NASA In-House Space Transportation Architecture Study Final Briefing

Kennedy Space Center

February 11, 1999

STAS5028cover

Agenda

- Introduction
- Process
- Architectures
- Results
- Architectural Assessment
- Implementation Issues
- Additional Analyses
- Conclusions and Recommendations

Introduction

Opening Remarks

- **Focus of study is on NASA's human transportation requirements for Earth-to-orbit transportation through 2020**
  - Space Station (baseline case)
  - Human Exploration (excursion case)

- **Goal is to significantly reduce NASA's costs by leveraging the investment of the commercial launch industry and estimating the marginal cost to NASA**

- **Fundamental questions:**
  - Industry: "Can industry meet NASA's requirements and be competitive in the commercial market?"

  - NASA: "Can industry meet NASA's requirements and be competitive in the commercial market?" *AND* "Can *NASA tailor our requirements to utilize commercial launch assets?* If not, what are NASA's alternatives?"

Study Background

- **The President's National Space Transportation Policy directs that a decision will be made by the end of the decade on development of a next generation reusable launch system.**

NASA is initiating U.S. industry led studies to determine:

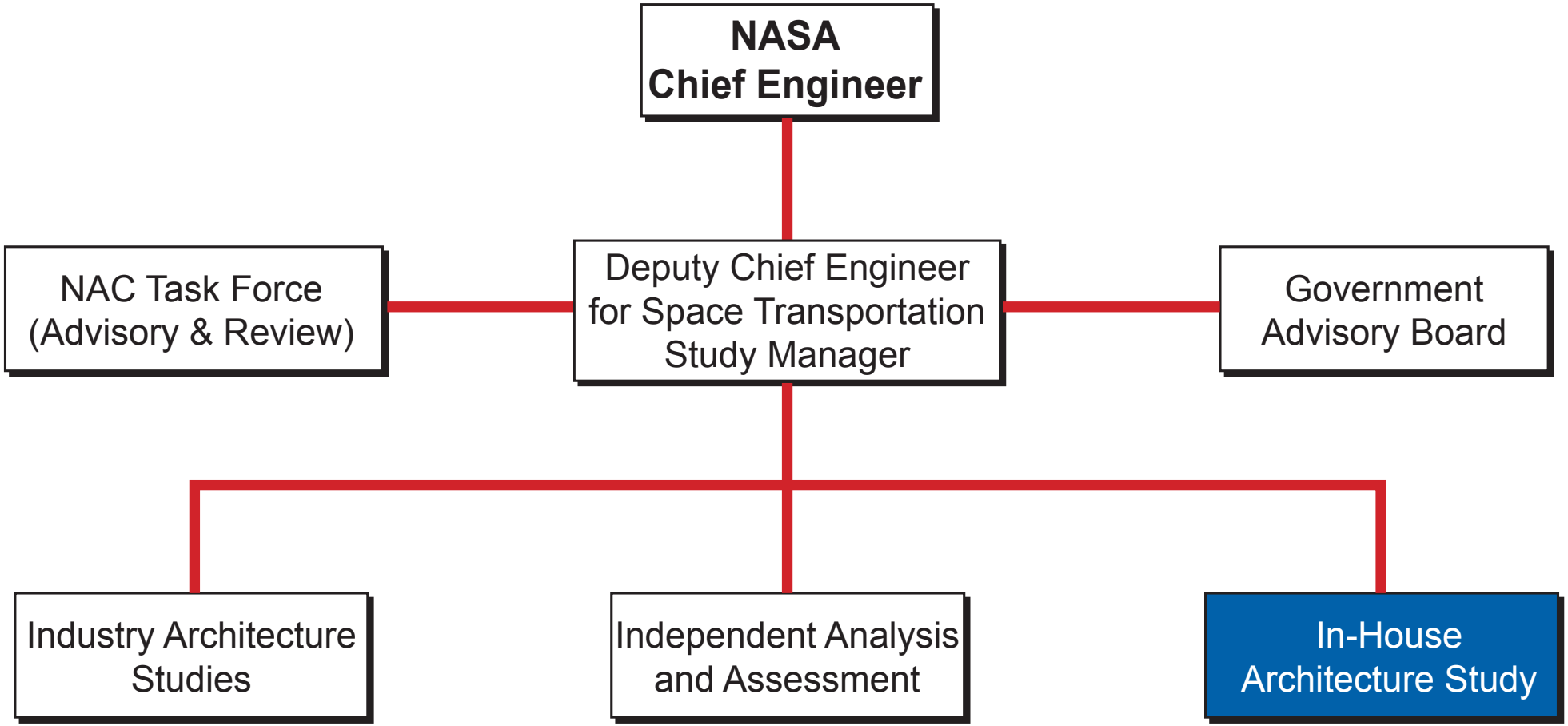
(1) If the Space Shuttle system should be replaced,

(2) If so, when the replacement should take place and how the transition should be implemented,

(3) If not, what is the upgrade strategy to continue safe and affordable flight of the Space Shuttle.

Five industry studies and an agency "in-house" study were conducted

Study Organization



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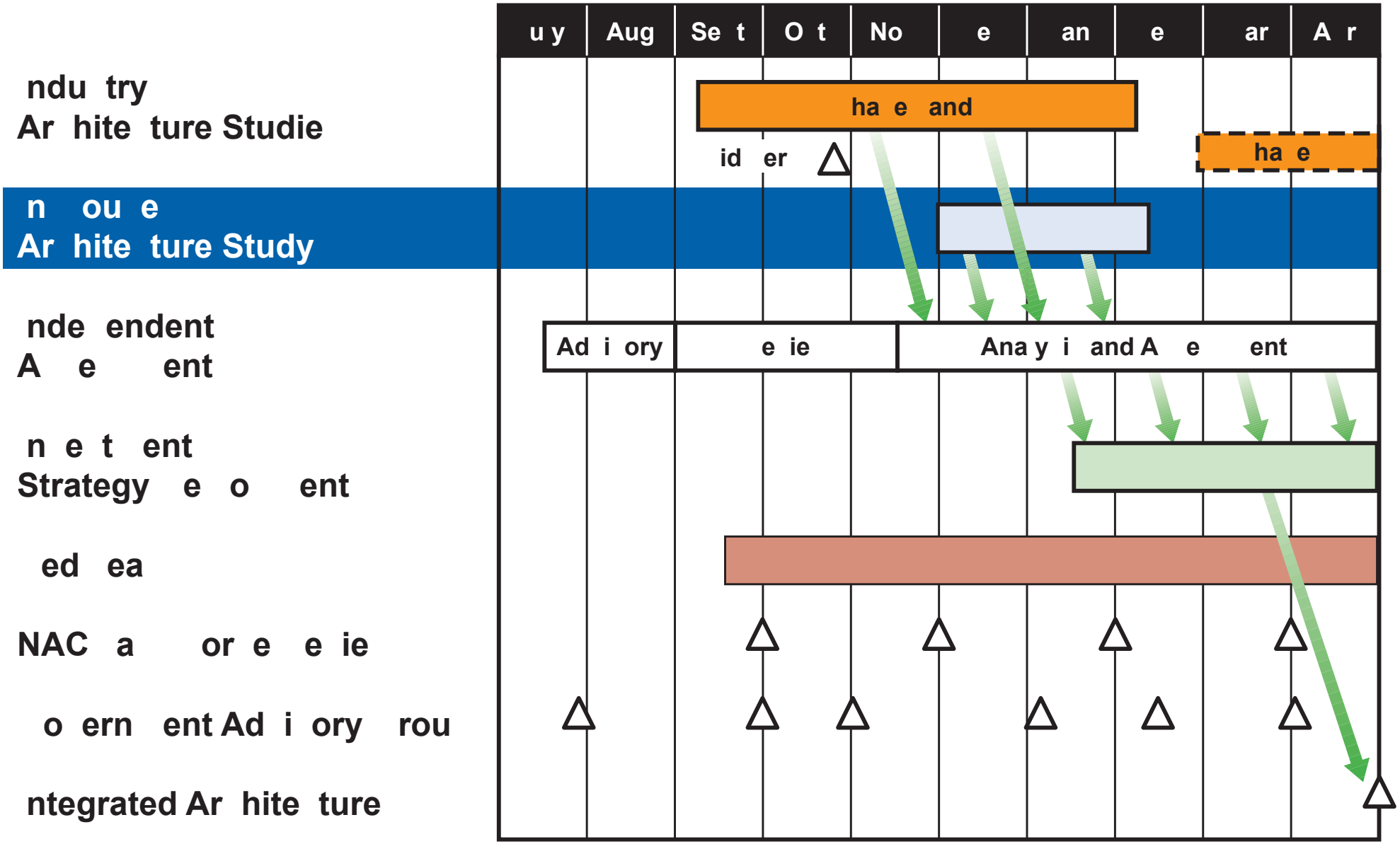

NASA In-House Study Team

- **Scott Graham** — **LeRC (study lead)**
- **Steve Cook** — **MSFC**
- **Joe Hamaker** — **MSFC**
- **Mike Gaunce** — **ARC**
- **Roger Lepsch** — **LaRC**
- **Frank Izquierdo** — **KSC**
- **Pepper Phillips** — **KSC**
- **Kent Joosten** — **JSC**
- **Rod Wallace** — **JSC**
- **Lt. Col. Jay McDaniel** — **USAF (detailed to Code R)**

- **Additional support from:**
  - MSFC: Eric Shaw, Andy Prince, Robert Shepard, Tom Dickerson, Ed Threet, Fayssal Safie, Bonnie Hankins, Dave Mercer, Bill Eoff, Bruce Shelton, Mike Crabb, Rich Drinkard
  - KSC: Carey McCleskey, Edgar Zapata
  - JSC: Bret Drake, Doug Whitehead, Elric McHenry, Mac Henderson, Jan Railsback,
  - LaRC: Bill Cirillo, Ted Talay, Paul Tartabini
  - Futron: Louis Fussell
  - SAIC: Maurice Hale, Joseph Fragola, Gaspare Maggio, Mary Heck, Joseph Minarick, Pat Odom, Dave Taylor, Lee Varnado, Bill Escher, Jay Laue, Howard Lester, Spencer Hill, Mike Tripp

Briefings Received

- **Requirements**
  - ISS servicing/maintenance/logistics
  - Human exploration
  - JSC human rating
- **Transportation elements**
  - Shuttle capabilities
  - Shuttle upgrade plans
  - Shuttle commercialization/privatization (USA)
  - Reusable First Stage (a.k.a. Liquid Flyback Booster)
  - X-38/CRV
  - VentureStar/X-33
  - EELV (both Atlas V and Delta IV)
  - USAF views on the value of competition (EELV experience)
  - X-37 (Advanced Technology Vehicle)
  - Advanced reusable transportation concepts (LaRC concept studies)
  - RLV crew module study
  - RLV cargo carrier study
  - Exploration transportation concepts (e.g., Magnum)
- **Past studies**
  - Hawthorne Report
  - Access to Space Study

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  - Commercial market capture based on price, number of competitors, and vehicle capability
  - Considered the potential of “emerging markets”

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  - “Closed” business cases from both industry and government perspectives
  - Evaluated business cases for both 2020 and 2030 time horizons

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  - Factored into cost estimates

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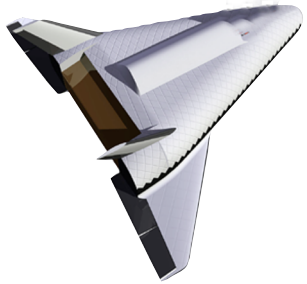

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Process
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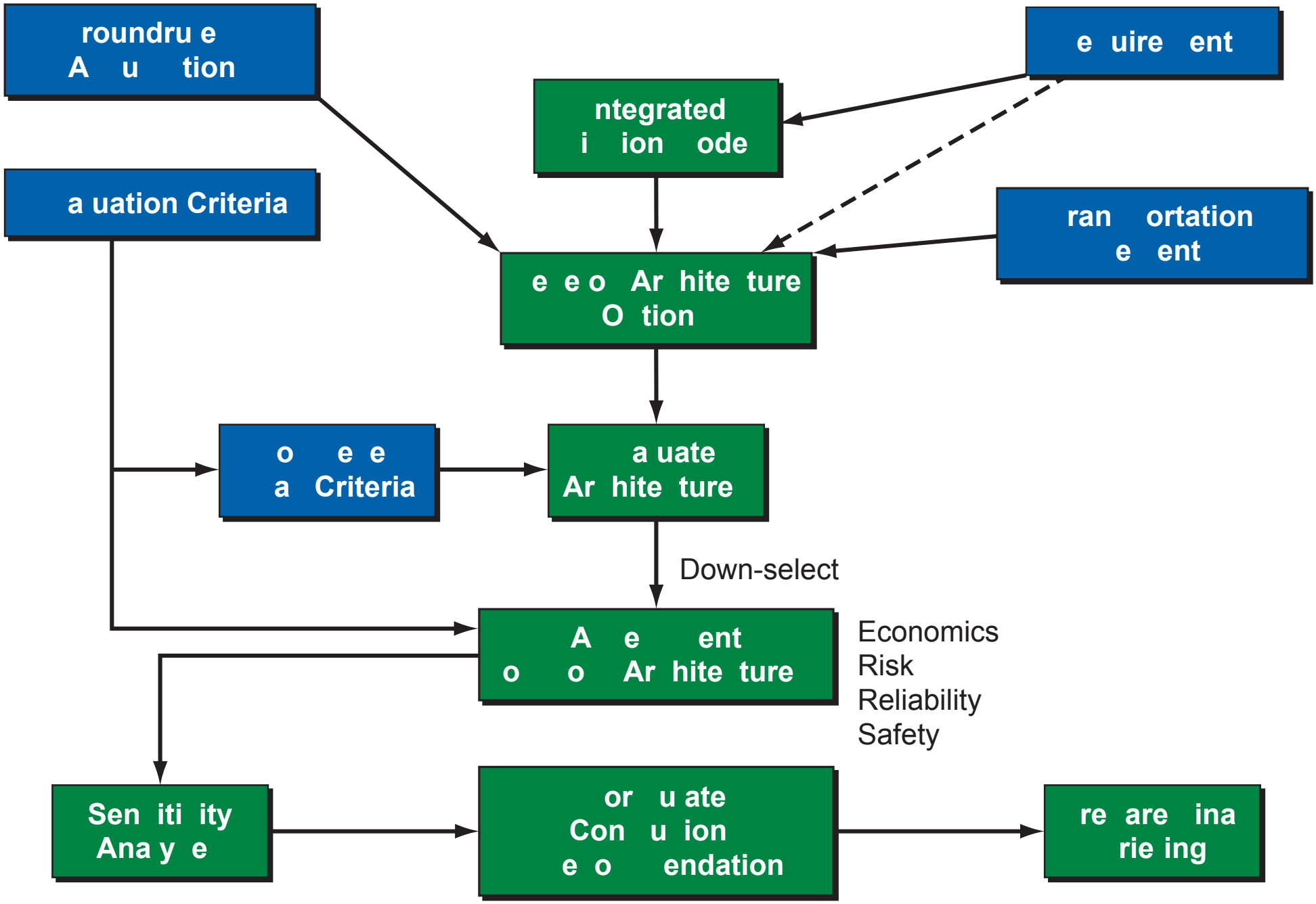

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Requirements

- **Continue to fly shuttle safely as long as required**
- **Architectures must meet the mission model through 2020**
  - Added one Shuttle-equivalent flight/year to ISS for contingency
  - Did not consider ISS module/element change-out/addition after assembly complete (not in mission model)
  - Analyses extended to 2030 to encompass new element life-span
- **Must be able to support the ISS microgravity requirement while providing adequate servicing**
  - 30 day continuous
  - 180 days per year
- **NASA / private investments must show a reasonable return on investment over a finite timeframe**
  - Exception: safety and obsolescence upgrades and human exploration

Requirements (Continued)

- **Considered the effect of JSC developed NASA Human Rating Requirements (JSC 28354)**
  - 0.99 cumulative probability of crew safe return over duration of program
  - Provide for crew escape across the flight envelope

- **Current budget plans**
  - Shuttle cost: $2.4B/yr for 8 flights (FY99 $'s);
  - Additional available budget: $300M/yr

Key Groundrules & Assumptions

- Representative, previously studied transportation elements used to construct and evaluate architecture themes
- Included only those elements needed to transfer people and/or cargo to and from final Earth orbit
- Existing commercial launch services can satisfy all national launch requirements except ISS and human exploration
- Government operated vehicles will not compete with the private sector
- No major changes in ISS transportation requirements until after initial construction complete

Key Groundrules & Assumptions (continued)

- **For the exploration excursion, assumed continuous human Mars mission capability beginning in 2014**
- **Funding information provided in constant FY99 dollars**
- **Architecture costs compared to a baseline including:**
  - Budgeted Shuttle operational costs
  - Additional space transportation budget
  - Estimated average NASA science mission launch costs
- **Market capture model drivers are vehicle payload mass capability and price per flight**
- **Technology Readiness Level 6 or greater required prior to system development decision**
- **Commercialization of any element has no impact on mission reliability**

Evaluation Criteria

Quantitative

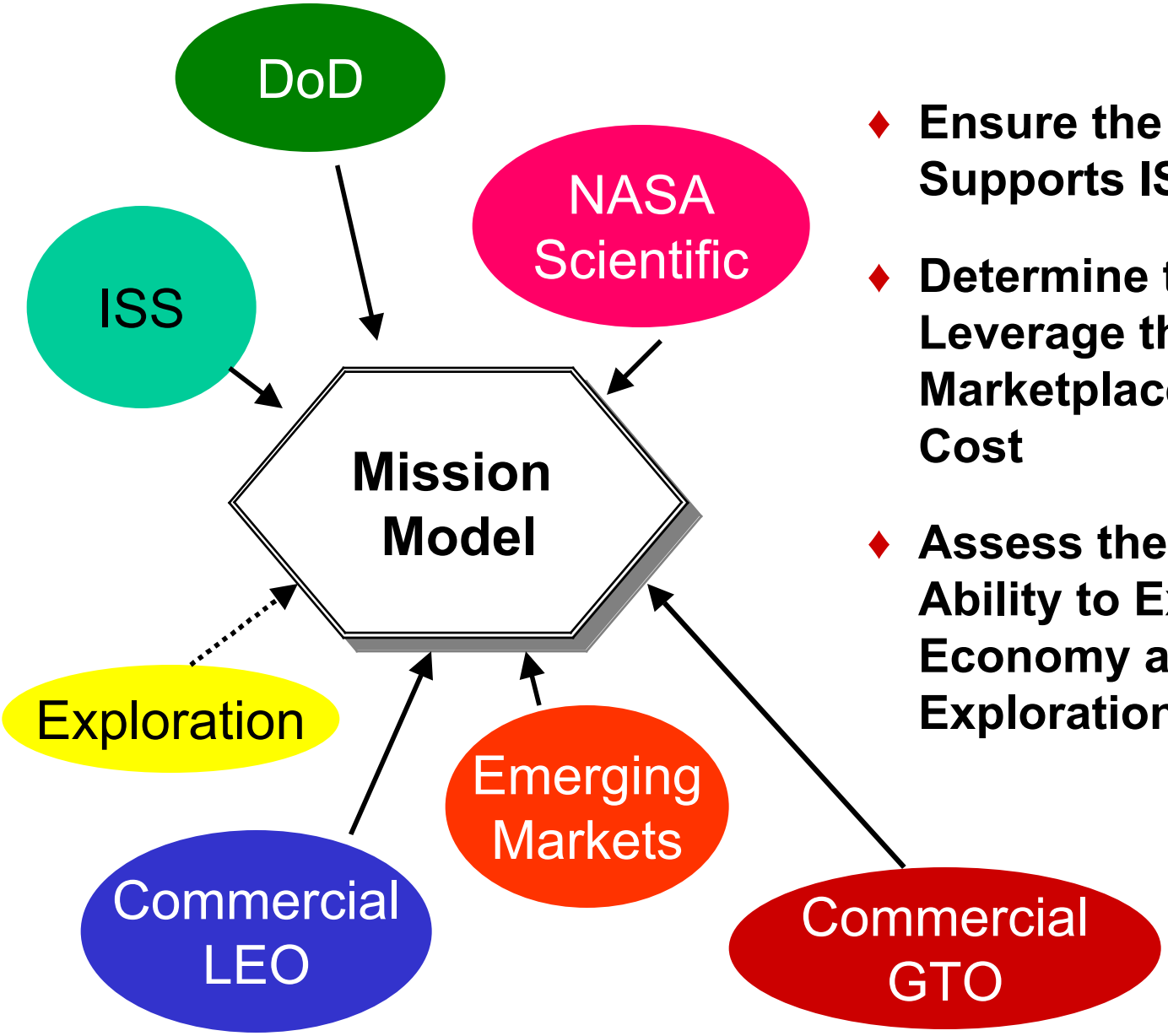
- **Discounted Life Cycle Cost to NASA**
- **Technical Risk (i.e. Probability of Successful Deployment)**
- **Reliability (i.e. Probability of Mission Success)**
- **Safety (i.e. Probability of Crew Loss)**

Qualitative

- **Intangible Criteria**
  - Resiliency
  - Continuity
  - Competition
  - Mission Capabilities
  - U.S. Competitiveness
  - U.S. Technological Leadership

Mission Model

Mission Model



- **Ensure the Architecture Supports ISS Servicing**
- **Determine the Potential to Leverage the Commercial Marketplace to Reduce NASA's Cost**
- **Assess the Architecture's Ability to Expand the Space Economy and Support Exploration**

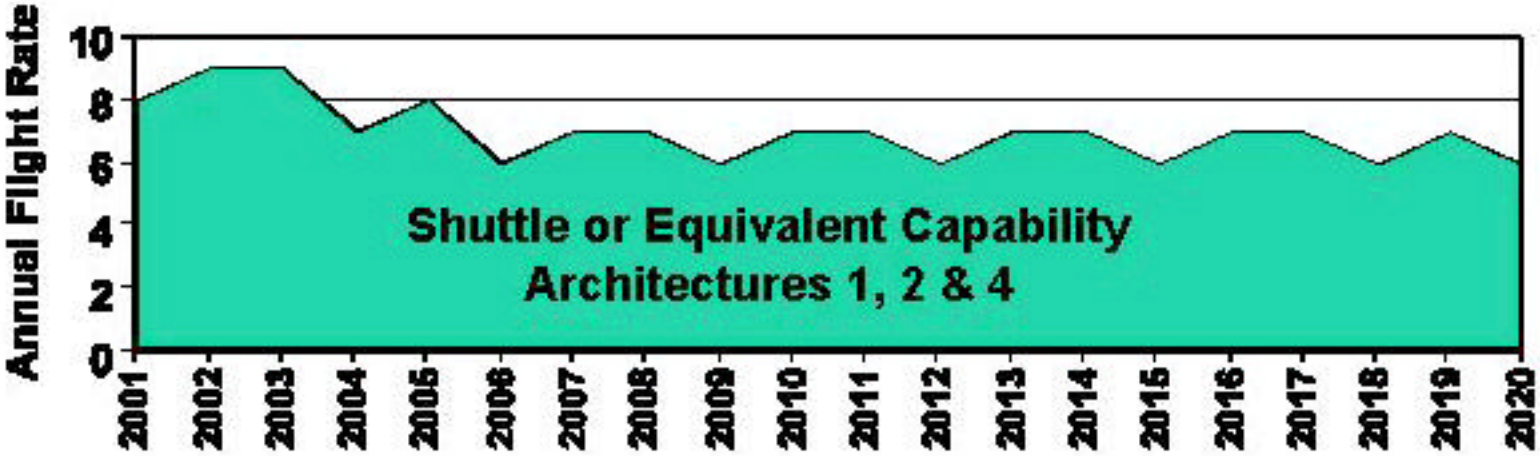
Mission Model Ground Rules and Assumptions

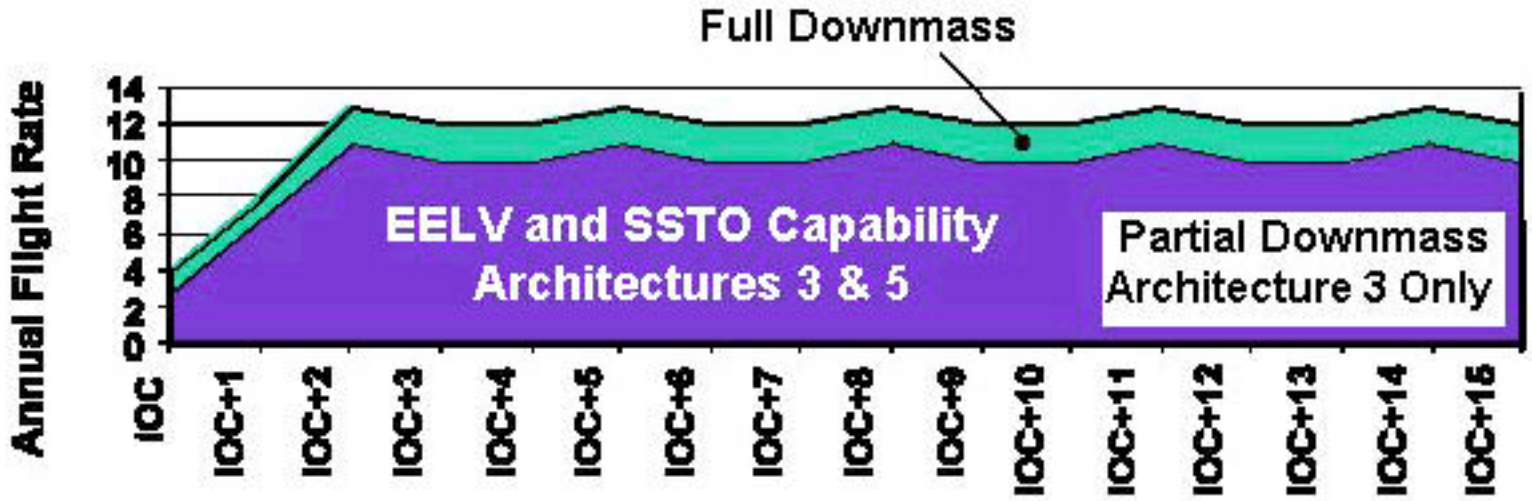
- The mission model projects launch service requirements to 2020. For sources that do not project to 2020, the last three years of the source are repeated
- Emerging market flights enabled at $1,000/lb or less
- Mission model does not include foreign government payloads for countries with indigenous launch capability

Mission Model Methodology

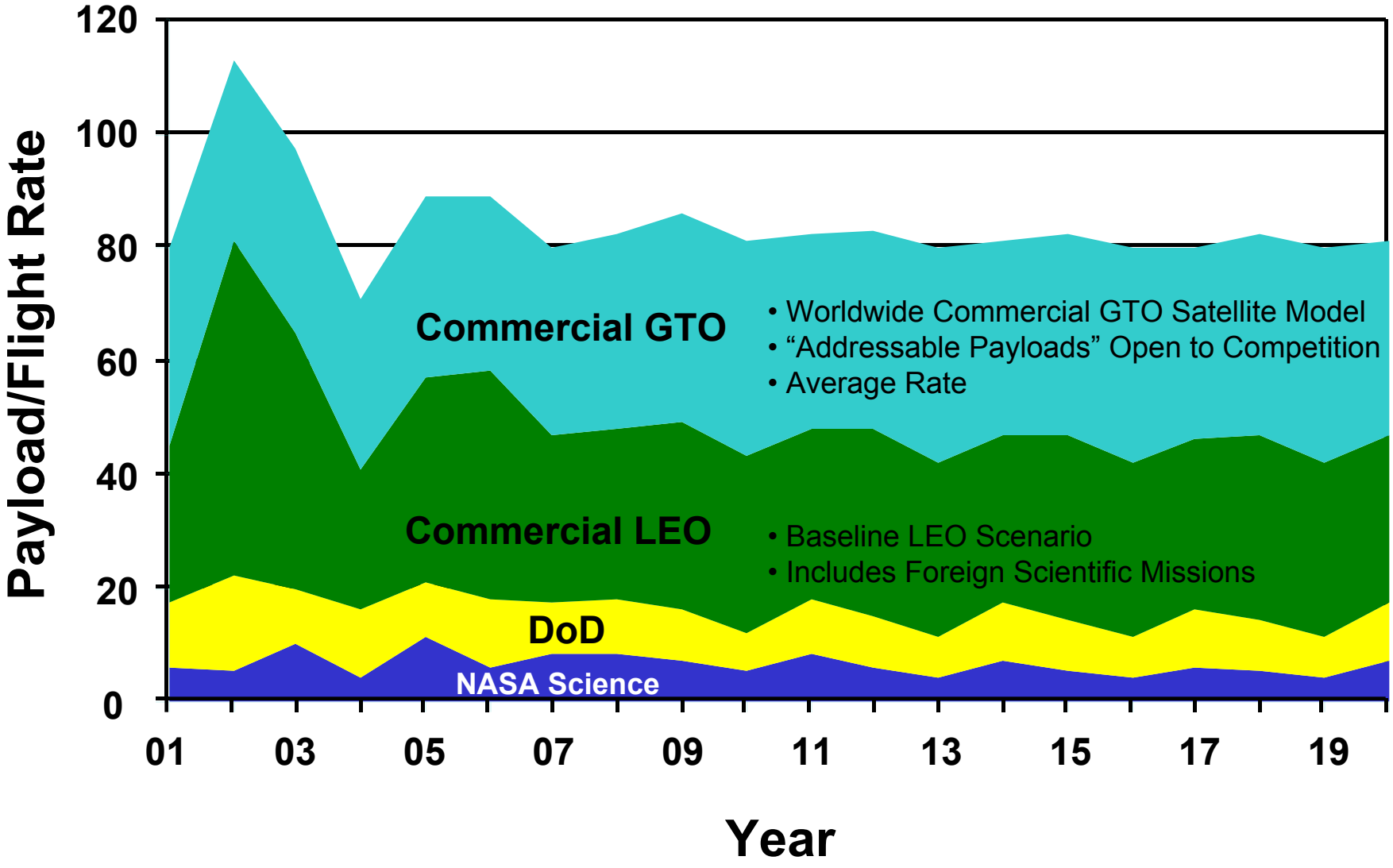
- **Data Sources**
  - ISS: JSC/LaRC Data
  - NASA Science: STAS Guidelines and National Mission Model
  - DoD: National Mission Model
  - Commercial LEO: FAA Model
  - Commercial GTO: COMSTAC Report
  - Emerging Markets: Commercial Space Transportation Study (CSTS)
  - Exploration: Exploration Office at JSC
- **Payload Classification**
  - Two Classes of ISS Servicing
    - Shuttle or Shuttle Equivalent (Architectures 1, 2 and 4)
    - 25K lbs to ISS (Architectures 3 and 5)
  - National Mission Model used for NASA Science and DoD
  - Commercial LEO Classifications same as FAA
  - All GTO Missions (Commercial and USG) Classified Consistent with COMSTAC
- **Multiple Manifesting**
  - No Multiple Manifesting of NASA Scientific or DoD LEO Payloads
  - Multiple Manifesting of Commercial LEO Missions Built into Source Material
  - GTO Payloads Multiple Manifested in Market Analysis Model

ISS Servicing Flight Rates





Non-ISS Payload/Flight Rates



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- Market Capture Analysis
- Market Penetration
- Emerging Market Model

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- STAS Mission Model
- Commercial Competitors

Economic Analysis

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Exploration Earth-to-Orbit Requirements

- **Current estimates for human Mars missions indicate spacecraft mass in low earth orbit ~880 klbs - *approximately equal to ISS final mass***
  - Reduced ~50% from previous studies due to different mission strategies, advanced propulsion technologies
- **43 flight ISS assembly strategy does not provide acceptable exploration assembly capability**
  - Large aeroshells for planetary aerocapture and entry
  - Potentially large quantities of cryogenic propellant
  - Planetary injection windows
- **When packaging inefficiencies and loss of aerocapture are considered, number of launches increases rapidly with decreasing launch vehicle capability**
  - 40 - 50 flights every 26 months for STS equivalent payload capability
  - On-orbit integration becomes exceedingly complex
- **Human Mars mission studies indicate efficient vehicle design and launch packaging with 180 klbs (80 metric tons) capability to orbit**
- **80 metric ton-class vehicle captures maximum commonality with existing infrastructure**

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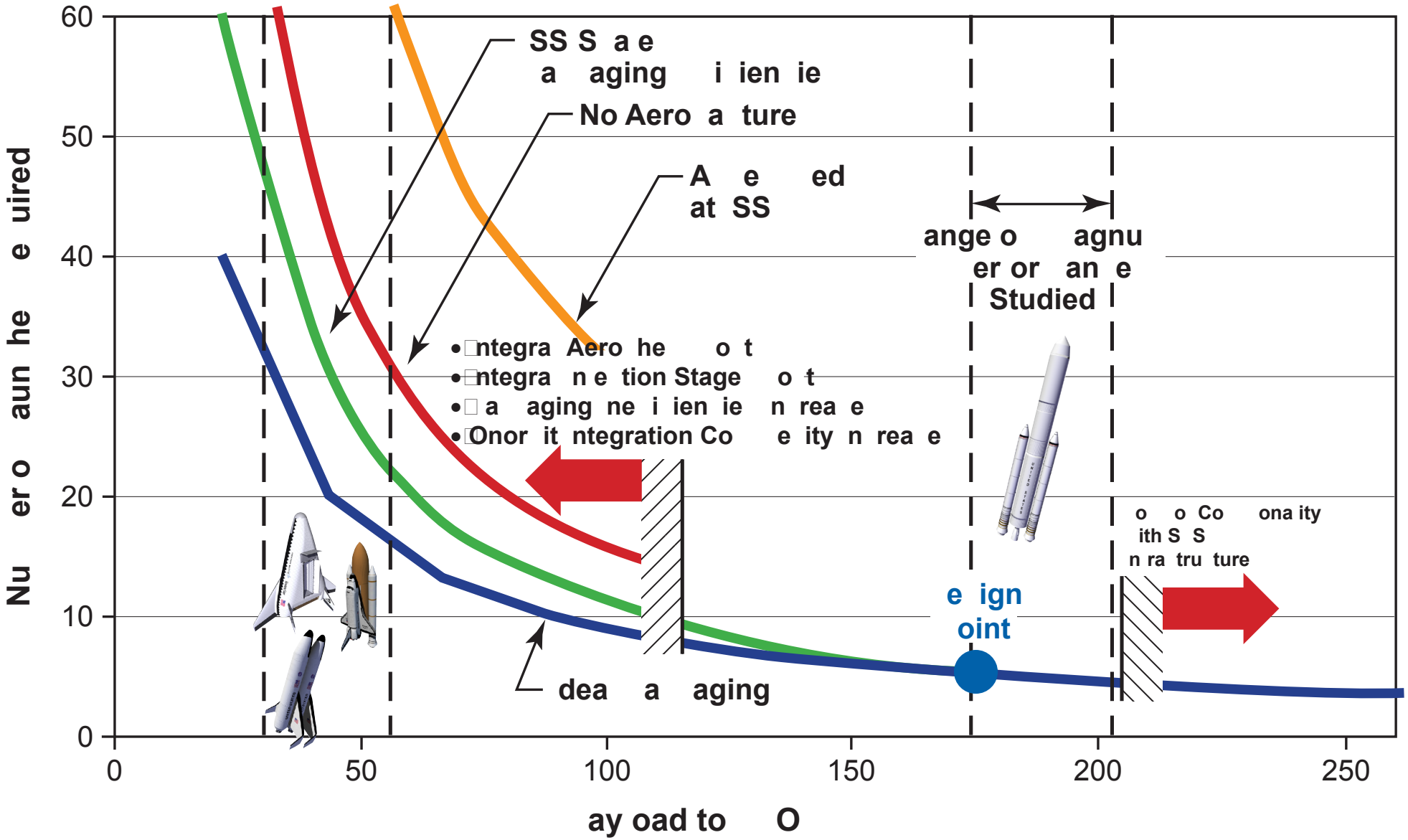

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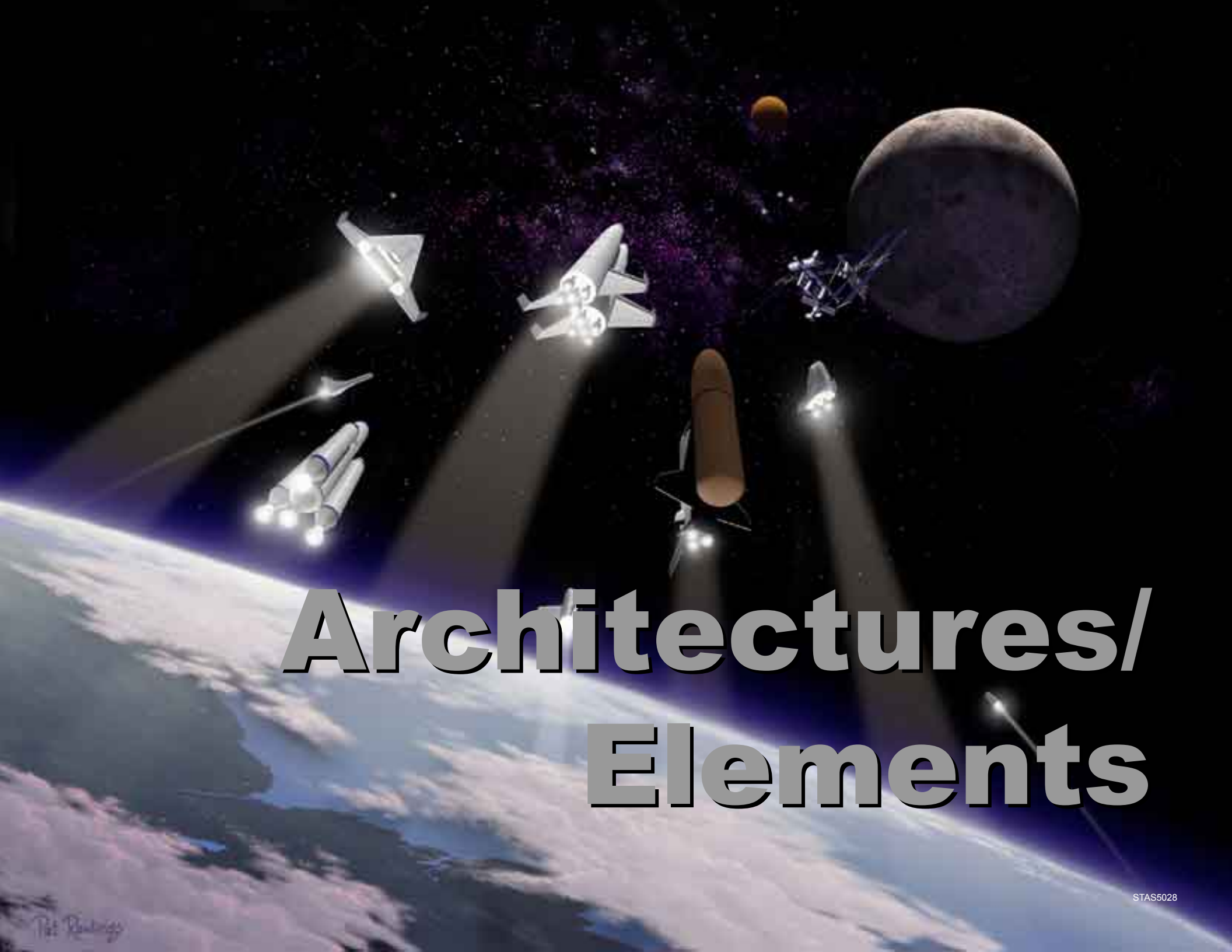
Architectures/
Elements
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Development of Architectures

- **Reviewed conclusions of past architecture studies (previous STAS, Human Transportation Study, Access to Space, etc.)**
- **Determined options for ISS transportation ranging from current to new systems:**

5 Major Themes

Shuttle

Shuttle w/RFS

EELV

New TSTO

New SSTO

- **Developed baseline cases and options/excursions**
  - Evaluated both USG and commercially funded options
- **Phased in new systems based on:**
  - Technologies at TRL 6 prior to ATP decision
  - Technology developments consistent with Code R Goal 9 and 10 roadmaps
  - Shuttle transition strategy: phase out Shuttle as soon as possible after appropriate test and transition period for new systems
- **Focused on attributes of systems, not specific system designs**
  - Developed “reference” system concepts

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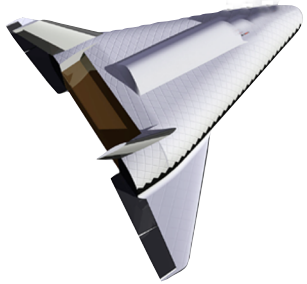

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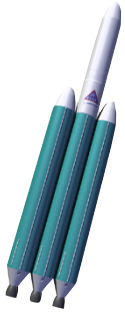
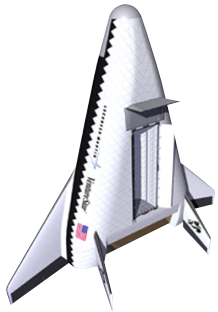
Shuttle

Shuttle w/RFS



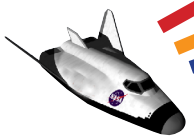
EELV

New TSTO



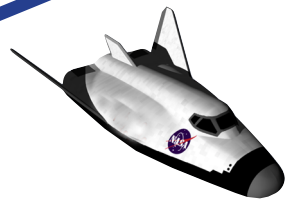
New SSTO

Cre Cargo Carrier



Crew Only

Internally Carried Crew Module



Crew + Limited Cargo

Cargo Up Only

Cargo Up /Down

A database of approx. 40 vehicle elements was developed for this study

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- **Shutt e i u ed or SS i ion through**
  - Limited set of phase III upgrades are implemented (safety, obsolesence, cost)
  - Cost to NASA is reduced based on Space Flight Operations Contract incentives

- **O tion or o er ia Shutt e a o it to o ete or ien e o and o er ia ay oad**
  - Requires development of a low cost LEO to GTO upperstage

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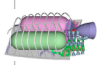

Shuttle Phase II/III Upgrades

Co er ia i e Shutt e

NASA In-House Space Transportation Architecture Study

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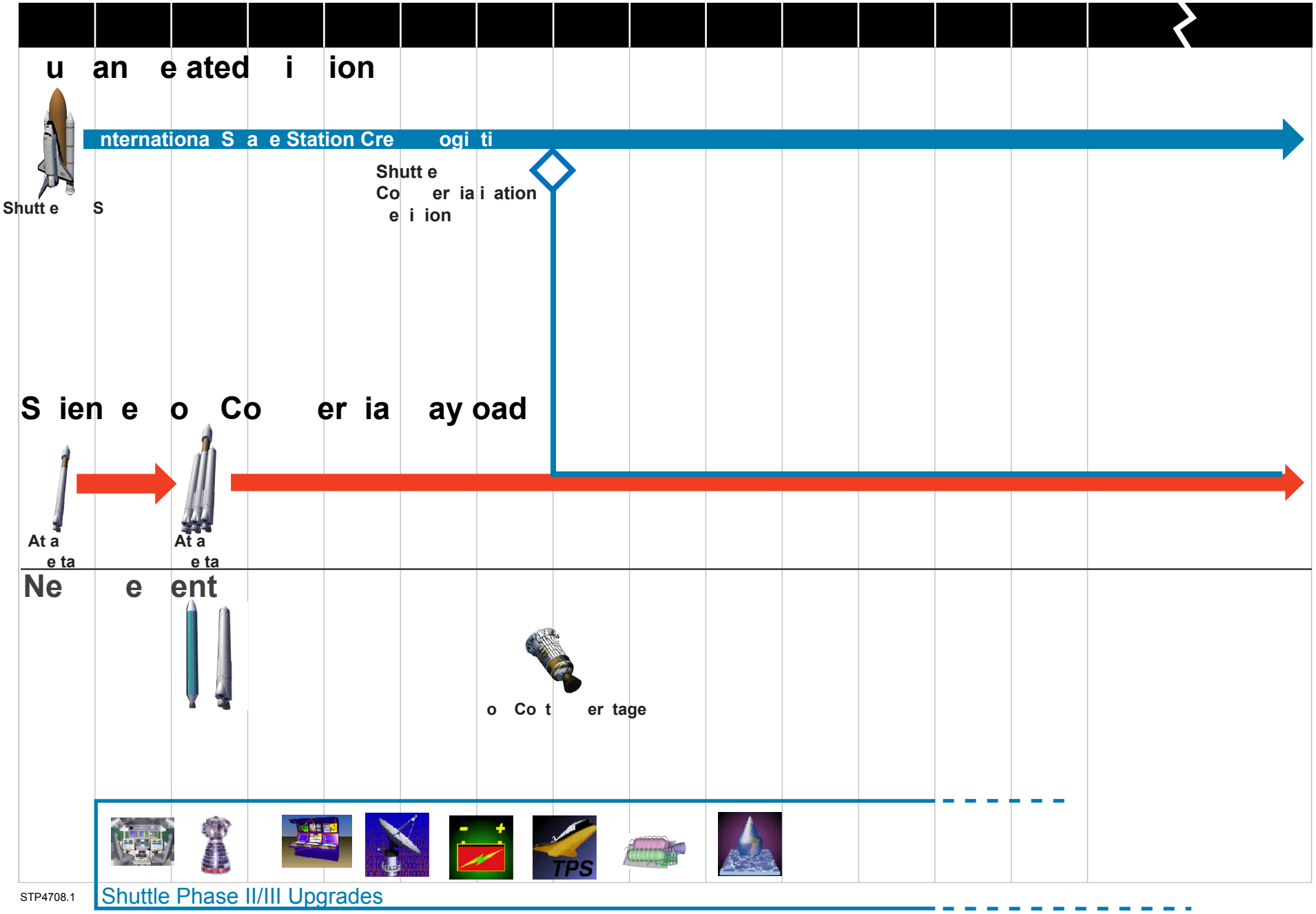

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NASA In-House Space Transportation Architecture Study

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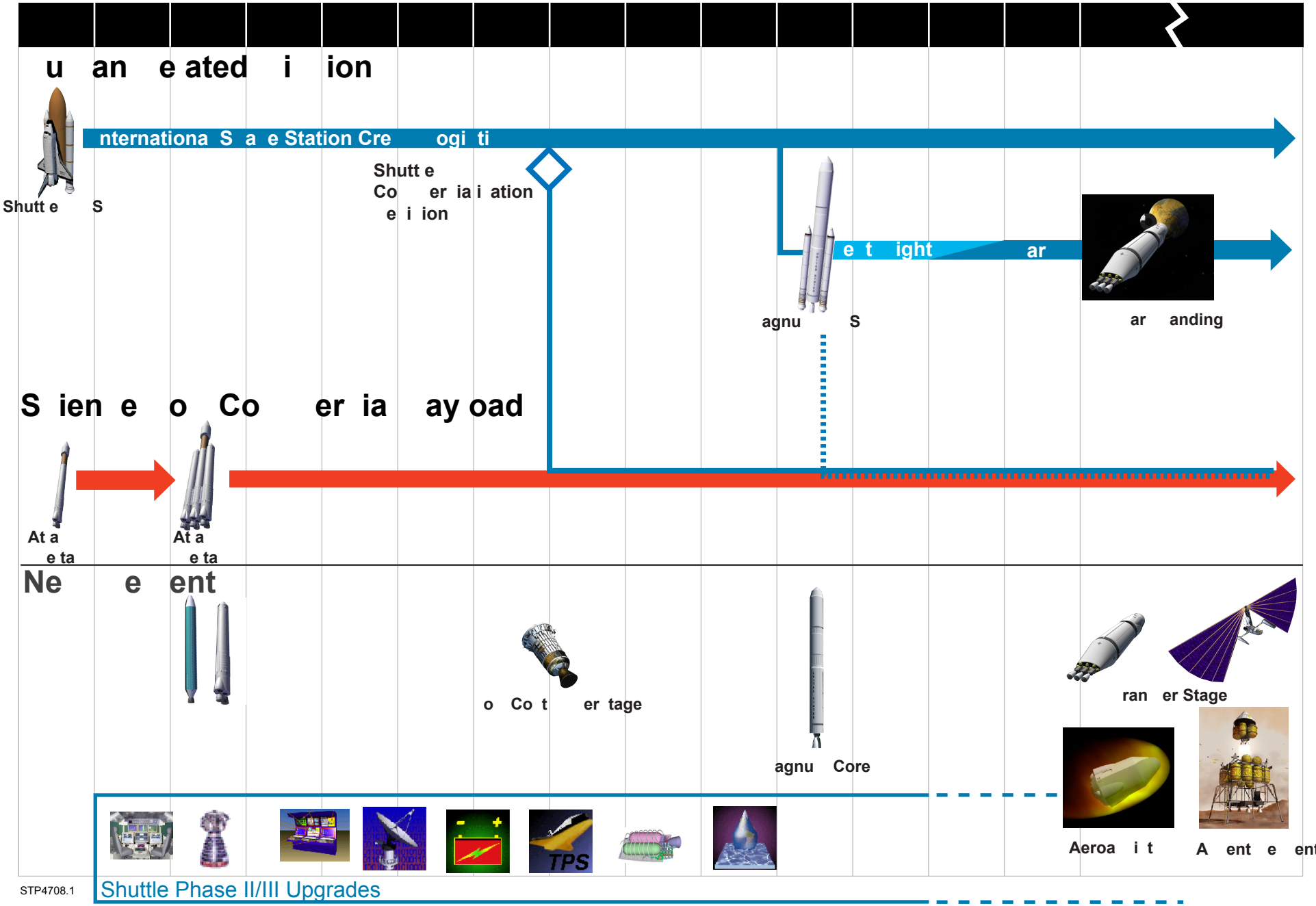

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  - **O tion or ne o er ia y de e o ed reu a e or iter or S**
    - Performs ISS missions
    - Competes for science, DoD and commercial payloads
    - Requires development of Crew Transfer Vehicle
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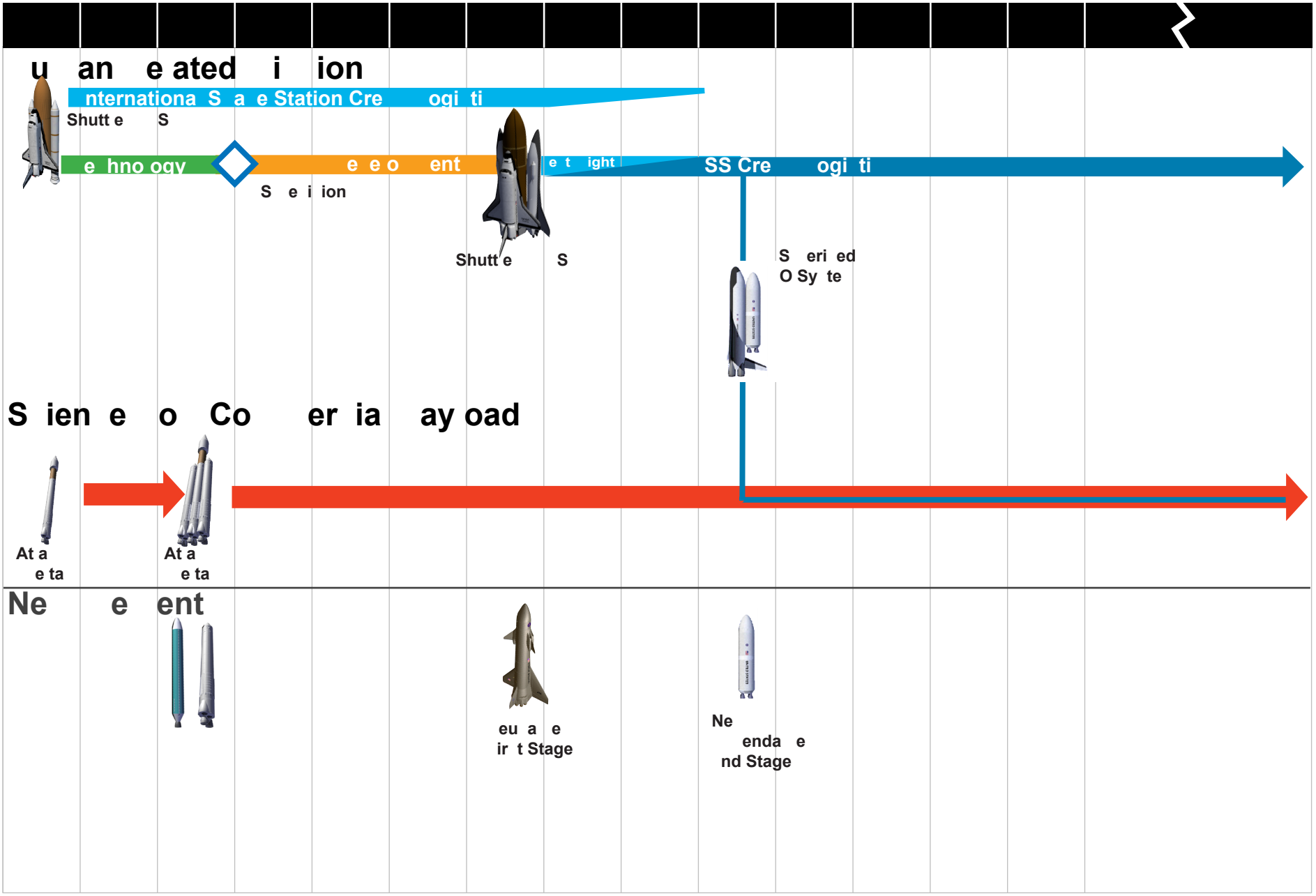

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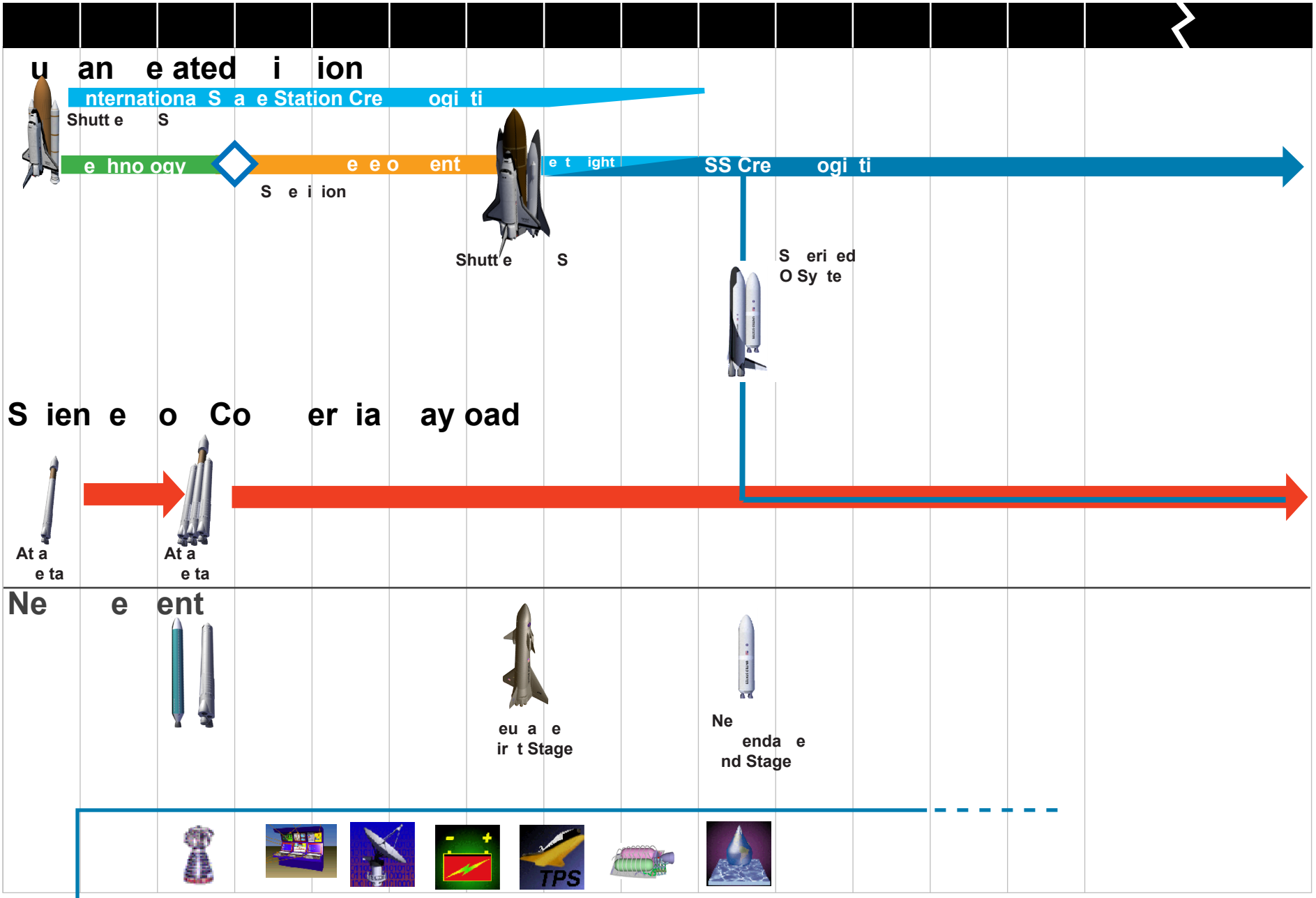

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Shuttle Phase II/III Upgrades

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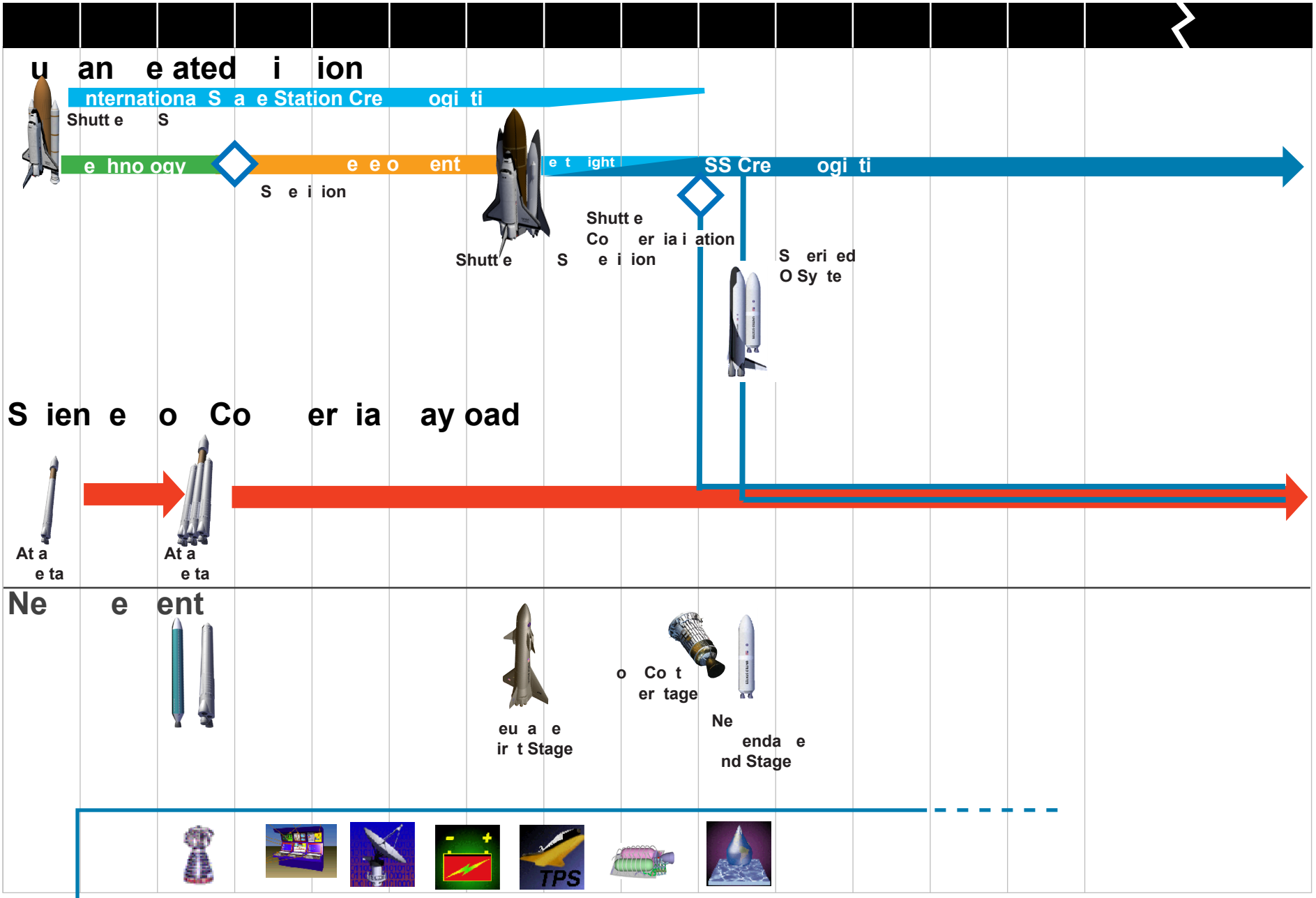

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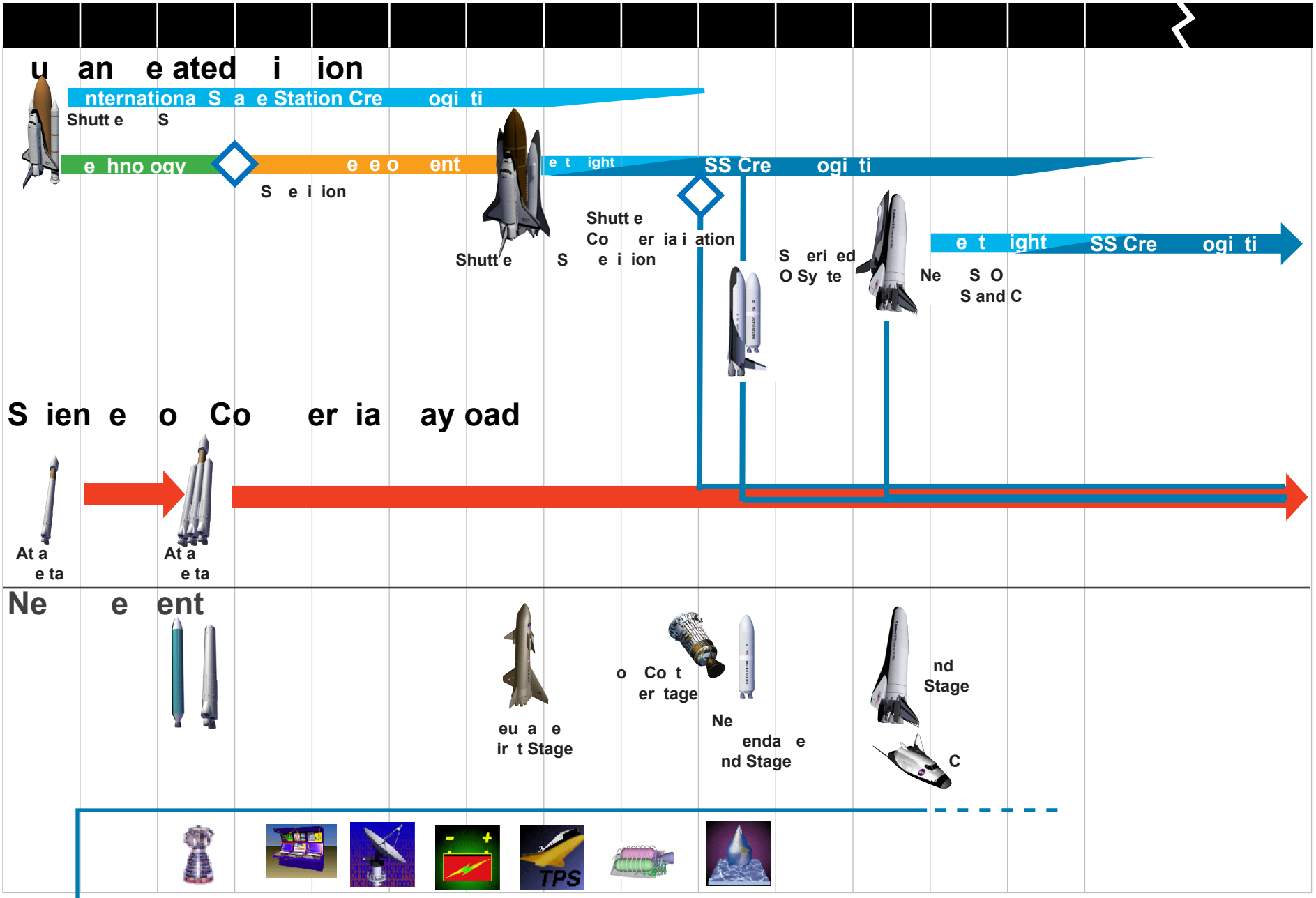

Shuttle Phase II/III Upgrades

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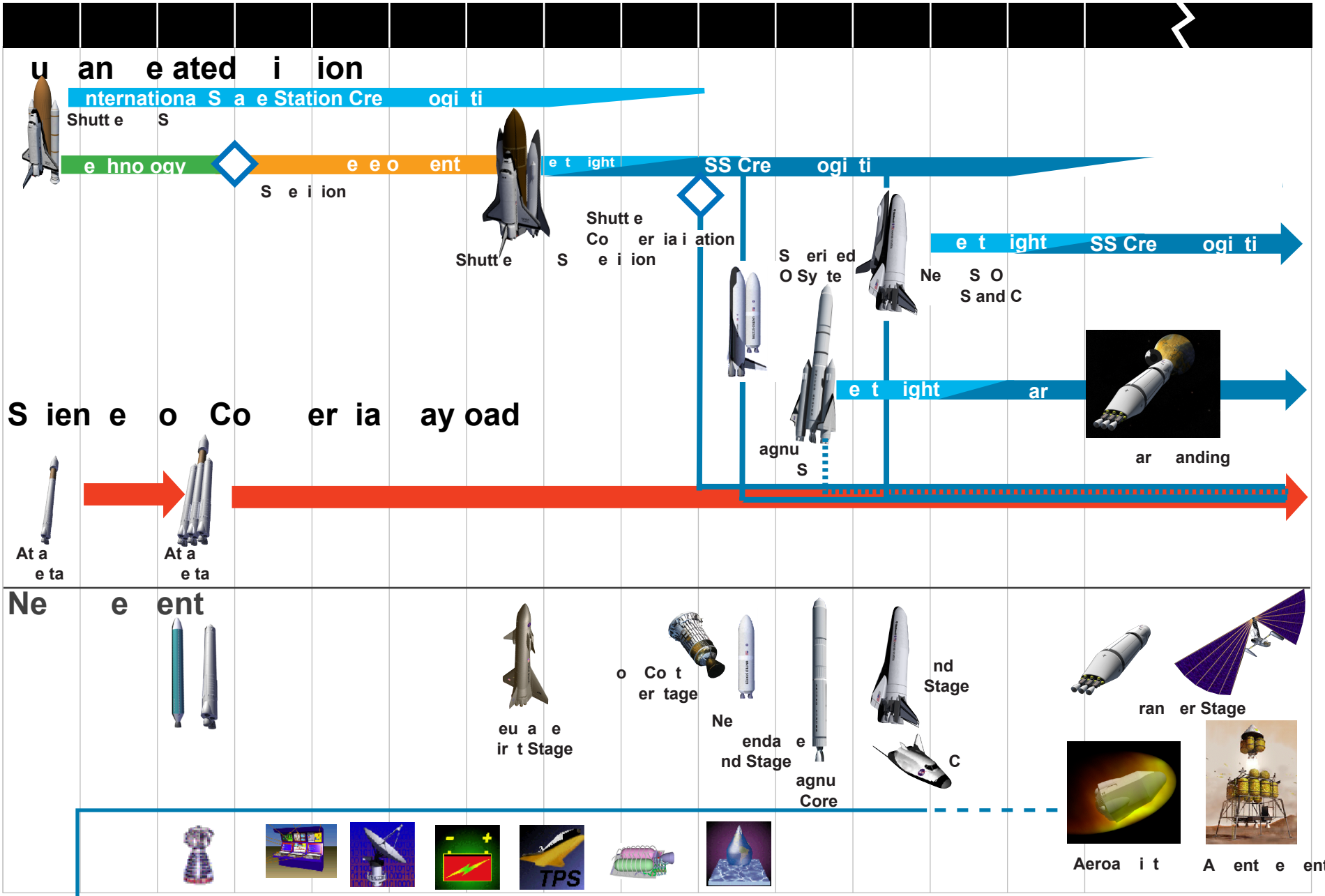

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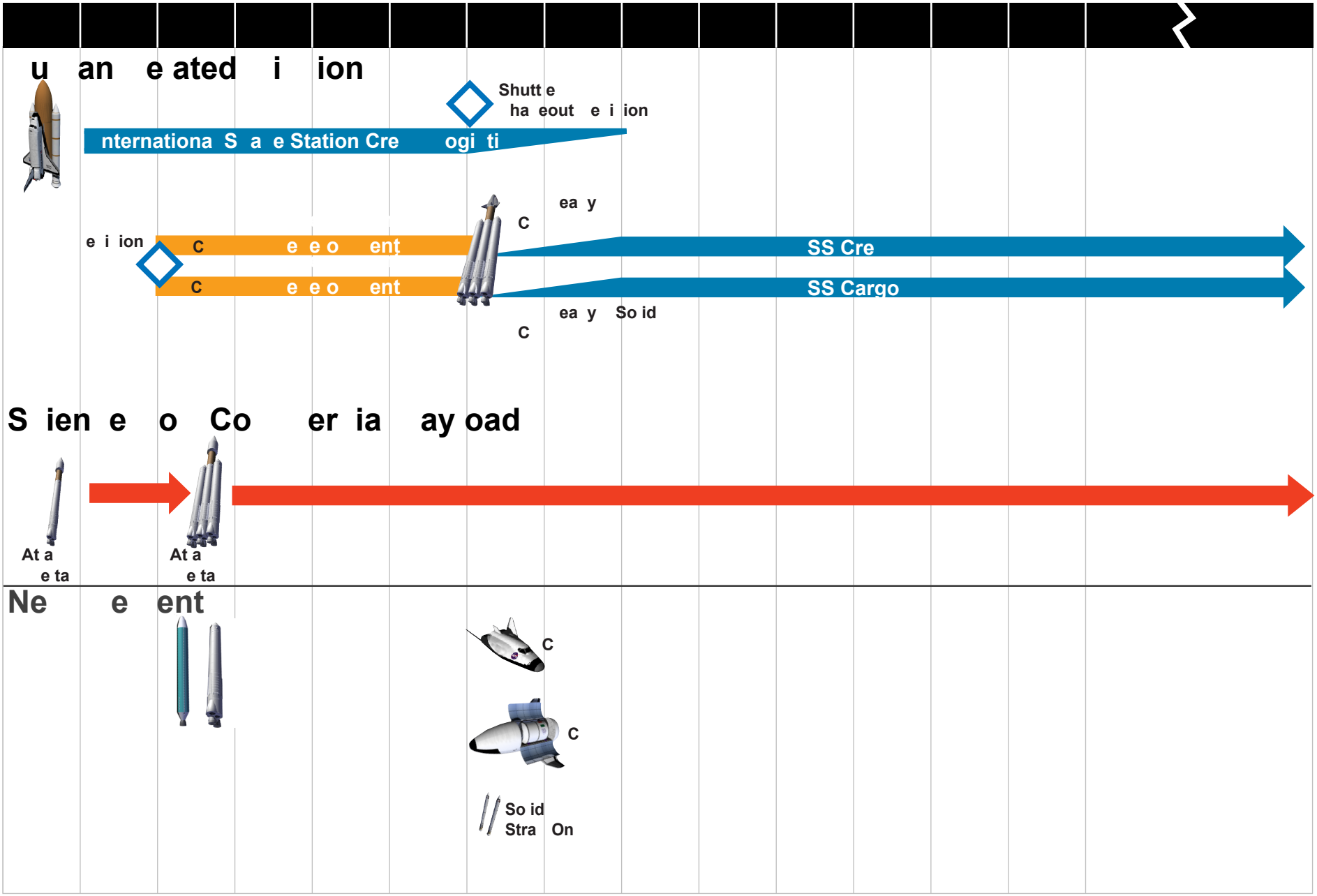
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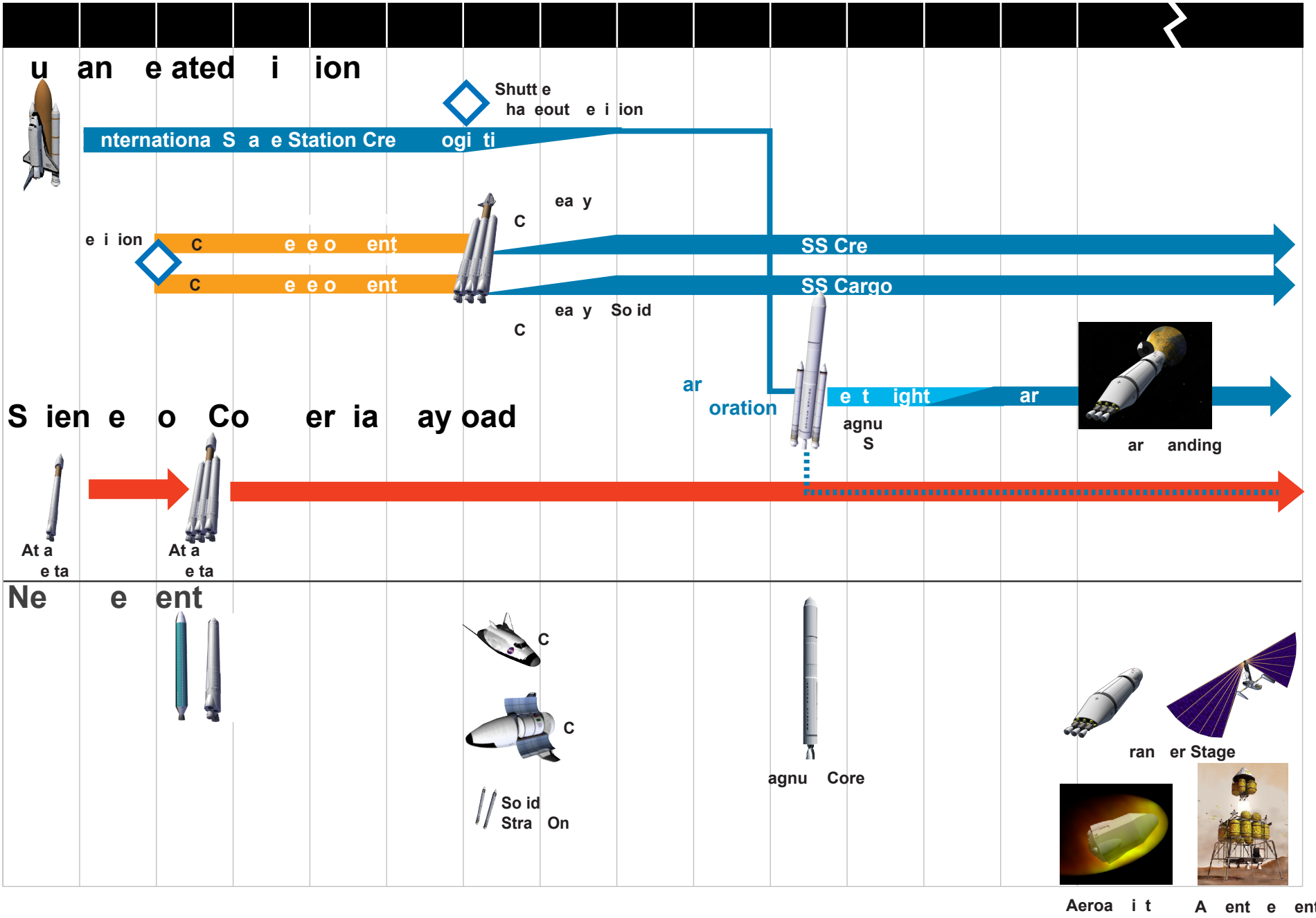
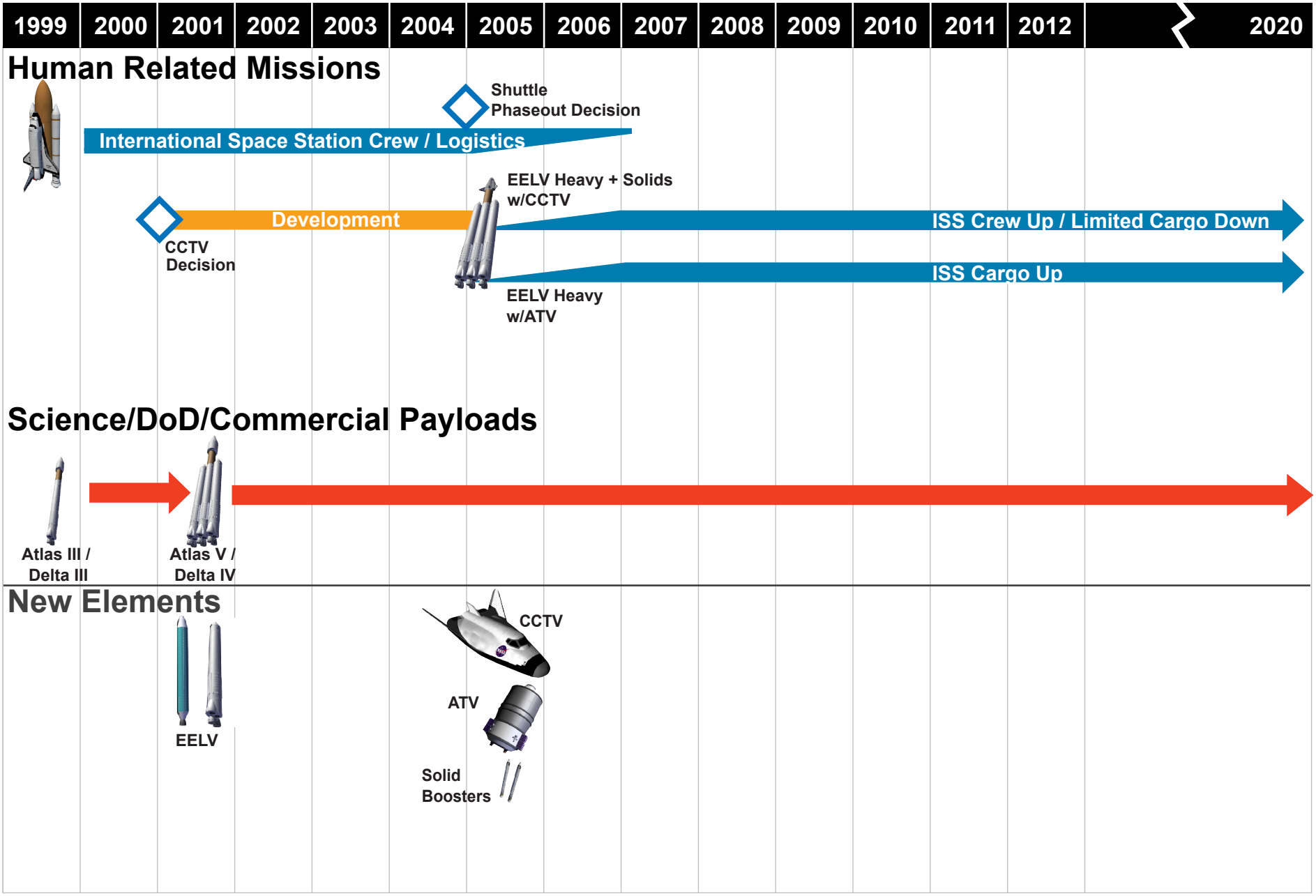


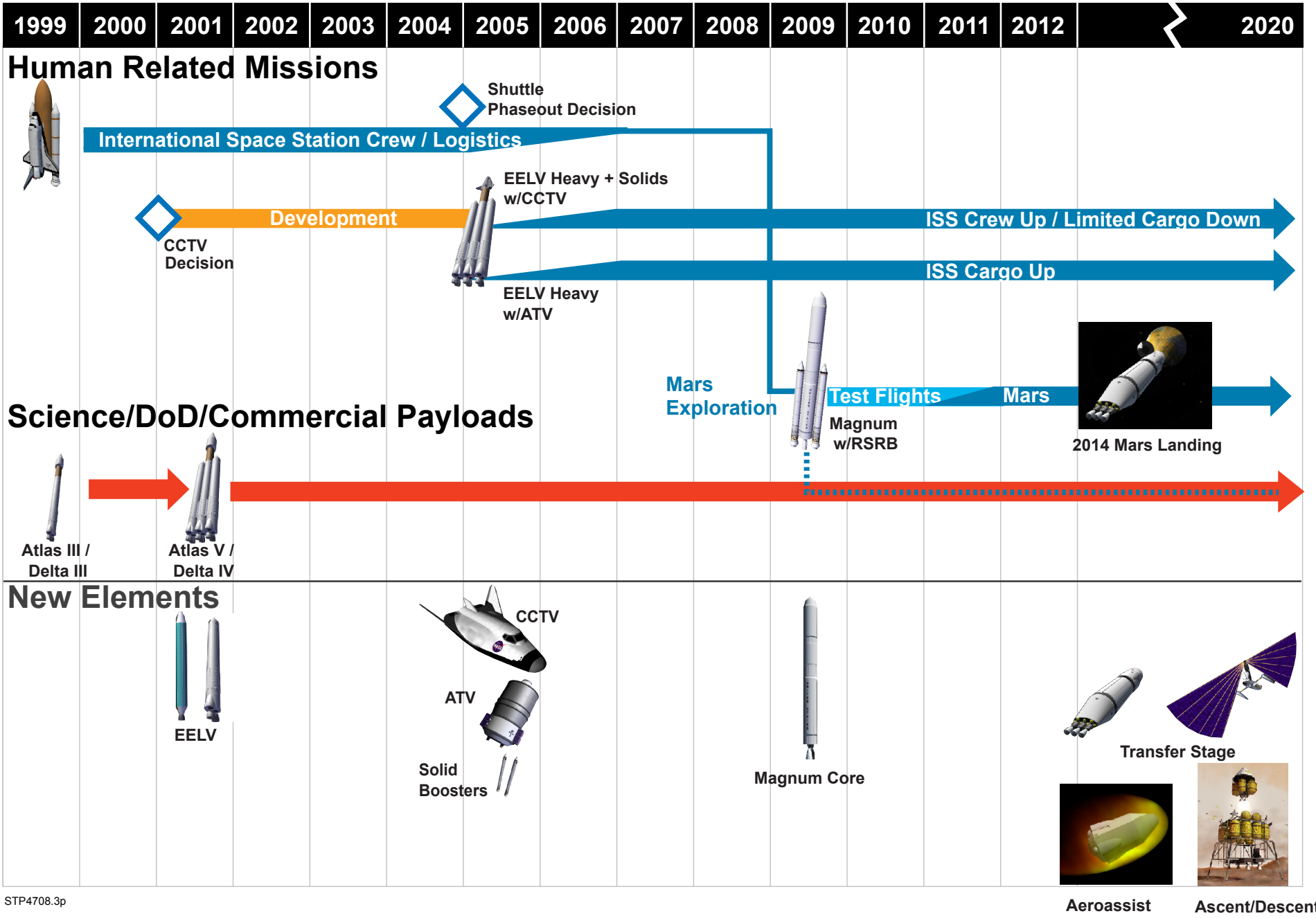
3–EELV Based Transportation Partial ISS Downmass



3–EELV Based Transportation Partial ISS Downmass

Exploration Excursion

NASA In-House Space Transportation Architecture Study



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ey eature o Ar hite ture

- Ne t o tage to or it S O ehi e re a e S a e Shutt e
  - New upperstage to capture GTO missions
- Cre ran er ehi e odu e u ed in on u tion ith S O or hu an i ion to SS
  - Potential alternate ISS access option using CTV on a human rated EELV
- S a reu a e aun her deri ed ro S O o ete or ien e o and o er ia ay oad
- oration e ur ion uti i e a agnu aun h ehi e u ing S O e e ent or oo ter

Ne eu a e aun h Sy te
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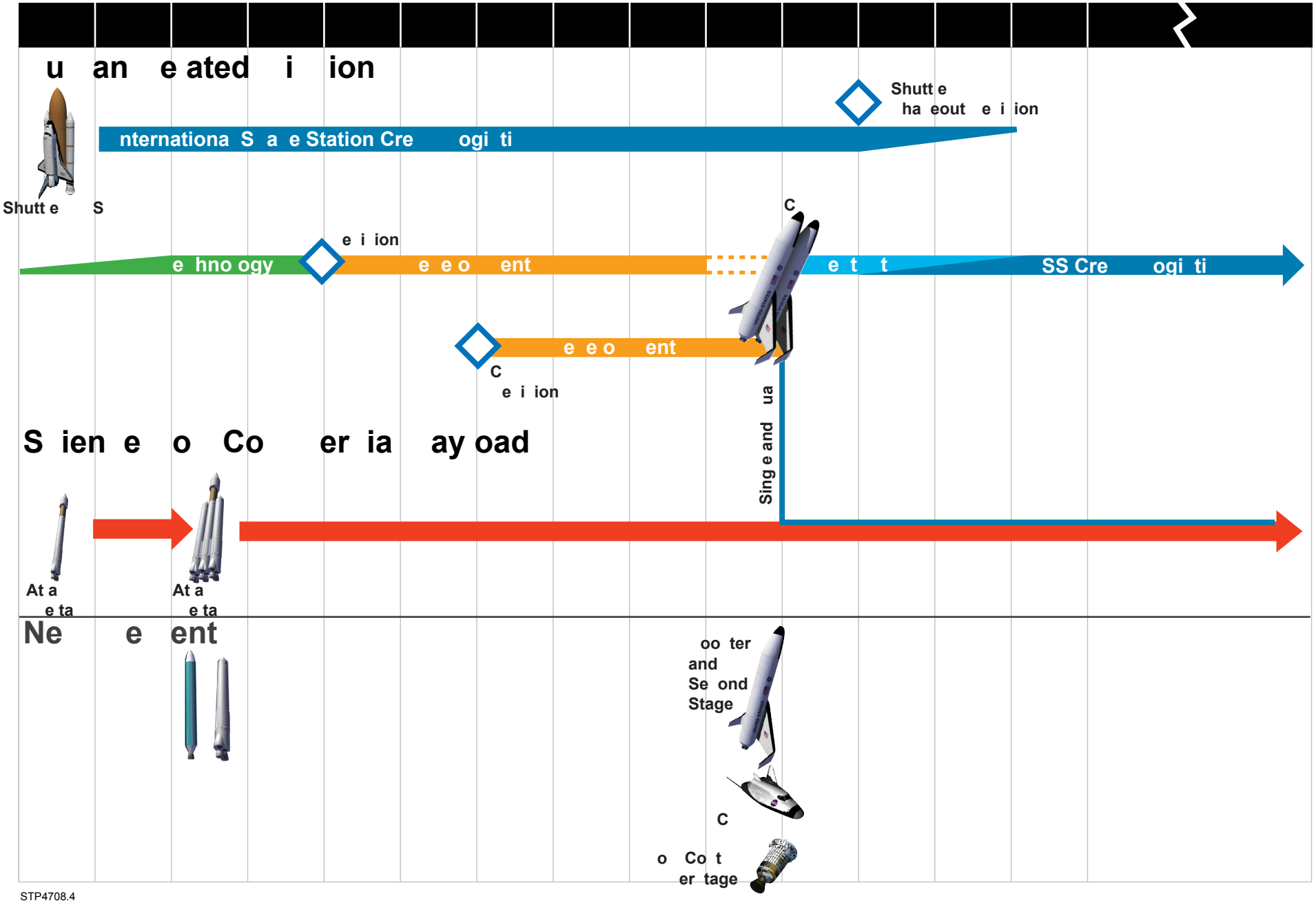
NASA In-House Space Transportation Architecture Study



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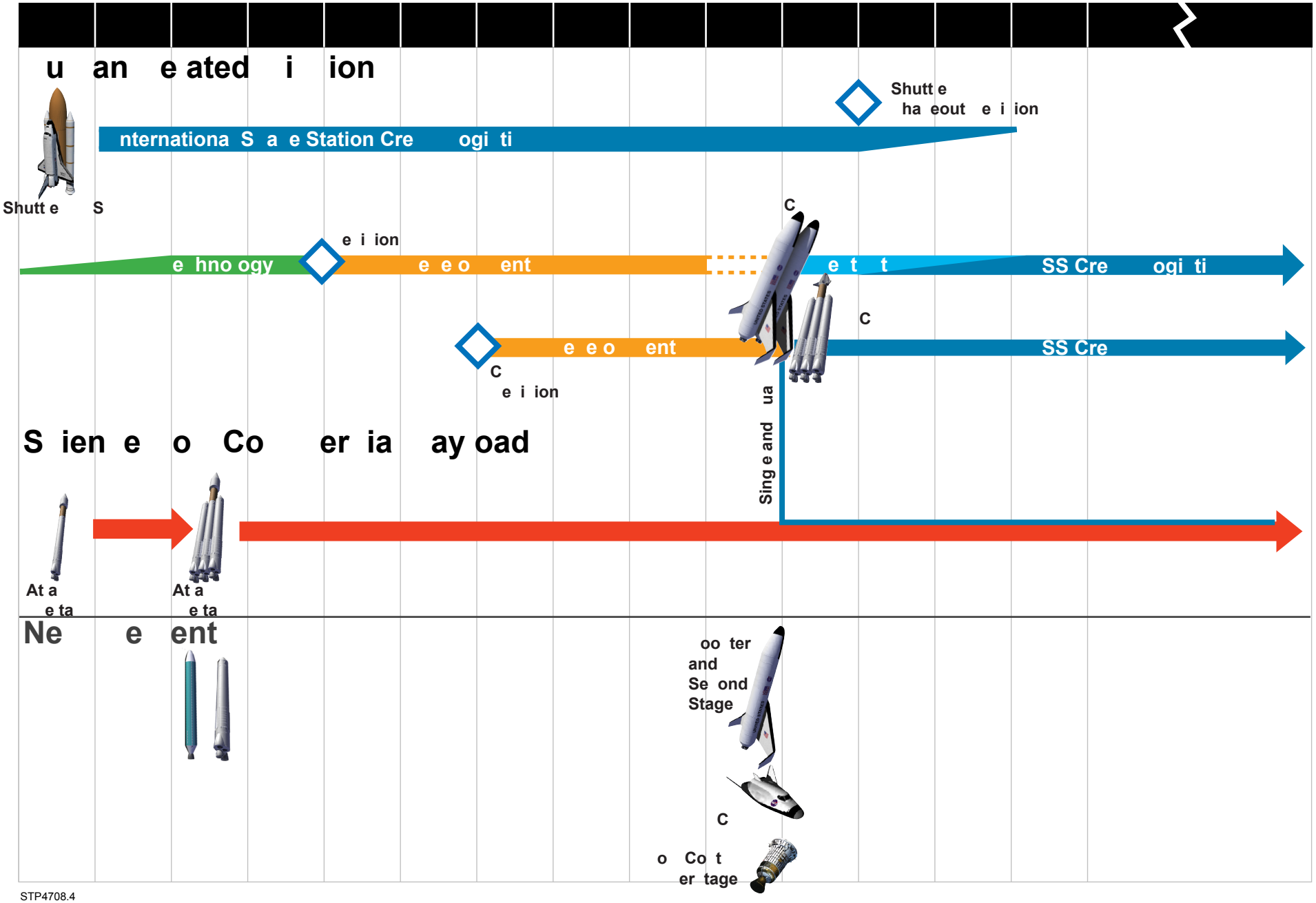
NASA In-House Space Transportation Architecture Study



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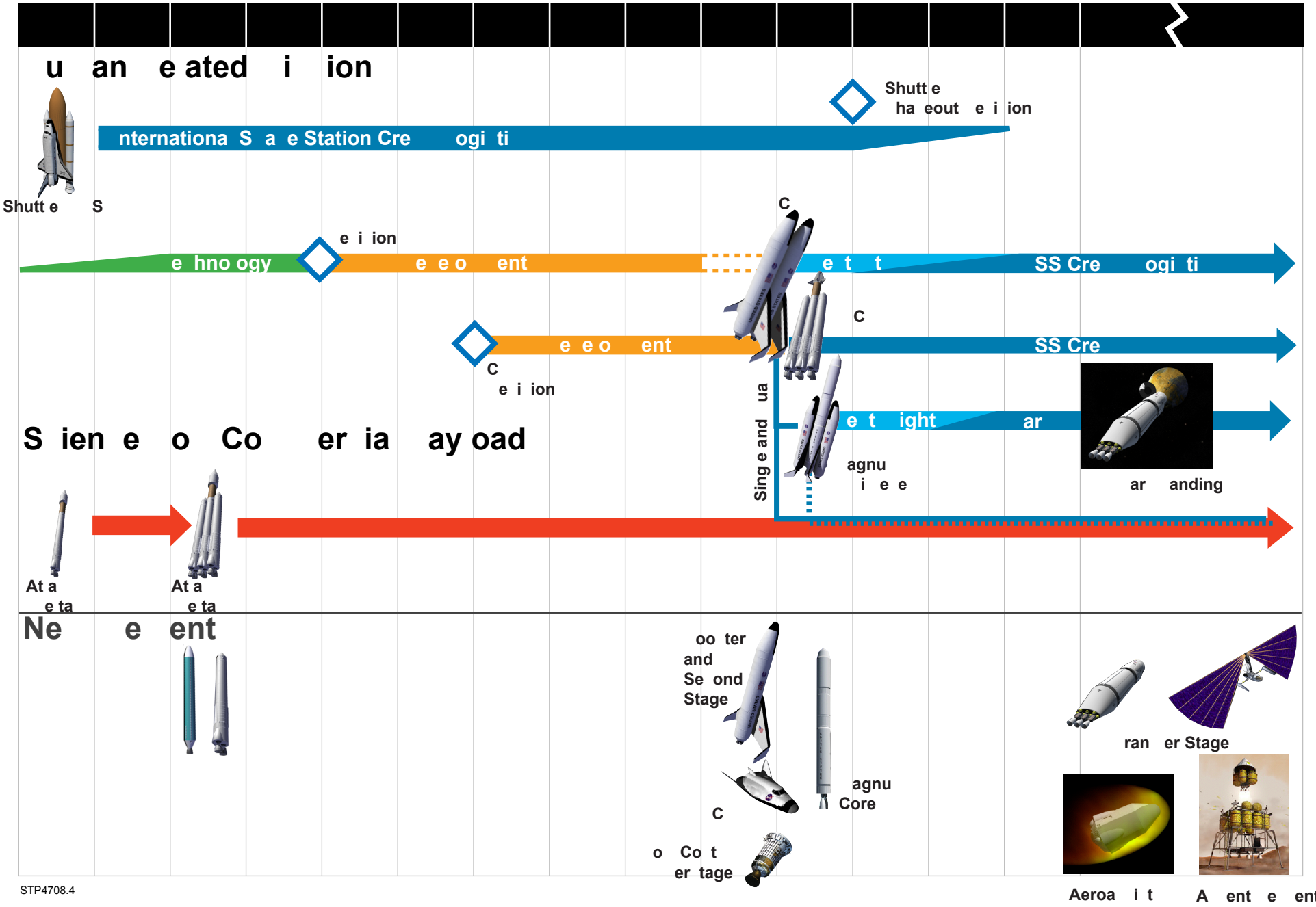

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ey eature o Ar hite ture

- **Ne ing e tage to or it SS O ehi e re a e S a e Shutt e**
  - New upperstage to capture GTO missions
- **Cre ran er ehi e odu e in on u tion ith SS O or hu an i ion to SS**
  - Potential alternate ISS access option using CTV on human rated EELV
- **oration e ur ion uti i e an S a ed agnu aun h ehi e**

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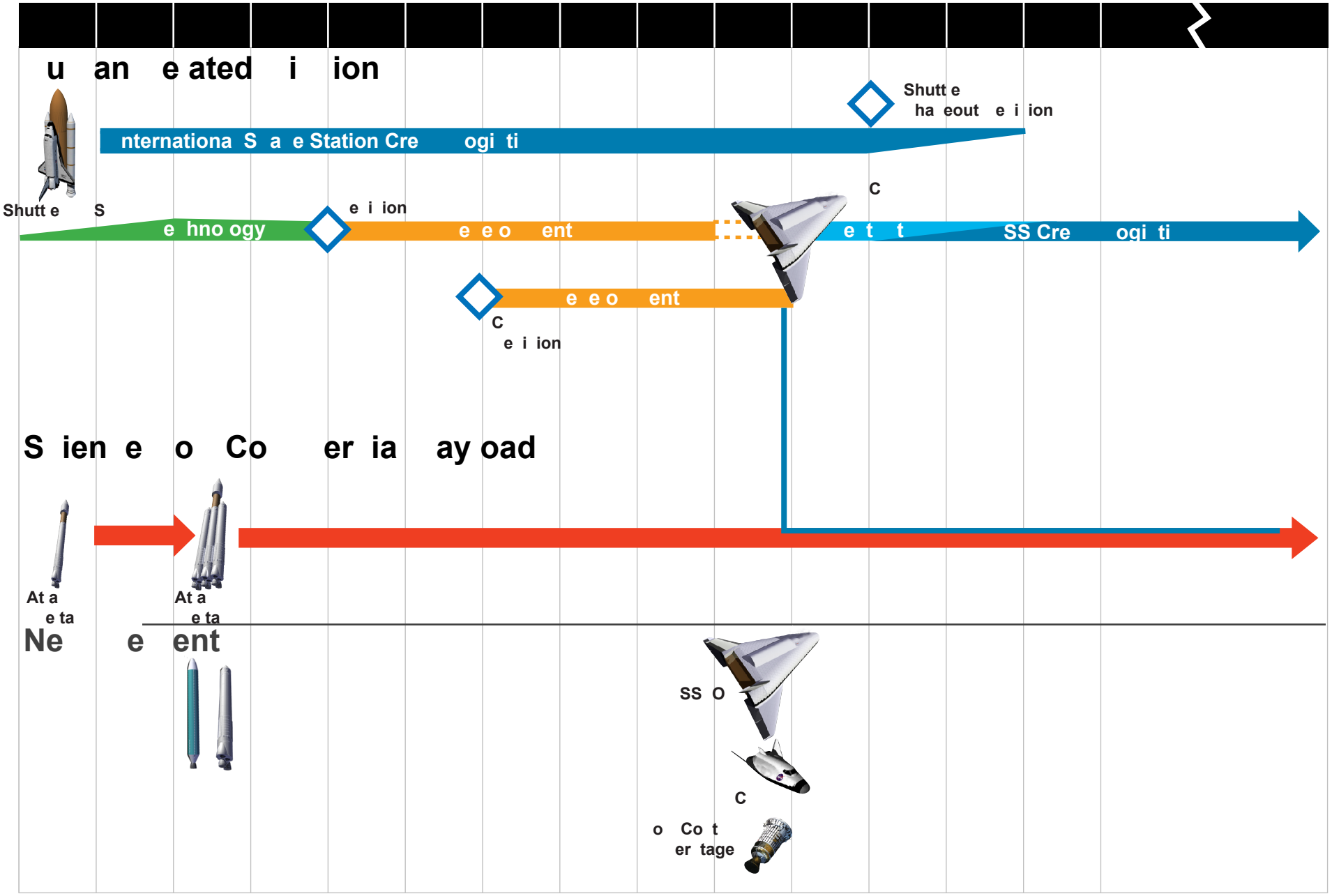

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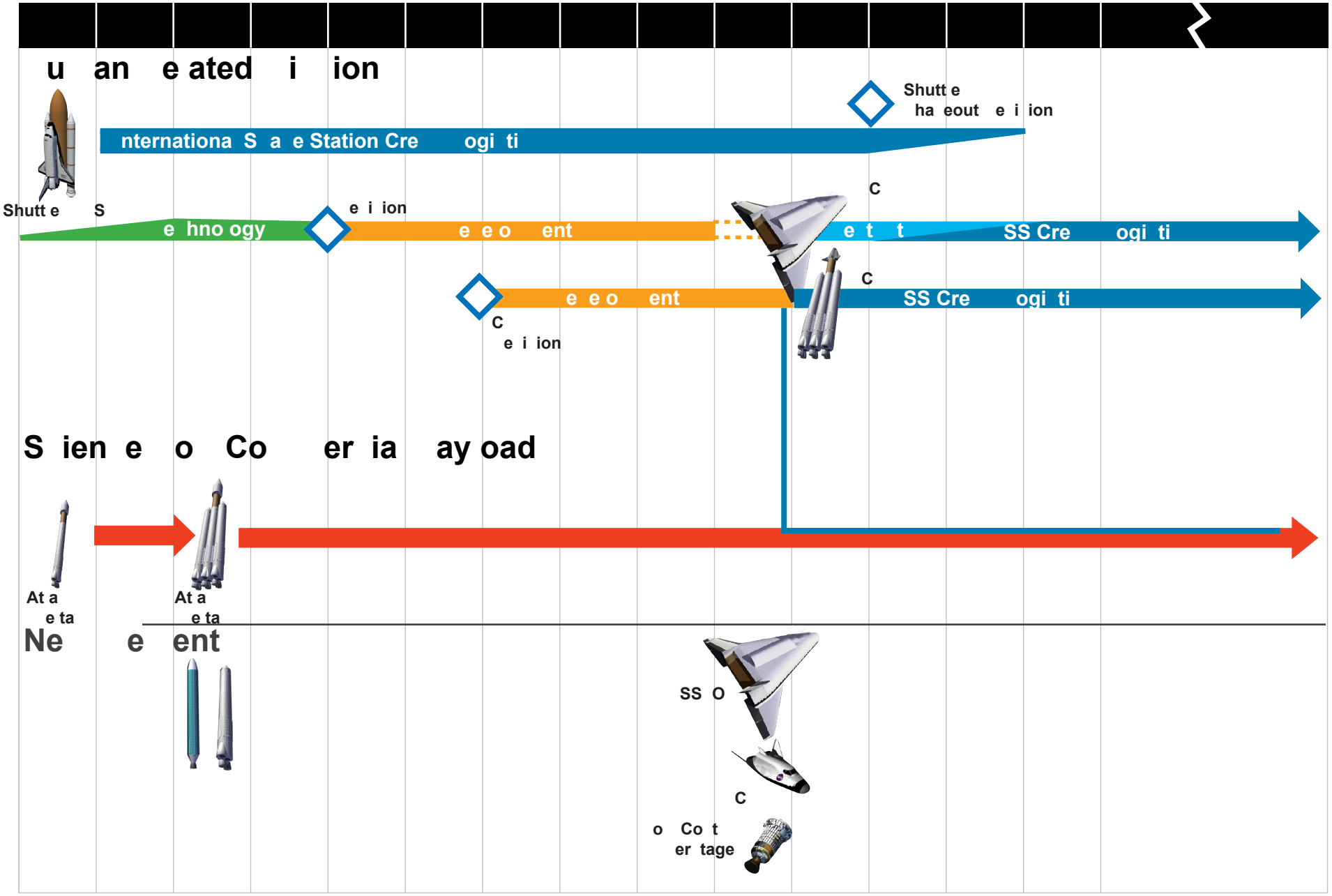
NASA In-House Space Transportation Architecture Study



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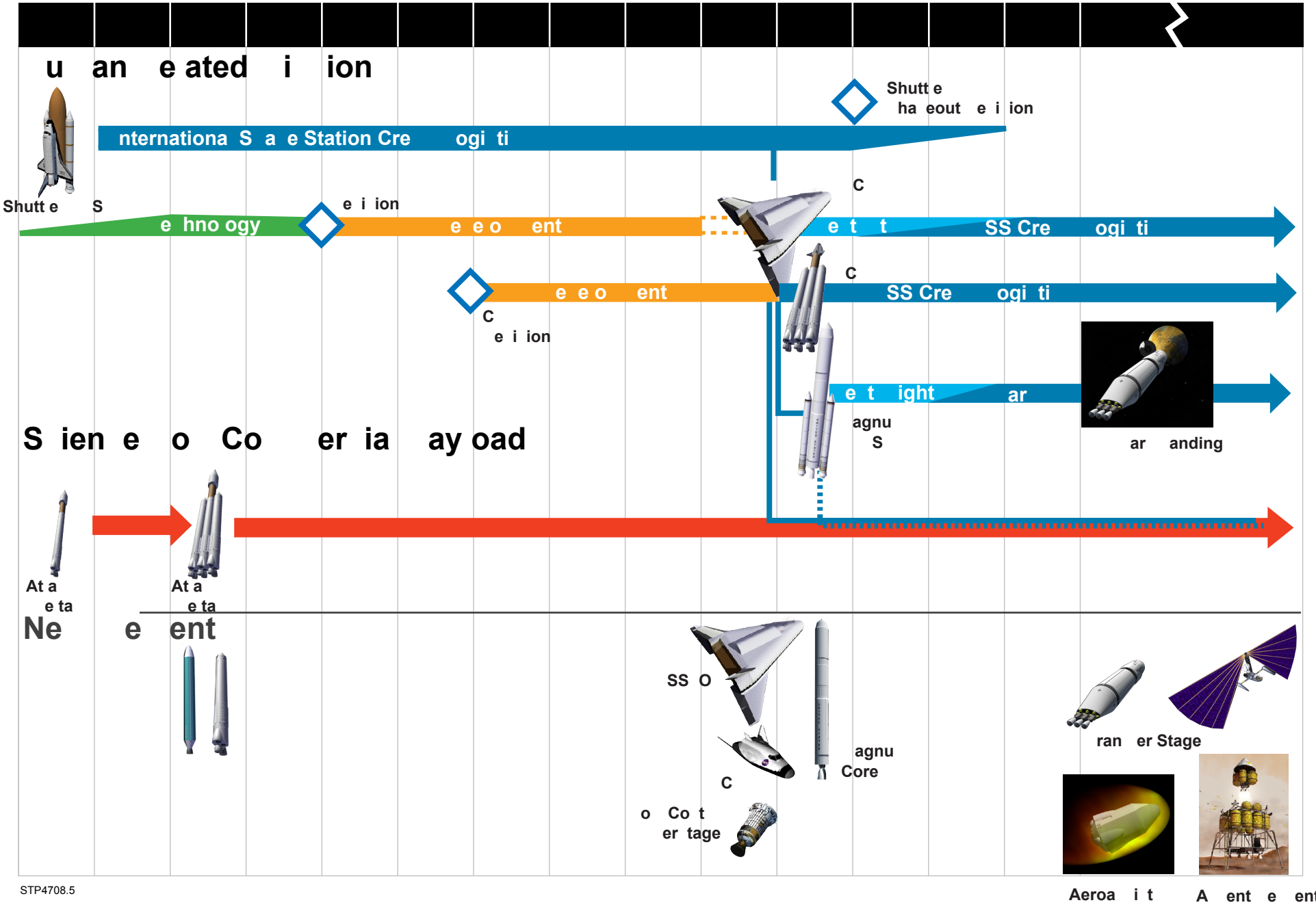

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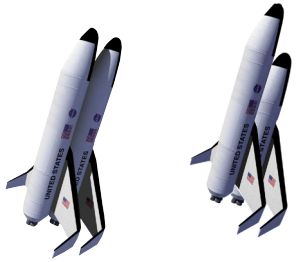
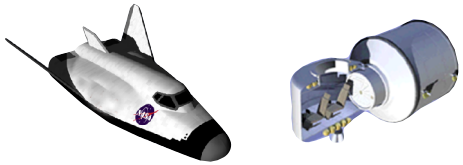
So e ehi e rade hi h Shou d e Addre ed

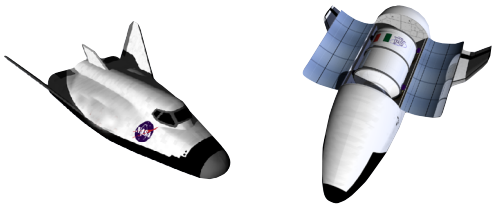
- **Con iguration o oo ter Se ond Stage on S O**
  - Identical or staging optimized system
  - Degree of technology insertion



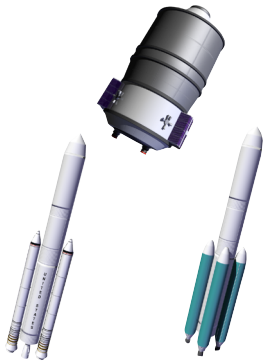
- **ntegration o re tran er ehi e odu e on a i a e aun h ehi e**
  - Internal vs. external carriage
  - Alternate access commonality



- **Co ona ity o re and argo arrier or u do n a a e**
  - Separate vs. some degree of commonality



- **SS or ita o eration**
  - Direct docking vs. standoff using a tug (ground- or space-based)



- **enda e agnu oo ter o tion**
  - RSRB vs. EELV derived

STAS5055a

Results
STAS5028

- Technical Risk
- Reliability
- Safety
- Cost
- Business Analysis

Risk Reliability and Safety

Technical Risk - Definition

- **Definition - The probability of a programmatic delay time in months beyond the baseline IOC.**

- **Description - The metric used is the 50 percentile of the estimated delay time distribution which accounts for potential developmental and integration difficulties of new technologies critical to deployment. Methodology accounts for the number of new technologies and difficulty of their integration.**

- **Metric - Median programmatic delay time (months).**

Technical Risk - Assumptions & Caveats

- All critical technologies are at TRL 6 or greater prior to the start of development.
- Development program technical risk is the discriminating architectural risk. It may or may not be the dominant program risk.
- All system/vehicle performance requirements are met.
- Specific subsystem technologies were selected for each element. They may or may not be the "best" technologies to implement the architecture.
- Schedule and cost risk are treated as a function of the technical risk.
- Integration is an exponential function of the weighted average of the critical technologies across these technology areas.
- Risk distribution can be formed by a linear combination of the integration complexity and development program duration.

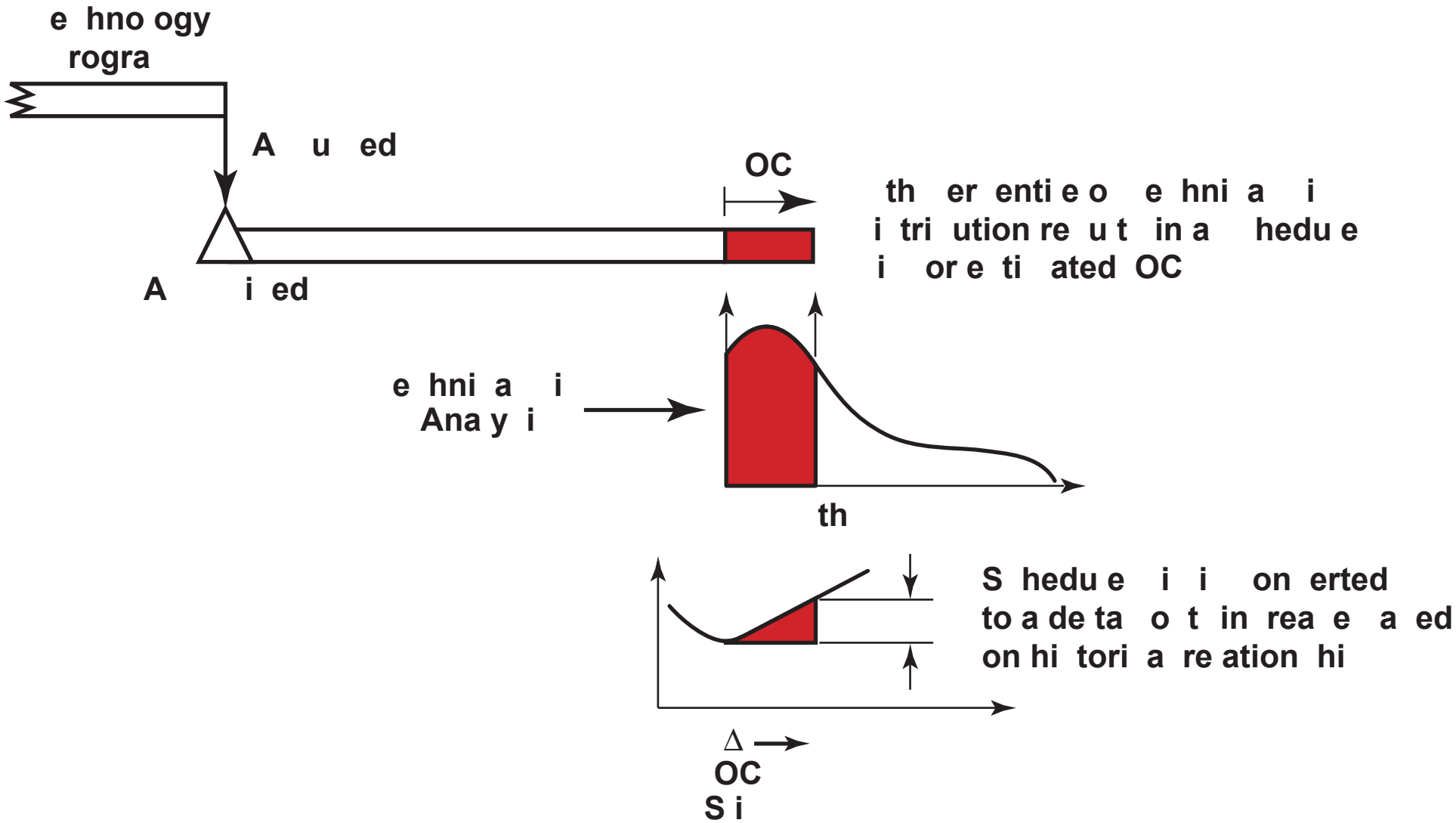
Technical/Programmatic Risk Methodology

- **Determine the number of critical developmental technologies in:**
  - Propulsion
  - Airframe (structures and TPS)
  - Avionics (GN&C)
- **Assign relative risk contribution weightings for these technology areas:**

	Staged Comb (%)	Gas Gen (%)
Propulsion	50	40
Airframe	30	35
Avionics	20	25

- **For each vehicle, multiply risk weightings by the number of required technologies and sum over technology areas.**
- **To account for integration complexity, form the exponential function of the weighted average.**
- **Select the delay time distribution shape based on integration complexity and duration of the development program.**
  - Form a linear combination of these two variables to define parameters of the delay risk distribution (gamma).
- **Determine the value of delay time at 50 percent cumulative probability. Delay time is input to cost modeling to account for the cost of a potential delay due to technical risk.**

e hni a rogra ati i ethodo ogy



Results approximate; actual impact depends on contractor business base, degree that program elements are integrated, etc.

e ent i ti ate

Ar hite ture e ent	e ay i e onth	e ay Co t i ion
	th er enti e	
Space Shuttle with RFS	2.5	55
Bimese TSTO - Dual Mode	8.8	247
Optimized TSTO	8.8	247
SSTO	13	500
RFS Exists:		
• RFS Booster with Upperstage	~0	~0
• RFS Based TSTO	1.5	229
EELV Exists:		
• EELV w/CTRV	.03	~0
• EELV w/CTV	.03	~0

Element Technical Risk-Observations and Conclusions

- The STAS technical risk methodology, while sufficient to discriminate, likely under predicts the total program risk (e.g., political risks, production risk, etc.).
- TRL 6 is a critical assumption. It assumes the technology program was fully successful. It also implies no decision should be made to go forward with an architecture until TRL 6 is demonstrated.
- The particular technologies selected may over predict the risk compared to a more conventional implementation (e.g., TSTO).

Reliability - Definition

- Definition - Mission Success Reliability - The probability of meeting all mission objectives, including payload delivery and intact vehicle return.
- Description - The metric used is an aggregated mean estimate of the probability of abort due to benign engine shutdown during ascent, and the probability of vehicle loss due to catastrophic engine failure during ascent or TPS failure during descent.
- Metric - Mission success reliability

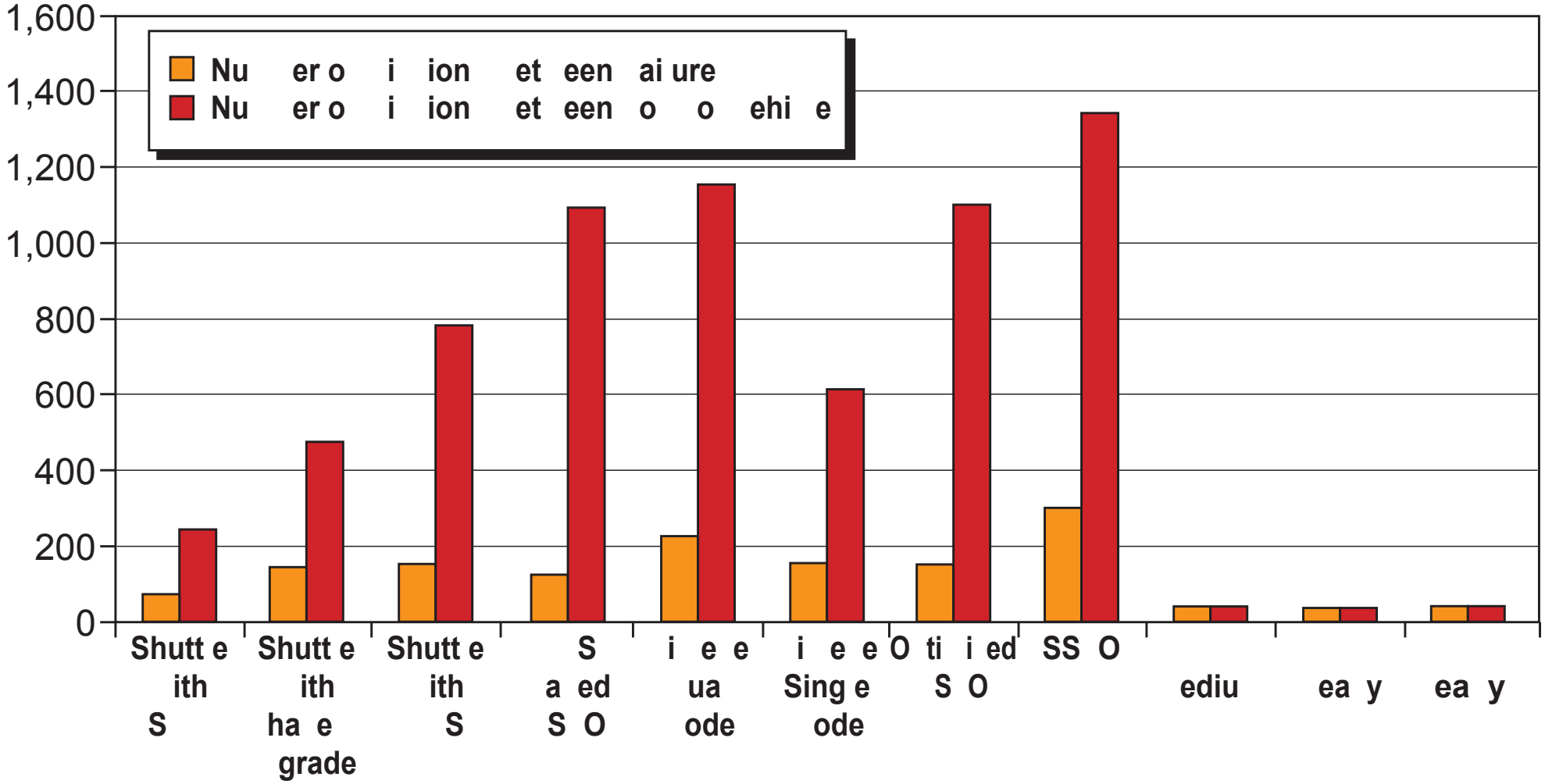
Reliability - Assumptions & Caveats

- **Main propulsion systems contribute majority of operational reliability risk.**
- **For new elements premature engine shutdown failures are independent (no common cause failures).**
- **On-pad abort probability not included in model.**
- **Shuttle mission reliabilities derived from Shuttle Program Office input**
  - Total mission catastrophic failure rate: ~1/250
    - Without RTLS abort risk
  - Total mission catastrophic failure rate: ~1/500
    - With phase III upgrades
    - Without RTLS abort risk
  - Total mission non-catastrophic failure rate: ~1/100
- **EELV mission reliabilities (Air Force requirement)**
  - Medium lift: 0.975
  - Heavy lift: 0.970
- **Commercialization has no effect on mission reliability.**

Reliability - Methodology

- **For each new element an estimate of engine shutdown/failure rate is generated using an heritage-based design approach.**
- **The design heritage approach accounts for:**
  - Engine cycle
  - Thrust class
  - Time of staging and engine cut-off
  - Power level
- **USG Program Office estimates used for shuttle and EELVs.**
- **Minimum engine burn time to achieve orbit estimated (booster or orbiter engine out); aka "Press to MECO"**
  - $LOV = \sum_{Stages} (1\text{-Eng } Rel_c^n)$ (total burn time)
  - $MS = 1 - [\, LOV + (1\text{-}LOV) \left(\sum_{Stages} (1\text{-Eng } Rel_{nc}^n) \right.$ (time to press to MECO))]
- **General methodology and inputs were coordinated with NASA center S&MA representatives (KSC, MSFC, and JSC)**

e ent e ia i ity ti ate



Element Reliability - Observations & Conclusions

- At the architecture level, increases in mission reliability due to engine out have to be traded against performance loss (i.e., possibility of additional flights to meet mission model).
- Phase III upgrade reliability improvements, if realized, double Shuttle mission reliability and have a significant positive impact on architecture level reliability and safety.
- New systems have no more than about a factor of 2 increase in mission reliability (compared to Shuttle with Phase III upgrades).

Sa ety e inition

- e inition
  - The probability of safe return of the crew
- e ri tion
  - The metric used is 1 minus the mean of all probabilities of a loss of crew event, given the catastrophic failure per mission probability, and crew survivability factor, based on the geometric separation between the crew module and the sources of catastrophic failure.
- Sa e re return ean any o the o o ing
  - (1) Successful mission
  - (2) Safe intact abort
  - (3) Crew escape/survival w/potential loss of vehicle
- etri
  - Mean number of flights between crew loss events

Sa ety A u tion Ca eat

- **o ontri utor to re o**
  (1) Loss of vehicle probability

  (2) Geometric distance between crew module & source of failure

- **Cre odu e ur i a i ity a tor range ro to**
  a ed on an ana ogy o i itary air ra t e a e y te
  he o er range in ude out o the en e o e a ort i e e e tion
  - 0.99 used for EELV
  - 0.8 used for other new vehicles

- **he e ui a ent a e a ort en e o e or a re odu e i**
  a di tan e ≥ eter

Sa ety ethodo ogy

- o o ehi e O re u t deter ined ro the i ion re ia i ity ana y i
- Cre ur i a i ity a tor CS a ed on a t re e a e tudie and the geo etri o ation o the re odu e
- ean nu er o i ion et een re o e ent

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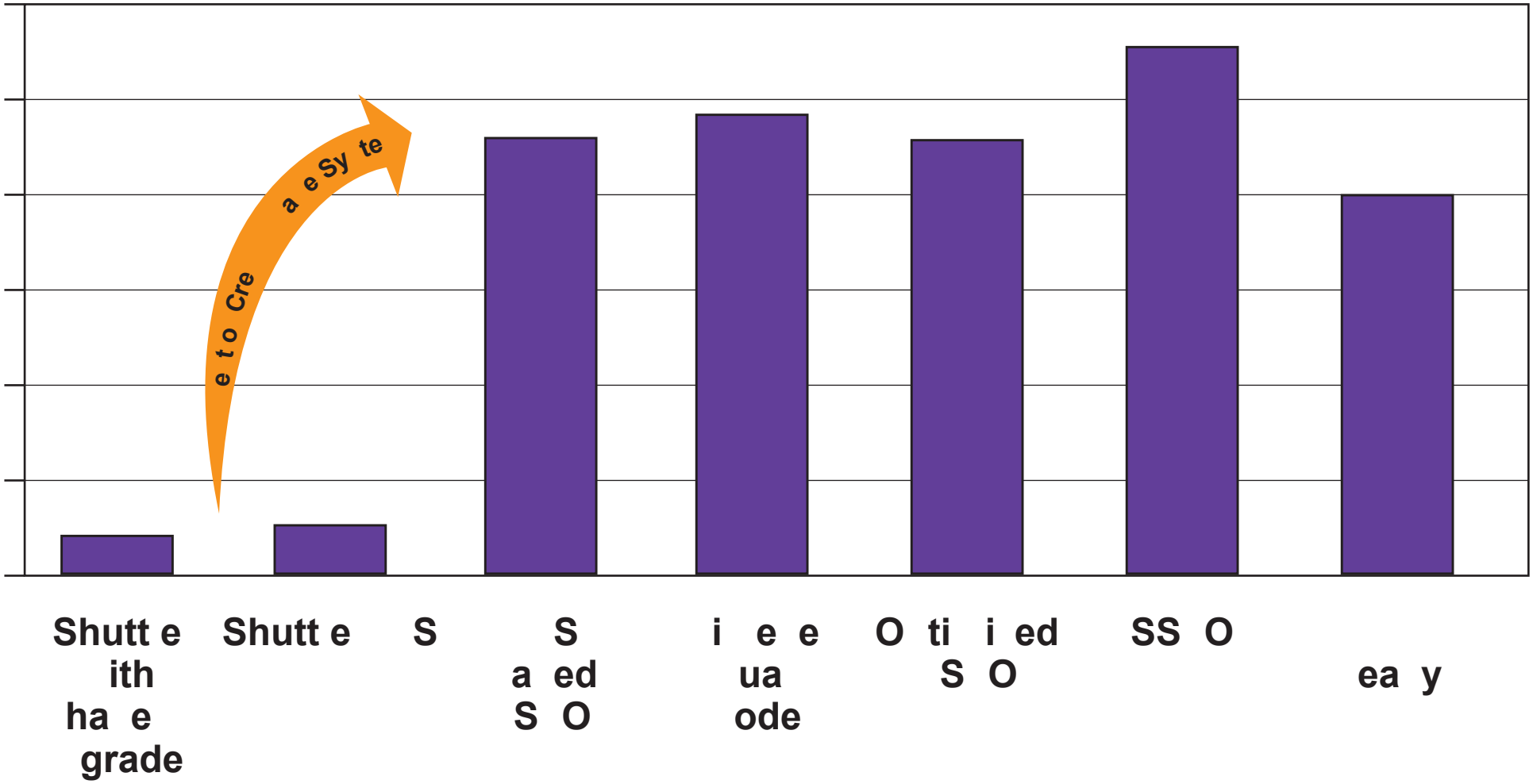
Sa ety ro e ent a tor O er Current Shutt e

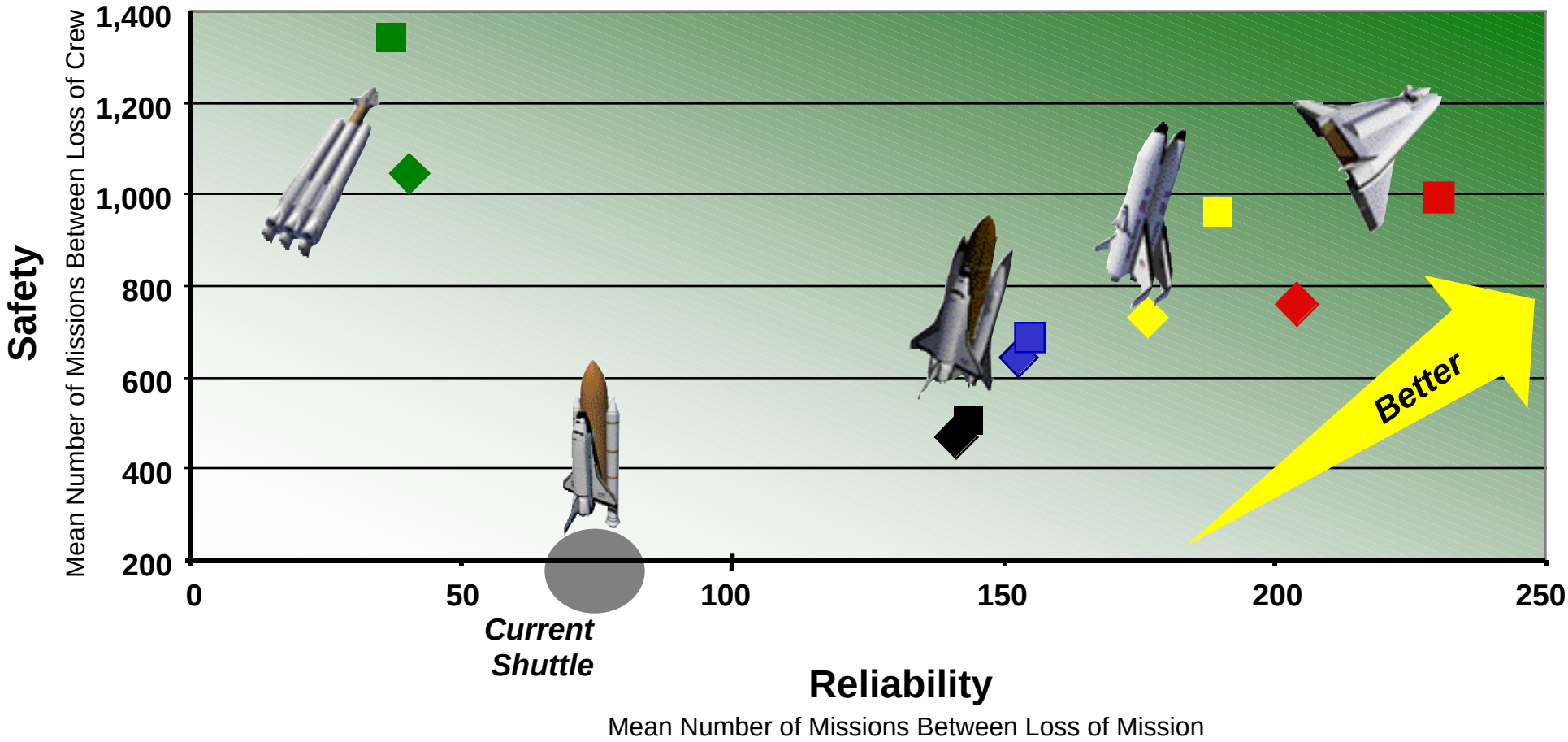


e ent Sa ety O er ation Con u ion

- No igni i ant di eren e et een S O and SS O ehi e e e ent
- Cre e a e y te otentia y ro ide igni i ant i ro e ent to ne ehi e a ety
- C geo etri e aration i an inherent y a er ehi e on iguration A though the o i ion re ia i ity in rea e the nu er o ehi e o e ent or de rea e ti e et een e ent the e e t o the geo etri e aration o en ate or the higher O ro a i ity

Architecture Level Safety / Reliability Summary

NASA Space Transportation Architecture Study



- Shuttle Based Architecture
- Shuttle w/RFS Based Architecture
- EELV Based Architecture
- TSTO Based Architecture
- SSTO Based Architecture

- Through 2020
- Through 2030

Ar hite ture e e i e ia i ity Sa ety e u t

	Ar hite ture				
edian e oy ent e ay onth	0	2	0	9	13
ight eighted e ia i ity	0.9929	0.9935	0.9730	0.9947	0.9957
ean Nu er o i ion et ai ure	141	155	37	190	230
ro o u e u argo de i ery	24%	27%	0%	34%	35%
ight eighted Sa ety	0.9979	0.9985	0.9993	0.9990	0.9990
ean Nu er o i ion et ai ure	475	686	1,344	961	995
ro o no re o e ent	65%	74%	90%	86%	86%

Economics

ey ono i A u tion

- unding in or ation ro ided in on tant do ar

- A ar hite ture o ared to a a e ine NASA S a e ran ortation e eren e Co t o i ion er year
  - Shuttle costs of $2.4 billion/year
  - Additional Space Transportation Budget at ≈$300 million/year
  - NASA Science Mission ELV launch costs estimated at ≈$350 million/year

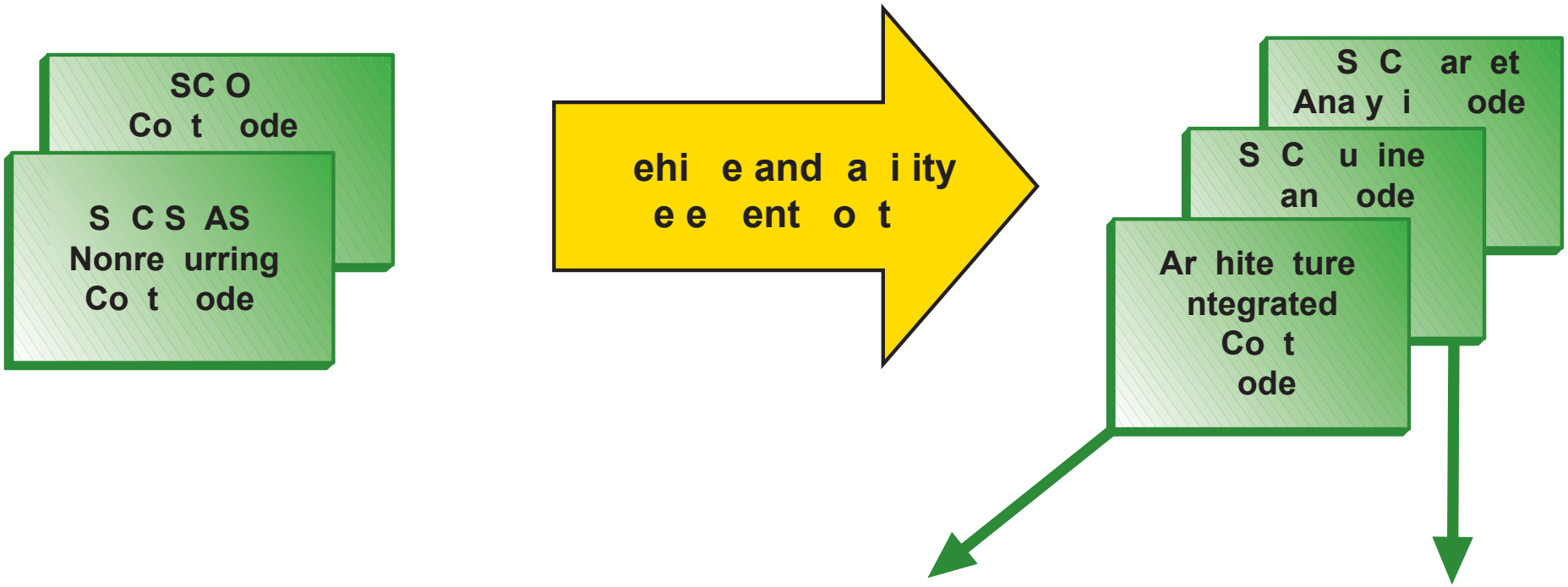
- i e y e o t a u e indu try ed de e o ent rogra u ing ature te hno ogie greater than or e ua to
  - MSFC estimated vehicle systems
  - KSC estimated facilities and operations

- re urring o t on i tent ith ate t SA e ti ate
  - Added nonrecurring cost for human rating and for EELV/human module integration

- Co t o te hno ogy aturation te hni a ri and ata tro hi unre ia i ity in uded e i i to ea h ar hite ture

- Co t o e oration e ur ion on y in ude earth to or it tran ortation eg ent

O era ono i ethodo ogy



- ntegrated ar hite ture
  i e y e o t to NASA
- ehi e u ine an
  - Price/Demand curves
  - Market capture
  - Vehicle financial metrics
    - Investment/Revenues
    - Cash flows
    - ROI metrics
    - Industry viewpoint

Steady State Shutt e Co t A u tion
i ion o o ar

	ota	i ed	aria e
Shutt e in	2,400	1,680	90
Ad u t ent or SA i ien ie	-200 [1]		
Shutt e ith SA ien ie grade	2,200	1,560	80
Ad u t ent or ha e	-128 [2]		
Shutt e ith SA i ien ie ha e grade	2,072	1,472	75
Ad u t ent or S	-150 [3]		
Shutt e ith SA i ien ie ha e grade S	1,922	1,362	70

Note

1 JSC/USA projections of $300 M/year discounted to $200 M/year to reflect anticipated cost sharing with USA.
2 Based on JSC projections of Phase III upgrades savings.
3 Based on KSC projections of RFS savings.

u ine Strategie Con idered

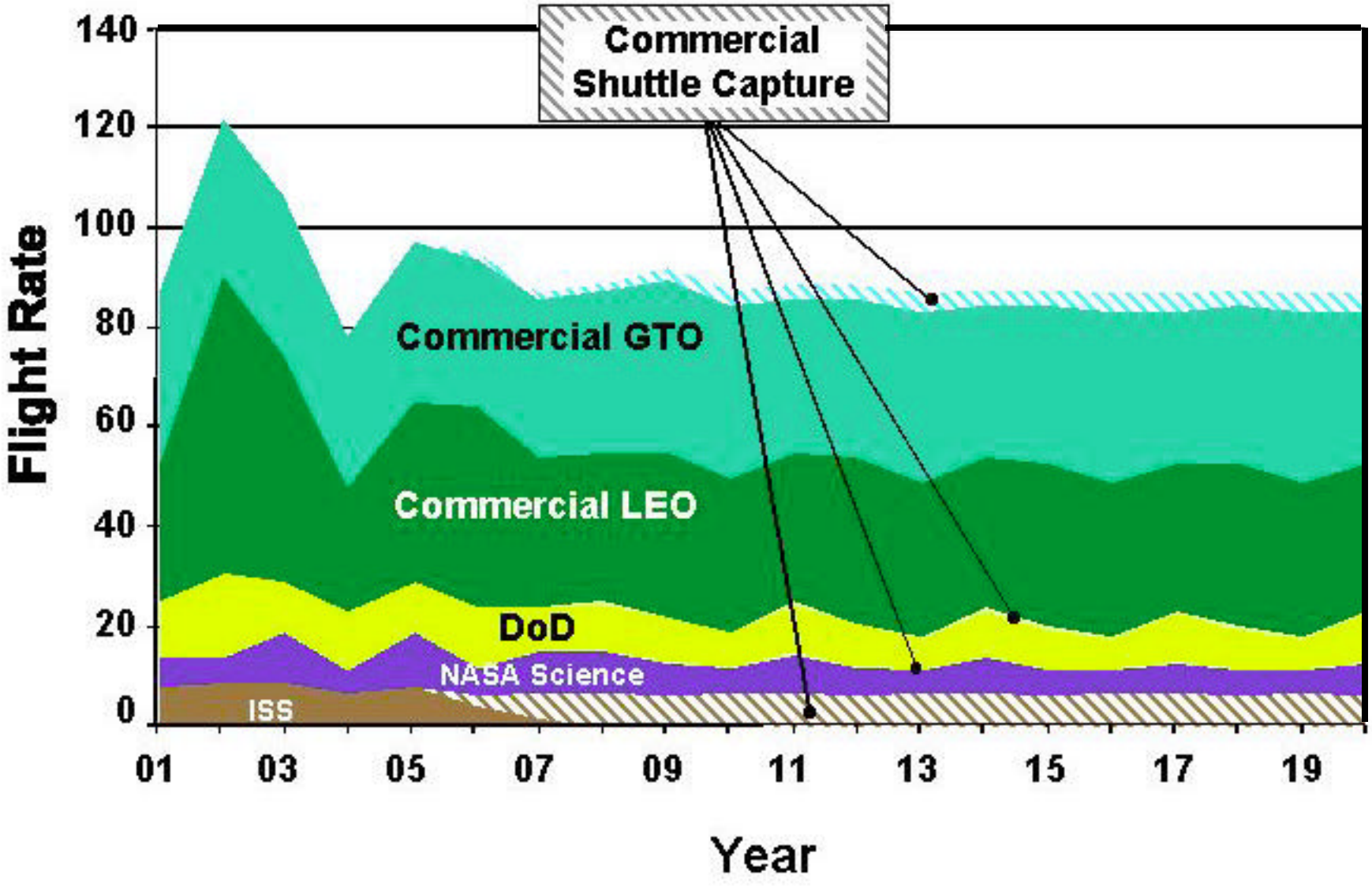
Strategie		u ine Ana y i a i
ndu try n enti e	e eren e	i ion S a ita i ation S guaranteed oan O or ndu try oan intere t rate de t ratio
ndu try Ca e ithout n enti e		O or ndu try oan intere t rate de t ratio
ndu try Ca e S		S Ca ita i ation Set to S guaranteed oan O or ndu try oan intere t rate de t ratio
S unded Ca e		No u ine Ana y i

C o ed u ine Ca e

Ar hite ture Shutt e	Ar hite ture Shutt e S	Ar hite ture	Ar hite ture S O	Ar hite ture SS O
• ndu try und ha e u grade	• ndu try und S	• and A on idered un o t	• ndu try und S O	• ndu try und SS O
• ndu try o ed y in rea ing NASA SS ri e to oint ne e ary to yie d indu try O	• ndu try o ed y in rea ing NASA SS ri e to oint ne e ary to yie d indu try O	• No u ine ana y i	• ndu try o ed y in rea ing NASA SS ri e to oint ne e ary to yie d indu try O	• ndu try o ed y in rea ing NASA SS ri e to oint ne e ary to yie d indu try O
• NASA o ed y in rea ing NASA SS ri e to oint ne e ary to yie d indu try O	• NASA o ed y o ering Shutt e S i ed annua o t to oint ne e ary to yie d indu try O	• NASA und CC or C C	• NASA und C	• NASA und C
• e uire o er ia hutt e at annua i ed o o t	• e uire o er ia hutt e at annua i ed o o t			

Reference Baseline Industry Incentivized Case ($1B Incentive)

Architecture 1 Flight Rate



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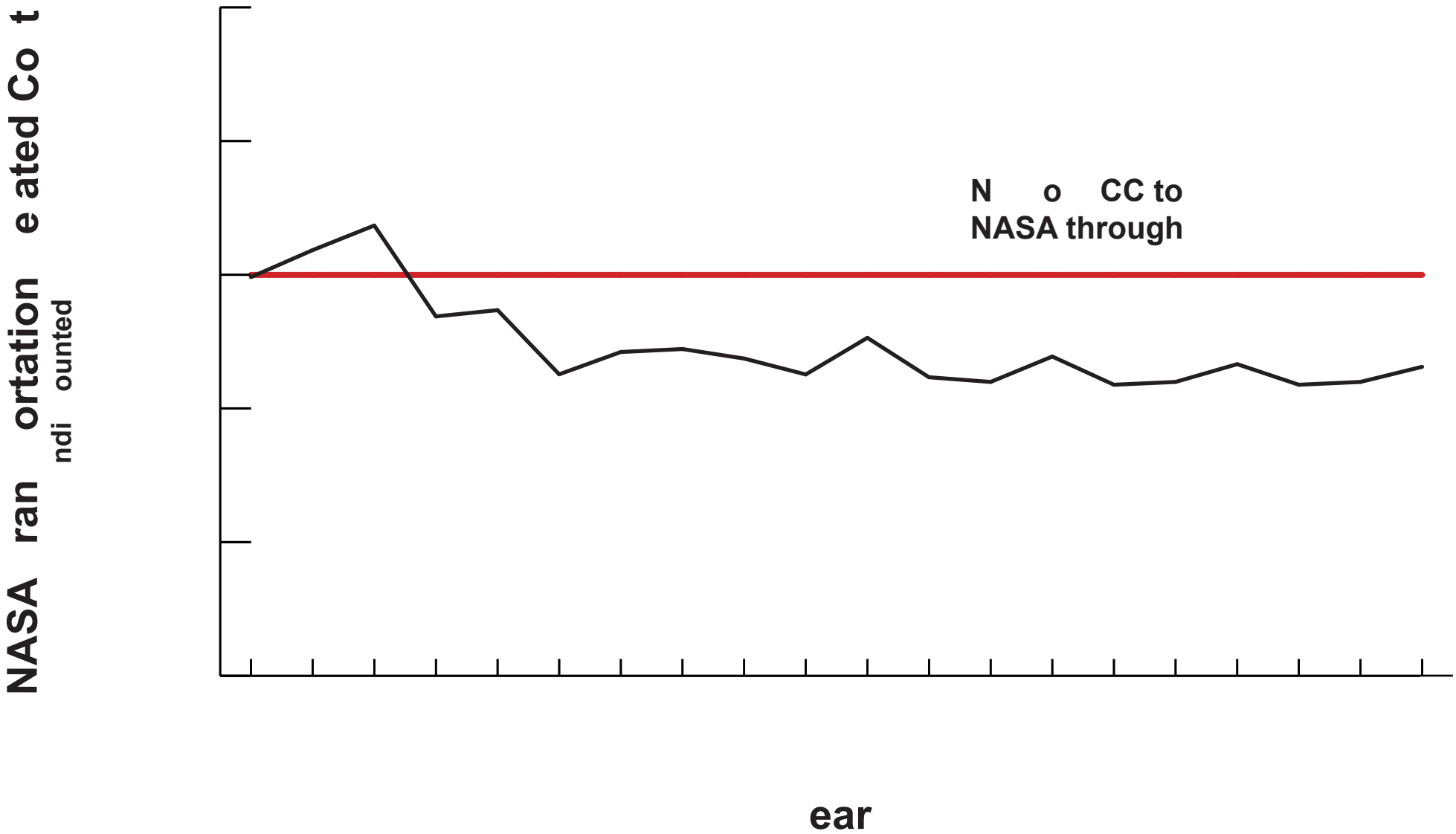

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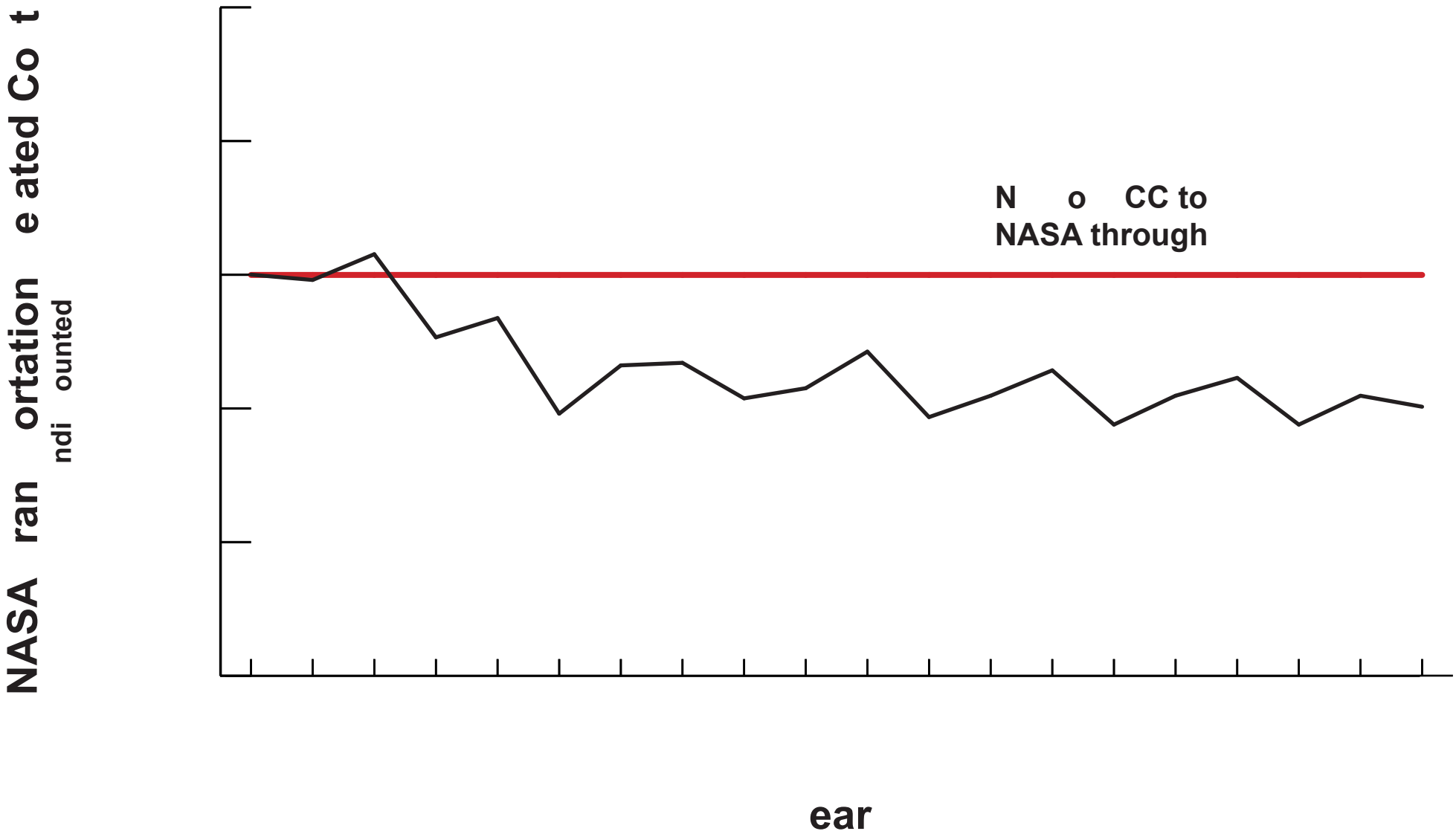
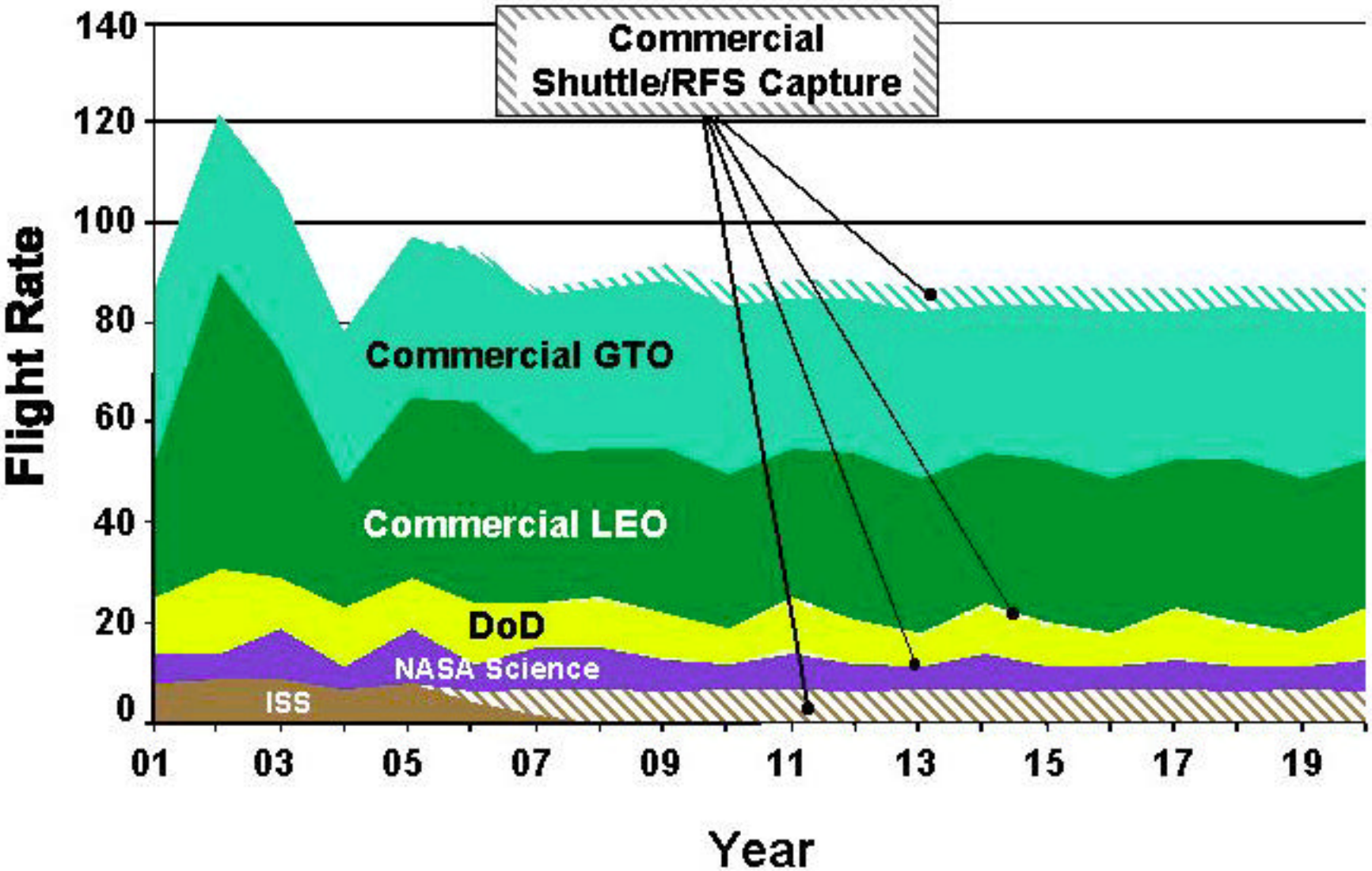


Architecture 2 Flight Rate



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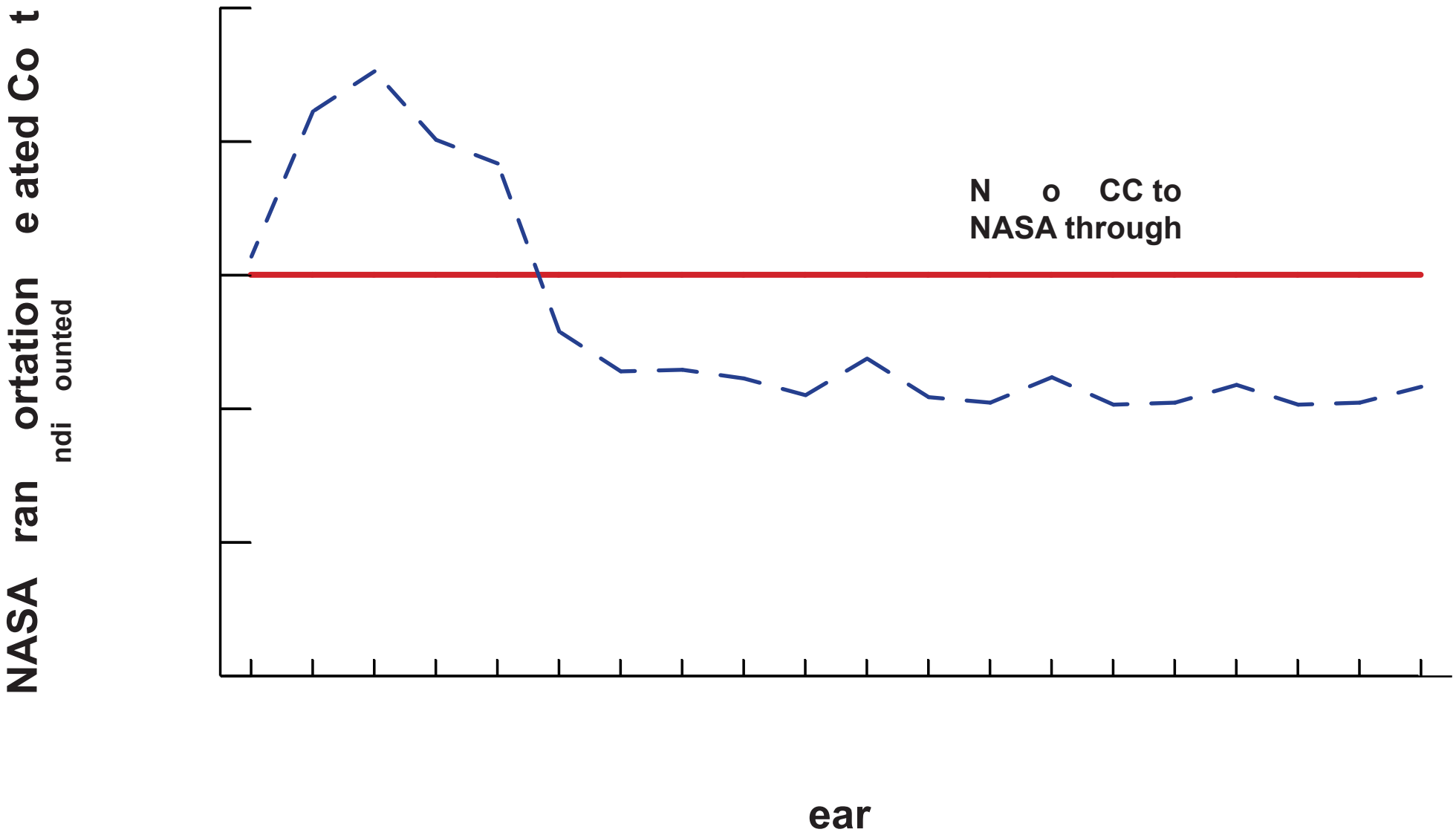
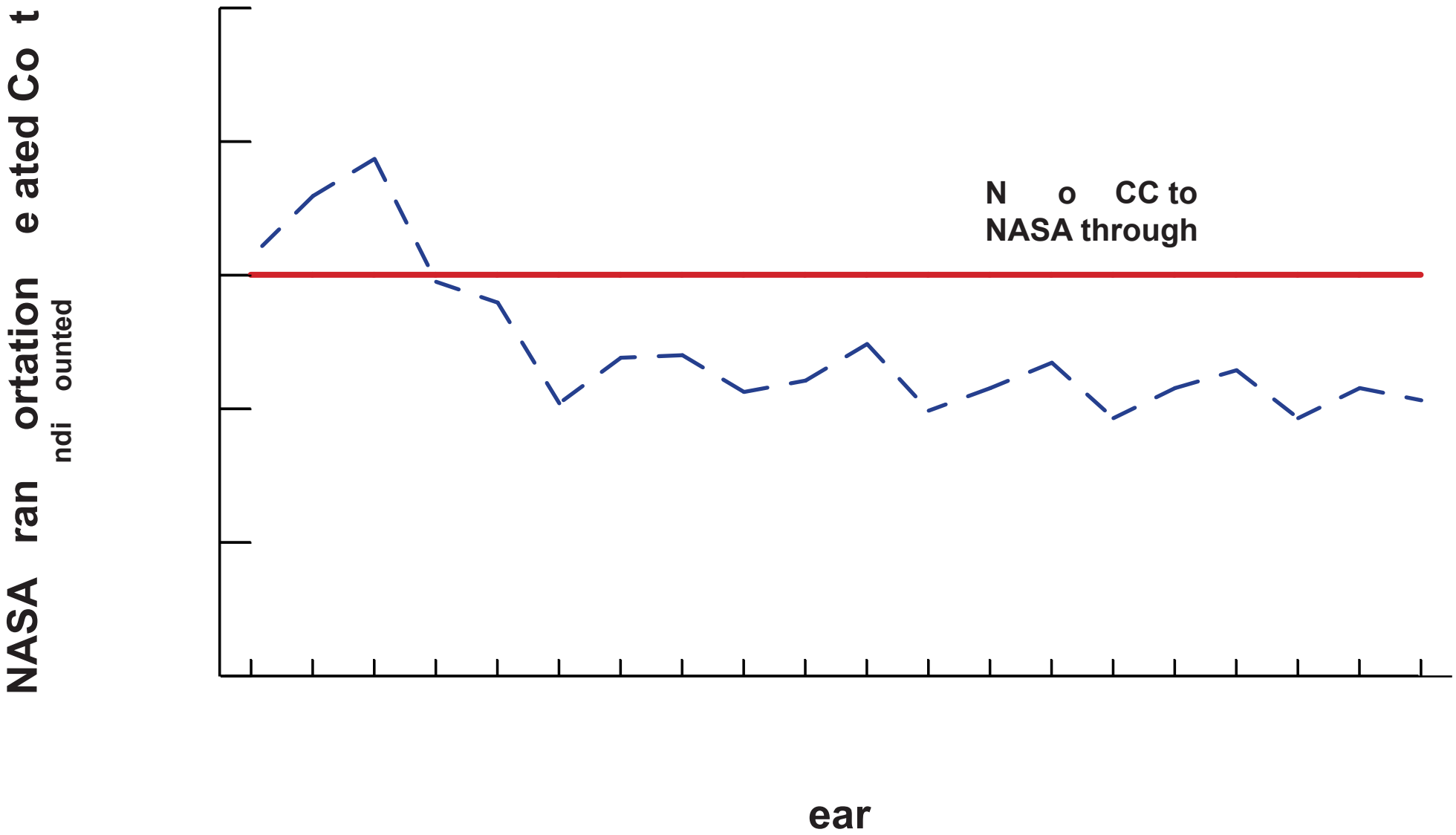
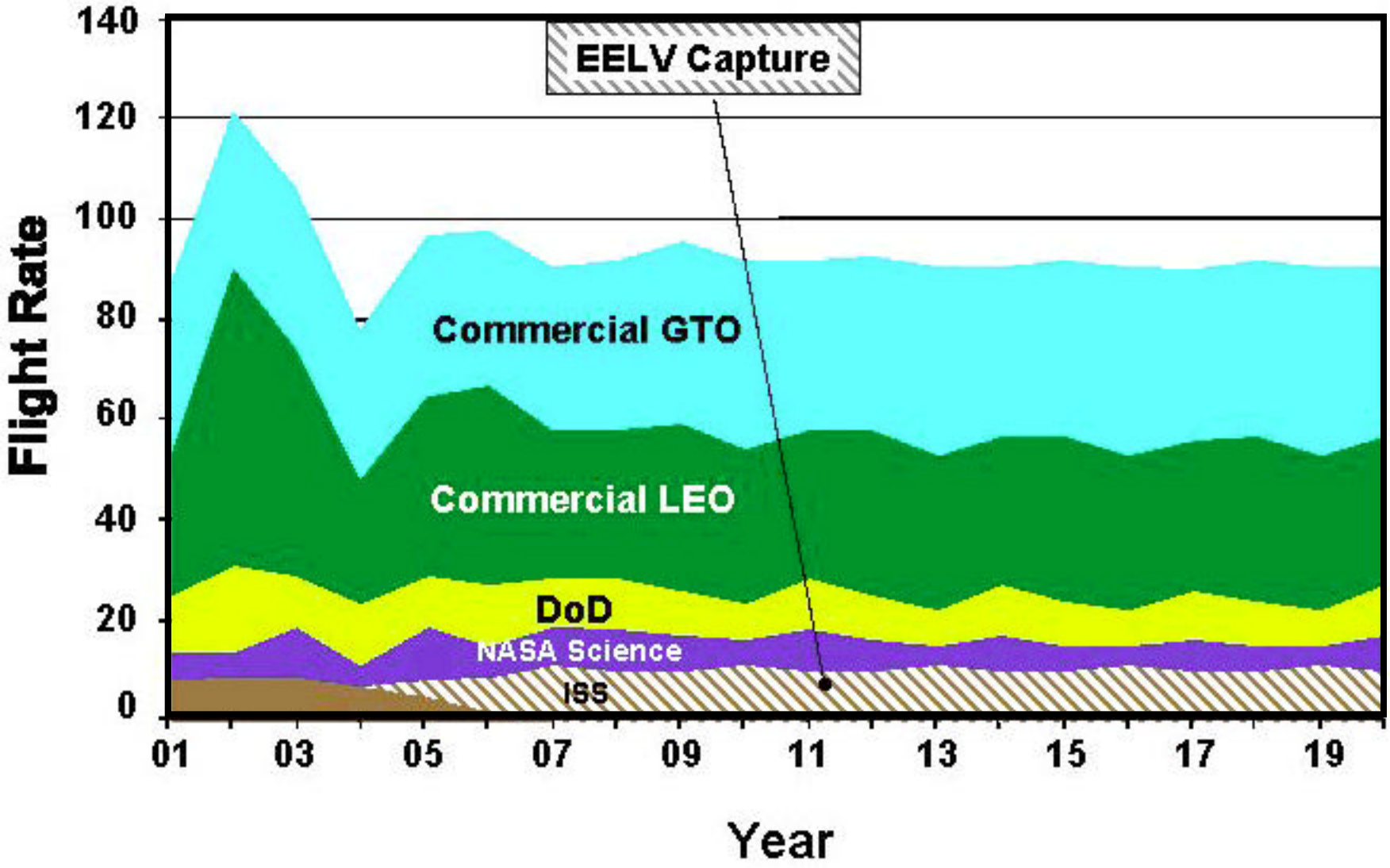


Ca h o Ana y i Co er ia Ca e
Ar hite ture Shutt e S



Architecture 3 Flight Rate



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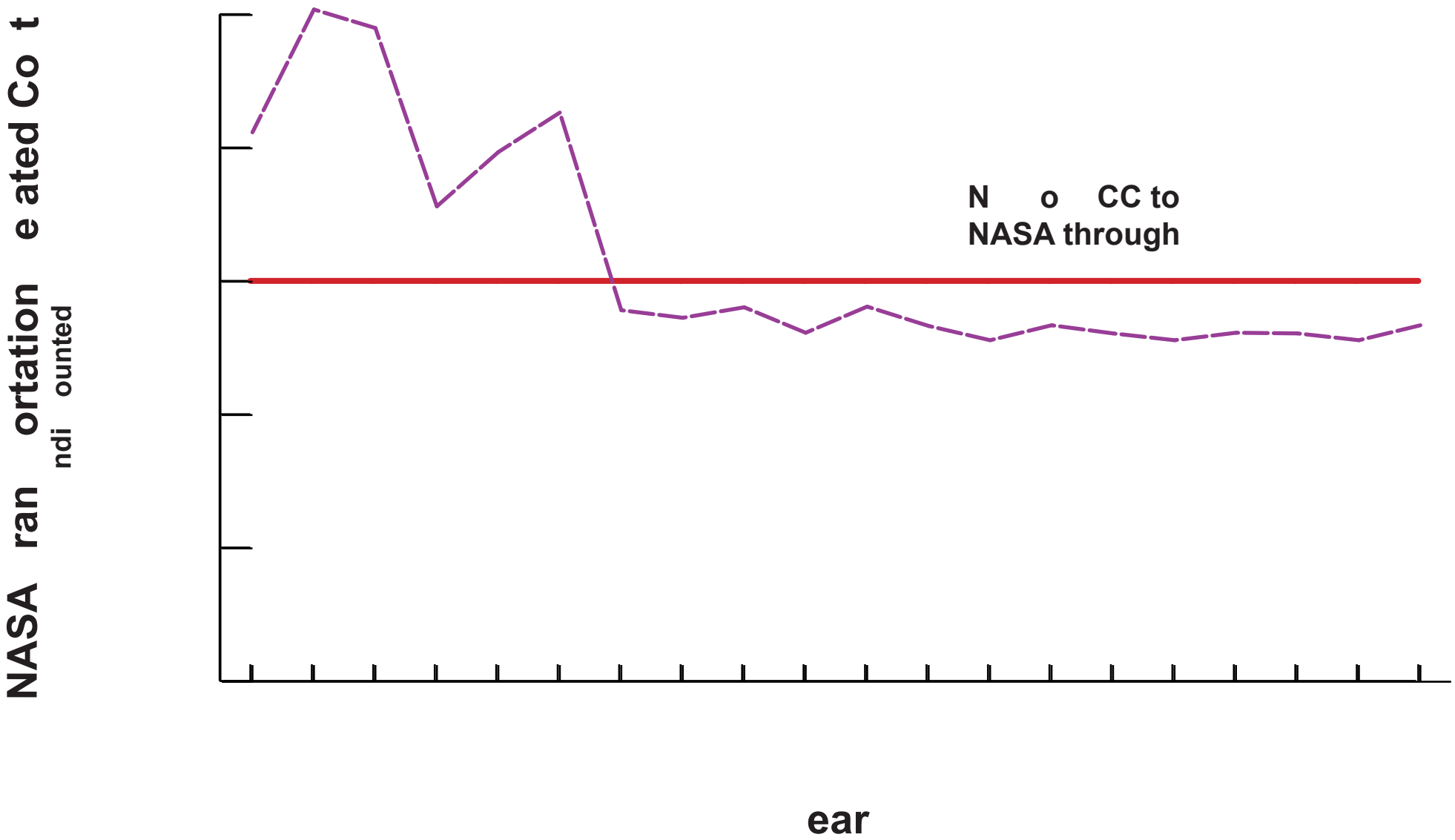

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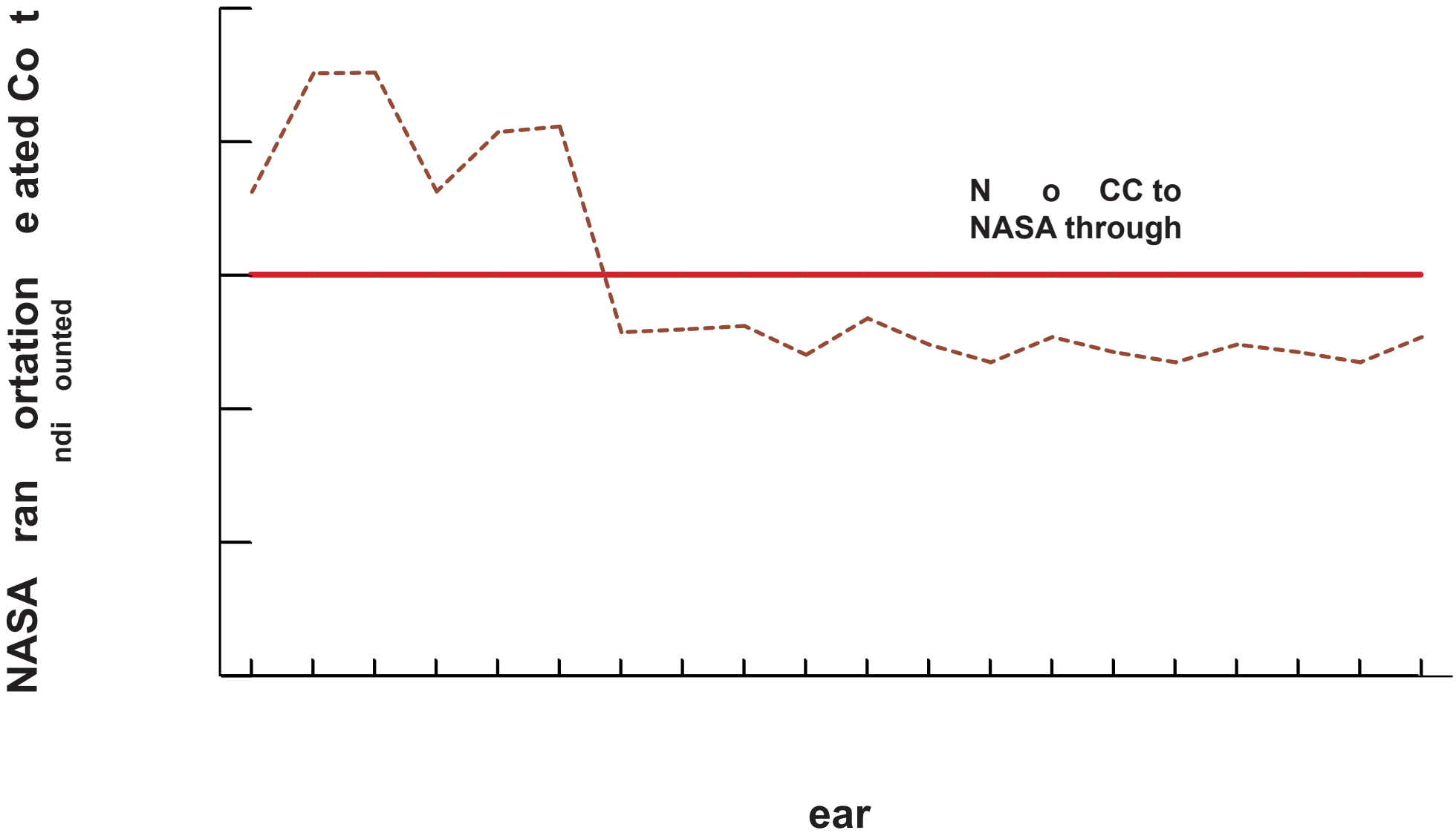
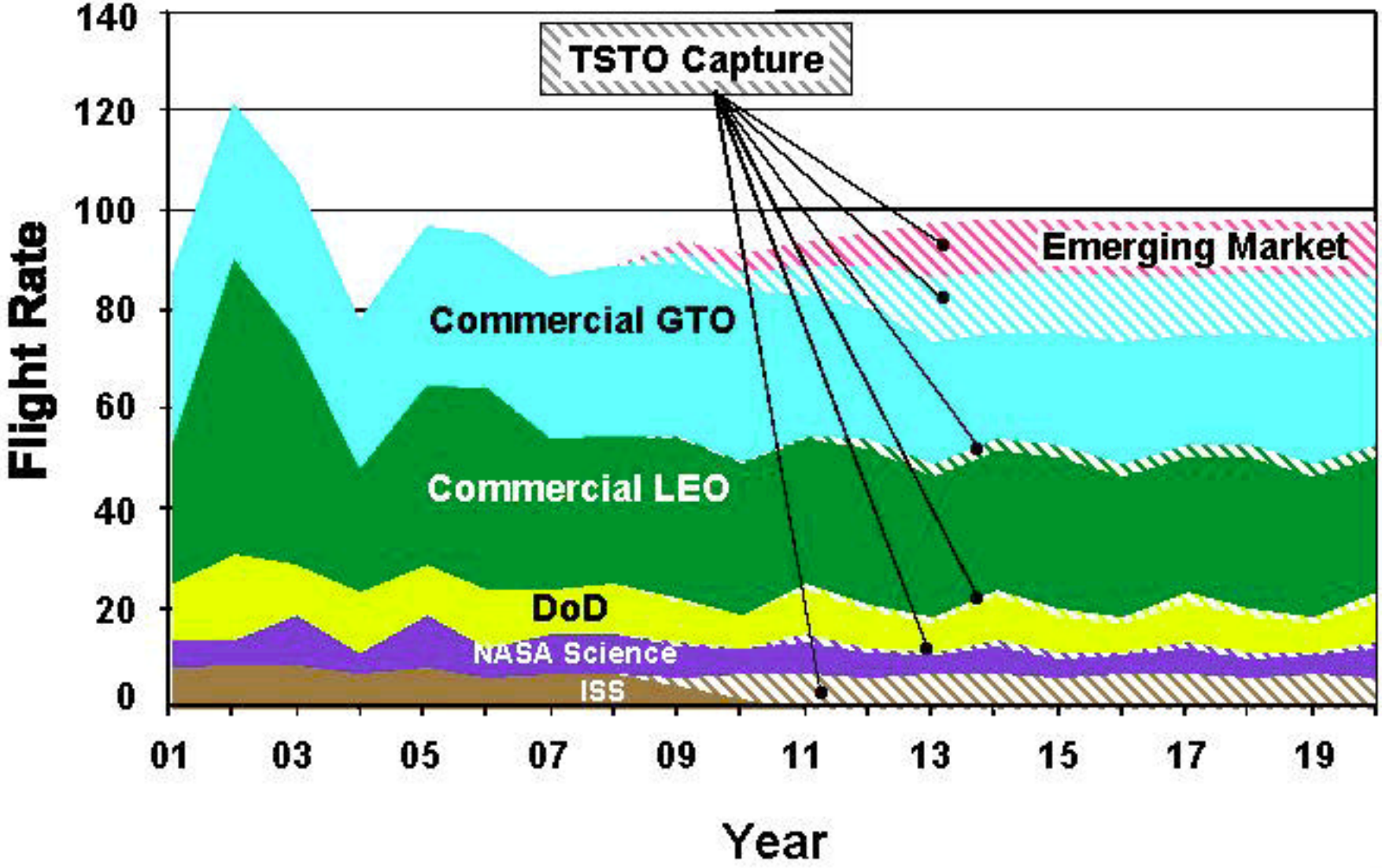
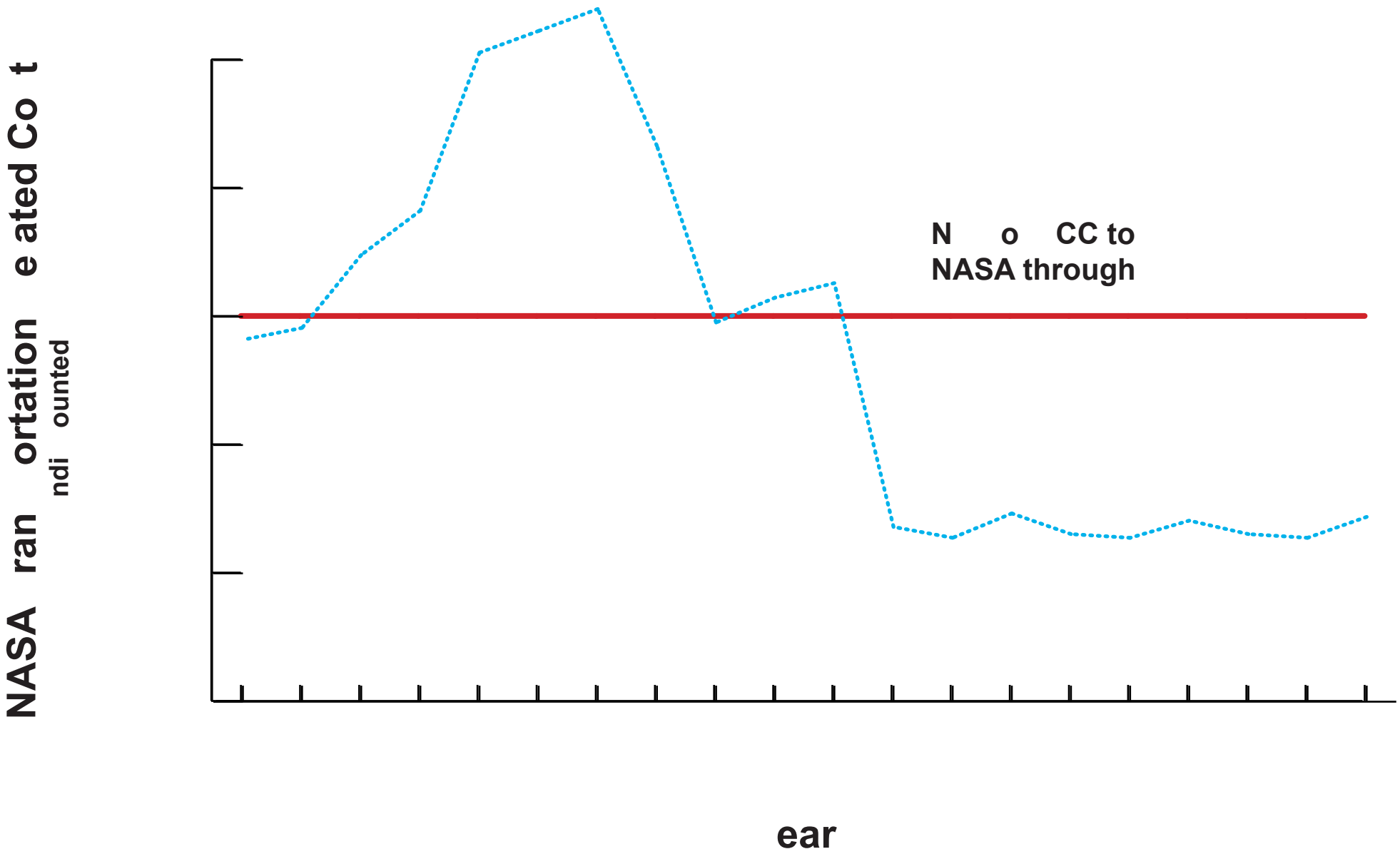


Architecture 4 Flight Rate

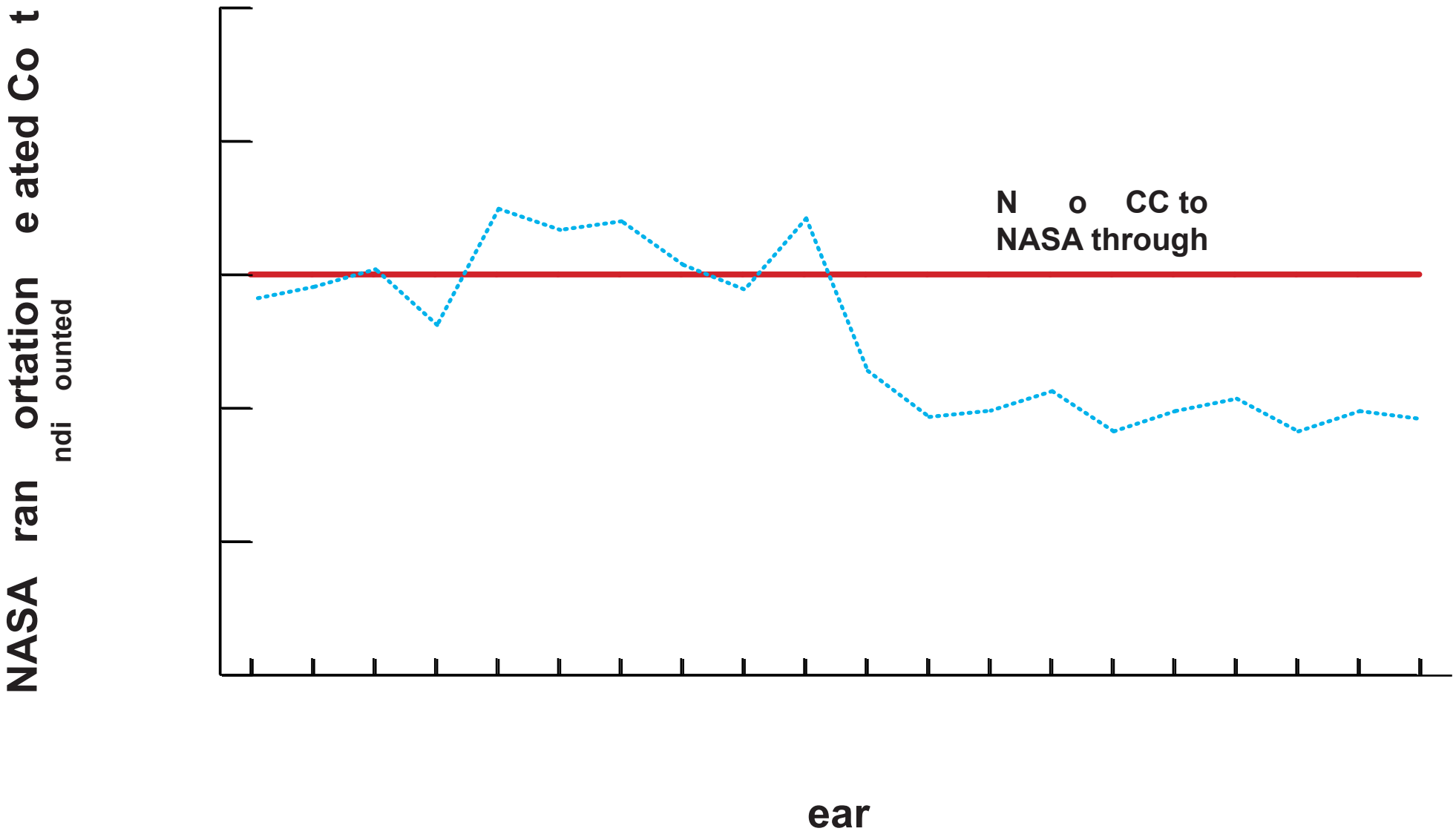


STAS5094

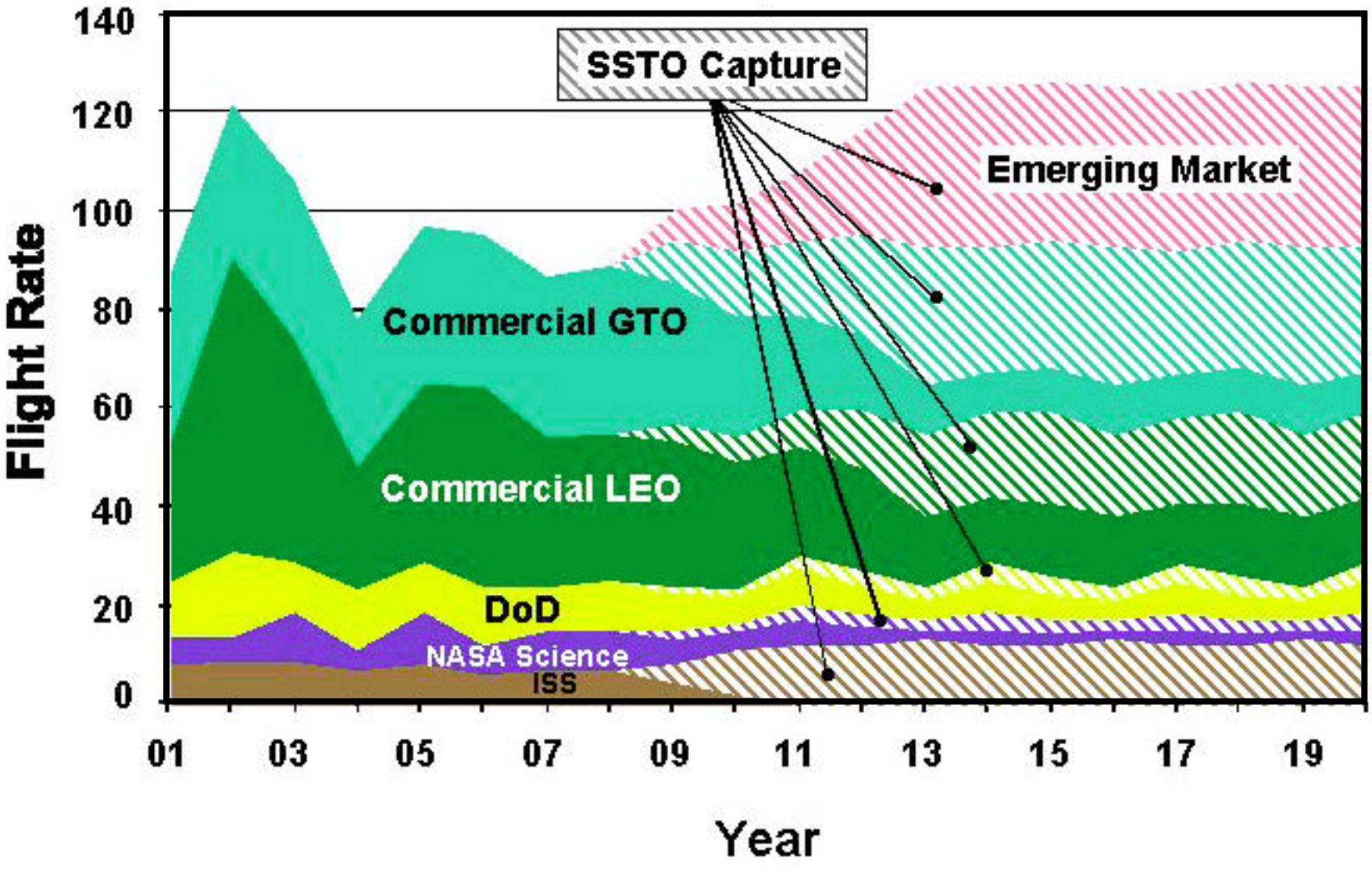
Ca h o Ana y i S unded Ar hite ture S O



Ca h o Ana y i Co er ia Ca e
Ar hite ture S O



Architecture 5 Flight Rate



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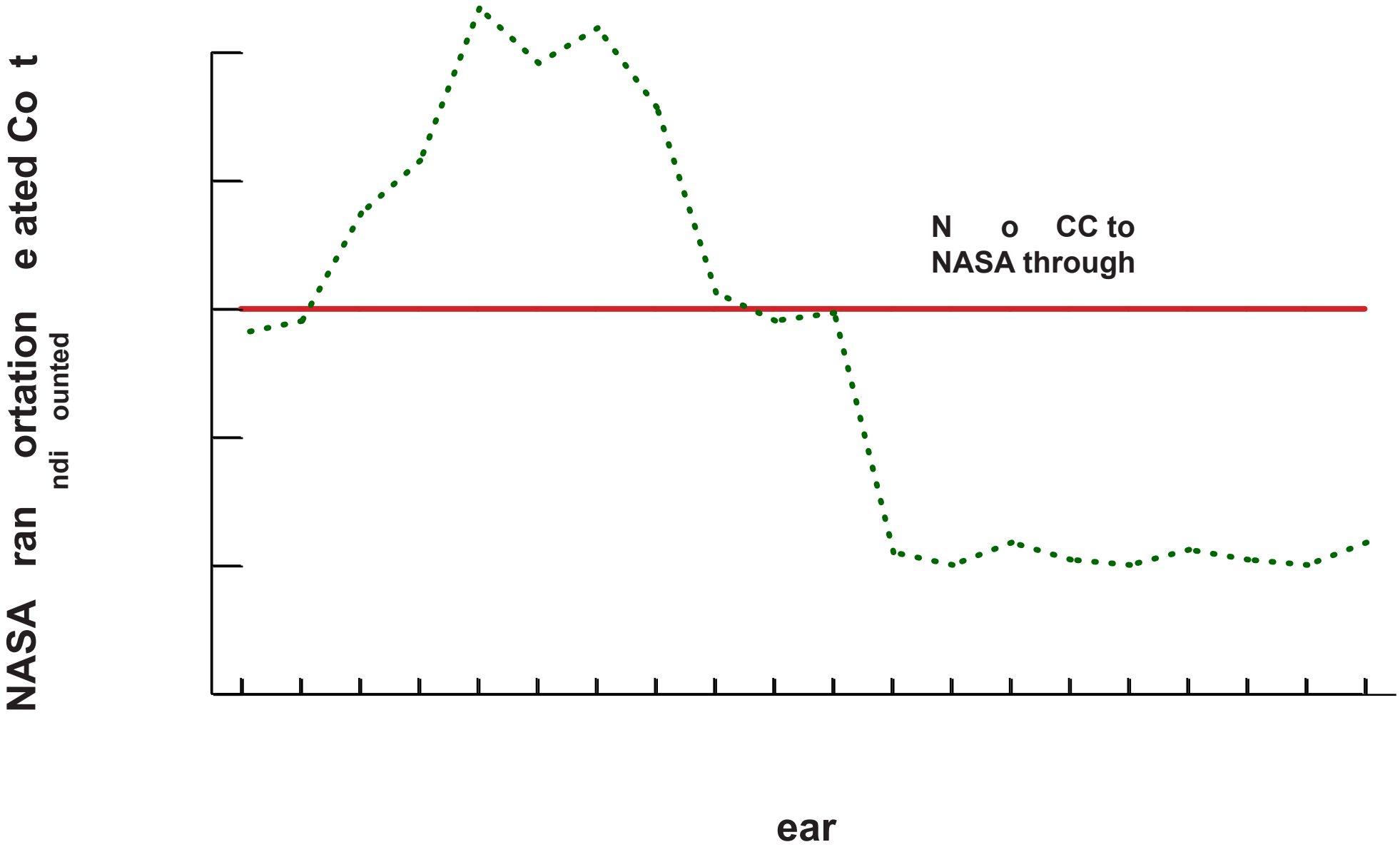

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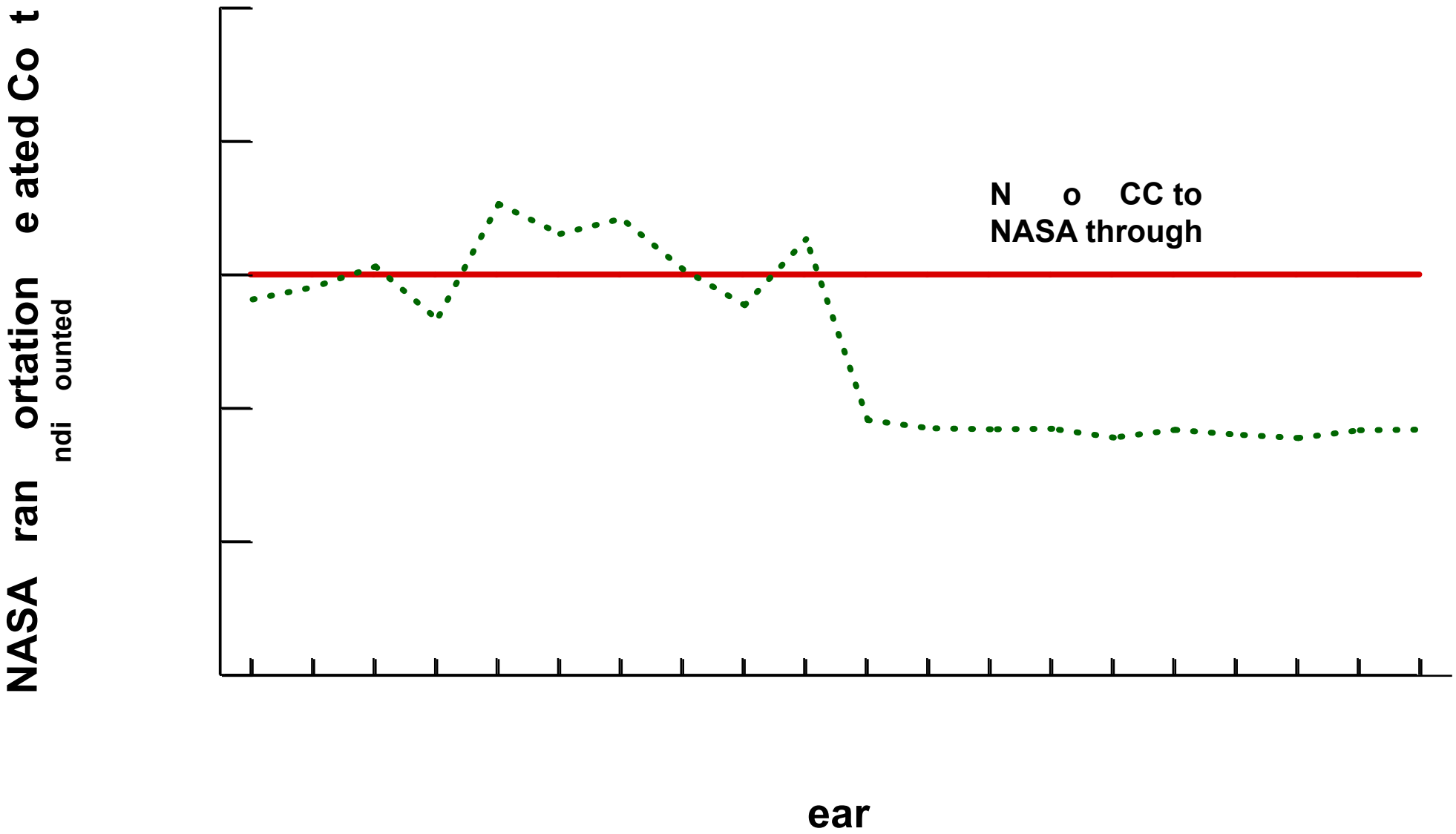

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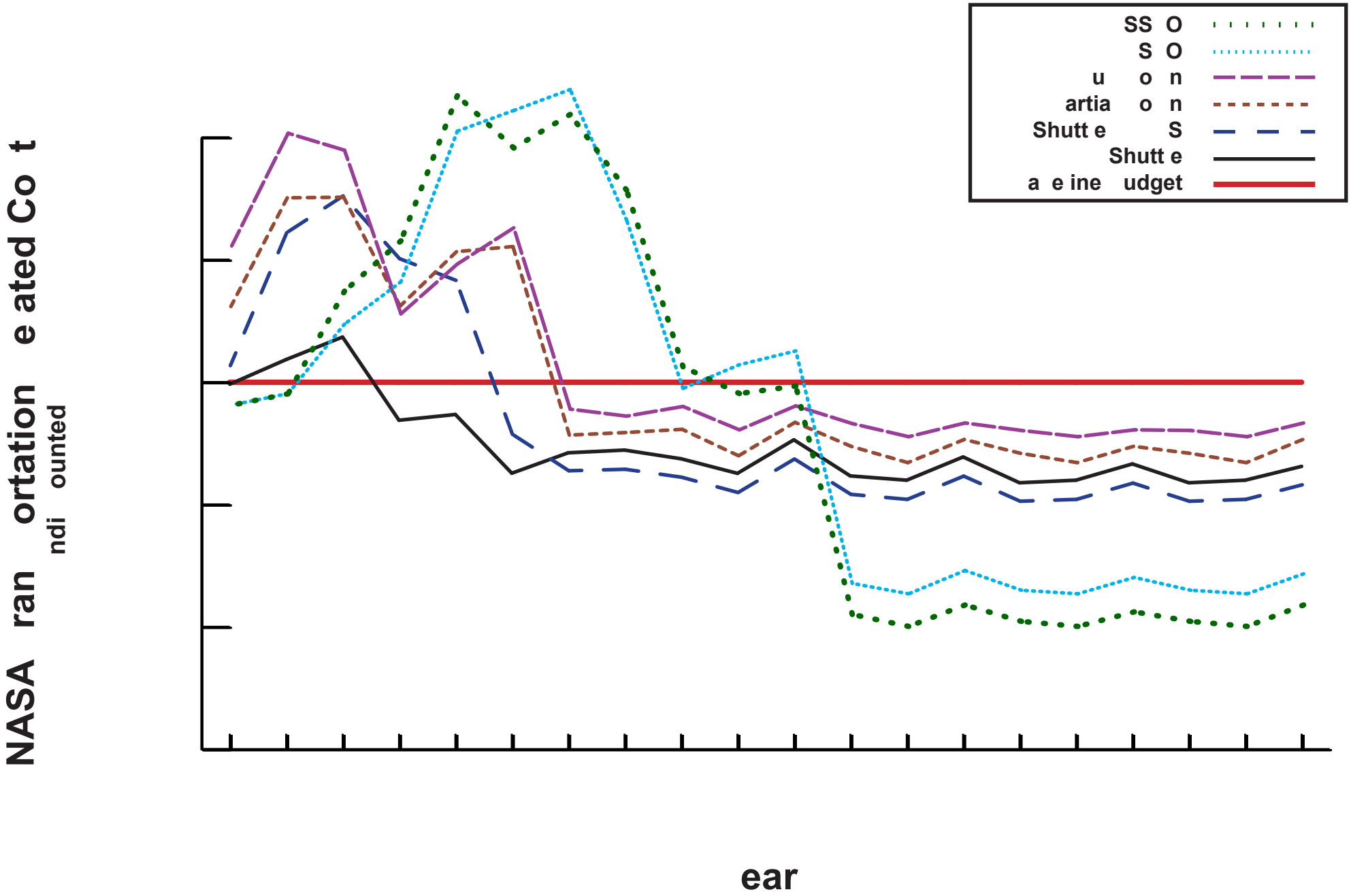

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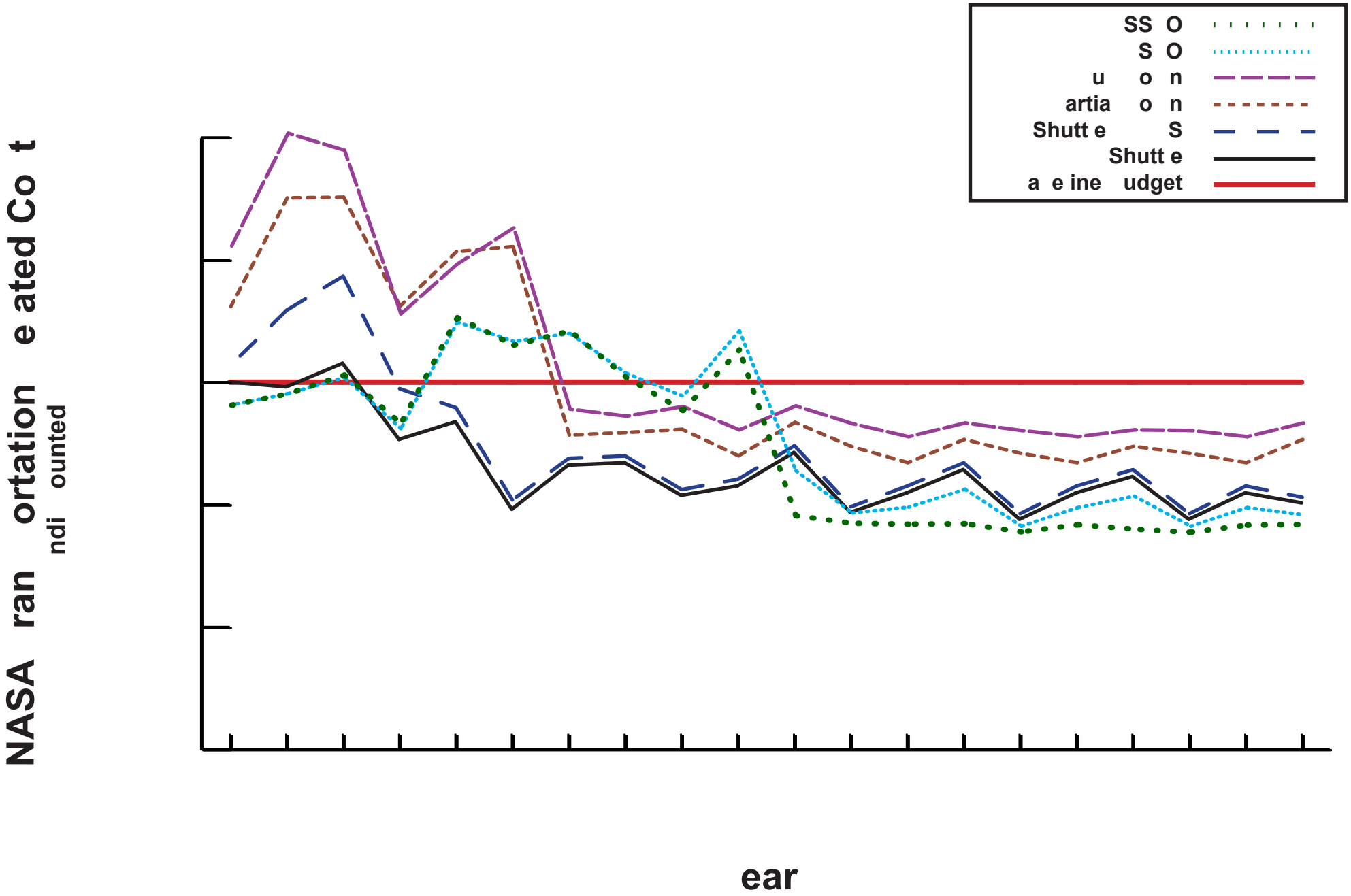
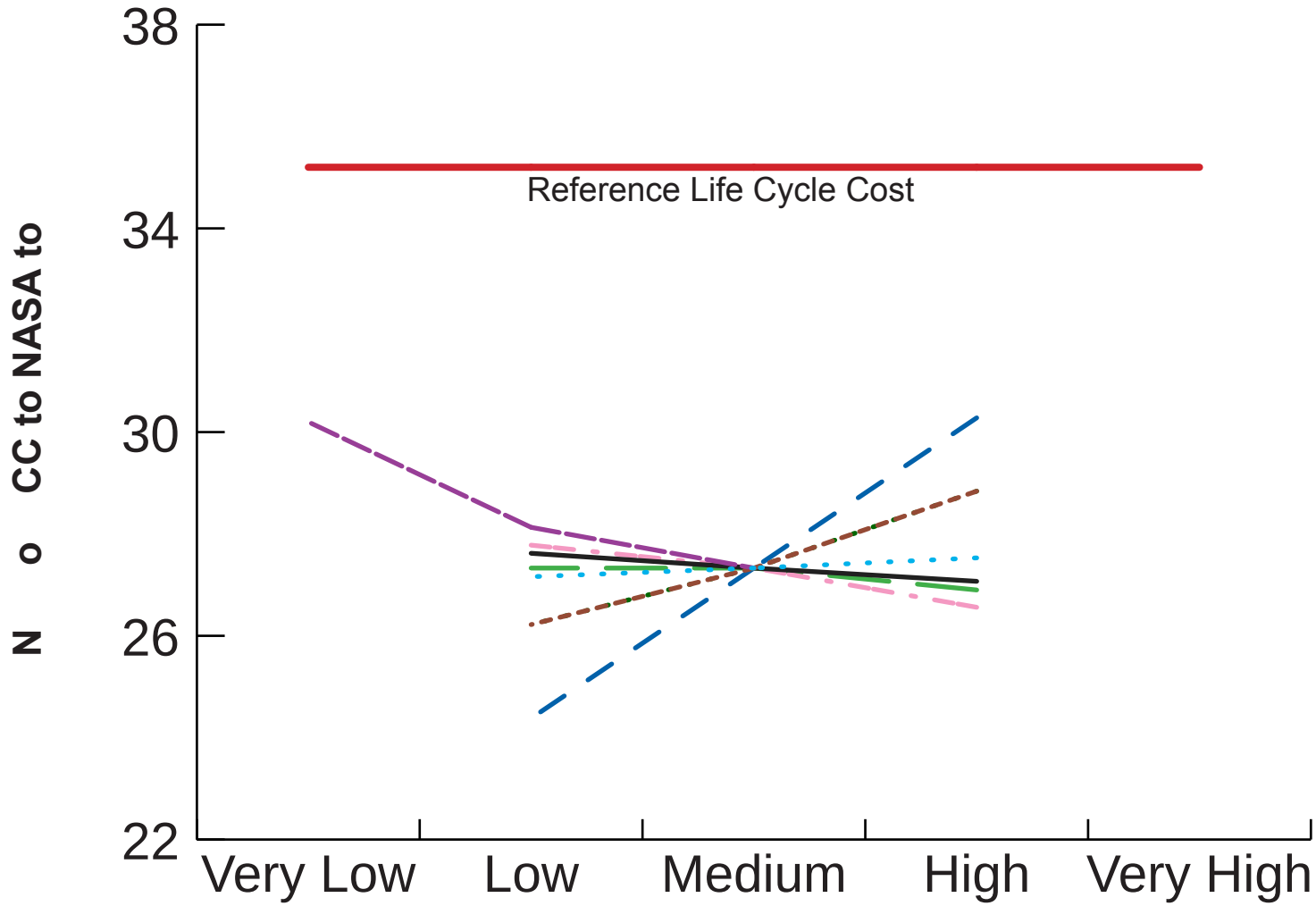
Co ari on o Ar hite ture



ono i Su ary
A Co t hrough

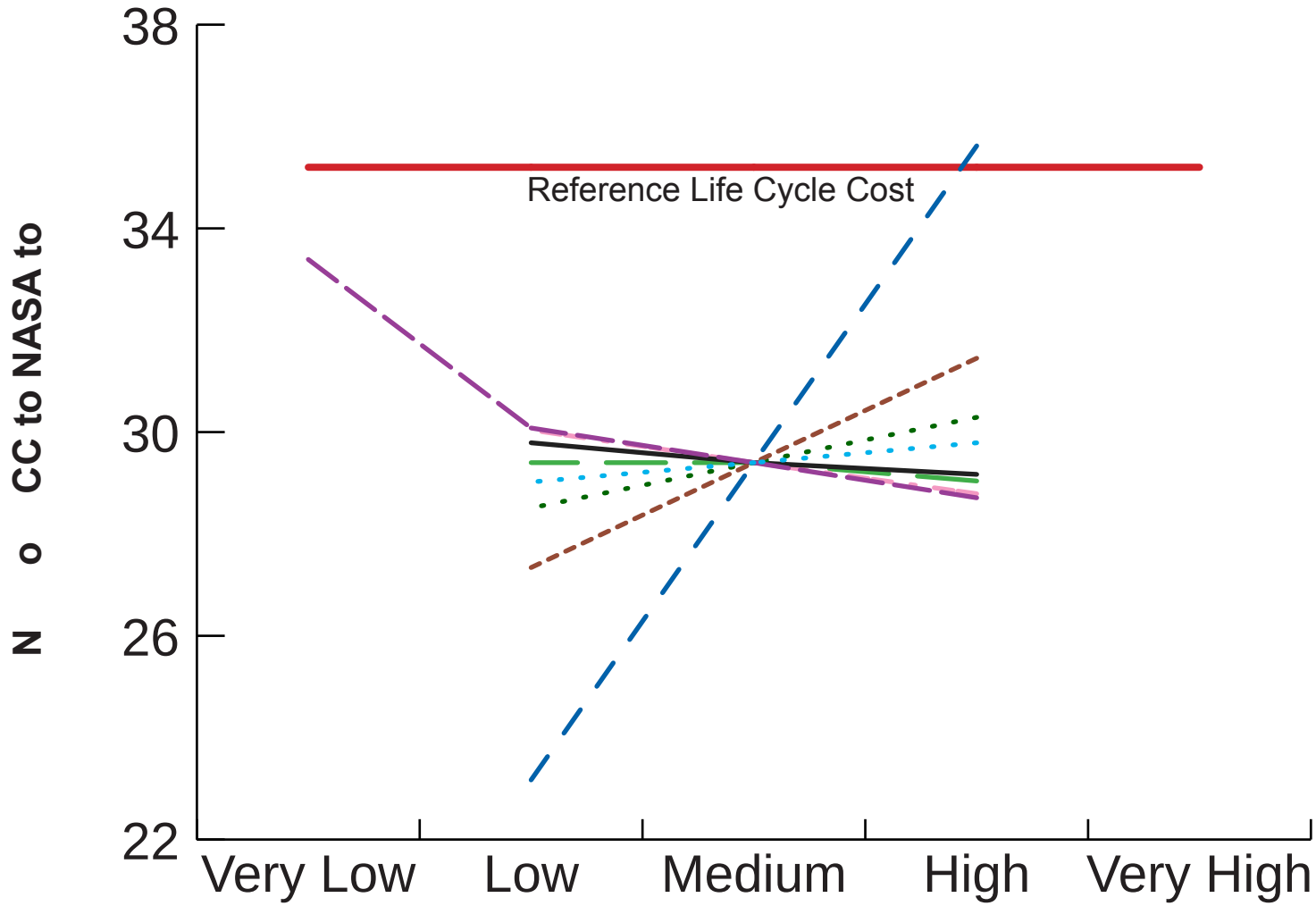
	Ar hite ture	Ar hite ture	Ar hite ture	Ar hite ture	Ar hite ture
∑ ndu try n enti e Ca e oan					
- USG LCC Undiscounted					
- USG LCC Discounted @ 10%					
- Peak Year Funding (Year)					
- Avg. $/lb LEO					
- ISS Price/Flight (Rate)					
- Com'l Price/Flight (Rate)					
- Emerging Price/Flight (Rate)			NA		
- Exploration Delta LCC Discounted					
∑ ndu try Ca e No n enti e					
- USG LCC Discounted at 10%			NA		
- Avg. $/lb LEO			NA		
∑ ndu try Ca e S					
- USG Capitalization Required			NA		
- USG LCC Discounted at 10			NA		
- Avg. $/lb LEO			NA		
∑ S unded Ca e					
- USG LCC Discounted @ 10%					
- Peak Year Funding (Year)					

Sen iti ity Ana y i Co er ia Ca e Ar hite ture



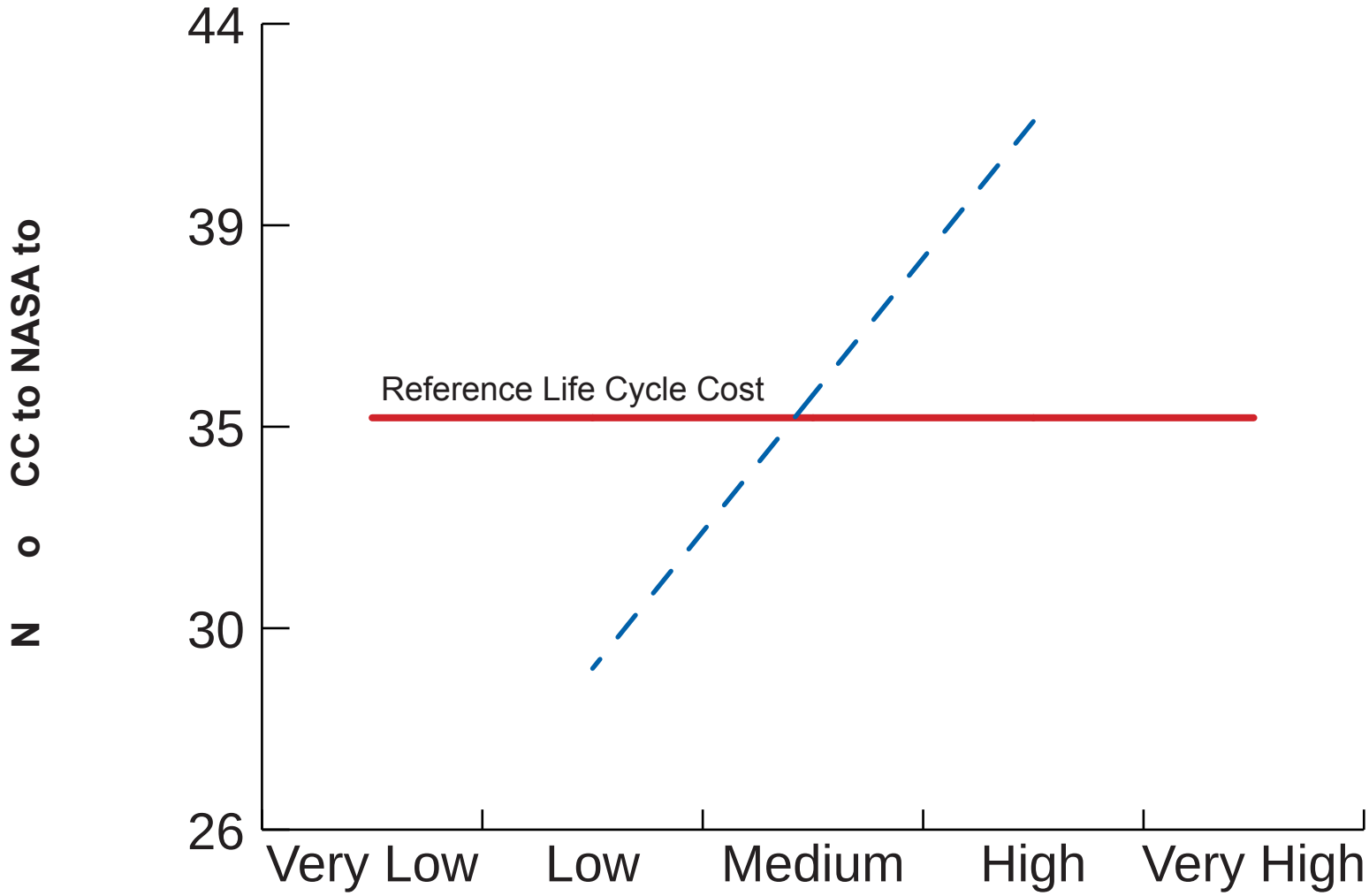
	Very Low	Low	Medium	High	Very High
urd e ate		20%	25%	30%	
n enti e	None	Loan Only	Loan + $1B	-	
		50%	-	150%	
nit Co t		-	-	-	
O eration Co t		80%	-	120%	
Co ar et Ca ture		50%	-	150%	
Co ar et A e ri e		75%	-	125%	
erging ar et e on e		None	$1,000/lb	$2,000/lb	

Sen iti ity Ana y i Co er ia Ca e Ar hite ture



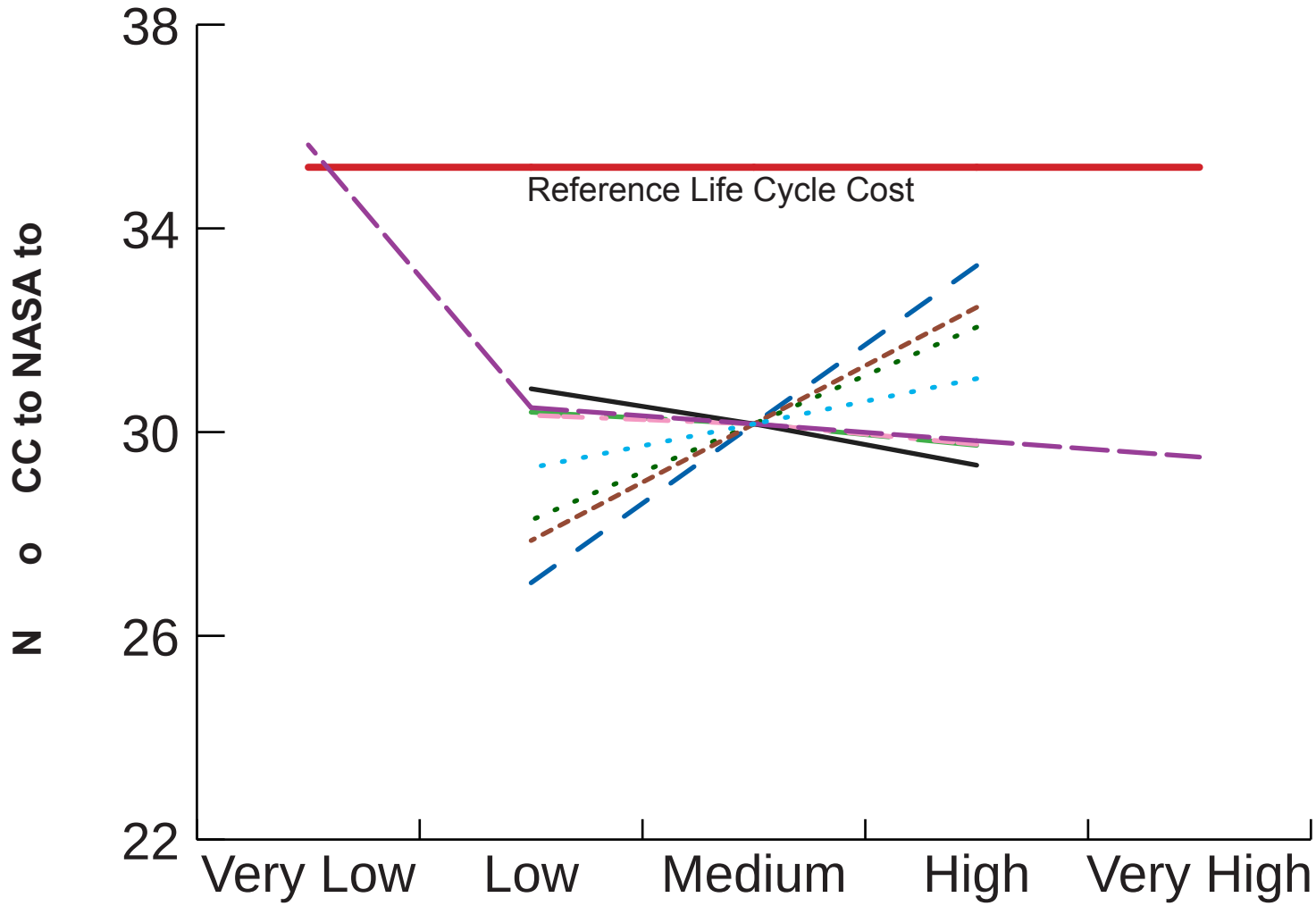
urd e ate		20%	25%	30%
n enti e	None	Loan Only	Loan + $1B	Loan + $2B
		50%	-	150%
nit Co t		50%	-	150%
O eration Co t		50%	-	150%
Co ar et Ca ture		50%	-	150%
Co ar et A e ri e		75%	-	125%
erging ar et e on e		None	$1,000/lb	$2,000/lb

Sen iti ity Ana y i Co er ia Ca e Ar hite ture



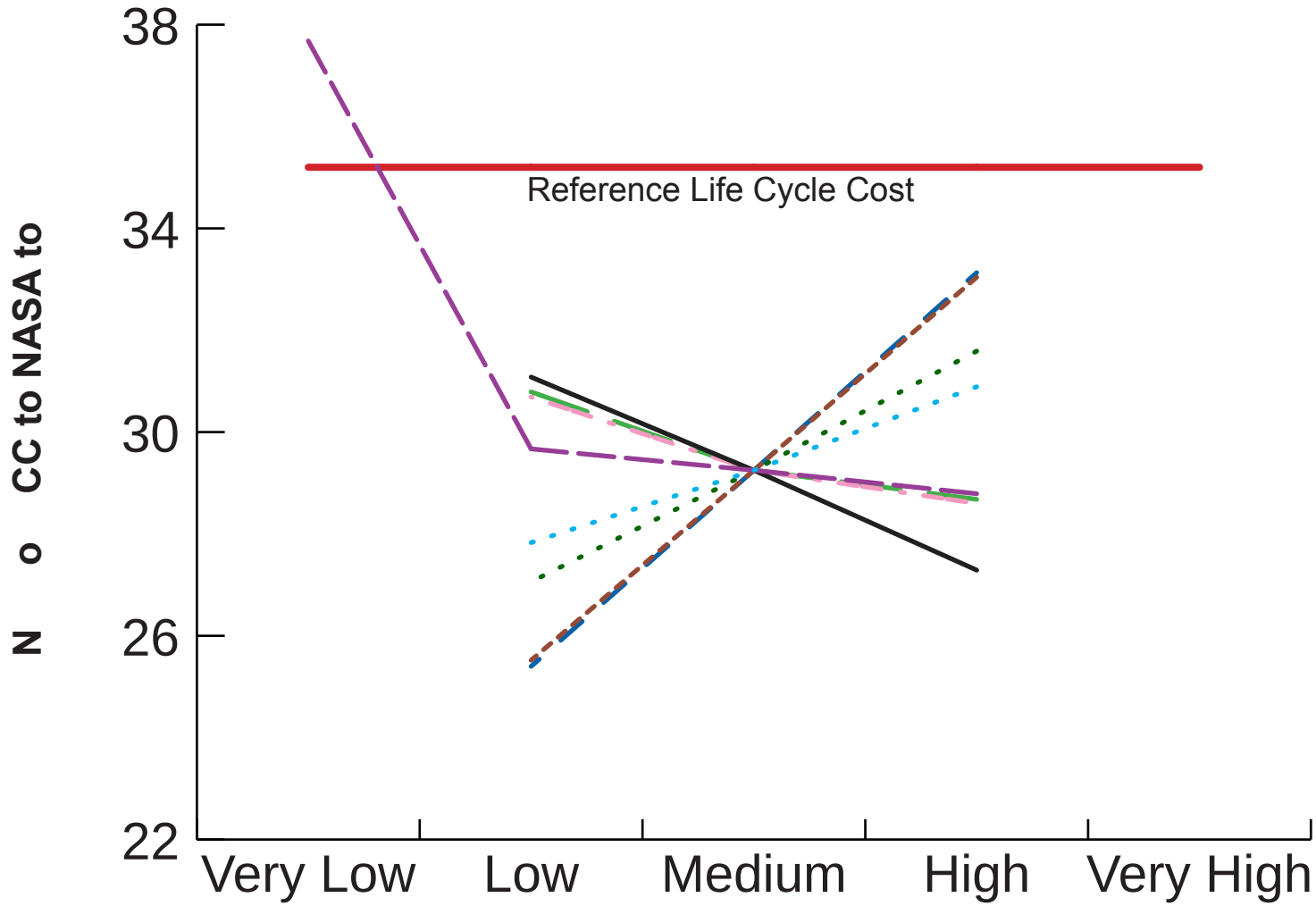
O eration Co t	None	50%	-	150%

Sen iti ity Ana y i Co er ia Ca e Ar hite ture



	Very Low	Low	Medium	High	Very High
urd e ate		20%	25%	30%	
n enti e	None	Loan Only	Loan + $1B	Loan + $2B	Loan + $3B
		50%	-	150%	
nit Co t		50%	-	150%	
O eration Co t		50%	-	150%	
Co ar et Ca ture		50%	-	150%	
Co ar et A e ri e		75%	-	125%	
erging ar et e on e		None	$1,000/lb	$2,000/lb	

Sen iti ity Ana y i Co er ia Ca e Ar hite ture



urd e ate		20%	25%	30%
n enti e	None	Loan Only	Loan + $1B	Loan + $2B
		50%	-	150%
nit Co t		50%	-	150%
O eration Co t		50%	-	150%
Co ar et Ca ture		50%	-	150%
Co ar et A e ri e		75%	-	125%
erging ar et e on e		None	$1,000/lb	$2,000/lb

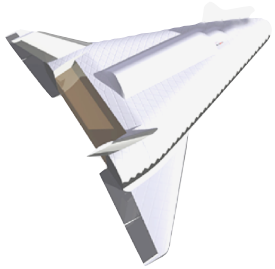
Economic Observations

- **Net Present Value (@10%) of Life Cycle Cost to NASA of all Architectures are +/-10%**
- **Time Phased Life Cycle Costs are Significantly Different**
  - Shuttle and Shuttle/RFS => Lower Investment, Lower Savings
  - EELV Least Cost Effective of All => High Investment, Low Savings
  - TSTO and SSTO => Higher Investments, Higher Savings
- **All Architectures with New Investments Exceed Available Budget in Peak Year Funding**
  - USG Funded Approach Requires Highest Peak Year Funding
  - USG Incentives Reduce Peak Year Funding
- **All Architectures Generate $0.5B to $1.0B Wedge in Outyear Savings**
  - EELV ~ $0.5B
  - SSTO ~ $1.25B
- **Closure of USG Business Case (NASA Breakeven @ 10%) Accomplished with Incentives Ranging from Guaranteed Loan to $3B in Capitalization Plus Loan**

Economic Observations (continued)

- **Industry Business Cases Close with $1B Capitalization plus USG Guaranteed Loan and ISS Servicing Market**
- **Lowest NASA LCC is Provided by Architectures which are Commercially Developed**
  - Benefits US Commercial Launch Industry
  - Stimulates the Emerging Market
  - Lowers NASA's Peak Year Funding from USG Funded Case
- **Business Analysis Yields Highest Outyear Savings Potential for TSTO and SSTO**
  - Lowest Prices for NASA ISS Servicing, Largest NASA Savings Wedge
  - Largest Commercial Market Capture, Largest Emerging Market Stimulus
- **Promise of Emerging Market will not Encourage Commercial Operators to Lower Prices**
  - Inexpensive Flights do not Contribute to Commercial Viability
  - Incentives should be Contingent upon Enabling the Emerging Market
- **Exploration Excursion Delta Cost was Lowest for Architectures 1, 2 and 4**

ey ara eter Su ary
A Co t hrough

	Ar hite ture	Ar hite ture	Ar hite ture	Ar hite ture	Ar hite ture
• ndu try n enti e Ca e oan - USG LCC Undiscounted - USG LCC Discounted @ 10% - Peak Year Funding (Year) - Avg. $/lb LEO - ISS Price/Flight (Rate) - Com'l Price/Flight (Rate) - Emerging Price/Flight (Rate) - Exploration Delta LCC Discounted					
			NA		
• Ar hite ture e ia i ity					
• Ar hite ture Sa ety					
• edian ro a e S i o					

Architectural Assessment

STAS5028

ono i

	ro	Con
Ar hite ture Shutt e	∑Smallest uncertainty band in cost estimates ∑Lowest investment cost	∑Significant CS workforce, overhead, infrastructure
Ar hite ture Shutt e S		∑Significant CS workforce, overhead, infrastructure
Ar hite ture	∑Small cost uncertainty in EELV boosters	∑Expendable elements increase costs at higher flight rates ∑High cost uncertainty in human-rated elements
Ar hite ture S O	∑Fully Reusable offers potential for high flight rate economies	∑High uncertainty band in cost estimates ∑High element cost
Ar hite ture SS O	∑Fully Reusable offers potential for high flight rate economies	∑No Shared infrastructure ∑Highest uncertainty band in cost estimates ∑High element cost

	ro	Con
Ar hite ture Shutt e	• Lowest overall risk (technical, cost, schedule)	
Ar hite ture Shutt e S	• Lowest risk compared to any new development	• Stage integration risk
Ar hite ture	• Low booster development risk for gov't	• Added aerodynamic element on top of EELV may pose additional flight control and structural problems
Ar hite ture S O	• TSTO offers lowest technical risk for achieving full reusability	• Stage integration risk
Ar hite ture SS O		• Highest risk

e ia i ity

	ro	Con
Ar hite ture Shutt e	• Reliability consistent with all but the most revolutionary concepts at the lowest cost	
Ar hite ture Shutt e S	• Reliability consistent with all but the most revolutionary concepts at the lowest cost	
Ar hite ture		• Significantly lower reliability as compared to any other architecture
Ar hite ture S O		
Ar hite ture SS O	• Factor of two reliability improvement over Architecture 1	

Sa ety

	ro	Con
Ar hite ture Shutt e	• Proven performance	• All RSRM failures are catastrophic • Low crew survivablility (essentially no crew escape during ascent)
Ar hite ture Shutt e S	• Improved first stage safety in eliminating TAL or RTLS aborts • Ability to verify nominal booster engine performance prior to launch commit • Eliminates potential of castastrophic incident in VAB which would eliminate single national asset for integration of vehicles	• Low crew survivability (essentially no crew escape during ascent)
Ar hite ture	• Ability to verify nominal engine performance prior to launch commit • Crew module location enhances crew survivability (crew escape)	• Use of escape system highly probable due to high catastrophic failure rate
Ar hite ture S O	• Ability to verify nominal engine performance prior to launch commit • Provides for crew escape	• Due to configuration, escape envelope may be limited
Ar hite ture SS O	• Ability to verify nominal engine performance prior to launch commit • Provides for crew escape	• Due to configuration, escape envelope may be limited

Continuity

	ro	Con
Ar hite ture Shutt e	• Highest synergy with existing launch infrastructure and ISS interfaces.	• Difficult to address commercial operation due to policy and legislative barriers/ launch rate limitations.
Ar hite ture Shutt e S	• Establishes a roadmap for gradually replacing STS components with (perhaps) commercially funded elements, with increased market capture as time progresses. • Evolves from existing shuttle infrastructure	• Difficult to address commercial operation due to policy and legislative barriers/ launch rate limitations.
Ar hite ture	• Takes advantage of EELV production and launch processing capabilities. Strong connection to EELV commercial market. • The development of a CTV may be derivative of a CRV for the ISS. The CTV can also be utilized for alternate access when launched on an EELV.	• Development of new human space transportation element required
Ar hite ture S O	• The development of a CTV may be derivative of a CRV for the ISS. The CTV can also be utilized for alternate access when launched on an EELV.	• All new booster, launch facilities, and human space vehicle element required.
Ar hite ture SS O	• Cleanest transition due to independence from existing shuttle infrastructure. • The development of a CTV may be derivative of a CRV for the ISS. The CTV can also be utilized for alternate access when launched on an EELV.	• All new booster, launch facilities, and human space vehicle element required.

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Co etition

	ro	Con
Ar hite ture Shutt e		• No competition
Ar hite ture Shutt e S Ar hite ture S O and Ar hite ture SS O	• Potential ops cost savings may allow NASA to maintain Shuttle for a longer transition. • Lower ops cost will expand the available space market and allow for more com-petitors.	
Ar hite ture	• Dual source EELV allows competition.	• Nothing competing with EELV

i ion Ca a i ity

	ro	Con
Ar hite ture Shutt e	• Minimizes ISS microgravity impacts because few ISS missions required • Certified, verified, and proven concept • Supports ISS EVA Requirements • STS is probably most flexible vehicle. Supports orbital missions that will be difficult to match with purely commercial vehicles • Provides good support for exploration ETO requirements due to shared production, processing facilities and launch	
Ar hite ture Shutt e S	• Minimizes ISS microgravity impacts because few ISS missions required • STS is probably most flexible vehicle. Supports orbital missions that will be difficult to match with purely commercial vehicles • Provides good support for exploration ETO requirements due to shared production, launch, and processing facilities. Probably provides lowest DDT&E and recurring cost exploration ETO	

i ion Ca a i ity ont

	ro	Con
Ar hite ture		• ISS CRV rotation requires CRV to perform a entry which uses up mission life just for recycle • May be difficult to maintain current Orbiter's mission capabilities in limited mass CCTV. No combined crew/cargo missions. May be unable to support down-mass requirements. Support of exploration ETO requirements are minimal
Ar hite ture S O	• May be possible to maintain Shuttle Orbiter's mission capabilities due to upmass/ downmass, performance margins • Provides some support for exploration ETO due to use of Bimese as boosters and some shared facilities • Provides capability for simultaneous transfer of crew and cargo to ISS	
Ar hite ture SS O	• Alternate access capability provided with development of CTV, which can be launched on either the SSTO or EELV	• More frequent interruption of ISS micro-gravity environment • Probably will abandon many Shuttle unique mission capabilities due to severe vehicle mass and operational limitations. Provides little direct support for exploration ETO requirements

i ion Ca a i ity

Ca a i ity	Ar hite ture				
	1	2	3	4	5
A ent er or an e to SS	40.3K	48K	22K/35K***	55K	25K
o n a er or an e ro SS	41.2K	45K	22K/9K	60K	60K
ay oad Ser i e	Yes	Yes	No	No	No
ehi e S	Yes	Yes	No	No	No
On or it a e y	Yes	Yes	No	No	No
A out o ehi e	Yes	Yes	No	No	No
ay oad Sate ite etrie a	Yes	Yes	No	No	No
ay oad Sate ite Ser i ing	Yes	Yes	No	No	No
ehi e generated ater and ga e	Yes	Yes	No	No	No
tended on or it duration	Yes	Yes	No	No	No
S ienti i at or	Yes	Yes	No	No	No
Cre and ay oad aun hed and returned together	Yes	Yes	No	Yes	No
erry	Yes	Yes	Yes	?	No
Cre i oted ehi e	Yes	Yes	?	?	?
Cre ay oad u ort	Yes	Yes	?	?	?
u an ntera tion trou e hooting re air et	Yes	Yes	?	?	?
nta t a ort a a i ity	Yes	Yes	?	?	?
ay oad Sate ite e oy ent	Yes	Yes	Yes	Yes	Yes
Cre a e odu e	No	No	Yes	Yes	Yes
Autono ou O eration	No	Partial	Yes	Yes	Yes
aun h to a a i uth	No	No	No	Yes	Yes

* Maximum abort landable payload based on minimum duration / crew mission
** Maximum nominal end of mission cargo return
*** Full downmass/partial downmass

e i ien e

	ro	Con
Ar hite ture Shutt e	• Shuttle has a demonstrated 95+% launch probability for each month of the year	• Orbiter turnaround time limiting flight rate (limited surge capability)
Ar hite ture Shutt e S		
Ar hite ture	• EELV expendability ensures production capability • Developed EELV/CCTV could provide alternate access for all architectures • Multiple EELV suppliers provides alternate access	
Ar hite ture S O	• TSTO provides greater potential for margin/robustness	
Ar hite ture SS O	• Single element provides for less complex ground and flight operations	• Larger weight and performance penalties incurred for extra design margins that would provide a more robust/forgiving vehicle.

S Co etiti ene

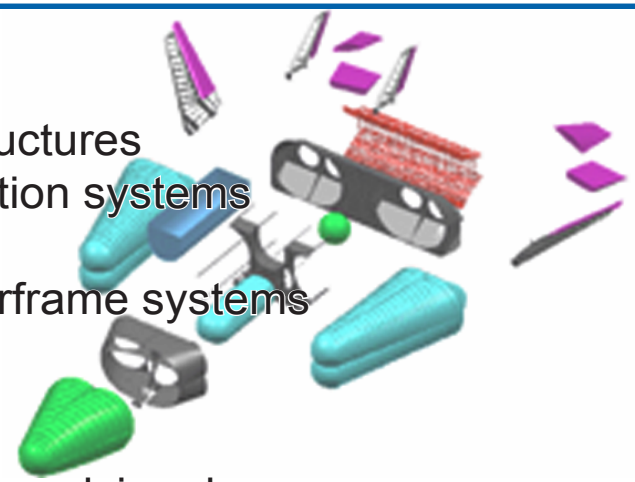
	ro	Con
Ar hite ture Shutt e		• Does not capture additional market share for the U.S.
Ar hite ture Shutt e S	• May allow commercial sector to capture limited additional GTO/LEO markets through evolution of RFS into partially reusable and reusable TSTO systems	• Does not capture additional market share for the U.S.
Ar hite ture	• NASA use of EELV could lower costs to enable greater market capture	
Ar hite ture S O	• Flexibility and potentially lower costs of the TSTO vehicle may allow additional global market capture	
Ar hite ture SS O	• Significantly lower costs result from the SSTO concept, additional global market should be captured	

S e hno ogi a eader hi

	ro	Con
Ar hite ture Shutt e		• No major technological advancements • Lowest level of technology development
Ar hite ture Shutt e S	• Paths exist to incorporate advancing technology in the RFS and in the eventual reusable upper stage. System can be used until higher technology elements are ready	• Low initial level of technology investment
Ar hite ture		• Little advanced technology
Ar hite ture S O	• Technology developed in several areas to support new vehicle development	
Ar hite ture SS O	• By being the most technologically challenging option, the SSTO vehicle element, pushes key material, structure, and manufacturing technologies that may find applications in other industries/DoD	

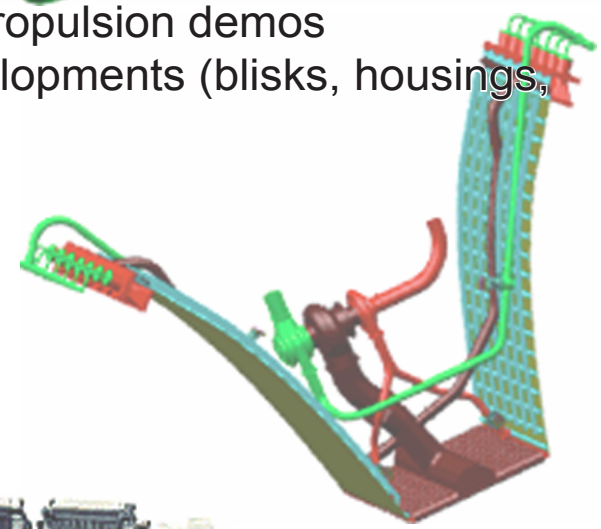
Implementation
Issues
STAS5028

e hno ogy e uire ent or



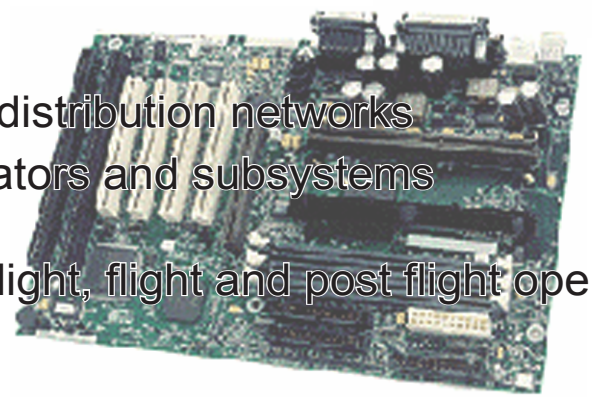
♦ Air ra e

- Large scale, manufacturable composite tanks and structures
- Durable, long life ceramic and metallic thermal protection systems
- Durable hot structures (leading edges, elevons, etc.)
- Large scale, integrated life cycle demonstrations of airframe systems (tanks, structures, TPS)



♦ ro u ion

- High T/W (70-80) and Isp integrated rocket engine propulsion demos
- Lightweight, long life high temperature materials developments (blisks, housings, thrusters, nozzles)
- Lightweight feedlines and ducts
- Long life, high performance turbomachinery
- Low cost, expendable upperstage engines
- Propellant densification
- Non-toxic OMS / RCS



♦ A ioni N C

- Automated rendezvous and capture
- High ef ficiency power sources and distribution networks
- Low maintenance / high power actuators and subsystems
- System level VHM
- Automated ground processing, pre flight, flight and post flight operations
- Containerized payloads
- Automated maintenance

o i y and egi ati e ue

♦ Nationa S a e o i y Change e uired

- Architecture 1 and 2
  - Commercial Payloads on Shuttle: *i inate Section III a*

- Architecture 3, 4, 5
  - None

♦ egi ation

- Architecture 1
  - Commercial Payloads on Shuttle: *rd arty ia i ity Insurance*
    - *on o ercia i hts*

- Architecture 2, 4, 5
  - *oan uarantees*
  - *ud et or NASA ontri utions to e e op ent*

Additional Analyses

e uire ent a t

	a t
Ar hite ture	• Does not meet JSC human rating requirements
Ar hite ture	• Partial downmass: - No return of logistics carriers (MPLM, ULC) spares, maintenance items, etc. - ~50% return of unpressurized user cargo - Loss of carriers/spares/equipment presents an annual cost (~$250M) and continuing production line issue - Buildup of cargo/debris on orbit • CRV design modifications required due to launch on EELV
Ar hite ture	• ISS Common Berthing Mechanism lifetime exceeded • ISS microgravity quiescent period (req't of 180 days) violated by ~40 to 120 days (1st cut analysis - may be able to relieve) • Loss of estimated 500 science hours annually due to inability to transport additional crew members along with logistics carriers for maintenance and cargo load/unload
Ar hite ture	• CRV design modifications required due to potential commonality with CTV

A ternate A e to S a e

- **Ar hite ture doe not e e ti e y a o a ternate a e**
  - Significant cost associated with developing a new CTV and integrating on EELV

- **Ar hite ture ay a o or a ternate a e**
  - Keep Shuttle with RFS and enable new TSTO with RFS
  - Would require the use of the projected outyear savings to NASA of the RFS

- **Ar hite ture inherent y a o a ternate a e**
  - Two approximately equal capability / price EELV's
  - Would require human rating two systems (not included in economics analyses)

- **Ar hite ture and ay a o or a ternate a e**
  - Launch humans to ISS on CTV / EELV
    - Would require upfront CTV design impacts
    - Would require human rating and integration on an EELV(s) (~ $700M delta)
  - Would require the use of the projected outyear savings to NASA of the new RLV

ight ui a ent or u ian SS e u y

- **Annua u ian tra i to SS o t a e y o ete**
  - Four Progress @ 5,170 lbs payload each
  - Two Soyuz @ 1,060 lbs payload and three crew each (6 month rotation)

- **ui a ent additiona ight**

Ar hite ture	Additiona Annua ight Cargo	Additiona Annua ight Cre
Shutt e to		
Shutt e to Signi i ant grade		
a ed artia o n a	A CC	CC
a ed u o n a	C Cargo	C Cre
Ne o Stage to Or it		
Ne Sing e Stage to Or it		

Conclusions and Recommendations

Ar hite tura Con u ion

- **ying a o er ia i ed S a e Shutt e ith i ited u grade Ar hite ture ou d o er igni i ant o t a ing ith the o e t te hni a ri**
  - This architecture does not expand the U.S. share of the commercial market
  - Requires an additional 25% reduction in annual operations cost

- **An S u grade Ar hite ture a o or in re enta ar hite ture e o ution ith i ited te hni a ri**
  - It has low life cycle cost, offers marginal increases in reliability and safety compared to Shuttle, but has high peak year funding
  - Requires a commercialized Shuttle

- **a ed Shutt e re a e ent y te Ar hite ture ho itt e ene it**
  - While Architecture 3 has the best overall safety and the lowest technical risk for any new system,
  - It has the highest life cycle cost, highest peak year funding, lowest reliability and largest loss of mission capability (launch vehicle & ISS)

Ar hite tura Con u ion ont d

- **SS O S O Ar hite ture and a ear to o er the highe t o er ia otentia**
  - Many similiarities exist between SSTO and TSTO based architectures in terms of safety, reliability and NASA LCC
  - However, significant technical risk remains, especially in SSTO, and needs additional technology investment prior to ATP
  - TSTO boosters provide an evolutionary path for Exploration

- **he i a t o a inde endent o anie hi e not e a uated ay o er a ath to ena e u ti e o etitor in the ong run or SS er i ing**

ur ion Con u ion

- **oration e ur ion**
  - Architectures 1,2 and 4 require an additional ~15% discounted LCC
  - Architectures 3 and 5 require an additional ~20% discounted LCC
  since exploration must bear the entire cost of the RSRB

- **o o u ian in o e ent in SS annua a ed on a**
  - Logistics: Single additional flight in architectures 1,2,4 and 5.
    One to two additional flights for architecture 3
  - Crew rotation: One additional flight in architectures 1,2 and 4.
    One to two additional flights for architecture 3.
    Two for architecture 5

enera Con u ion and *Recommendations*

® **Study ti e ra e o doe not a o o t and a ety ad antage to e u y de on trated**

oth econo ic per circu ar A- and sa ety i pro e ents shou d e considered throu h to et a ore accurate representation o ne ehic e ene its i en ti e ra e o ne ehic e operations

® **A ar hite ture ha e a di ounted i e y e o t to NASA o a ro i ate y**

∑ No significant Life Cycle Cost savings (undiscounted reference cases) to NASA between architectures.

® **n a ar hite ture e e t a igni i ant annua outyear udget edge yr i de e o ed hi edge ou d e u ed to**

∑ Offset costs of human exploration
∑ Bolster technology developments
∑ Shuttle upgrades
∑ Provide alternate access (CTV on EELV, Shuttle etc.)
∑ Other…..

enera Con u ion and *Recommendations* ont d

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enera Con u ion and *Recommendations* ont d

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- **he o t ene it o ha e u grade or S a e Shutt e need etter de inition**

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enera Con u ion and *Recommendations* ont d

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  NASA shou d und a study to etter uanti y the e er in ar et

- **he i a t o a ne ehi e to er i e SS ha e not een u y a e ed ro either an SS or ehi e er e ti e**

  rior to any ina decision concernin a ne ehic e s to ser ice ISS the ISS pro ra shou d conduct an assess ent o the i e cyc e cost i pacts o Shutt e rep ace ent a ter ISS asse y co p ete The ISS pro ra shou d identi y oth ir and desired re uire ents o a ne space transportation syste

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enera Con u ion and *Recommendations* ont d

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Need to ode ana y e and co pare cost uncertainty o a architectures

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e uire ents shou d e re or u ated to ena e co parisons o architectures

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otto ine

- **Not enough no edge i a ai a e today to o it to a Shutt e re a e ent**

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Backup Material
STAS5028

Intangible Attributes

- **Resiliency**
  - Ability of "system" to react minimally or favorably to variations in uncertainty (predicted or actual)
    - Robustness, Flexibility, Margin, …
- **Continuity**
  - Synergy with existing, planned, or future space transportation systems and/or elements
    - Linkage between government and commercial ventures
    - Heritage-based; evolutionary
- **Competition**
  - Fosters continuing space transportation competition within industry (including international) to drive costs down as low as possible in all market segments
- **Mission Capabilities**
  - Inherent capabilities of a system or element (i.e., a vehicle) within an architecture, independent of current needs or requirements
    - Growth potential for future missions
- **U.S. Competitiveness**
  - The ability of an architecture or vehicle element to ensure that U.S industry remains competitive in the global marketplace and enables the U.S. to increase its market share
- **U.S. Technological Leadership**
  - Fosters continued U.S. leadership in space technology
  - The ability to rapidly respond to problems and challenges with innovative solutions

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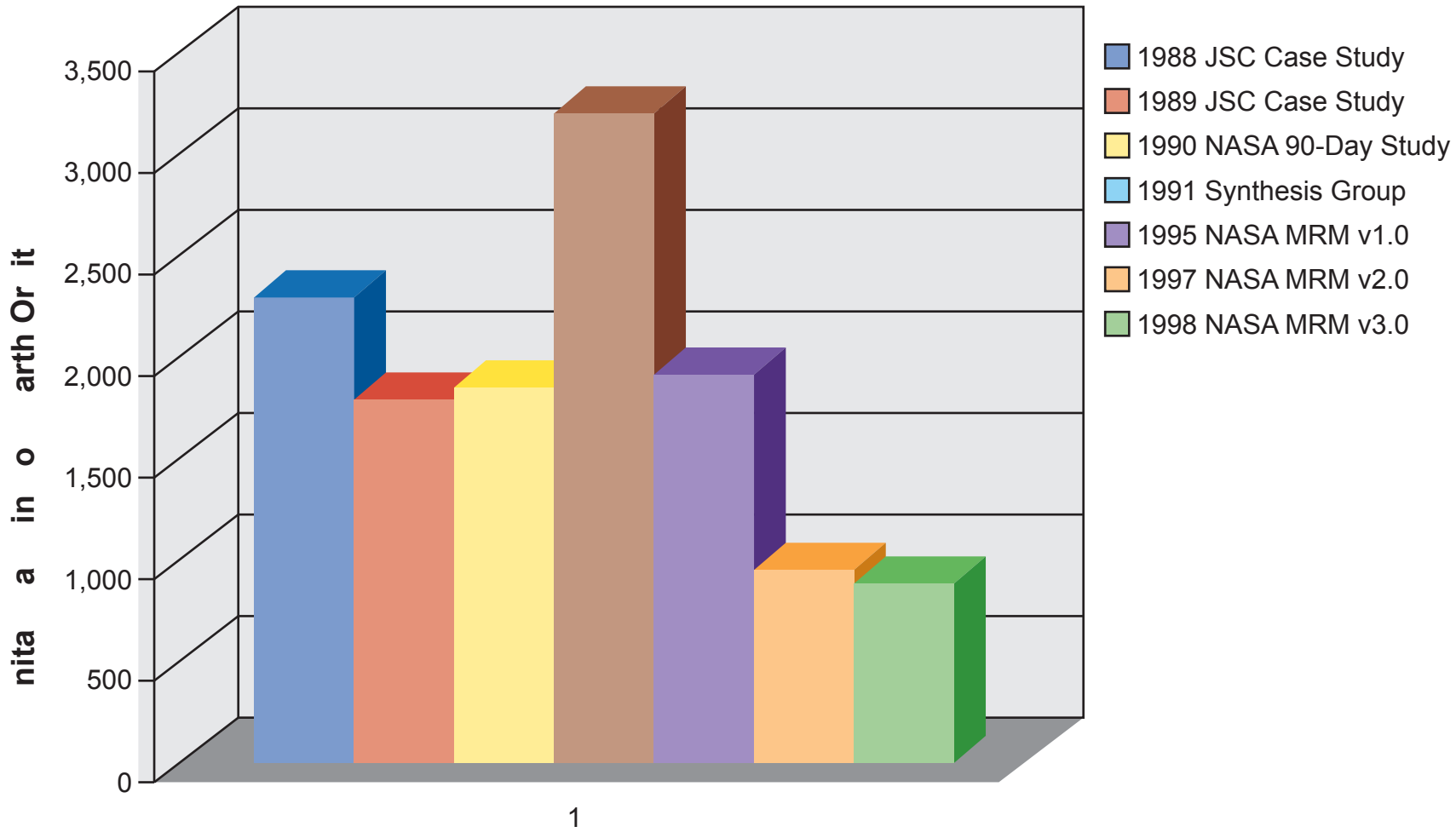


Groundrules & Assumptions - General

- **Timeframe studied: FY01 – 20:**
  - No new DDT&E starts until FY01.
  - To close economic analyses, examining payback out to 2030 (a representative life span of new launch systems).
- **NASA operated systems will not compete with private commercial services.**
- **Space launch policy and regulation changes (if any) will be documented**
- **The United States must be the primary lead for architecture development and operation, with international participation encouraged. (Non-US launchers available for commercial market.)**
- **"Assured Space Access" is desired, but not a requirement.**

Groundrules & Assumptions - Mission Model

- **Final architectures must meet the consolidated government/commercial mission model**
- **Sources for developing this mission model are:**
  - ISS Servicing – Baseline requirements for the Shuttle and a 25K lbs. to ISS RLV provided by LaRC. One CRV flight every three years is added beginning in 2004. One contingency flight per year is added to support unforeseen ISS needs.
  - NASA Scientific – Mission model in STAS guidelines.
  - Department of Defense – Air Force Space Command "National Mission Model" dated August 1998.
  - Commercial LEO – FAA Office of Commercial Space Transportation "LEO Commercial Market Projections," May 1998.
  - Commercial GTO – COMSTAC Commercial Mission Model Update, May 1998.
  - Emerging Markets – Commercial Space Transportation Study (CSTS), May 1994.
  - Exploration – Exploration Transportation Program Office at MSFC.

Groundrules & Assumptions - Mission Model (cont)

- **For component mission models that do not project launch rates to 2020, the launch rates for the last three years available will be repeated through 2020.**
- **Included only those transportation elements required to transfer people and cargo from the Earth's surface to final Earth orbit.**
- **Did not consider Bantam class missions.**
- **Did not consider foreign government payloads if those countries have an indigenous launch capability.**
  - Launch vehicle and payload classification for:
  - All GTO missions based on the COMSTAC methodology.
  - Commercial LEO vehicles developed using the FAA "LEO Commercial Market Projections."
  - US government LEO missions developed using the National Mission Model.
- **No emerging market flights occur until the price per flight is less than $1000 per pound, then vehicle which creates this market captures all available flights.**

Groundrules & Assumptions - Mission Model (cont)

- **Concerning multiple manifesting:**
  - No multiple manifesting of NASA Scientific and DoD payloads.
  - Multiple manifesting of LEO commercial missions built into the source material.
  - Multiple manifesting of GTO missions is performed for the large (i.e., 18 K lbs to GTO) vehicles.
- **Human exploration requirements are treated as a cost "excursion."**
- **All exploration vehicles (i.e., Magnum) have the same 80 metric ton lift capability.**
- **Commercial development of the magnum core vehicle was not explicitly expanded.**
- **If a launch system captures the mission weight requirement, assume it also captures the mission volume requirements.**
- **Shuttle, TSTO, and SSTO vehicles will use the new low cost upper stage for GTO missions.**

Groundrules & Assumptions - Mission Model (cont)

- The competitive marketplace is modeled on existing and future commercial ELVs and RLVs. Future vehicles must be in the development stage to be included in the competitor model. Capabilities and prices from the "International Space Industries Report (ISIR)," 8 Jun 98, supplemented with data from the AIAA "International Guide to Space Launch Systems," 2nd edition and selected briefings on EELV capabilities and prices.
- International competitor pricing structure fixed over time.
- The market capture models for the commercial and government markets assume rational competitor behavior based on the economic theory of the oligopoly market. The drivers for the market capture model are vehicle payload mass capability and price per flight.
- No more than 50% of the projected DoD EELV market is available to transition to a new launch vehicle to maintain alternate access.

Groundrules & Assumptions - Mission Model (cont)

- **Any new vehicle must take market share from existing competitors:**
  - For ISS missions, transition period is two years.
  - For all other missions, assumes five years to build customer base.
  - Initial market penetration is 20% and grows at a 50% rate.
- **Assumed market growth rate allows payloads to adapt to emerging launch system environments.**
- **Existing commercial launch services and architectures can satisfy all national launch requirements (i.e., NASA scientific, DoD, and commercial payloads) except ISS and human exploration.**

Groundrules & Assumptions - International Space Station

- **Will be operated through 2020.**
- **No major changes in ISS transportation until after initial construction is complete, including:**
  - No new systems.
  - No Shuttle commercialization.
- **Did not consider subsequent module change out/addition after initial construction complete.**
- **Did not consider crew rescue, except Crew Return Vehicle (CRV) rotation flights every three years. (CRV initially placed on-station in 2004 on a manifested ISS mission.)**
- **Did not consider CRV replacement flight after an emergency use.**
- **Did not consider any late or early cargo access requirements during ground processing.**
- **For crew rotation systems, assumed:**
  - Four rotation flights per year (starting in 2005).
  - Four astronauts being rotated per flight.

Groundrules & Assumptions - ISS (cont)

- Extra vehicular activity (EVA) capability on new systems and subsequent impacts on ISS not addressed.
- The Design Analysis Cycle (DAC) 6 traffic model was used.
- The station remote manipulator system will be used for cargo manipulation.
- ISS deorbit not a space transportation requirement, but a desired attribute.
- In the baseline, assumed international partners will continue to meet their launch and support obligations. Excursions captured in Mission Model sensitivity analysis.
- Small independent companies may be able to support ISS missions post 2010. (Just getting on their feet with small payload class missions now.)

Groundrules & Assumptions - EELVs & Human Exploration

- **The Evolved Expendable Launch Vehicle (EELV) "core" vehicle planned to be operational in 2001.**

- **Estimated EELV prices (in FY99 $s):**
  - EELV Medium - $65M
  - EELV Heavy - $140M
  - EELV Heavy + - $145M

- **EELV mission reliabilities (as provided by the Air Force) are:**
  - EELV Medium - 0.975
  - EELV Heavy - 0.970

- **Human space transportation (including to and from the ISS) is domestically a unique NASA requirement:**
  - For the Exploration Excursion, assumed it will be a Mars mission.
  - Identify architecture growth potential to enable human exploration for 2014 opportunity.
  - Mars exploration mission requires 80 metric ton lift capability.

Groundrules & Assumptions - Space Shuttle

- **Shuttle operational costs (as budgeted) are:**
  - $2.4B for 5-8 missions per year.
  - Missions 9 and 10 are $90M each.
- **Loss of vehicle failure frequency estimated at 1 in 500 (ascent only) and 1 in 250 for overall flight envelope; with mission success probability of 1 in 100 (i.e., 0.99) to deliver payload to correct orbit. (Phase III upgrades will increase mission success probability to 1 in 200, or 0.995.)**
- **Program termination costs will be included, if necessary (architecture dependent).**
- **No Shuttle Phase III upgrades except in those architectures recommending keeping the Shuttle until 2020.**
- **Assume all required Phase II/III upgrades are paid for out of existing operational baseline (i.e., $2.4B/year).**

Groundrules & Assumptions - Economic Analyses

- Costs were estimated with consistency valued above absolute accuracy.
- All funding information provided in constant FY99 dollars.
- Additional space transportation budget available is $160M in FY01 and $300M/year thereafter (in then year dollars).
- Architecture costs compared to a baseline consisting of budgeted Shuttle operational costs (i.e., $2.4B/year) plus additional available space transportation budget (described above) plus average NASA science mission launch costs (estimated at $325M/year).
- Previous study estimates used as a basis for Cost Estimating Relationships (CERs) to estimate new vehicles.
- New ways of doing business were assumed; i.e., Skunkworks development (rapid prototyping, firm requirements, single management authority, small technical staff, customers on-site, contractor inspections, limited outside access, timely funding, report only important work, simple drawing release).

Groundrules & Assumptions - Economic Analyses (cont)

- **Unreliability costs will be included in life cycle cost and economic analyses:**
  - Catastrophic unreliability cost will be estimated by adding the expected vehicle losses over the life of the mission model into initial fleet production and estimating the cost of downtime, investigations and fleet modifications as 2 months' net revenue and 25% of vehicle unit cost distributed on a per-flight basis. (Note: inclusion of these costs reflect self-insurance by the launch provider, and as such will replace the cost of commercially-obtained vehicle insurance.)
  - Mission unreliability cost, estimated as the cost of re-flight of unsuccessful missions, is a second-order cost and will not be included.
  - Economic impact of meeting JSC human-rating safety requirements will be quantified by extending flight test program and delaying revenues from ISS servicing missions.
- **Payload losses (i.e., dollars) are not factored into the cost of launch vehicle loss.**
- **Development cost spreads are:**
  - Four years using 60% cost / 50% time beta distribution.
  - HL-20, HL-42 and Crew Transfer Vehicle, and Cargo Carrier Transfer Vehicle are spread over six years.

Groundrules & Assumptions - Economic Analyses (cont)

- **Production costs are spread over three years using 30% / 40% / 30%.**
- **NPV benefits evenly distributed across entire US government, other customers, and launch contractors.**
- **For government funded investments:**
  - 10% discount rate for US government NPV calculations to measure economic worth of investments.
  - 10% is composed of 7% OMB real rate plus 3% inflation.
- **For industry funded investment**:
  - 25% hurdle rate (BTROE) required for "Wall Street" viability of commercial programs and to calculate commercial price per flight.
  - 14% debt interest rate, 40% debt ratio.
- **US government incentives applied to any program that enables phase-out of the Shuttle, including:**
  - $1B development assistance from NASA.
  - US government guaranteed loan (7% rate, 80% debt, and 10% fee scored on NASA budget).
  - ISS servicing advance purchase agreements from NASA.

Groundrules & Assumptions - Economic Analyses (cont)

- **Costs of government loan guarantees (i.e., 10%) are book kept against the NASA budget.**
- **Operations life cycle cost contributions performed using the KSC Architectural Assessment Tool (AAT - parametric model) which relies on multiple information sources including:**
  - The Access-to-Space Study Work Breakdown Structure that identified Space Shuttle operations cost elements (exclusive of STS Capability Development and Shuttle Production & Ops Capability).
  - The Shuttle Operations Zero Base Cost Study.
  - System attributes and priorities as defined in the Guide for the Design of Highly Reusable Space Transportation Systems and Appendix E of the HRST Study Integration Task Force Operations report titled An Operational Assessment of Concepts and Technologies for Highly Reusable Space Transportation.
- **Facility cost estimates generated by KSC AAT are discounted by 50% to reflect:**
  - Utilization of existing facilities versus new facilities.
  - Calibration to recent bottoms-up estimates (e.g., Reusable First Stage) and known programs (e.g., X-33).
  - Other management/engineering efficiencies.

Groundrules & Assumptions–Technical Risk Failure

- Technology Readiness Levels (TRLs) are required to be 6 or greater prior to system development decision:
  - Technologies will mature per Code R technology roadmaps.
  - Need for accelerating these technologies developments will be documented and priced.
  - Key technology developments beyond Code R roadmaps will be documented and priced.
- Following a successful experimental program:
  - An unconditional commitment has been made to continue with a specific architecture plan.
  - No decision points assumed to cancel or transfer to another architecture once development has begun.
- Technology base assumed constant and applicable across all architectural elements for simplicity; may not provide the optimum solution.
- Schedule and cost risk are treated as a functional of the technical risk.
- Integration is an exponential function of the weighted average of the critical technologies across these technology areas.
- Risk distribution can be formed by a linear combination of the integration complexity and development program duration.
- All system/vehicle performance requirements were met.

Groundrules & Assumptions - Mission Reliability

- **Main propulsion systems contribute a majority of the operational reliability risk.**
- **Premature engine shutdown failures are independent (i.e., no common cause failure).**
- **On-pad benign shutdown not counted against mission reliability.**
- **Loss of vehicle risk during an abort not considered.**
- **All crew escape modules (i.e., Crew Transfer Vehicles) will have a probability of survival of 0.99.**
- **Commercialization of any architecture element has no impact on mission reliability.**
- **Prior to transitioning to a new human transportation system:**
  - Fly the new system until JSC Human Rating Requirements are met. (Example – SAIC VentureStar study recommendation of 18 flights (minimum) before Shuttle transition begins.)
  - Shuttle transition will take 2 years after this point.

Constraints

- **Total of eleven weeks provided to complete the study (including three major holidays):**
  - Precluded detailed vehicle analyses; used currently available data and estimates.
  - Required examining architecture attributes based upon generalized representative element models. (For example, representative Single-Stage-to-Orbit vehicle vice all possible variants.)
  - Condensed 39 evaluation criteria down to smaller manageable set of highest priority required attributes.
- **Team not allowed to participate in contractor architecture studies, including the mid-term reviews.**
- **Study focused on ISS servicing as primary mission objective.**

Groundrules & Assumptions - Economic Analyses (cont)

- To model technical risk cost, authority to proceed (ATP) date established when all required technologies are estimated to be at TRL 6 or greater. The 50th and 80th percential delays were then added to the development program cost resulting in slipping the initial operational capability (IOC) date accordingly.

Groundrules & Assumptions - Catastrophic Failure

- **Main propulsion systems and TPS contribute a majority of the catastrophic failure risk for reusable vehicles.**
- **A catastrophic engine failure will result in immediate loss of the vehicle.**
- **Vehicle staging increases potential of the TPS damage and subsequent failure.**
- **Two contributions to crew loss:**
  - Geometric distance of crew module and source of failure.
  - Loss of vehicle probability.
- **Crew module survivability factor ranges from 0.8 to 0.99 based on a anology of military aircraft escape systems. The lower range includes out of the envelope aborts (I.e., ejections).**
- **The equivalent safe abort envelope for a crew module is at a geometric distance of greater than or equal to 30 meters.**

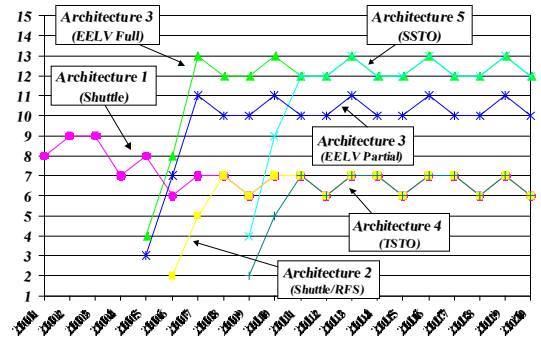
Market Analysis

Segment

ISS Servicing

- Marquee Vehicle Captures all Flights
- 2 Year Transition from Shuttle
- Linear Transition Rate

Demand Curve Assumption

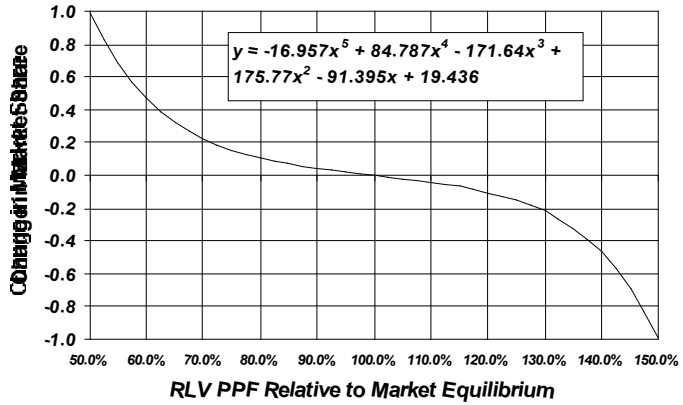


Summary Notes

- Two Vehicle Classes: Shuttle Equivalent and 25K lbs to ISS
- Crew Vehicle Performs Exploration Functions

Existing Commercial

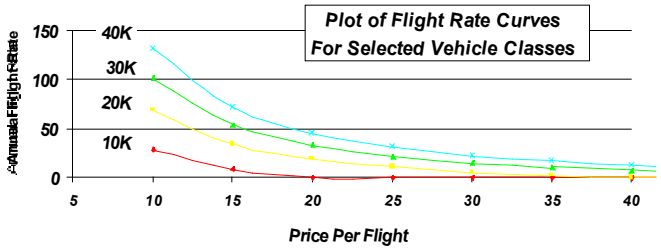
- Commercial GTO, Commercial LEO, DoD and NASA Scientific
- Competitors: Current and Future ELV's & RLV's
- Data from COMSTAC, FAA, DoD, NASA, ISIR, AIAA, EELV Companies



- Economic Theory of Oligopoly used to Determine Market Capture
  - At market equilibrium, competing vehicles share markets (1/N each)
  - Vehicle gains/loses market as price is set lower/higher
- Model Driven by Vehicle Capability and Price Per Flight

Elastic

- New (speculative) Business Opportunities
- Marquee Vehicle Captures all Flights
- Enabling Price: < $1000/lb.



- Summary Data from CSTS
- Demand curve derived from CSTS (but adjusted downward)
- Driven by Price and Vehicle Capability

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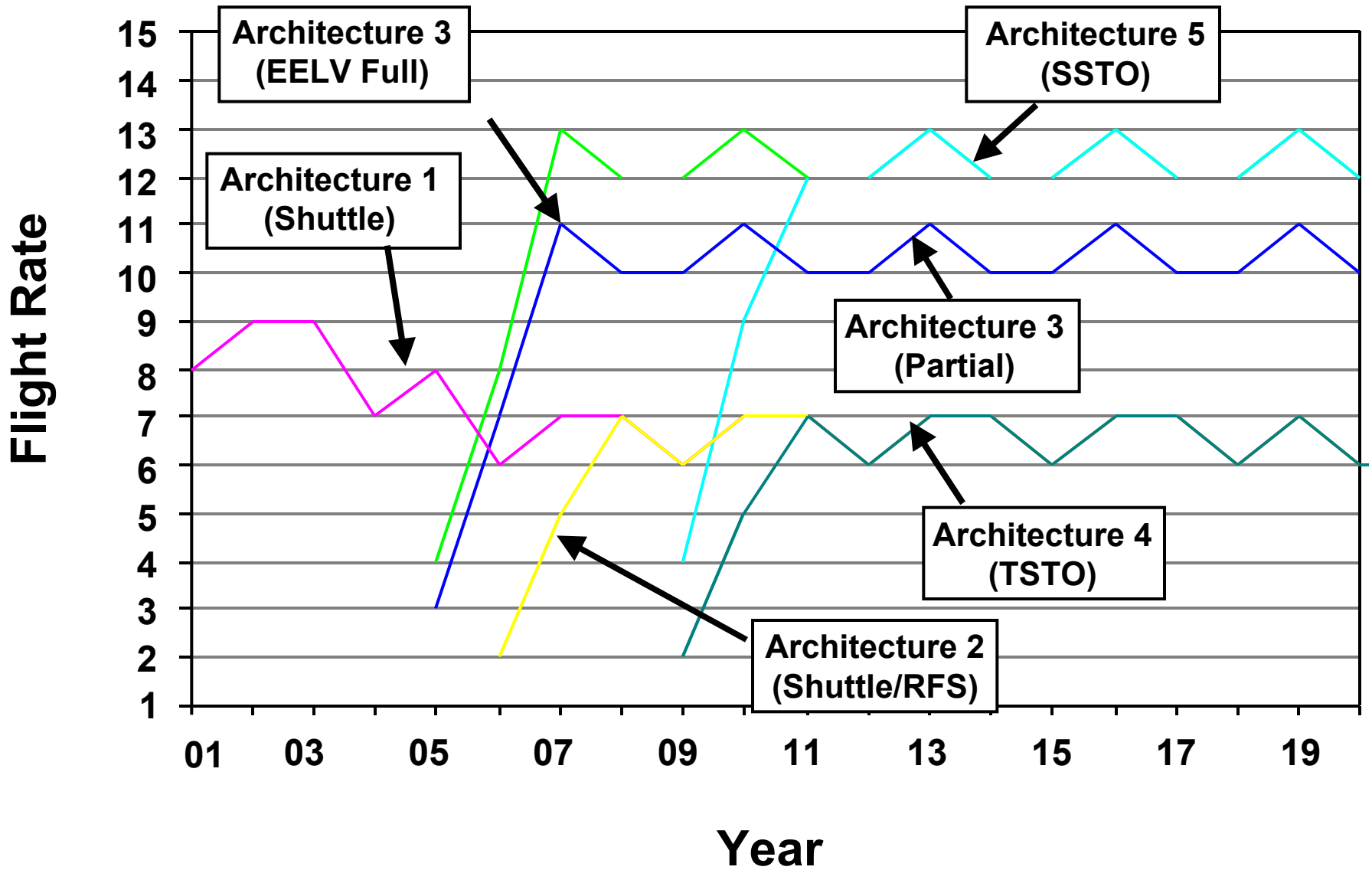
Government Funded Cases

Flight Rates



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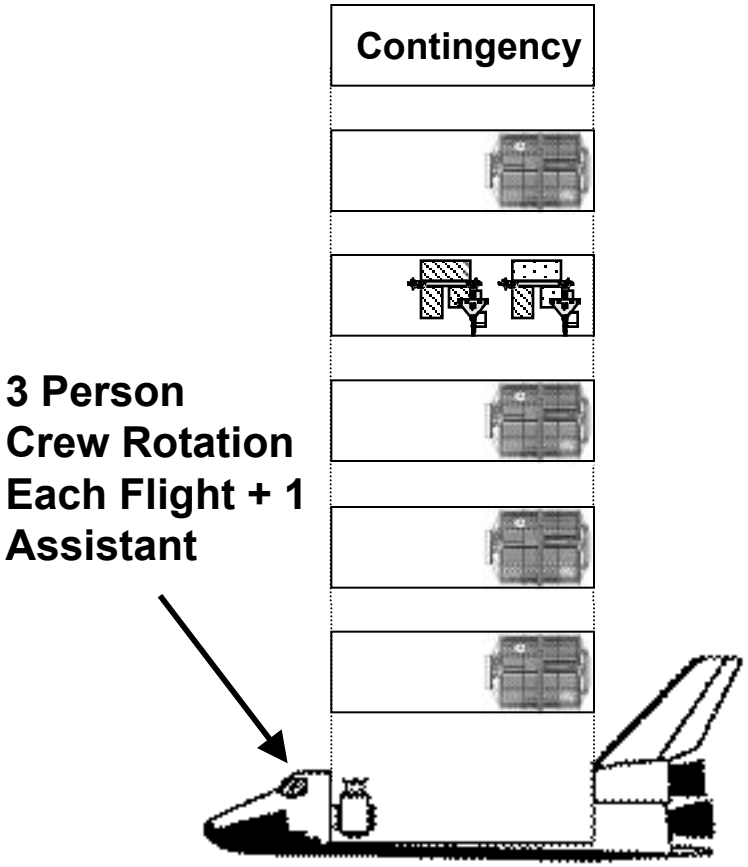
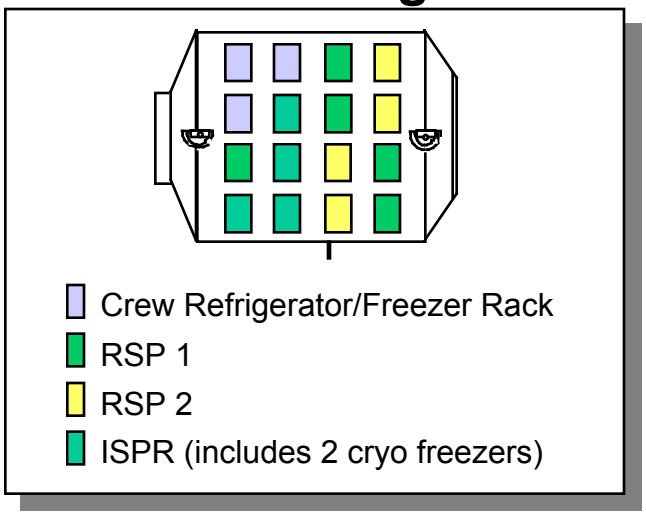
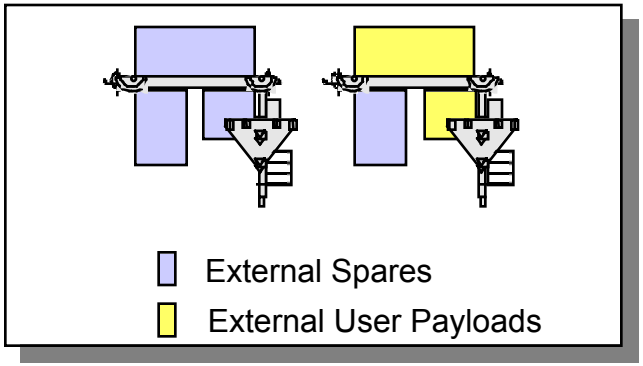
ISS Shuttle Mission Model



Pressurized Logistics

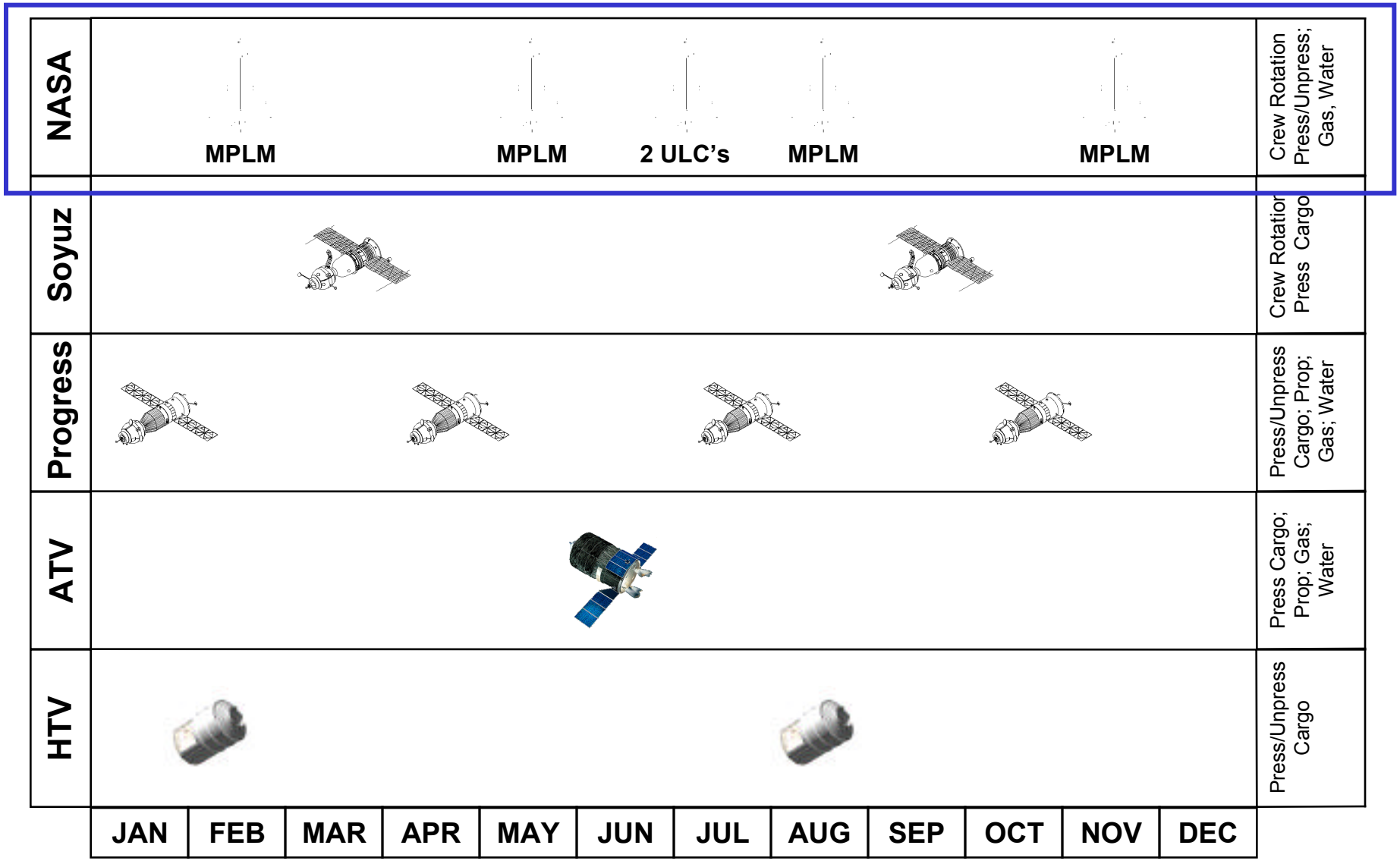


Unpressurized Logistics



Additional Flight Every 3 years Required for CRV Rotation

Shuttle Equivalent ISS Traffic Model



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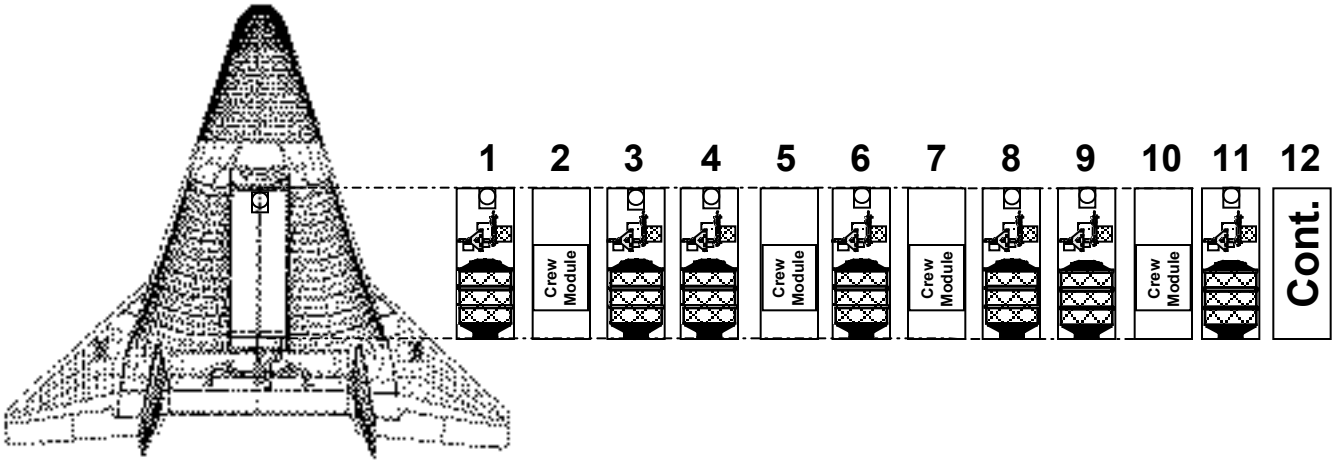
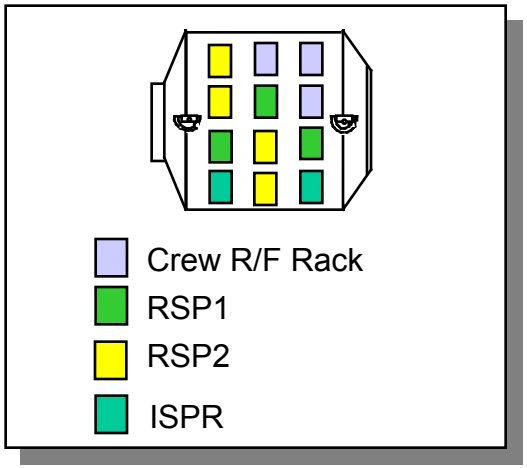
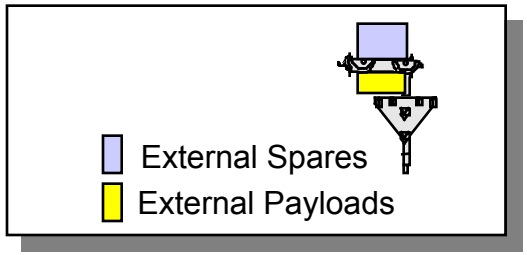
SSTO Flight Rate
Minimum Case



Pressurized Logistics

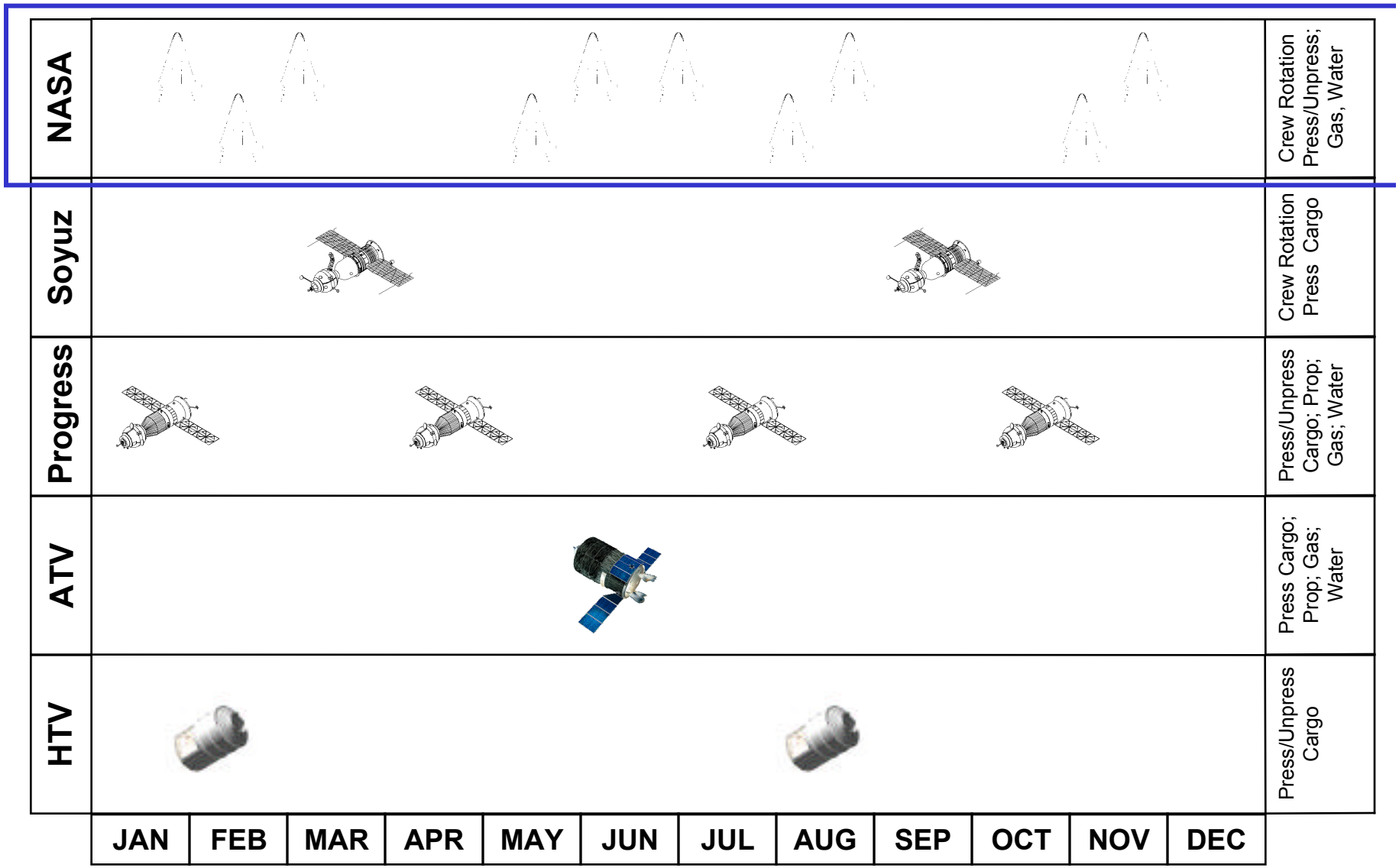


Unpressurized Logistics



Additional Flight Every 3 years Required for CRV Rotation

SSTO Equivalent ISS Traffic Model



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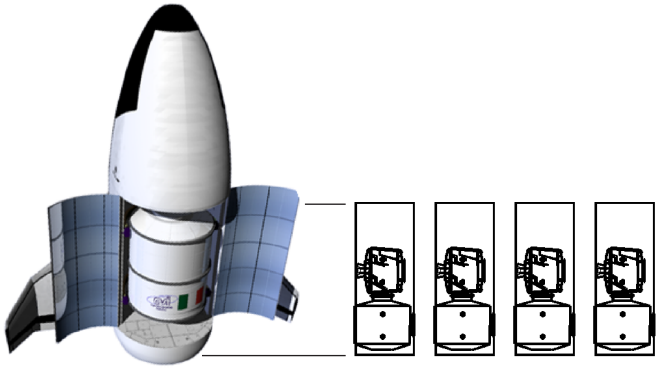
or CTV (4)



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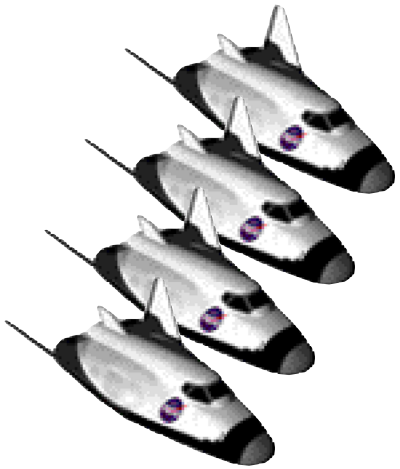
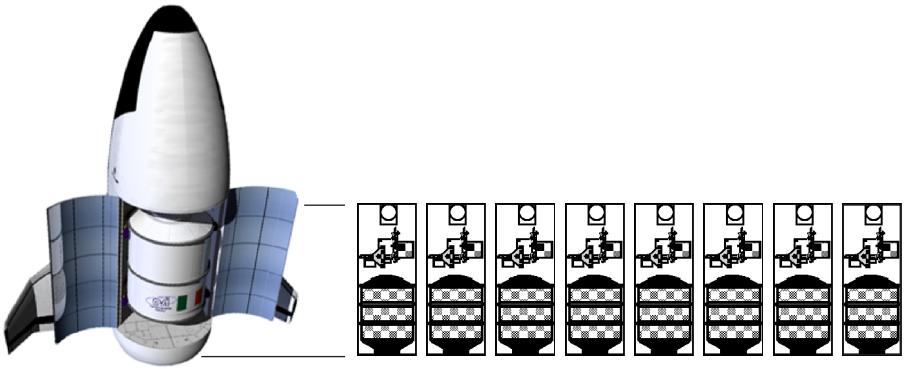


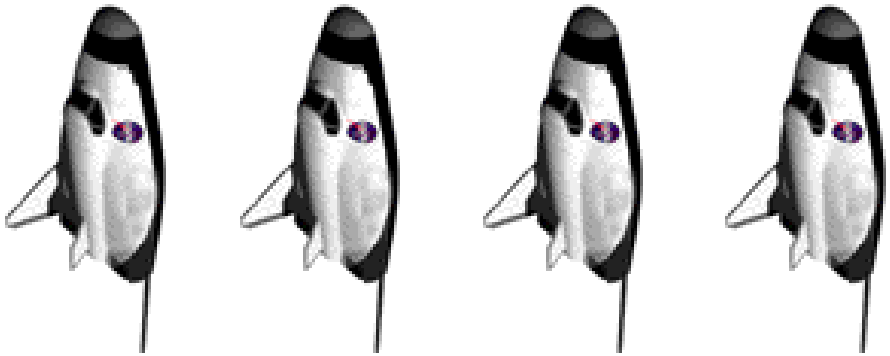
® **Cre e i ery eturn**
∑ CTRV with Press
and Unpress Log (8)



Additional Flight Every 3 Required for CRV Rotation

EELV Partial Downmass Flight Rate

Crew Rotation / ISS Payload Return
– CCTV (4)

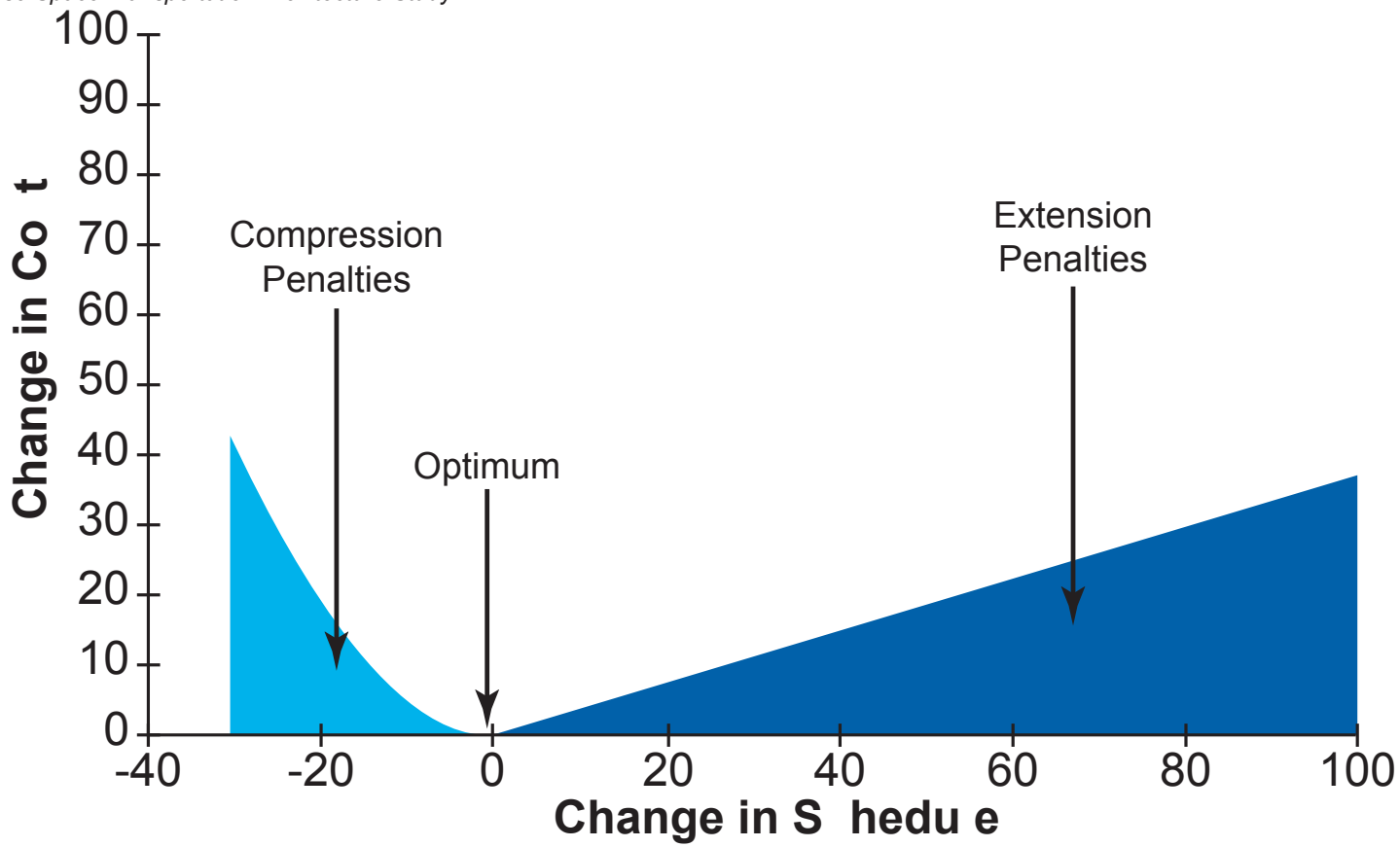


Pressurized Cargo
– ATV / MPLM (5)

Unpressurized Cargo
– ATV / 2 ULCs (1)

Additional Flight Every 3 years Required for CRV Rotation

Co t S hedu e Co re ion or e ay



- Technical risk analysis predicted the following schedule slips at 50% confidence level
  - STS/RFS 0.7 year slip
  - Bimese TSTO 0.7 year slip
  - Optimized TSTO 0.7 year slip
  - SST O 1.1 year slip

- Business analysis "costed" the slip using above "bathtub" function above plus delayed the initial operating capability

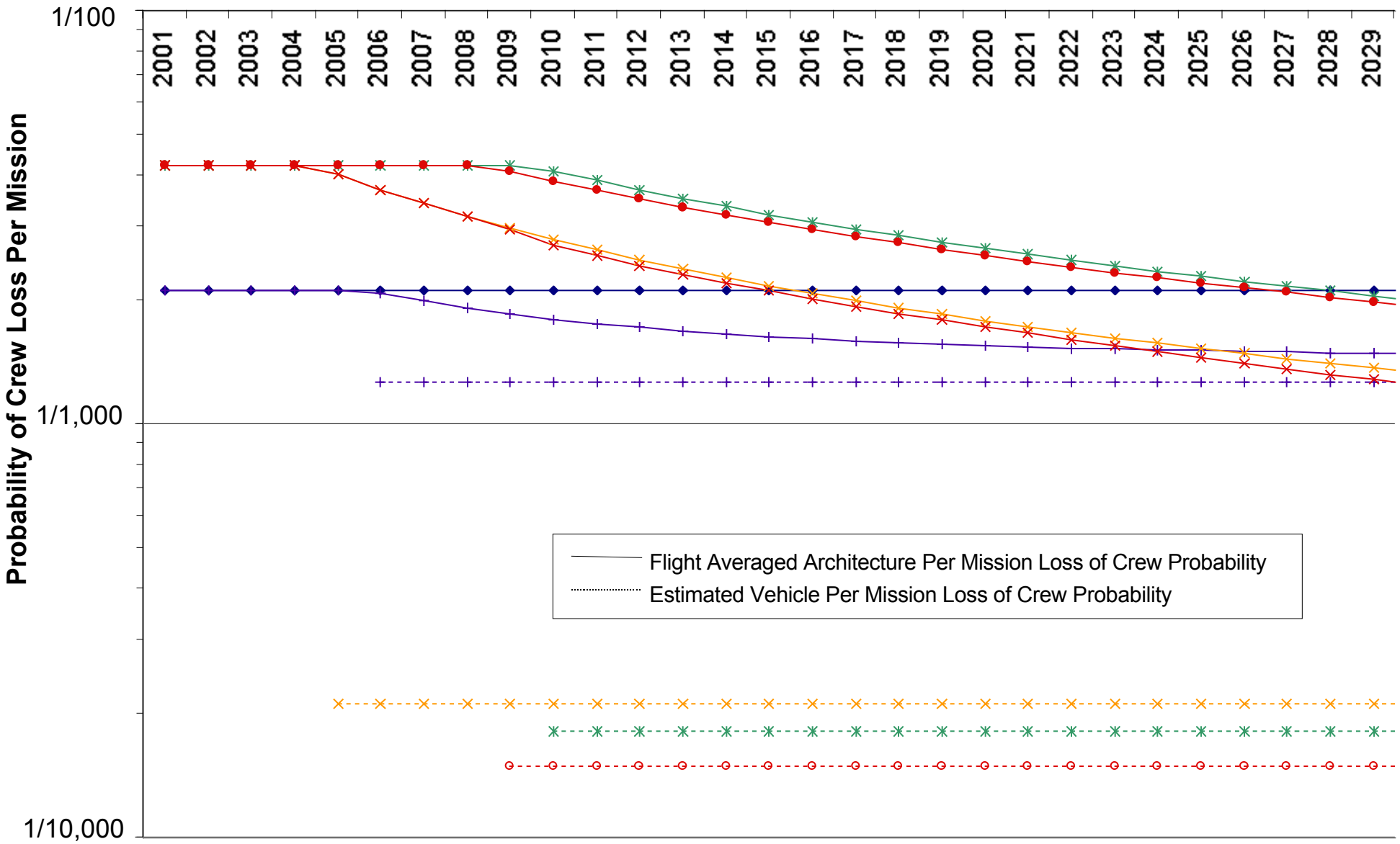
e ent e ia i ity ti ate

	N S	Or ita n ertion e ia i ity	Nu o i ion et een ai ure to Attain Or it	Cata tro hi ai ure ate O	Nu o i ion et een O	i ion e ia i ity	Nu er o i ion et een ai ure
	Ar hite ture e ent						
1	Shuttle with RSRB's	0.99	100	4.22E-03	237	0.9858	71
2	Shuttle with Phase III Upgrades	0.995	200	2.10E-03	475	0.9929	141
2A	Commercial Shuttle	0.995	200	2.10E-03	475	0.9929	141
3	Shuttle with RFS	0.995	200	1.26E-03	791	0.9937	160
4A	TSTO RFS w/small upper stage	0.9900	100	1.38E-03	7249	0.9898	99
4B	RFS Based TSTO	0.9944	177	8.95E-04	1118	0.9935	153
5C	Bimese Dual Mode	0.9965	284	8.64E-04	1157	0.9956	228
5D	Bimese Single Mode	0.9953	215	1.62E-03	617	0.9937	159
6	Optimized TSTO	0.9943	176	9.04E-04	1106	0.9934	152
7	SSTO (VentureStar)	0.9975	394	7.43E-04	1345	0.9967	305
9	• EELV - Medium	0.9750	40	2.50E-02	40	0.975	40
10	• EELV - Heavy	0.9700	33	3.00E-02	33	0.97	33
11	• EELV - Heavy+	0.9692	32	3.08E-02	32	0.969	32

Safety Results

	Crew Safety Comparison			
Element	No. of Missions Between LOV	CEV Survivability	No. of Missions Between Crew Loss	Improvement Factor Over Current Shuttle
1. Shuttle with RSRB's	237	N/A	237	-
2. Shuttle with Phase III Upgrades	475	N/A	475	2
3. Shuttle with Phase III & IV RFS	791	N/A	791	3
4. RFS Based TSTO	1118	0.8	5589	24
5. Bimise Dual Mode	1157	0.8	5780	24
6. Optimized TSTO	1106	0.8	5530	23
7. SSTO	1345	0.8	6725	28
8. EELV Heavy +	48	0.99	4750	20

Time Phased Safety Results



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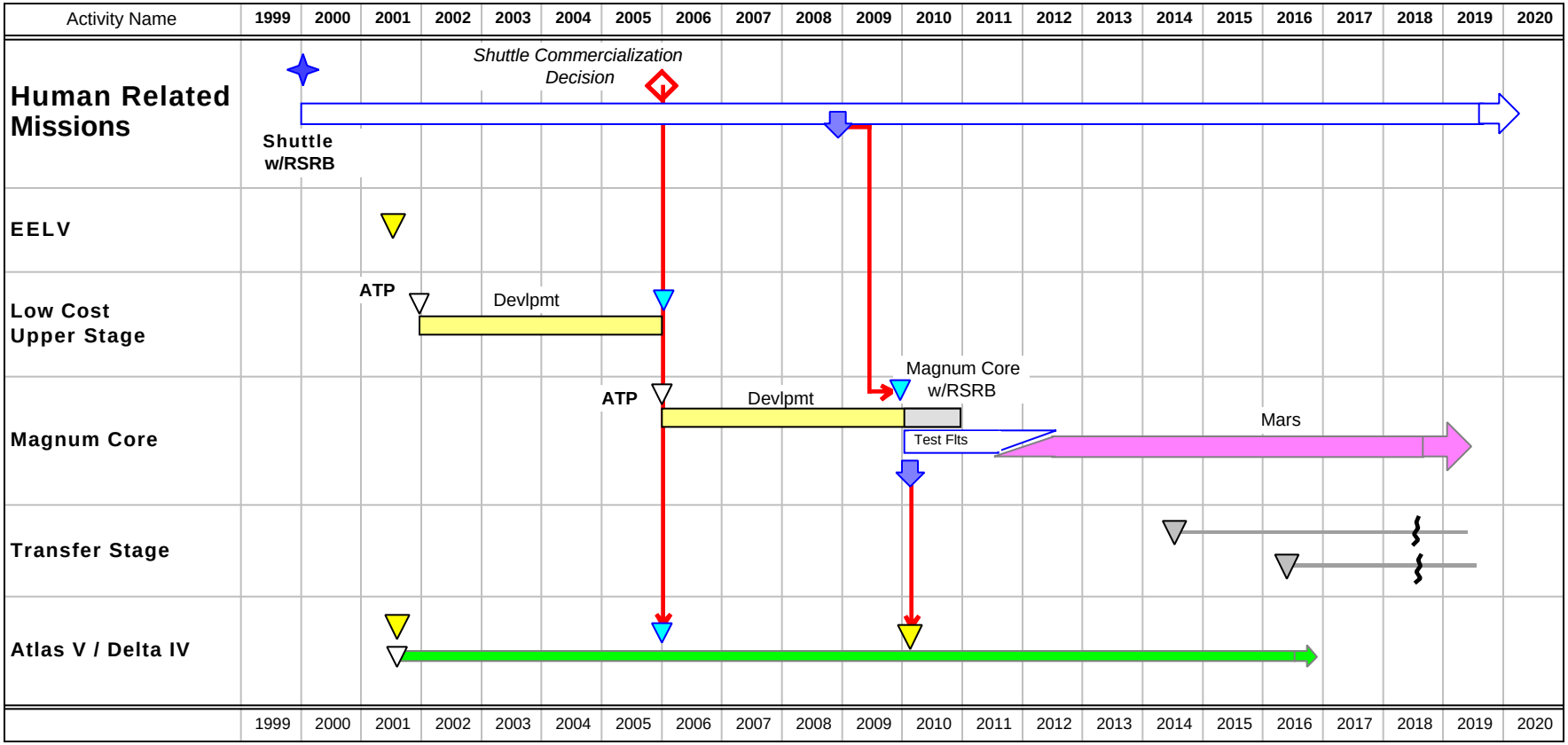
STAS Arch 1 RevA
Feb 4, 1999
2:21 PM

Architecture 1
Shuttle to 2020 Limited Upgrades

4 Feb 99



STAS Arch 2 RevA
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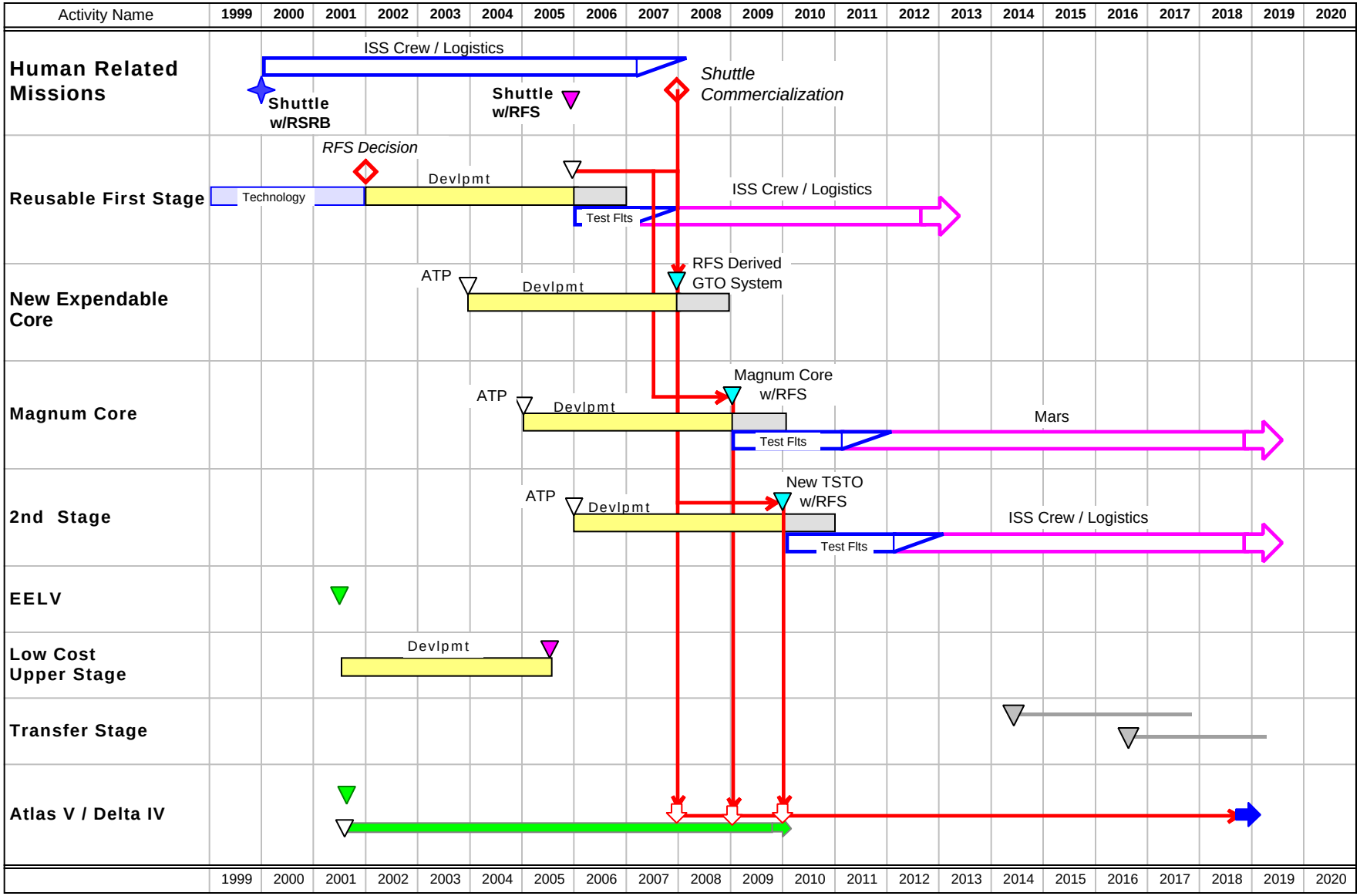
Architecture 2
Shuttle to 2020 - Significant Upgrades

4 Feb 98



STAS Arch 3 RevA
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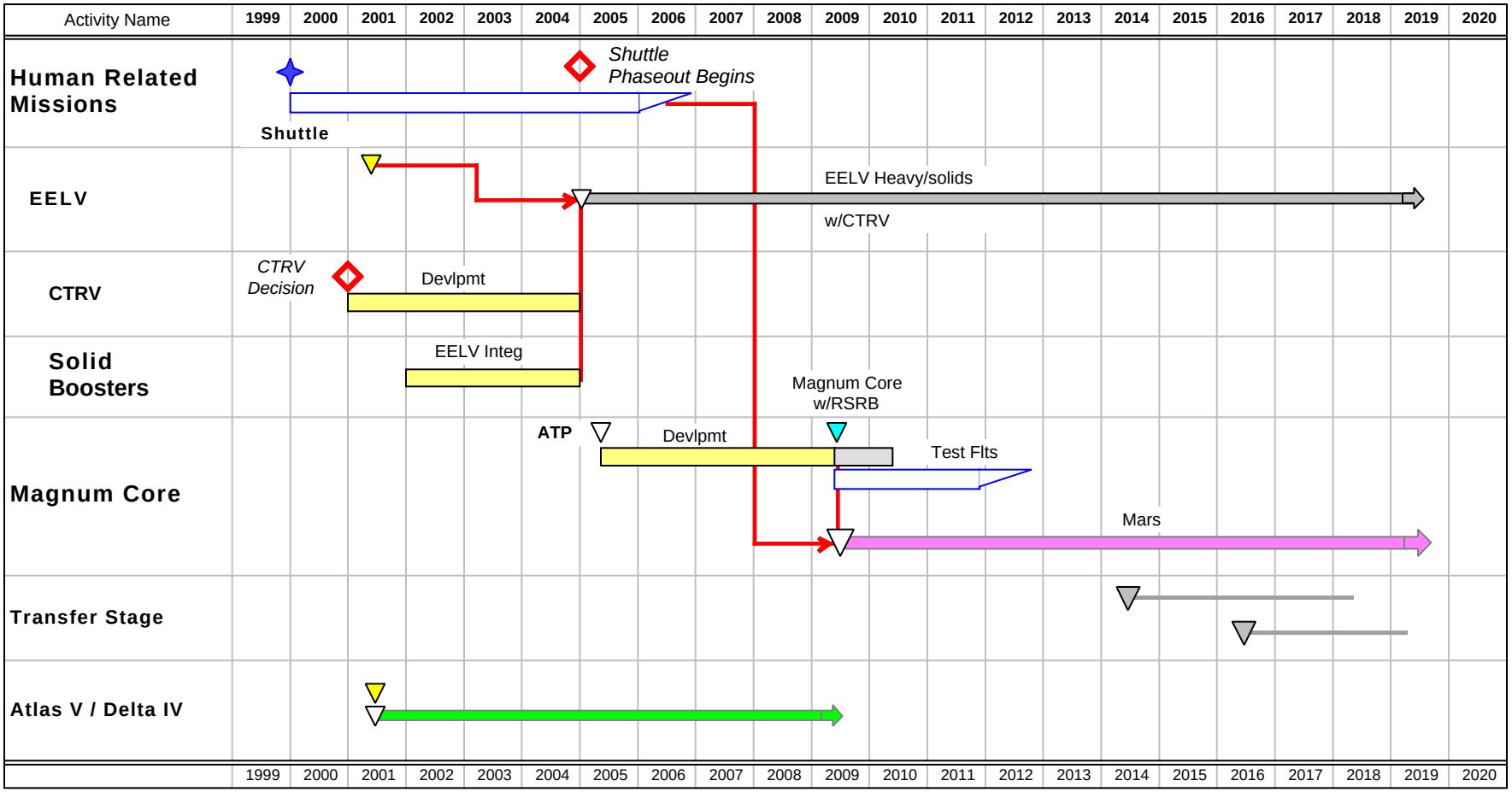
Architecture 3
Full ISS Downmass

4 Feb 99



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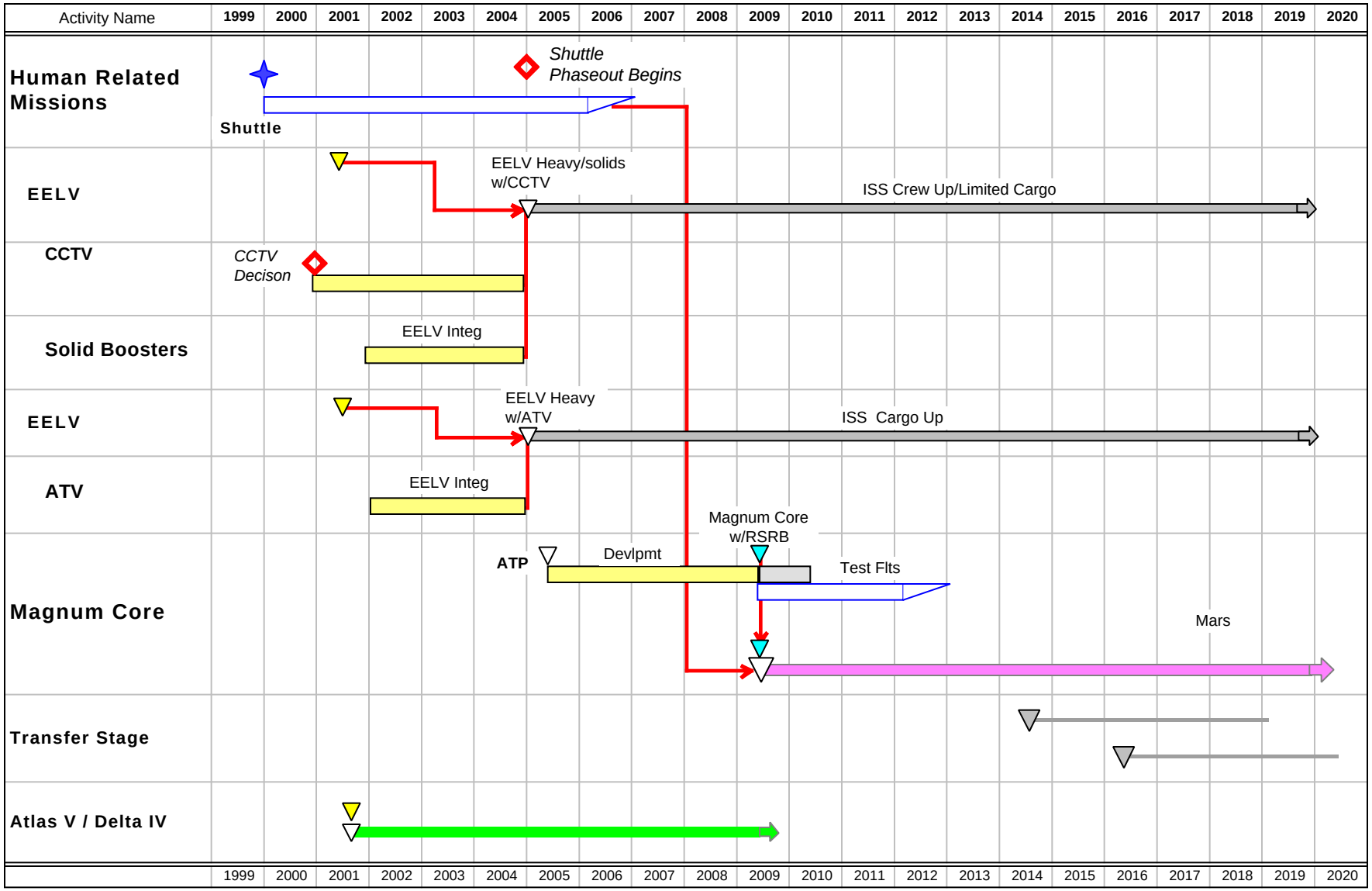
Architecture 3
Partial ISS Downmass

4 Feb 99



STAS Arch 4 RevA
Feb 5, 1999
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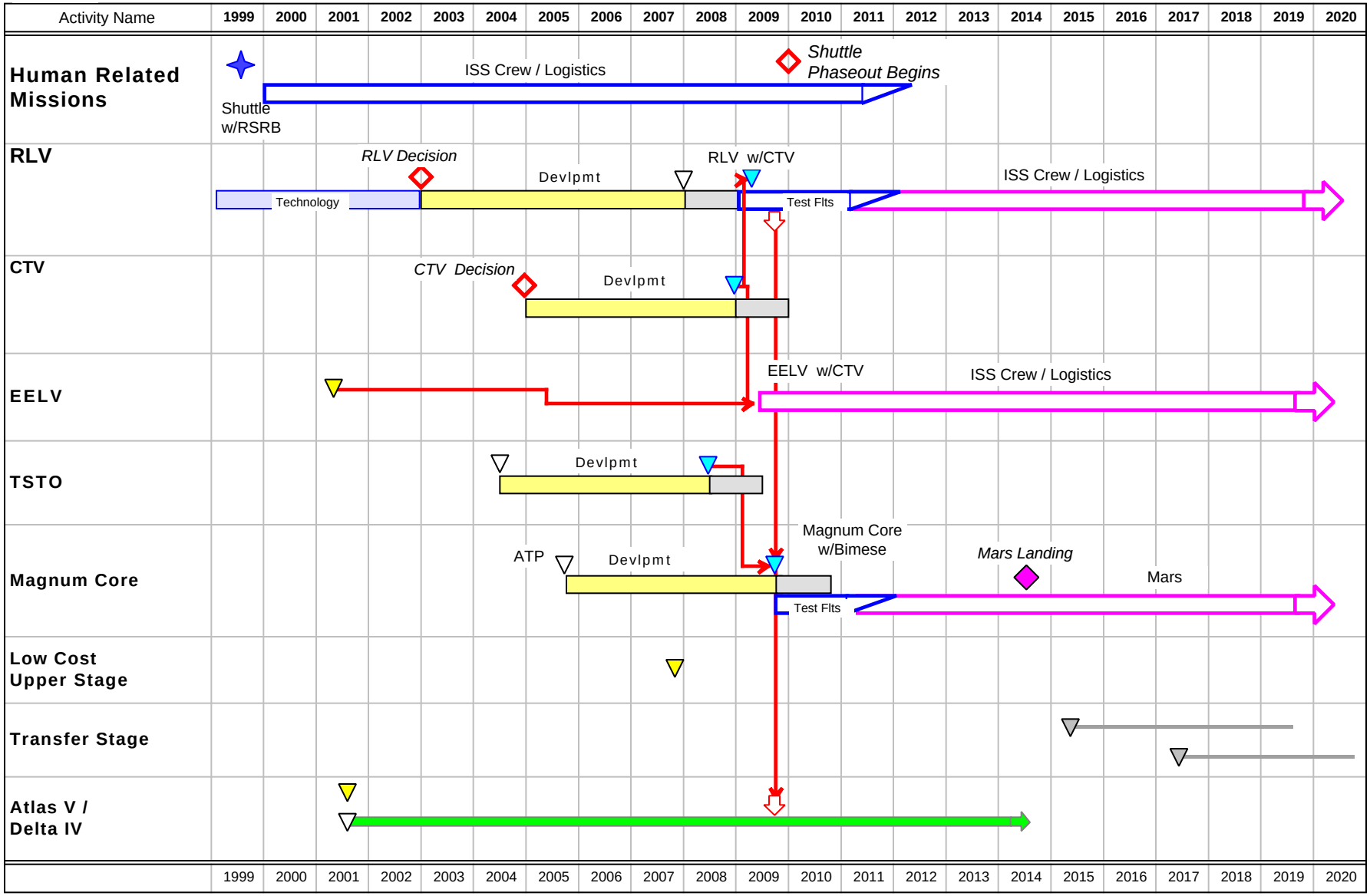
Architecture 4
New Reusable Launch System - TSTO

5 Feb 99



STAS Arch 5 RevA
Feb 5, 1999
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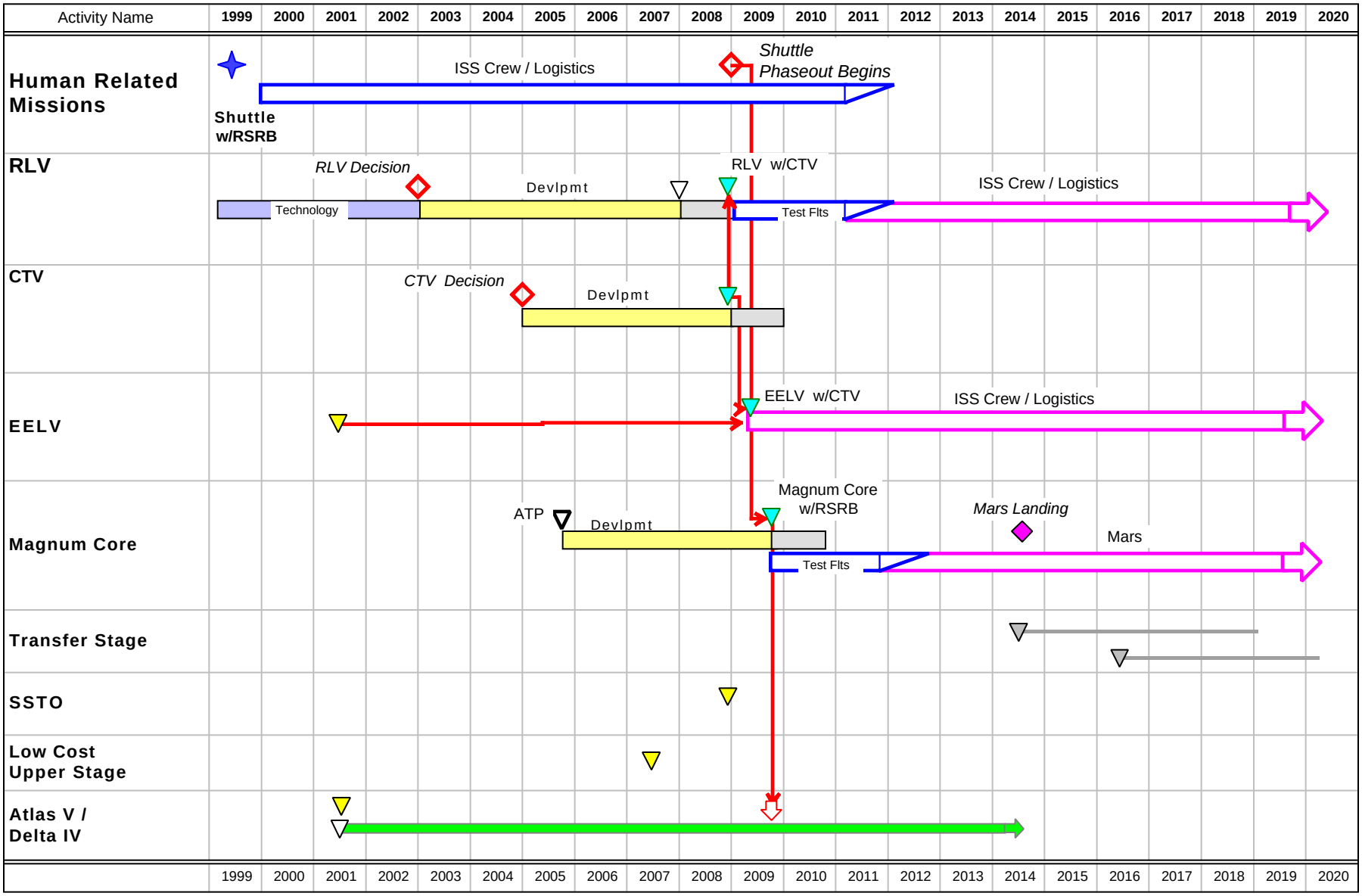
Architecture 5
New Reusable Launch System - SSTO

5 Feb 99



Architecture Economics Summary

All figures in $B99 except as noted	Arch #1	Shuttle	Arch #2	RFS	Arch #3	EELV PD	Arch #4	TSTO	Arch #5	SSTO
	2020	2030	2020	2030	2020	2030	2020	2030	2020	2030
Industry Incentive Case ($1B + loan)										
LCC Undiscounted	46.1	65.9	48.9	69.3	-	-	51.0	70.2	49.2	66.8
Co LCC Discounted at 10%	24.0	27.3	25.9	29.3	-	-	26.9	30.2	26.3	29.3
PYF (FY) / Dollars/lb. To LEO, Avg	3.2 (2003)	$3,400	3.9 (2003)	$3,350	-	-	3.5 (2005)	$1,400	3.5 (2005)	$670
ISS PPF / rate	$287M	7	$281	7	-	-	$209M	7	$100M	12
Com'l PPF / rate	$93M	4	$90M	5	-	-	$58M	16	$34M	50
Emerging PPF / rate	$86M*	0	$91M*	0	-	-	$42M	10	$27M	32
LCC Undisc. with Exploration	54.4	81.6	57.8	85.6	-	-	59.3	84.5	59.9	86.1
LCC Disc. at 10% with Explor.	27.1	31.7	29.2	33.9	-	-	30.2	34.4	30.4	34.8
Industry Case without Incentives										
LCC Undiscounted	52.2	76.6	57.5	84.1	-	-	64.3	95.1	66.3	101.6
LCC Discounted at 10%	26.1	30.2	28.9	33.4	-	-	31.5	36.8	31.7	37.7
PYF (FY) / Price/lb. To LEO, Avg	2.9 (2003)	$4,100	3.4 (2003)	$4,300	-	-	4.2 (2010)	$3,800	4.5 (2010)	$980
Industry Case @ USG 10% IRR	No Capitalization**		$1B Cap. (as above)				$3B Capitalization		$0.5B Capitalization	
LCC Undiscounted	48.1	69.8	49.1	69.5	-	-	49.1	65.0	49.8	68.3
LCC Discounted at 10%	24.4	28.1	25.9	29.4	-	-	26.8	29.5	26.3	29.5
PYF (FY) / Price/lb. To LEO, Avg	2.9 (2003)	$3,700	3.9 (2003)	$3,350	-	-	3.9 (2005)	$1,200	3.4 (2005)	$685
Government Funded Case										
LCC Undiscounted	49.4	71.5	52.5	73.3	59.3	81.8	54.6	67.8	52.5	63.2
Go LCC Discounted at 10%	25.5	29.3	28.5	32.0	31.8	35.7	30.7	32.9	30.2	32.1
PYF (FY) / Cost/lb. To LEO, Avg	3.4		4.5		4.5	$3,040	5.4		5.3	
LCC Undisc. with Exploration	55.5	82.0	58.2	83.0	71.7	102.9	60.8	78.3	62.0	81.0
LCC Disc. at 10% with Explor.	27.9	32.4	30.8	35.0	36.7	42.0	33.2	36.2	33.8	37.0
PYF with Exploration	3.4		4.5		4.6		5.8		5.7	
Exploration Change in LCC										
Commercial	8.3	15.7	8.9	16.3	-	-	8.3	14.3	10.7	19.3
Commercial Exploration Delta	3.1	4.4	3.3	4.6	-	-	3.3	4.2	4.1	5.5
Government-Funded	6.1	10.5	5.7	9.7	12.4	21.1	6.2	10.5	9.5	17.8
Government Exploration Delta	2.4	3.1	2.3	3.0	4.9	6.3	2.5	3.3	3.6	4.9

*Baseline case does not elicit emerging market response; values set in excursions

**IRR slightly higher than 10% with no capitalization; significantly lower without USG-guaranteed loan

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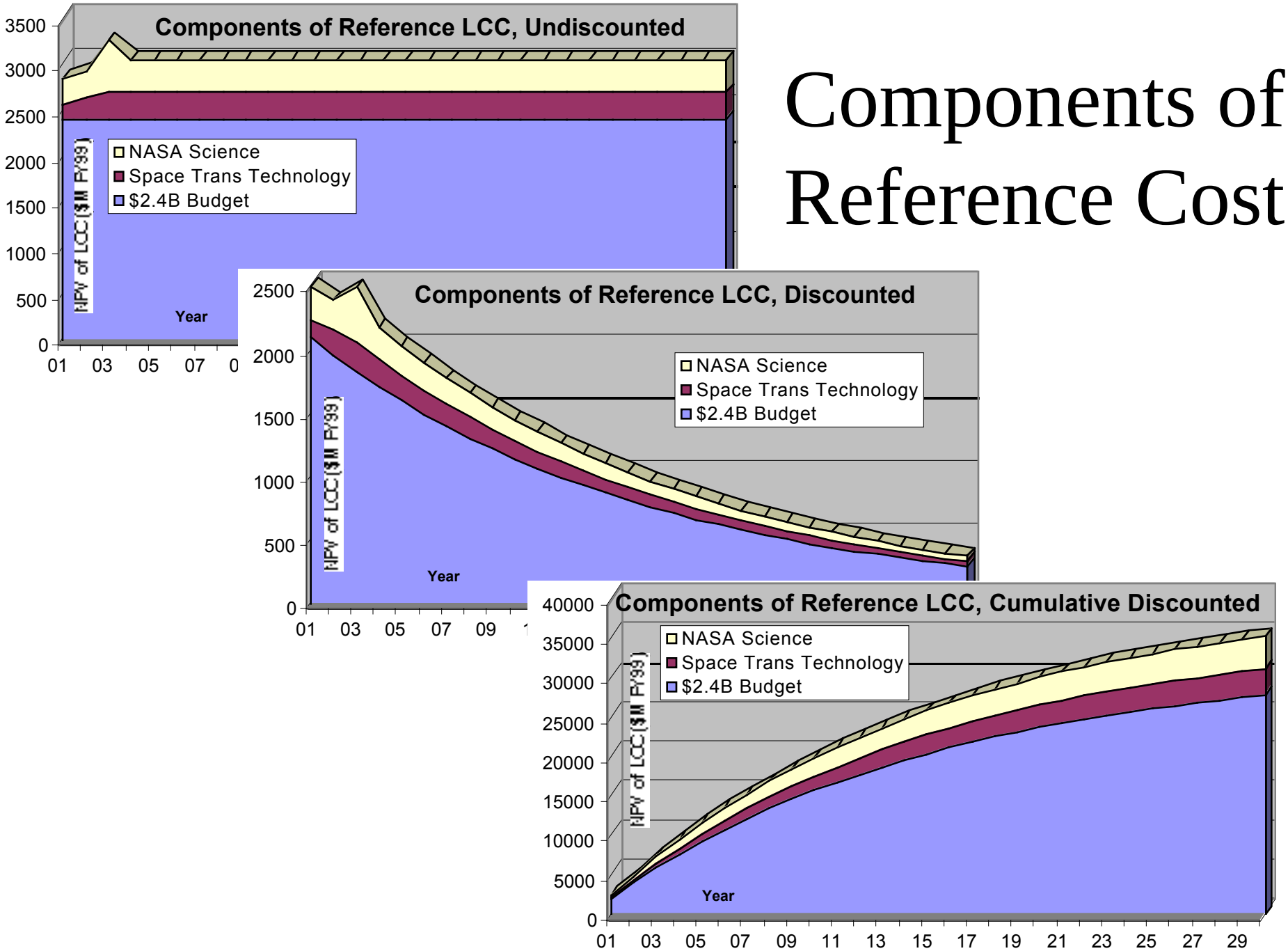
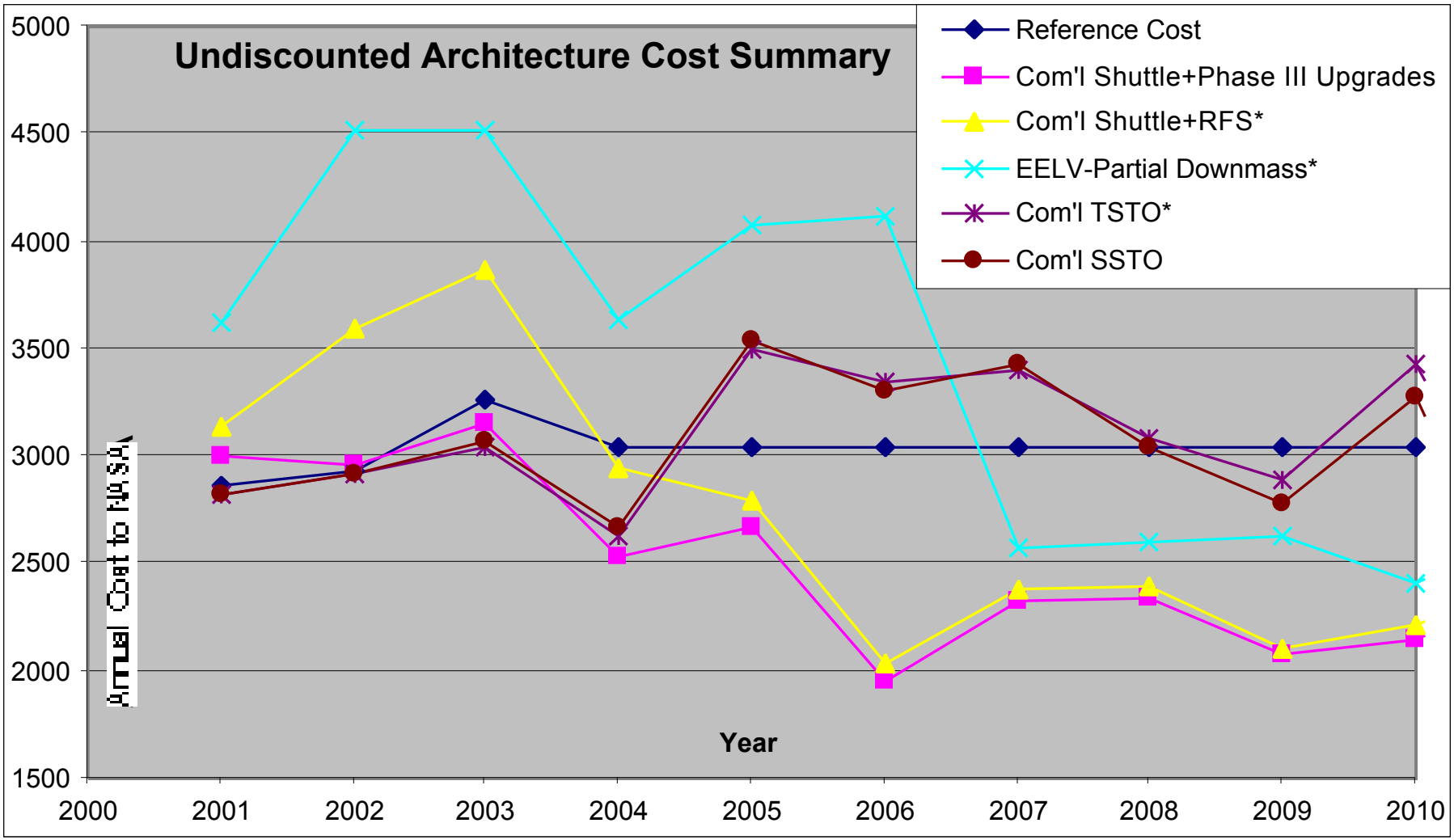
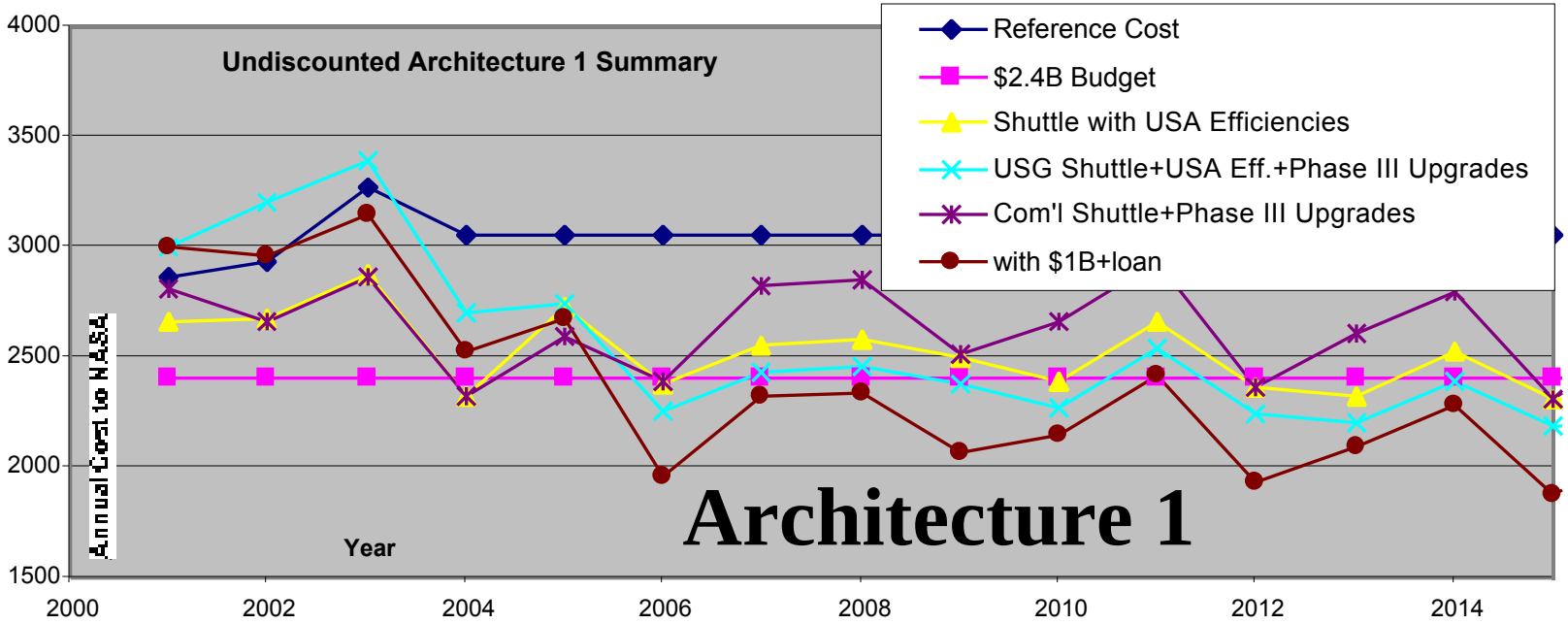
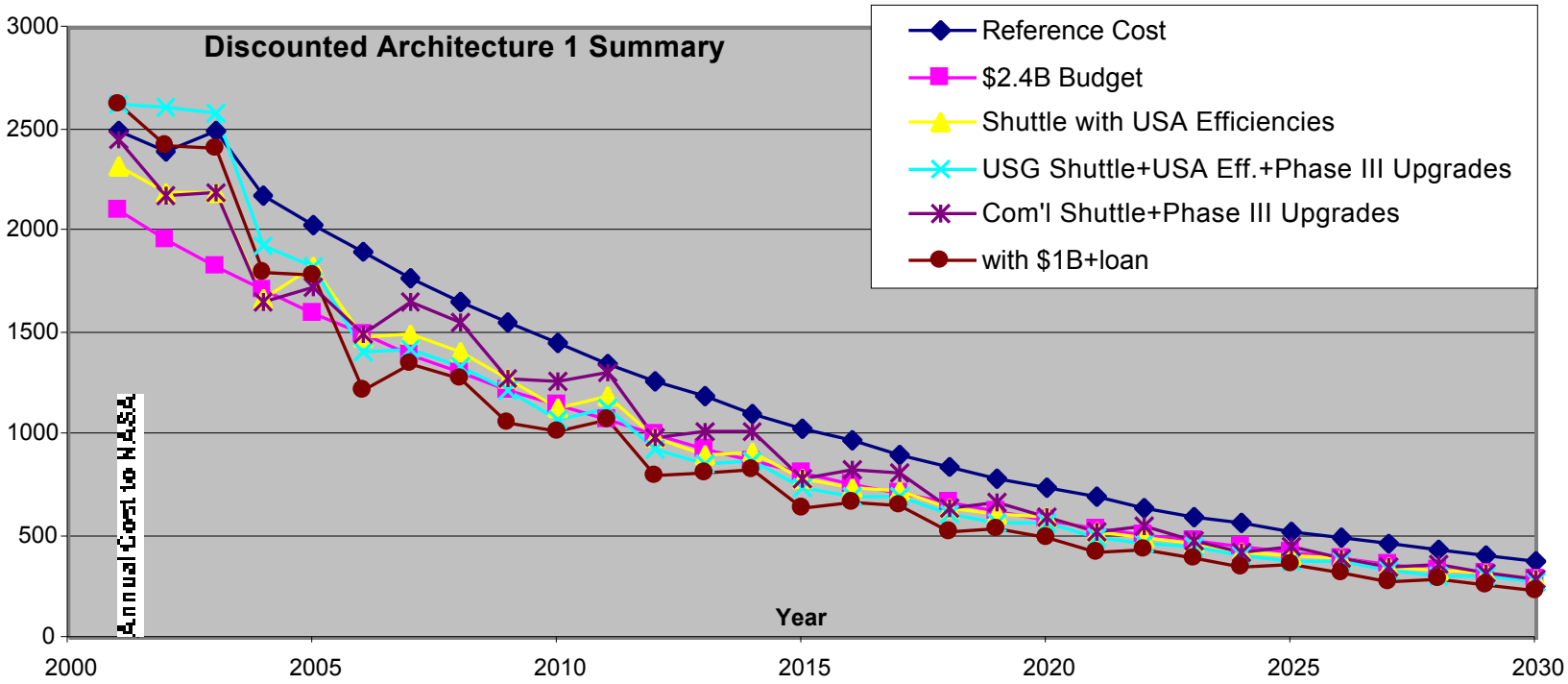
Components of Reference Cost



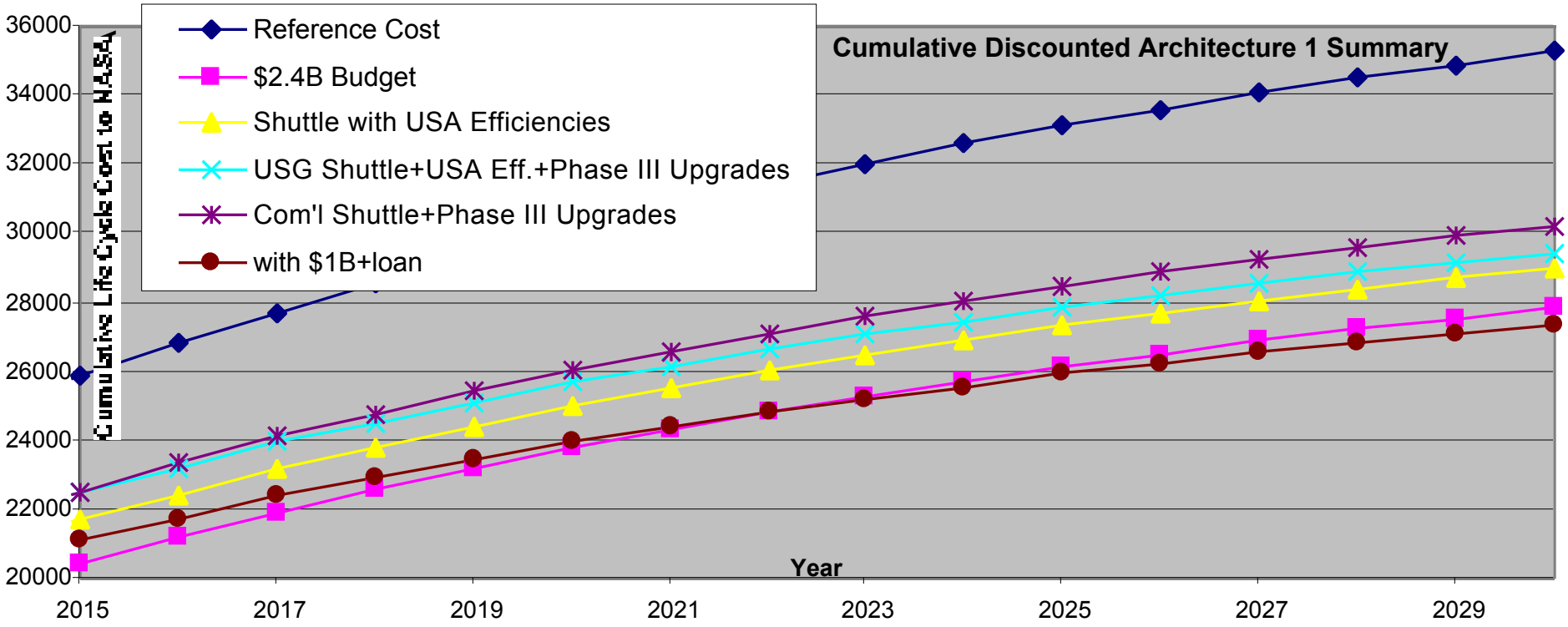
Undiscounted Architecture Summary, 2001-2010

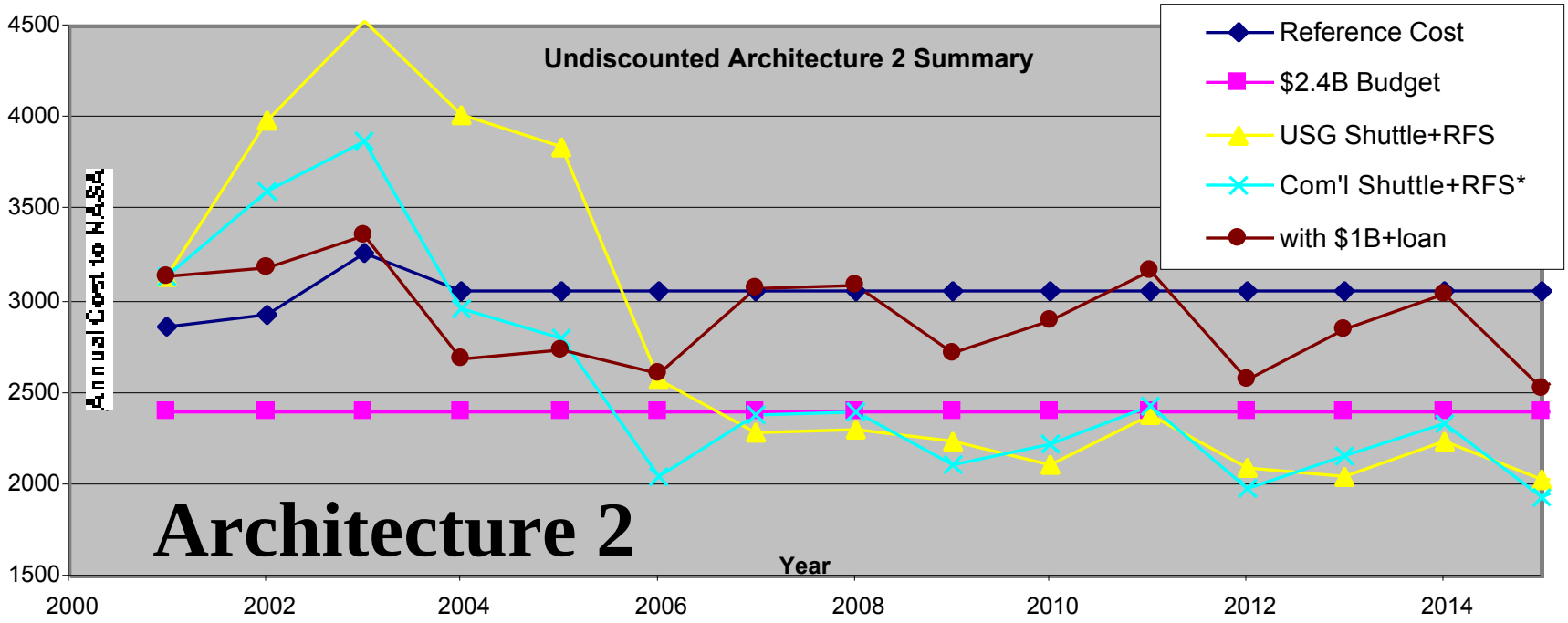


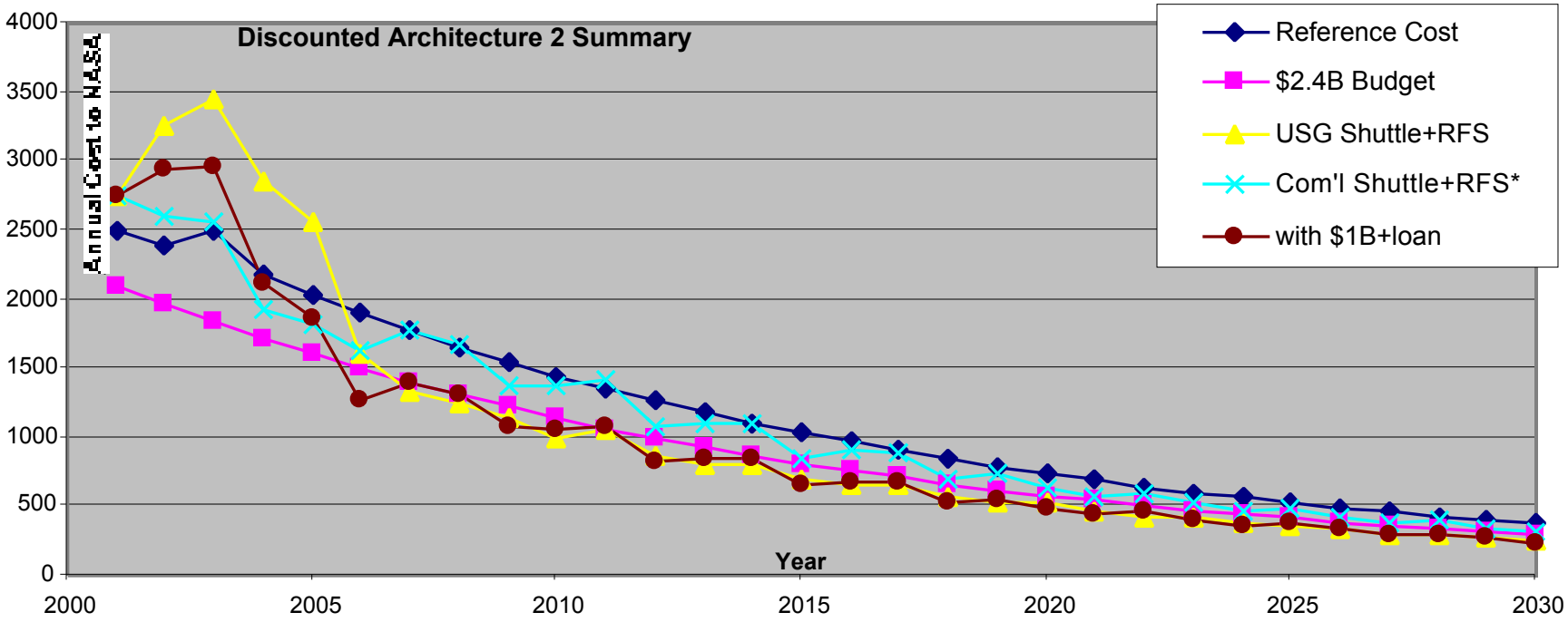

Undiscounted Architecture 1 Summary
Reference Cost
$2.4B Budget
Shuttle with USA Efficiencies
USG Shuttle+USA Eff.+Phase III Upgrades
Com'l Shuttle+Phase III Upgrades
with $1B+loan
Annual Cost to NASA
Year
Architecture 1
4000
3500
3000
2500
2000
1500
2000
2002
2004
2006
2008
2010
2012
2014


Discounted Architecture 1 Summary
Reference Cost
$2.4B Budget
Shuttle with USA Efficiencies
USG Shuttle+USA Eff.+Phase III Upgrades
Com'l Shuttle+Phase III Upgrades
with $1B+loan
Annual Cost to NASA
Year
3000
2500
2000
1500
1000
500
0
2000
2005
2010
2015
2020
2025
2030

Architecture 1




Undiscounted Architecture 2 Summary
Reference Cost
$2.4B Budget
USG Shuttle+RFS
Com'l Shuttle+RFS*
with $1B+loan
Annual Cost to NASA
Year
4500
4000
3500
3000
2500
2000
1500
2000
2002
2004
2006
2008
2010
2012
2014
Architecture 2


Discounted Architecture 2 Summary
Reference Cost
$2.4B Budget
USG Shuttle+RFS
Com'l Shuttle+RFS*
with $1B+loan
Annual Cost to NASA
Year
4000
3500
3000
2500
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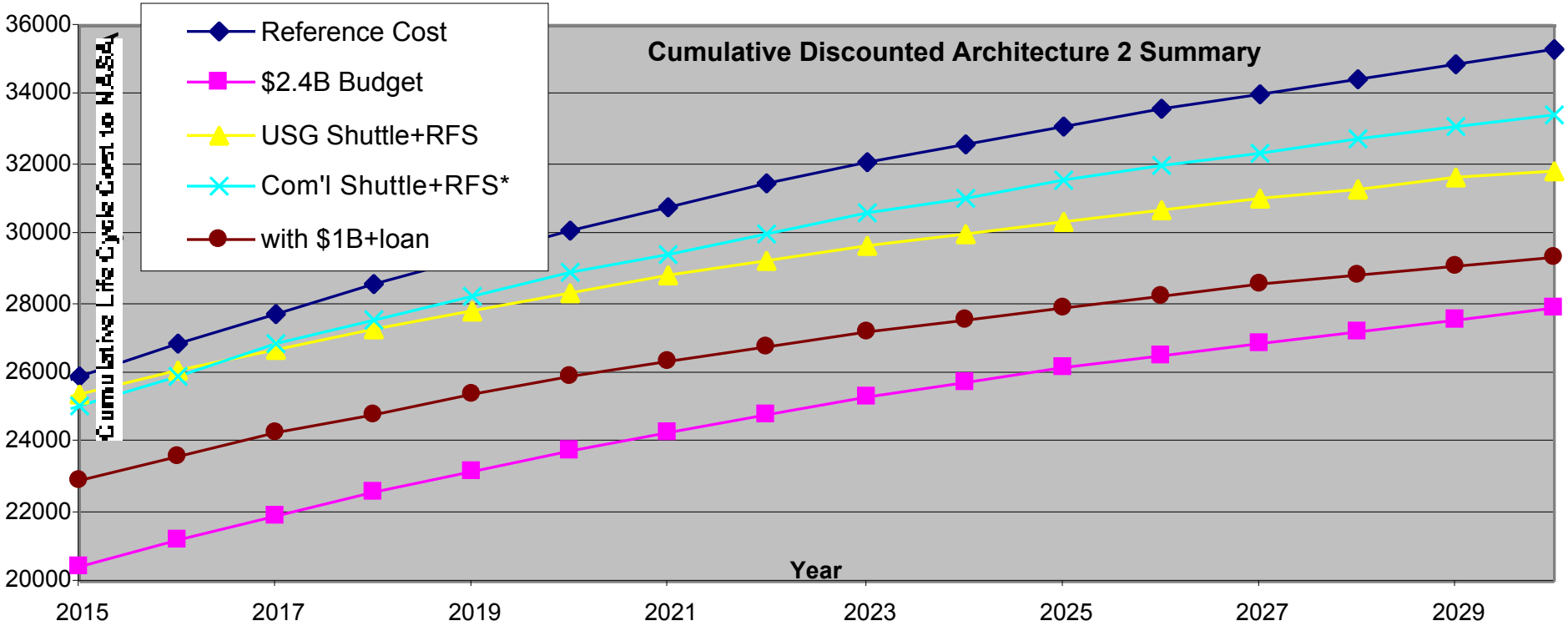
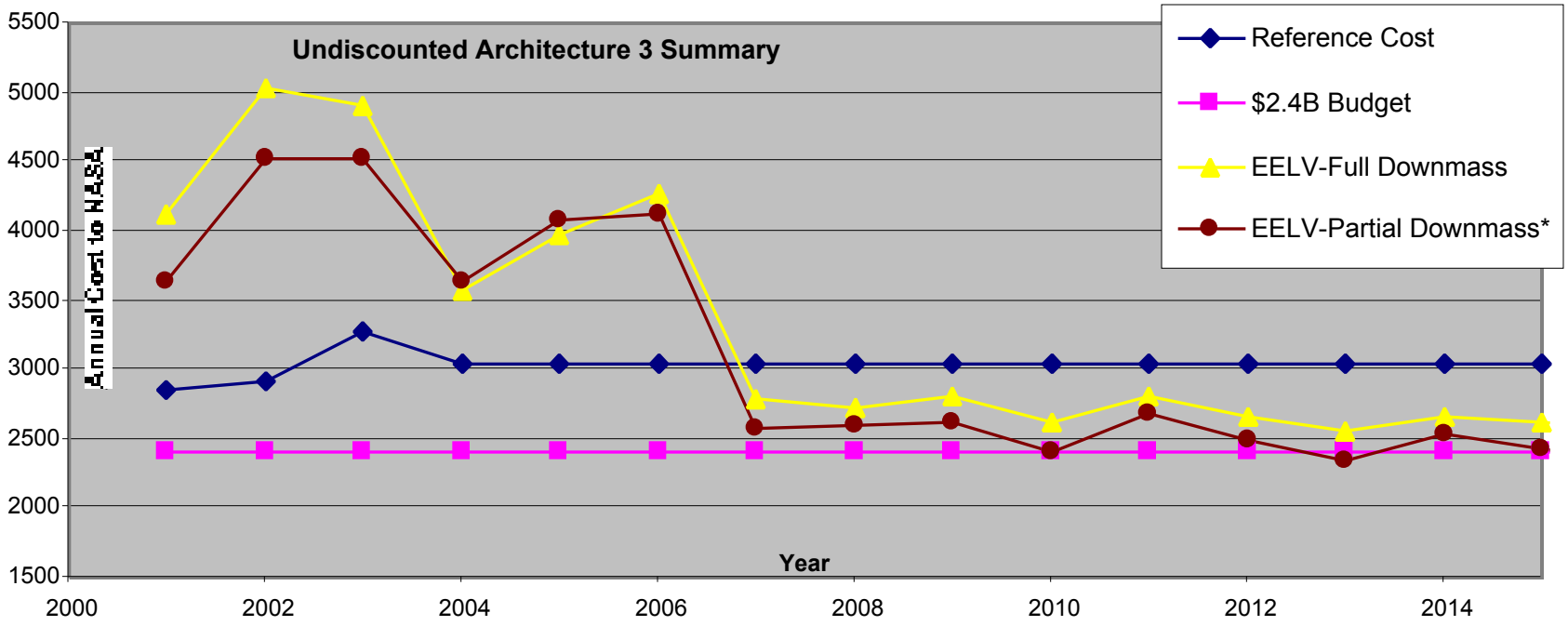
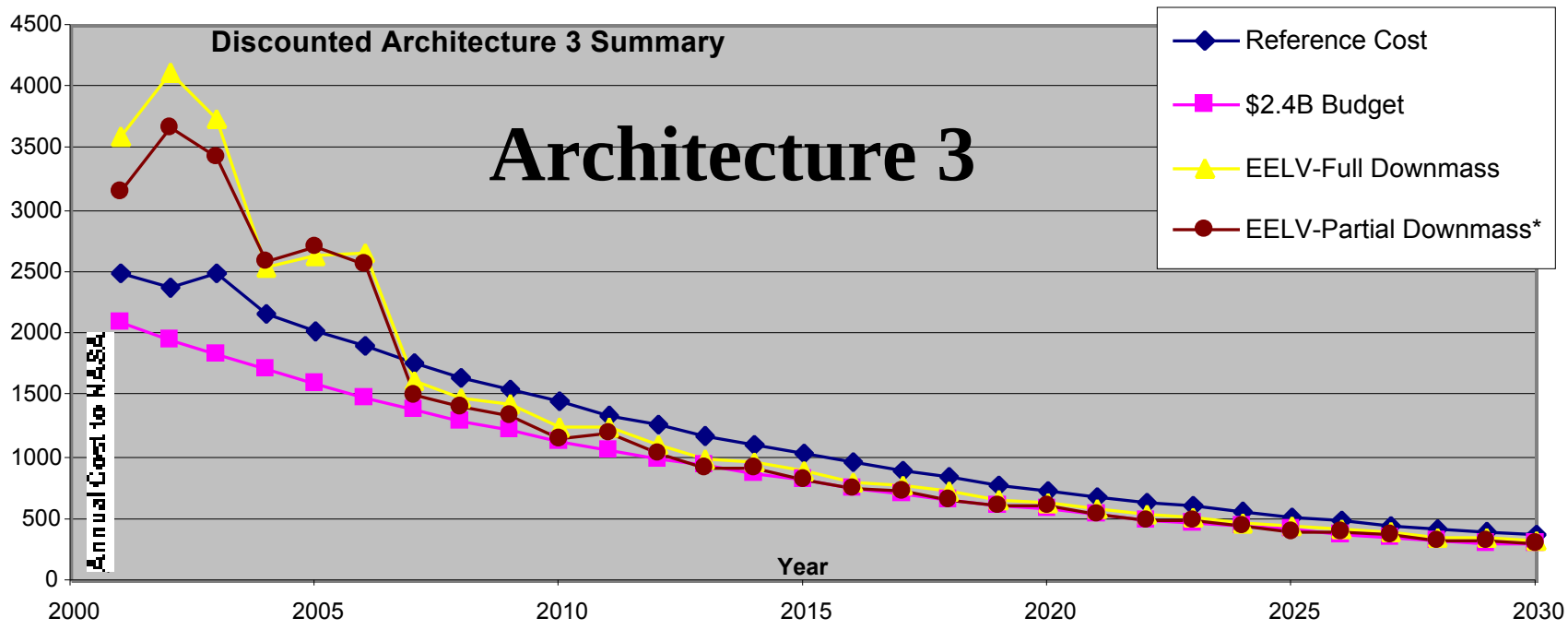
2000
2005
2010
2015
2020
2025
2030

Architecture 2




Undiscounted Architecture 3 Summary
Annual Cost to NASA
Year
5500
5000
4500
4000
3500
3000
2500
2000
1500
2000
2002
2004
2006
2008
2010
2012
2014
Reference Cost
$2.4B Budget
EELV-Full Downmass
EELV-Partial Downmass*


Discounted Architecture 3 Summary
Architecture 3
Annual Cost to NASA
Year
4500
4000
3500
3000
2500
2000
1500
1000
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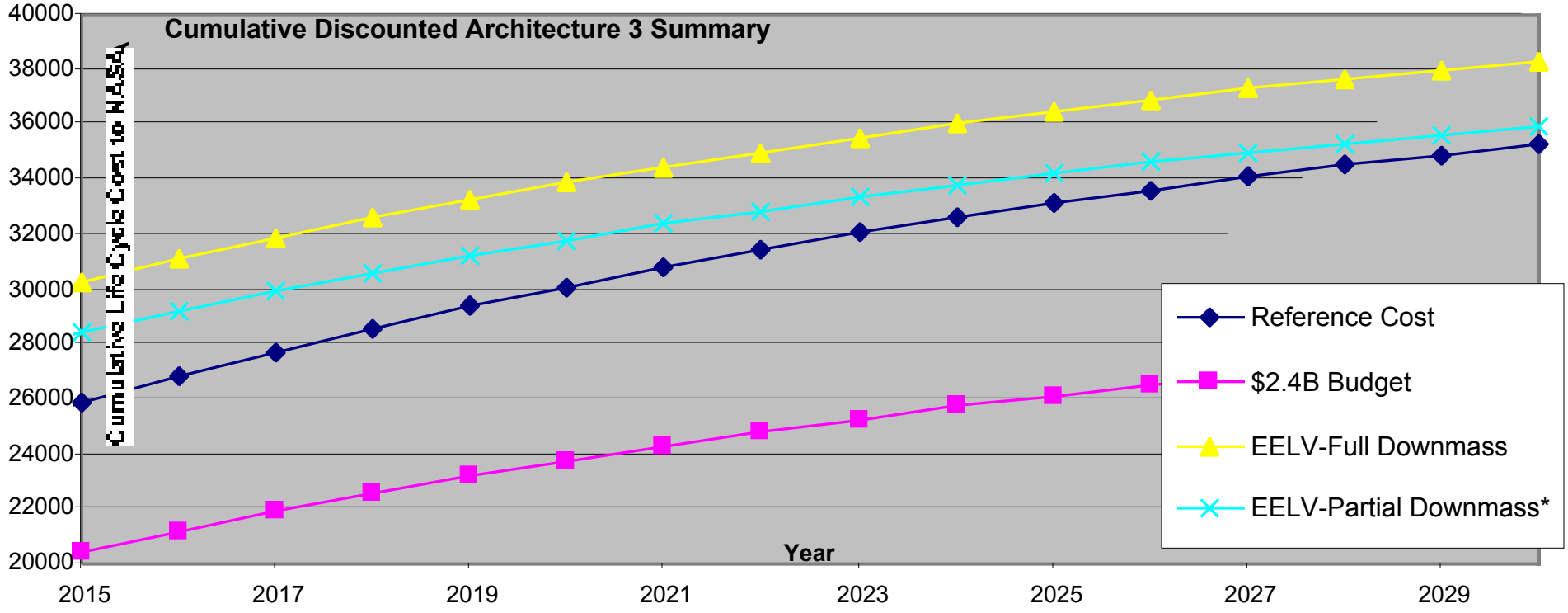
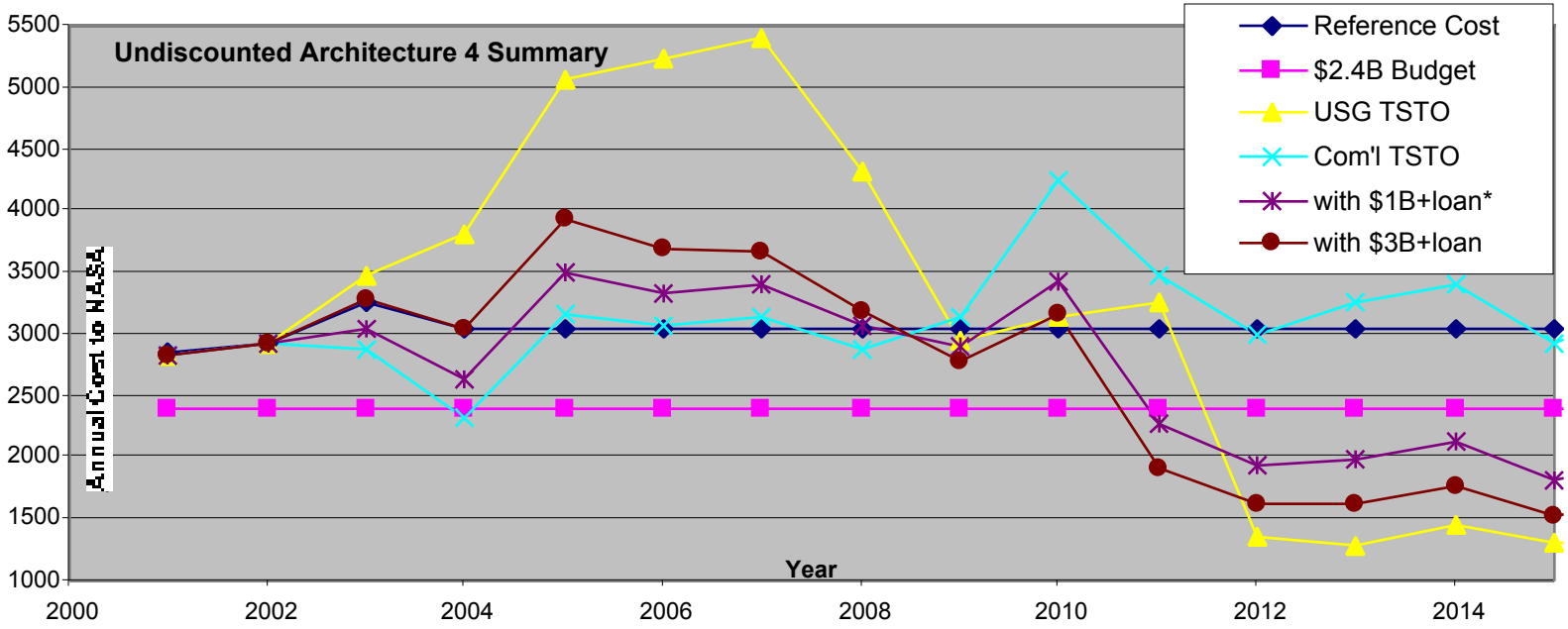
0
2000
2005
2010
2015
2020
2025
2030
Reference Cost
$2.4B Budget
EELV-Full Downmass
EELV-Partial Downmass*

Architecture 3




Undiscounted Architecture 4 Summary
Reference Cost
$2.4B Budget
USG TSTO
Com'l TSTO
with $1B+loan*
with $3B+loan
Annual Cost to NASA
Year
5500
5000
4500
4000
3500
3000
2500
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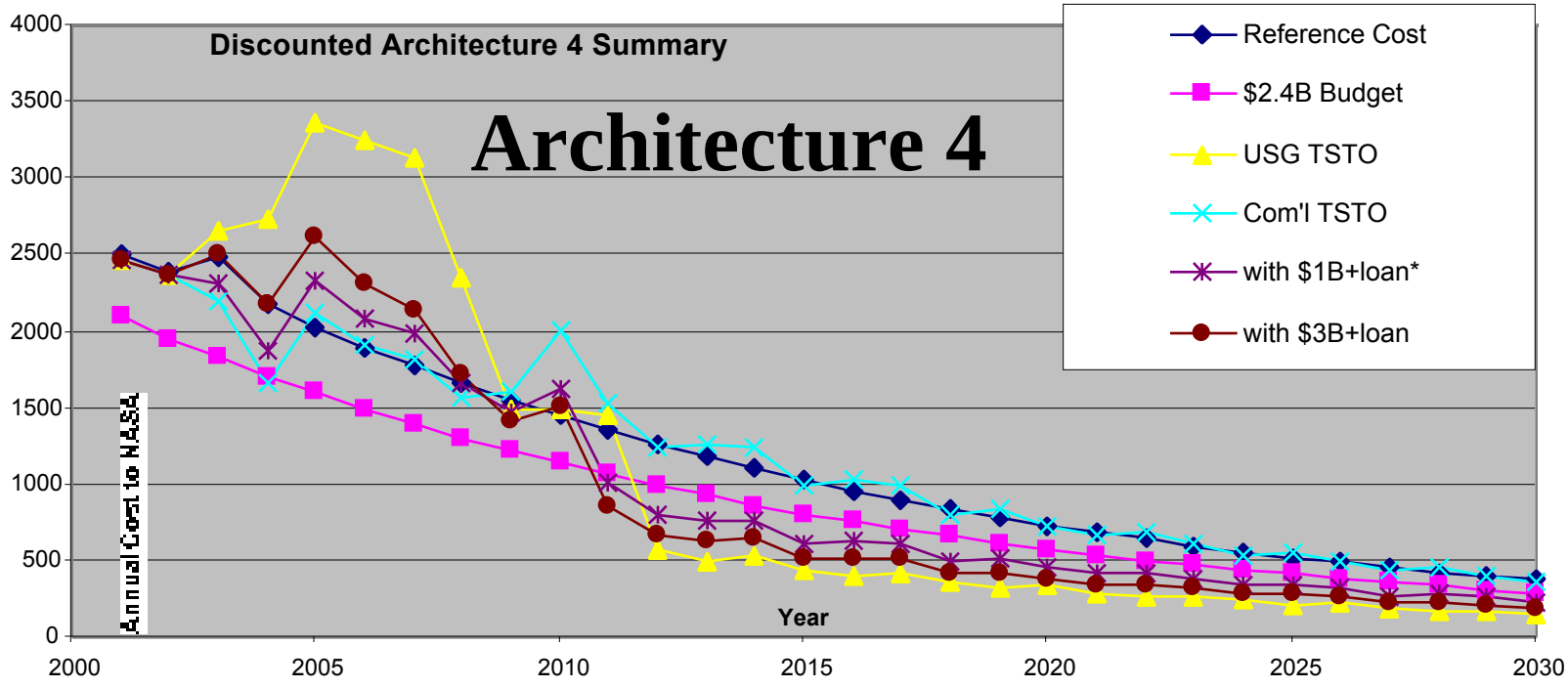
2012
2014


Discounted Architecture 4 Summary
Architecture 4
Reference Cost
$2.4B Budget
USG TSTO
Com'l TSTO
with $1B+loan*
with $3B+loan
Annual Cost to NASA
Year
4000
3500
3000
2500
2000
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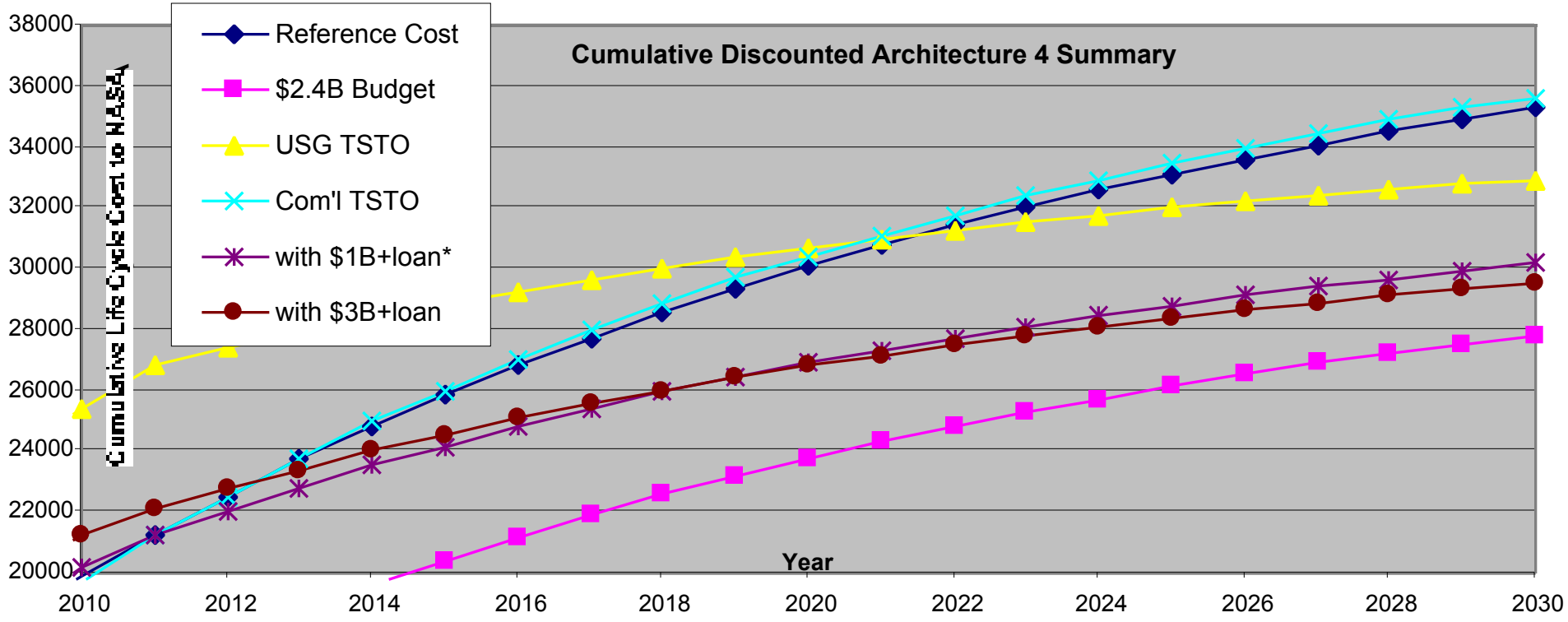
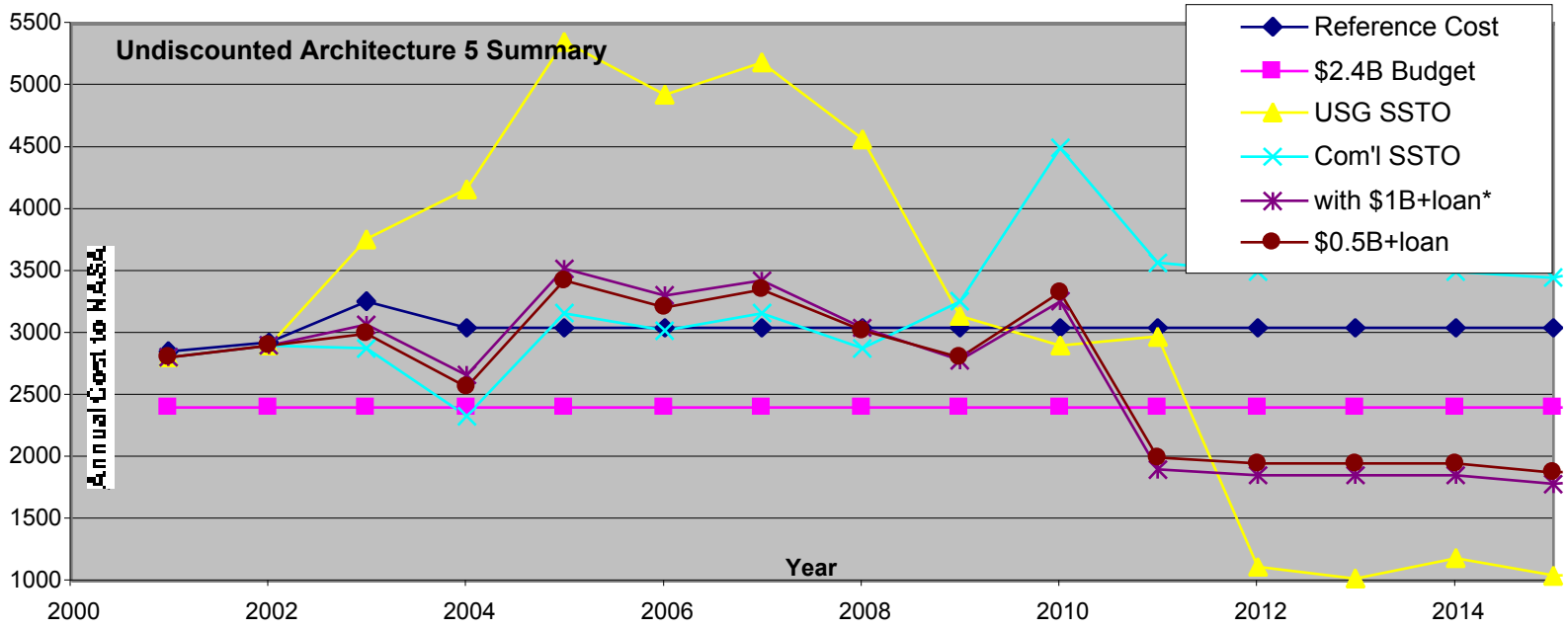
2025
2030

Architecture 4




Undiscounted Architecture 5 Summary
Reference Cost
$2.4B Budget
USG SSTO
Com'l SSTO
with $1B+loan*
$0.5B+loan
Annual Cost to NASA
Year
5500
5000
4500
4000
3500
3000
2500
2000
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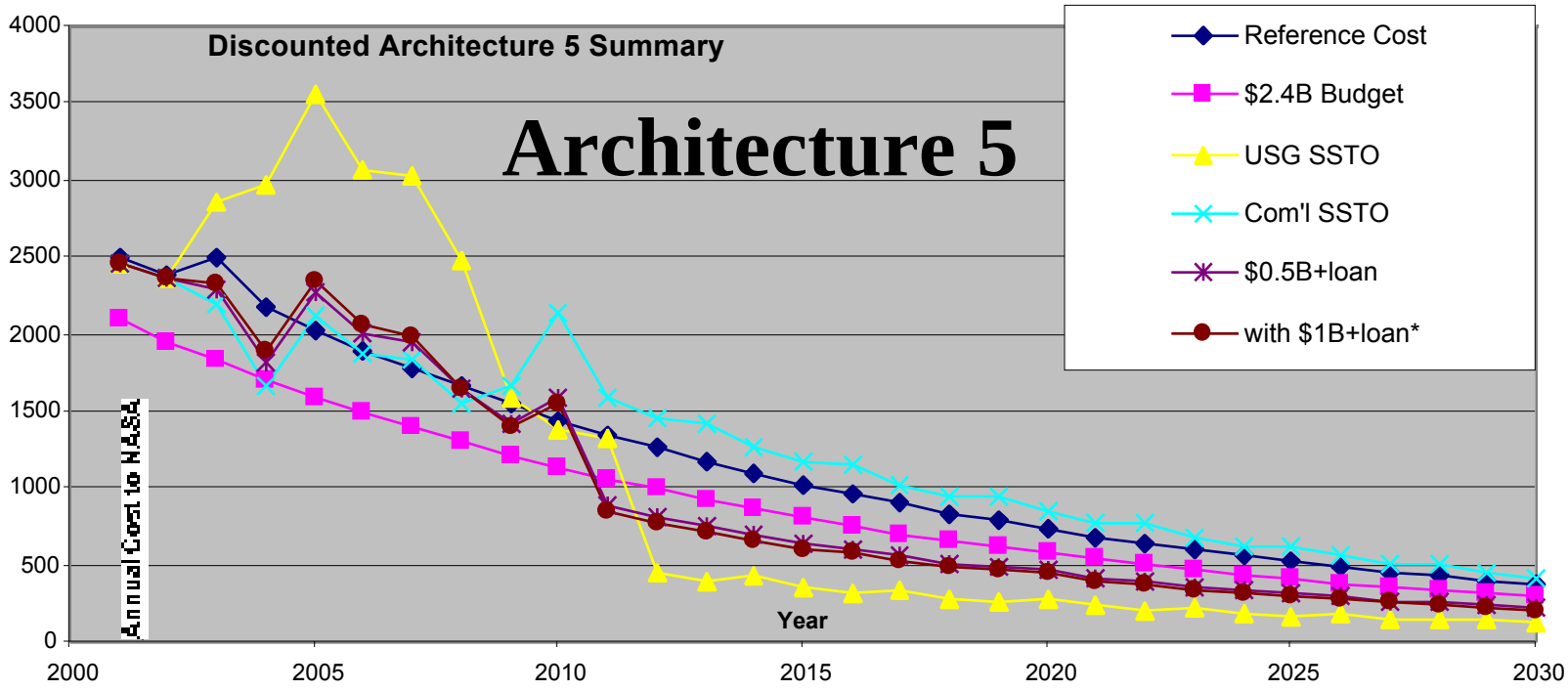
Discounted Architecture 5 Summary
Architecture 5
Reference Cost
$2.4B Budget
USG SSTO
Com'l SSTO
$0.5B+loan
with $1B+loan*
Annual Cost to NASA
Year
4000
3500
3000
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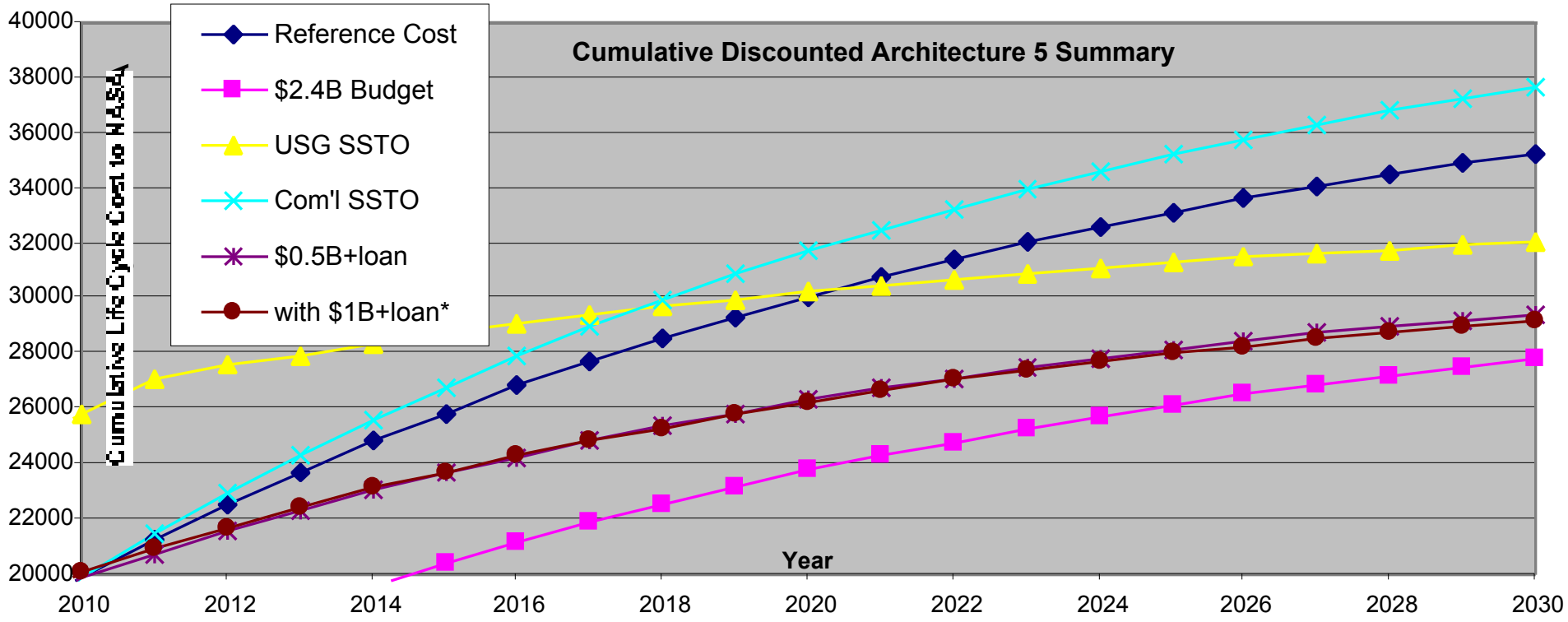
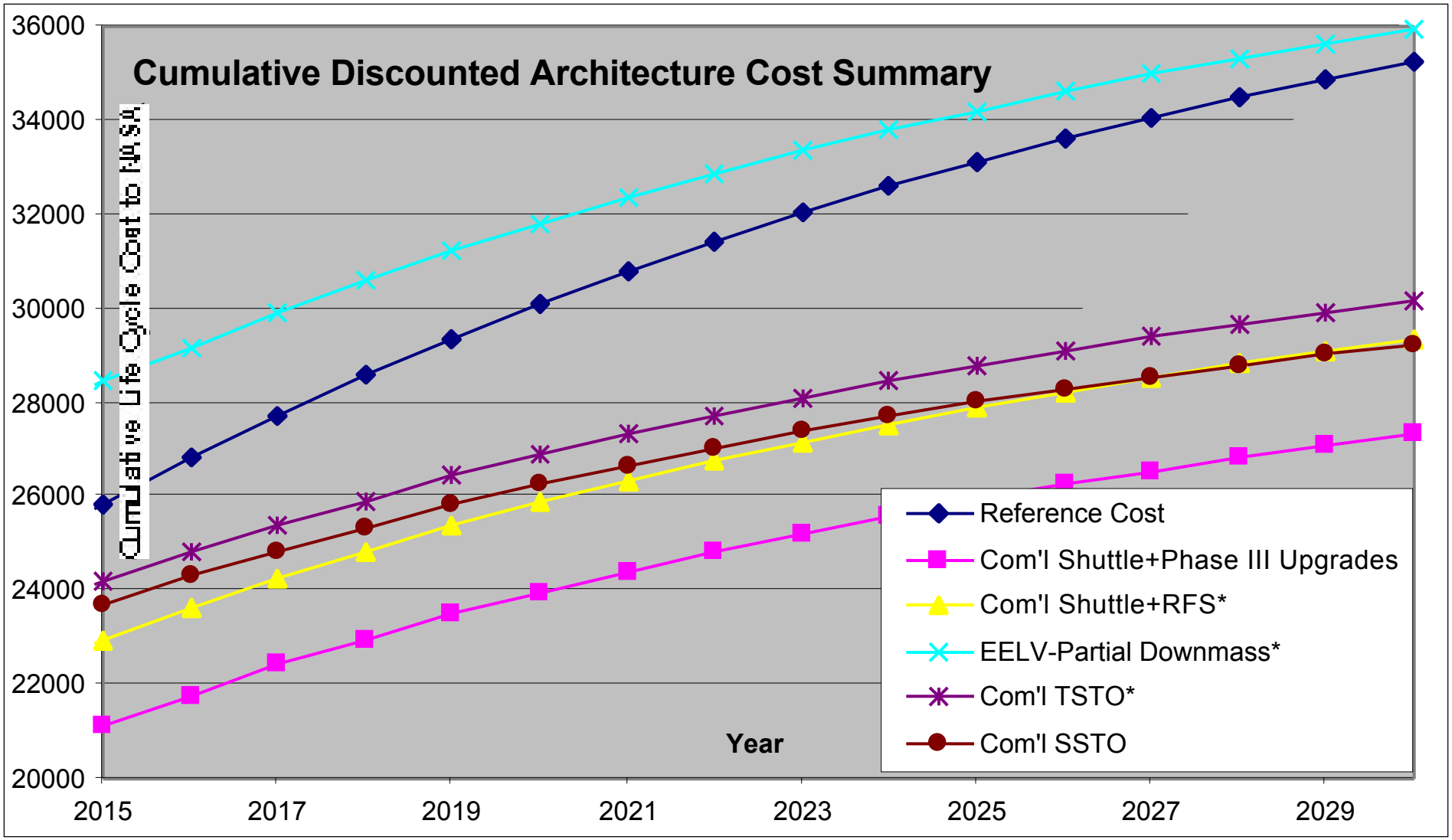
2025
2030

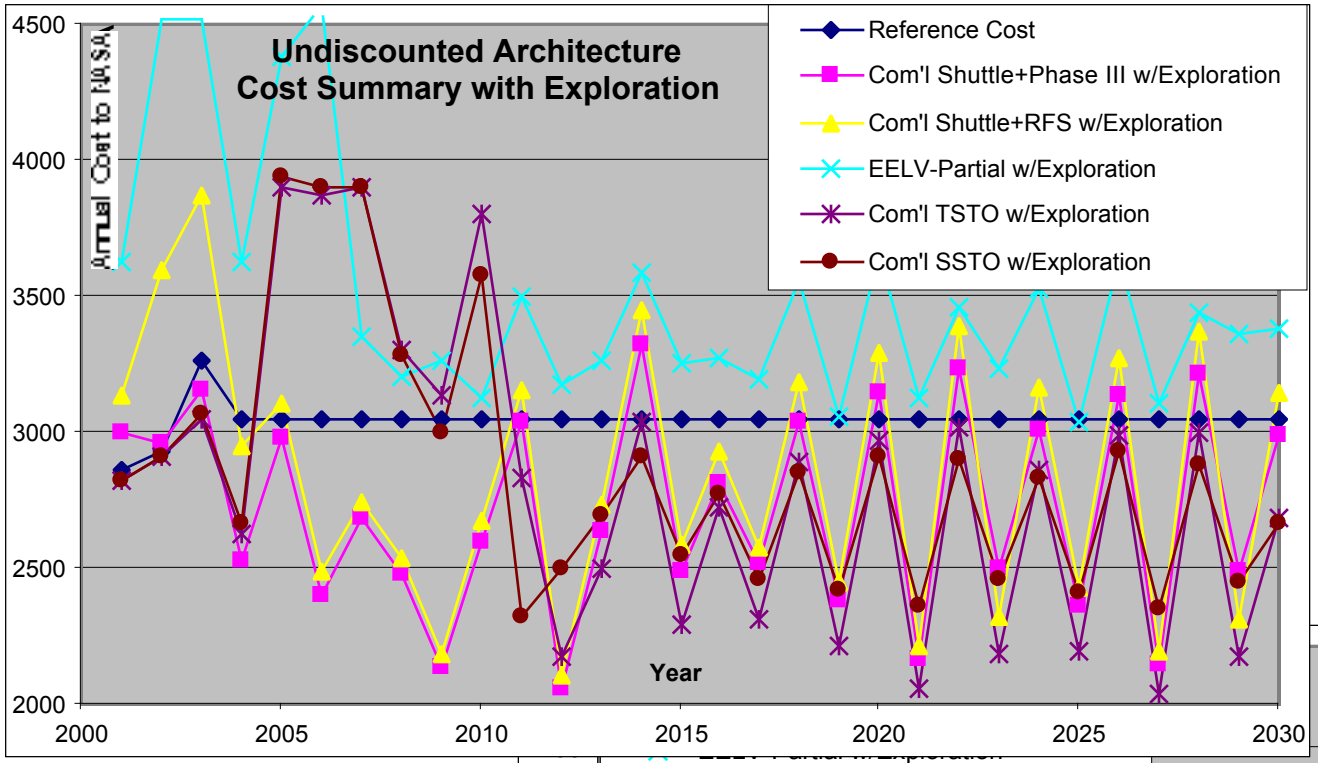
Architecture 5

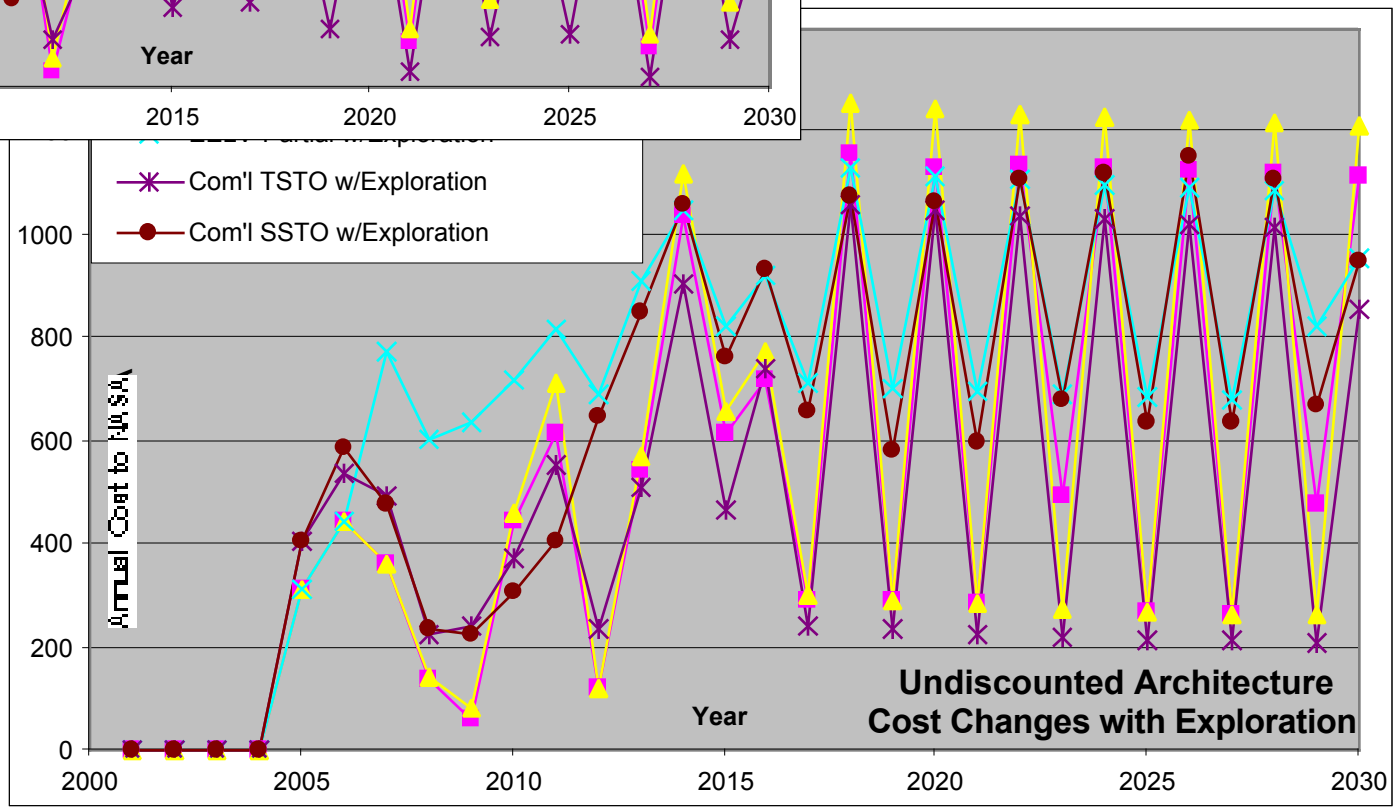


Architecture Summary

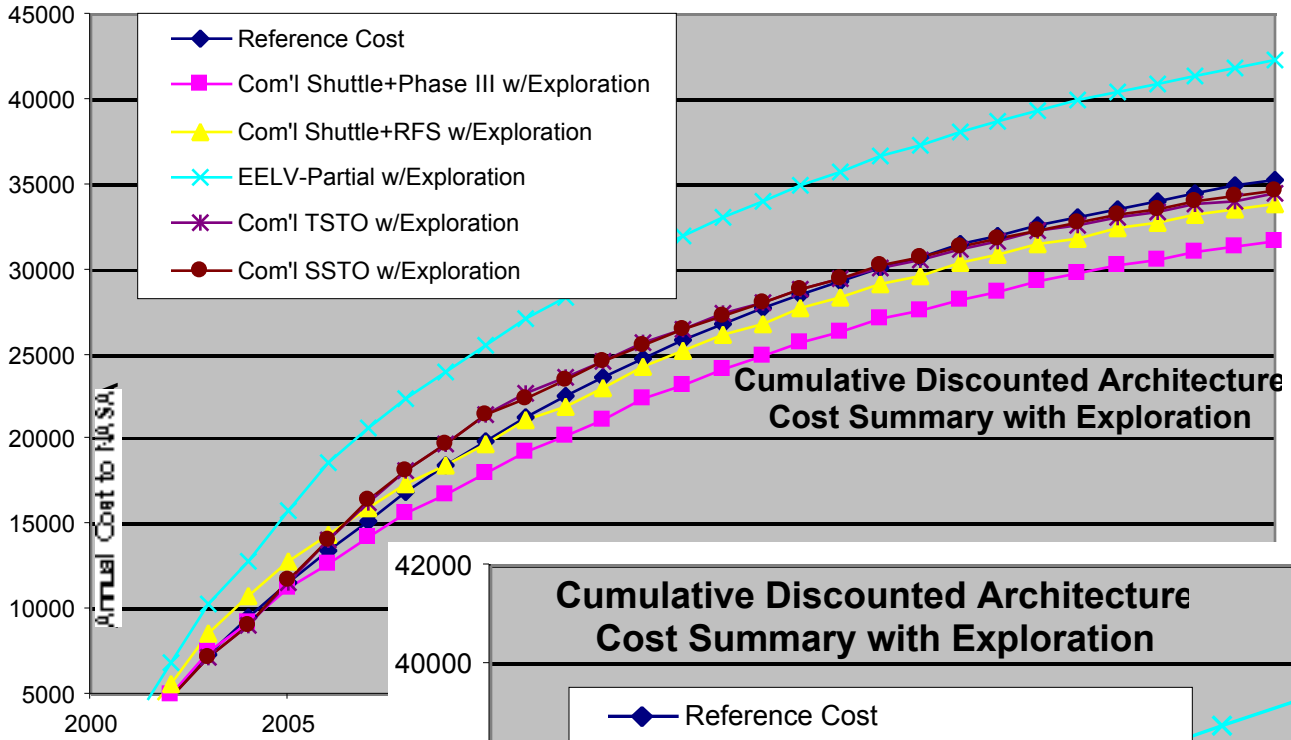


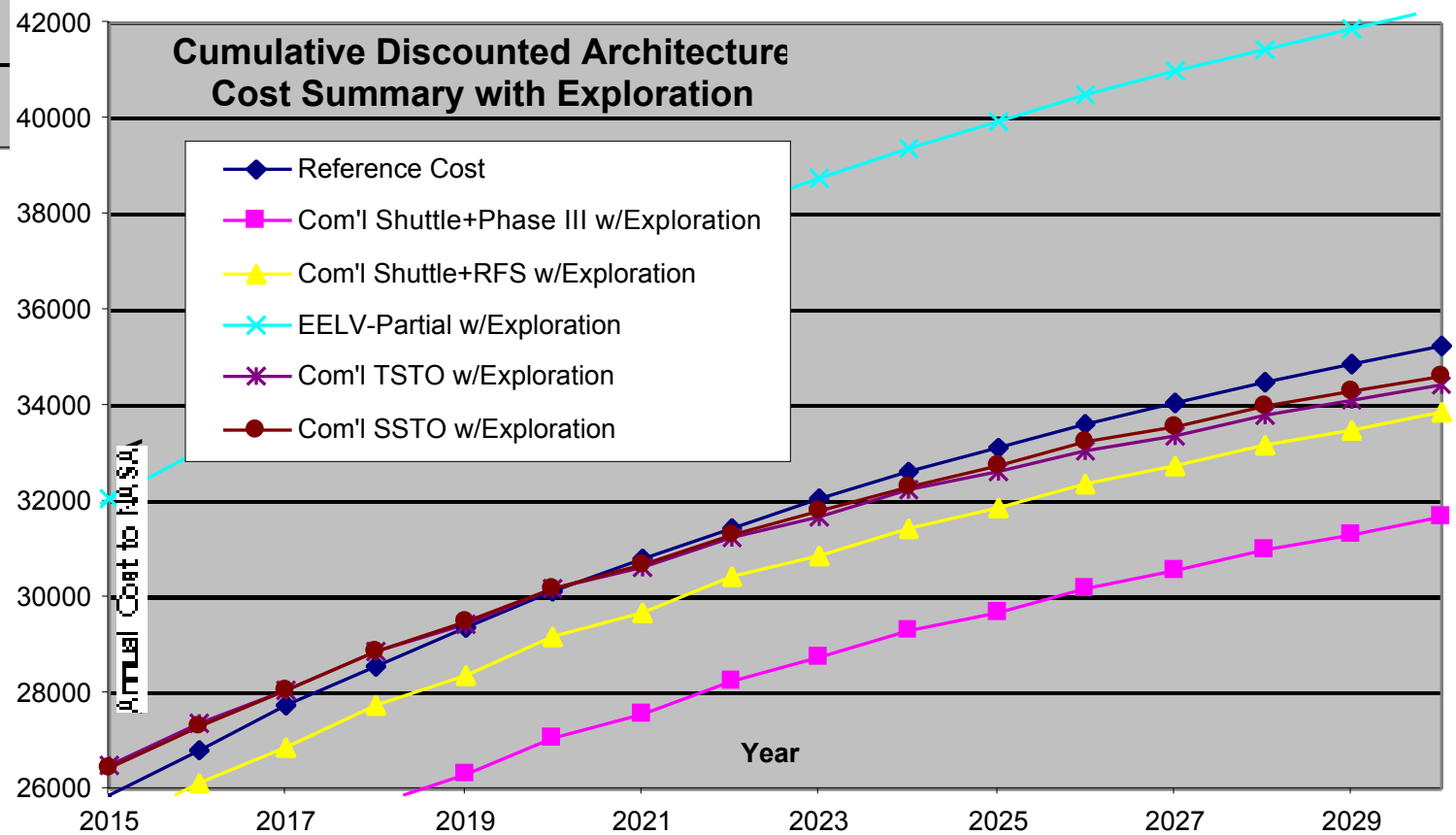
Exploration Excursion Summary, Undiscounted





Exploration Excursion Cumulative Summary



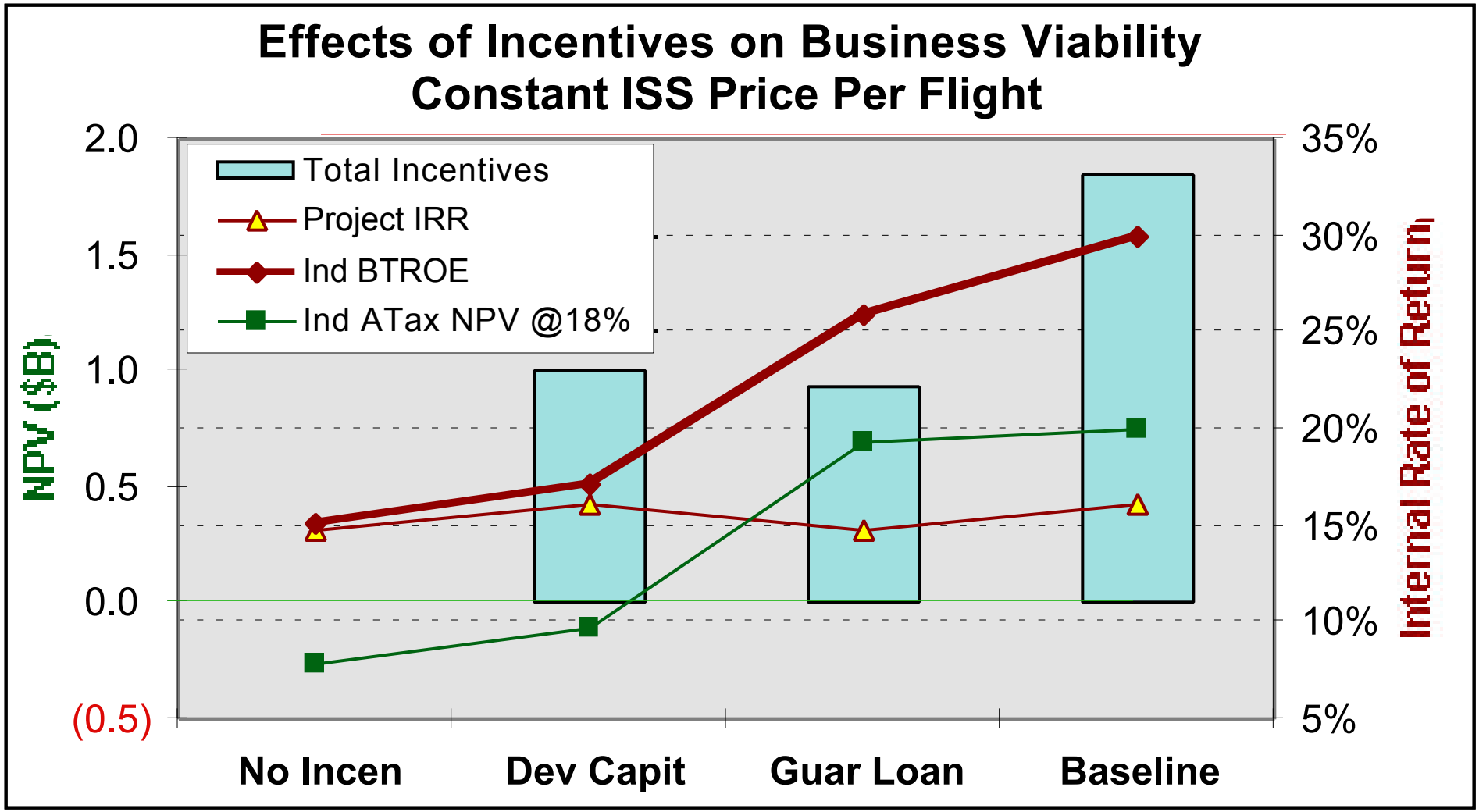


Additional Sensitivities on SSTO
(Architecture 5, Commercial)

- On Industry Returns
  - Incentives
  - Price Per Flight
  - Equilibrium Price and Upper Stage Price/Weight

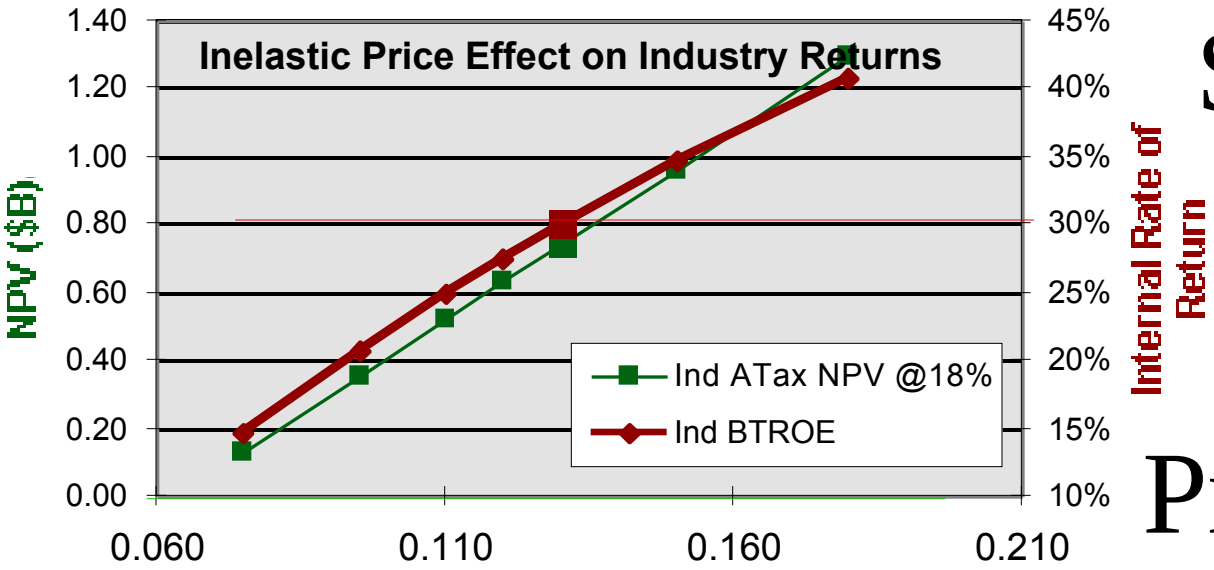
- On USG Returns
  - Incentives
  - Price Per Fight
  - Industry Hurdle Rate

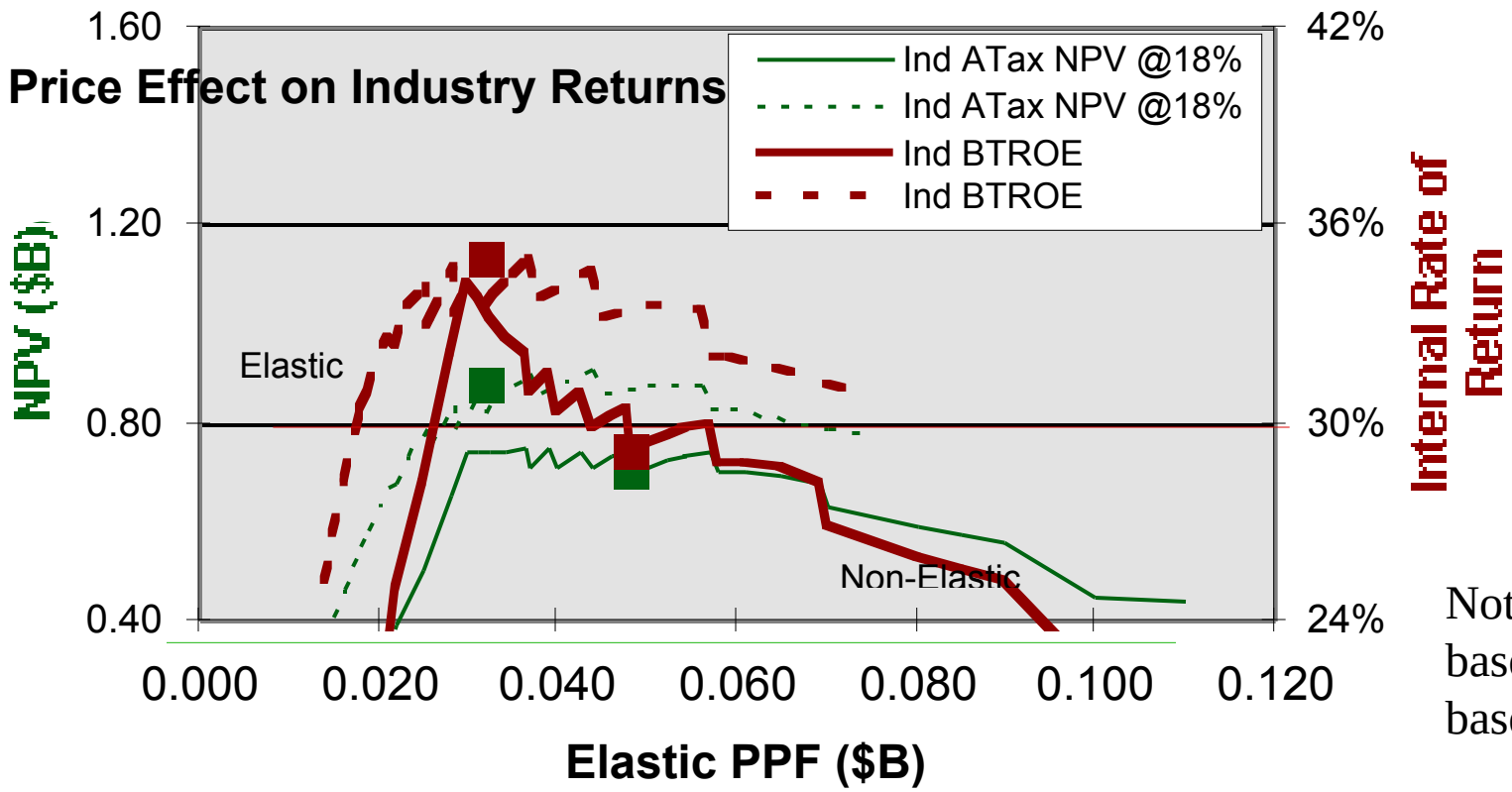
Sensitivity of Industry Returns to Government Incentives



Note: sensitivity based on previous baseline

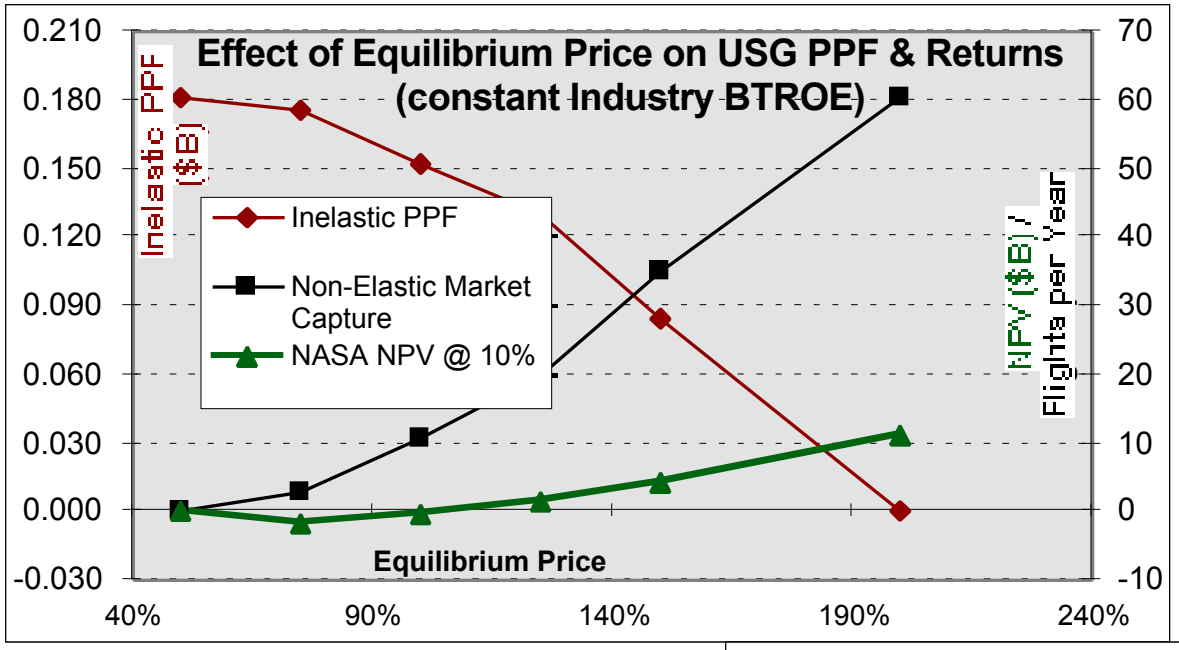
Sensitivity of Industry Returns to Price Per Flight

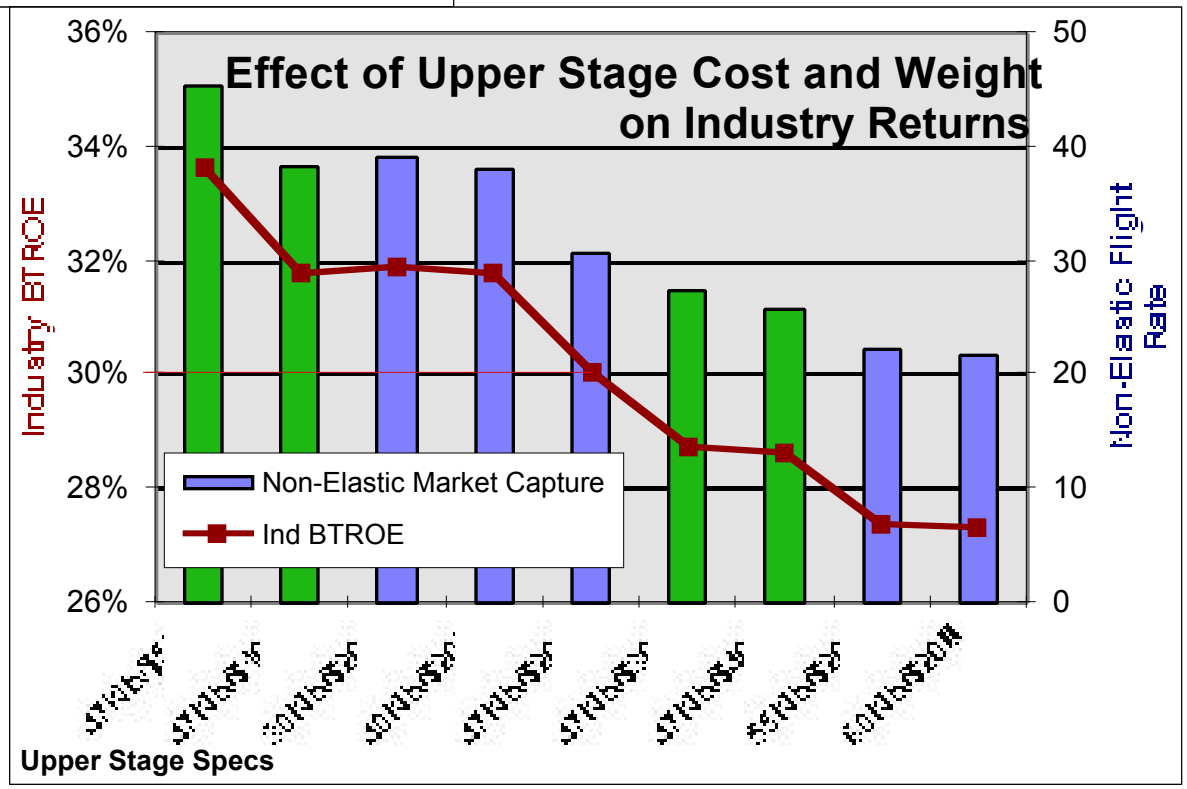




Note: sensitivity based on previous baseline

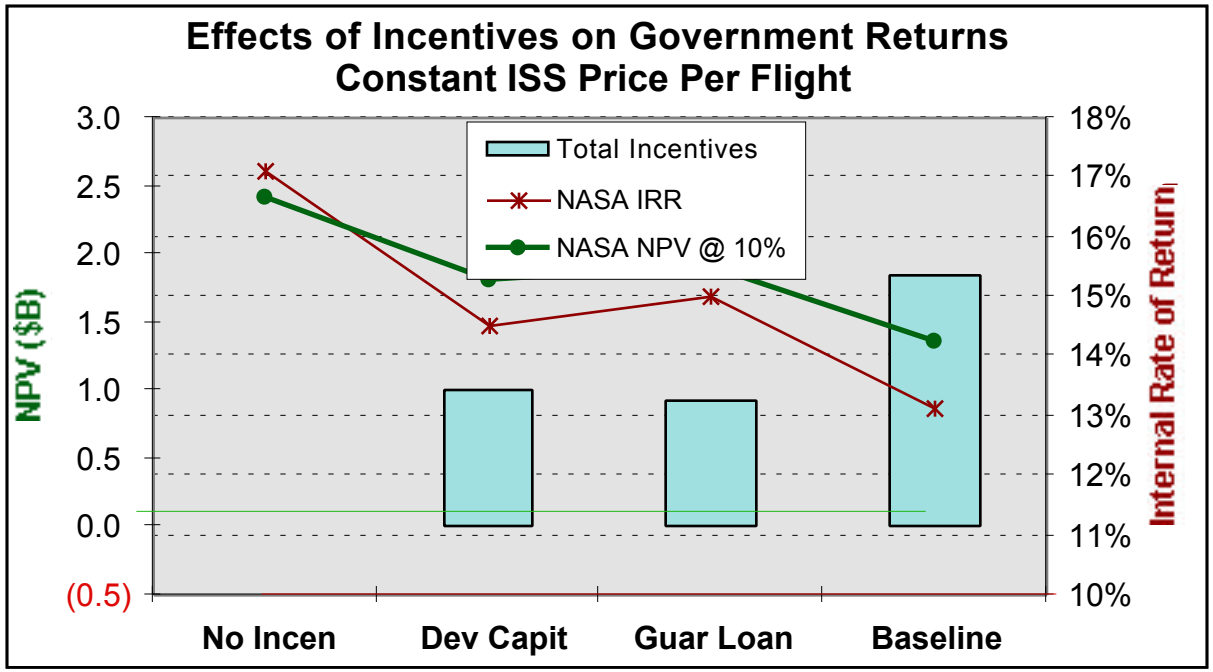
Sensitivity of Industry Returns to Market Equilibrium Price and Upper Stage Cost and Weight

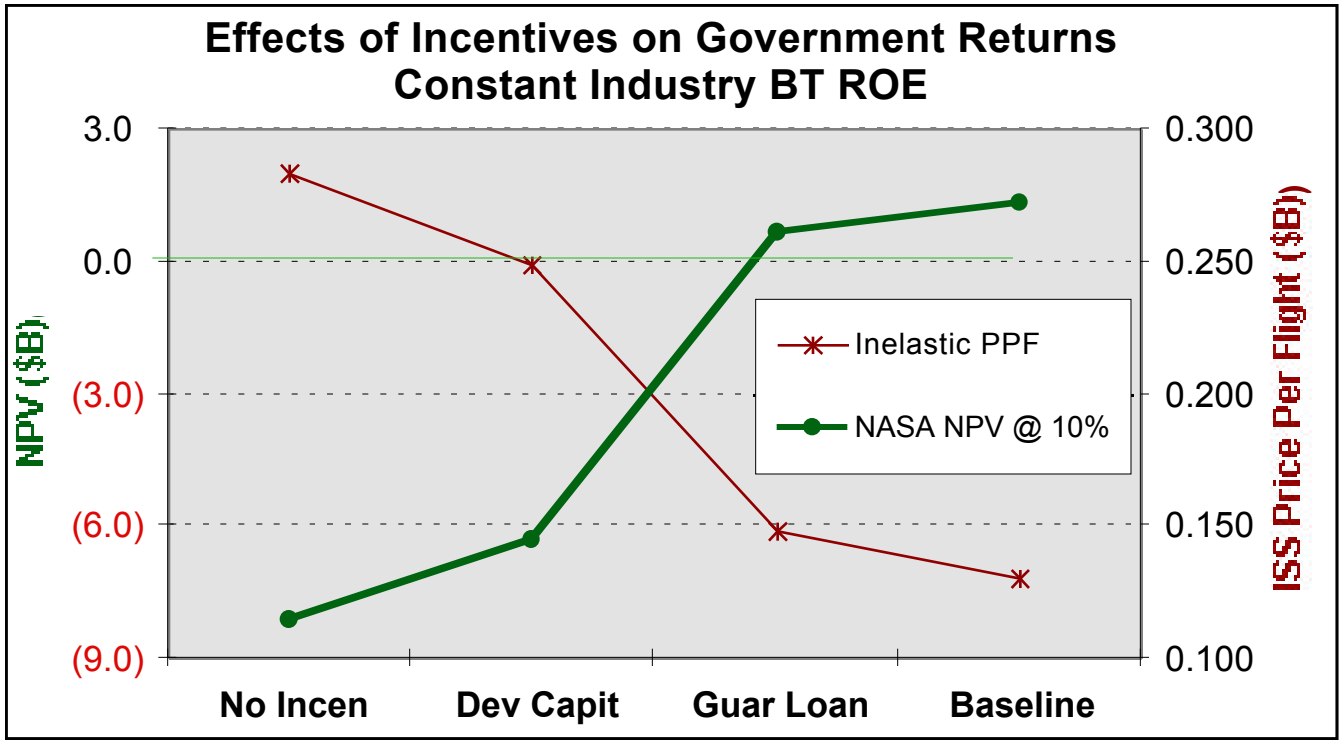




Note: sensitivity based on previous baseline

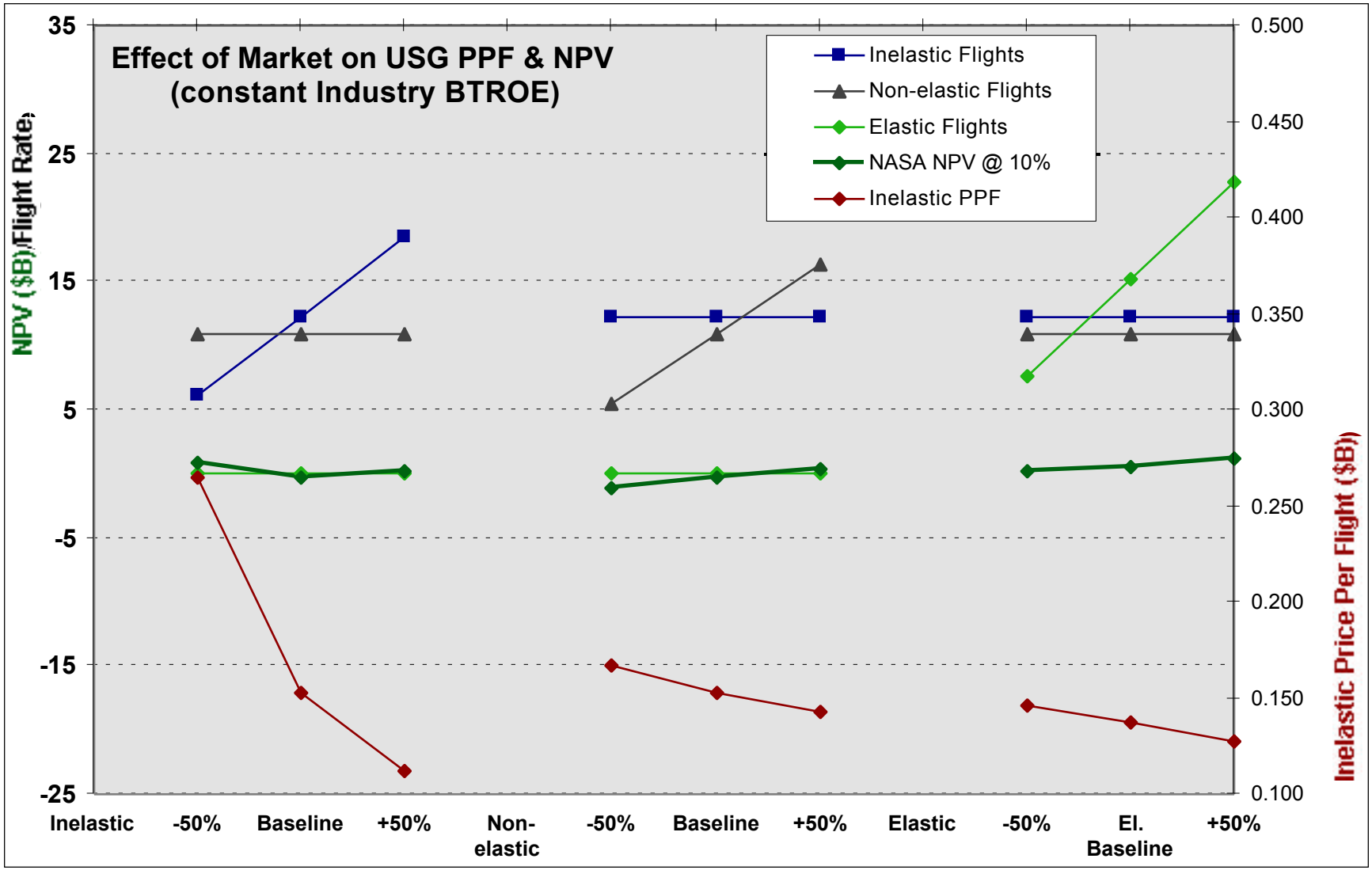
Sensitivity of NASA Life Cycle Cost to Government Incentives





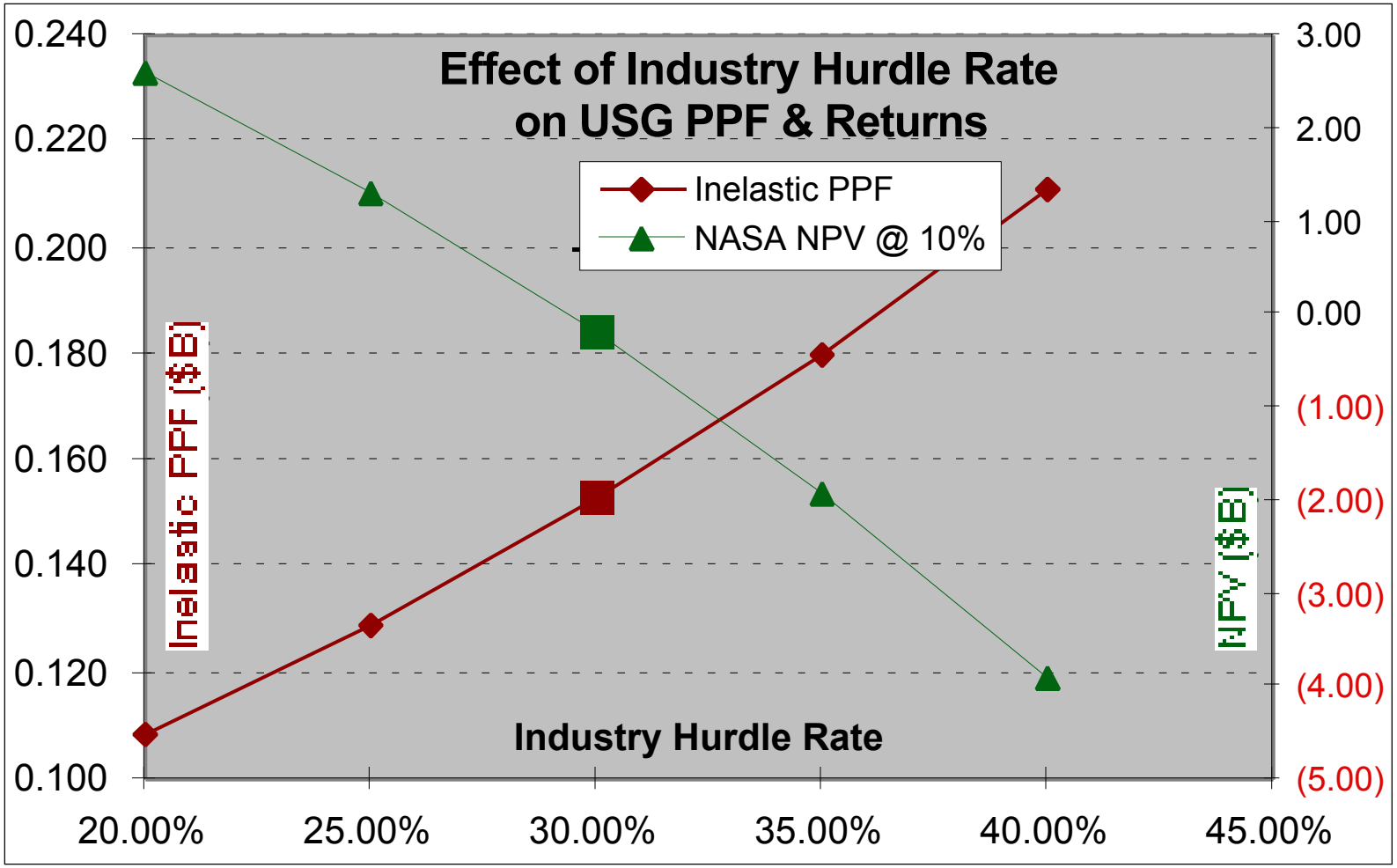
Note: sensitivity based on previous baseline

Sensitivity of NASA Life Cycle Cost to Price Per Flight



Note: sensitivity based on previous baseline

Sensitivity of NASA Life Cycle Cost and ISS Price Per Flight to Industry Hurdle Rate



Note: sensitivity based on previous baseline