

# **OPERATIONS ANALYSIS OF THE SECOND-GENERATION REUSABLE LAUNCH VEHICLE**

**Steven R. Noneman  
National Aeronautics and Space Administration  
Marshall Space Flight Center, Alabama**

## **Abstract**

The Space Launch Initiative (SLI) program is developing a second-generation reusable launch vehicle. The program goals include lowering the risk of loss of crew to 1 in 10,000 and reducing annual operations cost to one third of the cost of the Space Shuttle. The SLI missions include NASA, military and commercial satellite launches and crew and cargo launches to the space station. The SLI operations analyses provide an assessment of the operational support and infrastructure needed to operate candidate system architectures. Measures of the operability are estimated (i.e. system dependability, responsiveness, and efficiency). Operations analysis is used to determine the impact of specific technologies on operations. A conceptual path to reducing annual operations costs by two thirds is based on key design characteristics, such as reusability, and improved processes lowering labor costs. New operations risks can be expected to emerge. They can be mitigated with effective risk management with careful identification, assignment, tracking, and closure. SLI design characteristics such as nearly full reusability, high reliability, advanced automation, and lowered maintenance and servicing coupled with improved processes are contributors to operability and large operating cost reductions.

## **1. Introduction**

The Space Launch Initiative (SLI) program is developing a second-generation reusable launch vehicle and on-orbit elements. The program goals include lowering the risk of loss of crew to 1 in 10,000 and reducing operations cost to one third of the cost of the current launch system, the Space Shuttle. Operations analyses provide insight into the operability of reusable launch vehicles. The conceptual design phase is now underway in the SLI program and top-level operations analysis will support the definition of the system requirements. While most of the analysis work is yet to be performed, some operations insights based on the early SLI concepts are summarized herein.

## **2. Operations Analysis Process**

A process for performing SLI operations analyses is shown in figure 1. This process provides insight into the operability of the SLI system architecture as the design matures. It results in estimates of the operations phase cost, assessments of the system operability and utilization, system operations plans and processes, and risks to achieving the operations objectives.

Operations analyses are based on functional requirements, technology improvements, process improvements, architecture design information, and reference information for the Space Shuttle, expendable launch vehicle, and other relevant aerospace systems.

Process elements include benchmarking, modeling and simulation, cost estimation, metric estimation, uncertainty assessment, and risk identification. The process examines and assesses

system architectures and systems for the definition and scope of the integrated mission planning, ground operations, and flight operations elements. Assessing the impact of proposed “new ways of doing business” is a key element in the operations analysis process.

In addition, operations analysis is used to determine the relative impact of specific technologies on the operations of a given architecture. Tools and models are used to perform operations analysis and integrate collaboratively with other analyses such as reliability, maintainability, and supportability. This collaborative engineering is accomplished through the SLI Advanced Engineering Environment (AEE). The AEE enables engineering tools to exchange data and information easily allowing rapid and consistent analyses.

### 3. SLI Missions

NASA has identified its primary missions for the SLI. The first set supports the International Space Station (ISS): The ISS logistics mission re-supplies the ISS consumables, delivers new ISS payloads and returns equipment and spent supplies to earth; the ISS Crew Rotation and Maintenance mission transports ISS crewmembers to and from ISS; the rescue vehicle change-out mission delivers an ISS emergency escape vehicle to the station.

NASA has additional missions not associated with the ISS. These missions deliver payloads or satellites to low earth orbit (LEO) and other orbits, including Geo-stationary Transfer Orbits (GTO) and planetary transfer (earth escape) trajectories.

Additional NASA reference missions are under consideration by SLI. They include payload delivery, checkout, return; large and small space platform/module assembly and checkout; service, repair, and re-boost of on-orbit spacecraft and platforms; polar orbit, sun-synchronous payload delivery; and service, repair, and re-boost of on-orbit spacecraft and platforms (including re-boost of the ISS). NASA projects that it will utilize the SLI system to support approximately 15 missions a year.

The SLI system is also intended to support commercial and military missions. Commercial and military traffic forecasts have significant uncertainty but could potentially be equivalent to NASA's traffic.

### 4. Metrics

The SLI program has identified Figures of Merit (FOMs) to use for evaluating the SLI system. These FOMs are metrics that will be estimated for candidate architectures and used in trade studies. FOM values for the Space Shuttle may also be used as references for comparisons. The program FOMs are grouped as follows:

#### Safety --

- Probability of Loss Of Crew
- Probability of Loss of Vehicle
- Probability of Loss of Mission

#### Cost --

- Acquisition Cost (development and production)
- Annual Operations Cost
- Cost per pound to orbit

Technical Performance –

- Design Risk
- Technology Risk

Operability –

- Launch Availability: The probability of launching in the first advertised launch window.
- Turnaround Time: The time from the end of the previous mission to the beginning of the next mission.
- Dispatch Time: The time from the customer order for a mission to the launch of the mission.
- Cargo Integration Time: The time from delivery of the customer's payload to the time of launch of that payload.

In addition, for operations assessment, the following measures of utilization are used:

Utilization --

- Missions per year
- Flight-days per year
- Humans-launched per year
- Cargo Mass to orbit per year.

## 5. Reference Values

The program goals are referenced primarily to today's Space Shuttle operations. For assessments, a FOM reference value will be established and adjusted, if necessary, as the program evolves. Using annual operations cost as an example, the fiscal year 2001 (FY01) Space Shuttle budget was approximately \$3.1 billion.<sup>1</sup> There were 7 launches during that fiscal year. These flights launched 43 humans all to the ISS. Two flights performed ISS crew exchanges (STS-102 and STS-105). Table 1 summarizes reference values of selected FOMs for the Space Shuttle for FY01.<sup>2</sup>

Table 1. Selected FY01 Space Shuttle FOMs

<b>FOM</b>	<b>FY01 Value</b>
Missions	7
Flight-Days	86
Humans Launched	43
Mass Launched (lbm)	~217,000
P(loss of crew)	1/245
Annual Operations Cost	\$3.1 billion
Turnaround Time	129 days (For Endeavour from STS-97 to STS-100)
Cost/lbm launched	\$14.3K/lbm

## 6. Space Shuttle Operations Drivers

Figure 2 shows a first-level break down of the FY01 Space Shuttle cost. The solid rocket booster (SRB) and reusable solid rocket motors (RSRM) lines are combined as "1<sup>st</sup> stage" costs. The External Tank (ET) production and Space Shuttle Main Engine (SSME) production and test support costs are comprise "2nd stage" costs in figure 2.

Propulsion systems for the shuttle are a dominant cost contributor to the Space shuttle. Significant factors in these costs are recurring production, testing, and refurbishment of the propulsion elements. Maintenance, servicing, and sustaining engineering are also propulsion systems cost drivers.

The Shuttle Orbiter provides two major functions: (1) Crew accommodations and (2) payload accommodations. It has carried as many as 8 crewmembers on a single flight. It provides a robotic arm, extra-vehicular activity (EVA) suits, tools, and airlock. Its 15 by 60 foot cargo bay can carry over 50,000 pounds of cargo and can deploy, capture, transfer, and return its payloads. The Space Shuttle is highly functional and complex.

Ground operations include the functions of maintenance, servicing, and launch processing. Assuring system integrity, crew safety, and ground personnel safety requires significant time for inspections and careful handling of hazardous and cryogenics fluids. Thermal protection system and propulsion systems processing and payload integration are the pacing items in the workflows.

Human space flight support includes crew systems, training (T38 trainers, KC135, etc.) and crew health support of astronauts. Flight planning and operations includes development of flight products (procedures, software loads, flight plans and rules); mission training and certification of flight crews and mission controllers; and real-time flight systems monitoring, command, and control functions.

Upgrades are costs needed for safety assurance, enhancing systems performance and capabilities, and combating system obsolescence.<sup>3</sup>

Finally, program integration functions include program management support and construction of facilities for the overall Space Shuttle program. Across all program elements, labor is the greatest Shuttle operations cost.

## 7. SLI Changes for Operations

The SLI system must be significantly different from the Space Shuttle to achieve the operability and cost goals. The following design requirements are emerging as drivers:

- Reusability (elimination of recurring production)
- Separating crew and cargo transportation functions onto different elements
- Increased system reliability and robustness
- Automation (e.g., Integrated Vehicle Health Maintenance – IVHM)
- Decreased reliance on mission control
- Simplified flight crew duties and tasks (e.g., automated piloting)
- Simplified ground crew duties and tasks (e.g., automated re-planning, system monitoring and first-level failure responses)
- Decreased maintenance and servicing (notably propulsion, thermal protection, software, subsystems, and payloads)
- Standardized cargo interfaces
- Improved accessibility for maintenance and servicing
- Reduced use of hazardous fluids.

The process improvements with “lean processes”<sup>4</sup> will reduce labor costs:

- Reliability centered maintenance
- Simpler, quicker cargo loading

- Shortened mission planning template
- Automated flight products production
- Automated configuration management
- Enhanced modeling and analysis
- Efficient training of ground personnel and astronauts.

Based on the SLI design requirements, process improvements, and missions, goal values for the FOMs can be selected. Table 2 shows a subset of these FOM values for the NASA missions. Commercial and military missions are not included.

Table 2. SLI FOM Goal Values

<b>FOM</b>	<b>SLI Value</b>
NASA Missions	15
Flight-Days	150
Humans Launched	15
Mass Launched (lbm)	~450,000
P(loss of crew)	1/10,000
Annual Operations Cost	\$1 billion
Turnaround Time (days)	28
Cost/lb mass launched	\$1K/lb

#### 8. A Conceptual Distribution of Cost Reductions

Table 3 below provides a conceptual distribution of SLI annual operations costs when reduced to one-third of the Space Shuttle's corresponding costs. Also shown in the table and figure 3 is a conceptual redistribution of the SLI operations costs.

Table 3. Conceptual Path to the SLI Operations Cost Goal

<b>Operations Cost Elements</b>	<b>SLI (\$M)</b>	<b>Space Shuttle (FY01)</b>	<b>SLI % of Shuttle</b>
SRBs (1st Stage)	180	515	35%
ET, SSME (2nd stage)	150	596	25%
Orbiter	230	669	34%
Ground Operations	190	524	36%
Flight Planning and Operations	75	199	38%
Human Spaceflight Support	15	71	21%
Upgrades	80	256	31%
Program Integration	95	290	33%
<b>Total</b>	<b>1015</b>	<b>3119</b>	<b>33%</b>

In this example, using the same top-level cost breakdown for the shuttle, significant cost reductions are made in all operations cost elements through application of the changes described previously. Some SLI changes will reduce specific cost elements more than others. For example, reusability in the first and second stage propulsion systems (i.e., no expendable External Tank and no refurbished SRBs/RSRMs) will be cost effective by cutting recurring production costs. But some changes affect all cost elements. For example, fixed operations costs in all areas will also be spread over commercial and military missions reducing NASA's portion of fixed costs.

## 9. Operations Risks

Risks must be mitigated to implement these significant operations changes. One risk will be developing confidence in new systems and processes. This may be mitigated through the application of “off-the-shelf” industry hardware and software, where appropriate for the space flight environment. Testing and demonstration will also be necessary, especially for new technologies and systems.

Another risk will be changing to “new ways of doing business.” These changes will require leadership, training, education, practice, and experience with new processes and systems. Identifying new skill sets, developing training programs for these skills, and providing opportunities to gain experience applying these skills will be a management challenge.

New operations risks can be expected to emerge as the system is developed. They can be mitigated with effective risk management and careful identification, assignment, tracking, and closure.

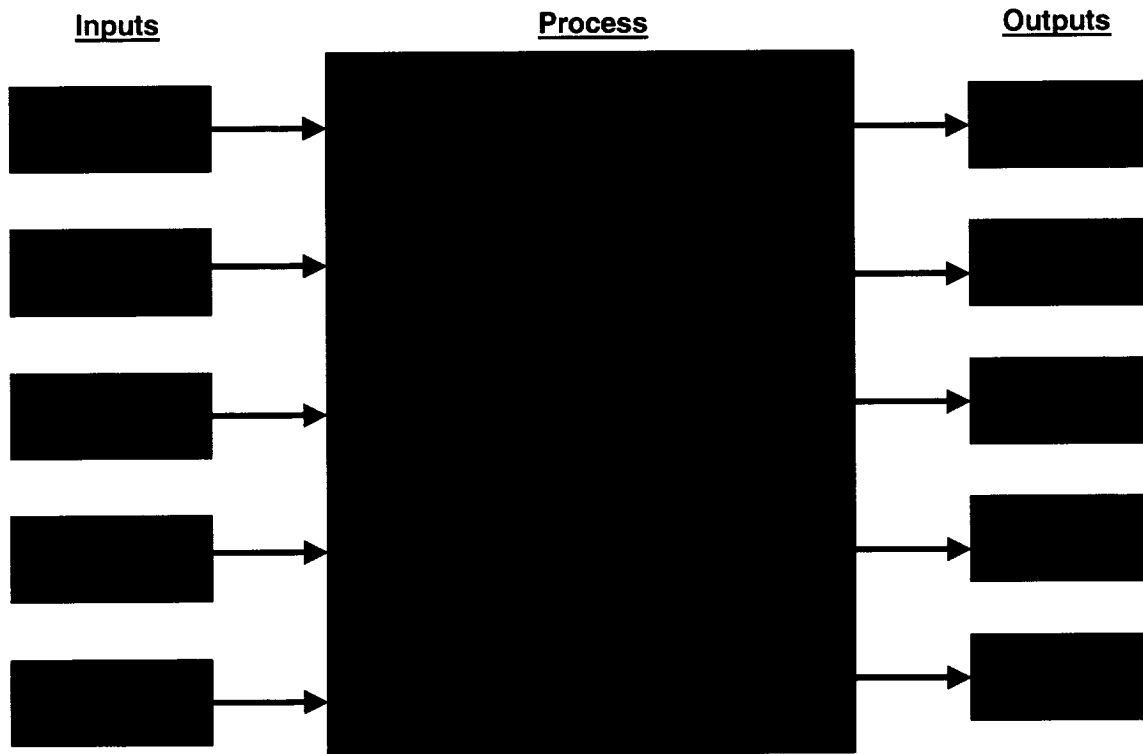
## 10. Summary

SLI has set challenging operations goals. Operations of the SLI system must be significantly different from the Space Shuttle to achieve the goals. The SLI system must be a highly operable design with nearly full reusability (i.e., elimination of recurring production and refurbishment), high reliability, reduced maintenance and servicing, and advanced automation. “New ways of doing business” are required with simpler, quicker, efficient processes that eliminate and streamline human tasks to decrease workforce size.

## 11. References

1. Space Shuttle FY01 Costs, NASA Chief Financial Office Web Site, [http://ifmp.nasa.gov/codeb/budget2002/06\\_space\\_shuttle.pdf](http://ifmp.nasa.gov/codeb/budget2002/06_space_shuttle.pdf)
2. FY01 STS Missions, <http://www-pao.ksc.nasa.gov/kscpao/shuttle/summaries/chronoc.htm>
3. STS Operability, <http://spaceflight.nasa.gov/shuttle/seconddecade/seconddecade.pdf>
4. Womack, James P. and Jones, Daniel T., Lean Thinking, Simon and Schuster, 1996.

**Figure 1. Operations Analysis Process**



**Figure 2. Annual Operations Costs Distribution**

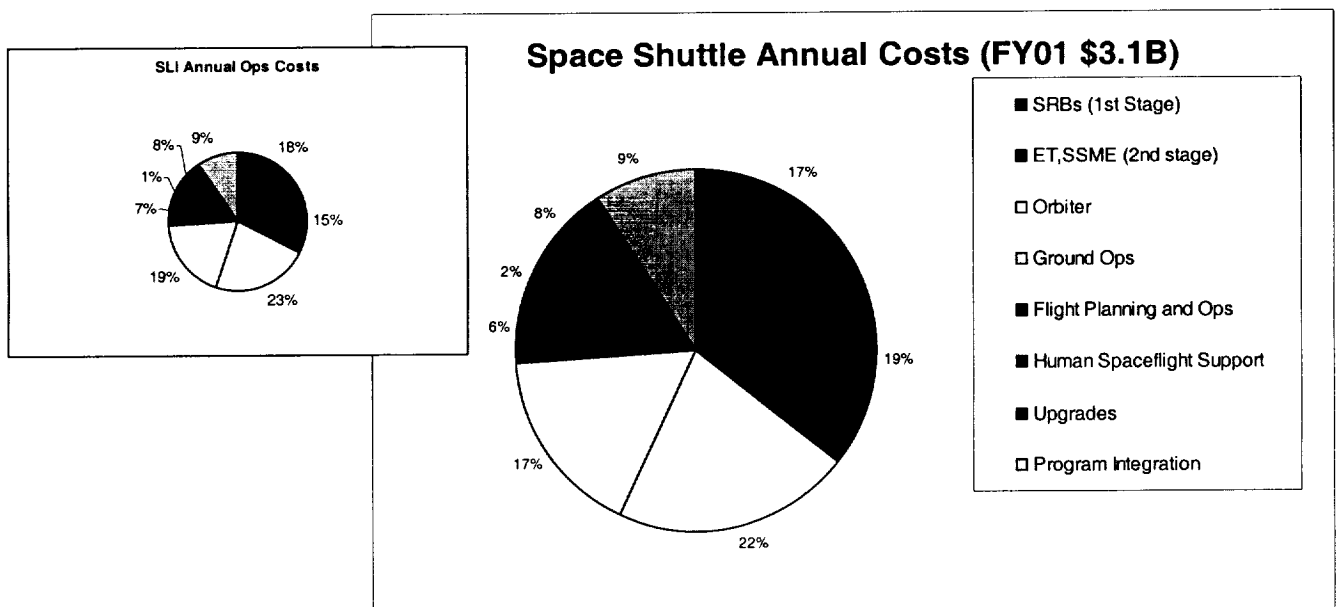
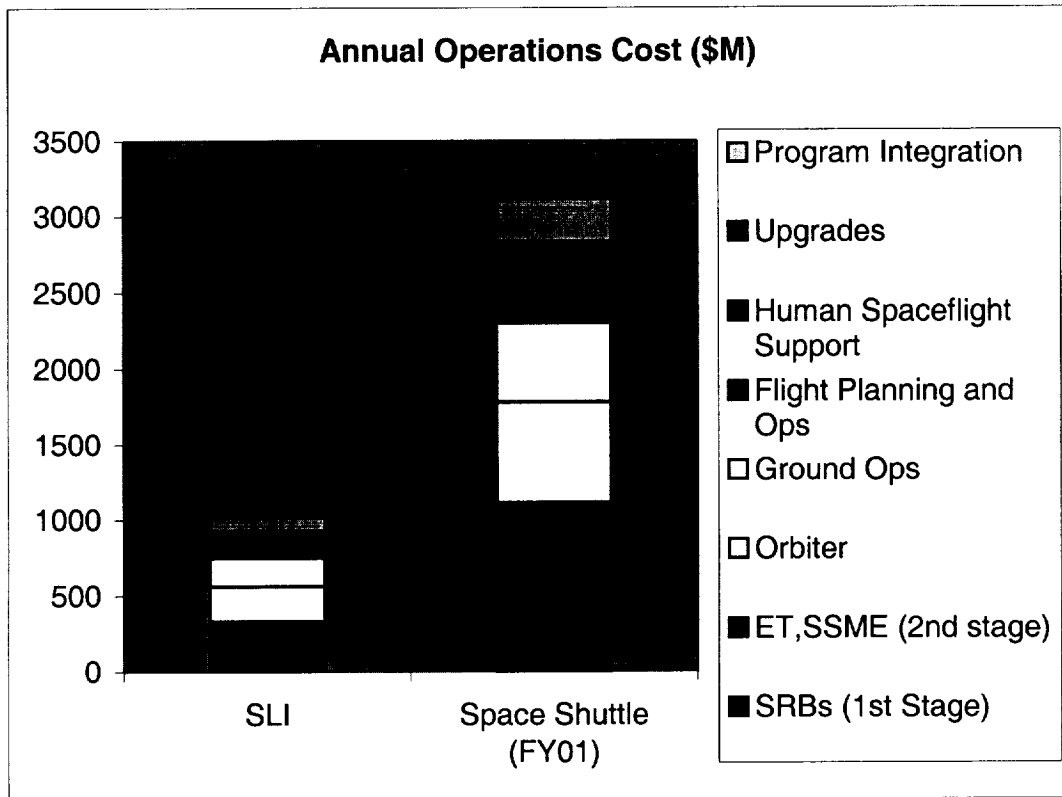


Figure 3.







## **Operations Analysis of the 2<sup>nd</sup> Generation Reusable Launch Vehicle**

**AIAA SpaceOps 2002 Conference  
Houston, Texas  
October 9-12, 2002**

**Steven R. Noneman  
NASA Marshall Space Flight Center**

**Steven R. Noneman  
National Aeronautics and Space Administration  
Marshall Space Flight Center, Alabama**



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### Abstract

The Space Launch Initiative (SLI) program is developing a second-generation reusable launch vehicle. The program goals include lowering the risk of loss of crew to 1 in 10,000 and reducing annual operations cost to one third of the cost of the Space Shuttle. The SLI missions include NASA, military and commercial satellite launches and crew and cargo launches to the space station. The SLI operations analyses provide an assessment of the operational support and infrastructure needed to operate candidate system architectures. Measures of the operability are estimated (i.e. system dependability, responsiveness, and efficiency). Operations analysis is used to determine the impact of specific technologies on operations. A conceptual path to reducing annual operations costs by two thirds is based on key design characteristics, such as reusability, and improved processes lowering labor costs. New operations risks can be expected to emerge. They can be mitigated with effective risk management with careful identification, assignment, tracking, and closure. SLI design characteristics such as nearly full reusability, high reliability, advanced automation, and lowered maintenance and servicing coupled with improved processes are contributors to operability and large operating cost reductions.



## Introduction



- **Space Launch Initiative (SLI) Goals:**

- Decrease the risk of loss of crew to better than 1 in 10,000
- Decrease annual operations costs to 1/3 of the Space Shuttle costs

- **SLI Status:**

- Conceptual design phase
- Defining system requirements
- Analyzing several candidate system architecture concepts

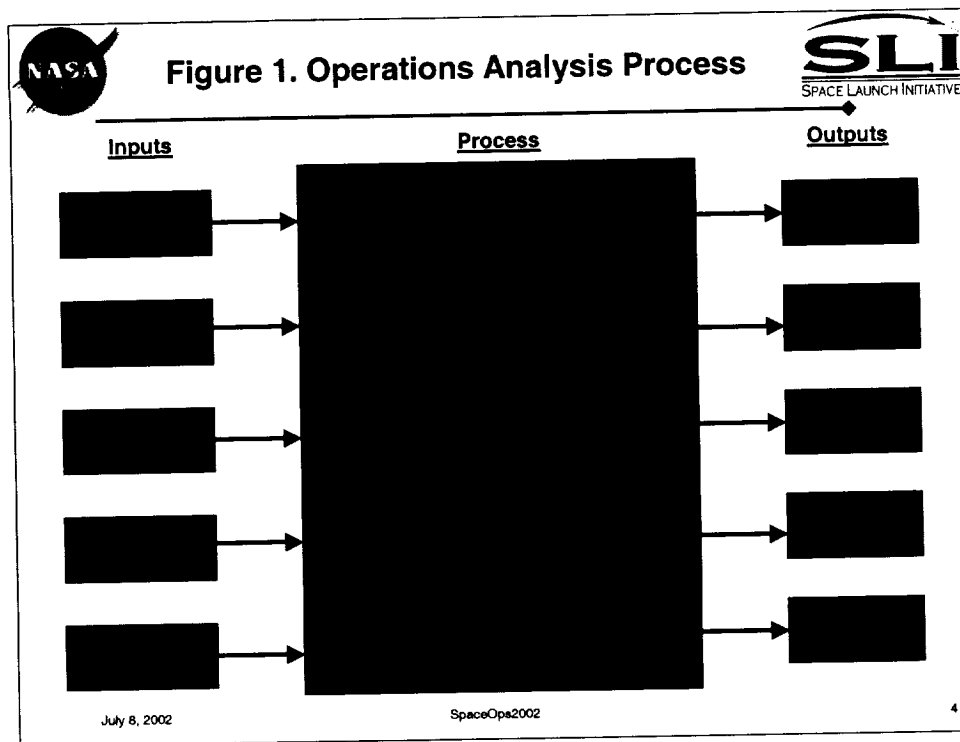
- **Operations analysis assesses operability, operations phases costs, and risks**

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The Space Launch Initiative (SLI) program is developing a second-generation reusable launch vehicle and on-orbit elements. The program goals include lowering the risk of loss of crew to 1 in 10,000 and reducing operations cost to one third of the cost of the current launch system, the Space Shuttle. Operations analyses provide insight into the operability of reusable launch vehicles. The conceptual design phase is now underway in the SLI program and top-level operations analysis will support the definition of the system requirements. While most of the analysis work is yet to be performed, some early operations insights based on the early SLI concepts are summarized herein.



A process for performing SLI operations analyses is shown in figure 1. This process provides insight into the operability of the SLI system architecture as the design matures. It results in estimates of the operations phase cost, assessments of the system operability and utilization, system operations plans and processes, and risks to achieving the operations objectives.

Operations analyses will be based on functional requirements, technology improvements, process improvements, architecture design information, and reference information for the Space Shuttle, expendable launch vehicle, and other relevant aerospace systems.

Process elements include benchmarking, modeling and simulation, cost estimation, metric estimation, uncertainty assessment, and risk identification. The process examines and assesses system architectures and systems for the definition and scope of the integrated mission planning, ground operations, and flight operations elements. Assessing the impact of proposed "new ways of doing business" is a key element in the operations analysis process.

In addition, operations analysis is used to determine the relative impact of specific technologies on the operations of a given architecture. Tools and models are used to perform operations analysis and integrate collaboratively with other analyses such as reliability, maintainability, and supportability. This collaborative engineering is accomplished through the SLI Advanced Engineering Environment (AEE). The AEE enables engineering tools to exchange data and information easily allowing rapid and consistent analyses.



## SLI Missions



- **NASA Primary Missions**

- ISS logistics
- ISS crew rotation and maintenance
- ISS rescue vehicle change-out
- Low earth orbit payload delivery and other orbit destinations
  - Low earth orbit (LEO)
  - Geo-stationary Transfer Orbit (GTO)
  - Planetary (earth escape)

- **NASA Reference Missions**

- Payload delivery/checkout/return
- Space platform/module assembly and checkout (small)
- Service/repair/re-boost on-orbit spacecraft and platforms
- Polar orbit/sun synchronous payload delivery
- Space platform module assembly and checkout (large)
- Service/repair/re-boost on-orbit spacecraft and platforms (re-boost ISS)

- **Commercial Missions**

- **Military Missions**

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Ref. SLI DRMs



## Metrics (Shuttle FY01)



- **Safety**

- Loss of crew (1/245 estimated)
- Loss of vehicle
- Loss of mission

- **Cost**

- Annual operations cost (\$3.1B)

- **Operability**

- Launch availability
- Turnaround time (129 days)
- Dispatch time
- Cargo integration time

- **Utilization**

- Flights per year (7)
- Flight-days per year (86)
- Humans-launched per year (43)
- Cargo mass to orbit per year (~217,000 lbs.)

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### Ref. SLI FOMs

The SLI program has identified Figures of Merit (FOMs) to use for evaluating the SLI system. These FOMs are metrics that will be estimated for candidate architectures and used in trade studies. FOM values for the Space Shuttle may also be used as references for comparisons. The program FOMs are grouped as shown here.

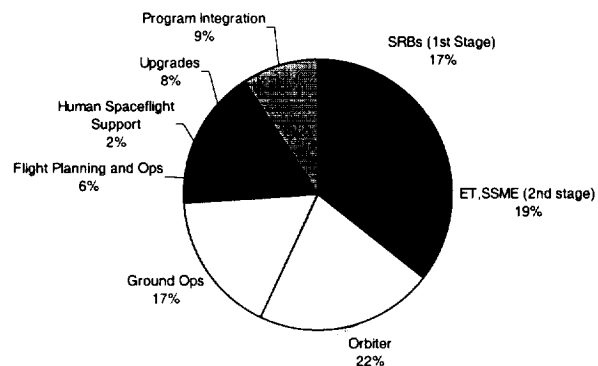
The program goals are referenced primarily to today's Space Shuttle operations. For assessments, a FOM reference value will be established and adjusted, if necessary, as the program evolves. Using annual operations cost as an example, the fiscal year 2001 (FY01) Space Shuttle budget was approximately \$3.1 billion.<sup>1</sup> There were 7 launches during that fiscal year. These flights launched 43 humans all to the ISS. Two flights performed ISS crew exchanges (STS-102 and STS-105). Table 1 summarizes reference values of selected FOMs for the Space Shuttle for FY01.<sup>2</sup>



## Operations Cost Reference



Space Shuttle Costs (FY01 \$3.1B)



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Ref. NASA Human Space Flight Budget Summary, NASA CFO



## Operations Cost Drivers



- **Propulsion Systems**
  - Production and refurbishment
  - Sustaining engineering
  - Maintenance, servicing, and launch processing
- **On-orbit Segment Payload Accommodations/Capabilities**
  - Cargo envelope, communications, servicing, deployment, return, etc.
- **Human Space Flight**
  - Flight planning, analysis, and support
  - Crew systems, life support, and health
  - Systems management
  - Training and certification
- **Systems Design**
  - Safety and performance
  - Reliability, maintainability, and supportability (e.g., TPS)
  - Payload integration, accommodations, and processing

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### Ref HSF Budget

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Propulsion systems for the shuttle are a dominant cost contributor to the Space shuttle. Significant factors in these costs are recurring production, testing, and refurbishment of the propulsion elements. Maintenance, servicing, and sustaining engineering are also propulsion systems cost drivers.

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Ground operations include the functions of maintenance, servicing, and launch processing. Assuring crew and ground safety requires significant time for inspections and careful handling of hazardous and cryogenics fluids. Thermal protection system and propulsion systems processing and payload integration are the pacing items in the workflows.

Human space flight support includes crew systems, training (T38 trainers, KC135, etc.) and crew health support of astronauts. Flight planning and operations includes development of flight products (procedures, software loads, flight plans and rules); mission training and certification of flight crews and mission controllers; and real-time flight systems monitoring, command, and control functions.

Upgrades are costs needed for safety assurance, enhancing systems performance and capabilities, and combating system obsolescence.<sup>3</sup>

Finally, program integration functions include program management support and construction of facilities for the overall Space Shuttle program. Across all cost elements, labor is the greatest Shuttle operations cost.





## SLI Design Changes



- **Reusability (elimination of recurring production)**
  - SLI Reusable 1<sup>st</sup> stage chemical rocket engines vs. STS SRB/SRM refurbishment each flight
  - SLI Reusable 2nd stage chemical rocket engines with reusable propellant/oxidizer tanks vs. STS expendable External Tank
- **Increase system reliability and robustness**
- **Automation (e.g, Integrated Vehicle Health Maintenance – IVHM)**
- **Simplified crew duties and tasks**
- **Decreased maintenance and servicing (propulsion, thermal protection, software, subsystems)**
- **Standardized cargo interfaces**

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The SLI system must be significantly different from the Space Shuttle to achieve the operability and cost goals. The following design requirements are emerging as drivers:

- Reusability (elimination of recurring production)
- Separating crew and cargo transportation functions onto different elements
- Increased system reliability and robustness
- Automation (e.g., Integrated Vehicle Health Maintenance – IVHM)
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- Decreased maintenance and servicing (notably propulsion, thermal protection, software, subsystems, and payloads)
- Standardized cargo interfaces
- Improved accessibility for maintenance and servicing
- Reduced use of hazardous fluids.



## SLI Process Improvements



- **Reliability centered maintenance**
- **Simpler, quicker cargo loading**
- **Shortened mission planning template**
- **Automated flight products production**
- **Automated configuration management**
- **Enhanced modeling and analysis**
- **Efficient training of ground personnel and astronauts.**

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The process improvements with “lean processes”<sup>4</sup> will reduce labor costs:

- Reliability centered maintenance
- Simpler, quicker cargo loading
- Shortened mission planning template
- Automated flight products production
- Automated configuration management
- Enhanced modeling and analysis
- Efficient training of ground personnel and astronauts.



## SLI Metrics: Goal Values



<u>FOM</u>	<u>SLI Value</u>
NASA Missions	15
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Based on the SLI design requirements, process improvements, and missions, goal values for the FOMs can be selected. Table 2 shows a subset of these FOM values for the NASA missions. Commercial and military missions are not included.



## Conceptual Path to the SLI Operations Cost Goal



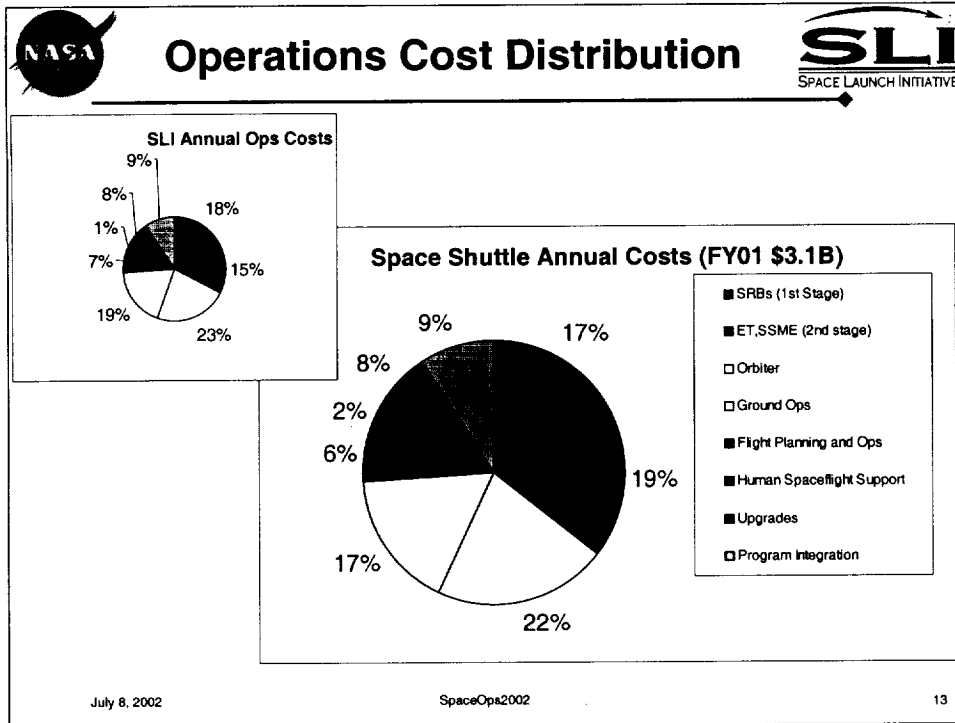
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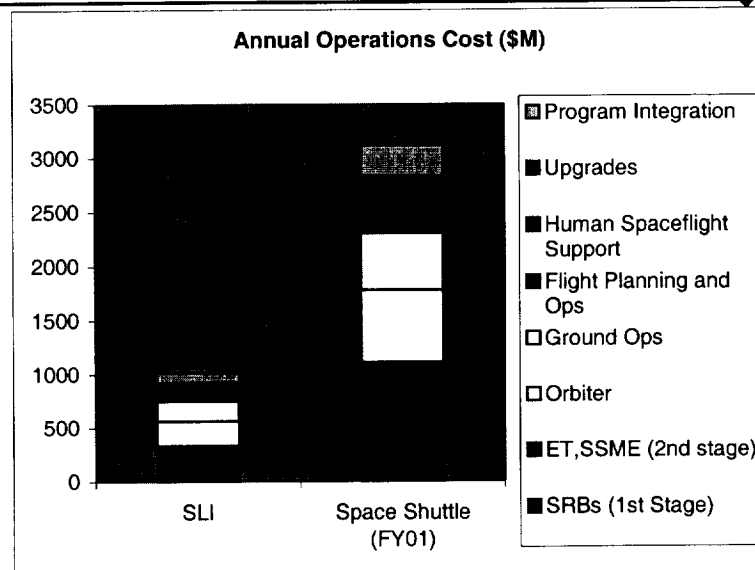
Table 3 below provides a conceptual distribution of SLI annual operations costs when reduced to one-third of the Space Shuttle's corresponding costs. Also shown in the table and figure 2 is a conceptual redistribution of the SLI operations costs.



In this example, using the same top-level cost breakdown for the shuttle, significant cost reductions are made in all operations cost elements through application of the changes described previously. Some SLI changes will reduce specific cost elements more than others. For example, reusability in the first and second stage propulsion systems, i.e., moving from the expendable External Tank and refurbished SRBs/RSRMs, will be cost effective by cutting recurring production costs.



## SLI Shuttle Costs Comparison



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But some changes affect all cost elements. For example, fixed operations costs in all areas will also be spread over commercial and military missions reducing NASA's portion of fixed costs.



## Risks



- **Developing confidence in new systems**

- Mitigation:
  - Application of common industry hardware and software design of the current decade, where appropriate for the space flight environment
  - Testing and demonstration

- **Adopting “new ways of doing business”**

- Mitigation:
  - Leadership
  - Training and education
  - Practice

- **Operations risk management**

- Manage technical, schedule, cost, and human performance risks through identification, assignment, tracking, and closure

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Risks must be mitigated to implement these significant operations changes. One risk will be developing confidence in new systems and processes. This may be mitigated through the application of “off-the-shelf” industry hardware and software, where appropriate for the space flight environment. Testing and demonstration will also be necessary, especially for new technologies and systems.

Another risk will be changing to “new ways of doing business.” These changes will require leadership, training, education, practice, and experience with new processes and systems. Identifying new skill sets, developing training programs for these skills, and providing opportunities to gain experience applying these skills will be a management challenge.

New operations risks can be expected to emerge as the system is developed. They can be mitigated with effective risk management and careful identification, assignment, tracking, and closure.



## Summary



- **SLI has set challenging operations goals**
  - Operations of the SLI system must be significantly different from the Space Shuttle
- **A highly operable design is required to achieve the goals**
  - Nearly full reusability (elimination of recurring production)
  - High reliability
  - Lower maintenance and servicing (propulsion, thermal protection, software, subsystems)
  - Advanced automation
- **Improved, efficient processes required to decrease manpower**
  - Simpler, quicker processing
  - Highly skilled, reduced workforce
  - Elimination of tasks

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SLI has set challenging operations goals. Operations of the SLI system must be significantly different from the Space Shuttle to achieve the goals. The SLI system must be a highly operable design with nearly full reusability (i.e., elimination of recurring production and refurbishment), high reliability, reduced maintenance and servicing, and advanced automation. “New ways of doing business” are required with simpler, quicker, efficient processes that eliminate and streamline human tasks to decrease workforce size.





## References



- **Space Shuttle FY01 Costs, NASA Chief Financial Office Web Site,**
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