Trouble with the Curve: Engineering Changes & Manufacturing Learning Curves

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Introduction

- **Learning curves demonstrate cost reduction that occurs when an identical product is built over and over again**
- **But what happens when the product design is changed – and the product is different from what was previously manufactured…what happens to our learning?**
- **An engineering change may require an operator:**
  - **Review drawings and specifications for new engineering requirements**
  - **Learn new manufacturing methods**
  - **Use new or modified tools**
  - **Work in a new or altered space**
  - **Work to new or revised production schedules**
  - **Meet new or revised inspection criteria**
- **In addition, a change may:**
  - **Introduce errors in design or tooling that create downstream rework in fab or assembly**
  - **Create late engineering releases that create downstream part shortages and disruption**

Engineering Changes Increase Cost, At Least Initially

Engineering Change Proposals

- **Design changes are usually introduced via an Engineering Change Proposal (ECP)**

- **ECPs vary widely in terms of scope and extent of change. An aircraft ECP may affect:**
  - **Structure (bulkheads, skins, ribs/spars, longerons, floors)**
  - **Provisioning (wiring harnesses and cables, tubing/ducting, associated clips/brackets)**
  - **Electronics or equipment**

- **At the top level, an ECP can do any or all of these things:**
  - **Add tasks which did not previously exist**
  - **Delete tasks which no longer need to be performed**
  - **Reconfigure or modify an existing task**

Hypothetical ECP

Additions:
* Add two (2) new antennas
* Add coax cables
* Add provisions (brackets, fittings)
* New access door

Reconfigured:
* Relocate existing systems
* Relocate existing harnesses and tubes
* Move bulkhead penetrations to accommodate changed provisions

Deletions:
* Remove one (1) existing antenna
* Remove related provisions

Last unit built (before change)	HPU	New part (after change, but w/o reversionary impacts)	HPU
Total (current design)	60	Unchanged task	42
		Reconfigured task	15
		Deleted task	(3)
		Added task	6
		Total (new design)	60

Questions:

- **What is the cost of the part or assembly before the change?**
- **What portion of the effort is unchanged by the design change?**
- **For the changed task, what portion is new? Reconfigured? Deleted?**
- **Using actual hours, analogy, subject matter expert judgment, or parametric weight in / weight out analysis, what is the expected cost for the changed task?**
- **In this example, the cost of the new part (60 hours) is equal to the cost before the change (60 hours). Are we finished?**

Reversionary Impact

- *No*, because we have not accounted for reversionary impact
- Reversionary impact is loss of learning that occurs due to a design change
- To set back unit cost on curve means to assume unit costs are based on cumulative unit positions earlier in the curve, i.e., we repeat a prior level of performance at a higher hours per unit (HPU) cost
- Reversionary impact is usually expressed in terms of units of setback on the learning curve

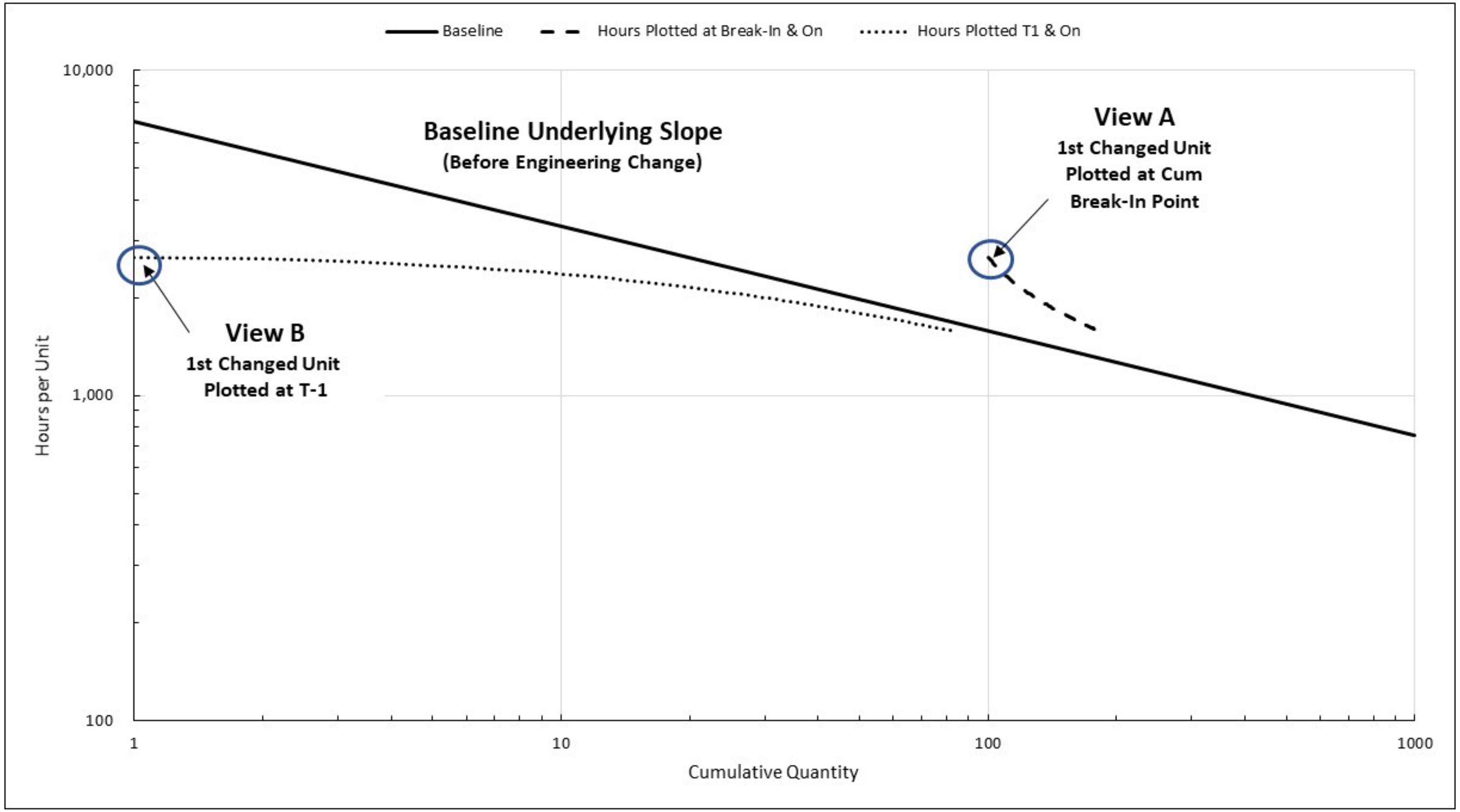
Break-in position x (1 – Setback %) = Setback position

- If a change breaks in at T-300 & we experience a 40% setback, the HPU reverts back to where it was previously at T-180:

T-300 x (1 – 40%) = T-180

Every Engineering Change Requires Consideration of Reversionary Impact

Reversionary Impact, Two Views



- **View A – 1st changed unit plotted at cumulative unit break-in point**
- **View B – 1st changed unit plotted at T-1**
- **HPU & setbacks are exactly the same in both cases – just different ways to view it**
- **View A gives us a better understanding of historical continuity pre- and post-change, however**

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How Much Do We Set Back?

- **One school of thought argues any new or reconfigured task should set all the way back to T-1**

- **That seems overly conservative**
  - **Studies like Jefferson (1981) show that operator improvement only contributes about 20% to overall cost improvement – tooling and engineering improvements are bigger contributors (55% combined)…even if operator has to relearn, does it make sense for impacted costs to go back to T-1?**

- **Say we relocate a harness in a bay…the operator has to learn to string and install a harness & its bracketry in a new location**
  - **But he does not have to relearn how to route a harness through a hole in structure, install clamps and studs properly, make connections, or perform electrical bond.**
  - **May not affect tooling, create any part shortages, or require learning new manufacturing processes or methods.**

- **Careful dissection of historical engineering changes rarely shows a setback all the way back to the first unit**

Setback Sensitivity

- **The choice of setback significantly impacts the estimate**

		Slope = 80%		Slope = 90%	
Setback	Setback Unit	Unit Factor @ Setback	Increase from T1000	Unit Factor @ Setback	Increase from T1000
80%	200	0.1816	68%	0.4469	28%
50%	500	0.1352	25%	0.3888	11%
0%	1000	0.1082	0%	0.3499	0%

- **Two things are apparent:**
  - **For a given learning curve slope, the higher the setback value, the larger the cost impact.**
  - **For a given setback percentage, the steeper the learning curve slope, the larger the cost impact.**

Notional Setback Table

X1% Setback (Highest)

- New weapons system or design concept

X2% Setback

- Current weapons system but major revision to design, e.g., outer mold line change, total subsystem affected by change

X3% Setback

- Relocation of aircraft systems components with associated rerouting of provisioning (harnesses, cables, tubes, ducts)
- Substantial wiring and tubing changes creating greater density and associated installation complexity
- Material substitution within established manufacturing techniques

X4% Setback

- Moderate change in structure in part design details
- Relocations of aircraft systems adjacent to original location
- Lesser number of wires, tubes, ducts added

X5% Setback

- Limited change in structure with changes confined to hole patterns and locations, revisions in tolerances, etc.
- Relatively small addition of wires, tubes, ducts

X6% Setback (Lowest)

- Minimal revisions in structural design
- Very limited added wires, tubes, ducts

- **Based on prior experience from current or past programs, we can construct a table of setback values to use when certain conditions are met**
- **Extensive changes equate to high setback percentages, while modest changes produce low setback percentages**
- **Insures consistency in application, easier customer negotiation**

Recovery

- **Traditional way to calculate recovery is to resume the prior learning curve from the setback point going forward**
  - **Rarely, a manual process will be replaced by a semiautomated or automated process…then we can expect the learning curve to flatten**
  - **“[F]or most situations the items and units produced are similar and the work environment (company policy, management attitudes, etc.) is sufficiently stable that we expect the same rate of learning.” (Smith, 1976)**

- **If an ECP breaks in at T-100 and the setback position is T-20 (80 units of setback), the follow-on units will be calculated as if learning was at units 21, 22, 23, etc.**
- **For HPU calculation purposes, there will always be 80 units of setback in the cumulative build quantity**
- **This continues *ad infinitum*….even at T-1000, the HPU will be calculated with a 80 unit setback (T-920)…of course, the HPU difference will be small (+2.0% on 85% curve) but it is still present**

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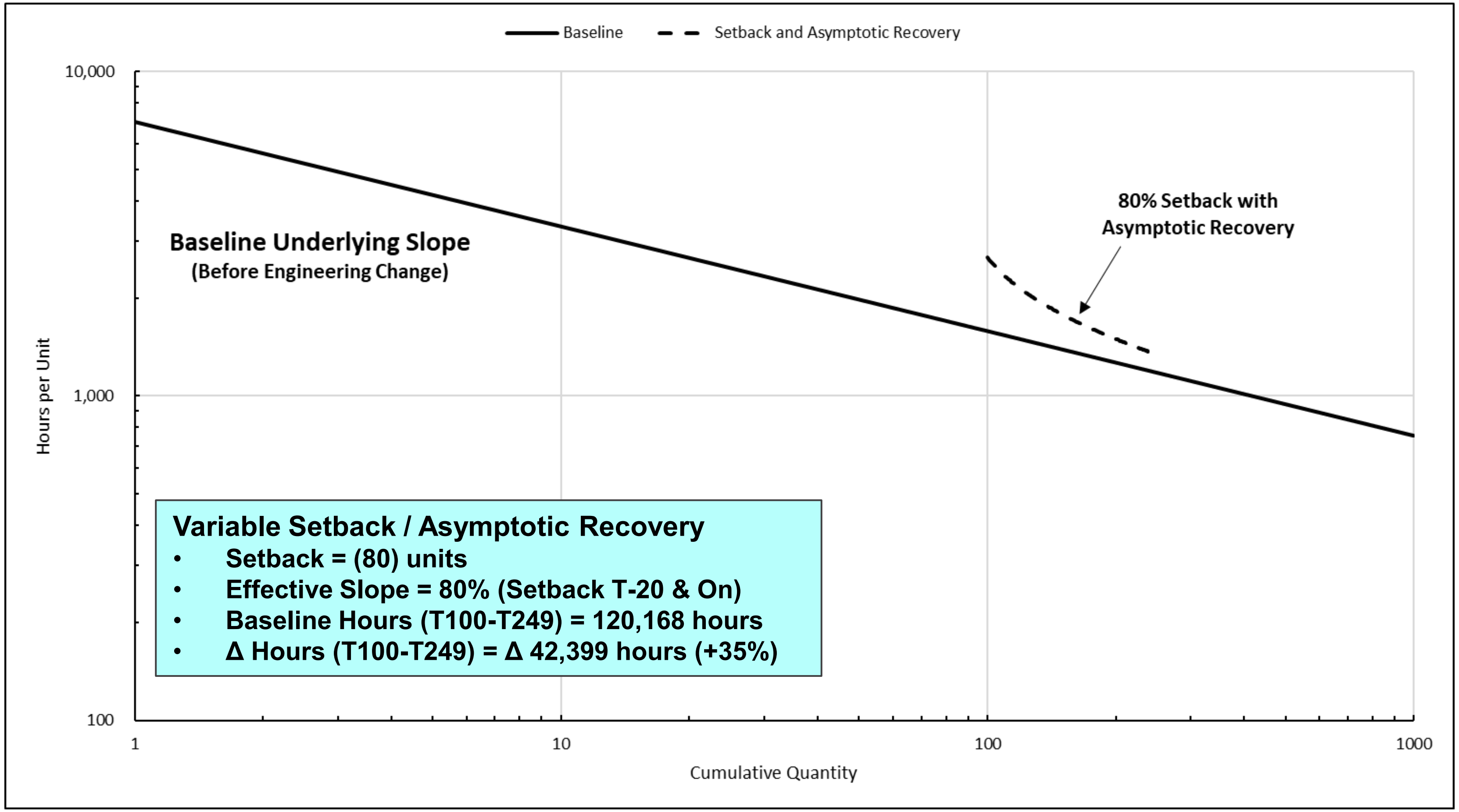
Setback with Asymptotic Recovery



- **Post-change HPU will approach the baseline as more units are built, but it never quite reaches it**
- **Recovery will be asymptotic to the underlying curve**

Alternative Approach

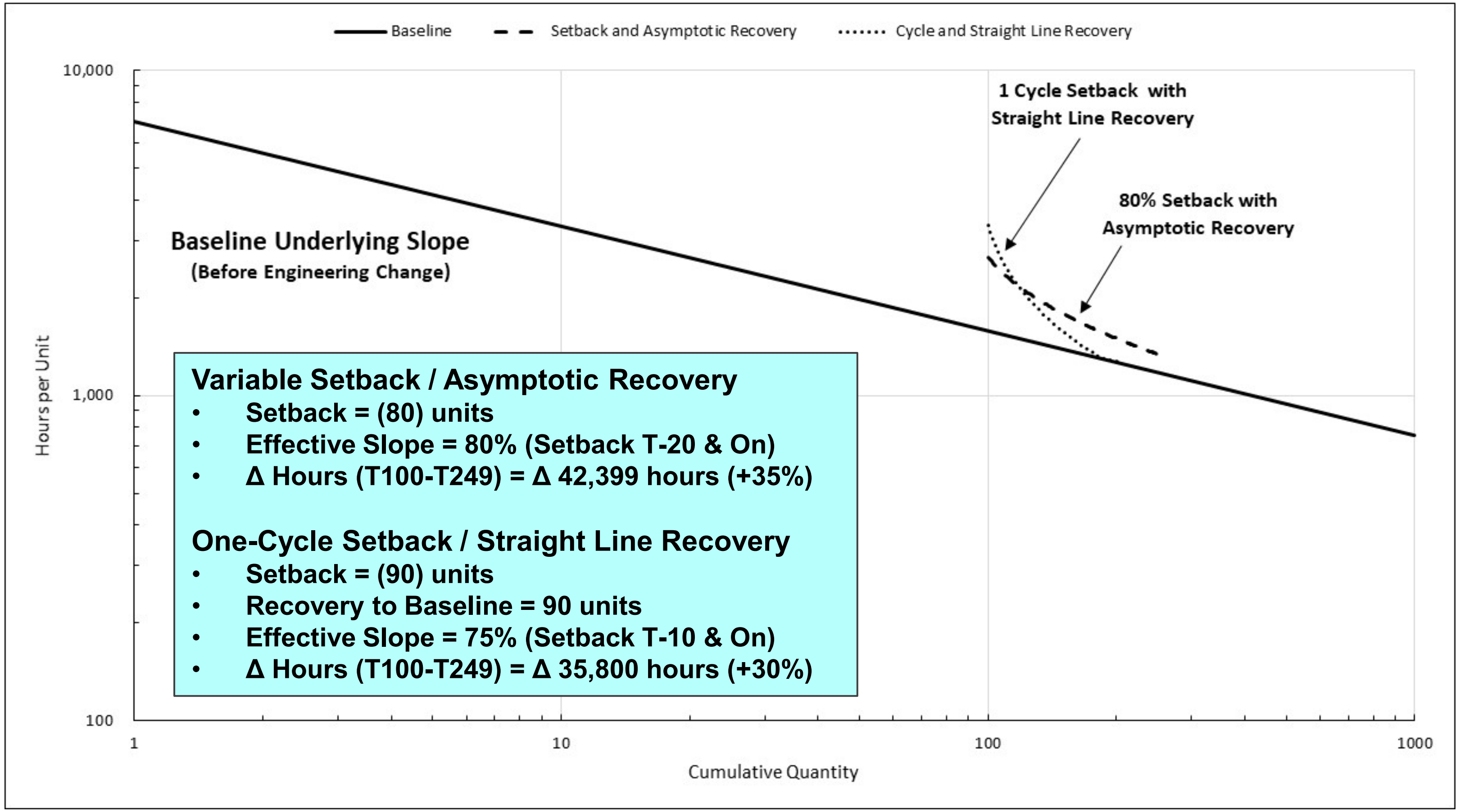
- **Setback is calculated as one logarithmic cycle away from the break-in point**
  - **Break-in at unit 700 will set back to unit 70 (700/10) = 70**
  - **An extensive change might set back two logarithmic cycles (700/100) = 7**

- **Traces back to the days of hand plotted charts on special paper pre-printed with logarithmic scales (not so long ago!)**

- **Combined with a straight line recovery to the baseline curve over a set number of units**
  - **Unlike asymptotic recovery approach, the HPU actually returns to the baseline curve**
  - **Extent of the change determines the number of units it takes to recovery (10 – 200 units)**

- **Unlike prior approach, amount of setback is fixed and the length of recovery slope varies with the extent of the design change**

One Cycle Setback with Straight Line Recovery



- **A one-cycle setback will usually produce higher HPU at the first post-change unit**
- **On the other hand, HPU will actually return to the underlying curve (not the case in the asymptotic recovery)**
- **Typically, asymptotic recovery generates higher estimates due to the slower recovery**

Application Requires Consistent Rules for Length of Recovery

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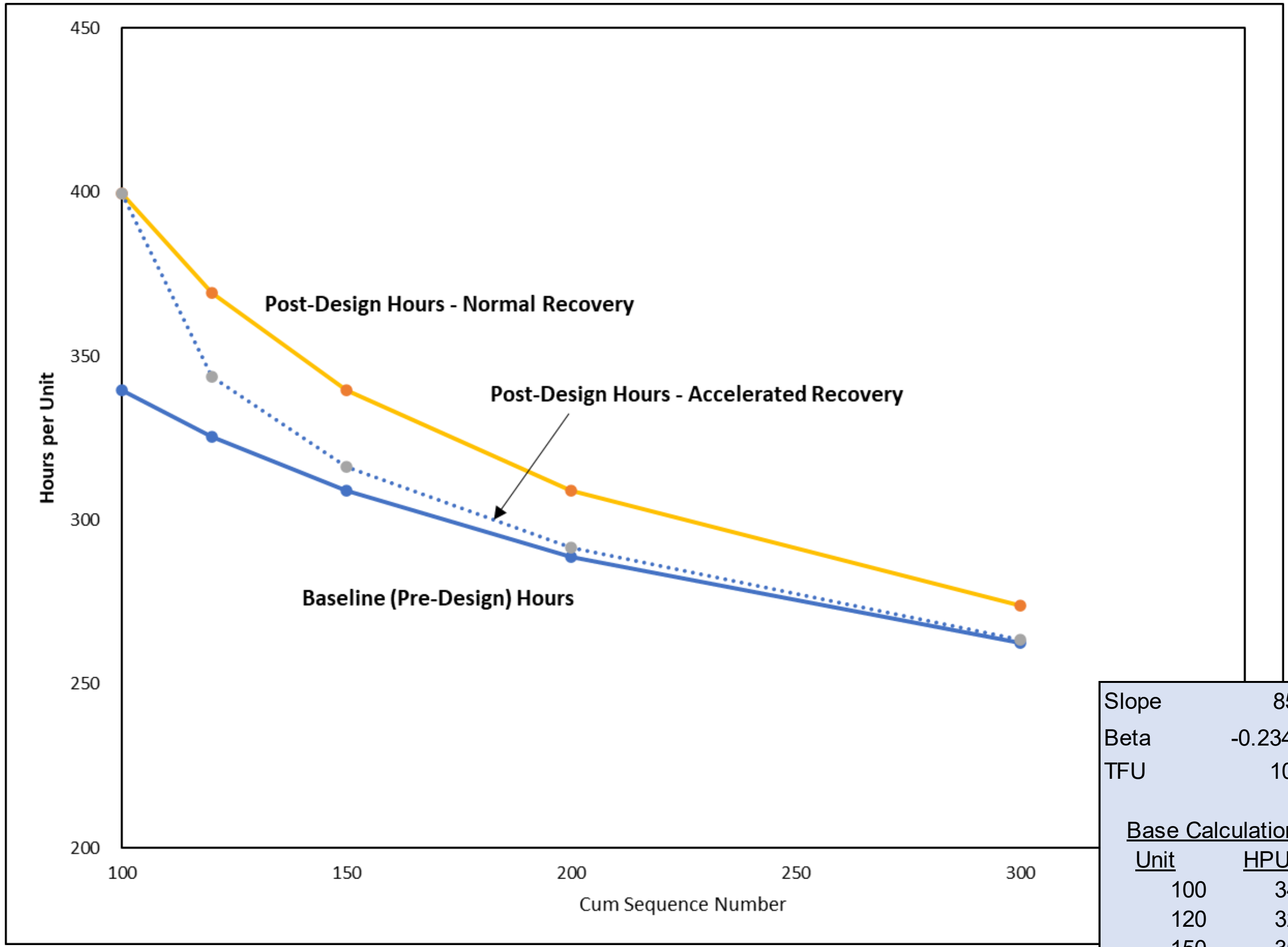
Setback Approaches, Compared

- Which approach is correct? There are pros and cons to each approach

Variable Setback/ Asymptotic Recovery	One-Cycle Setback/ Straight Line Recovery
• PRO - Variable setback more flexible, easier “sell” to customers	• CON – Strict one-cycle setback less flexible, harder “sell”
• PRO – Assumes recovery slope equal to previously achieved learning curve slope	• CON – One-cycle setback can result in very steep recovery slopes, particularly for small ECPs with rapid recoveries
• CON – At some point, the asymptotic delta becomes too small for concern	• PRO – Computationally easier, no need to carry insignificant deltas forever

Accelerated Recovery Curve



- **Asymptotic recovery approach can be modified in cases where a more accelerated recovery seems justified**
- **Cochran (1968) demonstrates a methodology to accelerate the recovery curve so it approaches the baseline HPU quicker**

$$k_n = \frac{d}{d + (n - n_1)}$$

where d is typically between 20 and 50 (the smaller d, the faster the recovery)

Slope	85%	d =	20 units					k = d / [d + (n - n_1)]				
Beta	-0.23447	n_1 =	100 units cum experience before break-in unit									
TFU	1000											
Base Calculation		50 Unit Setback - Normal Recovery				50 Unit Setback - Accelerated Recovery						
Unit	HPU	Setback	Unit	HPU	Delta	k	Setback	Unit	HPU	Delta		
100	340	-50	50	400	18%	1.00	-50	50	400	18%		
120	325	-50	70	369	13%	0.50	-25	95	344	6%		
150	309	-50	100	340	10%	0.29	-14	136	316	2%		
200	289	-50	150	309	7%	0.17	-8	192	292	1%		
300	263	-50	250	274	4%	0.09	-5	295	263	0%		

Example ECP

* Last unit built	200
* HPU at last unit built	60
* Assumed slope	80%
* Theoretical first unit (TFU)	330
* Setback	75%
* Equivalent last built	50

		HPU at Break
Added Task	10%	6.0
Reconfigured Task	25%	15.0
Deleted Task	-5%	(3.0)
No Change	70%	42.0
Total	100%	60.0

Baseline Slope (no Engineering Change)

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	201	250	225	50	8.7459	2,889	58
11	251	300	275	50	8.1975	2,708	54
12	301	350	325	50	7.7677	2,566	51
13	351	400	375	50	7.4177	2,450	49
14	401	450	425	50	7.1246	2,353	47
15	451	500	475	50	6.8739	2,271	45
				300	46.1273	15,236	51

* CFD = Cum Factor Difference (sum of learning curve unit factors over range of units in lot)

- **Let's go back to our hypothetical ECP…how many hours will this change cost over the next 300 units?**
- **Earlier we calculated the HPU by category (added / reconfigured / deleted) without reversionary impact**
- **First, let's calculate the hours as if there was no engineering change (baseline) from T-201 and on**

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Added Task

Added Task - Debit

Added Task Hours Before Setback	6.0		
Unit Factor at Break-In	0.1816		
Added Task TFU	33.0	10%	of total TFU

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	51	100	73	50	12.5291	414	8
11	101	150	124	50	10.5827	350	7
12	151	200	174	50	9.4864	313	6
13	201	250	225	50	8.7459	289	6
14	251	300	275	50	8.1975	271	5
15	301	350	325	50	7.7677	257	5
				300	57.3093	1,893	6

- **Using the variable setback / asymptotic recovery methodology, we'll calculate the added task**
- **Using a 75% setback, the added task is calculated at T-51 and on**

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Reconfigured Task

Reconfigured Task - Credit

Reconfigured Task Hours Before Setback	(15.0)		
Unit Factor at Break-In	0.1816		
Reconfigured Task TFU	(82.6)	-25%	of total TFU

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	201	250	225	50	8.7459	(722)	(14)
11	251	300	275	50	8.1975	(677)	(14)
12	301	350	325	50	7.7677	(641)	(13)
13	351	400	375	50	7.4177	(613)	(12)
14	401	450	425	50	7.1246	(588)	(12)
15	451	500	475	50	6.8739	(568)	(11)
				300	46.1273	(3,809)	(13)

Reconfigured Task - Debit

Reconfigured Task Hours Before Setback	15.0		
Unit Factor at Break-In	0.1816		
Reconfigured Task TFU	82.6	25%	of total TFU

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	51	100	73	50	12.5291	1,035	21
11	101	150	124	50	10.5827	874	17
12	151	200	174	50	9.4864	783	16
13	201	250	225	50	8.7459	722	14
14	251	300	275	50	8.1975	677	14
15	301	350	325	50	7.7677	641	13
				300	57.3093	4,732	16
					Delta Hours for Reconfigured Tasks	923	3

- **Reconfigured task impacts are calculated in two steps**
- **First, calculate a credit without setback at T-201 and on**
- **Second, calculate a debit with reversionary impact at T-51 and on**
- **The sum of the two will be the delta hours (over and above the baseline) for reconfigured tasks**

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Deleted Task

Deleted Task - Credit

Deleted Task Hours Before Setback	(3.0)		
Unit Factor at Break-In	0.1816		
Deleted Task TFU	(16.5)	5%	of total TFU

Lot	From	To	Midpt	Qty	CFD	Hours	HPU
10	201	250	225	50	8.7459	(144)	(3)
11	251	300	275	50	8.1975	(135)	(3)
12	301	350	325	50	7.7677	(128)	(3)
13	351	400	375	50	7.4177	(123)	(2)
14	401	450	425	50	7.1246	(118)	(2)
15	451	500	475	50	6.8739	(114)	(2)
				300	46.1273	(762)	(3)

- **The deleted task is calculated as a credit at T-201 and on**

Summary of Changes

Sum of the Totals

Lot	Baseline	Credit Reconfig	Debit Reconfig	Debit Added	Credit Deleted	Total Hours	HPU	% Delta
10	2,889	(722)	1,035	414	(144)	3,471	69	20.1%
11	2,708	(677)	874	350	(135)	3,119	62	15.2%
12	2,566	(641)	783	313	(128)	2,893	58	12.7%
13	2,450	(613)	722	289	(123)	2,726	55	11.3%
14	2,353	(588)	677	271	(118)	2,595	52	10.3%
15	2,271	(568)	641	257	(114)	2,487	50	9.6%
	15,236	(3,809)	4,732	1,893	(762)	17,291	58	13.5%

Baseline Hours (Lots 10-15)		15,236
Debits:		
Added Task	1,893	
Reconfigured Task Delta	923	
Credits:		
Deleted Task	(762)	
Total Cost of Change	2,055	
ECP Hours (Lots 10-15)		17,291

- **Adding the debits and credits will yield the total cost of the change**
- **Note that the delta percentage declines lot over lot as we approach the baseline (pre-change) HPU**

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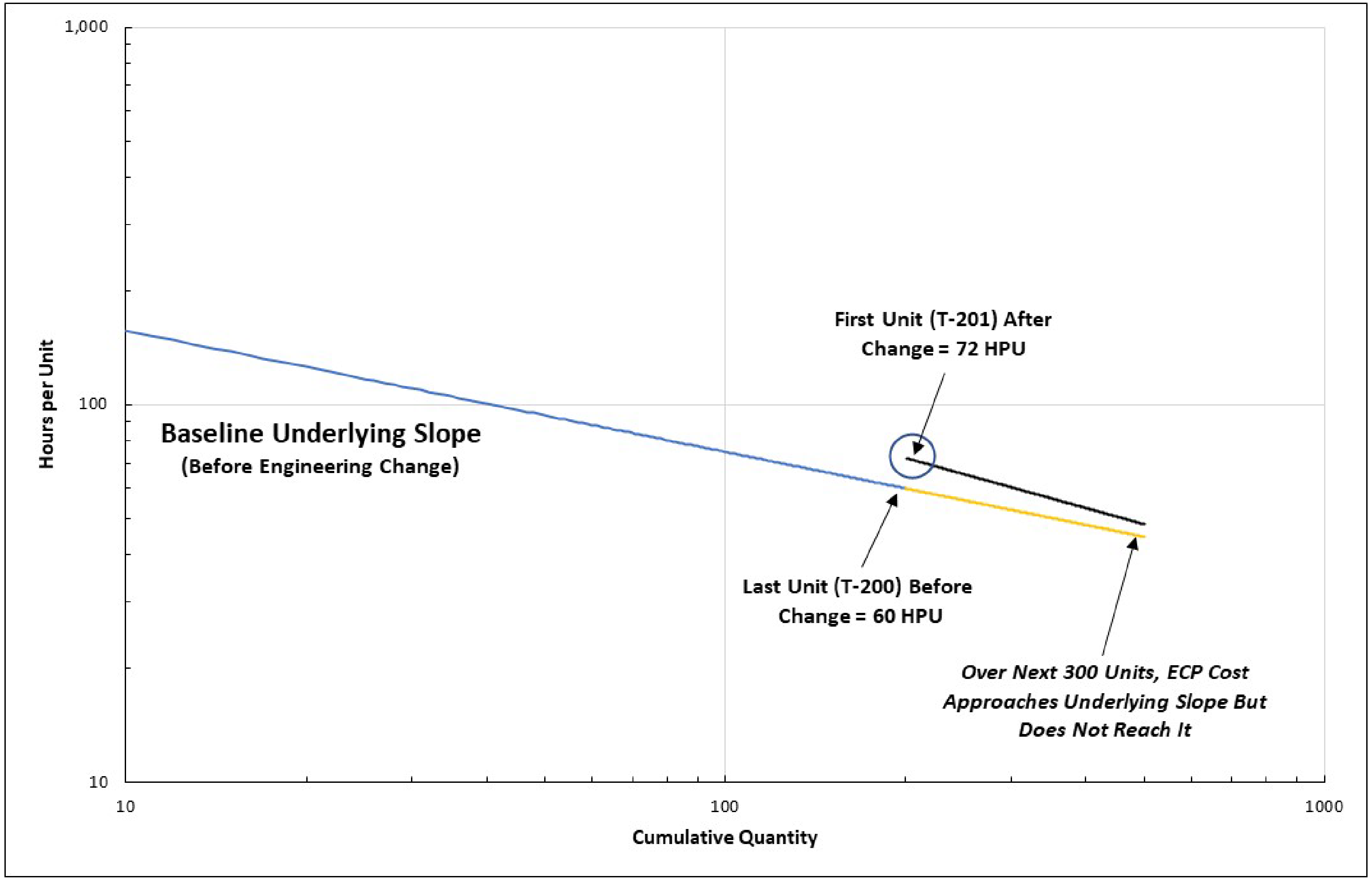
ECP Example Graphed



- **Our ECP example displayed graphically…**
- **Note that the “scallop” pattern for the post-change HPU observed in previous charts is not so pronounced….that’s because in our example, 70% of the task was unaffected by the change**

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Conclusions

- **Analytical breakdown of ECP by task is critical**
  - **What is added, what is deleted, what is reconfigured**
- **Every engineering change must consider reversionary impact**
- **Two methods for calculating reversionary impact:**
  - **Variable setback / asymptotic recovery**
  - **One-cycle setback / straight line recovery**
- **Rules-based system for establishing setback (variable setback) or length of recovery (straight line recovery) can be helpful**
- **Example application shows how each category is considered – adds, deletes and reconfigurations**

"Everything changes, and nothing stands still" - Heraclitus

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