Satellite Mass Growth

Presented to
International Cost Estimating and Analysis Association

June, 2016

Don MacKenzie
MacKenzie Consulting, Inc.
dwmackenz@comcast.net

Erik Burgess
erik@burgess-consulting.net

This Research was Sponsored by

U.S. National Reconnaissance Office (NRO)
Cost and Acquisition Assessments Group (CAAG)

Definitions

Basic mass, CBE mass, raw weight

Assessment of the most recent design

+ Mass growth allowance (MGA @ unit level)

Expected mass growth resulting from lack of maturity in the current design … in-scope design changes included

= Predicted mass

Basic mass + MGA

Expected to increase over program duration as requirements mature

+ Mass margin (@ spacecraft level)

Mitigates potential mass increases from omissions or refinement of existing requirements

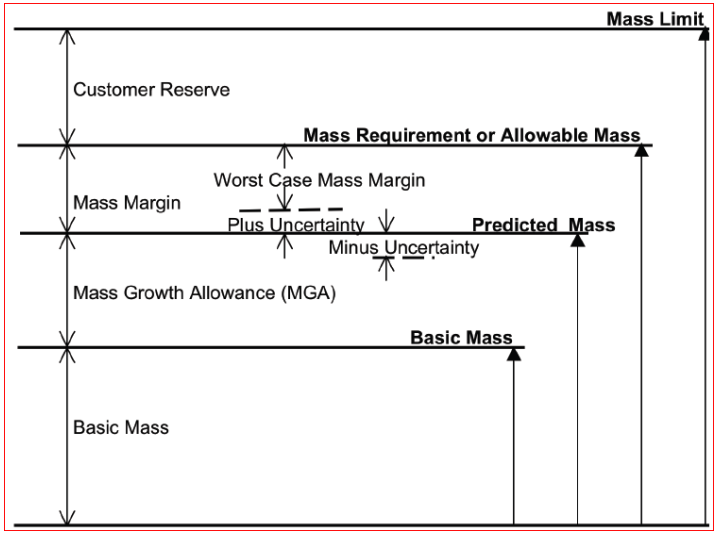
Must cover the upper limit of uncertainties

= Allowable mass

+ Customer reserve

For out-of-scope changes

= Mass limit



NRO Mass Growth Study

- Goals:
  - Predict unit-level mass for all types of space hardware
  - Give confidence ranges (20%tile, mean, 80%tile)
  - Provide other metrics (subsystem, bus, payload, spacecraft)
- Contract award-to-final growth
  - Included requirements as eventually refined/added
  - Closest equivalent is AIAA “Allowable mass”
- 21 NRO and DoD contracts, 1980 to present
  - 6 New, Competitive Acquisitions
  - 11 Sole-source awards
  - 4 Demos

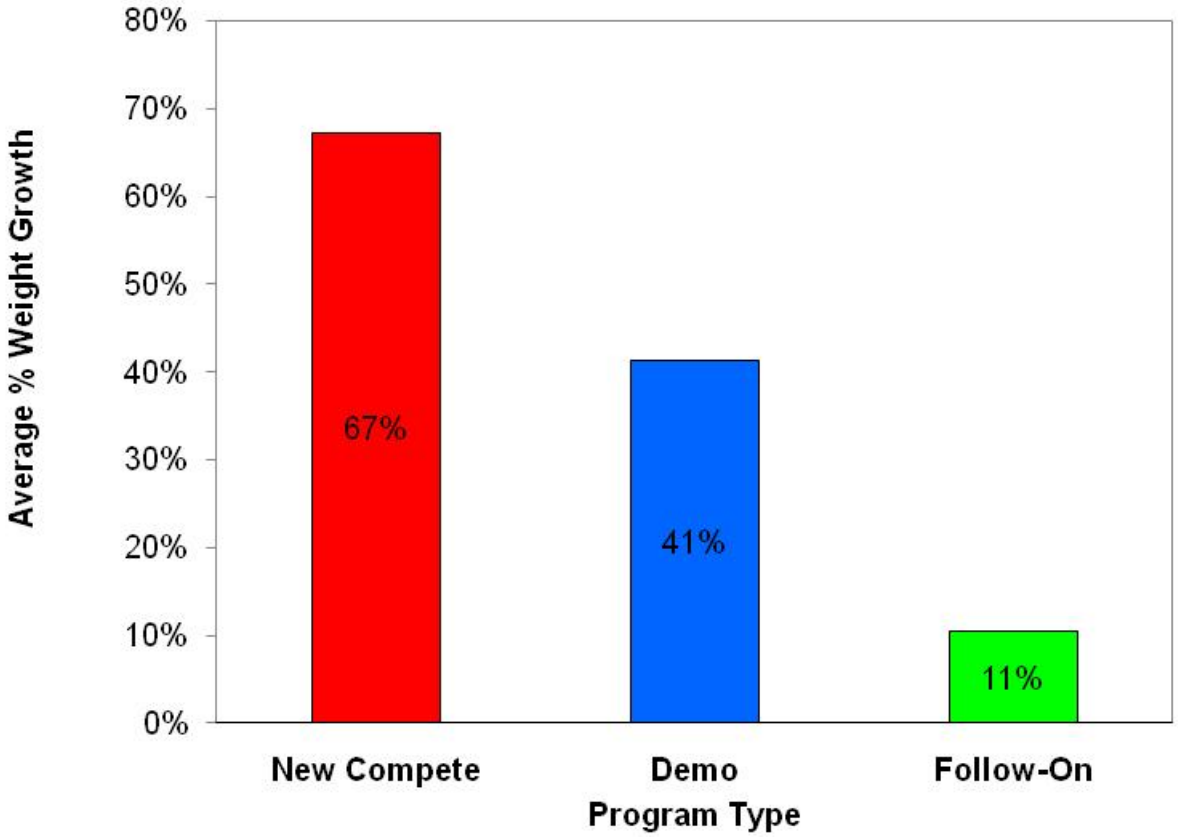
Sources of Data

Contract	Beginning Data Source	Final Data Source
A	Data supporting ICE	Final data sheets
B	Data supporting ICE	Final data sheets
C	First mass props report	Final Mass Props Report
D	Proposal	Final data sheets
E	Proposal	Final Mass Props Report
F	Proposal	Final data sheets
G	Data supporting ICE	Final data sheets
H	Data supporting ICE	Final Mass Props Report
I	Data supporting ICE	Final data sheets
J	Data supporting ICE	USCM
K	Proposal	Final Mass Props Report
L	Data supporting ICE	Final data sheets
M	Data supporting ICE	Final data sheets
N	Data supporting ICE	Final data sheets
O	Data supporting ICE	Final data sheets
P	Proposal	Final data sheets
Q	Data supporting ICE	Final data sheets
R	CARD	Final data sheets
S	Proposal	Final data sheets
T	CARD	Final data sheets
U	Proposal	Final data sheets

ICE data sheets at contract award are most relevant data source

- Raw weights (i.e., basic, no MGA), percent new design
- Mass properties report not yet available

Spacecraft-Level Totals



Growth measured from contract award to first launch;

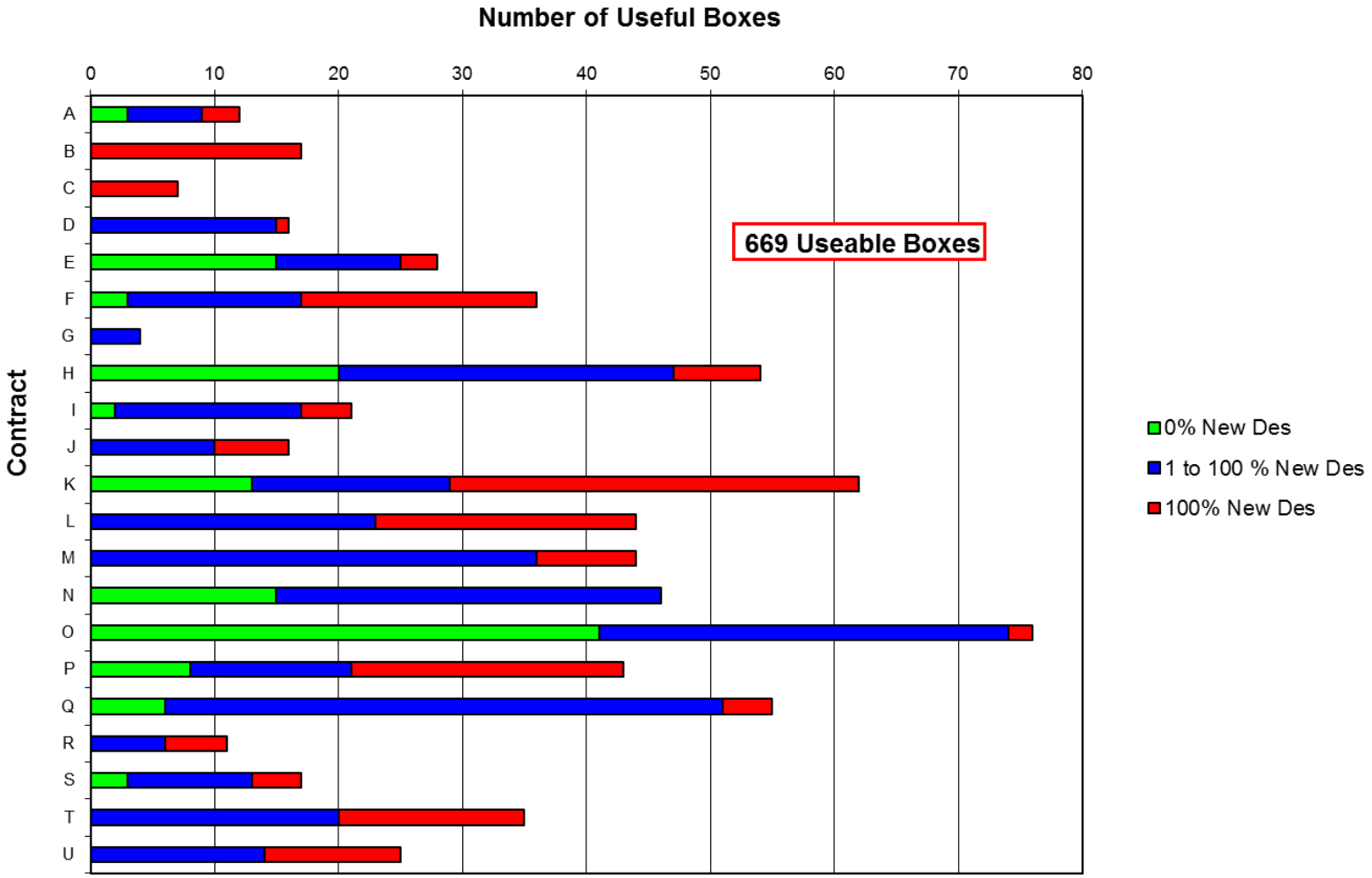
Percentage of basic (raw) weight

Weight growth is related to amount of heritage

Unit-Level Data Set

- 1218 original boxes
- 550 boxes deleted
- Reasons for deletions:
  - Box/box group not in both beginning & final configuration (245)
  - Quantity per vehicle change (68)
  - Likely mismatch between beginning & final (49)
  - Percent new design issues (44)
  - Percent new design not known (40)
  - Likely concept change (25)
  - GFE, Crypto or ballast (17)
  - Other (62)

Box Percent New Design Summary By Program



Regression Analysis

- Statistical regression used to develop predictive models
- Independent variables:

Continuous

% new design	**% unique (repetition)**
unit cost	**beginning raw weight**

Discrete

HW type: Up to 17 categories

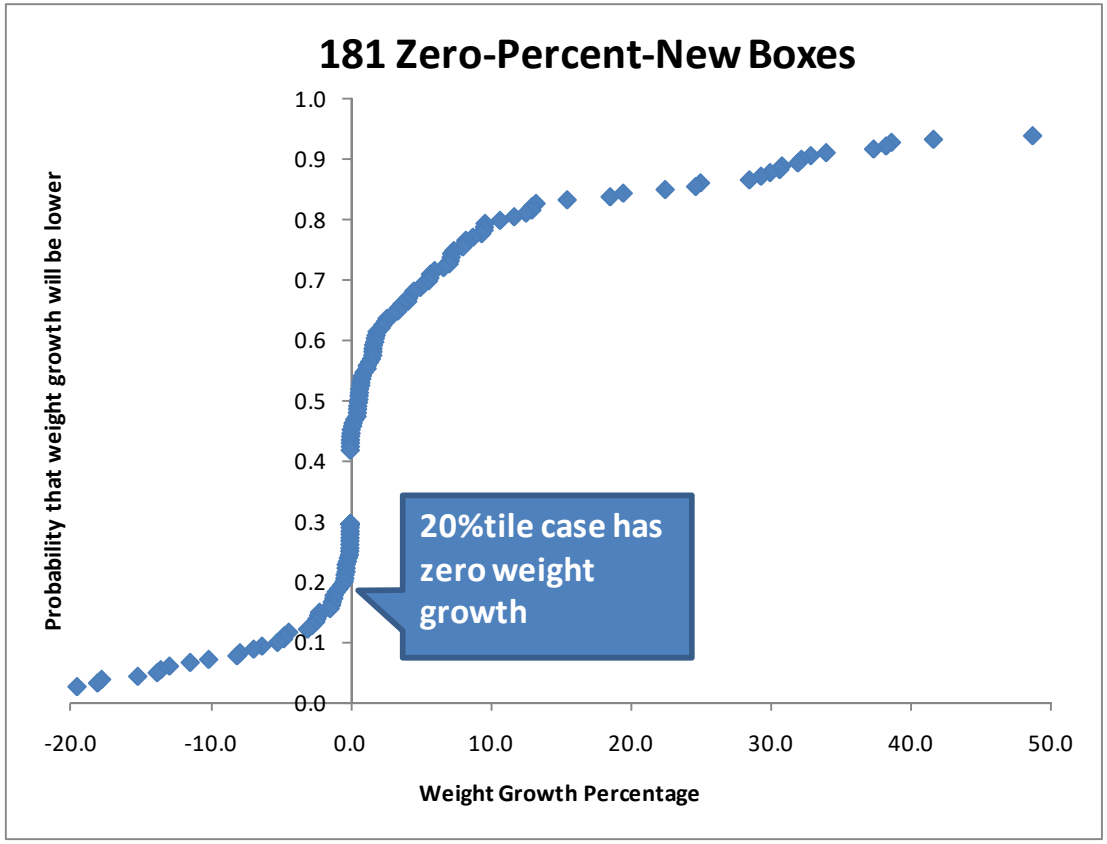
Acquisition type: Demo, Follow-On, New Compete

- Model selected by CAAG
  - Estimates unit-level increase in basic weight from award to launch
  - Uses % new design as continuous variable
  - Is based on 9 hardware categories
  - Includes acquisition-type stratification variable

Key Findings: Unit-Level Analysis

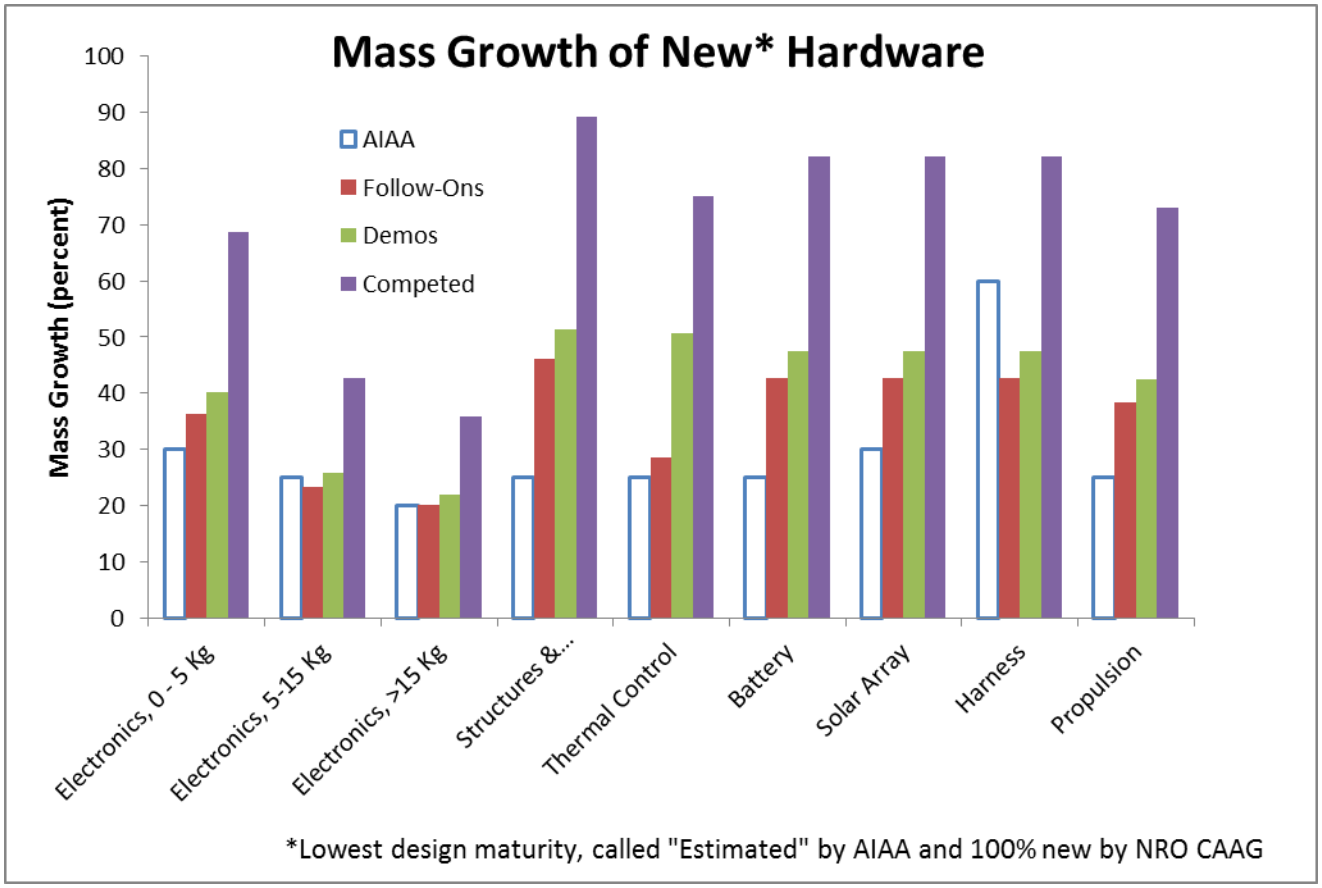
- Heritage (percent new design) drives weight growth
- Sole-source follow-on contracts show less unit-level growth
  - For same amount of new design
  - Possibly caused by contractor experience with similar hardware, less aggressive “buy-in” designs
- Units planned with 0% new design often have changes and associated positive or negative mass growth
- Industry guidelines for mass growth allowance are lower than our dataset indicates

Units with 0% New Design



- Large number of boxes start at 0% new
- Most are eventually modified
- Most of those grow (rather than shrink)

Comparison to AIAA Standard



AIAA-S-120-2006

AIAA recommended MGA is Lower than Actuals in Most Areas
Actuals include requirements maturation that MGA does not

Comparison to AIAA Mass Growth Allowance

AIAA Hardware Category	AIAA-S-120-2006 MGA for Design Maturity = "Estimated"	NRO total mass growth for 100% new units		
		Follow-Ons	Demos	Competed
Electronics, 0 - 5 Kg	30	36	40	69
Electronics, 5-15 Kg	25	23	26	43
Electronics, >15 Kg	20	20	22	36
Structures & Mechanisoms	25	46	51	89
Thermal Control	25	29	51	75
Battery	25	43	47	82
Solar Array	30	43	47	82
Harness	60	43	47	82
Propulsion	25	38	43	73

AIAA recommended MGA is Lower than Actuals in Most Areas
Actuals include requirements maturation that MGA does not

Depletion Methods and Results Differ

- NRO CAAG:
  - Beginning % new always used to estimate total growth from award to launch
  - Remaining growth as a percent of total weight growth is a function of time

Unit-level WG model X Depletion Model = Estimated WG

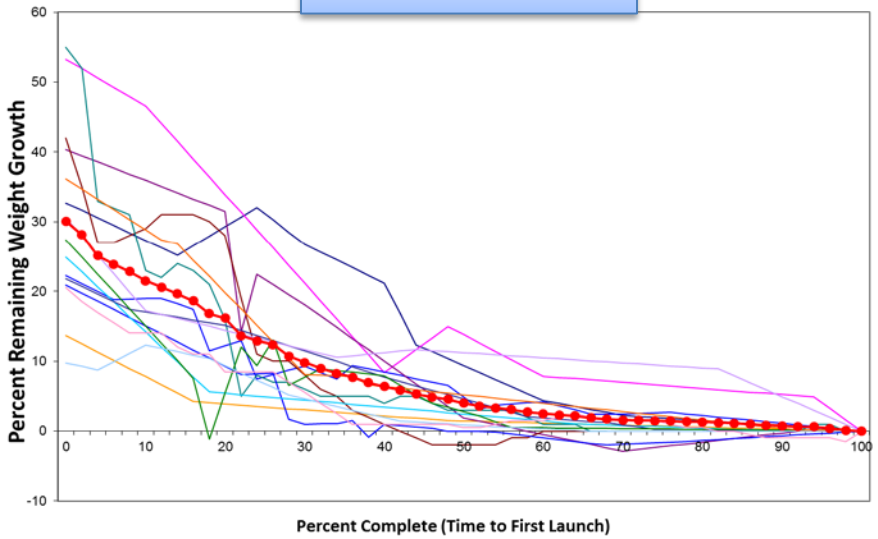
- AIAA standard:
  - Hardware maturity improves during development
  - MGA based on maturity -- depletion schedule is inherent
  - Satellite-level depletion schedule vs. time is notional

Depletion Schedule

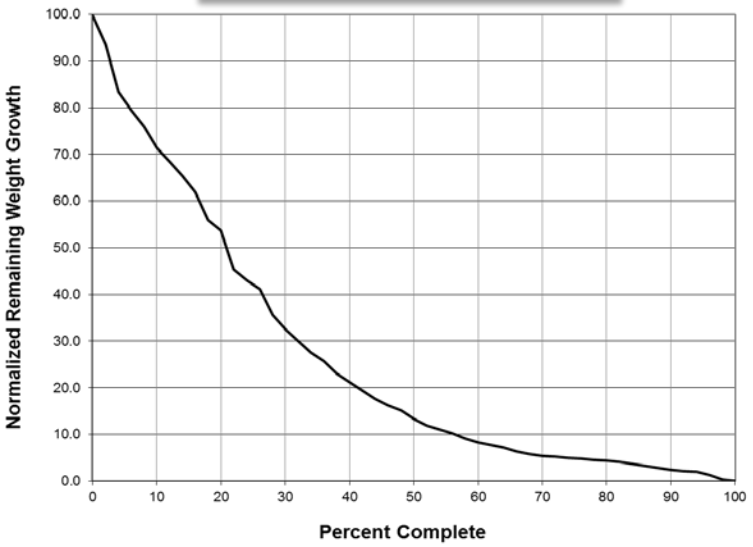
(Remaining Weight Growth)

- Satellite-level data from 15 NRO and Air Force programs provided by Aerospace Corporation
- Different dataset than used for unit-level model (some overlap)

Raw Data



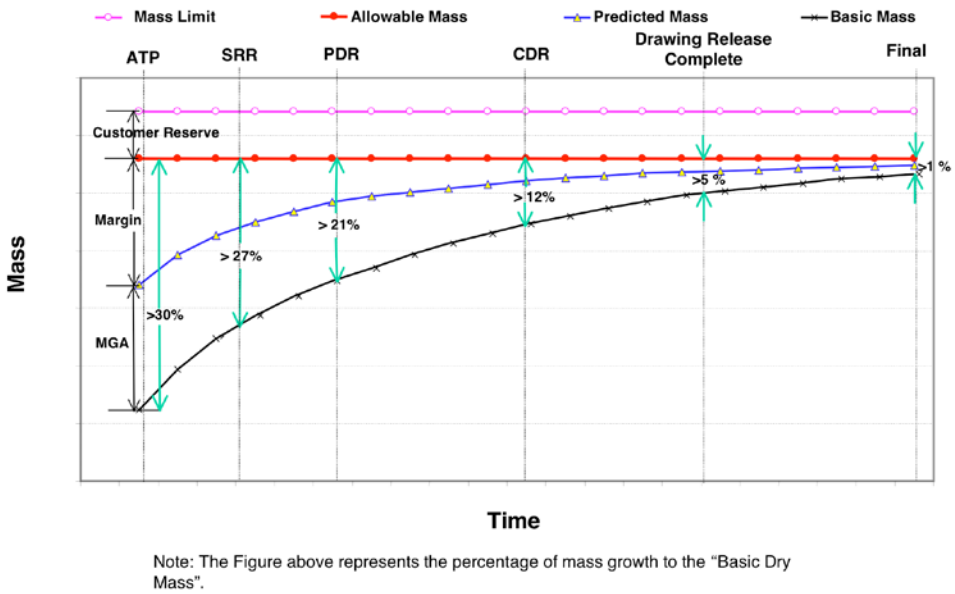
Normalized 0-100



Normalized curve used for CAAG estimates during program execution
Unit-level WG model X Depletion Model = Estimated WG

Comparison to AIAA Depletion Schedule

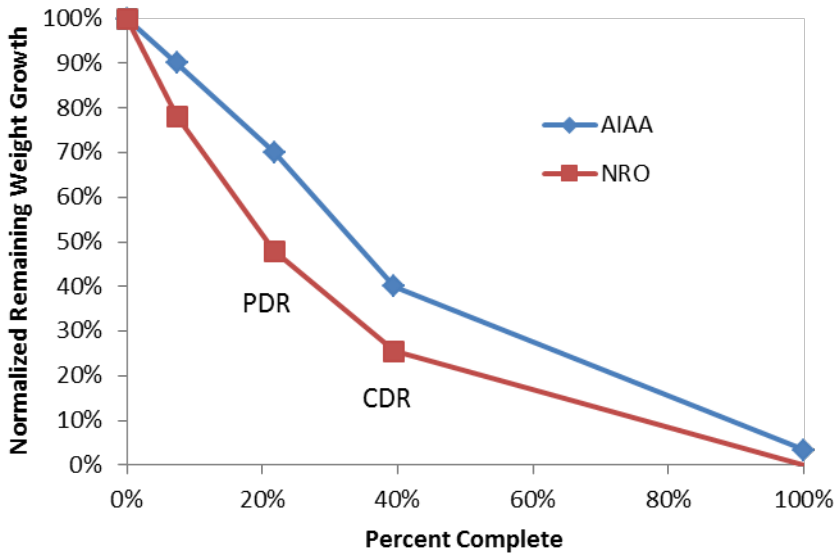
AIAA Depletion Schedule



Note: The Figure above represents the percentage of mass growth to the "Basic Dry Mass".

Note: AIAA does not draw to scale on either axis!

Milestone	% Complete (NRO schedule database)	AIAA MGA+Margin	AIAA Normalized Remaining	NRO Normalized Remaining
ATP	0%	30.0%	100%	100%
SRR	7%	27.0%	90%	78%
PDR	22%	21.0%	70%	48%
CDR	39%	12.0%	40%	25%
Launch	100%	1.0%	3%	0%



AIAA Depletion Schedule is Conservative

Recent NASA Studies

- Cost Analysis Division, NASA HQ
  - 2012-2013: Instrument mass growth
  - 2014: Spacecraft subsystems

- Key similarities
  - Depletion schedule follows same functional form as NRO model (exponential decay)
  - Average growth from SRR to launch is higher than AIAA standard
    - 30-50% for spacecraft (vs. 27% for AIAA)
    - 30-40% for instruments (unspecified for AIAA)

Conclusions

- Unit-level weight growth is significantly higher than MGA as indicated in AIAA S-120-2006
  - NRO's total-growth data is not directly comparable
  - Units may include some growth due to refinement or omission of existing requirements
- AIAA guidelines for satellite-level margin (additional 15%) are insufficient to cover "worst-case" uncertainties
- Government/Industry should consider re-evaluating the standard

BACKUP

AIAA Mass Growth Allowance (MGA)

Table 1 — Mass Growth Allowance and Depletion Schedule

Major Category	Maturity Code	Design Maturity (Basis for Mass Determination)	Mass Growth Allowance (%)											
			Electrical/Electronic Components			Structure	Brackets, Clips, Hardware	Battery	Solar Array	Thermal Control	Mechanisms	Propulsion	Wire Harness	Instrumentation	ECLSS, Crew Systems
			0-5 kg	5-15 kg	>15 kg										
E	1	**Estimated** 1) an approximation based on rough sketches, parametric analysis, or undefined requirements, 2) a guess based on experience, 3) a value with unknown basis or pedigree.	30	25	20	25	30	25	30	25	25	25	55	55	23
	2	**Layout** 1) a calculation or approximation based on conceptual designs (equivalent to layout drawings), 2) major modifications to existing hardware	25	20	15	15	20	15	20	20	15	15	30	30	15
C	3	**Preliminary Design** 1) calculations based on a new design after initial sizing but prior to final structural or thermal analysis, 2) minor modification of existing hardware	20	15	10	10	15	10	10	15	10	10	25	25	10
	4	**Released Design** 1) calculations based on a design after final signoff and release for procurement or production, 2) very minor modification of existing hardware, 3) catalog value	10	5	5	5	6	5	5	5	5	5	10	10	6
A	5	**Existing Hardware** 1) actual mass from another program, assuming that hardware will satisfy the requirements of the current program with no changes, 2) values based on measured masses of qualification hardware	3	3	3	3	3	3	3	2	3	3	5	5	4
	6	**Actual Mass** measured hardware	No mass growth allowance – use appropriate measurement uncertainty values												
	7	**Customer Furnished Equipment or Specification Value**	Typically a "not-to-exceed" value is provided; however, contractor has the option to include MGA if justified												

AIAA Mass Margin

Program Milestone	MGA		Recommended Dry Mass Margin	
	%[1]	Grade	%[1]	Grade
ATP	> 15	Green	> 15	Green
	9 < MGA ≤ 15	Yellow	10 < Mass Margin ≤ 15	Yellow
	≤ 9	Red	≤ 10	Red
SRR	> 15	Green	> 12	Green
	9 < MGA ≤ 15	Yellow	6 < Mass Margin ≤ 12	Yellow
	≤ 9	Red	≤ 6	Red
PDR	> 12	Green	> 9	Green
	8 < MGA ≤ 12	Yellow	5 < Mass Margin ≤ 9	Yellow
	≤ 8	Red	≤ 5	Red
CDR	> 7	Green	> 5	Green
	4 < MGA ≤ 7	Yellow	3 < Mass Margin ≤ 5	Yellow
	≤ 4	Red	≤ 3	Red
Drawing Release Complete	> 3	Green	> 2	Green
	2 < MGA ≤ 3	Yellow	1 < Mass Margin ≤ 2	Yellow
	≤ 2	Red	≤ 1	Red
Final	0		> 1	

[1] The percentages of MGA and Margin in the above chart are defined as follows:

MGA = predicted dry mass - basic dry mass
MGA % = (MGA/basic dry mass) * 100
Mass Margin % = [(allowable dry mass – predicted dry mass)/predicted dry mass] * 100