximum probable loss determination (dollar amount due to bodily injury or property damage), an environmental determination (impact of launch on environment), and a safety review (range and launch site safety issues).

Launch or reentry sites (commonly referred to as spaceports) must obtain licenses, however the process is slightly different. The steps are: policy review (national security and foreign policy), launch site location review (ground boundaries, flight corridors, and risk assessments), agreements (airspace and marine), an explosive site plan (minimum safe distances), and an environmental impact review (based on any hazardous materials). In addition, spaceports must have plans in place for accident response and investigation.

The second mandate for FAA AST is to encourage, facilitate, and promote the CST industry. Tasks that support this mandate include generating a series of industry reports such as launch forecasts, economic impact reports, Year in Review reports, Developments and Concepts reports, and others. In addition FAA AST conducts research and development outside of the COE to further technologies that would be a benefit to the industry as a whole. FAA AST also conducts a CST Grants program, conducts an annual conference and has active international outreach activities.

The Center Of Excellence for Commercial Space Transportation (COE CST), established "in order to identify solutions for existing and anticipated commercial space transportation problems," aids in both mandates by identifying and completing research tasks that are important. These tasks can be geared towards informing regulatory practices or towards developing components and systems that many companies could use in order to reduce engineering and development costs.

4. Theme 1: Space Traffic Management & Operations

Mission Statement

The Space Traffic Management & Operations research theme will focus on facilitating commercial utilization of suborbital vehicles, orbital space resources, and spaceports. It will also focus on integrating commercial space vehicle and spaceport operations into the NAS by providing equitable sharing of NAS resources for both air and space traffic.

Description and Impact

Theme 1 is centered on finding the best way to deal with the traffic associated with the anticipated rapid increase in orbital and suborbital vehicle operations. Several major problems will be engendered by this rise in traffic.

Currently in the US there are roughly 850,000 commercial airline flights per month, while there are rarely as many as 10 commercial rocket launches per month. The FAA requires a large stay-out zone around these launches, but because they are rare occurrences from a handful of locations, the impact on commercial aviation has been minimal. However, in the coming years the number of launch vehicles operating regularly is projected to increase dramatically from an increasing number of launch sites. The net result of this is a logistical and economic impact that could easily become monumental and simply unacceptable.

Aside from the conflict between launch vehicles and airplanes, the current upper limit for air traffic control is 60,000 ft. If the number of vehicles and objects above this limit becomes large, some new form of traffic management will become necessary to reduce the risk of collision.

A third major task involves developing something akin to the operational procedures in place at our nation's airports, but optimized for the requirements of orbital and suborbital launch vehicles.

Space Traffic Management & Operations Research Program Structure

- Program 1.1 Orbital STM Research
  - Project 1.1-1 Orbital STM Services
  - Project 1.1-2 Guidelines
  - Project 1.1-3 Standardization
- Program 1.2 Suborbital STM Research
  - Project 1.2-1 Space Environment
  - Project 1.2-2 Traffic
- Program 1.3 NAS Integration Research
  - Project 1.3-1 Takeoff and Landing Requirements
  - Project 1.3-2 Transit Requirements
  - Project 1.3-3 Integration Into NextGen
- Program 1.4 Spaceport Operations Research
  - Project 1.4-1 Launch and Landing Requirements
  - Project 1.4-2 Interoperability
  - Project 1.4-3 Support Services Requirements
- Program 1.5 Integrated Air/Space Traffic Management Research
  - Project 1.5-1 Placeholder

Priority Research Tasks

- Airspace
  - Deconfliction between air and space traffic
    - What kind of airspace do we need for the vehicle?
    - Do we need to reserve portions of NAS for rocket traffic?
    - Do we need transition corridors from air to space?
    - Do we need a new class of airspace?
  - How does space transportation interface with NextGen?

Example of a Current Research Task

Task 185: Unified 4-D Trajectory Approach for Integrated Traffic Management

Principal Investigator: Dr. Juan Alonso, Stanford University

The projected growth in demand for the use of the traditional airspace by commercial space transportation entities will make it increasingly difficult to accommodate launches on a Special Use Airspace basis. The purpose of this project is to use 4-D time-space probabilistic trajectories and safety assessments to develop the foundation of a plausible Integrated Airspace Management System. Some sample results showing these modeled trajectories are shown in Figure 2 below.

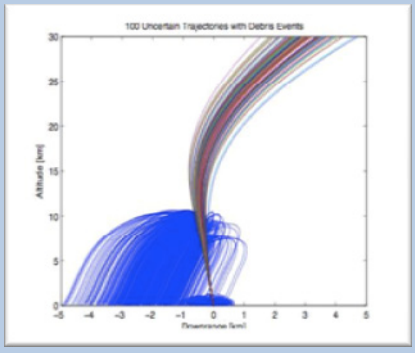

Figure 2: Possible trajectories, including debris

- Spaceport Requirements
  - What are the vehicle specific requirements (fueling, servicing, passengers, etc)?
  - Talk with existing launch sites to determine best practices?
- Air Traffic Issues
  - What are the navigational requirements?
  - What are the flight planning requirements?
  - How are anomalies resolved?
  - Who do we tell that we're aborting?
- Weather and Space Weather
  - Triggered lightning
- Command and Control
  - What should be command and control element at spaceports?
  - What are the vehicle specific command and control requirements?
  - What is the integrated concept of operations?
  - Who offers these services?

5. Theme 2: Space Transportation Operations, Technologies & Payloads

Mission Statement

The intent of the Space Transportation Operations, Technologies & Payloads research theme is to perform research to significantly improve reliability/safety/risk posture and availability for stakeholders in full mission cycle vehicle operations and ground operations while ensuring that proper business case closes (and no negative interactions with rest of the participants).

Description and Impact

The wide span of this research area makes it difficult to define concisely. However, it can be subdivided broadly into two areas: component-level and systems-level research. From there, the best description is via examples.

Component-level research includes developing new thermal protection systems for re-entry, black boxes that could be integrated into spacecraft and launch vehicles, and standardized sensors.

System-level research includes developing operational procedures, safety analyses, licensing and certification processes, and human-rating standards.

Currently this type of work is only performed with a specific application or customer in mind. NASA develops technologies and systems and operations specific to its own vehicles and missions, while space transportation companies do similar work for their own purposes.

As the field of commercial space transportation increases in size it will be beneficial to develop more generic components and systems that can be adapted to different applications rather than be re-designed for each new case.

Space Transportation Operations, Technologies & Payloads Research Program Structure

- Program 2.1 Ground System & Operations Safety Technologies Research
  - Project 2.1-1 Roles & Responsibilities
  - Project 2.1-2 Ground Support & Operations Technologies
  - Project 2.1-3 Maintenance & Inspection Requirements
  - Project 2.1-4 Space Operations
  - Project 2.1-5 Ground Operations
  - Project 2.1-6 Pre-Launch Processing
- Program 2.2 Vehicle Safety Analyses Research
  - Project 2.2-1 Parameter Maximization Analyses
  - Project 2.2-2 Operational Limitation Analyses
  - Project 2.2-3 Simulation and Testing
- Program 2.3 Vehicle Safety Systems & Technologies Research
  - Project 2.3-1 Safety Equipment
  - Project 2.3-2 Post-Flight Diagnostic Equipment
  - Project 2.3-3 Crew Survivability (ECLSS)
  - Project 2.3-4 Other Safety Equipment
- Program 2.4 Payload Safety Research
  - Project 2.4-1 Extent of Disclosure
  - Project 2.4-2 Interfaces
  - Project 2.4-3 Impact on Flight Safety
  - Project 2.4-4 Handling Procedures
  - Project 2.4-5 Electro-Magnetic Interference
  - Project 2.4-6 Non-Operational Payloads
  - Project 2.4-7 Connectors & Interfaces
- Program 2.5 Vehicle Operations Safety Research
  - Project 2.5-1 Abort Procedures
  - Project 2.5-2 Other Off-Nominal Operations
  - Project 2.5-3 Return to Flight After Incident
  - Project 2.5- 4 Safety Reporting Systems
  - Project 2.5- 5 Mandatory Reporting Requirements
  - Project 2.5- 6 Go/No-Go Decisions

Example of a Current Research Task

Task 228: Magneto-Elastic Sensing for Structural Health Monitoring

Principal Investigators: Dr. Andrei Zagrai & Dr. Warren Ostergren, New Mexico Tech

Structural health monitoring of modern satellites is very expensive and time-consuming. Future spacecraft require sensing technologies that are reliable, multi-purpose, durable, and long-lived. These sensors need to perform a multitude of tasks, such as: detect and characterize impact damage from space debris, assess structural integrity of the spacecraft, provide information on structural interfaces, explore spacecraft electrical signature, enable reusable component requalification for flight, and possibly conduct non-contact inspection in space. The purpose of this task is to develop innovative magneto-elastic sensing technologies for structural diagnosis of space vehicles. A schematic showing a sample design of these sensors is shown below in Figure 3.

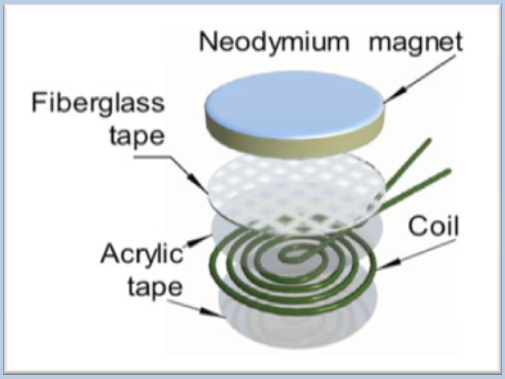

Figure 3: Diagram of a magneto-elastic sensor

Priority Research Tasks

- Research and recommend safe, expeditious, and cost efficient processing of reusable manned or unmanned vehicles that are payloads on ELV's
  - Landing, inspection, modification if needed, transportation, and integration
- Explore expeditious procedures for licensing and permitting
  - When minor changes to a licensed spacecraft, consider between having to re-license entire spacecraft or license the specific change
- Explore expeditious processes to migrate technologies and payloads to be tested in flight
- Research the physics and impacts of re-entry debris
- Study how to facilitate small companies to have access to NASA and FAA test facilities (e.g. test chambers)
- Investigate what NASA and FAA do for handling CG locations for aircraft before flight in order to develop a reliable procedure that can be used to process payloads
- Analyze which safety equipment and systems can be leveraged from aviation, and identify the type of analysis required
- Study literature on redundancy for safety critical systems to develop guidelines for redundancy levels
- How much information does a developer/operator need to tell the FAA in order to safely fly a payload (leverage work from the NASA Flight Opportunities Program)?
- Case study of a generic deployment of a payload on an RLV, and how to do a safety analysis on this
- Develop minimum requirements and guidelines for a return to flight after off nominal operation
- Study interoperability of commercial space safety management system with other FAA and TBD agencies and develop guidelines for vehicles, spaceports, and operators
- Hazmat template of what toxic materials information need to be provided to fire departments to assess resulting fire due to a vehicle crash

6. Theme 3: Human Spaceflight

Mission Statement

It is the goal of the human spaceflight research theme to optimize the human and spacecraft systems for performance, safety, and access for commercial human spaceflight.

Description and Impact

Since the beginning of manned spaceflight in 1961 and with very few exceptions since then, humans sent to space have gone through intensive physical training and screening. In the near future companies like Virgin Galactic, XCOR, Sierra Nevada Corporation and others may begin flying tourists on suborbital or even orbital flights. These tourists are unlikely to be prepared and screened to the levels that astronauts or cosmonauts are accustomed to.

This presents a host of unknowns about how medications and medical conditions will be affected by the space environment.

Human Spaceflight Research Program Structure

- Program 3.1 Aerospace Physiology & Medicine Research
  - Project 3.1-1 Standards Development
  - Project 3.1-2 Data Collection
  - Project 3.1-3 Databases
  - Project 3.1-4 Risk Mitigation
  - Project 3.1-5 Informed Consent
- Program 3.2 Personnel Training Research
  - Project 3.2-1 Medical
  - Project 3.2-3 Passengers
  - Project 3.2-3 Ground
  - Project 3.2-4 Crew
- Program 3.3 ECLSS
  - Project 3.3-1 Standards
  - Project 3.3-2 Modeling
- Program 3.4 Habitability & Human Factors Research
  - Project 3.4-1 Normal Conditions Assessment
  - Project 3.4-2 Emergency Conditions Assessment
- Program 3.5 Human Rating Research
  - Project 3.5-1 Protection & Utilization Considerations

Priority Research Tasks

Throughout the two workshops, there wasn't a consensus opinion on research prioritization.

Example of a Current Research Task

Task 255: Wearable Biomedical Monitoring Equipment for Passengers on Suborbital & Orbital Flights

PI: Dr. Richard Jennings, University of Texas Medical Branch

Collection of biomedical data from the diverse population of commercial spaceflight participants (SFP's) will greatly enable the FAA in developing relevant regulations for SFP's. The purpose of this task is to identify the gaps between current technologies and the medical data needs for SFP's, and then develop sensors that could be used by the CST industry to fill those gaps. In the photo below, Dr. Richard Jennings undergoes centrifugal testing at the NASTAR Center.

Figure 4: Dr. Richard Jennings at the NASTAR Center

7. Theme 4: Space Transportation Industry Viability

Mission Statements

The purpose of the Industry Viability research theme is to support effective policy decision-making and reflect the dual regulatory and promotional missions of the FAA Office of Commercial Space Transportation. Additionally, research addressing regulation is designed to maximize regulatory cost-effectiveness; research concerning industry viability aims to maximize industry growth.

Description and Impact

One of the largest unanswered questions in the commercial space transportation industry is "what is the market?" Different companies have vastly different opinions about what

will happen to demand in the coming decades. In Theme 4, answering this question is one of the primary goals.

Other topics that require detailed research and planning include domestic and international policies, legalities, and regulation.

Space Transportation Industry Viability Research Program Structure

- Program 4.1 Market Research
  - Project 4.1-1 Industry Description Research
  - Project 4.1-2 Industry Analyses
  - Project 4.1-3 Proposed Future Options
- Program 4.2 Policy Research
  - Project 4.2-1 Domestic Policy Research
  - Project 4.2-2 International Policy Research
- Program 4.3 Law Research
  - Project 4.3-1 Liability
  - Project 4.3-2 Insurance
  - Project 4.3-3 Barrier Analyses
- Program 4.4 Regulation Research
  - Project 4.4-1 Regulatory Parameters
  - Project 4.4-2 Historic Analyses & Analogies
  - Project 4.4-3 Comparative Analyses
- Program 4.5 Cross-Cutting Topics Research
  - Project 4.5-1 Omnibus

Priority Research Tasks

- Markets
  - CST demand market research
  - Retrospective analysis of:
    - Transition from government to private customers
    - Commercial failures
  - Workshop of industrial organization economists looking at CST industry
- Policy
  - Options of a single international space regulatory regime
- Law
  - Liability limitation: history, issues, and options
- Regulation
  - Barrier analysis of existing regulations

Example of a Current Research Task

Task 193: Defining the Future by Engaging Emerging Leaders

PI: Dr. George Born, University of Colorado at Boulder

The FAA COE program has three primary goals: research, training, and outreach. This activity emphasizes COE CST's outreach goal by engaging students in graduate seminar activities, conference attendance that emphasizes commercial space topics, and the execution of specific research work for presentation at professional space conferences in commercial space paper sessions. In Figure 5, students are shown at the first Emerging Space Industry Leaders Conference.

Figure 5: ESIL-01 Conference in Boulder, CO

8. Cross-Cutting Tasks and Integration

There are many research tasks that fall under more than one research theme. In some cases the interaction is two-way, where both research groups will need varying degrees of input from each other. This could range from full collaboration to simple periodic

information transfers. In other cases the interaction is only in one direction, with one research group simply requiring the output or knowledge base of another.

Below, some of the specific cases of interaction that were emphasized in our workshops are shown graphically in Figure 6. In addition these interactions are listed and detailed below the figure.

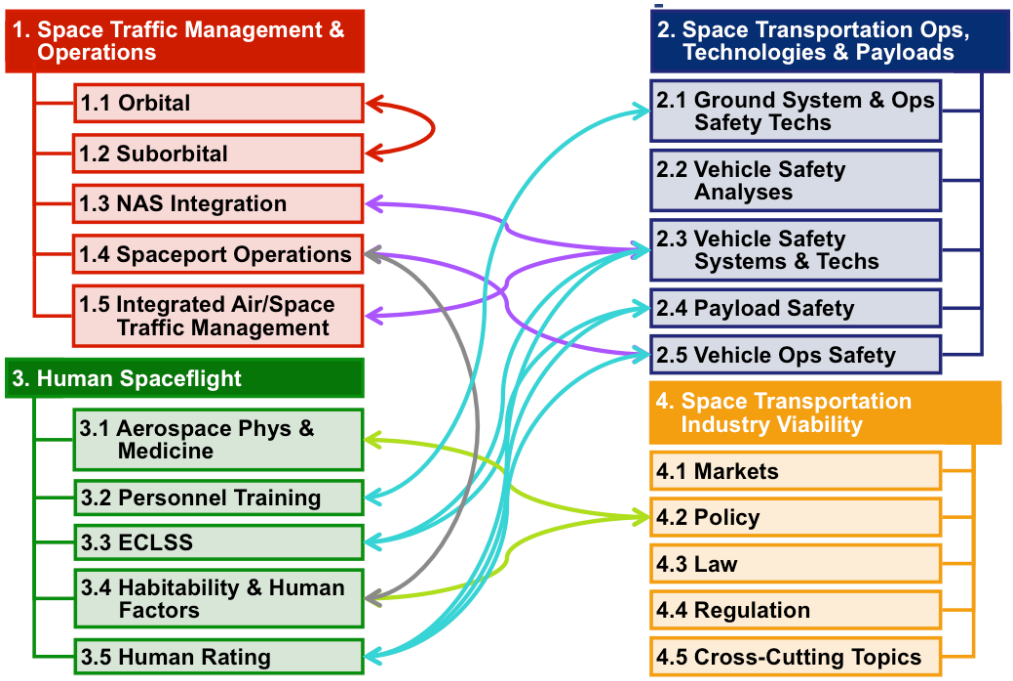

Figure 6: Research area dependencies

Dependencies between Communications, transponders, and beacons, NAS integration & Air and Space Traffic Management

- Inputs for the design of transponders, beacons, and communications systems (Theme 2.3) are needed from the researchers developing air and space traffic management strategies (Theme 1.3 and 1.4).

Dependencies between Flight diagnostic equipment & ECLSS

- Inputs from the ECLSS experts (Theme 3.2) are needed in order to design flight diagnostic equipment (Theme 2.3) that measures parameters related to ECLSS functionality.

Dependencies between Payload Safety & Occupant protection capabilities

- Interaction between the payload safety researchers (Theme 2.4) and those from the occupant protection capabilities group (Theme 3.4) is required in order to establish any possible dangers to the spaceflight participants from particular payloads.

Dependencies between Vehicle safety operations & Spaceport operations

- Interaction between the vehicle safety operations (Theme 2.5) group and the spaceport operations group (Theme 1.4) is required in order to establish:
  - Guidelines for contingency operations.
  - Off-nominal operation protocols
  - Determine what equipment is needed

- Desired interaction between the FAA and the vehicle operator to solve problems

Dependencies between Pre-flight care & Policy

- Interaction between the pre-flight care group (Theme 3.1) and the policy group (Theme 4.2) is needed to develop drug and alcohol testing standards for the CST industry.

Dependencies between Passengers & Space Transportation Operations, Technologies & Payloads

- Inputs are needed from Theme 2 for the development within Theme 3.2 of standardized training templates for spacecraft and/or missions.

Dependencies between ECLSS & Policy

- In order to provide a starting point for work in ECLSS (Theme 3.3), inputs from the policy group (Theme 4.2) are needed in order to review, analyze and summarize information on existing regulations and policies for ECLSS.

Dependencies between Habitability & human factors, Spaceport Operations & Space Transportation Operations, Technologies & Payloads

- Interaction is needed between the habitability & human factors group (Theme 3.4), the spaceport operations group (Theme 1.4), and Theme 2 in order to develop databases related to accidents and incidents. This will also include an anonymous reporting system to notify authorities of applicable events. Procedures for assessing the human factors associated with such an event must also be developed.

Dependencies between Human Rating / Vehicle Safety Systems & Technologies/ Vehicle Operations Safety

- Research into human rating procedures and standards will require extensive work between the human rating group within Theme 3.4 and the vehicle safety systems & technologies group (Theme 2.3) and the vehicle operations safety group (Theme 2.5).

9. Other Research Road Mapping Efforts within the COE

Within COE CST there are two other research road mapping efforts to define work structures for specific tasks that cannot be tackled by a single research group. Examples of this include flight software validation & verification and autonomous rendezvous and docking standards.

Software independent validation and verification is regarded as one of the major issues today and in the future for the timely and cost-effective development and certification of launch and re-entry systems. The goal of this effort is to hold a workshop in early 2012 for industry representatives and experts in the field in order to develop a research roadmap for impacting flight software validation & verification for CST systems.

In order to make LEO autonomous rendezvous and docking (AR&D) a routine and safe activity, a framework is needed to enable licensing of multiple vehicle systems. This will require a set of standards for AR&D, including approach trajectories, sensing, estimation, guidance and control, human interaction, and reliability. This activity will develop a research roadmap that will lead the way to a set of standards via individual research projects.

10. Conclusions

Through our series of workshops representative of more than 50 organizations with a stake in the CST industry were able to gather and discuss what they see as important research. These discussions have been transcribed into a detailed roadmap that the COE CST can use to achieve its goal of identifying solutions for existing and anticipated commercial space transportation problems.

The highest priority research items are summarized below:

- **Theme 1 - Space Traffic Management (STM) and Operations**
  - A minimum safe corridor for launches and re-entries must be identified.
- **Theme 2 - Space Transportation Operations, Technologies, and Payloads**
  - Further effort is required to identify top research objectives from the technological landscape, but the overriding issue is safety of flight.
- **Theme 3 - Human Spaceflight**
  - Extensive data on the risks of various medications and conditions in the space environment are required.
- **Theme 4 - Space Transportation Industry Viability**
  - Identifying and verifying the suborbital and orbital microgravity commerce and research opportunities is of prime importance.

While this roadmap and these research priorities have been developed with the COE as its main user, there is no true limit to its applicability. The views represented are a consensus view from many perspectives within the industry and the result is information that is if value to any organization that seeks to further CST in the US.

These research tasks contained within the roadmap will significantly benefit the industry by informing forthcoming regulations from the FAA and by using academic research to develop solutions to key problems retarding progress in the industrial sectors. Without sufficient funding for this research, however, this progress will be delayed needlessly.

In 2010, there were 4 licensed or permitted launches. In 2011 there were a total of 5. However, combining commercial satellite launches with COTS and CRS flights, OCT's Flight Opportunities Program, and Virgin Galactic's SpaceShipTwo there could easily be more than 40 in 2012. In 2013 that number could climb to 100 or above.

There are some who are skeptical of the predicted growth in CST, and for good reason. The industry is plagued by delays and it's not uncommon for launch dates to be postponed months or even years. Nevertheless, it is quite clear that commercial launch frequency will be increasing dramatically in the coming years and, in order to keep pace with this acceleration, AST will need to grow simply to maintain current licensing and permitting operations.

As milestones are reached and passed in the CST industry, new problems will arise and different priorities may result for research tasks. Therefore, this research roadmap will be updated on an annual or biennial basis. By cultivating a living document we will not only serve its original purpose for the COE, but also maintain it as a standard that other organizations may utilize.

Appendix I. COE CST Research Roadmap Workshop 1

Center of Excellence for Commercial Space Transportation
Research Roadmap Workshop I, April 6-7, 2011
Stanford University, Stanford CA

Attendee List

First	Last	Organization
Doc	Aguilar	Air Force Research Laboratory
Juan	Alonso	Stanford University
Farrukh	Alvi	Florida State University
Jim	Ball	NASA Kennedy Space Center
Herb	Bachner	CSSI, Inc.
Karl	Bilimoria	NASA Ames Research Center
Gary	Chambers	Cimarron, Inc.
Brad	Cheetham	University of Colorado
Jon	Clark	Baylor College of Medicine
Kelvin	Coleman	FAA AST
Ken	Davidian	FAA AST
Diane	Dimeff	Center for Space Entrepreneurship
Paul	Eckert	The Boeing Company
Carl	Ehrlich	SpaceWorks Engineering
Norm	Fitz-Coy	University of Florida
Jeff	Forrest	Metropolitan State College of Denver
Jeff	Foust	Futron Corporation
Paul	Guthrie	The Tauri Group
William	Hoffman	Webster University
Scott	Hubbard	Stanford University
Pat	Hynes	New Mexico State University
Richard	Jennings	University of Texas Medical Branch
Jay	Kapat	University of Central Florida
Barry	King	Dynetics

First	Last	Organization
Dan	Kirk	Florida Institute of Technology / Starfighters, Inc.
Dave	Klaus	University of Colorado
Glenn	Law	Aerospace Corporation
Mark	Leifeste	NASA White Sands Test Facility / Jacobs Technology, Inc.
John	Logsdon	George Washington University
Alan	Lovell	Air Force Research Laboratory
Will	Marshall	NASA Ames Research Center / International Space University
Charles	Miller	NASA Headquarters
Diane	Murphy	WMP Communications
Scott	Norris	Lockheed-Martin
Lori	Paulin	Hewlett-Packard Laboratories
Dan	Rasky	NASA Ames Research Center
Larry	Richardson	United Launch Alliance
Van	Romero	New Mexico Institute of Mining & Technology
Merri	Sanchez	Sierra Nevada Corporation
Jay	Santee	OSD Policy
Chris	Smith	Wyle
David	Spencer	Penn State University
James	Stanley	QinetiQ NA
Gerrit	van Ommering	Space Systems Loral
John	West	Draper Laboratory
Mark	Weyland	NASA Johnson Space Center

Agenda

Center of Excellence for Commercial Space Transportation
Research Roadmap Workshop
April 6-7, 2011
at Stanford University, Paul Brest Hall, Munger Conference Center

DAY I : Wednesday, 6 April 2011

Time	Topic	Key Speaker or Panel Moderator
8:00 - 8:30 a.m.	Coffee and continental breakfast	
8:30 – 8:45	Welcome, announcements and logistics	Prof. Scott Hubbard, Stanford
8:45 - 9:00	FAA Welcome	Mr. Ken Davidian, FAA
9:00 – 9:30	Agenda Overview and Workshop Charter	Prof. Scott Hubbard
9:30 – 10:15	Overview of Research Theme 1: **Space Traffic Management and Launch Operations**	Mr. Kelvin Coleman, FAA
10:15 - 10:30	Break	
10:30 - 11:15	Overview of Research Theme 2: **Launch Vehicle Systems, Payloads, Technologies, and Operations**	Dr. Dan Rasky, NASA
11:15 – 11:35	Commercial Space Transportation and the DoD Perspective	Brig. Gen Jay Santee, USAF
11:35 – 12:00	International Collaboration and Commercial Space Transportation	Prof. John Logsdon, GWU
12:00 – 1:00 p.m.	Lunch	On your own at Munger Center
1:00 – 1:45	Overview of Research Theme 3: **Human Space Flight**	Dr. Jon Clark, Baylor College of Medicine
1:45 - 2:30	Overview of Research Theme 4: **Industry Viability**	Mr. Ken Davidian, FAA
2:30 – 2:45	Break	
2:45 – 5:00	1st Breakout Sessions	Parallel Sessions on Themes 1 - 4
6:00 – 8:00 p.m.	Reception and Dinner	Stanford Faculty Club

DAY II: Thursday, 7 April, 2011

8:00 – 8:30 a.m.	Coffee and breakfast	
8:30 – 9:00	Plenary Session, Announcements, Logistics	Prof. Scott Hubbard
9:00 – 10:00	Breakout Sessions	
10:00 – 10:15	Break	
10:15 – 12:00	Breakout Sessions	
12:00 – 1:00 p.m.	Lunch	On your own at Munger
1:00 - 2:00	Breakout Sessions	
2:00 – 2:30	Presentation on **Space Traffic Management and Launch Operations**	Mr. Kelvin Coleman
2:30 – 3:00	Presentation on **Launch Vehicle Systems, Payloads, Technologies, and Operations**	Dr. Dan Rasky
3:00 – 3:15	Break	
3:15 – 3:45	Presentation on **Human Space Flight**	Dr. Jon Clark
3:45 – 4:15	Presentation on **Industry Viability**	Mr. Ken Davidian
4:15 – 5:00	Group discussion	
5:00	Adjourn	

Appendix II. COE CST Research Roadmap Workshop 2

Center of Excellence for Commercial Space Transportation
Research Roadmap Workshop II, August 15-17, 2011
Lockheed Martin Global Vision Center, Washington DC

Attendee List

First	Last	Organization
Doc	Aguilar	AFRL
Eleanor	Aldrich	AIAA
Juan	Alonso	Stanford University
David	Anhalt	Space Systems/Loral
Herb	Bachner	CSSI, Inc.
Jim	Ball	NASA KSC
Stephanie	Bednarek	SpaceX
Haym	Benaroya	Rutgers State University
Dan	Brockway	United Space Alliance
Francisco	Capristan	Stanford University
Faith	Chandler	NASA Headquarters
Brad	Cheetham	University of Colorado
Tom	Colvin	Stanford University
Ken	Davidian	FAA AST
Craig	Day	AIAA
Nick	Demidovich	FAA AST
Dominic	DePasquale	SpaceWorks Commercial
Michael	Draper	OSD Policy
Paul	Eckert	The Boeing Company
Carl	Ehrlich	SpaceWorks Engineering
Edward	Ellegood	ERAU & Cape Canaveral Spaceport
Tristan	Fiedler	FIT
Norm	Fitz-Coy	University of Florida
Jeffrey	Forrest	Metropolitan State College of Denver
Jeffrey	Foust	Futron Corporation
John	Gedmark	CSF
Jan	Gou	UCF
Nicolas	Guerra	NASA IVVF
Paul	Guthrie	The Tauri Group
Brienna	Henwood	NASTAR Center
William	Hoffman	Webster University
Scott	Hubbard	Stanford University
Patricia	Hynes	NMSU
Matt	Isakowitz	CSF
Richard	Jennings	UTMB

First	Last	Organization
Kelly	Kabiri	FAA AST/NASA HQ
Jay	Kapat	UCF
Barry	King	Dynetics
Dan	Kirk	FIT
David	Klaus	CU & BioServe Space Technologies
Rajun	Kumar	Florida State University
Glenn	Law	Aerospace Corporation
Mark	Leifeste	Jacobs Technology Inc.
John	Logsdon	GWU
Alan	Lovell	AFRL
Mike	Machula	NASA
Nicole	Maillet	FIT
Vernon	McDonald	Wyle
Mike	McElligott	FAA AST
Brian	Meade	FAA AST
Karin	Nilsdotter	Spaceport Sweden
Scott	Norris	Lockheed Martin Space Systems Company
Rene	Rey	FAA AST
Larry	Richardson	United Launch Alliance
Van	Romero	NMT
Jay	Santee	OSD Policy
Samantha	Segall-Anderson	SAIC
Audrey	Schaffer	OSD Policy
David	Spencer	Penn State University
James	Stanley	QinetiQ North America
Ken	Stroud	SNC
Jim	Van Laak	FAA AST
James	Vanderploeg	UTMB
Nathaniel	Villaire	FIT
Justin	West	Cimarron Inc
Mark	Weyland	NASA JSC
Richard	Wolf	NASA IVVF
Jonah	Zimmerman	Stanford University

Agenda

Day 0: Monday, 15 August 2011

Time	Topic	Key Speaker or Panel Moderator
1:00 – 2:00 p.m.	Overview of AST and Commercial Space Industry	Ken Davidian
2:00 – 3:30	Overview of ELV and RLV Licensing	Phil Brinkman
3:30 – 5:00	Overview of Permits and Safety Applications	Sherman Council

Day 1: Tuesday, 16 August 2011

Time	Topic	Key Speaker or Panel Moderator
8:00 – 8:30 a.m.	Coffee and breakfast/snacks	
8:30 – 8:45	Welcome, announcements and logistics	Scott Hubbard
8:45 – 9:00	FAA Welcome	Jim Van Laak
9:00 – 9:15	NASA Welcome	Faith Chandler
9:15 – 9:45	Commercial Space and the DoD Perspective - update	Maj. Gen. Jay Santee
9:45 – 10:15	Market Studies	Jeff Foust
10:15 – 10:30	Break	
10:30 – 11:15	Breakout Session Overview and Charter	Scott Hubbard / Ken Davidian
11:15 – 11:45	Overview of Research Theme 1: Space Traffic Management and Operations	Mike McElligott
11:45 – 1:00	Lunch	
1:00 – 1:30	Overview of Research Theme 2: Space Transportation Operations, Technologies, and Payloads	Nick Demidovich
1:30 – 2:00	Overview of Research Theme 3: Human Spaceflight	Mark Weyland
2:00 – 2:30	Overview of Research Theme 4: Space Transportation Industry Viability	René Rey
2:30 – 2:45	Break	
2:45 – 4:45	Breakout Sessions	
4:45 – 5:00	Regroup for end of day 1 and outlook for day 2	
5:00 – 7:00	Reception at the GVC sponsored by AIAA	

Day 2: Wednesday, 17 August 2011

Time	Topic	Key Speaker or Panel Moderator
8:00 – 8:30 a.m.	Coffee and breakfast/snacks	
8:30 – 9:00	Plenary Session, Announcements, Logistics	Scott Hubbard
9:00 – 10:00	Breakout Sessions	
10:00 – 10:15	Break	
10:15 – 12:00	Breakout Sessions	
12:00 – 1:00	Lunch	
1:00 – 2:00	Breakout Sessions	
2:00 – 2:30	Presentation on Space Traffic Management and Operations	Mike McElligott
2:30 – 3:00	Presentation on Space Transportation Operations, Technologies, and Payloads	Nick Demidovich
3:00 – 3:15	Break	
3:15 – 3:45	Presentation on Human Spaceflight	Mark Weyland
3:45 – 4:15	Presentation on Space Transportation Industry Viability	René Rey
4:15 – 5:00	Group discussion	
5:00	Adjourn	

Appendix III. CST Research Theme Structure

1. STM & OPS

1.1. Orbital STM

- 1.1.1. Services
  - 1.1.1.1. Service Provider Roles and Responsibilities
  - 1.1.1.2. Space Situational Awareness
    - 1.1.1.2.1. Surveillance Sensor Technologies
  - 1.1.1.3. Conjunction Prediction Analysis
  - 1.1.1.4. Real-Time Conjunction Analysis
  - 1.1.1.5. Collision Avoidance
- 1.1.2. Guidelines
  - 1.1.2.1. Slot Allocation / Zoning
  - 1.1.2.2. End of Life / Deorbit (Object Specific)
  - 1.1.2.3. Certification and Liability (Theme IV Interaction)
- 1.1.3. Standardization
  - 1.1.3.1. State vector / Ephemeris (eg. Pos, Vel, etc.)
  - 1.1.3.2. Modeling
    - 1.1.3.2.1. Space Environment
    - 1.1.3.2.2. Propagation
    - 1.1.3.2.3. Macro Approach
  - 1.1.3.3. Time Systems

1.2. Suborbital STM

- 1.2.1. Space Environment
  - 1.2.1.1. Space Weather
  - 1.2.1.2. Debris
- 1.2.2. Traffic
  - 1.2.2.1. Traffic Above NAS

1.3. NAS Integration

- 1.3.1. Takeoff and Landing Requirements
  - 1.3.1.1. STC Demand and Integration with NAS
  - 1.3.1.2. Spacecraft Escape / Abort Paths
  - 1.3.1.3. Breakup Debris Models
    - 1.3.1.3.1. Hazmat Behavior
  - 1.3.1.4. Ascent / Reentry Trajectory Models
- 1.3.2. Transit Requirements
- 1.3.3. Integration Into NextGen
  - 1.3.3.1. Launch/Landing Traffic Management Modeling

1.4. Spaceport Operations

- 1.4.1. Spaceport Launch/Landing Requirements
  - 1.4.1.1. Demand Studies
  - 1.4.1.2. Traffic Modeling
  - 1.4.1.3. Noise Modeling
- 1.4.2. Spaceport Interoperability
  - 1.4.2.1. Domestic
  - 1.4.2.2. International
- 1.4.3. Support Services Requirements
  - 1.4.3.1. Industry
    - 1.4.3.1.1. Fuel Farms
    - 1.4.3.1.2. Hazmat Procedures
    - 1.4.3.1.3. Infrastructure
    - 1.4.3.1.4. Safety
  - 1.4.3.2. Passengers

1.5. Integrated Air/Space Traffic Management

- 1.5.1. Forthcoming

2. SPACE TRANSPORTATION OPS, TECH, & PAYLOADS

2.1. Ground Systems & Operations Safety Technology

- 2.1.1. Roles & Responsibilities
  - 2.1.1.1. Spaceport Facilities/Infrastructure
  - 2.1.1.2. Propellant Handling
  - 2.1.1.3. Licensing Guideline Requirements
  - 2.1.1.4. Maintenance Technician Certification
  - 2.1.1.5. Ground Abort/Range Safety
  - 2.1.1.6. Residual Fluid Handling/Disposal
  - 2.1.1.7. Personal Protection Equipment
  - 2.1.1.8. Frequency Spectrum Management
  - 2.1.1.9. EMC/RF
    - 2.1.1.9.1. Susceptibility
    - 2.1.1.9.2. Degaussing Procedures
- 2.1.2. Ground Support & Operations Technologies
  - 2.1.2.1. Identification
  - 2.1.2.2. Development
- 2.1.3. Maintenance & Inspection Requirements
- 2.1.4. Space Operations Training
- 2.1.5. Ground Operations Training
- 2.1.6. Pre-Launch Processing

2.2. Vehicle Safety Analyses

- 2.2.1. Parameter Maximization Analyses
  - 2.2.1.1. Handling
  - 2.2.1.2. Redundancy
  - 2.2.1.3. Analysis Frameworks
  - 2.2.1.4. Software Safety
  - 2.2.1.5. Materials & Propulsion Systems
  - 2.2.1.6. Safety Metrics
    - 2.2.1.6.1. Probability Risk Assessment
    - 2.2.1.6.2. Reliability
    - 2.2.1.6.3. FMEA
  - 2.2.1.7. Reliability Allocation

2.2.1.8. Guidance, Navigation, and Control
2.2.2. Operational Limitation Analyses
2.2.2.1. Environmental Limits
2.2.2.2. Life-Cycle Predictions
2.2.2.3. Regulatory Support
2.2.2.3.1. Instantaneous Impact Point
2.2.2.3.2. Probability of Failure
2.2.2.3.3. Trajectory
2.2.2.3.4. Debris List
2.2.2.3.5. Debris Dispersion
2.2.2.3.6. Impact Probability
2.2.2.3.7. Vulnerability
2.2.2.3.8. Maximum Probable Loss
2.2.3. Simulation and Testing
2.2.3.1. Rapid Prototyping
2.2.3.2. Hardware
2.2.3.3. Software

2.3. Vehicle Safety Systems & Technologies

2.3.1. Real Time Instrumentation
2.3.1.1. Communications / Transponders and Beacons
2.3.1.2. Flight Termination Systems
2.3.1.3. Detection Systems
2.3.1.4. Propellant Monitoring
2.3.1.5. Integrated Vehicle Health Systems/Fault Detection Isolation and Recovery
2.3.2. Post Flight Diagnostic Equipment
2.3.2.1. Black Boxes
2.3.2.2. Life Cycle Detection
2.3.3. Crew Survivability (ECLSS)
2.3.4. Additional Safety Critical Subsystems / Safety Enabling Technologies

2.4. Payload Safety

2.4.1. Extent of Disclosure
2.4.2. Interfaces
2.4.2.1. Power
2.4.2.2. Communications
2.4.2.3. Storage & Deployment
2.4.2.4. Busses, Plug & Play
2.4.3. Impact on Flight Safety
2.4.3.1. Vehicle
2.4.3.2. Crew
2.4.4. Handling Procedures
2.4.4.1. Fluids
2.4.4.2. Battery
2.4.4.3. Coolant
2.4.5. Electro-Magnetic Interference
2.4.5.1. Programmable Frequency Transmitters
2.4.6. Non-Operational Payloads
2.4.7. Connectors and Interfaces
2.4.7.1. Low Cost
2.4.7.2. Space-Reliable

2.5. Vehicle Operations Safety

2.5.1. Abort Procedures
2.5.1.1. Handling
2.5.1.2. Size of Dead Zone
2.5.1.3. Environmental Effects
2.5.2. Other Off-Nominal Operations
2.5.2.1. Reentry
2.5.2.2. Abort
2.5.2.3. FTS
2.5.2.4. TTS
2.5.3. Return to Flight Status After Off-Nominal Operation
2.5.4. Safety Reporting Systems
2.5.4.1. Voluntary
2.5.4.2. Mandatory
2.5.5. Mandatory Reporting Requirements
2.5.6. Go/No-Go Decisions
2.5.6.1. Allocation

3. HUMAN SPACEFLIGHT

3.1. Aerospace Physiology & Medicine

3.1.1. Develop medical standards for crew and develop acceptance criteria for passengers
3.1.2. Data collection
3.1.2.1. Develop methods and procedures to collect and analyze biomedical data from space flight crews and space flight participants to determine any unique medical risks that humans encounter during launch, ascent, on-orbit, reentry, landing and repetitive flights.
3.1.2.2. Investigate novel ways to track health of space crews including DNA analysis for radiation injury, fatigue, and stress. Also, consider options for the use of DNA and other body fluids/tissues in body identification and other environmental exposures in the event of a fatal accident.
3.1.2.3. Physiological sensor hardware utilization
3.1.2.4. Centrifuge evaluation of specific medical conditions
3.1.3. Databases
3.1.3.1. Review all medications that have been used in spaceflight to aid in medical standard development and special issuance procedures for crew on medications.
3.1.3.2. Develop database to track medical outcomes among crewmembers that experience repetitive and frequent spaceflights.
3.1.4. Risk mitigation
3.1.4.1. Pre-flight care

3.1.4.1.1. Support the validation of drug and alcohol testing standards used in the commercial aviation industry for application in the manned commercial space transportation industry (coordinate with Theme 4).

3.1.4.2. In-flight care

3.1.4.2.1. Support the development of medical kits for various suborbital and orbital flight scenarios.

3.1.4.3. Post-flight care

3.1.4.4. Special issuance (waiver) procedures for crew

3.1.4.4.1. In a cooperative effort with NASA and previous commercial spaceflight participants, review outcome of flight experience involving astronauts with commonly occurring medical conditions in order to create an evidence-based approach to special issuance decision-making.

3.1.5. Informed consent

3.1.5.1. Provide input for an Informed Consent Briefing for spacecraft and mission specific profiles.

3.2. Personnel Training

3.2.1. Medical

3.2.2. Passengers

3.2.2.1. Develop a standardized training template for spacecraft and mission specific profiles.

3.2.3. Ground

3.2.3.1. Support the development of human factors standards for aerospace vehicle maintenance to prevent maintenance-related incidents/accidents.

3.2.4. Crew

3.2.4.1. Support the development of appropriate standards for emergency medical kits, equipment, and procedures for use onboard aerospace vehicles. Recommend CPR and basic life support training requirements for space crews. Evaluate and recommend the use of telemedicine systems for the diagnosis, treatment, and monitoring of unexpected medical emergencies during aerospace vehicle operations.

3.3. ECLSS

3.3.1. Review, analyze and summarize existing standards

3.3.2. Coordinate with Theme 2 and A/C Environment COE

3.3.3. Standalone generic ECLSS model

3.3.4. Adapt existing NASA modeling tools for commercial human spaceflight, such as MMOD Model (Bumper) and Cabin Depressurization Model (Killer Press) to allow comparison of tradeoffs and risks.

3.4. Habitability & Human Factors

3.4.1. Review, analyze and summarize information on existing regulations and policies

3.4.1.1. Evaluate human factors related to Reusable Launch Vehicles (RLV) cockpit/panel/ layouts, with emphasis on the capability to visually reacquire a runway, spaceport/airport, runway environs i.e. approach lighting requirements, visual approach slope indicators for re-entering vehicles, unique runway marking requirements for suborbital re-entry in visual flight conditions.

3.4.1.2. Support the development of a computerized accident/incident database. In addition, an anonymous incident database similar to NASA's ASRS (Aviation Safety Reporting System) database should also be available for aerospace vehicle operations. Develop appropriate procedures for the assessment of human factors issues in aerospace vehicle accident investigation. Coordinate with Theme 1.

3.4.2. Assess occupant protection capabilities during nominal and emergency conditions

3.4.2.1. Identify hazards

3.4.2.2. Physiological effects under appropriate g-loads of all potential participants across age, gender, anthropometry, etc.

3.4.2.3. Seat design

3.4.2.4. Seat materials

3.4.2.5. Restraint design

3.4.2.6. Suited versus unsuited

3.4.3. Assess pilot performance under sustained G-loads

3.4.3.1. Identify safety-related human-centered automation issues related to the design and operation of aerospace vehicles to determine if

ascent profiles and/ or contingency aborts should be automated.
3.4.4. Assess effects of repeat flight on pilot performance
3.4.4.1. Pre-flight pilot condition
3.4.4.2. Develop a risk analysis report on medical incapacitations and situations (e.g. fatigue, anxiety, stress) that might occur in RLV flight crew and space flight participants.
3.4.4.3. Trajectory following
3.4.4.4. Situational Awareness / Spatial Disorientation
3.4.5. Consider performance factors of pilot/ground crew using remote-piloted vehicles
3.4.6. Determine minimum passenger tasks and safety knowledge
3.4.6.1. Nominal
3.4.6.2. Emergency
3.4.6.3. Assess personal carry-on item risk
3.4.6.4. Assess payload materials risk
3.4.6.4.1. Coordinate with Theme 2

3.5. Human Rating

3.5.1. Review, analyze and summarize human rating work and spacecraft lessons learned
3.5.1.1. Close calls
3.5.1.2. Mishaps
3.5.1.3. Recent work
3.5.2. Consider implications of crew versus passenger/ground personnel on protection and utilization
3.5.3. Integrating with launch vehicle team (Coordinate with Theme 2)

4. SPACE TRANSPORTATION INDUSTRY VIABILITY

4.1. Markets

4.1.1. Industry Description
4.1.1.1. Description of companies
4.1.1.2. Comprehensive repository for industry resources
4.1.2. Industry Analysis
4.1.2.1. Historical studies
4.1.2.2. Modeling
4.1.3. Future Options
4.1.3.1. Applications of industry description and analysis for future policy directions
4.1.3.2. Prospective analysis of support of transition to multiple customers

4.2. Policy

4.2.1. International
4.2.1.1. Options for new regulatory initiatives
4.2.1.2. Options for a single international space regulatory regime
4.2.2. Domestic
4.2.2.1. Economic actor, customer (anchor tenant), market analysis, government interaction with commercial sector (transition)
4.2.2.2. Service provider (range safety, debris removal, etc.)
4.2.2.3. Technology research and development support
4.2.2.4. Legal, regulatory actions

4.3. Law

4.3.1. Liability
4.3.1.1. Historical analogies with other industries
4.3.1.2. Role of government (different than current regime)
4.3.1.3. State vs. federal jurisdiction
4.3.1.4. Assessment of liability risk
4.3.2. Insurance
4.3.2.1. What's the insurance for and how is it relevant to business viability?
4.3.2.2. Kind of insurance required is a policy decision, implemented through laws and regulations
4.3.2.3. Insurance considerations and approaches
4.3.3. Barrier analysis of existing laws

4.4. Regulation

4.4.1. Regulatory parameters
4.4.1.1. Scope of regulations
4.4.1.2. Characteristics
4.4.2. Historical analyses and analogies
4.4.2.1. Regulatory case studies in aviation, railroad, and maritime transportation to provide historical context on the evolution of US and international regulatory regimes
4.4.3. Comparative analysis
4.4.3.1. Contemporary issues
4.4.3.2. International analysis

4.5. Cross-Cutting Topics

The Research Roadmap Workshops were generously supported by contributions from the following companies: