Second Source Manufacturing: Lessons from the Second World War

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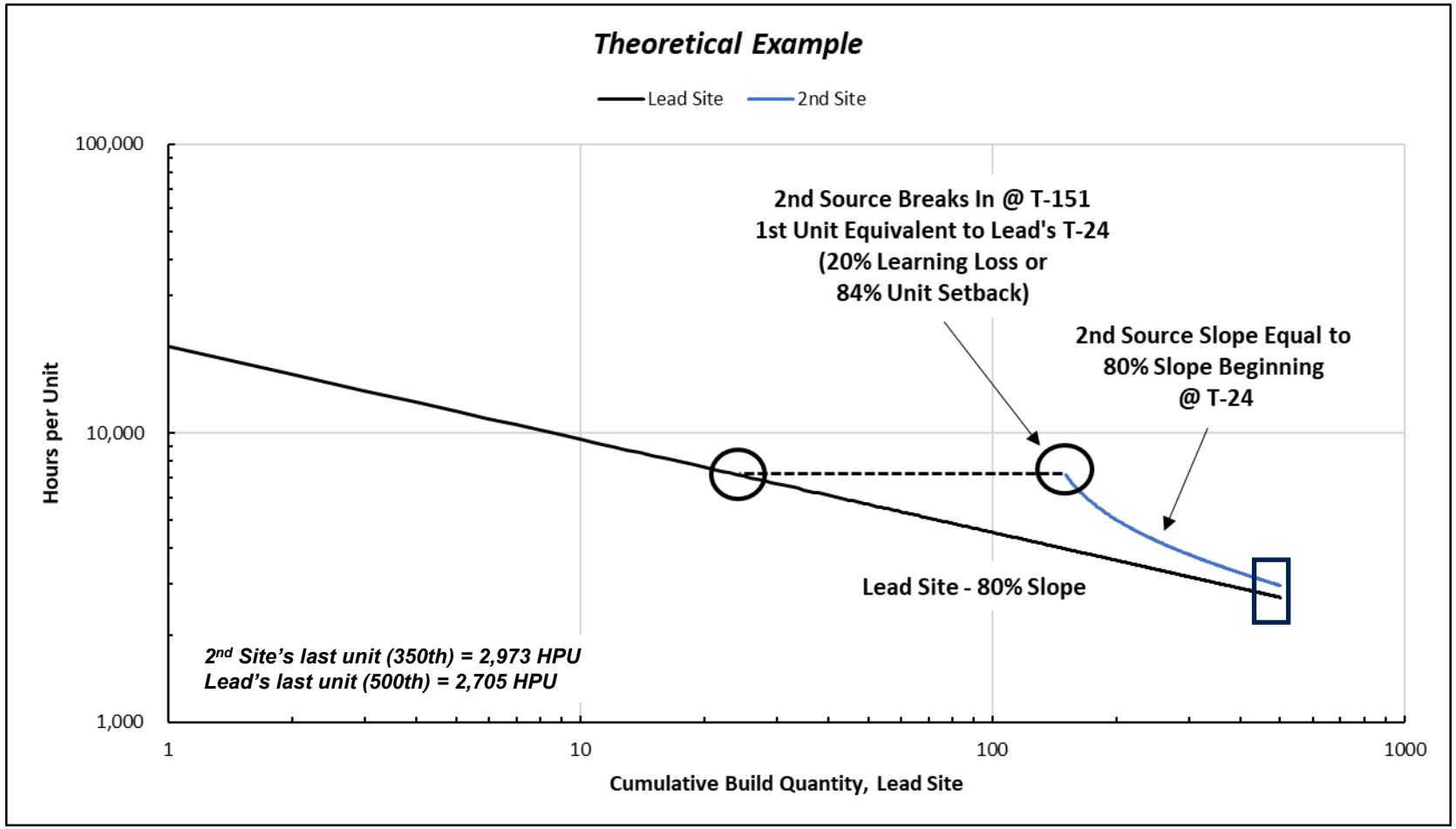
Introduction

- **Estimators may be asked to determine impact of building the same product at two different manufacturing sites**

- **Why might this happen?**
  - **Production at different facilities owned by same company**
    - **Boeing 787 Dreamliner produced simultaneously in Washington & South Carolina (2011-2021)**
  - **Foreign coproduction**
    - **Examples: F-86, T-33, T-34, S-2, P-2H, F-104, F-5, F-4, P-3C, F-16, AV-8B, F-35**
    - **Coproducer may be responsible for complete aircraft build, components, or mate through delivery**
  - **International cooperative ventures**
    - **Examples: Jaguar, Tornado, Eurofighter Typhoon, Airbus commercial**
  - **Competing companies producing same item**
    - **More common in missile production (AMRAAM, Hellfire, Maverick, Phoenix, Sparrow, Sidewinder, Tomahawk)**

- **Not to be confused with typical workshare arrangement, where two or more companies work together but don't make the same components**

Hypothetical Example

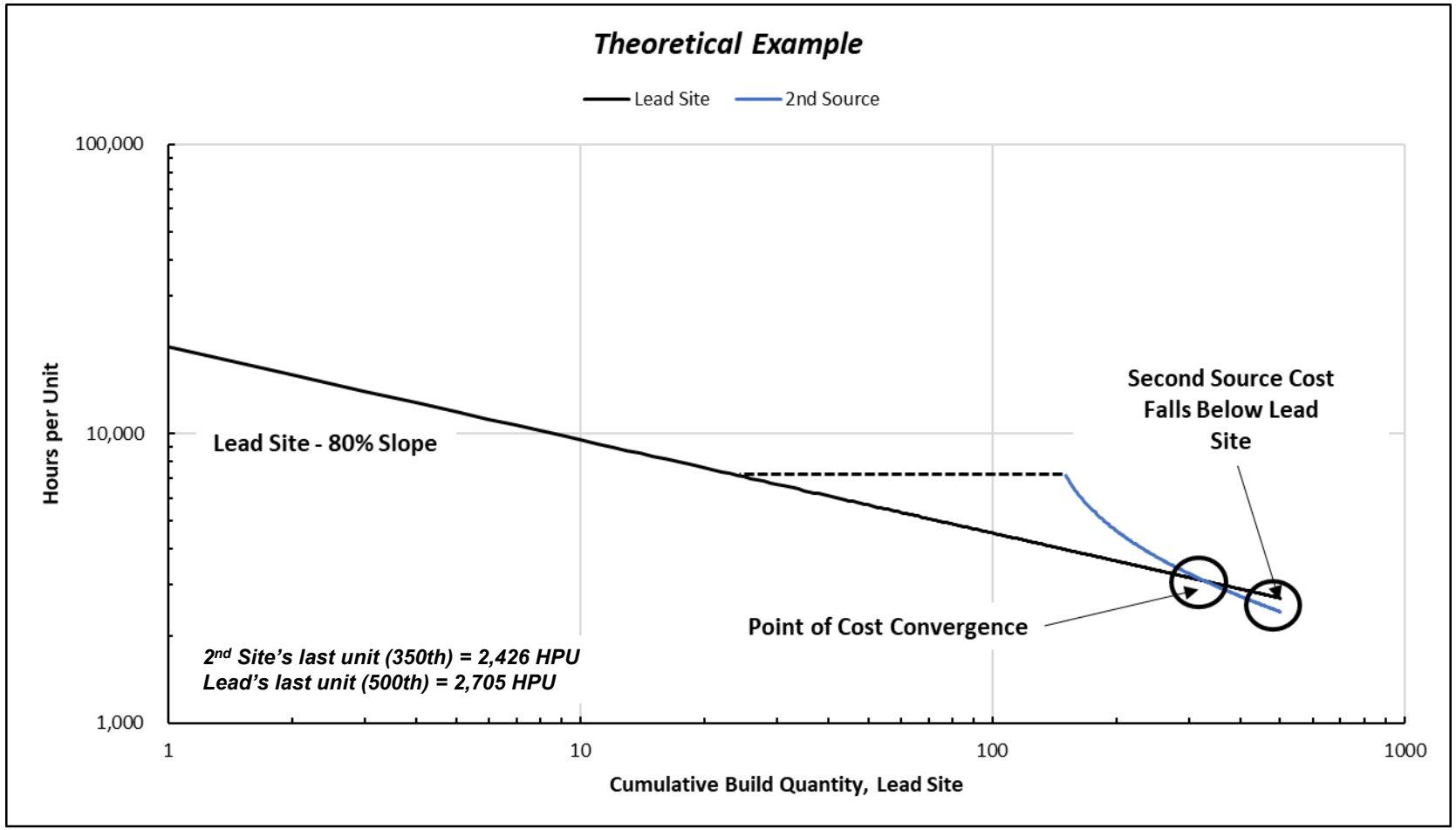


Questions:

- How much learning can be transferred from the lead site to the second source?
- What kind of learning curve slope will the second source achieve beginning at its break-in unit?
- Is it possible for the second site's learning curve to intersect the lead site's?
- Is it possible for the second site to produce at a lower cost than the lead site?

The second source never converges with the lead site's cost

Hypothetical Example (II)



- **Suppose we assume the second source achieves a 76% slope from setback unit #24 and on (versus the lead site's 80% slope)**
- **Now it intersects the lead site's learning curve and it ends program producing at a lower hours per unit than the lead**

So much for assumptions…what guidance exists for the estimator?

Four Propositions To Be Tested

- **Some learning will be transferred to the second source – it will not begin back at T-1 – but not all the lead's learning will be transferred.**
- **A strong effort by the lead to promote technology transfer should result in less learning loss**
- **The second source will not fully converge to the lead's learning curve – that is, the two learning curves will not intersect**
  - **Said differently, the second source's learning curve slope (measured from the setback unit) will be equal to or greater than the lead company's**
- **The second source will not be able to produce at a lower cost than the lead company – the coproducer's best hours per pound will be greater than the lead company's best hours per pound**

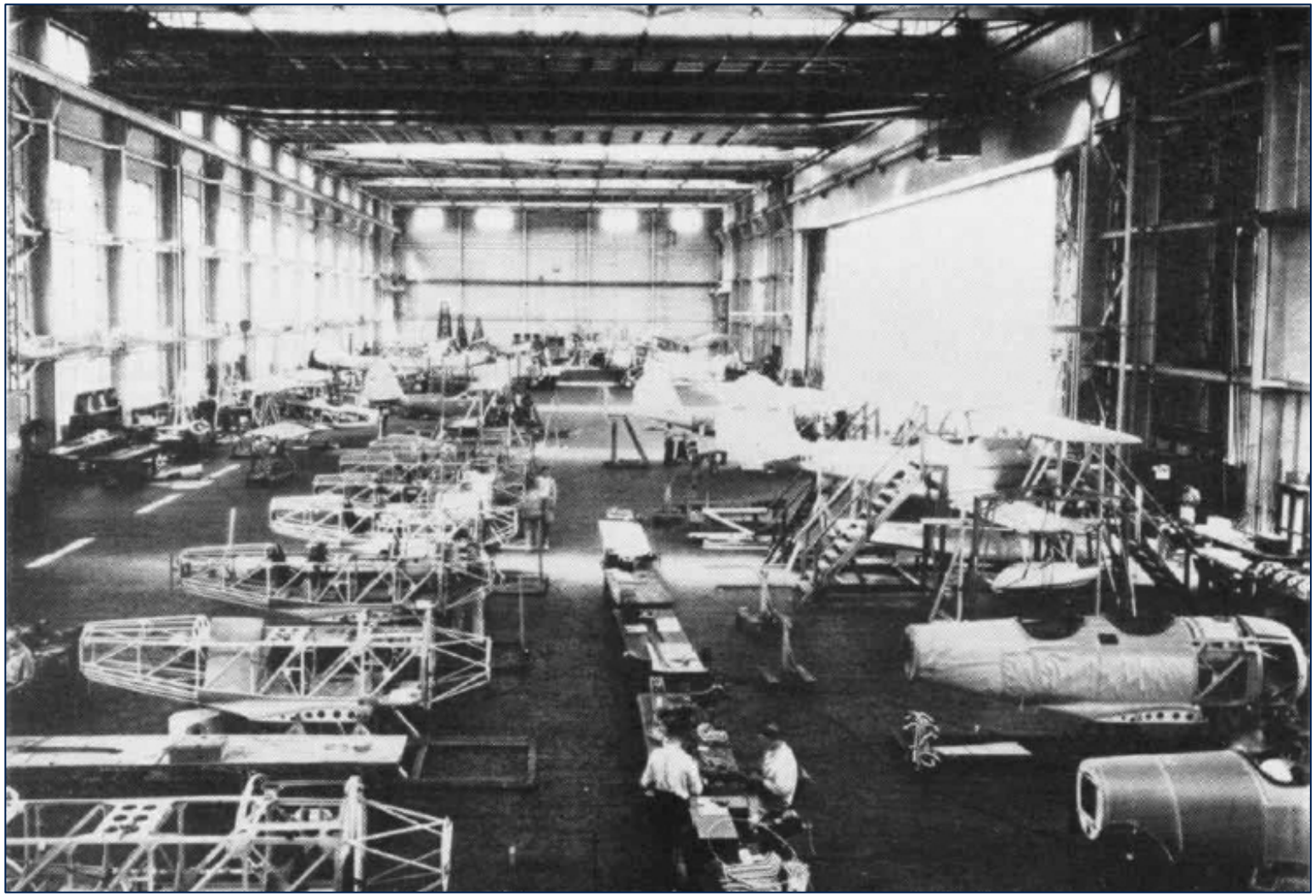
Is there a public domain dataset we can use to test these assumptions?

Multiple-Site Manufacturing Data

- **Current data is closely-held proprietary information**
- **But there *is* a dataset which is public domain and which has been used for a variety of learning curve studies over the years: *Source Book of World War II Basic Data***
- **Provides hours per unit and hours per pound data per month by model and company – with a number of examples where the same aircraft model was built at different sites**
- **Although the data is "old," it can still provide valuable insights into learning transfer and learning curve performance**

At the end, we will compare results at a high level to modern day examples to see if our conclusions are still valid

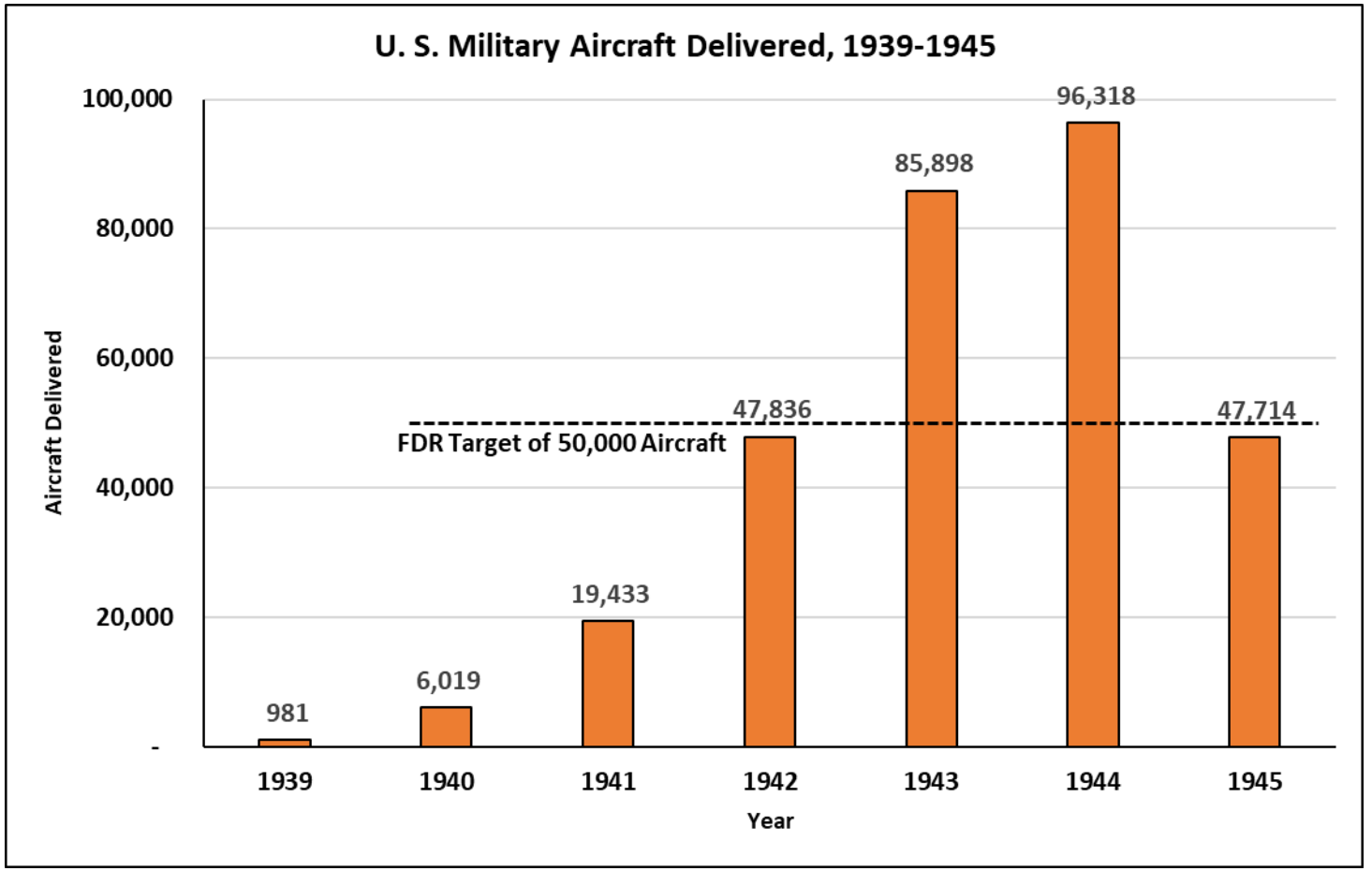
The Pre-War Aircraft Industry



N3N Trainer Production, Naval Aircraft Factory, Philadelphia, Pennsylvania (1937)

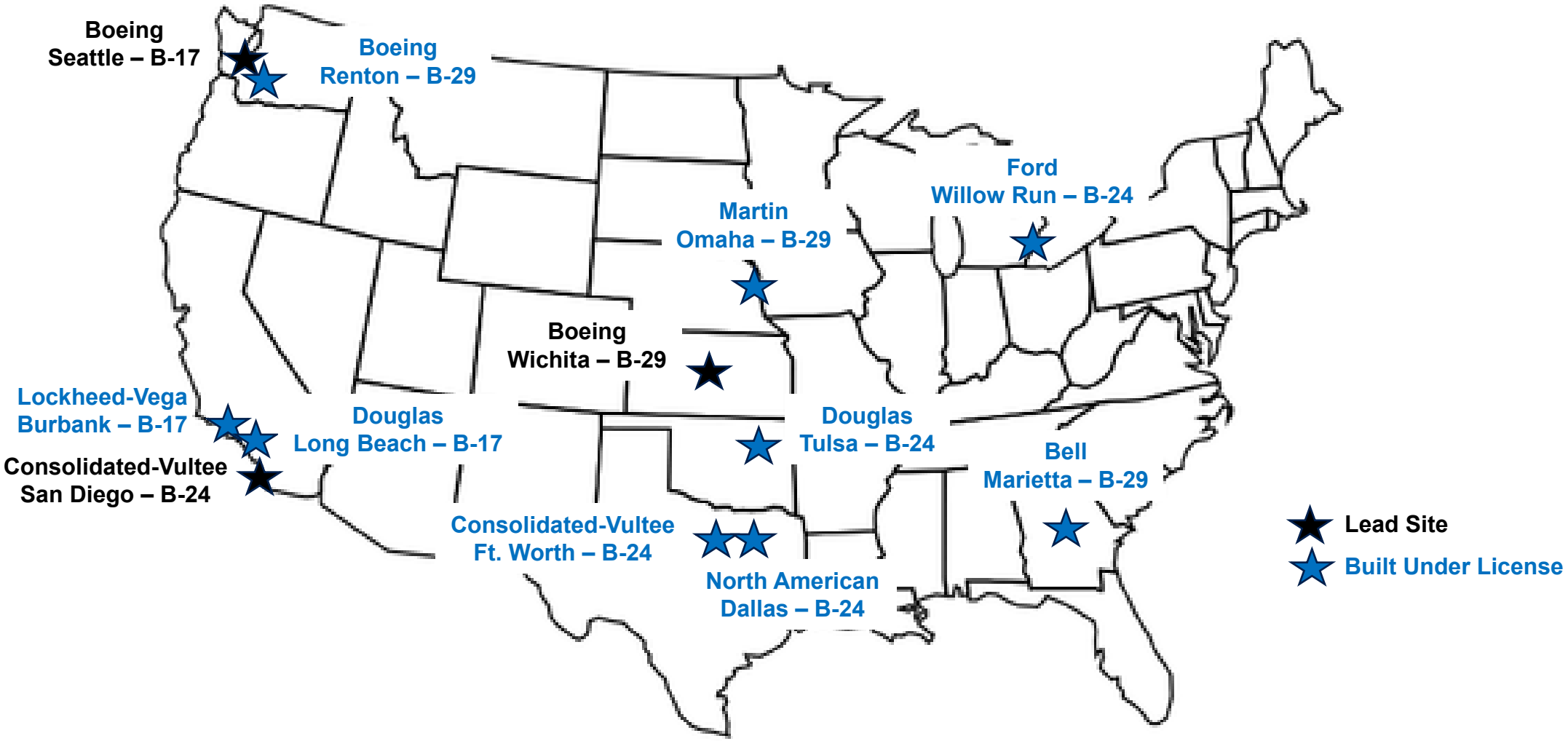
- US aircraft industry before World War II was not designed for mass production
- Aircraft made in small quantities in an artesian “job shop” environment
- Typically aircraft not moved down an assembly line, but built in one spot on the factory floor in their entirety
- US aircraft industry employed 36,000 people in 1938 – less than the knit-hosiery industry

World War II: The Challenge



"I should like to see this nation geared up to the ability to turn out at least 50,000 planes a year."
- President Franklin D. Roosevelt, May 1940 Address to Congress

Heavy Bomber Production Sites, 1940-1945



B-17 Flying Fortress

B-17, 323rd Bombardment Group (Europe)

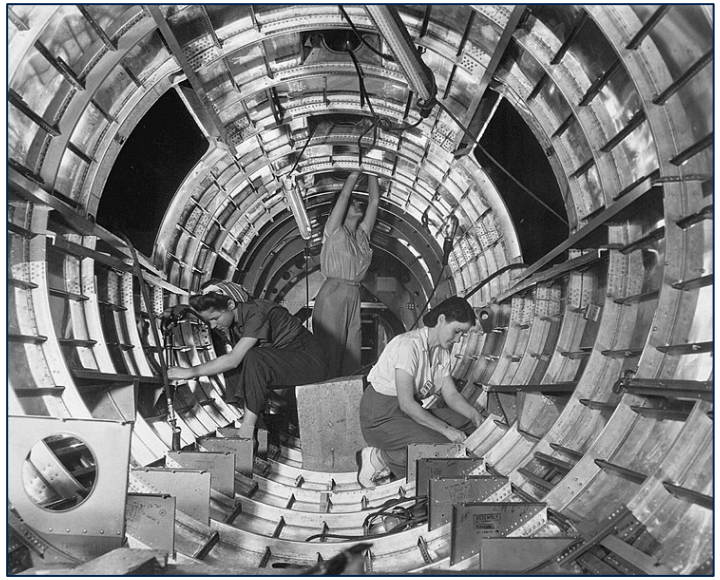
Lead Site:
- **Boeing (Seattle)**

Additional Sites:
- **Lockheed-Vega (Burbank)**
- **Douglas (Long Beach)**

Total Production (1940-1945):
12,692 Aircraft

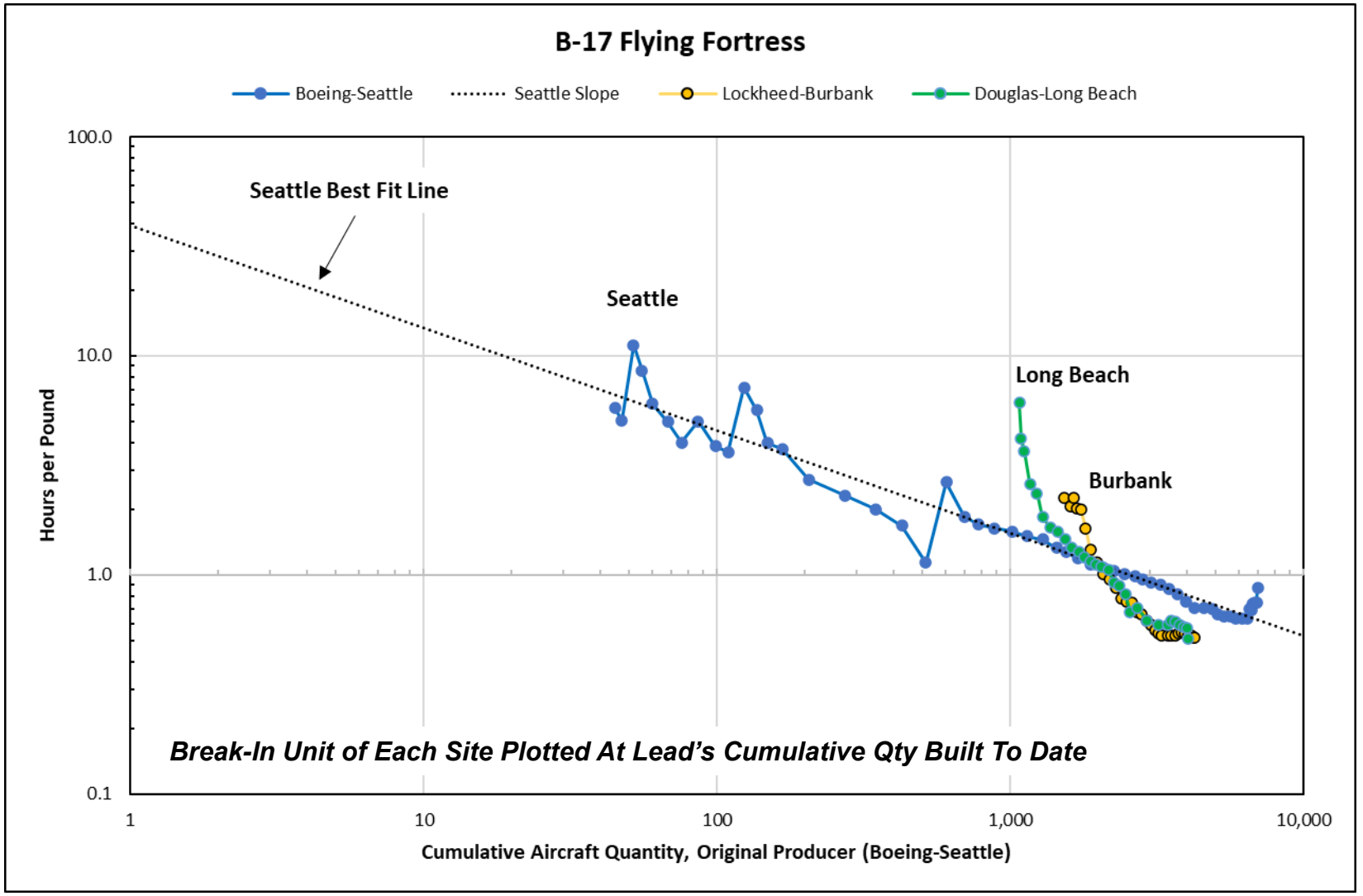
Average Flyaway Cost (1944):
$204K (Then-Year)
$3.2M (CY2021)

B-17 Hours Per Pound



B-17 Fuselage Assembly, Long Beach, California

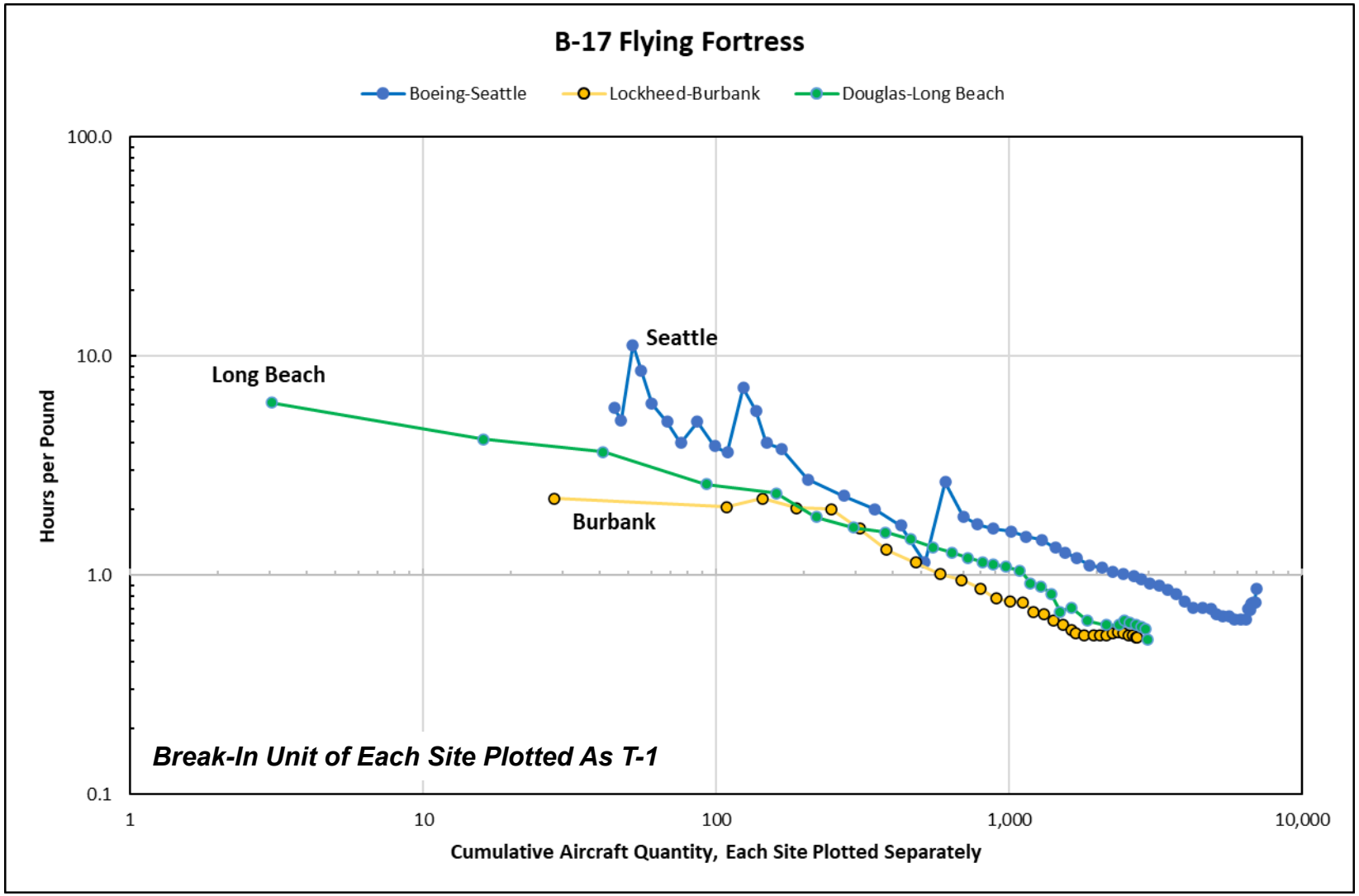
- **Burbank & Long Beach converged to Seattle's learning curve**



B-17 Hours Per Pound

B-17 Fuselage Assembly, Seattle, Washington

- **Burbank & Long Beach able to produce at lower hours per pound than Seattle**



B-17 Performance Summary

B-17 Assembly Worker, Long Beach, California

B-17 Flying Fortress		*Lead* **Boeing Seattle**	*Coproducer* **Douglas Long Beach**	*Coproducer* **Lockheed Burbank**
Initial Build Plotted as T-1	Actual 1st Lot (Hrs/Lb)	5.79	6.12	2.24
	Theoretical First Unit (TFU) (Hrs/Lb)	39.57	13.79	16.31
	Unit Curve Coefficient	(0.4689)	(0.3886)	(0.4406)
	Unit Curve Slope	72.3%	76.4%	73.7%
	R-Square (R^2)	94.2%	95.4%	92.3%
	Minimum Hrs/Lb	0.63	0.51	0.52
Initial Build Plotted at Setback Unit #	Setback Unit on Lead's Learning Curve	N/A	54	457
	% Learning Loss	N/A	12.1%	2.5%
	% Unit Setback	N/A	95.0%	69.5%
	Unit Curve Slope	N/A	67.9%	55.1%
Additional Data	1st Delivery	1938	Oct-42	Jan-43
	Prior Units Produced by Lead	N/A	1,073	1,495
	Total Aircraft Built	6,981	3,000	2,750
	Achieve Convergence to Lead's Learning Curve?	N/A	Yes	Yes
	Achieve Lower Cost Than Lead?	N/A	Yes	Yes

- **Very low rates of learning loss (2% Burbank, 12% for Long Beach)**
  - **High level of cross-company coordination (so-called "BDV committee") coordinating material purchases, master production schedules, engineering releases, inspection criteria & production lessons learned**
- **Very steep learning curves (55% Burbank, 68% Long Beach) relative to Seattle (72%)**

B-24 Liberator

B-24 Liberators, 33rd Bombardment Squadron (Europe)

Lead Site:
- **Consolidated-Vultee (San Diego)**

Additional Sites:
- **Consolidated-Vultee (Fort Worth)**
- **Ford Motor (Willow Run)**
- **Douglas (Tulsa)**
- **North American (Dallas)**

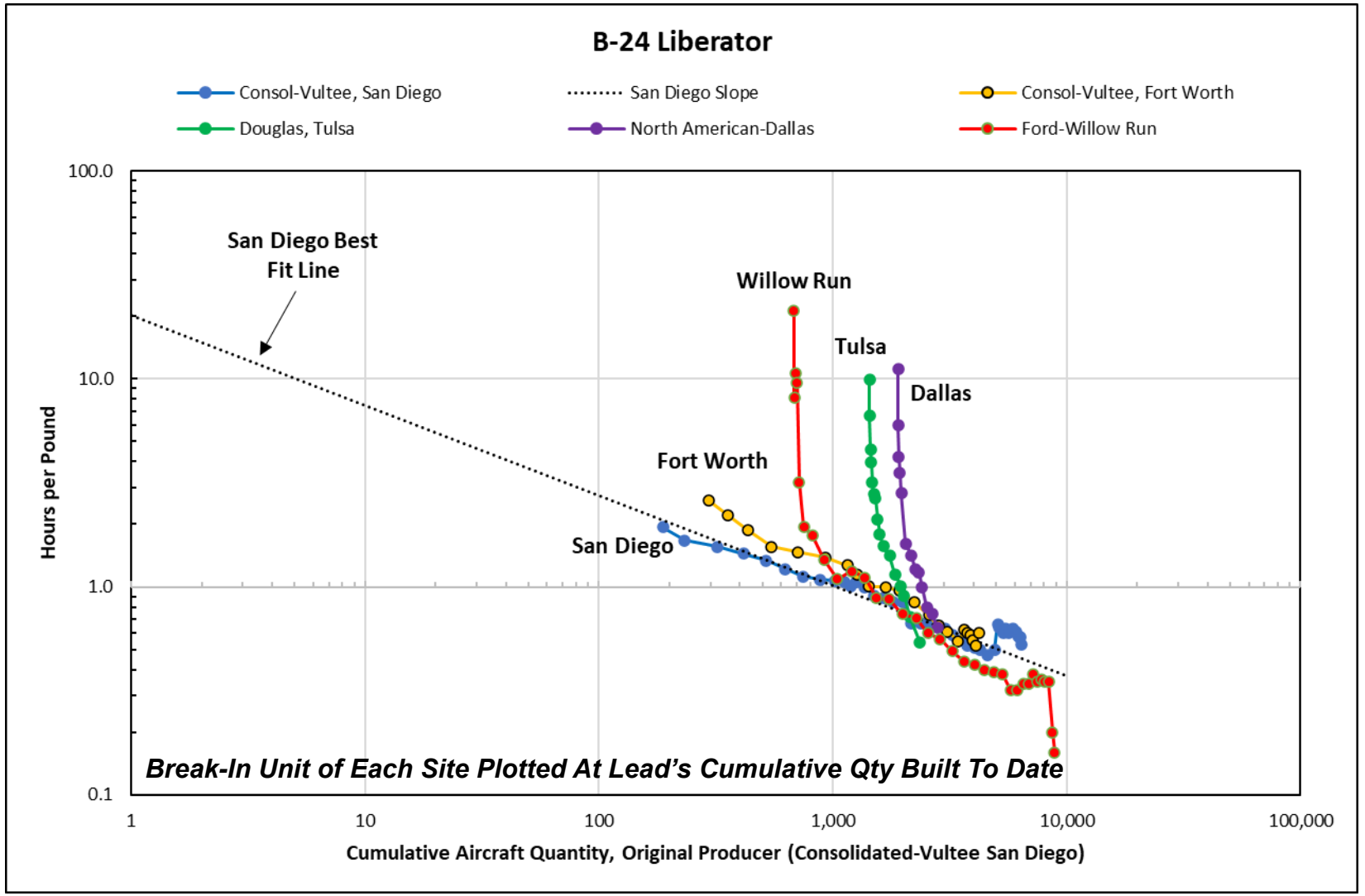
Total Production (1940-1945):
18,190 Aircraft

Average Flyaway Cost (1944):
$216K (Then-Year)
$3.4M (CY2021)

B-24 Hours Per Pound

B-24 Final Assembly, Fort Worth, Texas

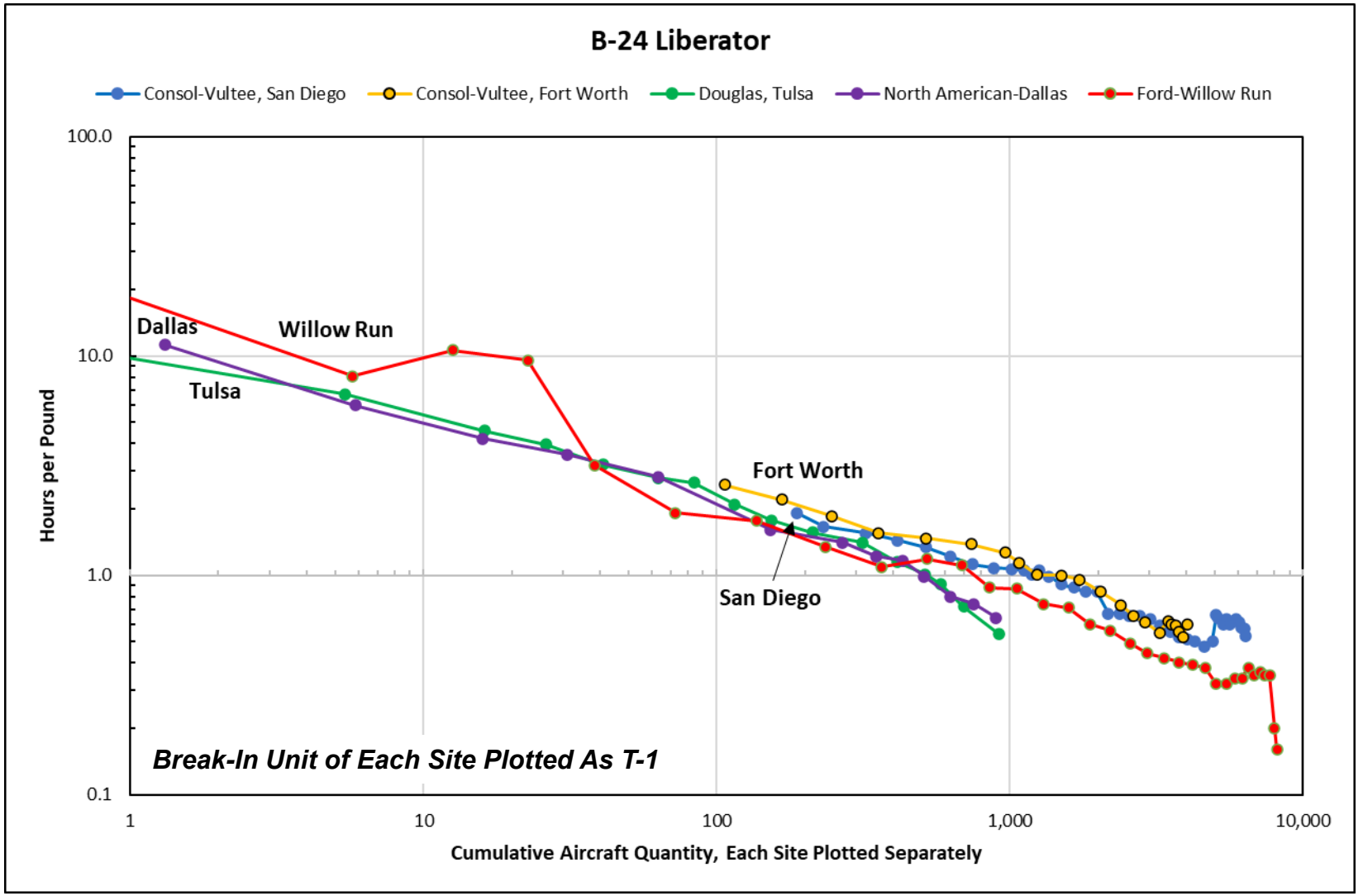
- **Fort Worth, Willow Run, Tulsa & Dallas all converged to San Diego's learning curve**



B-24 Hours Per Pound

B-24 Final Assembly, San Diego, California

- **Willow Run was able to produce at lower hours per pound**



The Willow Run Story

Inside the [Consolidated] plant I watched men putting together wing sections and portions of the fuselage…. [W]hat I saw reminded me of nearly thirty-five years previously when we were making Model N Fords…before we achieved the orderly sequence of the assembly line and mass production.

The nearer a B-24 came to its final assembly the fewer principles of mass production there were as we at Ford had developed and applied over the years. Here was a custom-made plane, put together as a tailor would cut and fit a suit of clothes.

The B-24's final assembly was made out of doors under the bright California sun and on a structural steel fixture. The heat and temperature changes so distorted this fixture that it was impossible to turn out two planes alike without further adjustment….[I]t was obvious that if the wing sections had uniform measurements, the way we made parts for automobiles, they would not fit properly under out-of-doors assembly conditions.

All this was pretty discouraging, and I said so. Naturally, and quite properly, the reply was "How would you do it?" I had to put up or shut up. "I'll have something for you tomorrow morning," I said.

-- Charles Sorensen, *My Forty Years at Ford*

- **Ford Motor rejected Consolidated's assembly approach in favor of an automotive-based process**
  - **New plant based on automobile mass production principles**
  - **Enormous investment in tooling ($1-1.5B today's dollars)**
  - **Planned for a B-24 delivered every hour (>700/month)**
- **Substantial growing pains**
  - **Could not reconcile Consolidated's drawings to what was required to build the part on the shop floor**
  - **Eventually re-drew 30,000 engineering drawings**
  - **Struggled with thousands of engineering design changes**
  - **Built 21,000 jigs and tools but scrapped 10,000**
- **No learning gain experienced (Ford's first unit cost higher than Consolidated-San Diego's)**
- **Once initial problems were overcome, Ford became most cost-effective B-24 supplier**
  - **Eventually produced over 400 aircraft per month at a lower hours per pound than any other B-24 site**

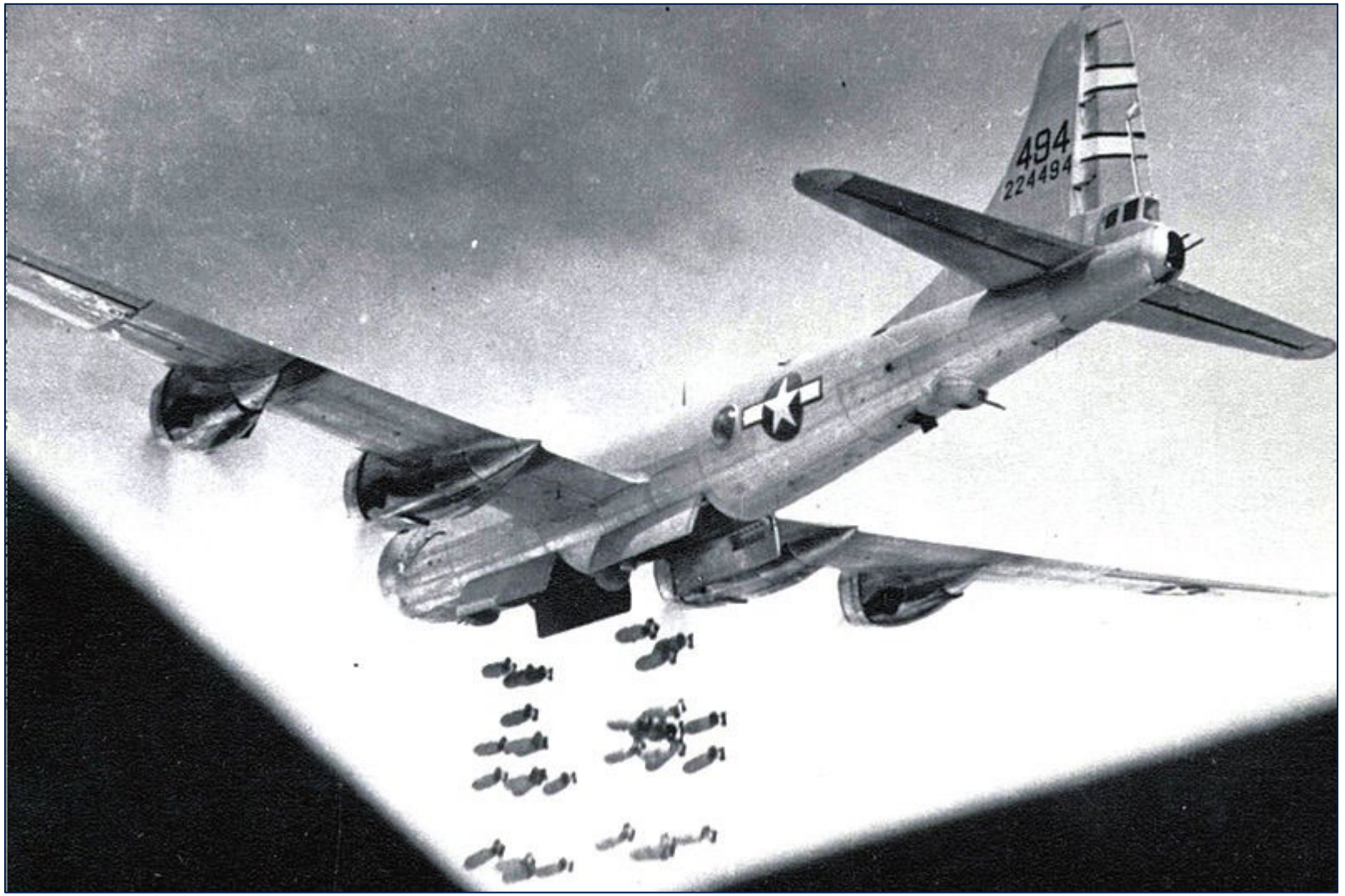
B-24 Performance Summary

B-24 Assembly Worker, Willow Run, Michigan

B-24 Liberator		*Lead* Consol-V San Diego	*Coproducer* Consol-V Fort Worth	*Coproducer* Ford Willow Run	*Coproducer* Douglas Tulsa	*Coproducer* N. American Dallas
Initial Build Plotted as T-1	Actual 1st Lot (Hrs/Lb)	1.93	2.59	21.25	9.91	11.21
	Theoretical First Unit (TFU) (Hrs/Lb)	20.10	22.18	22.95	13.53	13.74
	Unit Curve Coefficient	(0.3641)	(0.4393)	(0.4882)	(0.4146)	(0.4249)
	Unit Curve Slope	77.7%	73.7%	71.3%	75.0%	74.5%
	R-Square (R^2)	91.8%	96.7%	96.4%	95.5%	98.5%
	Minimum Hrs/Lb	0.47	0.52	0.16	0.54	0.64
Initial Build Plotted at Setback Unit #	Setback Unit on Lead's Learning Curve	N/A	113	1	5	4
	% Learning Loss	N/A	2.8%	106.1%	47.0%	54.0%
	% Unit Setback	N/A	39.9%	99.9%	99.6%	99.8%
	Unit Curve Slope	N/A	72.6%	71.0%	70.2%	71.3%
Additional Data	1st Delivery	Early 1940	Apr-42	Sep-42	Apr-43	Jul-43
	Prior Units Produced by Lead	N/A	188	680	1,433	1,897
	Total Aircraft Built	6,435	4,105	8,233	1,052	1,000
	Achieve Convergence to Lead's Learning Curve?	N/A	Yes	Yes	Yes	Yes
	Achieve Lower Cost Than Lead?	N/A	No	Yes	No	No

- **Wide range of learning loss (3% Fort Worth to 106% for Willow Run)**
  - **No coordinating committee like B-17 & B-29**
  - **San Diego provided cadre of engineers & management to new sister plant in Fort Worth**
  - **Dallas had issues with drawings provided by Willow Run, communication of engineering changes**
- **Steeper learning curves for coproducers (70% - 73% slopes) relative to San Diego (78%)**

B-29 Superfortress



B-29, 468th Bombardment Group (Pacific)

Lead Site:
- **Boeing (Wichita)**

Additional Sites:
- **Bell (Marietta)**
- **Boeing (Renton)**
- **Martin (Omaha)**

Total Production (1943-1945):
3,898 Aircraft

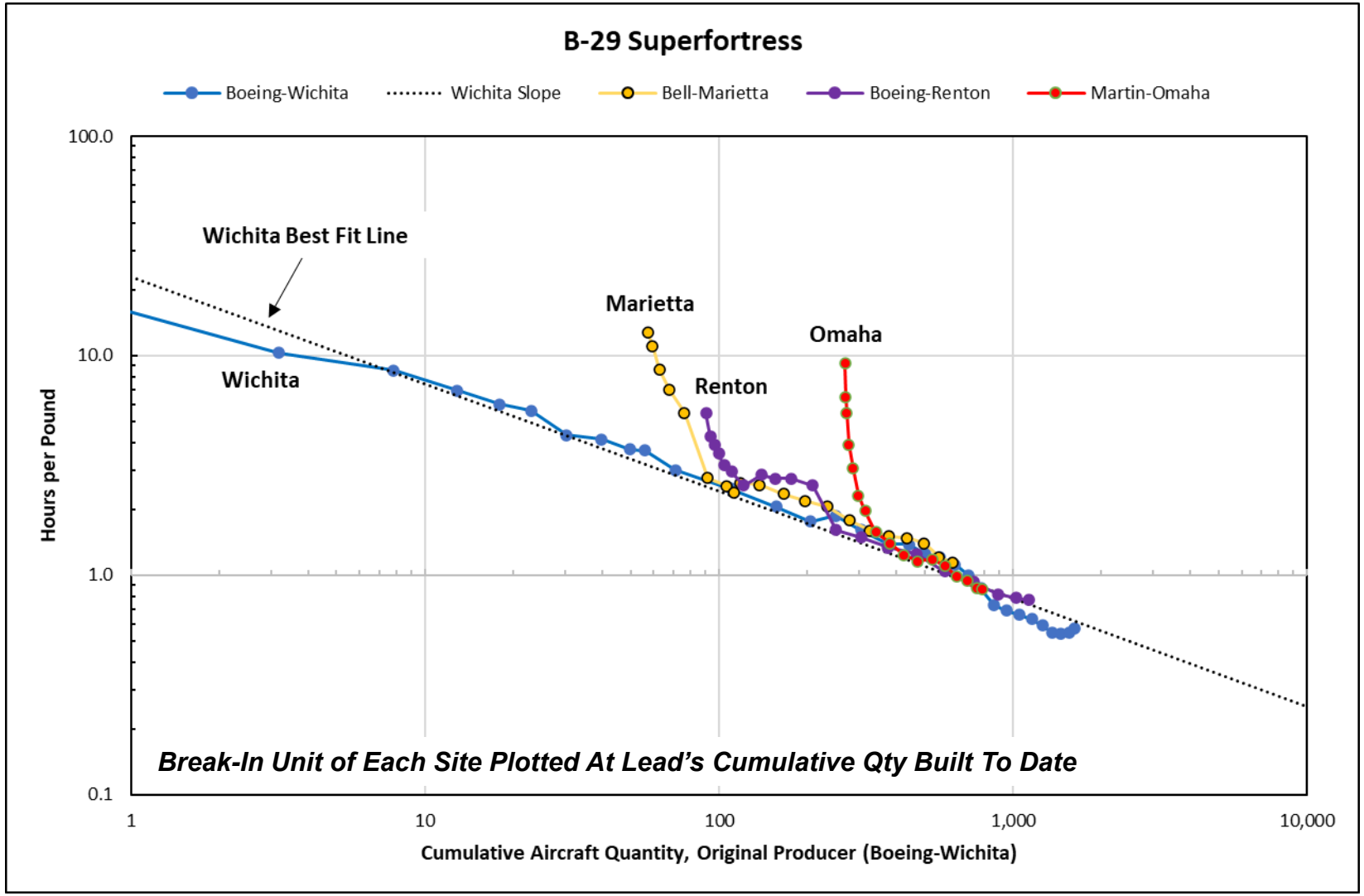
Average Flyaway Cost (1944):
$639K (Then-Year)
$9.9M (CY2021)

Total Cost of Program:
$3B (Then-Year)
$45B (CY2021)

B-29 Hours Per Pound

B-29 Final Assembly, Wichita, Kansas

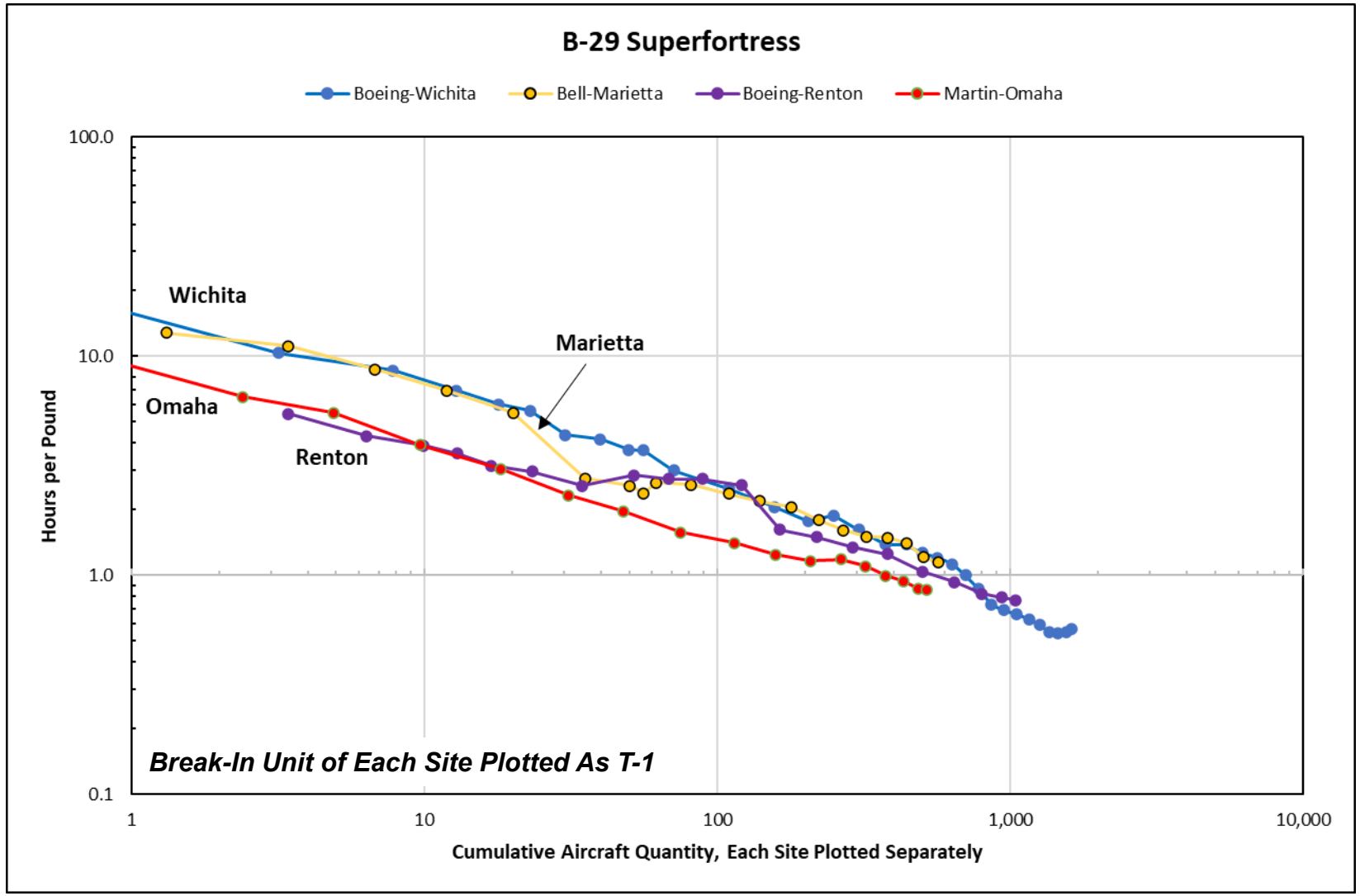
- Renton & Omaha converged to Wichita's learning curve
- Marietta briefly converged, then stayed above



B-29 Hours Per Pound

B-29 Superfortress

- No site was able to produce at lower hours per pound than Wichita



B-29 Performance Summary

B-29s Post-Delivery, Wichita, Kansas

B-29 Superfortress		*Lead* **Boeing Wichita**	*Coproducer* **Bell Marietta**	*Coproducer* **Boeing Renton**	*Coproducer* **Martin Omaha**
Initial Build Plotted as T-1	Actual 1st Lot (Hrs/Lb)	16.15	12.77	5.45	9.25
	Theoretical First Unit (TFU) (Hrs/Lb)	22.81	16.30	9.09	9.05
	Unit Curve Coefficient	(0.4883)	(0.4168)	(0.3382)	(0.3793)
	Unit Curve Slope	71.3%	74.9%	79.1%	76.9%
	R-Square (R^2)	97.8%	96.6%	94.0%	99.4%
	Minimum Hrs/Lb	0.54	1.14	0.77	0.86
Initial Build Plotted at Setback Unit #	Setback Unit on Lead's Learning Curve	N/A	3	19	6
	% Learning Loss	N/A	48.8%	14.2%	36.4%
	% Unit Setback	N/A	94.1%	78.4%	97.6%
	Unit Curve Slope	N/A	72.2%	73.4%	71.7%
Additional Data	1st Delivery	Feb-43	Dec-43	Feb-44	May-44
	Prior Units Produced by Lead	N/A	56	87	267
	Total Aircraft Built	1,642	636	1,096	531
	Achieve Convergence to Lead's Learning Curve?	N/A	No	Yes	Yes
	Achieve Lower Cost Than Lead?	N/A	No	No	No

- **Wide range of learning loss (14% Renton to 49% Marietta)**
  - **Cross-company coordination committee similar to B-17**
  - **Five companies (Chrysler, Hudson, Goodyear, McDonnell, Republic) provided components/subassemblies**
  - **B-29 was "most complex joint production undertaking of the war" (Holley, 1964)**

- **Slightly flatter learning curves (72% - 73%) relative to Wichita (71%)**

Summary - Bomber Second Source Manufacturers

B-17 Fuselage Assembly, Seattle, Washington

Aircraft	Coproducer Company/Site	% Learn Loss	Setback Unit	% Setback	Converge to Lead's Cost at Equiv Position?	Best Cost Lower Than Lead's Best?
B-17	Douglas-L. Beach	12%	53.6	95.0%	Yes	Yes
	Lockheed-Burbank	2%	456.7	69.5%	Yes	Yes
B-24	Consolidated-Ft. Worth	3%	113.1	39.9%	Yes	No
	Ford-Willow Run	106%	0.9	99.9%	Yes	Yes
	Douglas-Tulsa	47%	5.1	99.6%	Yes	No
	N. American-Dallas	54%	3.8	99.8%	Yes	No
B-29	Bell-Marietta	49%	3.3	94.1%	No	No
	Boeing-Renton	14%	18.8	78.4%	Yes	No
	Martin-Omaha	36%	6.3	97.6%	Yes	No
Statistics	Mean	36%	73.5	86.0%	N/A	N/A
	Median	36%	6.3	95.0%	N/A	N/A
	Minimum	2%	0.9	39.9%	N/A	N/A
	Maximum	106%	456.7	99.9%	N/A	N/A

- **On average, the bomber second sources experienced 36% learning loss**
- **Eight of 9 converged with lead site's learning curve**
- **Three of 9 eventually produced at lower hours per pound than lead site**
  - **Caveat: Coproducers experienced exceptionally high production runs (500 – 8,000 aircraft)**

Modern-Day Experience

- **For proprietary reasons, cannot identify the specific case studies (all are within last 30 years)**

	% Learn Loss	% Setback	Converge to Lead's Cost at Equiv Position?	Best Cost Lower Than Lead's Best?
Component A	28%	64%	Yes	Yes
Component B	23%	71%	Yes	Yes
Component C	49%	86%	Yes	Yes
Component D	31%	94%	Yes	No
Component E	44%	88%	No	No
Component F	56%	95%	No	No
Mean	38%	83%	N/A	N/A
Median	37%	87%	N/A	N/A
Minimum	23%	64%	N/A	N/A
Maximum	56%	95%	N/A	N/A

- **On average, the second source experienced 38% learning loss (vs 36% for WW II)**
- **Narrower range of learning loss (23-56%)**
  - **Strong emphasis based on successful technology transfer (data, training, on-site management, assistance teams, furnishing start-up parts, etc.)**
- **Able to converge to lead's cost in more than half the cases**
- **In some cases, second source able to produce lower HPU than lead**

Four Propositions - Revisited

- **Some learning will be transferred to the second source – it will not begin back at T-1 – but not all the lead's learning will be transferred. 36% average learning loss from World War II data.**

- **A strong effort by the lead to promote technology transfer should result in less learning loss. Ability to transfer engineering data & manufacturing processes critical factor in determining degree of learning loss.**

- **The second source will not fully converge to the lead's learning curve – that is, the two learning curves will not intersect. In more cases than not, the second source was able to converge, given sufficient production quantities.**

- **The second source will not be able to produce at a lower cost than the lead company – the coproducer's best hours per pound will be greater than the lead company's best hours per pound. Data shows this is possible, given a steep learning curve & sufficient quantities.**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