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AF/SA

SABER SUSTAINER

PREDICTION OF MAINTENANCE DEMAN
FOR AIRLIFT AIRCRAFT AS A
FUNCTION OF SORTIE LENGTH (U)

23032

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41

Air Force

Headquarters, USAF
Asst. Chief of Staff

Studies & Analyses

SABER SUSTAINER

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THIS BRIEFING IS UNCLASSIFIED

SABER SUSTAINER

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MARCH 1981

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SABER SUSTAINER SCRIPT

SABER SUSTAINER AN ORIGINAL PROJECT CURRENTLY UNDERWAY AT HQ USAF/ STUDIES AND ANALYSES. THE SUBJECT IS THE PREDICTION OF MAINTENANCE DEMAND FOR AIRLIFT AIRCRAFT AS A FUNCTION OF SORTIE LENGTH.

BACKGROUND

- POWER PROJECTION
- INVENTORY MODELS
- LINEAR AIR FORCE METHOD
- $1 BILLION PROBLEM

AIRLIFT PROVIDES THE MEANS FOR RAPID PROJECTION OF MILITARY POWER. IN PERFORMING THEIR MISSION, AIRCRAFT CONSUME MAINTENANCE MAN-HOURS AND SPARE PARTS. AIR FORCE LOGISTICS COMMAND (AFLC) USES SOPHISTICATED MODELS TO MANAGE THE INVENTORY LEVEL OF SPARE PARTS. HOWEVER, THEIR LINEAR METHOD OF PREDICTING MAINTENANCE MAN-HOUR AND SPARE PARTS REQUIREMENTS MAY OR MAY NOT ACCURATELY ANTICIPATE ACTUAL DEMAND. IT ASSUMES THAT THE MAINTENANCE PER FLIGHT HOUR, AND CONSEQUENTLY SPARE PARTS CONSUMPTION, IS A CONSTANT, REGARDLESS OF HOW LONG THE AIRCRAFT IS FLOWN ON A GIVEN SORTIE, ACCURATELY FORECASTING THE DEMAND FOR SPARE PARTS IS IMPORTANT BECAUSE OF THEIR HIGH COST. AS AFLC FILLS THE SHORTAGES IN STRATEGIC AIRLIFT WARTIME RESERVE MATERIAL (WRM), THE TOTAL COST OF THE SPARE PARTS INVENTORY WILL APPROACH ONE BILLION DOLLARS. THUS, ACCURATE PREDICTION OF DEMAND FOR SPARE PARTS COULD AVOID WASTING MONEY SPENT ON THE PURCHASE OF EXCESS SPARES WHILE INSURING ADEQUATE INVENTORY LEVELS FOR WARTIME STRATEGIC AIRLIFT OPERATIONS.

PURPOSE

TO TEST THE FIXED PLUS VARIABLE COST CONCEPTS OF BUSINESS THEORY ON THE BEHAVIOR OF MAJOR SUBSYSTEMS OF STRATEGIC AIRLIFT AIRCRAFT TO DETERMINE THE RELATIONSHIP, IF ANY, BETWEEN THEIR FAILURE RATES AND THE LENGTH OF A SORTIE.

THE PURPOSE OF THIS STUDY IS AS STATED AND INVOLVES THREE PHASES: (1) TO DEVELOP A THEORY FOR PREDICTING THE MAINTENANCE DEMAND, (2) TO TEST THIS THEORY USING AVAILABLE FIELD DATA, AND (3) TO COMPARE THESE RESULTS TO THOSE OBTAINED FROM THE LINEAR AIR FORCE METHOD TO DETERMINE IF THERE IS A SIGNIFICANT DIFFERENCE THAT COULD IMPACT THE LEVEL OF WRM REQUIRED.

OVERVIEW

- LITERATURE SURVEY
- HYPOTHESIS FORMULATION
- DATA BASES
- RESULTS
- IMPACT
- OBSERVATIONS

THE BODY OF THE BRIEFING BEGINS WITH THE LITERATURE SURVEY WHICH LED TO THE FORMULATION OF OUR THEORY FOR PREDICTING MAINTENANCE. THE BRIEFING CONTINUES WITH A DESCRIPTION OF THE DATA BASES WE OBTAINED TO TEST THE HYPOTHESIS, FOLLOWED BY SOME SAMPLE RESULTS. THE IMPACT PORTION COMPARES OUR METHOD WITH THE LINEAR AIR FORCE METHOD. THE BRIEFING THEN CONCLUDES WITH SEVERAL OBSERVATIONS.

PREVIOUS STUDIES

AFLC - "WORLDWIDE REQUIREMENTS DETERMINATION"

RAND - "THE RELATIONSHIP OF FLIGHT-LINE MAINTENANCE MANHOURS TO AIRCRAFT FLYING HOURS"

BOEING - "B-52D OPERATIONS"

LOCKHEED - "C-5A RELIABILITY"

AWC - "AIRCRAFT MAINTENANCE MANAGEMENT"

RAND - "PREDICTING AIRCRAFT COMPONENT REMOVAL RATES WITH VARYING FLYING PROGRAMS"

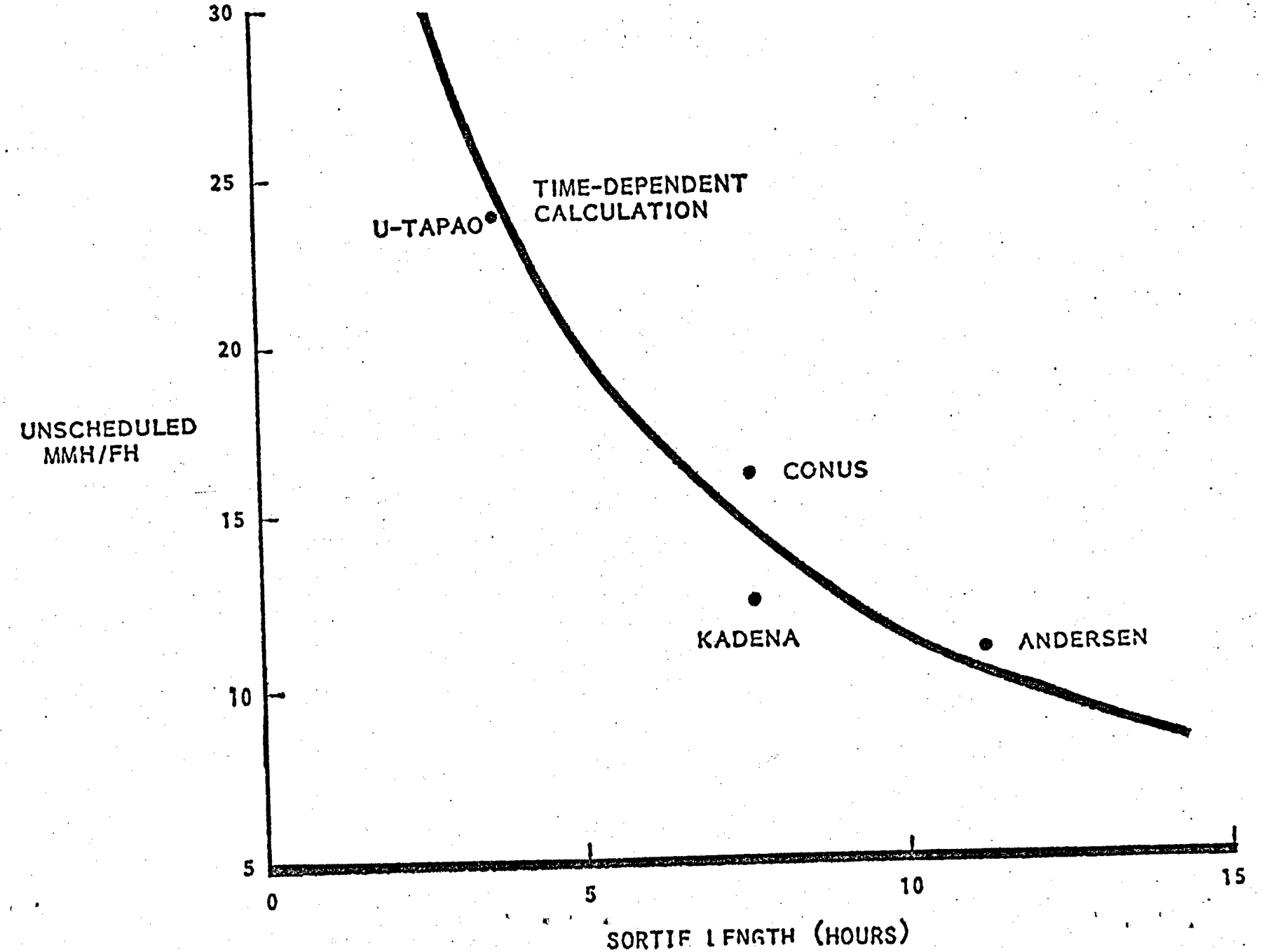
LOCKHEED - "IMPROVED OPERATIONAL MAINTENANCE FORECASTING TECHNIQUES"

UNITED - "RELIABILITY CENTERED MAINTENANCE"

SHURMAN - "IN-FLIGHT STEADY STATE FAILURE RATES"

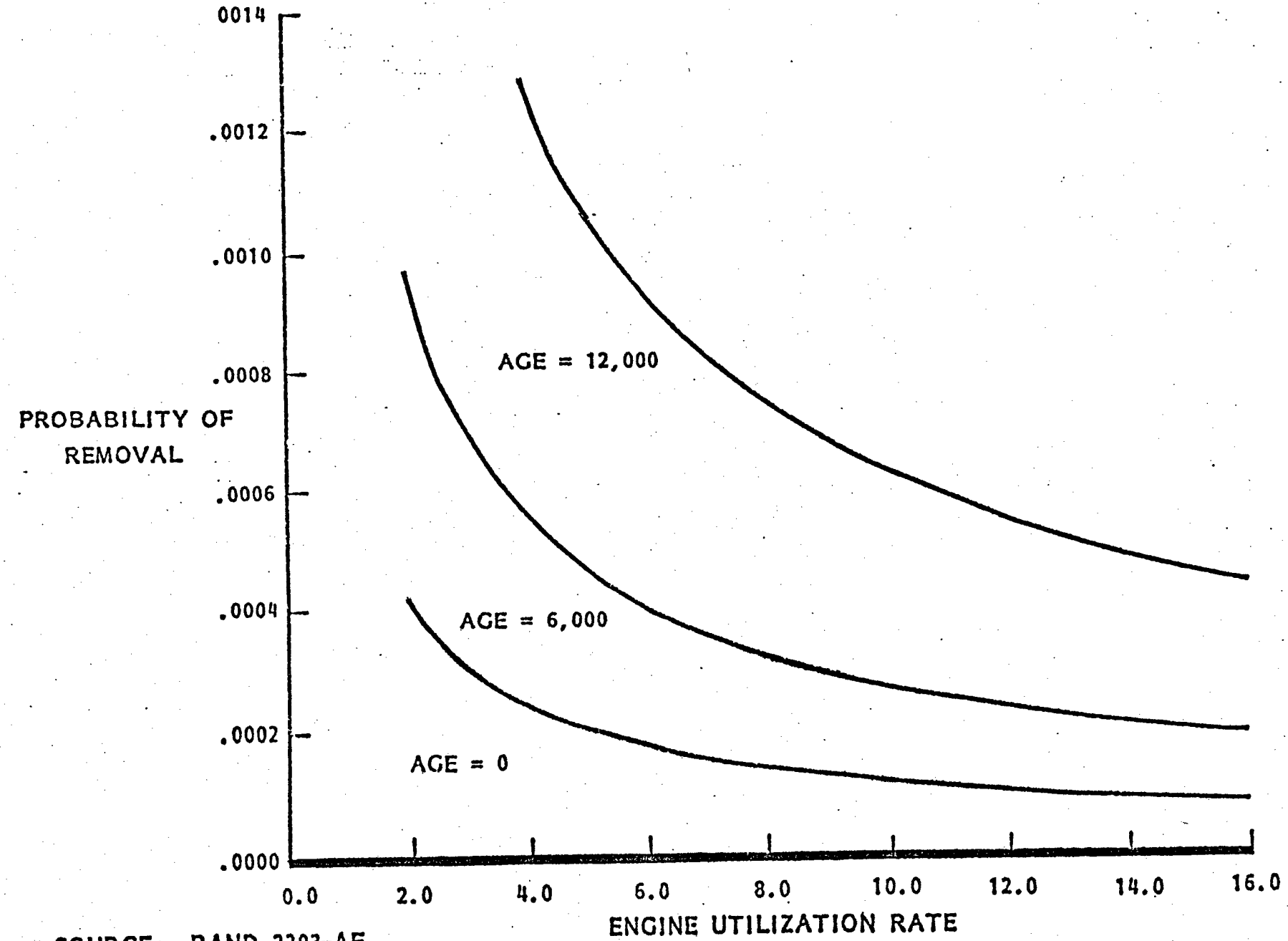
LISTED HERE ARE SOME OF THE MORE IMPORTANT STUDIES TO THIS PROJECT. THE AFLC BRIEFING PROVIDES A GOOD EXPLANATION OF THE PEACETIME OPERATING SPARES (POS), WARTIME RESERVE SPARES KIT (WRSK), BASE LEVEL SELF-SUFFICIENCY (BLSS) AND OTHER WARTIME RESERVE MATERIAL (OWRM) COMPONENTS OF THE SPARES INVENTORY. IN 1967 DONALDSON AND SWEETLAND OF RAND STUDIED THE MAINTENANCE MAN-HOURS PER FLYING HOUR (MMH/FH) REQUIRED TO SUPPORT C-130s FLYING DIFFERENT MISSIONS FROM CCKAB, TAIWAN.

B-52D


30
25
20
15
10
5
UNSCHEDULED
MMH/FH
TIME-DEPENDENT
CALCULATION
U-TAPAO
CONUS
KADENA
ANDERSEN
0
5
10
15
SORTIE LENGTH (HOURS)

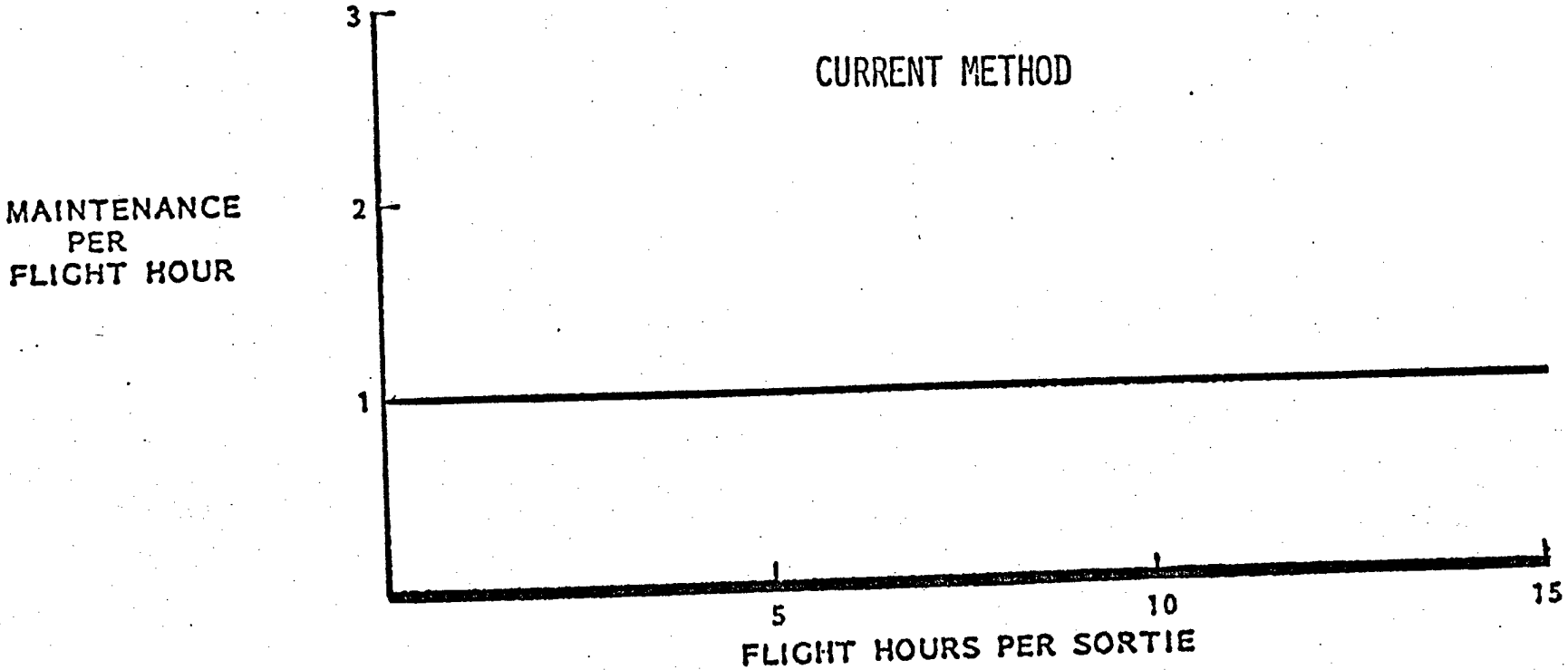
THE BOEING REPORT IS THE CLOSEST THING TO AN EXPERIMENTAL DESIGN FIELD TEST. THE SAME MISSION-DESIGN-SERIES (MDS), OR B-52Ds, PERFORMED CONVENTIONAL BOMBING MISSIONS FROM THREE DIFFERENT LOCATIONS. ONLY THE LENGTH OF THE SORTIE CHANGED FROM LOCATION TO LOCATION. IN 1973 LOCKHEED PUBLISHED TWO REPORTS ON THE C-5. THE FIRST REPORT CONTAINED THE ESTIMATED FAILURE RATES FOR MAJOR SUBSYSTEMS ON THE C-5. IT WAS BASED ON FLIGHT TEST DATA AND MANUFACTURER'S RELIABILITY CALCULATIONS. THE SECOND REPORT PROVIDED 13 FUDGE-FACTORS TO INCREASE THE PREDICTED FAILURE RATES BY 70% TO MATCH ACTUAL FIELD EXPERIENCE WITH THE NEW AIRCRAFT. COLONEL SHUMAKER'S AIR WAR COLLEGE RESEARCH REPORT CITED THE FOLLEY OF REDUCING MAINTENANCE MANPOWER AUTHORIZATIONS BY 50% WHEN THE C-141s UTILIZATION RATE WAS REDUCED BY 50%, FROM EIGHT TO FOUR HOURS PER DAY. THE SECOND RAND ENTRY IS A C-141 ENGINE COMPONENT FAILURE RATE STUDY.

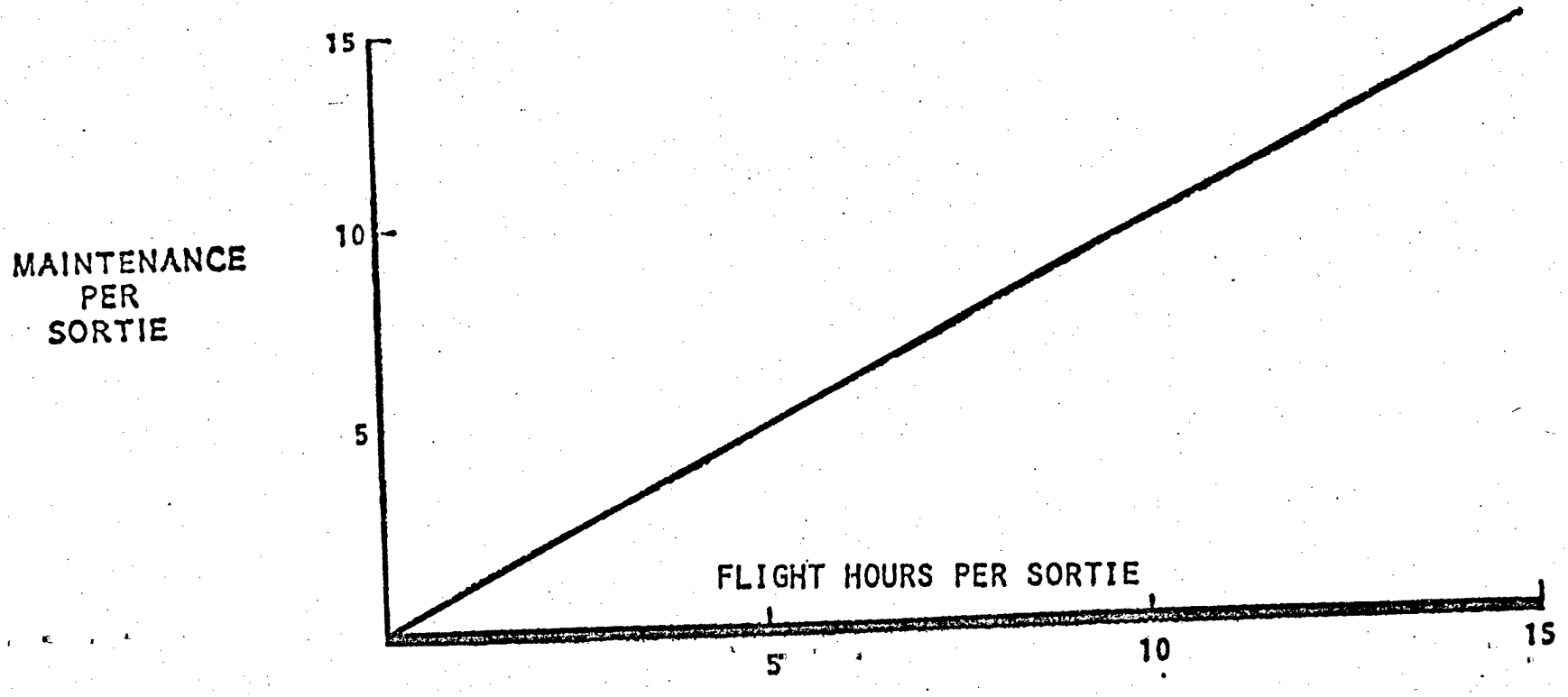
TF 33-7



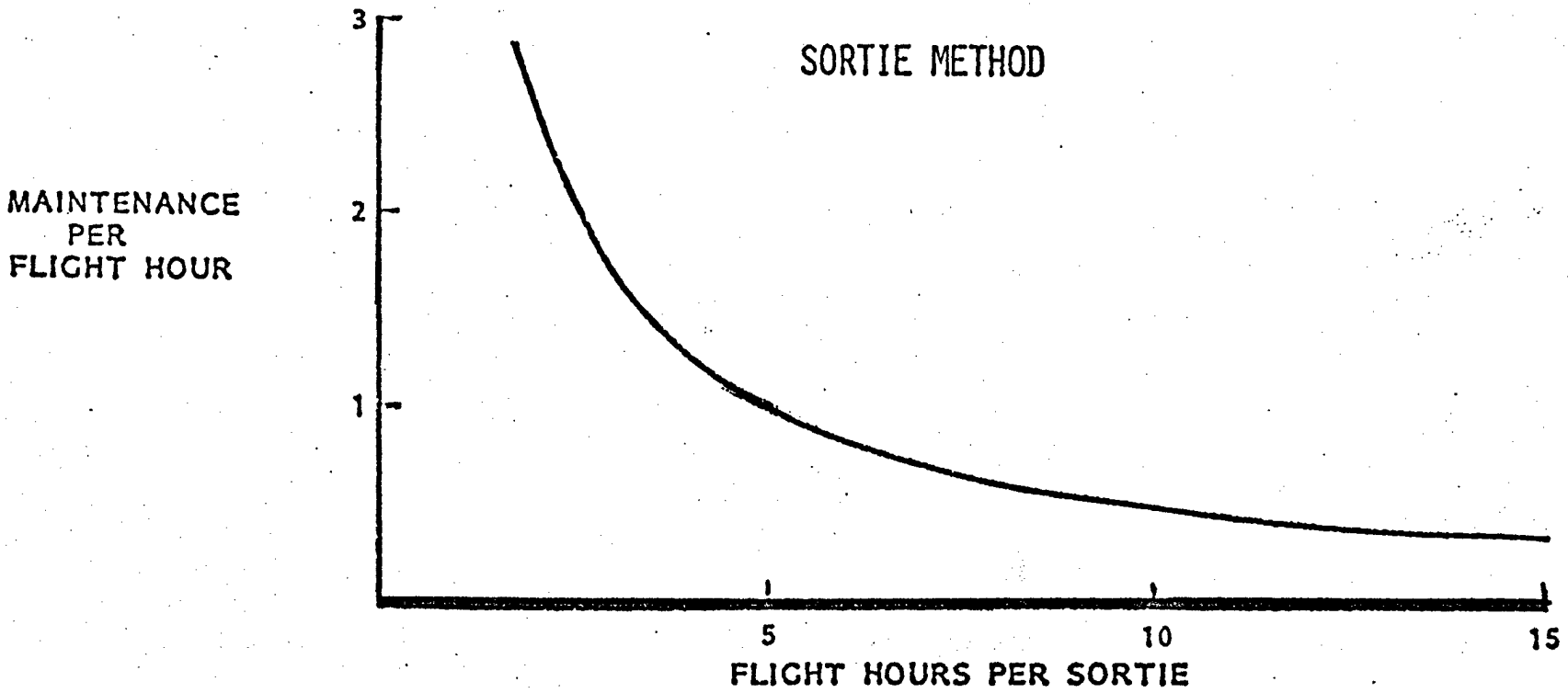
SOURCE: RAND 2203-AF

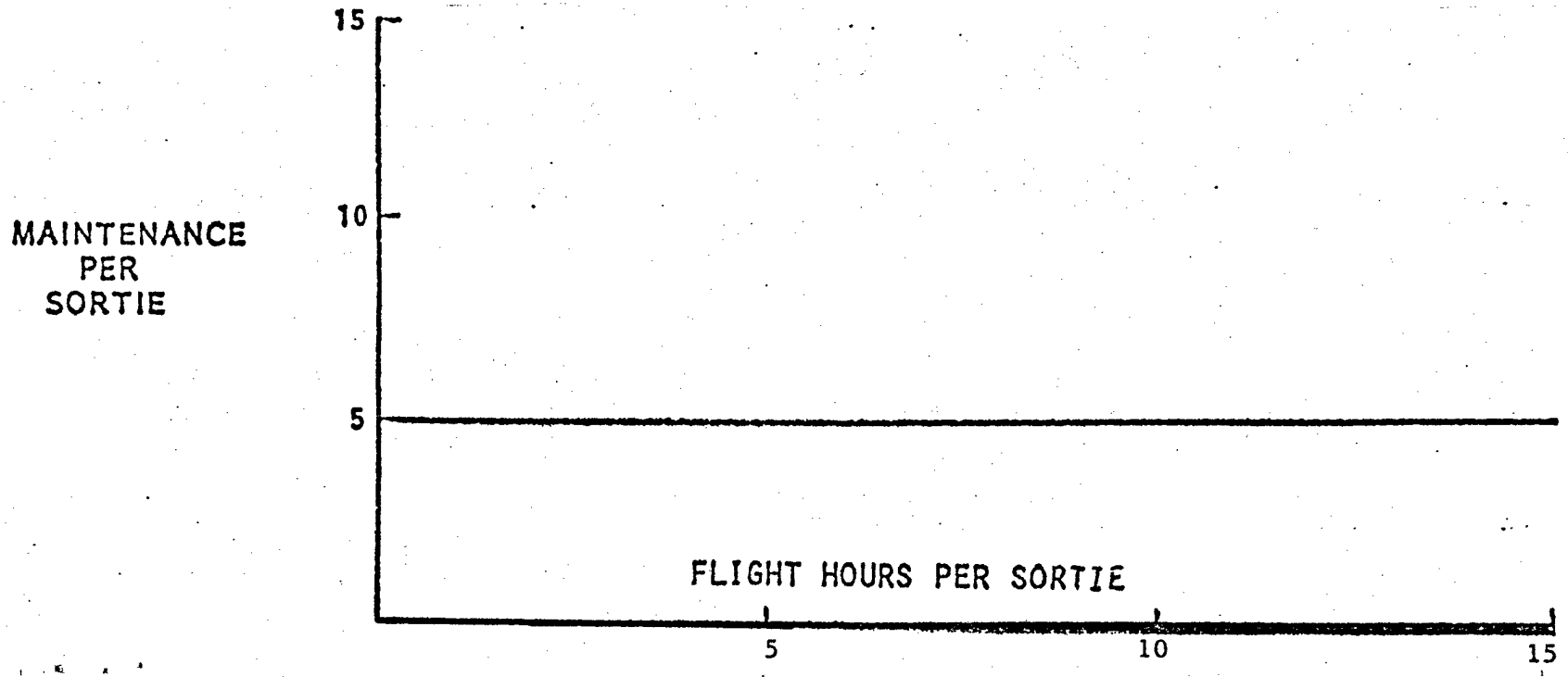
BERMAN, LIPPIAT, SIMS, AND POGGIO SHOWED THAT COMPONENT FAILURE RATE PER FLIGHT HOUR DECREASED AS DAILY UTILIZATION RATE INCREASED. SIMILAR WORK HAS BEEN ACCOMPLISHED BY LOCKHEED. THEY FOUND THAT BOTH MAINTENANCE MAN-HOURS PER FLYING HOUR AND FAILURES PER FLYING HOUR DECREASED AS UTILIZATION RATE INCREASED. UNITED AIR LINES GIVES AN EXCELLENT EXPLANATION OF STRESS IN VARIOUS PHASES OF FLIGHT AND DEFINED FAILURE AS THE EFFECTS OF CUMULATIVE STRESS EXCEEDING THE INHERENT RESISTANCE OF A COMPONENT. MAURY SHURMAN DEVELOPED A TIME-DEPENDENT FAILURE RATE MODEL AND IDENTIFIED A STEADY-STATE (OR CRUISE-STATE) FAILURE RATE. THESE LAST TWO WORKS, UNITED AIR LINES AND SHURMAN, PLAYED A MAJOR ROLE IN THE FORMULATION OF THE COMBINED HYPOTHESIS AND ITS MODIFICATION AS WILL BE EXPLAINED LATER IN THE BRIEFING.


CURRENT METHOD
MAINTENANCE PER FLIGHT HOUR
3
2
1
5
10
15
FLIGHT HOURS PER SORTIE


MAINTENANCE PER SORTIE
15
10
5
FLIGHT HOURS PER SORTIE
5
10
15

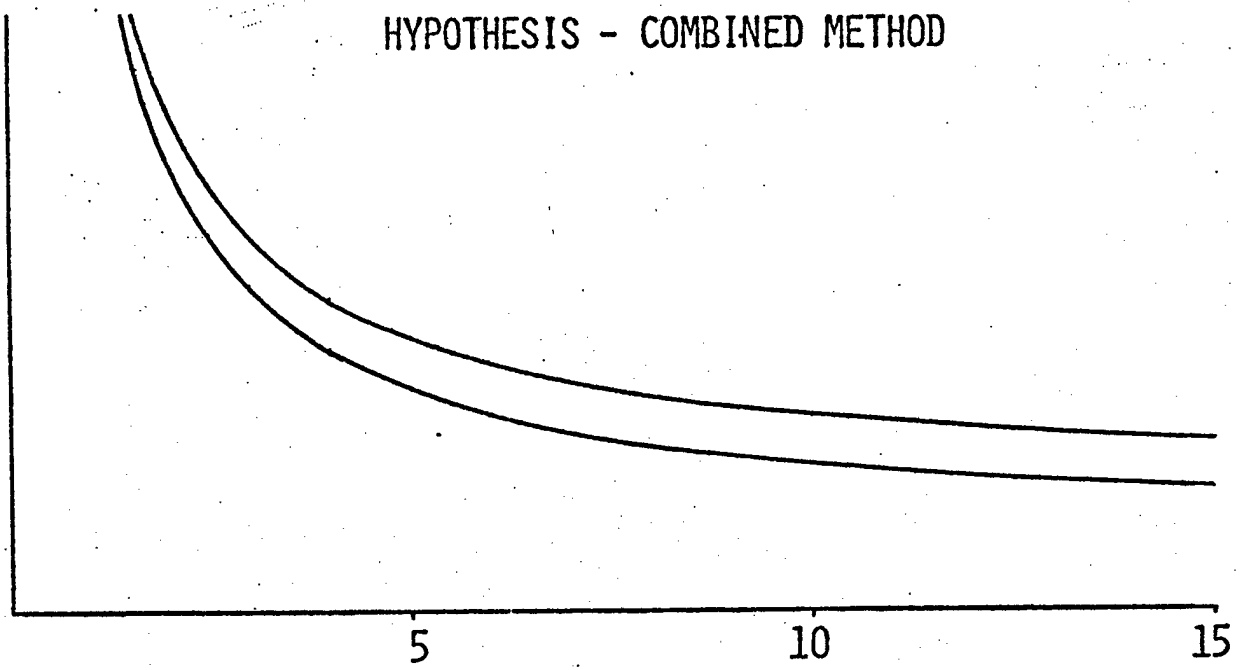
THE HYPOTHESIS FORMULATION PROCESS BEGINS BY REVIEWING WHAT SOME METHODS LOOK LIKE ON DIFFERENT KINDS OF GRAPHS. THE CURRENT AIR FORCE METHOD IS ALSO CALLED "LINEAR" BECAUSE IT YIELDS A STRAIGHT LINE OR A CONSTANT, WHEN PLOTTED AS MAINTENANCE PER FLIGHT HOUR. WHEN PLOTTED AS MAINTENANCE PER SORTIE, IT GIVES A CONSTANTLY INCREASING STRAIGHT LINE WHICH STARTS AT THE ORIGIN (THE INTERSECTION OF THE AXES).

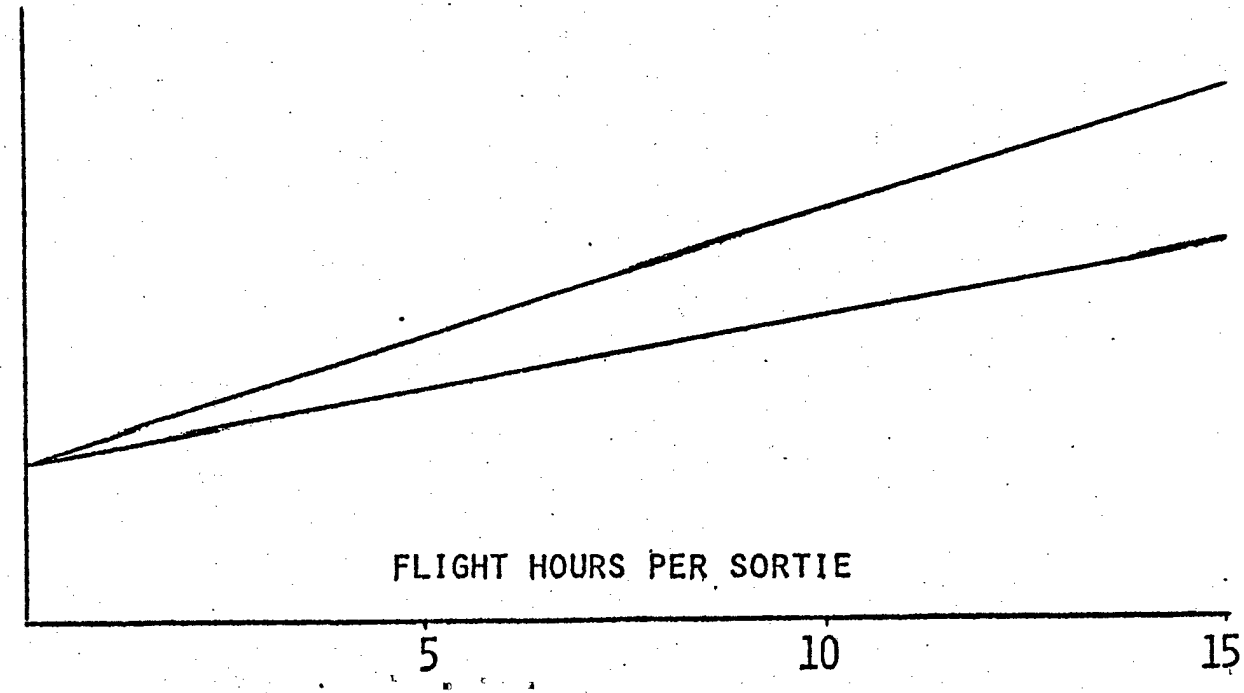

SORTIE METHOD
MAINTENANCE PER FLIGHT HOUR
3
2
1
5
10
15
FLIGHT HOURS PER SORTIE


MAINTENANCE PER SORTIE
15
10
5
FLIGHT HOURS PER SORTIE
5
10
15

IN 1978, THE GENERAL ACCOUNTING OFFICE RECOMMENDED THE USE OF THE SORTIE METHOD. IT ASSUMES THAT ALL MAINTENANCE IS CAUSED BY THE GENERATION OF THE SORTIE INSTEAD OF THE NUMBER OF FLIGHT HOURS. THIS ASSUMPTION YIELDS A MONOTONIC DECREASING CURVE ON THE TOP GRAPH. ON THE BOTTOM, IT PRODUCES A CONSTANT AMOUNT OF EXPECTED MAINTENANCE PER SORTIE REGARDLESS OF SORTIE LENGTH. ALTHOUGH THIS METHOD IS APPLICABLE TO FIGHTERS WHOSE SORTIE LENGTH IS NEARLY CONSTANT, IT HAS NOT BEEN ADOPTED FOR AIRLIFT AIRCRAFT.

HYPOTHESIS - COMBINED METHOD





THE COMBINED METHOD HYPOTHESIZED IN THIS STUDY IS A CROSS BETWEEN THE PREVIOUS ONES. IT ASSUMES THAT BOTH SORTIE GENERATION AND FLIGHT TIME PRODUCE MAINTENANCE DEMANDS. THIS METHOD ALSO GIVES MONOTONIC DECREASING CURVES WHEN PLOTTED AS MAINTENANCE PER FLIGHT HOUR. AS MAINTENANCE PER SORTIE, IT GIVES LINES WITH POSSIBLY NON-ZERO INTERCEPTS FOR SORTIE GENERATION AND CONSTANTLY INCREASING STRAIGHT LINES FOR FLIGHT HOURS PER SORTIE. AS PREVIOUSLY MENTIONED, THE STRESS EXPLANATION OF UNITED AIRLINES AND MAURY SHURMAN'S STEADY-STATE FAILURE RATE WORK ENABLED US TO REFINE THE COMBINED METHOD. ESSENTIALLY WE HAVE ALLOWED ONE HOUR FOR THE TAKE-OFF AND LANDING PHASES OF FLIGHT. THUS, OUR SORTIE RELATED MAINTENANCE RATE INCLUDES ONE HOUR OF FLIGHT. ANY SORTIE LESS THAN ONE HOUR LONG WOULD THEREFORE NEVER EXPERIENCE THE CRUISE MODE OF FLIGHT AND THE STEADY-STATE FAILURE WOULD NOT BE OBSERVED. THUS, THE FAILURE PATTERN FOR SUCH SORTIES SHOULD BE DIFFERENT FROM LONGER ONES. TO ACCOUNT FOR THIS DIFFERENCE, WE SEPARATED ALL DATA POINTS WITH AN AVERAGE SORTIE LENGTH LESS THAN ONE HOUR FROM OUR REGRESSION ANALYSES. THESE SHORT SORTIES ARE SIMPLY AVERAGED AND SHOWN AS A SINGLE DATA POINT AND PROVIDE AN APPROXIMATION FOR SORTIE GENERATION RELATED FAILURES.

DATA BASES

CASEY - "LOGISTICS IMPACT OF LONGER C-5 MISSIONS"

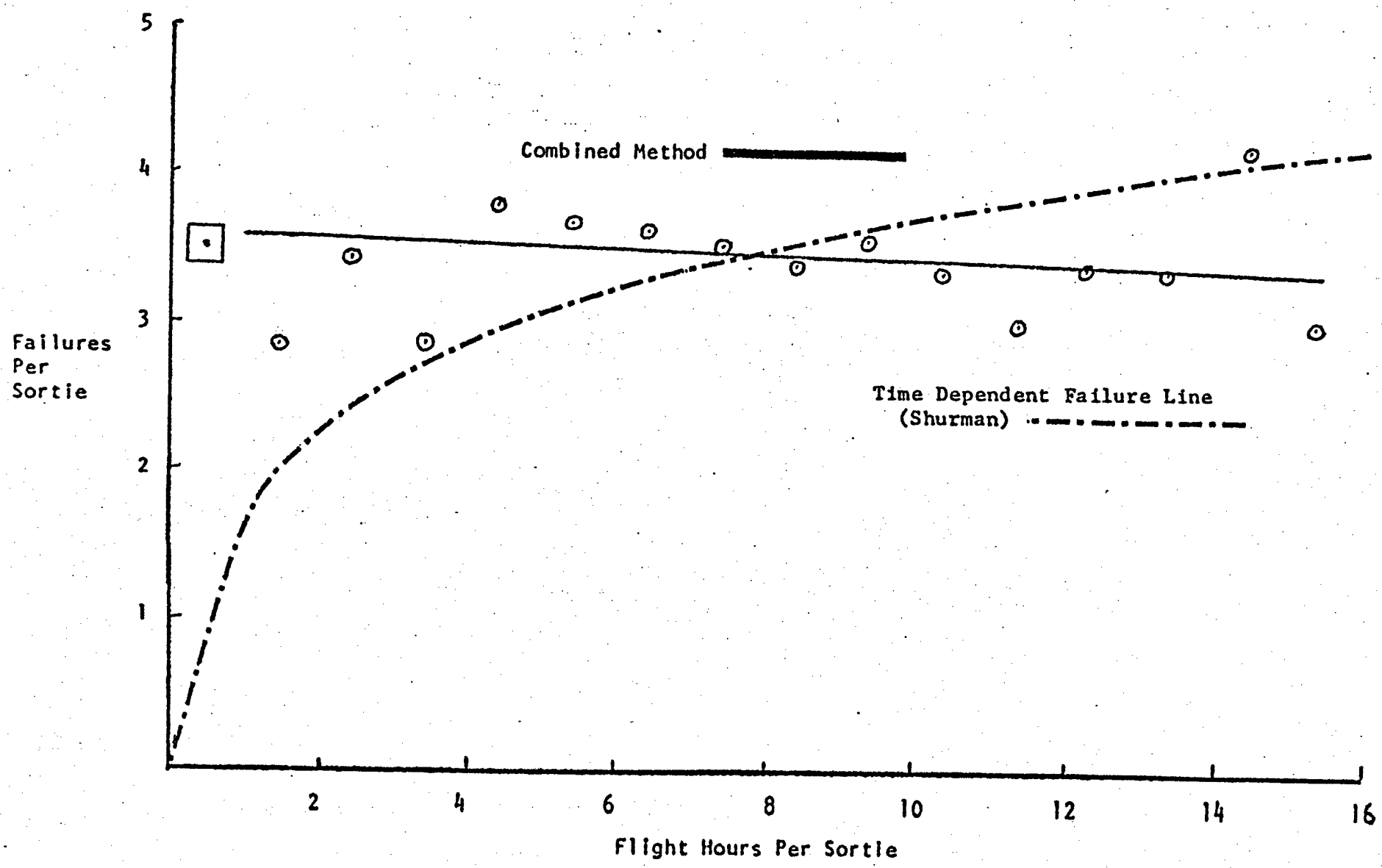
TUTTLE - "MARITIME PATROL AIRCRAFT" (P-3)

HOWELL - "A METHOD FOR ADJUSTING MAINTENANCE FORECASTS TO ACCOUNT FOR PLANNED SORTIE LENGTH" (C-141 AND C-130)

SA-ALC - "C-5 AND C-141 FAILURE DATA"

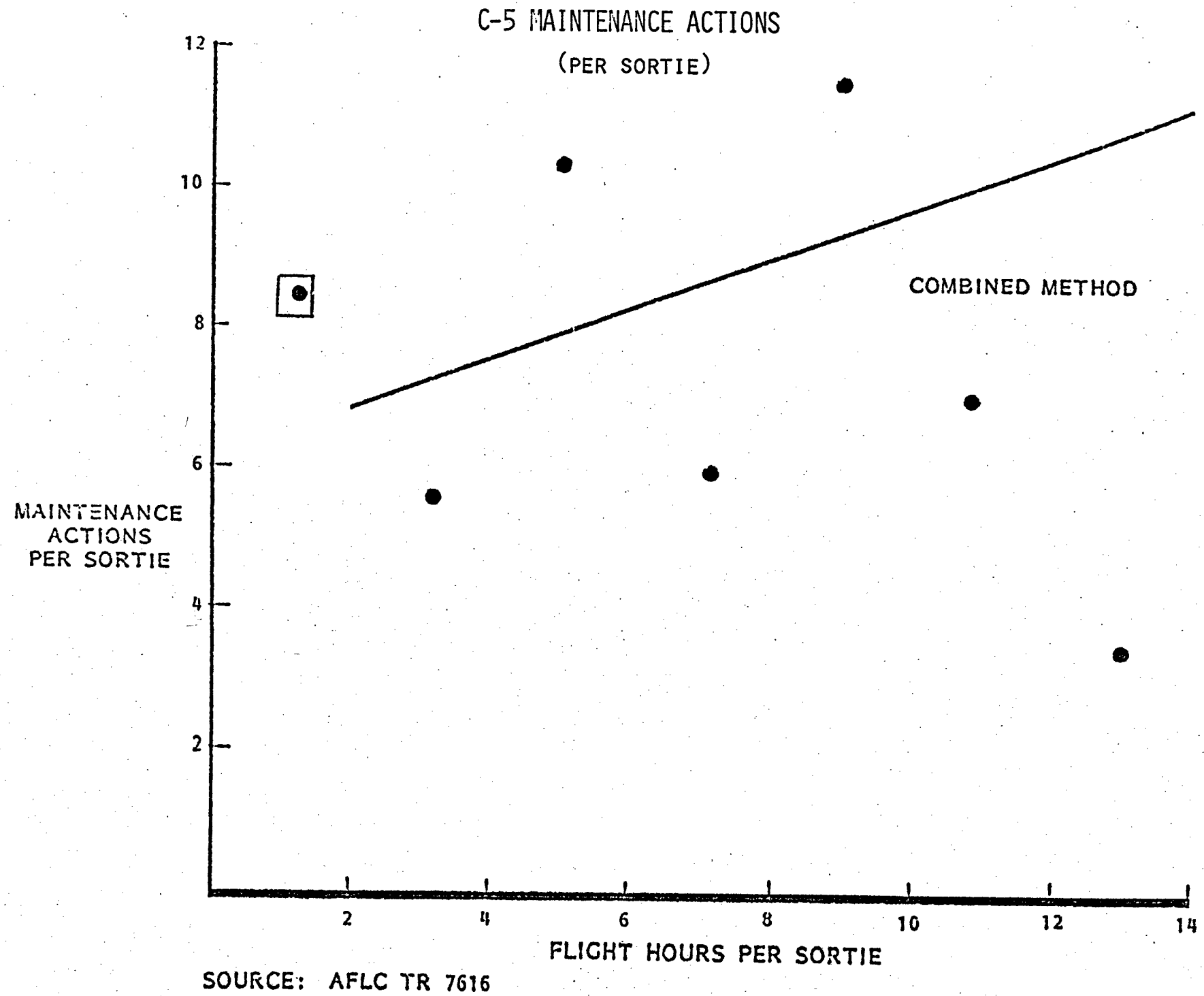
WE LOCATED FOUR DATA BASES TO USE IN TESTING THE COMBINED METHOD. CASEY'S REPORT CONTAINS DATA ON ALL C-5 MAINTENANCE WRITE-UPS FROM THE MADARS SYSTEM ALONG WITH FLIGHT DATA FOR THE PERIOD AUGUST TO DECEMBER 1976. HE ALSO ELIMINATES ALL SORTIES WITH MORE THAN ONE LANDING REPORTED. TUTTLE'S REPORT HAS A SUMMARY OF P-3 FAILURE DATA AND FLIGHT INFORMATION. PART OF THE DATA BASE USED BY HOWELL IS THE MAINTENANCE DATA COLLECTION SYSTEM (G098) INFORMATION ON THE C-141A AND THE C-130E. HIS DATA COUNTS ALL UNSCHEDULED MAINTENANCE ACTIONS FROM JUNE 1976 TO MAY 1977. OUR BIGGEST DATA BASE CAME DIRECTLY FROM THE G098 SYSTEM MAINTAINED AT THE SAN ANTONIO AIR LOGISTICS CENTER (SA-ALC). THEY PROVIDED US WITH A MONTHLY HISTORY OF FAILURES FOR MAINTENANCE ACTION CODES P (REMOVE ONLY) AND R (REMOVE AND REPLACE) ON THE C-5 AND C-141, BROKEN DOWN BY TAIL NUMBER BY TWO DIGIT WORK UNIT CODE. THE FLYING HOURS, SORTIES, AND LANDINGS PER MONTH ARE ALSO REPORTED. WE TESTED THE COMBINED METHOD FOR GOODNESS OF FIT WITH EACH OF THESE DATA BASES.

P-3C FAILURE DATA
(PER SORTIE)



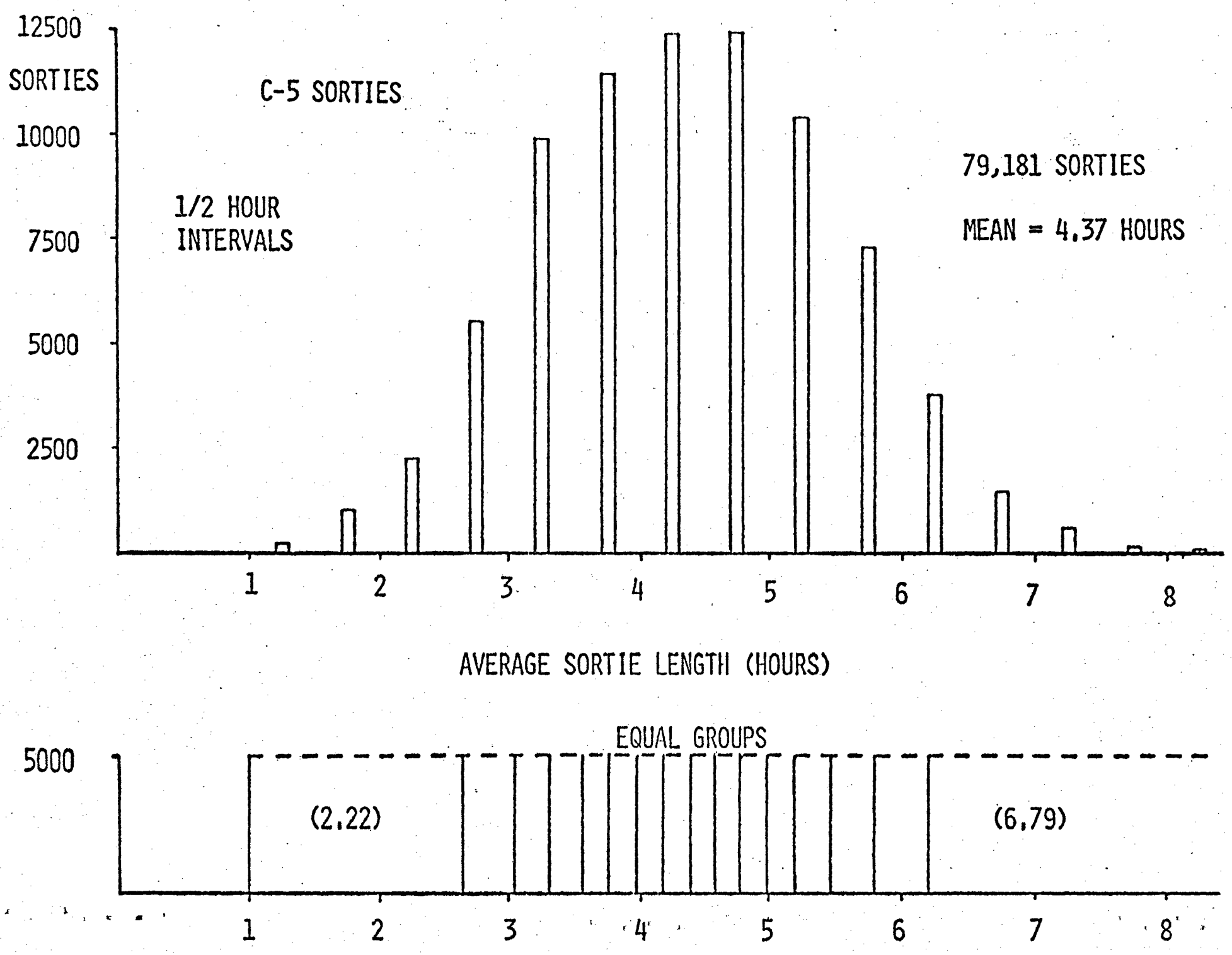
Source: LR 29113

THIS GRAPH BEGINS THE RESULTS SECTION. THE DATA POINTS PLOTTED ARE THE AVERAGE FAILURES PER SORTIE ASSOCIATED WITH THE AVERAGE SORTIE LENGTHS ON WHICH THEY OCCURRED. THE COMBINED METHOD HERE GIVES AN EXCELLENT FIT TO THE POINTS. ALTHOUGH THE SLIGHTLY NEGATIVE SLOPE IS SOMEWHAT ILLOGICAL, ITS 95% CONFIDENCE INTERVAL INCLUDES ZERO, SO MORE DATA COULD VERY WELL GIVE A POSITIVE SLOPE. ALSO SHOWN IS THE PLOT OF SHURMAN'S STEADY-STATE, TIME DEPENDENT FAILURE RATE MODEL. IT IS A CONTINUOUS FUNCTION, STARTING AT ZERO, INCREASING RAPIDLY DURING THE FIRST HOUR AND THEN AT A LESSER RATE EACH HOUR. BY CONTRAST, OUR APPROACH IS A DISCRETE PLUS A CONTINOUS FUNCTION. THE DOT IN THE BOX IS THE SEPARATE VALUE CALCULATED FROM SHORT SORTIES THAT NEVER GOT TO THE STEADY-STATE CRUISE PHASE. THE LINE IS THE CONTINUOUS, OR STEADY-STATE FAILURE RATE FUNCTION.

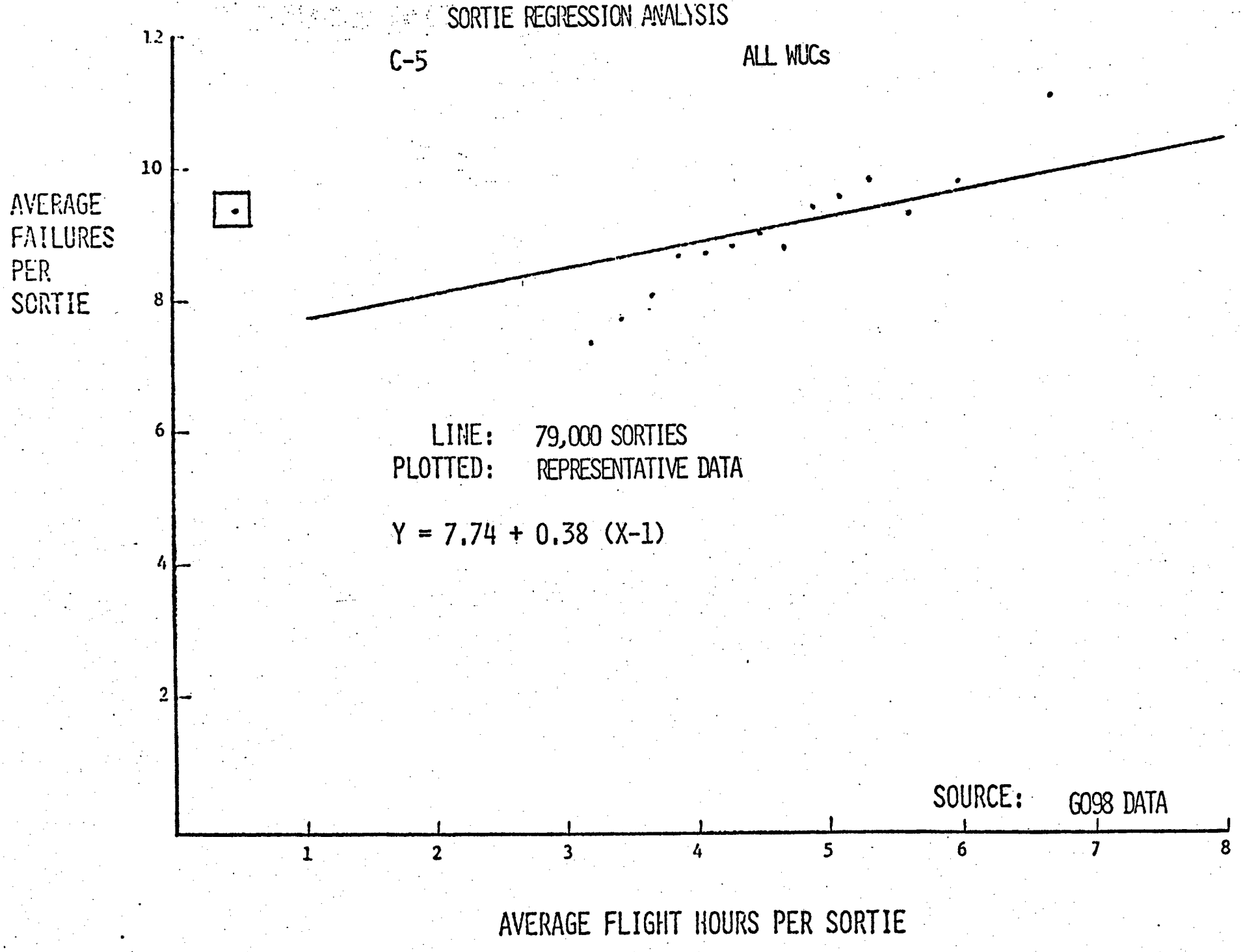


SOURCE: AFLC TR 7616

THE DATA POINTS SHOWN HERE ARE FROM CASEY'S REPORT. THE VERY WIDE SCATTER IN THE DATA IS PROBABLY DUE TO THE RELATIVELY LOW NUMBER OF SORTIES USED (LESS THAN 2,000) COMPARED TO THE OTHER DATA BASES. IN SPITE OF THAT, THE REGRESSION LINE STILL SHOWS THE EXPECTED SHAPE.


12500
SORTIES
10000
7500
5000
2500
C-5 SORTIES
1/2 HOUR
INTERVALS
79,181 SORTIES
MEAN = 4.37 HOURS
1
2
3
4
5
6
7
8
AVERAGE SORTIE LENGTH (HOURS)
EQUAL GROUPS
5000
(2,22)
(6,79)
1
2
3
4
5
6
7
8

THIS SLIDE SHOWS HOW WE TREATED THE G098 DATA TO GIVE OUR SPECIFIC DATA POINTS. THE TOP GRAPH DIVIDES THE AVERAGE SORTIE LENGTH INTO HALF HOUR INTERVALS AND SHOWS THE NUMBER OF SORTIES OCCURRING IN EACH INTERVAL. ALTHOUGH HALF HOUR INTERVALS ARE SHOWN FOR DISPLAY PURPOSES, OUR PROCEDURE ACTUALLY USED ONE-TENTH OF AN HOUR INSTEAD. EACH INTERVAL THUS BECAME ONE DATA POINT WITH THE NUMBER OF SORTIES BECOMING THE WEIGHTING FACTOR FOR THAT POINT (SEE BACKUP SLIDE B2). THE DATA TREATMENT SHOWN ON THE BOTTOM FORCED ON EQUAL NUMBER OF SORTIES INTO EACH DATA POINT (1,000 SORTIES PER POINT WAS ACTUALLY USED). THIS TREATMENT ALLOWS THE AVERAGE SORTIE LENGTH FOR EACH POINT TO FALL WHERE IT MAY AND PROVIDED 79 POINTS FOR THE REGRESSION ANALYSIS. WE USED THE SAME TECHNIQUES ON HOWELL'S DATA FOR THE C-141 AND THE C-130E AIRCRAFT.


SORTIE REGRESSION ANALYSIS
C-5
ALL WUCs
AVERAGE FAILURES PER SORTIE
12
10
8
6
4
2
LINE: 79,000 SORTIES
PLOTTED: REPRESENTATIVE DATA
Y = 7.74 + 0.38 (X-1)
SOURCE: G098 DATA
1
2
3
4
5
6
7
8
AVERAGE FLIGHT HOURS PER SORTIE

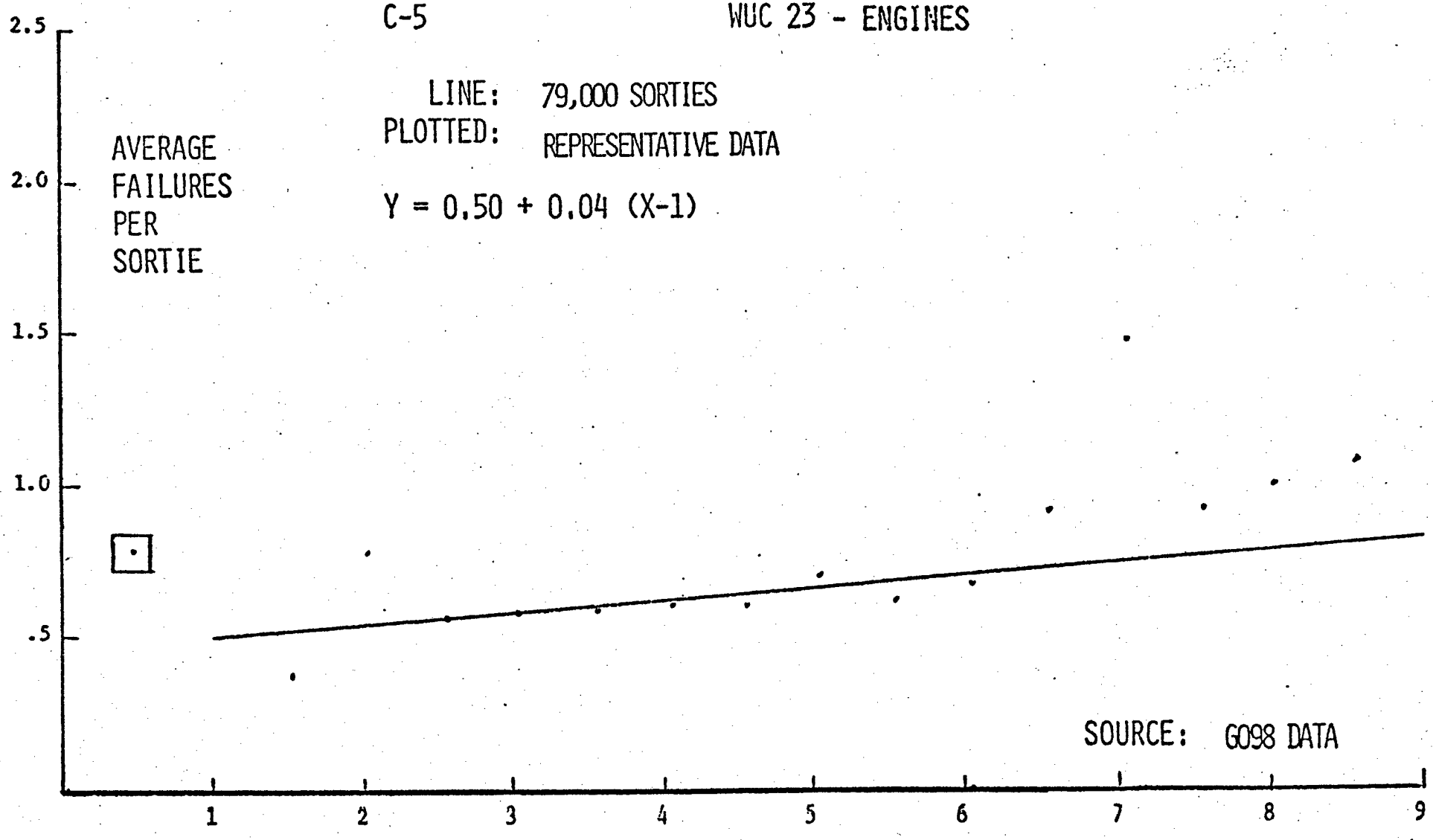
THIS GRAPH SHOWS 5,000 SORTIE DATA POINTS FOR THE C-5 AND THE RESULTING REGRESSION ANALYSIS LINE. AS EXPECTED, THE LINE HAS BOTH A POSITIVE INTERCEPT AND A POSITIVE SLOPE.

TIME INTERVAL REGRESSION ANALYSIS

C-5 WUC 23 - ENGINES

LINE: 79,000 SORTIES
PLOTTED: REPRESENTATIVE DATA

$Y = 0.50 + 0.04 (X-1)$



SHOWN HERE ARE THE DATA POINTS EVERY HALF HOUR FOR THE EQUAL TIME INTERVAL METHOD USING WEIGHTED REGRESSION LINE FOR WUC 23. THE EXCELLENT FIT SHOWS THAT THE COMBINED METHOD ALSO WORKS WELL FOR TWO DIGIT WUC's.

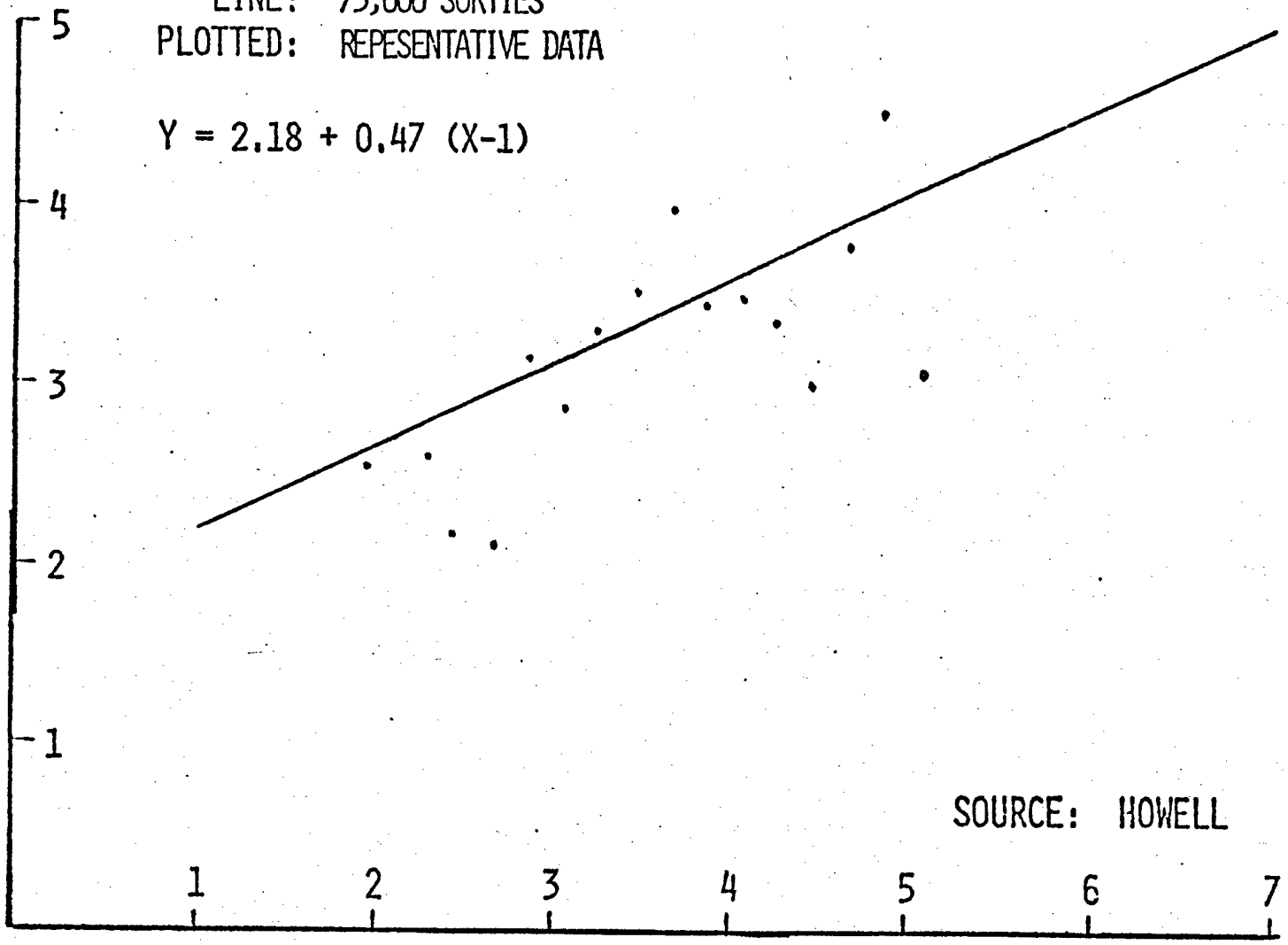
TIME INTERVAL REGRESSION ANALYSIS

C-141

ALL WUCs

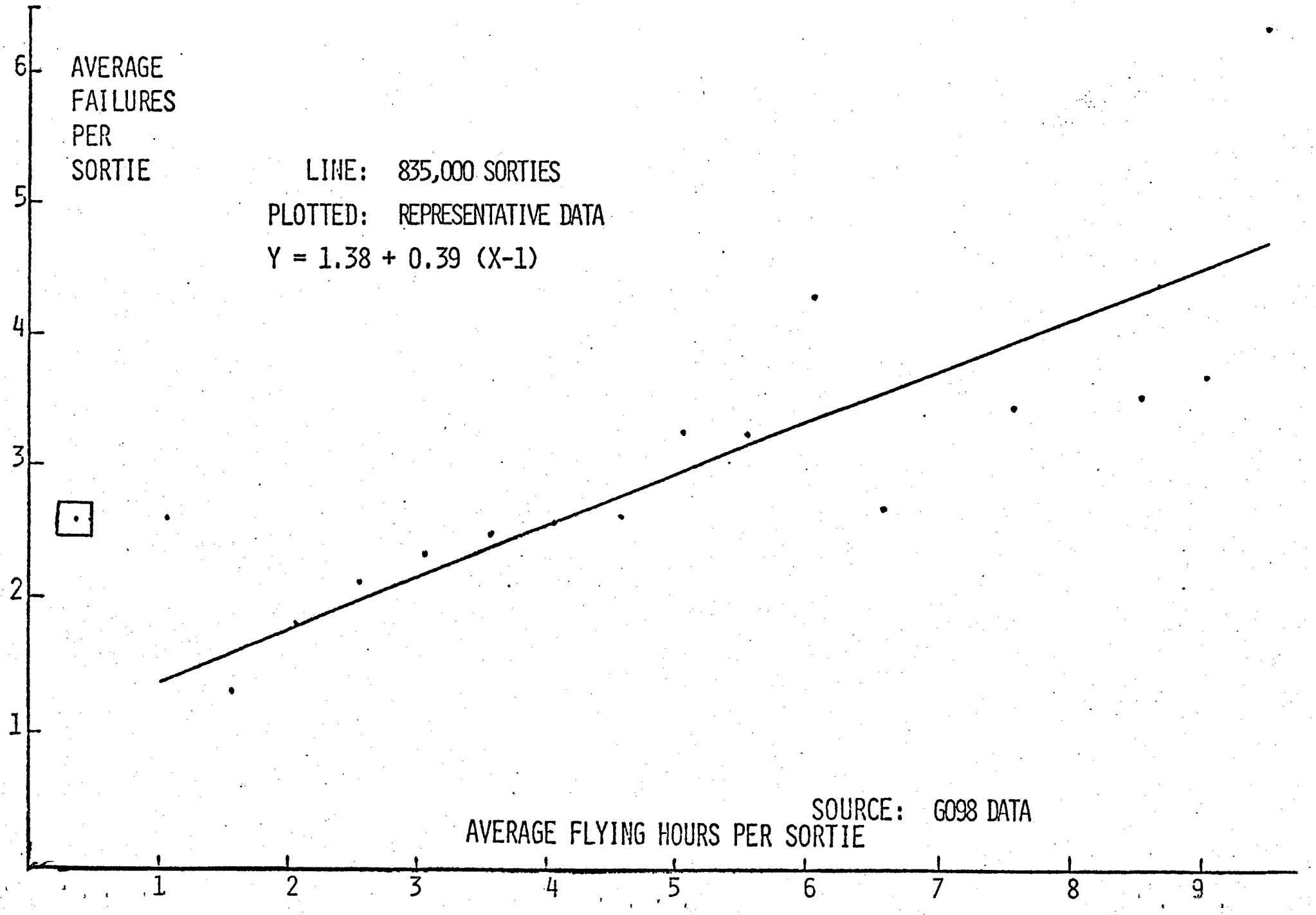
LINE: 73,000 SORTIES
PLOTTED: REPESENTATIVE DATA

$Y = 2.18 + 0.47\ (X-1)$



HOWELL'S DATA CONTAINS LESS THAN ONE-TENTH OF THE G098 DATA ON THE C-141. THUS, THERE IS A FAIR AMOUNT OF SCATTER ABOUT THE REGRESSION LINE. EVEN SO, THE LINE STILL SHOWS A GOOD FIT WITH A POSITIVE INTERCEPT AND SLOPE.

C-141 TIME INTERVAL REGRESSION ANALYSIS ALL WUCs



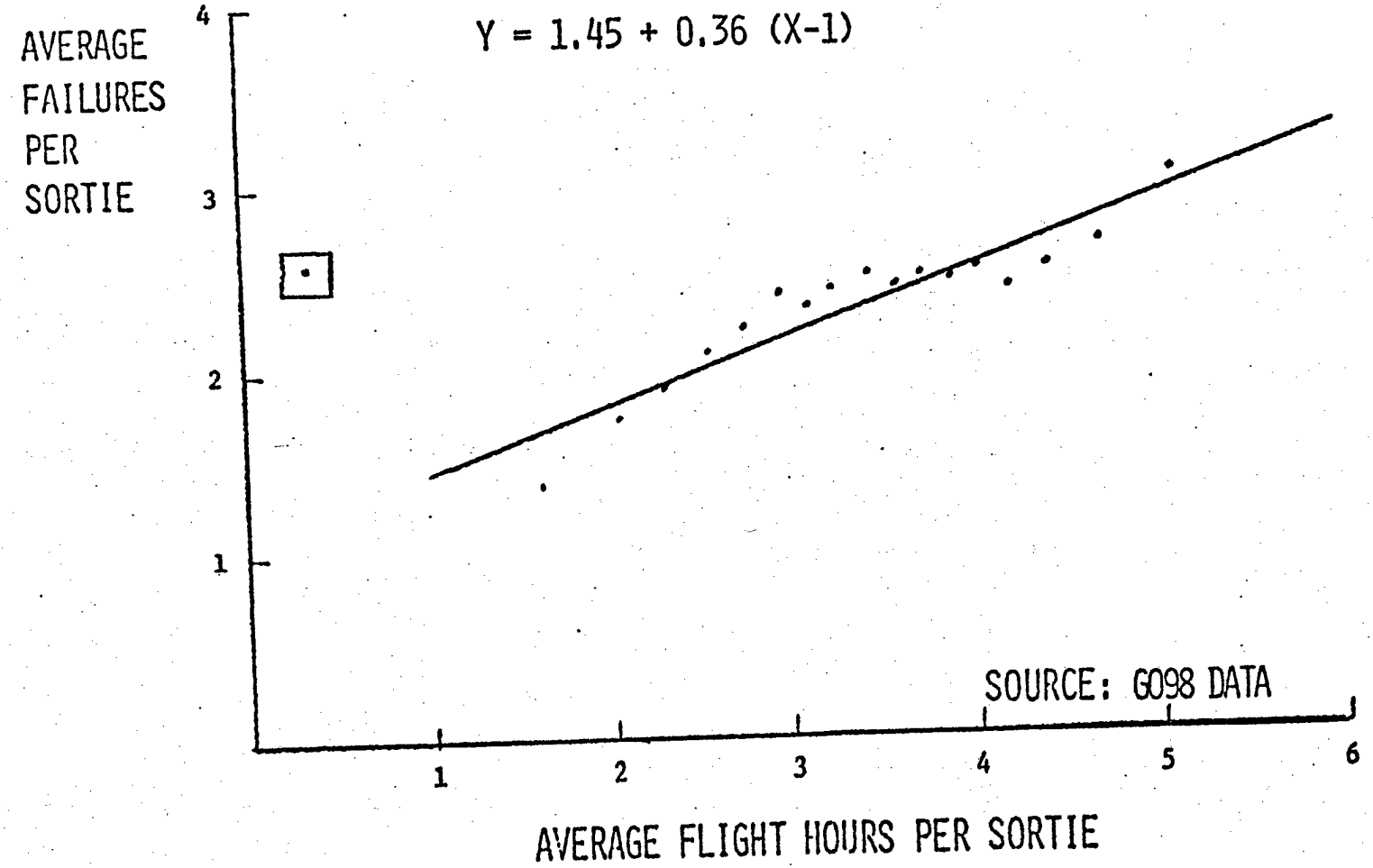
THE FIT OF THE COMBINED METHOD REGRESSION LINE IMPROVES WHEN THE G098 DATA IS USED. THE EFFECT OF USING MANY MORE SORTIES IS TO DAMPEN THE AMOUNT OF SCATTER.

SORTIE REGRESSION ANALYSIS

C-141 ALL WUCs

LINE: 835,000 SORTIES

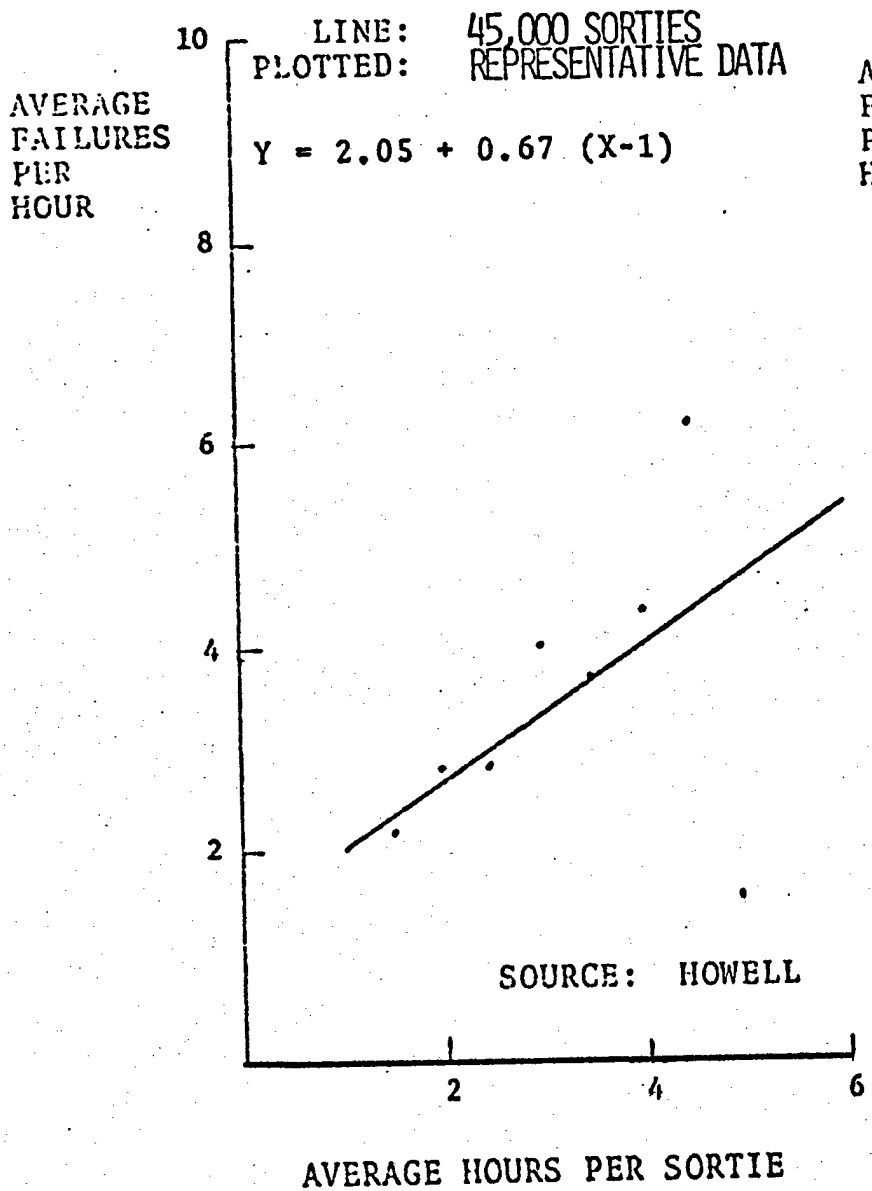
PLOTTED: REPRESENTATIVE DATA



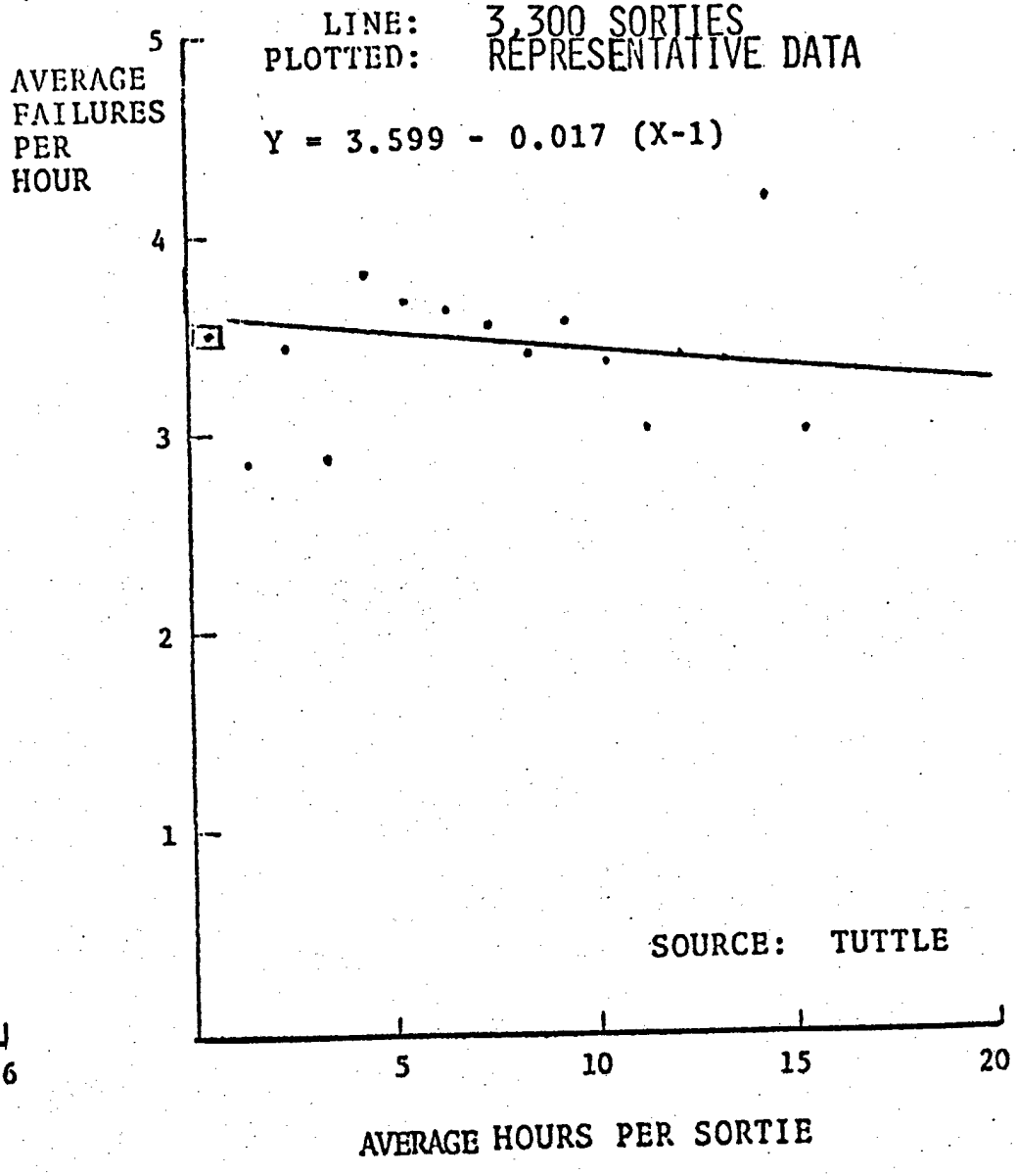
THE PARAMETERS FROM OUR EQUAL-SORTIE G098 DATA ARE VERY CLOSE TO THOSE FROM THE EQUAL-TIME-INTERVAL REGRESSION. THE SORTIE GENERATION VALUE INCREASED FROM 1.38 TO 1.45. THE CRUISE VALUE DECREASED FROM 0.39 TO 0.36 FAILURES PER HOUR OF FLIGHT. IT IS INTERESTING TO NOTE THAT THESE SMALL CHANGES ARE DUE TO THE CHANGE IN APPROACH TO THE SAME DATA BASE.

TIME INTERVAL REGRESSION ANALYSIS

C-130 ALL WUCs



P-3 ALL WUCs



THE C-130 DATA FROM HOWELL LIKEWISE GIVES A LINE WITH A POSITIVE INTERCEPT AND SLOPE. ALTHOUGH THE SLOPE FOR THE OTHER TURBO-PROP DRIVEN AIRCRAFT, THE P-3, IS QUITE DIFFERENT, BOTH TYPES OF BEHAVIOR CAN BE PREDICTED USING THE COMBINED METHOD.

REGRESSION ANALYSIS
RESULTS SUMMARY

AIRCRAFT	C-5	C-5
SOURCE	CASEY	G098
DISCRETE VALUE (SORTIES LESS THAN ONE HOUR)	8.47	9.39
A	6.23	7.62
B	0.36	0.42
R^2_u	.929	.928
AIRCRAFT	C-141	C-141
SOURCE	HOWELL	G093
DISCRETE VALUE (SORTIES LESS THAN ONE HOUR)	----	2.58
A	2.18	1.38
B	0.47	0.39
R^2_u	.989	.987

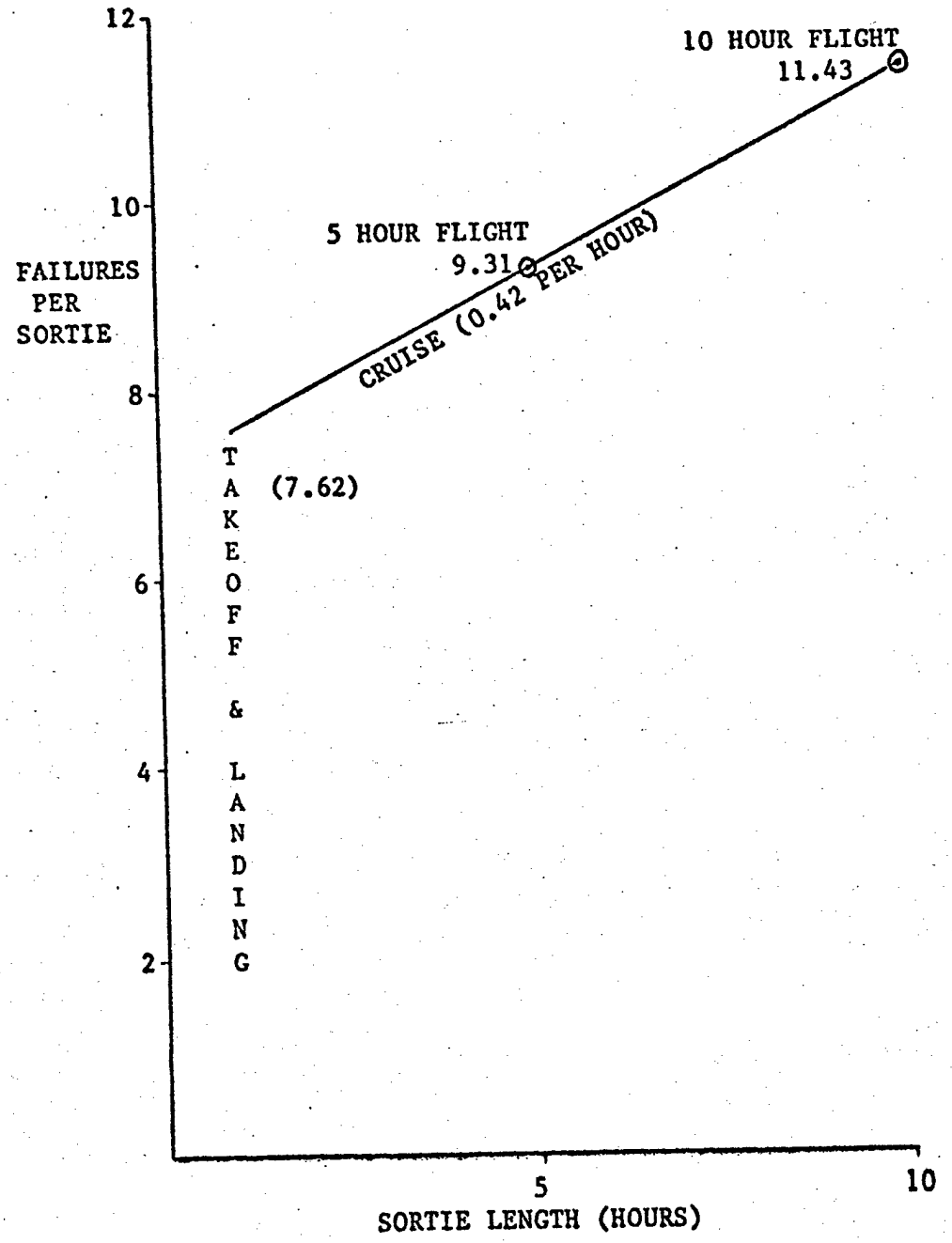
THE RESULTS SUMMARY SLIDE SHOWS THE PARAMETER VALUES OBTAINED FOR THE C-5 AND C-141 FROM THEIR DIFFERENT DATA BASES. NOTE THAT R^2_U IS DIFFERENT FROM THE R^2 NORMALLY ASSOCIATED WITH LINEAR REGRESSIONS (SEE BACKUP SLIDE B4). R^2_U SHOWS THE CONTRIBUTION OF BOTH FLIGHT HOURS AND SORTIE GENERATION IN PREDICTING THE MAINTENANCE DEMAND. THUS, IT IS MORE APPROPRIATE FOR OUR PURPOSE OF TESTING THE COMBINED METHOD. THE USE OF THE NORMAL R^2 METHOD WOULD MEASURE HOW MUCH OF THE VARIANCE IN MAINTENANCE IS EXPLAINED BY FLIGHT LENGTH ONLY.

IMPACT

- SUSTAINABILITY - MEASURE OF MERIT
- INVENTORY ENHANCEMENT - MANAGEMENT TOOL
- INITIAL SPARES STOCKAGE

USING THE COMBINED METHOD IN PLACE OF THE LINEAR METHOD COULD HAVE A SIGNIFICANT IMPACT IN THE AREAS OF SUSTAINABILITY, INVENTORY ENHANCEMENT, AND INITIAL SPARES STOCKAGE, AS WE'LL SHOW IN THE NEXT FEW SLIDES.

EFFECT OF INCREASED C-5 SORTIE LENGTH



EXPECTED FAILURES WHEN FLYING
A 12.5 HOUR UTILIZATION RATE

5 HOUR SORTIE LENGTH
9.31/5 = 1.862 FAILURES/HOUR
1.862 X 12.5 = 23.275 FAILURES/DAY

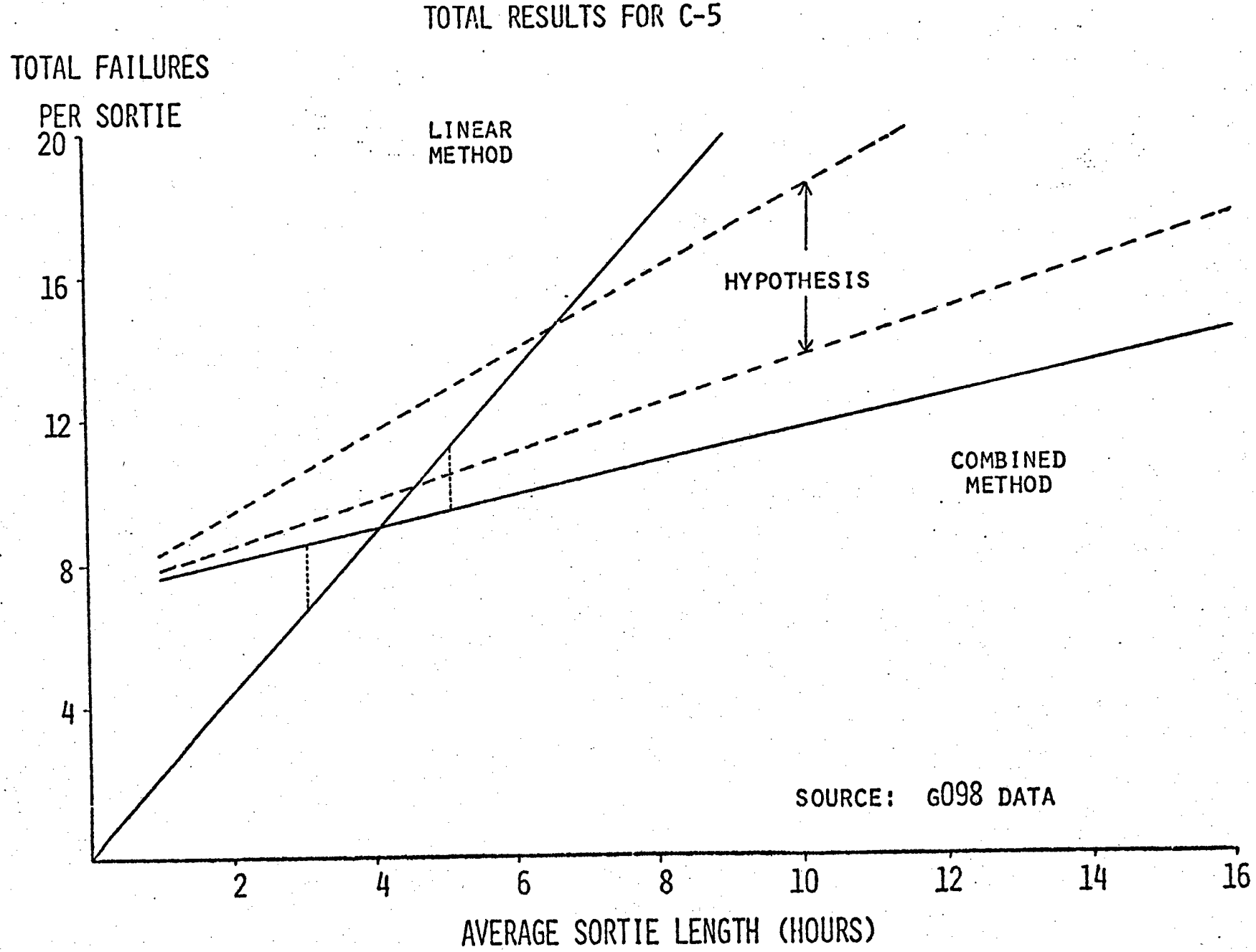
10 HOUR SORTIE LENGTH
11.43/10 = 1.143 FAILURES/HOUR
1.143 X 12.5 = 14.288 FAILURES/DAY

23.275 - 14.288 =
8.987 FEWER FAILURES/DAY

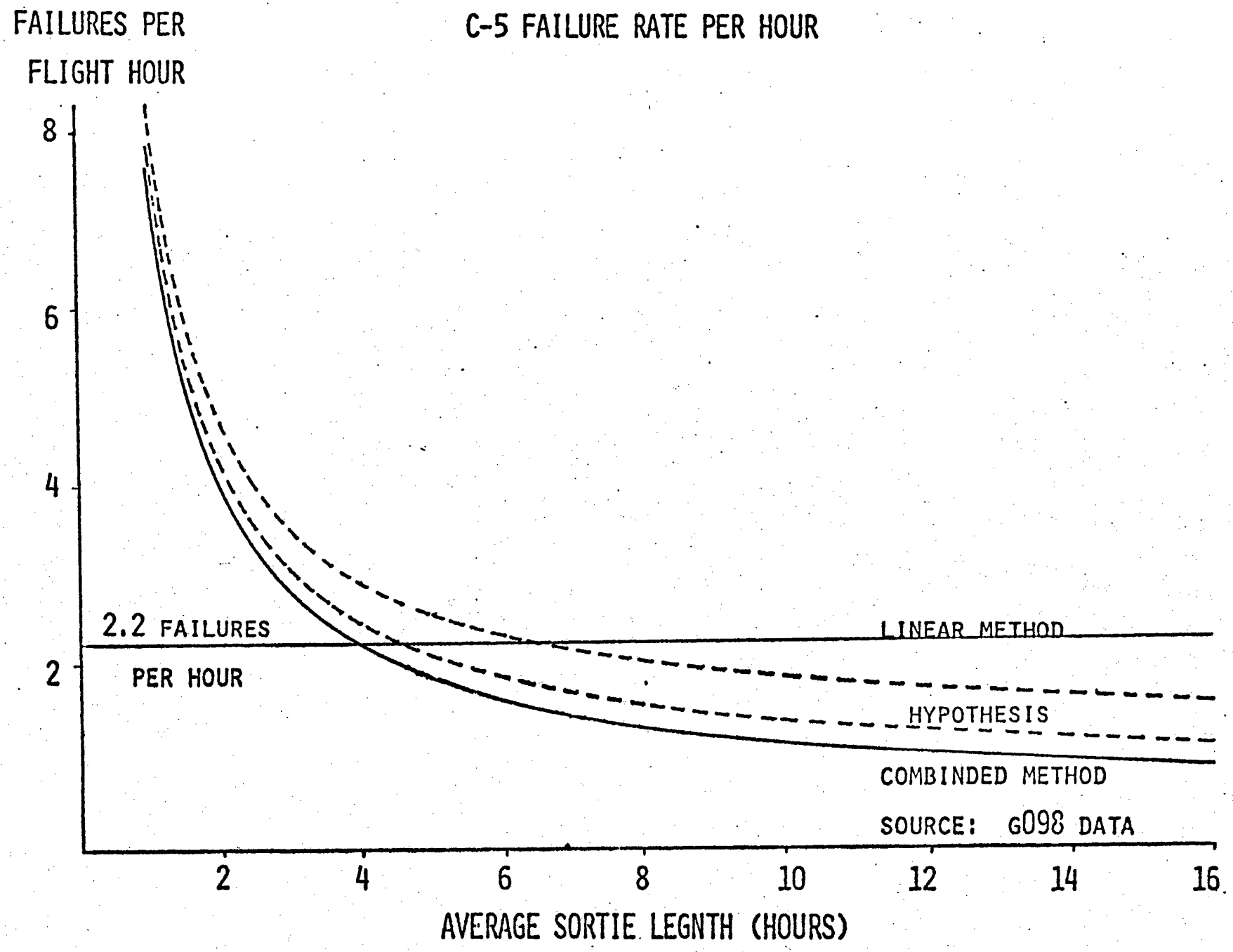
$\frac{8.987}{23.275}$ = 39% FEWER FAILURES/DAY

$\frac{23.275}{14.288}$ = 1.63 OR
63% INCREASED SUSTAINABILITY

THIS SLIDE SHOWS THE EFFECT OF DOUBLING THE C-5 SORTIE LENGTH FROM 5 TO 10 HOURS. THE COMBINED METHOD PREDICTS AN AVERAGE OF 9.31 SPARES NEEDED FOR A FIVE HOUR FLIGHT AND 11.43 SPARES FOR A 10 HOUR FLIGHT. AT A UTILIZATION RATE OF 12.5 HOURS/DAY, THE LONGER SORTIES WOULD REQUIRE 39% FEWER SPARES PER DAY. THIS SAVING RESULTS IN 63% MORE C-5 FLYING TIME WITH A GIVEN SET OF SPARE PARTS.

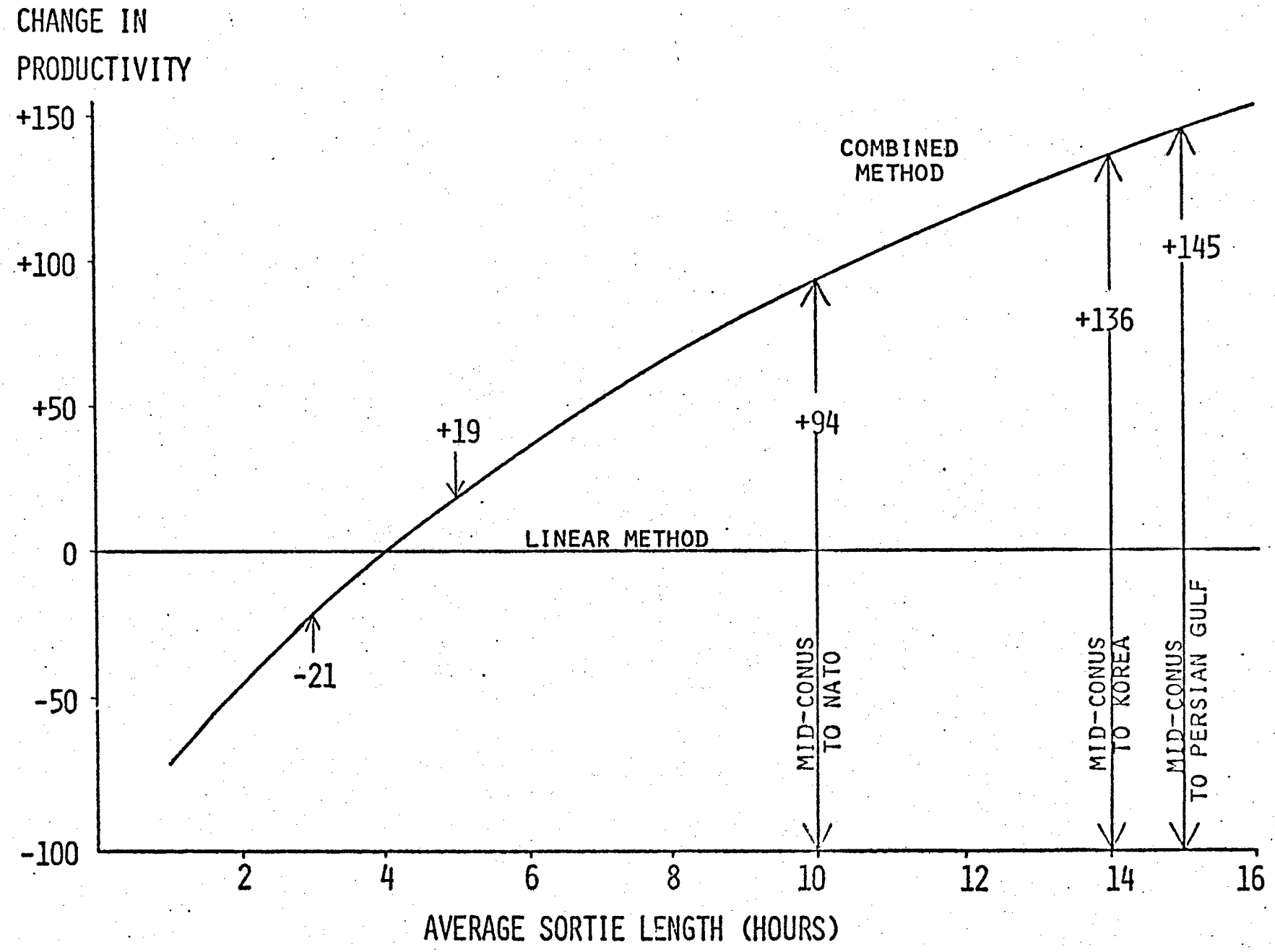

TOTAL RESULTS FOR C-5
TOTAL FAILURES
PER SORTIE
20
16
12
8
4
LINEAR
METHOD
HYPOTHESIS
COMBINED
METHOD
SOURCE: G098 DATA
2
4
6
8
10
12
14
16
AVERAGE SORTIE LENGTH (HOURS)

THIS GRAPH SHOWS THE EXPECTED CHANGES IN FLYING HOURS PRODUCED BY A PACKAGE OF SPARE PARTS WHEN THE COMBINED METHOD OF ESTIMATING FAILURES IS USED. THEY ARE NORMALIZED TO THE FLYING HOURS PREDICTED BY THE LINEAR METHOD WHEN THE AVERAGE SORTIE LENGTH IS IN THE 3 TO 5 HOUR RANGE, THE FLYING HOURS PRODUCED WILL BE ABOUT THE SAME AS THOSE PREDICTED BY THE LINEAR METHOD. HOWEVER, IF AERIAL REFUELING IS AVAILABLE TO INCREASE THE SORTIE LENGTH OF THE C-5, THE SUSTAINABILITY OF SURGE RATES COULD BE INCREASED SUBSTANTIALLY. MORE TOTAL FLYING HOURS CAN BE PRODUCED FROM THE SAME SET OF SPARES. THIS IS A "HIDDEN BENEFIT" OF AERIAL REFUELING, REVEALED BY THE COMBINED METHOD OF ESTIMATING THE DEMAND FOR SPARE PARTS.


C-5 FAILURE RATE PER HOUR
FAILURES PER
FLIGHT HOUR
8
6
4
2
2.2 FAILURES
PER HOUR
LINEAR METHOD
HYPOTHESIS
COMBINDED METHOD
SOURCE: G098 DATA
2
4
6
8
10
12
14
16
AVERAGE SORTIE LEGNTH (HOURS)

THIS SLIDE COMPARES THE RESULTS FOR THE C-5 TO THE LINEAR AIR FORCE METHOD AND TO OUR HYPOTHESIS. THE FACT THAT THE COMBINED METHOD IS BELOW OUR HYPOTHESIZED REGION INDICATES THAT FAILURES ON THE C-5 ARE EVEN MORE HEAVILY SORTIE-GENERATION RELATED THAN WE SUPPOSED. WHEN THE AVERAGE SORTIE LENGTH IS IN THE 3 TO 5 HOUR RANGE, THE TOTAL FAILURES PREDICTED BY THE COMBINED AND LINEAR METHODS ARE ROUGHLY THE SAME. THEY DIFFER SIGNIFICANTLY ONLY WHEN THE SORTIE LENGTH BECOMES QUITE SHORT OR LONG. FOR THESE CASES THE COMBINED METHOD IS A BETTER PREDICTOR OF THE DEMAND FOR MAINTENANCE. ALSO, THE FURTHER AWAY FROM THE AVERAGE SORTIE LENGTH WE GO, THE WORSE THE AIR FORCE LINEAR METHOD REFLECTS ACTUAL EXPERIENCE.

C-5 SPARES PACKAGE PRODUCTIVITY



THESE CURVES ARE CONSTRUCTED FROM THE SAME POINTS USED ON THE PREVIOUS GRAPH, BUT PLOTTED AS FAILURES PER FLIGHT HOUR INSTEAD OF FAILURES PER SORTIE. CONSIDER THE IMPACT OF USING LONG SORTIE LENGTHS TO ESTIMATE THE DEMAND FOR INITIAL SPARES. AN INITIAL SPARES PURCHASE BASED ON 10 HOUR FLIGHTS WOULD CALL FOR AN AVERAGE OF 1.1 SPARES PER FLIGHT HOUR. INITIAL CADRE TRAINING FLIGHTS WITH SHORT SORTIE LENGTHS COULD EASILY RESULT IN FAILURE RATES THREE AND FOUR TIMES HIGHER THAN THE 10 HOUR FAILURE RATE, QUICKLY EXHAUSTING THE INITIAL SPARES STOCKAGE.

OBSERVATIONS

- SUSTAINABILITY IS A FUNCTION OF AVERAGE SORTIE LENGTH.
- APPROXIMATELY 75% OF ALL FAILURES OCCUR DURING TAKEOFF AND LANDING.
- LONGER SORTIE LENGTHS MEAN GREATER SUSTAINABILITY.
  - FLY THE SAME UTILIZATION RATE FOR A LONGER PERIOD OF TIME.
  - FLY MORE TOTAL HOURS WITH A FIXED SET OF SPARES AND TECHNICANS.
- MORE MEANINGFUL MTBF DATA CAN BE OBTAINED BY FLYING IOT&E SORTIES OF VARIOUS LENGTHS.
- INITIAL SPARE STOCKAGE WILL IMPROVE WHEN AVERAGE SORTIE LENGTH IS USED.
- INCREASING SORTIE LENGTH INCREASES SUSTAINABILITY.

A NUMBER OF OBSERVATIONS CAN BE DRAWN FROM THE RESULTS OF THIS STUDY. SINCE THE FAILURE RATE DURING CRUISE IS LOWER THAN THE FAILURE RATE DURING TAKE-OFF AND LANDING, LONGER SORTIES AVERAGE FEWER FAILURES PER FLIGHT HOUR THAN SHORTER SORTIES. FOR A FIXED SET OF SPARE PARTS, THAT TRANSLATES INTO GREATER SUSTAINABILITY AT A GIVEN UTILIZATION RATE. ALSO, FLYING VARIOUS SORTIE LENGTHS DURING IOT&E WOULD PROVIDE MORE MEANINGFUL DATA TO DEVELOP THE FAILURE RATE FOR A NEW AIRCRAFT. IT SHOULD YIELD MORE ACCURATE DATA TO BE USED IN BUYING INITIAL SPARES AND THEY SHOULD BE BOUGHT USING THE EXPECTED AVERAGE SORTIE LENGTH FOR THE AIRCRAFT DURING PEACETIME TRAINING. INITIAL SPARES STOCKAGE BASED ON WARTIME MISSION LENGTHS ARE INADEQUATE TO SUPPORT PEACETIME TRAINING.

BACKUP MATERIAL

HYPOTHESIS FORMULATION

$$Y = A + B(X-1) + C \quad \text{OR} \quad Y = A + BX - B + C$$

WHERE Y = TOTAL MAINTENANCE REQUIRED PER SORTIE
A = MAINTENANCE DUE TO START
B = STEADY STATE MAINTENANCE PER HOUR DURING CRUISE
C = MAINTENANCE DUE TO STOP
X = SORTIE LENGTH IN HOURS

FOR SUBSYSTEM "I"

$$Y_I = A_I + B_I(X-1) + C_I \quad \text{OR} \quad Y_I = A_I + B_IX - B_I + C_I$$

THE SPECIFIC HYPOTHESIS EQUATIONS TESTED INCLUDE ALLOWANCES FOR MAINTENANCE DURING START (PRE-FLIGHT, TAKE-OFF, AND CLIMB-OUT), CRUISE, AND STOP (DESCENT, LANDING, AND COOL-DOWN). THE "X-1" FACTOR INDICATES THE ONE HOUR ALLOWED FOR THE START AND STOP PHASES. THE SAME EQUATION FORM APPLIES TO ALL SUBSYSTEMS AS WELL AS THE TOTAL SYSTEM MAINTENANCE DEMAND WHICH IS OBTAINED BY SUMMING ALL THE A_Is VALUES TO EQUAL A, THE B_Is TO GET B AND THE C_Is TO GET C. SIMPLY STATED, THE TOTAL IS EQUAL TO THE SUM OF ITS PARTS.

REGRESSION EQUATIONS

SINGLE SORTIE

TERMS: X_I = FLIGHT HOURS

Y_I = FAILURES

E_I = ERROR TERM

EQUATION: $Y_I = A + BX_I + E_I$

VARIANCE: $V(E_I) = \sigma^2$

AVERAGE OF MULTIPLE SORTIES

TERMS: S = NUMBER OF SORTIES

X = TOTAL FLIGHT HOURS = $\sum_{I=1}^{S} X_I$

Y = TOTAL FAILURES = $\sum_{I=1}^{S} Y_I$

EQUATION: $Y = AS + BX + \sum_{I=1}^{S} E_I$

OR $Y/S = A + BX/S + \sum_{I=1}^{S} E_I/S$

VARIANCE: $V\left(\sum_{I=1}^{S} E_I\right) = S\,V(E_I) = S\sigma^2$

OR $V\left(\sum_{I=1}^{S} E_I/S\right) = V\left(\sum_{I=1}^{S} E_I\right)/S^2 = \sigma^2/S$

WEIGHTED REGRESSION FORMULAE

EQUATION: $Y/\sqrt{S} = A\sqrt{S} + BX/\sqrt{S} + \sum_{I=1}^{S} E_I/\sqrt{S}$

VARIANCE: $V\left(\sum_{I=1}^{S} E_I/\sqrt{S}\right) = V\left(\sum_{I=1}^{S} E_I\right)/S = S\sigma^2/S = \sigma^2$

OUR DATA ANALYSIS STARTED WITH THE BASIC REGRESSION EQUATION FORM FOR A SINGLE SORTIE. HOWEVER, THE MAINTENANCE DATA COLLECTION (MDC) REPORTING SYSTEM AGGREGATES DATA BY MONTH. THUS, SINGLE SORTIE DATA WAS NOT READILY AVAILABLE. SOME OF THE DATA HAD TO BE GROUPED BY AVERAGE SORTIE LENGTH FOR A MONTH BEFORE THE REGRESSION COULD BE DONE. WITH MULTIPLE SORTIES IN EACH DATA POINT, THE STANDARD REGRESSION ASSUMPTION OF CONSTANT VARIANCE IS NO LONGER TRUE. (THE VARIANCE IN EACH DATA POINT DEPENDED ON THE NUMBER OF SORTIES USED TO CONSTRUCT THAT DATA POINT.) WE THEREFORE SWITCHED TO WEIGHTED EQUATIONS FOR THE ACTUAL REGRESSION ANALYSIS. (IN THIS FORM THE VARIANCE IS CONSTANT REGARDLESS OF THE VALUE OF "S".) IN THIS FORM, THE EQUATION CONTAINS TWO INDEPENDENT VARIABLES ($\sqrt{S}$, $X/\sqrt{S}$) AND NO CONSTANT TERM.

ASSUMPTIONS

THE ERROR TERM, "E", IN THE SINGLE SORTIE EQUATION FOLLOWS A NORMAL DISTRIBUTION WITH ZERO MEAN

THE VARIANCE OF "E" IS CONSTANT: $V(E) = \sigma^2$

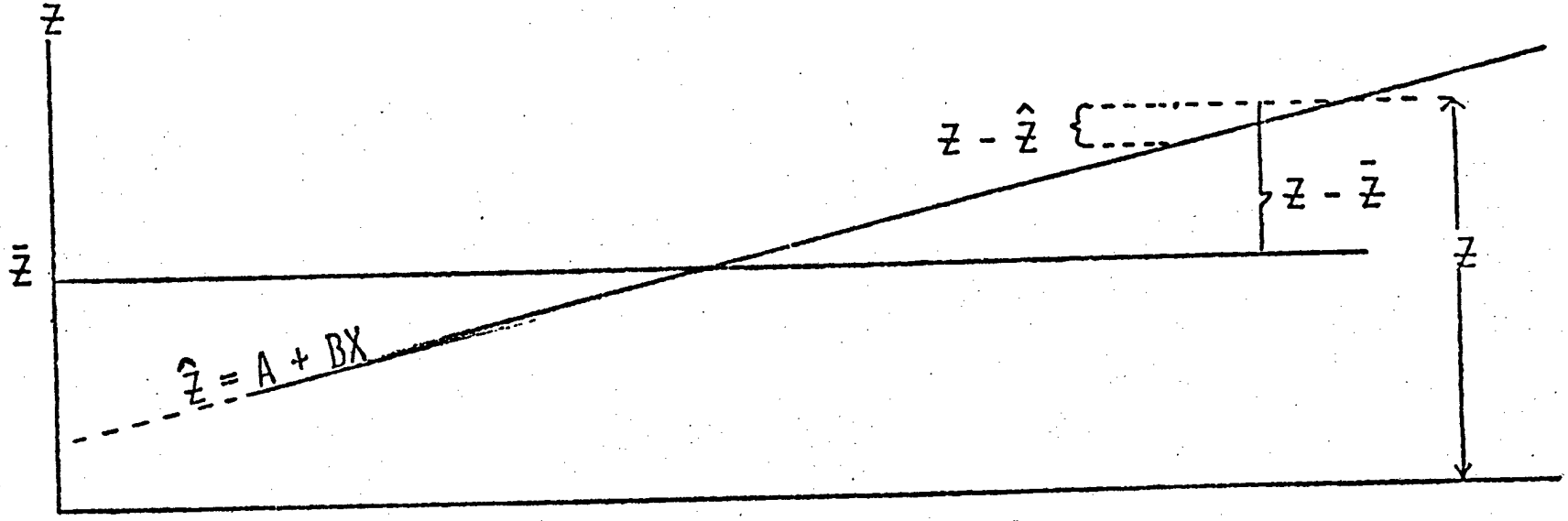
THE ERROR TERMS ARE ALL INDEPENDENT

SORTIES LASTING ONE HOUR OR LONGER CONTAINED ONE COMPLETE TAKEOFF PHASE AND ONE COMPLETE LANDING PHASE

ALL DEPOT LEVEL MAINTENANCE WAS EXCLUDED

THE FIRST TWO ASSUMPTIONS ARE THE STANDARD ONES USED IN PERFORMING A LINEAR REGRESSION. THE INDEPENDENCE OF THE ERROR TERMS IS A NECESSARY ASSUMPTION IN CALCULATING THE VARIANCE FOR MULTIPLE SORTIE DATA POINTS. IT IS PROBABLY NOT COMPLETELY CORRECT, BUT CONSIDERING THE NUMBER OF AIRCRAFT INVOLVED AND THE MANY DIFFERENT FLIGHT CONDITIONS, IT DOES SEEM TO BE REASONABLE. THE FOURTH ASSUMPTION JUST MEANS WE DID NOT CONSIDER THE NUMBER OF LANDINGS AS A SEPARATE EXPLANATORY VARIABLE. IN OTHER WORDS, THE FAILURES PER SORTIE SHOULD BE RELATIVELY CONSTANT REGARDLESS OF THE NUMBER OF LANDINGS. DEPOT LEVEL MAINTENANCE WAS EXCLUDED BECAUSE IT COULD NOT READILY BE ASSOCIATED WITH ANY ACTUAL FLYING DATA.

COEFFICIENT OF DETERMINATION



R^2 ADJUSTED FOR THE MEAN

$$R^2_A = 1 - \frac{\Sigma(Z - \hat{Z})^2}{\Sigma(Z - \bar{Z})^2}$$

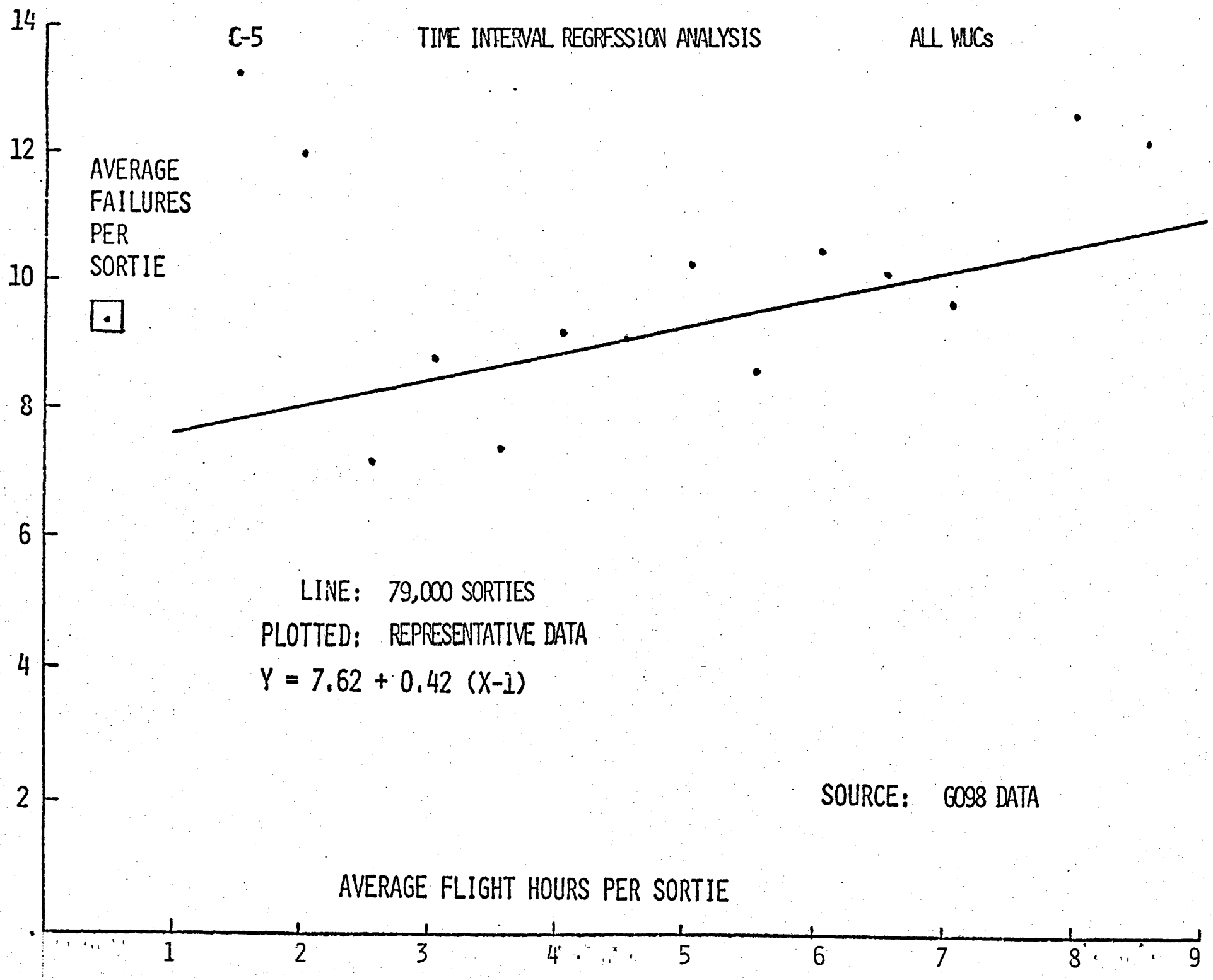
R^2 UNADJUSTED

$$R^2_U = 1 - \frac{\Sigma(Z - \hat{Z})^2}{\Sigma Z^2}$$

SPECIFIC R^2 FOR THIS STUDY

$$Z = Y/\sqrt{S} \qquad R^2_U = 1 - \frac{\Sigma(Y/\sqrt{S} - \hat{Y}/\sqrt{S})^2}{\Sigma(Y/\sqrt{S})^2} = 1 - \frac{\Sigma(Y - \hat{Y})^2/S}{\Sigma Y^2/S}$$

THE COEFFICIENT OF DETERMINATION ADJUSTED FOR THE MEAN IS THE ONE COMMONLY USED WHEN THE EQUATION FORM CONTAINS AN INTERCEPT TERM. IT SHOWS THE CONTRIBUTION OF THE INDEPENDENT VARIABLES ONLY, BUT NOT THE CONSTANT. NOTE THAT WHEN $\hat{Z}$ IS NEAR $\bar{Z}$, R_A^2 CAN BE NEAR ZERO EVEN IF THE FIT IS GOOD. FOR OUR PURPOSE, THEN, R_U^2 WAS MORE APPROPRIATE SINCE IT INCLUDES THE CONTRIBUTION OF BOTH VARIABLES (SORTIE GENERATION AND FLIGHT LENGTH.) IT IS NORMALLY USED WHEN THE EQUATION CONTAINS NO CONSTANT TERM. FOR OUR SPECIFIC EQUATION FORM, THE ACTUAL DEPENDENT VARIABLE WAS THE TOTAL FAILURES WEIGHTED BY THE SQUARE ROOT OF THE NUMBER OF SORTIES INVOLVED. THE CALCULATION OF R_U^2 CAN THEN BE MADE AS SHOWN.


C-5
TIME INTERVAL REGRESSION ANALYSIS
ALL WUCs
AVERAGE FAILURES PER SORTIE
14
12
10
8
6
4
2
LINE: 79,000 SORTIES
PLOTTED: REPRESENTATIVE DATA
Y = 7.62 + 0.42 (X-1)
SOURCE: G098 DATA
AVERAGE FLIGHT HOURS PER SORTIE
1
2
3
4
5
6
7
8
9

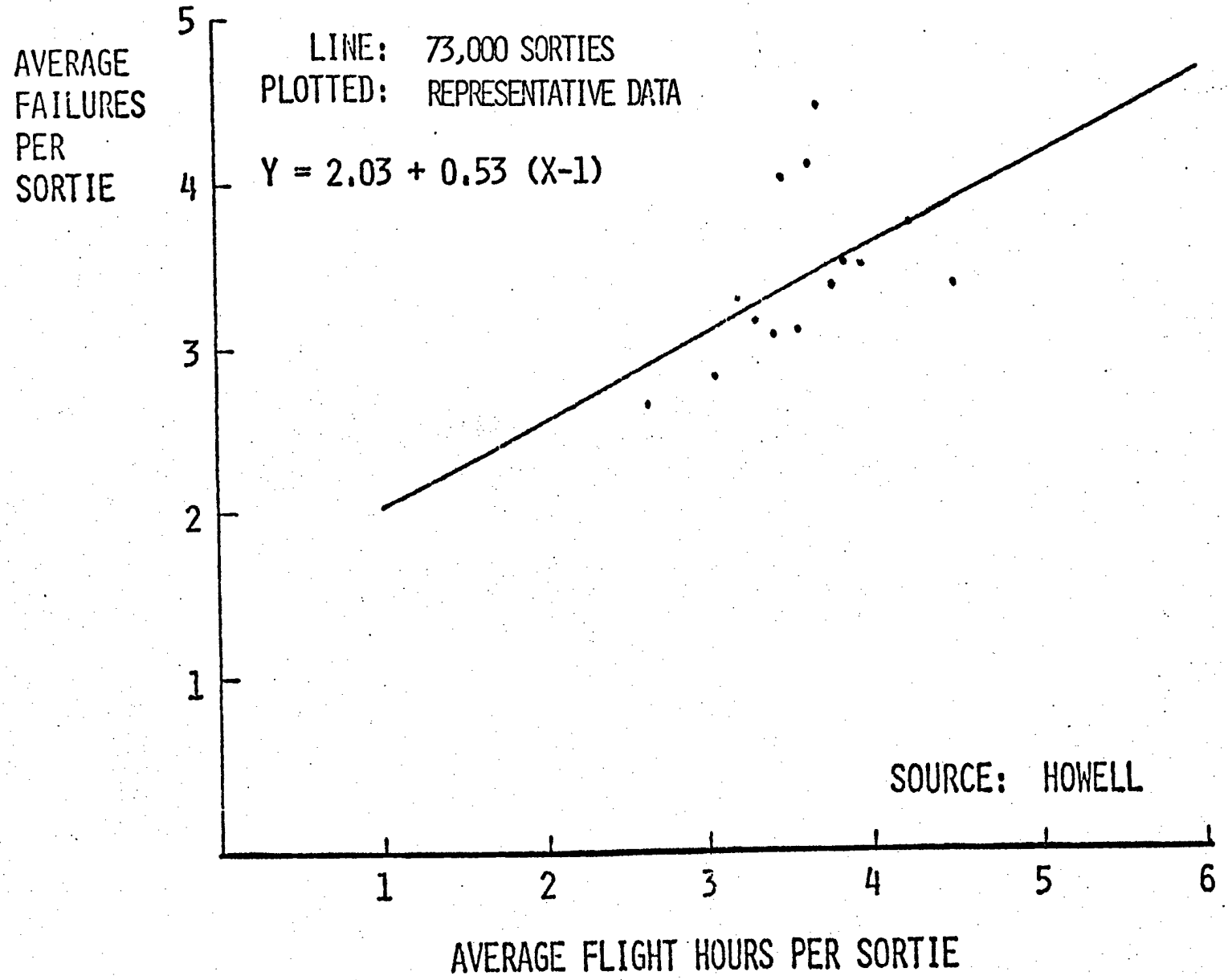
THE RESULTS OF THE REGRESSION ANALYSIS OF C-5 DATA USING A CONSTANT TIME INTERVAL IS PRESENTED HERE. THE EQUATION VALUES ARE SIMILAR TO THOSE SHOWN IN SLIDE 15.

SLIDE 15: $Y = 7.74 + 0.38\ (X-1)$

SLIDE B-5: $Y = 7.62 + 0.42\ (X-1)$

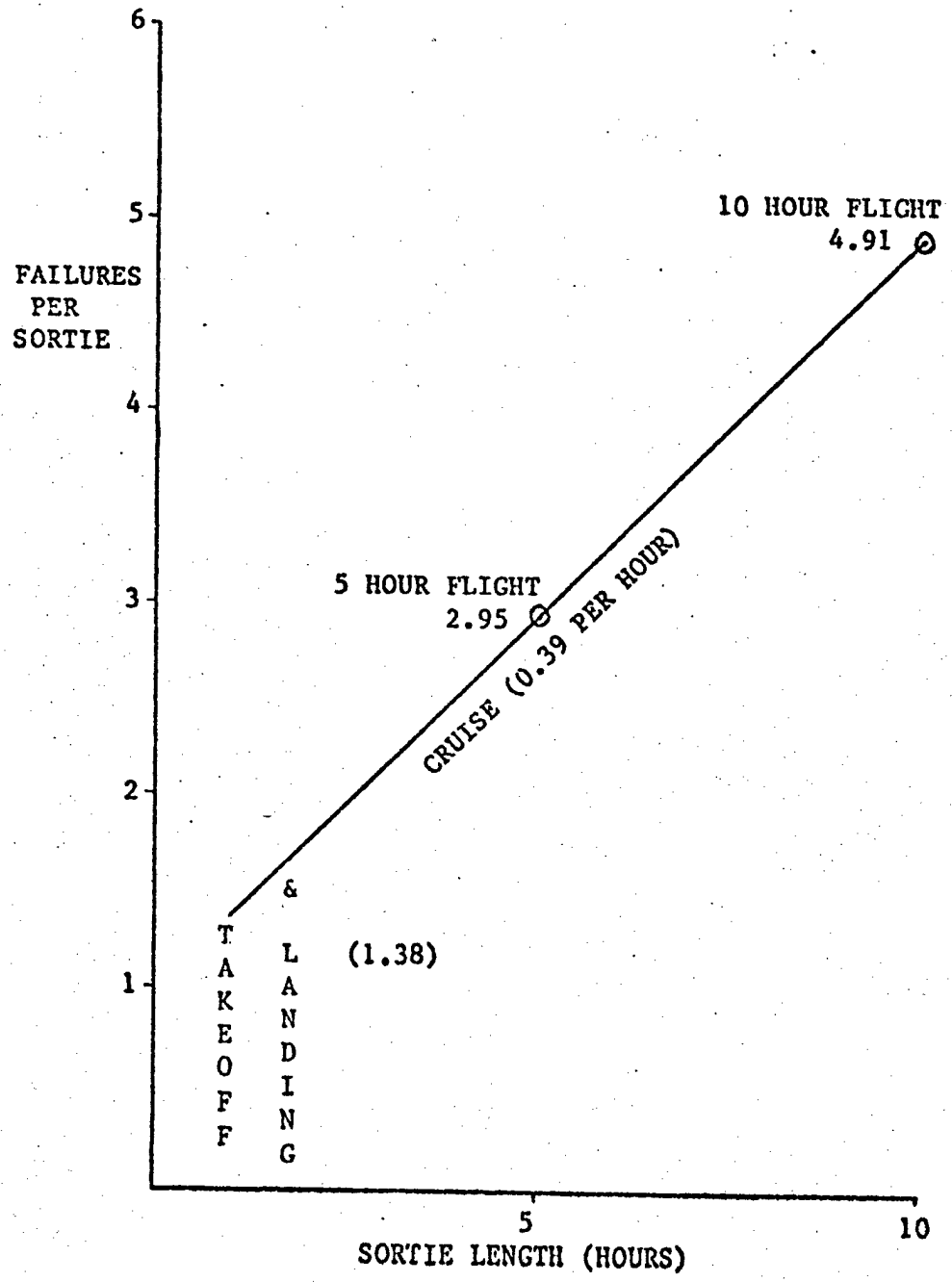
SORTIE REGRESSION ANALYSIS

C-141 ALL WUCs



SHOWN HERE ARE THE REGRESSION ANALYSIS RESULTS ON HOWELL'S C-141 DATA.

EFFECT OF INCREASED C-141 SORTIE LENGTH



EXPECTED FAILURES WHEN FLYING
A 12.5 HOUR UTILIZATION RATE

5 HOUR SORTIE LENGTH
2.95/5 = .59 FAILURES/HOUR
.59 X 12.5 = 7.37 FAILURES/DAY

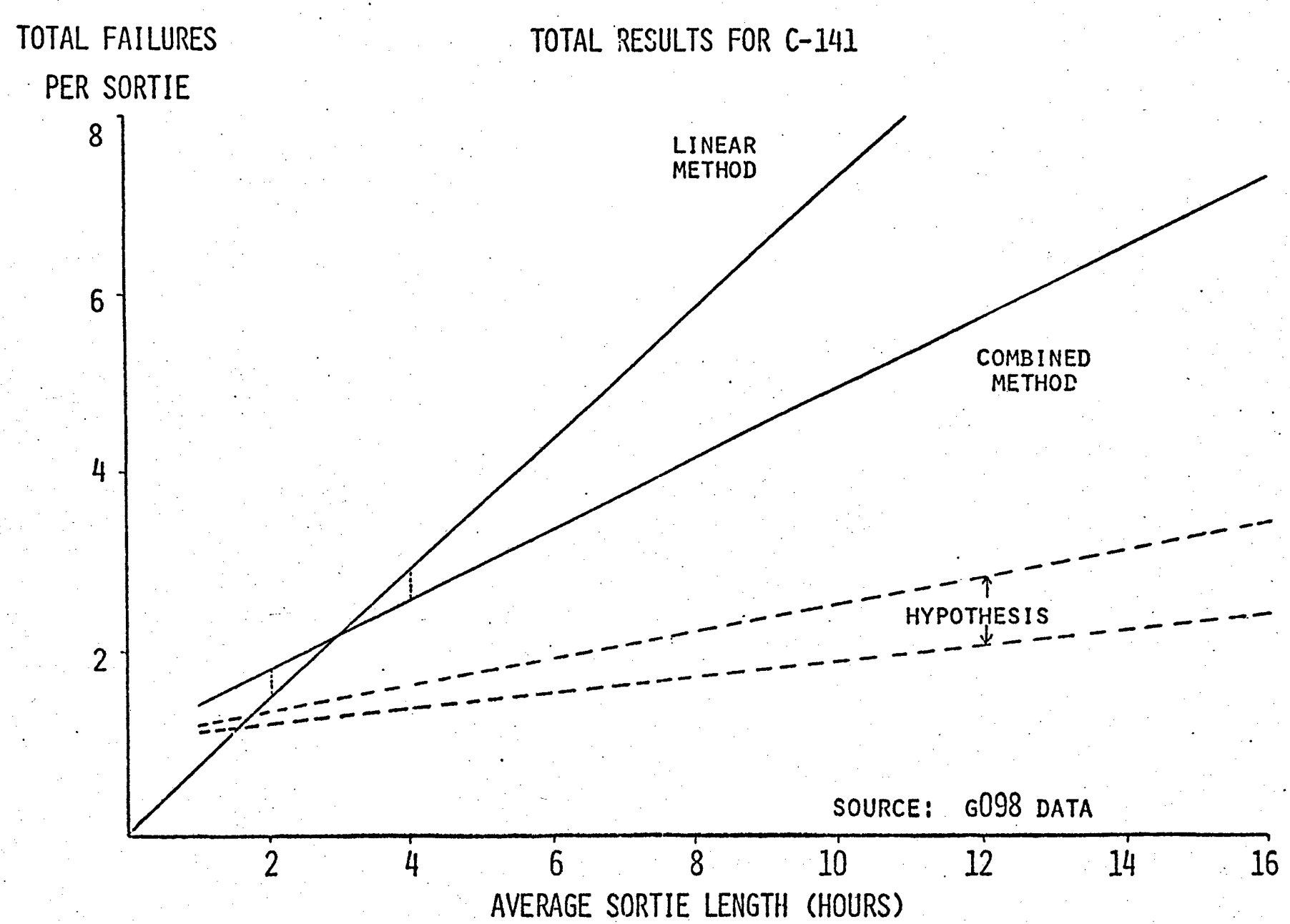
10 HOUR SORTIE LENGTH
4.91/10 = .491 FAILURES/HOUR
.491 X 12.5 = 6.14 FAILURES/DAY

7.37 - 6.14 =
1.23 FEWER FAILURES/DAY

$\frac{1.23}{7.37}$ = 17% FEWER FAILURES/DAY

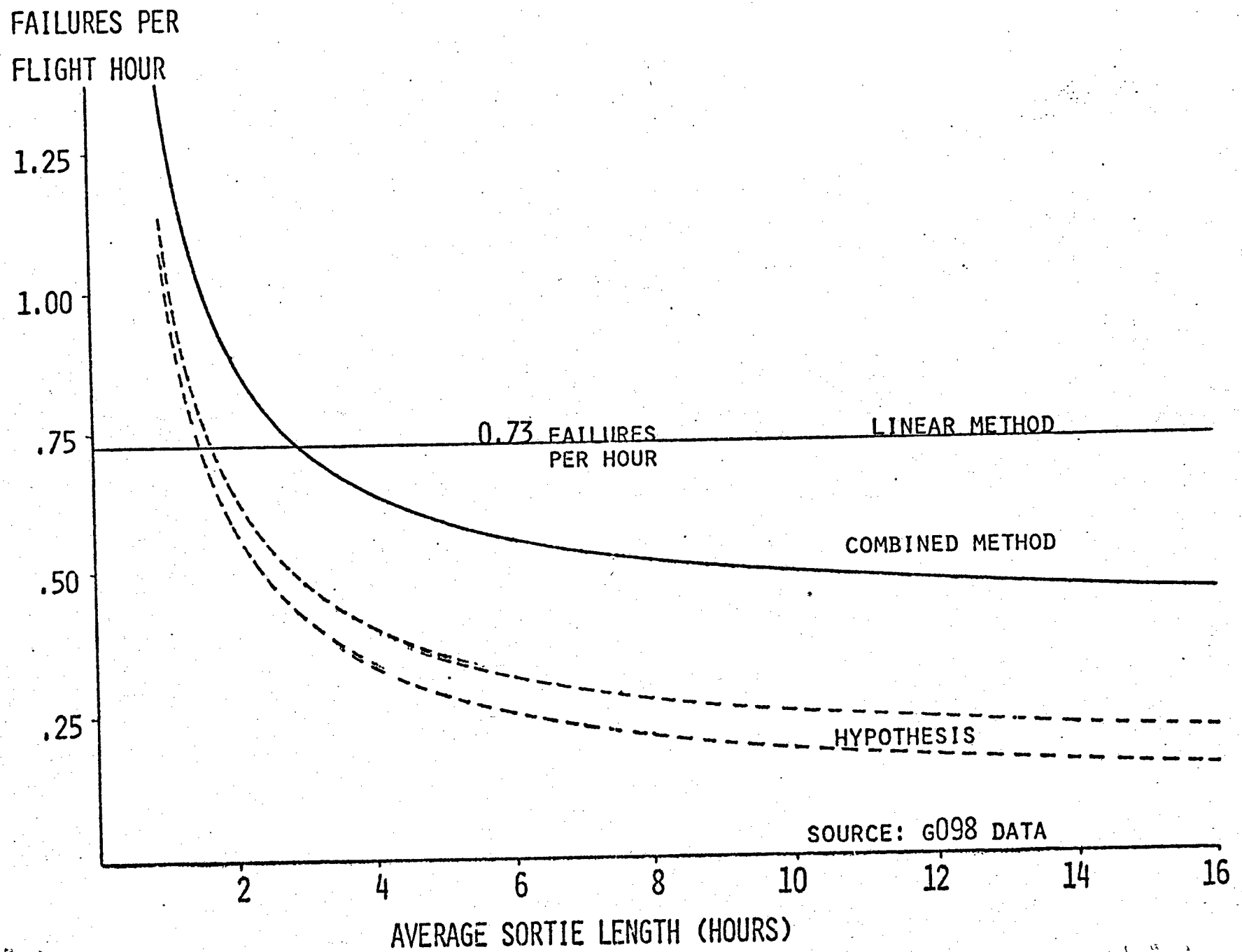
$\frac{7.37}{6.14}$ = 1.20 OR
20% INCREASED SUSTAINABILITY

THIS SLIDE SHOWS THE C-141 DATA THAT CORRESPONDS TO THE METHOD USED IN SLIDE 23 FOR THE C-5.


TOTAL RESULTS FOR C-141
TOTAL FAILURES
PER SORTIE
8
6
4
2
LINEAR
METHOD
COMBINED
METHOD
HYPOTHESIS
SOURCE: G098 DATA
2
4
6
8
10
12
14
16
AVERAGE SORTIE LENGTH (HOURS)

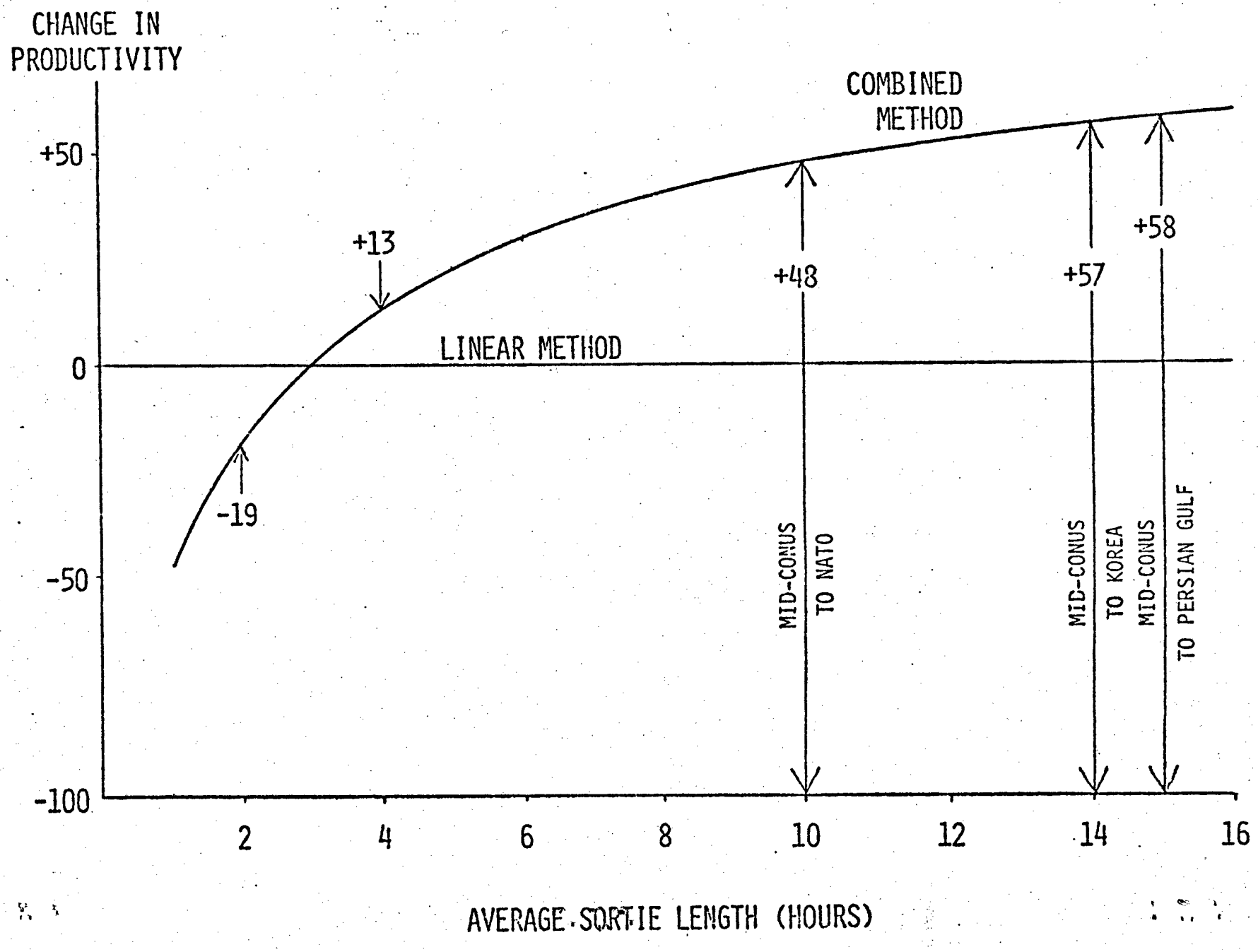
THIS IS THE COMPANION SLIDE TO B-7 AS SLIDE 24 WAS CONSTRUCTED FROM THE DATA IN SLIDE 23. IT SHOWS THAT THE C-141 HAS LESS CHANGE AS A FUNCTION OF SORTIE LENGTH.

C-141 FAILURE RATE PER HOUR



THE C-141 RESULTS SHOWN HERE ARE LESS SORTIE GENERATION DEPENDENT THAN THE HYPOTHESIS PREDICTED, BUT STILL MORE SO THAN THE LINEAR METHOD SUGGESTS.

C-141 SPARES PACKAGE PRODUCTIVITY



C-141 SUSTAINABILITY WILL INCREASE SOME, BUT NOT AS MUCH AS THAT OF THE C-5, WHEN SORTIE LENGTH IS INCREASED.