AFCEC-TR-78-1

# RUNWAY ROUGHNESS EVALUATION LASER PROFILOMETER IMPLEMENTATION STUDY

DIRECTORATE OF ENGINEERING MATERIALS

OCTOBER 1977



Final Report: November 1975 - September 19~~75~~

Approved for Public Release; Distribution Unlimited.

AIR FORCE CIVIL ENGINEERING CENTER
(AIR FORCE ENGINEERING AND SERVICES AGENCY)
TYNDALL AIR FORCE BASE
FLORIDA 32403

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

(14)

| | |
|---|---|
| 1. [redacted] AFCEC-TR-78-1 | 2. GOVT ACCESSION NO. |
| | 3. RECIPIENT'S CATALOG NUMBER (9) |
| 4. TITLE (and Subtitle) (6) RUNWAY ROUGHNESS EVALUATION LASER PROFILOMETER IMPLEMENTATION STUDY. | 5. TYPE OF [redacted] Final rept. Nov[redacted] [redacted]975 — Sept [redacted]77 |
| | 6. [redacted] |
| 7. [redacted] (10) [redacted] Dannie O./Burk [redacted] James I./Clark | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS AIR FORCE CIVIL ENGINEERING CENTER DIRECTORATE OF ENGINEERING MATERIALS TYNDALL AFB, FL 32403 | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE CIVIL ENGINEERING CENTER Tyndall AFB, FL 32403 | (11) 12. REPORT DATE Oct[redacted] [redacted]77 |
| | 13. NUMBER OF PAGES |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (12) 65p. | 15. SECURITY CLASS. (of this report) Unclassified |
| | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Airfields
Pavement roughness
Runway profiles
Runway roughness standards

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Runway profiles and aircraft vertical acceleration responses were analyzed to develop an evaluation methodology for runway roughness and to develop roughness standards against which runways can be evaluated. Root mean square values of filtered profile data and vertical aircraft accelerations were statistically developed on a segmental basis into runway roughness standards. A methodology was developed to evaluate runway profiles against these standards; and to recommend corrective construction of the profile to reduce →

20. (Continued)

aircraft response. Profile roughness has therefore been based on a numerically relative bases. The establishment of runway roughness standards and evaluation methodology is considered incomplete, and additional work is recommended in this report.

## PREFACE

This report was prepared by the Pavement Evaluation Division, Directorate of Engineering Materials, Air Force Civil Engineering Center.

Inclusive dates of the research were November 1975 through September 1977 by the authors, Captain Dannie O. Burk and Major James I. Clark.

Distribution Limitation Statement A. This report has been reviewed by the Chief, Interagency/Intergovernment Coordination (OI) and is releasable to the National Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

DANNIE O. BURK, Capt, USAF
Project Officer

A. STANLEY DALTON
Director, Engineering Materials

ROBERT E. BRANDON
Technical Director

ROBERT M. ITEN, Colonel, USAF
Commander





(The reverse of this page is blank)

## TABLE OF CONTENTS



## LIST OF TABLES

## LIST OF FIGURES

# SECTION I

# INTRODUCTION

## BACKGROUND

This study was begun to provide the United States Air Force (USAF) and the Air Force Civil Engineering Center (AFCEC) with a procedure to evaluate long wave runway profile irregularities which could cause pavement roughness problems. This specific work was directed at developing runway roughness standards for evaluation of operational USAF runways and a methodology for location of segments of the runway which contribute to surface roughness problems. A corollary objective was to develop a methodology for determining the most effective engineering solution to correct the roughness problems identified.

The USAF became interested in a technique to identify runway roughness because of aircrew complaints and maintenance problems which stemmed from aircraft operations on reported rough runways. Unfortunately, no capability existed to identify specific runway segments which caused these problems. Time constraints prohibited doing standard engineering elevation surveys (required excessive runway closure period) to produce accurate runway profiles. Precise identification of the specific area of pavement irregularity was infeasible because of delayed aircraft response to the rough runway segment. In addition, the lack of a rational rating system caused a great inconsistency in reporting of the form and indicated severity of roughness. The rating of a runway surface based on personal opinion depends on the age, experience, and condition of the rater as well as the type and condition of the aircraft operating on the runway. Finally, the limiting roughness criteria for safe aircraft operations had not been quantified. Because of these problems and USAF concern with safe aircraft operations, studies were started to develop methods to locate and quantify runway irregularities which threaten aircraft operations.

# SECTION II

## DEVELOPMENT OF EVALUATION METHODOLOGY

Two primary tasks were included in the search for systems to evaluate runway roughness. These were to develop equipment for quick and accurate runway profiles and to derive the methodology to analyze and quantify roughness problems.

### Equipment Development

Because the runway profile is the basic data source for any analysis of runway roughness, the development of adequate profiling equipment became a first priority. Two types of equipment were developed, an inertial profilometer and a LASER profilometer. Physical descriptions of both systems are included in Reference 1.

The inertial profilometer provides a quick method for obtaining a runway profile. It requires about 10 minutes to obtain a profile line of an 11,000 foot (3353 m) runway with data recorded at every 6-inch (152 mm) interval along the line. The inertial profilometer is not highly accurate. It does, however, provide the required elevation data for an initial rapid surface irregularity analysis. Further developmental work is in progress on the inertial profilometer system with operational availability for field work anticipated by mid-1978.

The LASER profilometer is being used by the AFCEC to gather runway profile data. This equipment provides sufficient vertical profile elevation accuracy for runway roughness evaluation work. However, improvement in the horizontal control data acquisition is required to accurately identify pertinent runway segments. This equipment records elevation data on 6-inch (152 mm) horizontal increments along the runway profile path. The improved accuracy of elevation data is obtained at the expense of increased time requirements to complete the survey. An 11,000-foot (3353 m) runway profile requires about 5 hours to complete. Additionally, because of the LASER profilometer's low power LASER, the surveys can only be accomplished at night when sunlight and heat waves do not affect the equipment. The relationship between the LASER profilometer profiles and the runway roughness evaluation technique will be discussed later in this report.

## Evaluation Methodology

The second area of concern in the development of an operational runway roughness evaluation system is the methodology to analyze and quantify pavement roughness. Initial attempts were made to find and/or develop a runway roughness standard based on either human tolerances or aircraft structural limitations. Research revealed that, in general, human limitations to the effects of pavement roughness would be reached before aircraft structural limitations (Reference 1). However, defining and quantifying the limits of human endurance to pavement roughness is essentially impossible because of personal variables involved.

Other potential methods of quantifying runway roughness are presented in Reference 2. The most promising method, as developed here, involves a statistical analysis of the runway profile including an assumption that the profile can be defined by a series of mathematical expressions.

This technique includes a filtering process to remove certain wavelengths from the mathematical expression of the profile and to quantify the pavement roughness. A high-pass digital filtering technique is used to remove the long wavelength components from the profile mathematical expression. The assumption used here is that wavelengths beyond a certain value will not produce a measurable aircraft response. The technique essentially eliminates noise that could interfere with the analysis.

A typical input profile and the resulting filtered profile using a cutoff wavelength of 400 feet (122 m) are presented in Figure 1. Quantification of the pavement roughness is done through computation of a root-mean-square (RMS) value of the displacement distances from the mean profile for the entire length of the profile at 2-foot (0.608 m) intervals. As can be seen in the filtered profile, the RMS technique is required since a simple averaging would produce a zero or near zero answer. The overall profile will have no slope as a result of the filtering technique. This RMS value is then compared to an arbitrary standard and the runway is evaluated as being smooth, transitional, or rough.

Further attempts to quantify runway roughness included analysis of the effect of the runway profile on aircraft response (vertical accelerations) through the use of a computer program identified as "TAXI code." This computer

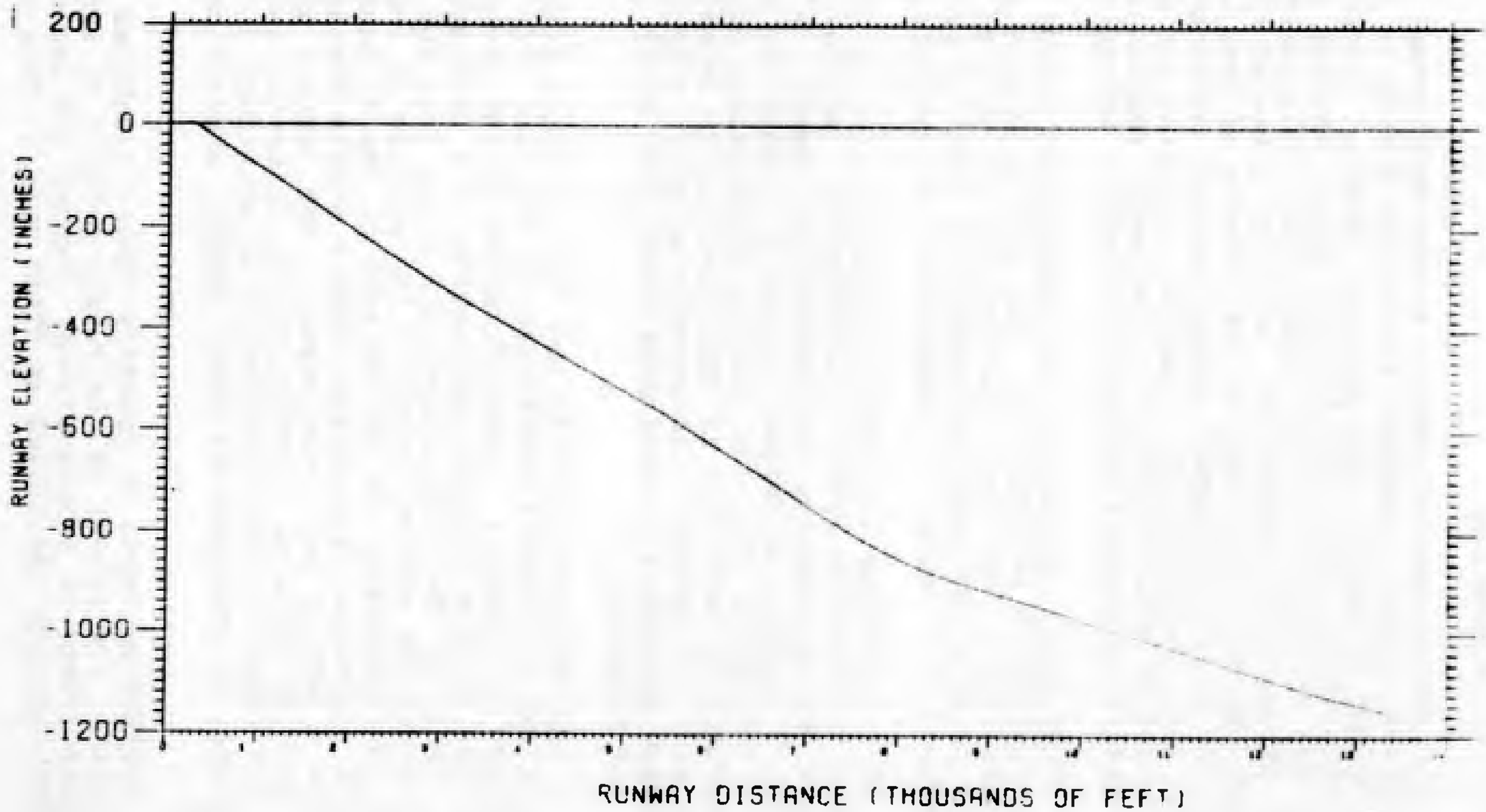



**FIGURE 1 TYPICAL RUNWAY PROFILE**

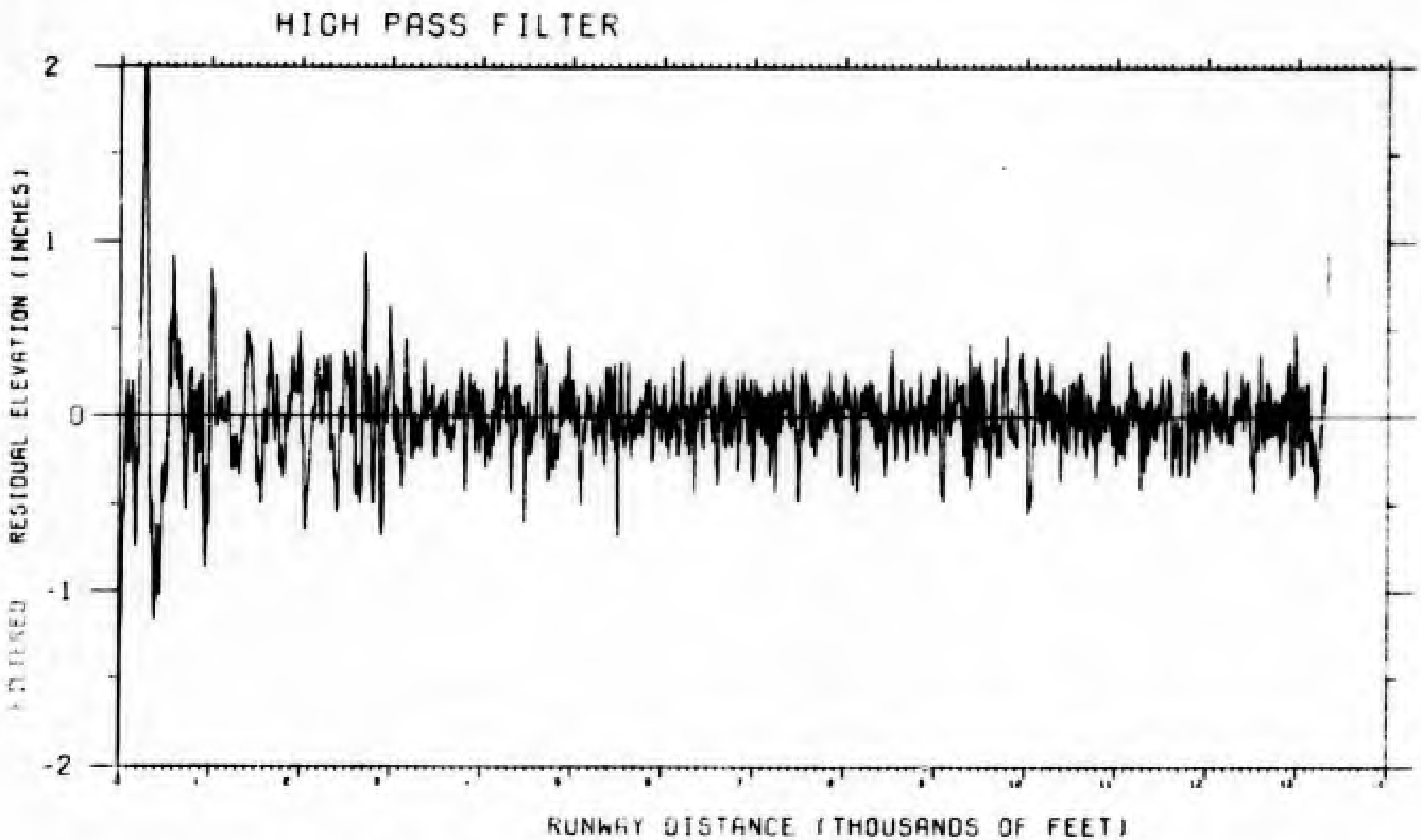



**FIGURE 1(cont) TYPICAL FILTERED PROFILE**

program simulates the expected vertical acceleration responses to the runway profile during constant speed taxi or takeoff operations (Reference 5). The TAXI code is a relatively simple simulation that produces the expected aircraft response at three aircraft stations while traversing a given profile. The aircraft stations include the pilot's position, center of gravity and tail section. Several simplifying assumptions were used to develop the TAXI code that limits the usefulness of the output. However, the accuracy of the computer product meets the requirements of this roughness evaluation system (Reference 4). The RMS of the vertical accelerations produced by the TAXI Code for a runway profile were then compared to an arbitrary standard to identify runway roughness in general terms. Appendix C contains parts of typical taxi outputs.

Evaluation Technique

After the general direction of research had been established as discussed above, we could then begin to develop working procedures, techniques, and roughness standards for use by an operational AFCEC team in relative evaluations of runway roughness. This section will describe and discuss the flow of work and techniques used to develop the final analysis and evaluation procedures.

The first step included selection of the data base for the study. Runway profiles developed in conjunction with earlier research (Reference 2) and the first surveys accomplished by AFCEC at HQ USAF request were reviewed. Twenty-four of these were selected for use based on apparent validity and consistency of data. The centerline profile from each of the runways selected (Table 1) was used for this study. While the runways used as a data base were not randomly selected, 17 of the originally surveyed runways were chosen for the original survey without prior knowledge of the runway roughness characteristics. The other seven runways were surveyed because of alleged roughness problems. The histograms presented in figures 7, 8, and 9 indicate the bias introduced into the study by runway selection criteria. This bias will cause conservative results in application of the resulting evaluation methodology. Additionally, since the objective is to determine the relative roughness of the runway, the bias, while recognized, is not considered to be an overriding factor.

Having developed the data base, the specific variables to be analyzed while trying to quantify runway roughness on a statistical basis were chosen. Because it was necessary to analyze the runway profile as well as the aircraft response

TABLE 1

TABULATION OF OVERALL AIRCRAFT RESPONSE INDEX (ARI) AND RUNWAY ROUGHNESS INDEX (RRI)

| RUNWAY | RRI (400) | RRI (200) | RRI (100) | RRI ( 50) | ARI (F4C) C | ARI (F4C) P | ARI (F4C) C G | ARI (F4C) T | ARI (B52) C | ARI (B52) P | ARI (B52) C G | ARI (B52) T |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Albany | .456 | .346 | .181 | .100 | .581 | .406 | .287 | .876 | .272 | .295 | .092 | .353 |
| Ashville | .376 | .291 | .215 | .174 | .666 | .461 | .380 | .987 | .231 | .284 | .102 | .262 |
| Buffalo | .350 | .226 | .146 | .092 | .610 | .460 | .291 | .905 | .198 | .225 | .073 | .249 |
| Cannon | .115 | .093 | .0814 | .066 | .344 | .213 | .182 | .526 | .103 | .141 | .042 | .101 |
| Charleston (old) | .275 | .198 | .153 | .108 | .538 | .364 | .276 | .813 | .171 | .200 | .071 | .206 |
| Charleston R/W 15 | .272 | .198 | .153 | .108 | .546 | .363 | .278 | .817 | .173 | .203 | .071 | .208 |
| Craig R/W 007 | .274 | .197 | .124 | .077 | .469 | .335 | .232 | .703 | .220 | .244 | .076 | .284 |
| Craig R/W 010 | .277 | .260 | .163 | .078 | .693 | .570 | .316 | 1.002 | .230 | .236 | .082 | .309 |
| Craig R/W 013 | .321 | .240 | .150 | .083 | .553 | .431 | .266 | .814 | .208 | .221 | .077 | .274 |
| Dallas | .180 | .120 | .0848 | .059 | .463 | .280 | .236 | .714 | .119 | .136 | .044 | .149 |
| Dobbins | .215 | .142 | .104 | .071 | .469 | .329 | .231 | .706 | .132 | .149 | .050 | .166 |
| Dyess | .328 | .218 | .115 | .074 | .480 | .358 | .238 | .712 | .156 | .169 | .061 | .203 |
| Edwards | .173 | .137 | .0986 | .071 | .431 | .278 | .226 | .655 | .131 | .147 | .051 | .165 |
| Ellsworth | .253 | .159 | .107 | .066 | .458 | .308 | .230 | .694 | .149 | .163 | .054 | .193 |
| Grand Forks (old) | .176 | .145 | .108 | .077 | .405 | .263 | .212 | .614 | .147 | .161 | .056 | .188 |
| Kirtland | .274 | .208 | .130 | .074 | .489 | .389 | .230 | .716 | .212 | .246 | .071 | .262 |
| Newark | .299 | .233 | .152 | .091 | .503 | .484 | .251 | .803 | .226 | .254 | .081 | .287 |
| New York | .274 | .212 | .171 | .112 | .727 | .534 | .354 | 1.083 | .280 | .284 | .107 | .378 |
| Offutt | .278 | .165 | .114 | .084 | .455 | .310 | .236 | .685 | .150 | .180 | .056 | .178 |
| O'Hare | .310 | .174 | .089 | .059 | .397 | .288 | .185 | .557 | .147 | .163 | .052 | .187 |
| Palmdale | .174 | .115 | .137 | .118 | .433 | .286 | .248 | .648 | .145 | .183 | .066 | .160 |
| Thule | .512 | .362 | .265 | .159 | .813 | .669 | .367 | 1.184 | .364 | .412 | .134 | .456 |
| Wash Nat'l Rd1 | .375 | .290 | .-86 | .164 | .647 | .514 | .301 | .949 | .233 | .257 | .085 | .300 |
| Norfolk | .610 | .328 | .218 | .125 | 1.256 | .534 | .354 | 1.083 | .280 | .284 | .107 | .378 |

to operations on that runway profile, the RMS values from the filtered profile data and the aircraft vertical accelerations both would have to be used. The RMS value obtained from the filtered profile data has been called the Runway Roughness Index (RRI) and the RMS value obtained from the aircraft vertical acceleration data has been called the Aircraft Response Index (ARI). These terms were selected to identify and avoid confusing the different RMS values.

Because the cutoff wavelength used in the filtering process affects the RRI values obtained, various cutoff wavelengths were included in the study. The notation of $RRI_{400}$ will be used to denote the RRI derived from the filtered profile data using a cutoff wavelength of 400 feet (122 m), etc.

In order to compare aircraft with differing characteristics, the B-52G and F-4C aircraft were selected to generate ARIs for each runway profile being analyzed. These aircraft with their differing wheel bases, gross weights, and missions were included to test the hypothesis that different roughness evaluation results would be obtained due to differing aircraft characteristics. Additionally, since these two aircraft represent the mission aircraft at a large number of USAF bases, they would simulate actual aircraft operational conditions. The notation used for RMS values obtained from vertical accelerations generated by the TAXI Code for F-4C and B-52G aircraft were $ARI_{F-4C}$ and $ARI_{B-52G}$, respectively.

With the data base available including profiles from 24 runways and the analysis aircraft selected, the actual investigation into the possible runway roughness evaluation techniques was begun. All profiles were filtered using a cutoff wavelength of 400 feet (122 m). The Taxi Code was run for each profile using the F-4C and B-52G aircraft. The aircraft speeds and weights were somewhat arbitrarily selected. The maximum gross weight was selected based on the recommendations of Reference 3. The aircraft speed of 100 feet per second (30.5 m/sec) was selected to represent the speed used in previous research. The potential inaccuracies resulting from lack of a comprehensive aircraft analysis being built into the study by using only one gross weight and aircraft speed are recognized. However, due to time constraints, it was not feasible to investigate each aircraft sufficiently to determine the most critical combination of gross weight and speed. Additionally, the differing characteristics of each runway produce the possibility that a speed and gross weight combination will be critical on one runway but not necessarily on another. If these factors are taken into consideration, the selected weight and speed are presumed to be a good compromise.

The data resulting from the filtered profile and TAXI Code products for all runways were then used to calculate the $RRI_{400}$, $ARI_{F-4C}$, and $ARI_{B-52G}$ for each runway. These values are based on the profile and acceleration data for the complete runway length and represent the "overall" RRI or ARI for each runway. The relationships between these RRIs and ARIs are presented in Figure 2. The equations of the lines shown were calculated using least squares linear regression techniques. The coefficient of determination between the $RRI_{400}$ and the $ARI_{F-4C}$ was found to be 0.736 while that between the $RRI_{400}$ and the $ARI_{B-52G}$ was found to be 0.508. These coefficients were not as high as had been anticipated, based on previous research. Therefore, as discussed previously, and based on Reference 4, the analysis was repeated using cutoff wavelengths of 200, 100, and 50 feet (61, 30.5, and 15.25 m). The values resulting from these additional analyses are presented in Figures 3, 4, and 5. As shown, the resulting coefficients of determination were found to be even less than those obtained using a cutoff wavelength of 400 feet (122 m). Use of the lower cutoff wavelengths should have resulted in a better correlation. However, other unknown factors apparently entered into the problem resulting in lesser correlation of the variables. Based on dynamics theory, as the cutoff wavelength approaches twice the aircraft wheel base, the correlation between the overall ARI and RRI should improve (Reference 4). Because the use of these lower cutoff wavelengths did not result in improved correlation, selection of suitable wavelength cutoffs for various aircraft will be included in the recommendations as an area requiring additional study.

The use of runway profile data, based on a specific wavelength cutoff to evaluate runway roughness, makes the analysis much simpler and more straightforward. However, examination of Figures 2 through 5 clearly shows the need to identify and account for response differences between the various aircraft. Many unknown variables, such as roughness effects in an F-4C, compared to a B-52G and variability of roughness at various aircraft weights and ground speeds, justify including aircraft response in the study of runway profiles and pavement roughness.

To determine if the cutoff wavelength used affected the comparative results of the aircraft response data, a rank order statistical analysis was accomplished for each of the

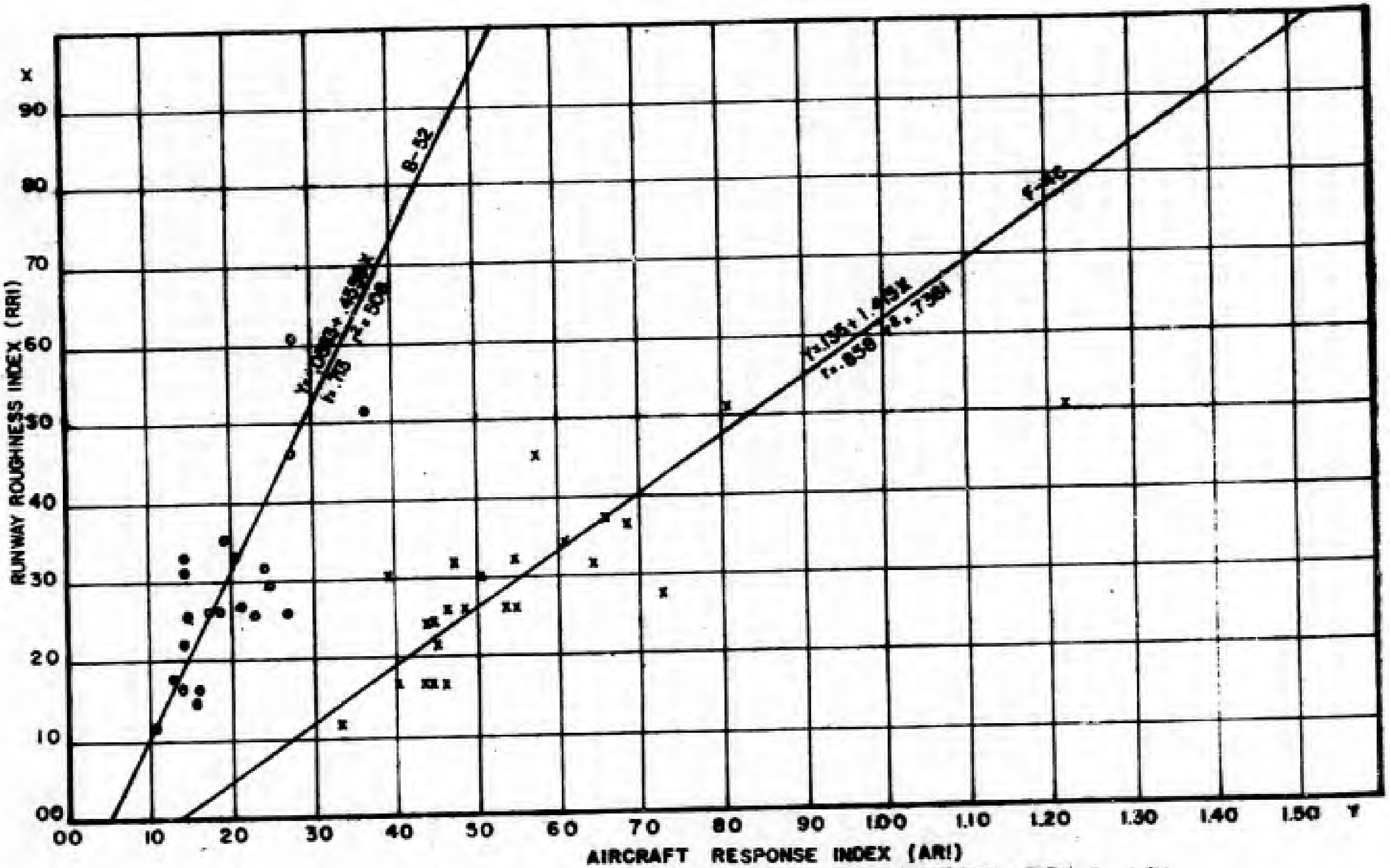



**FIGURE 2 CORRELATION BETWEEN RRI & ARI**
(400 ft (122 m) WAVELENGTH CUTOFF)

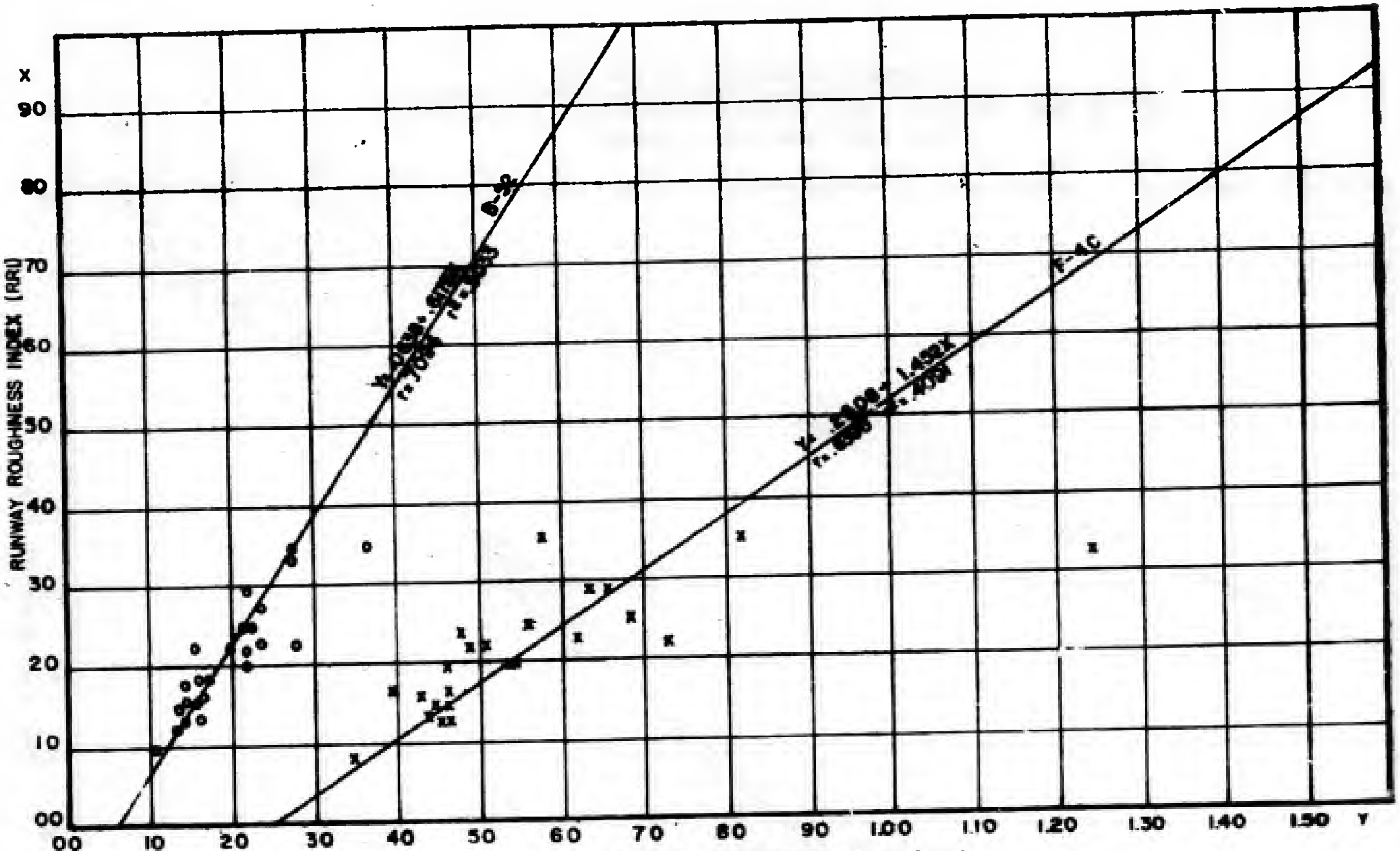



**FIGURE 3 CORRELATION BETWEEN RRI & ARI**
(200 ft (61.0m) WAVELENGTH CUTOFF)

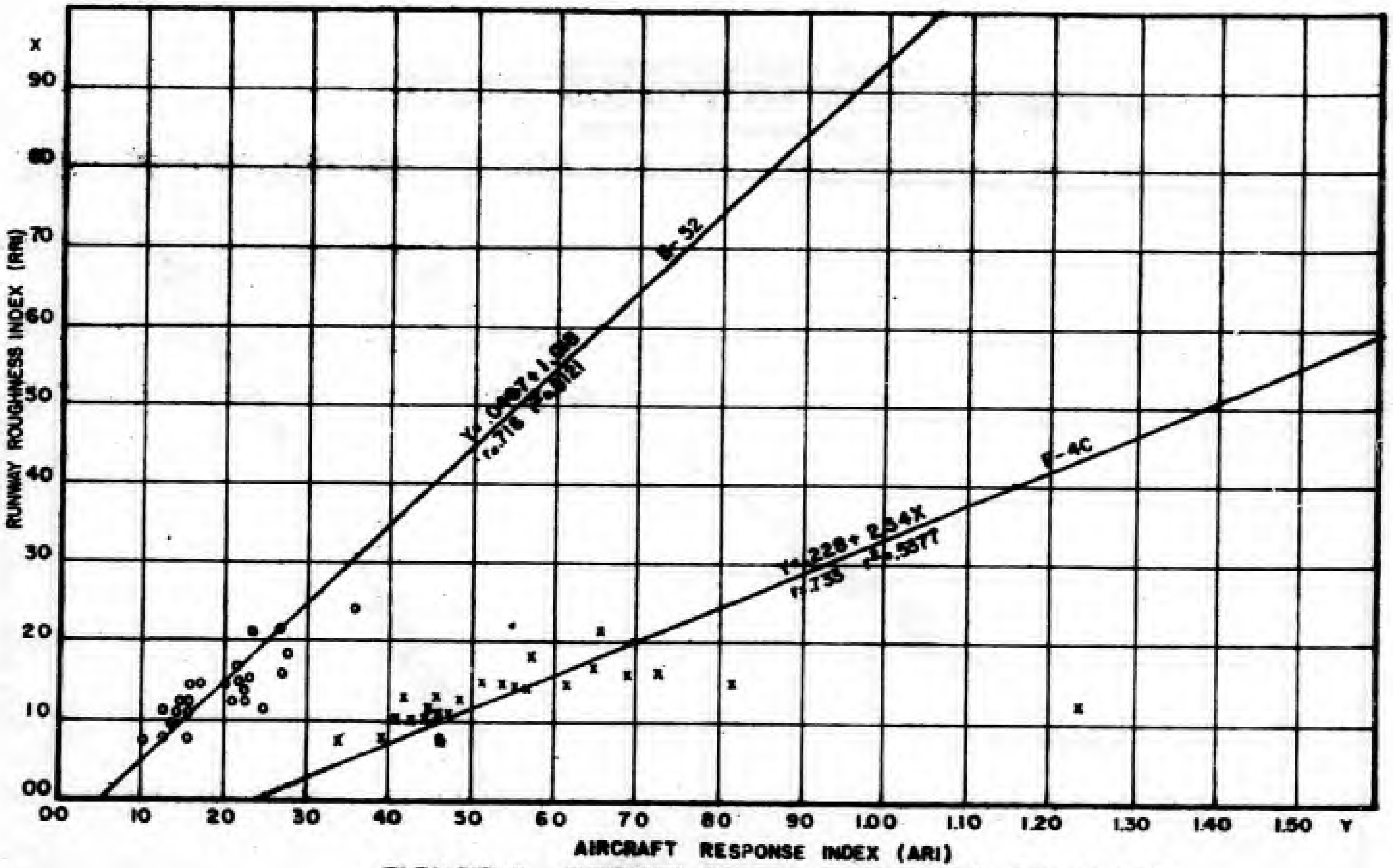



**FIGURE 4 CORRELATION BETWEEN RRI & ARI**
(100 ft(305m) WAVELENGTH CUTOFF)

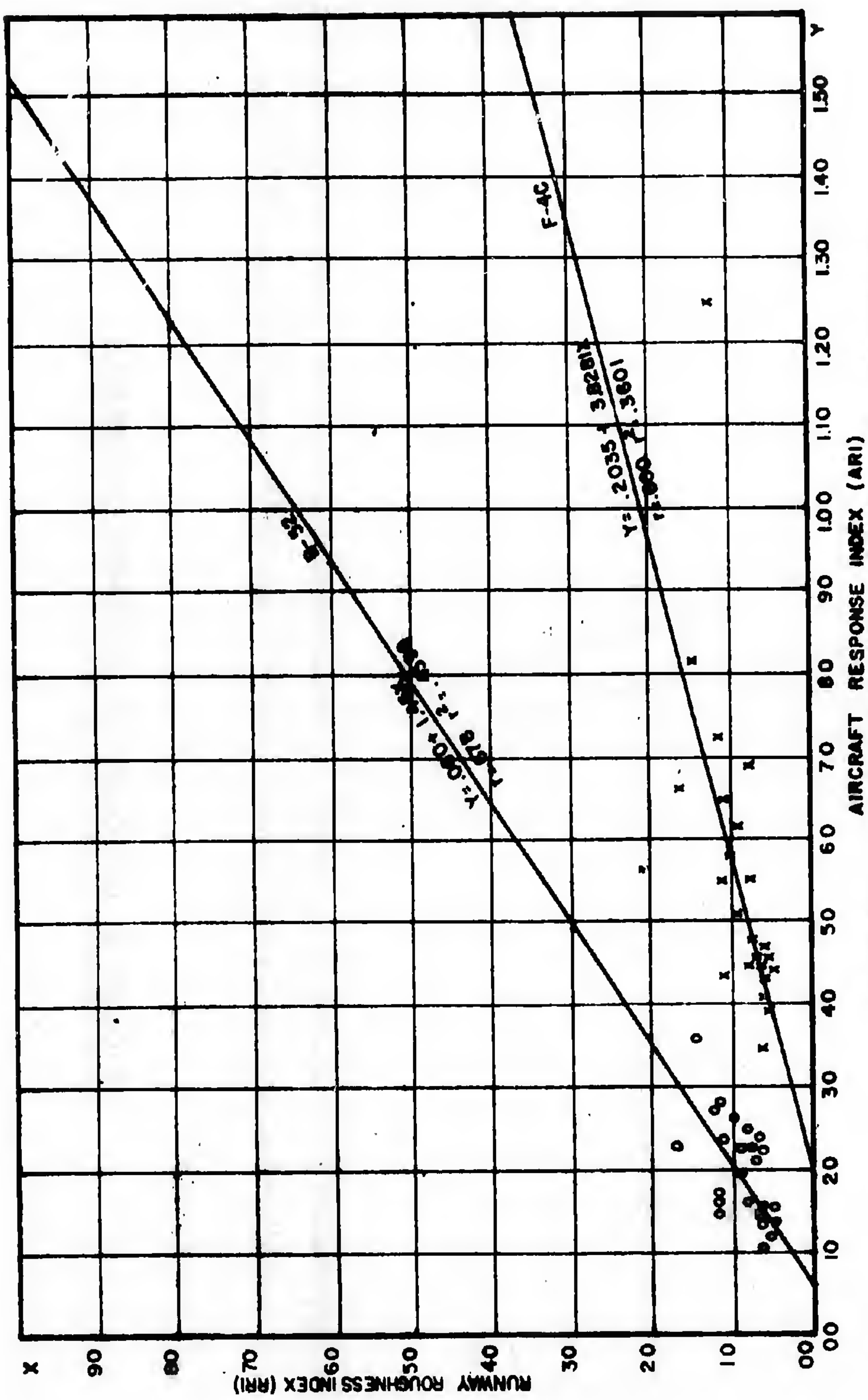



**FIGURE 5 CORRELATION BETWEEN RRI & ARI**

(50 ft (15.2m) WAVELENGTH CUTOFF)

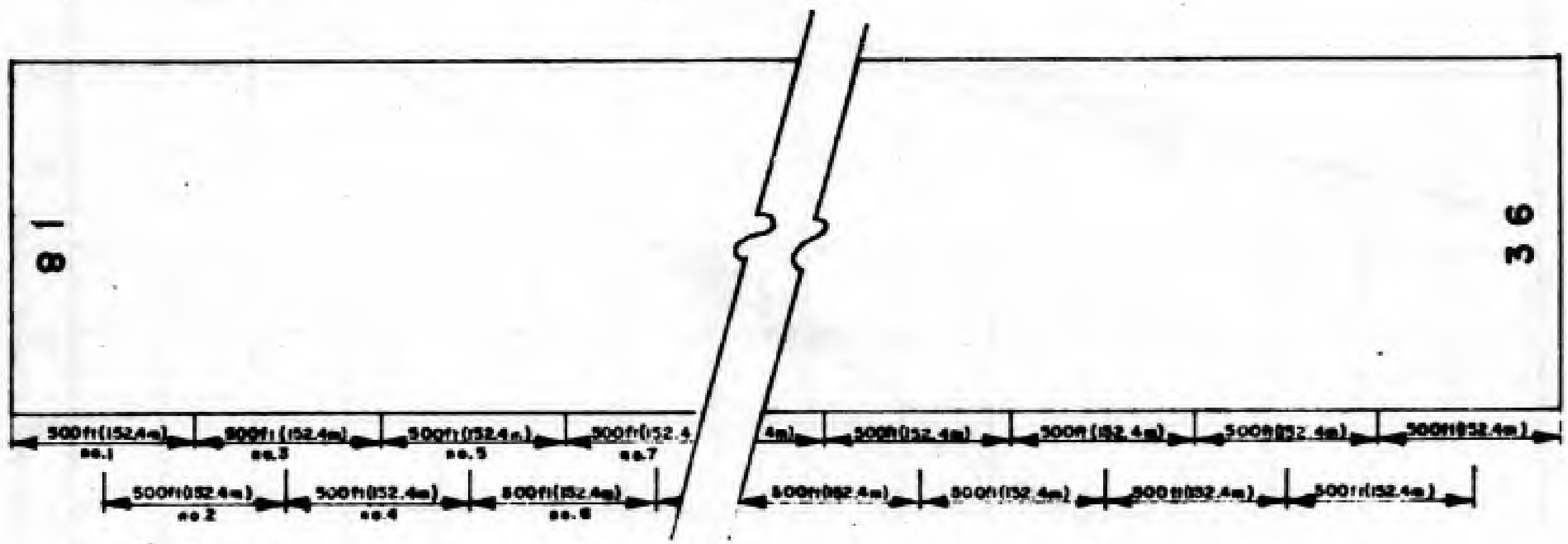



FIGURE-6 LAYOUT OF RUNWAY SEGMENTS

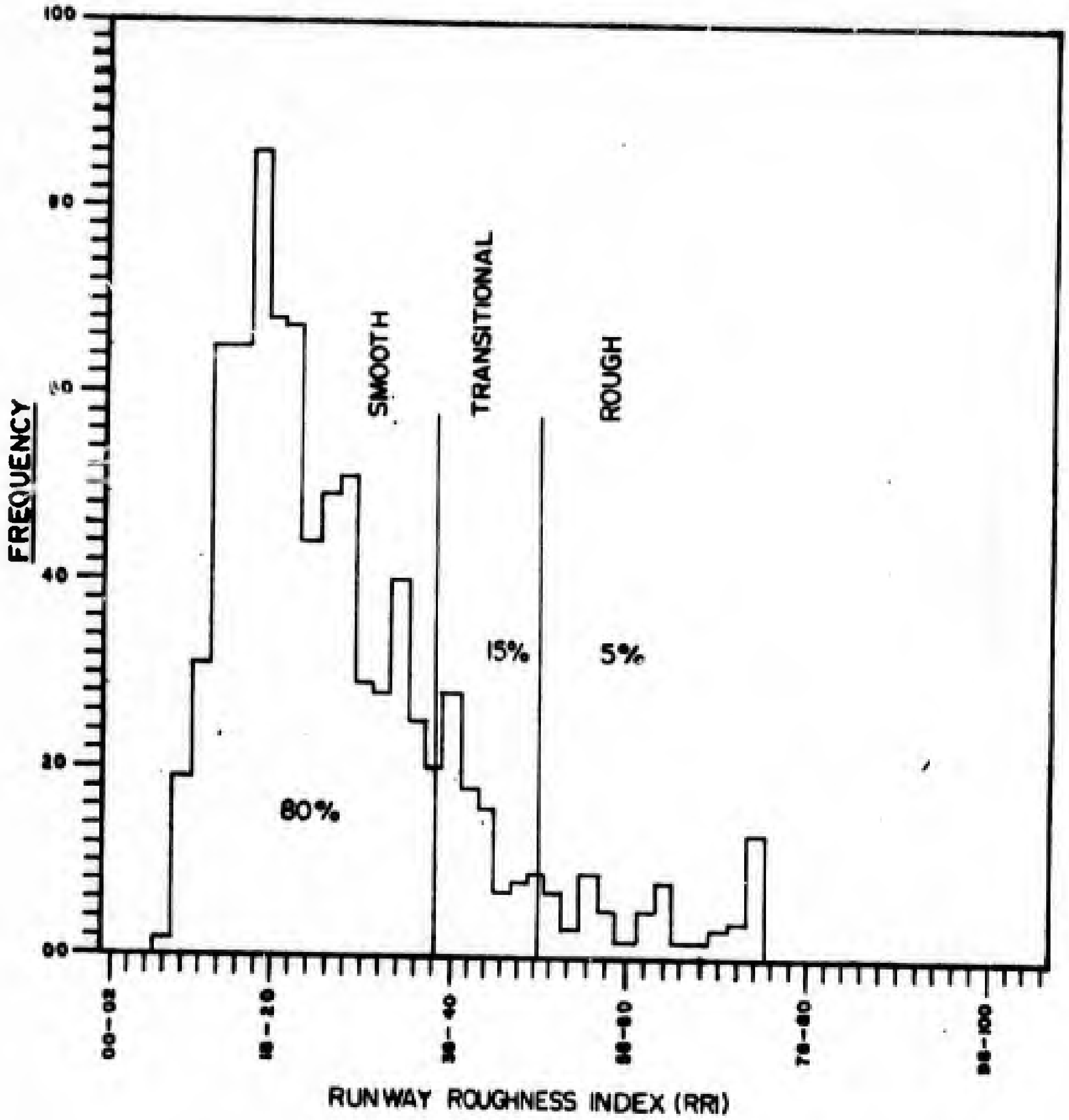



**FIGURE -7 SEGMENTAL HISTOGRAM**
RUNWAY ROUGHNESS INDEX (400' WAVELENGTH CUTOFF)

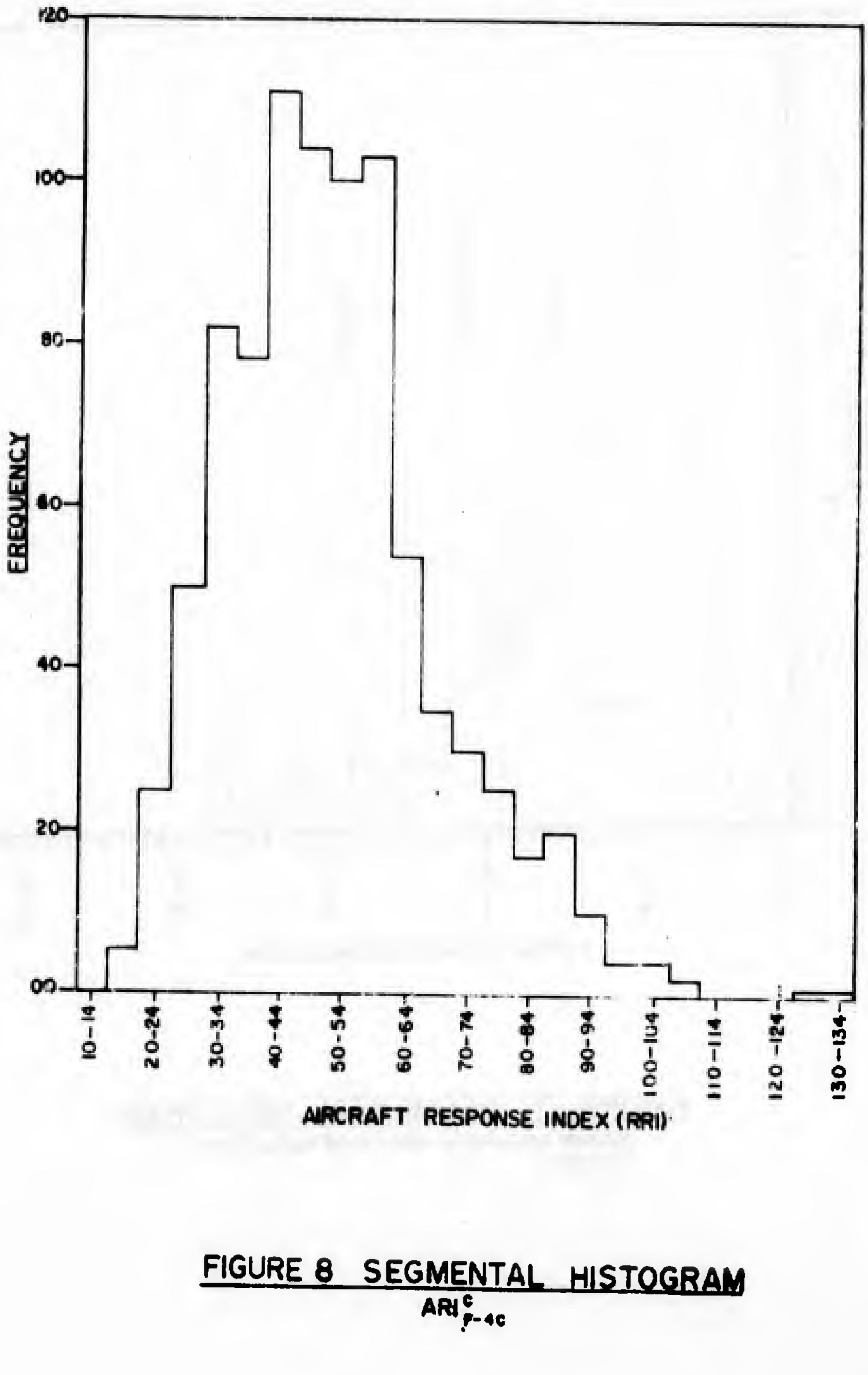



FIGURE 8 SEGMENTAL HISTOGRAM

$ARI^{C}_{F-4C}$

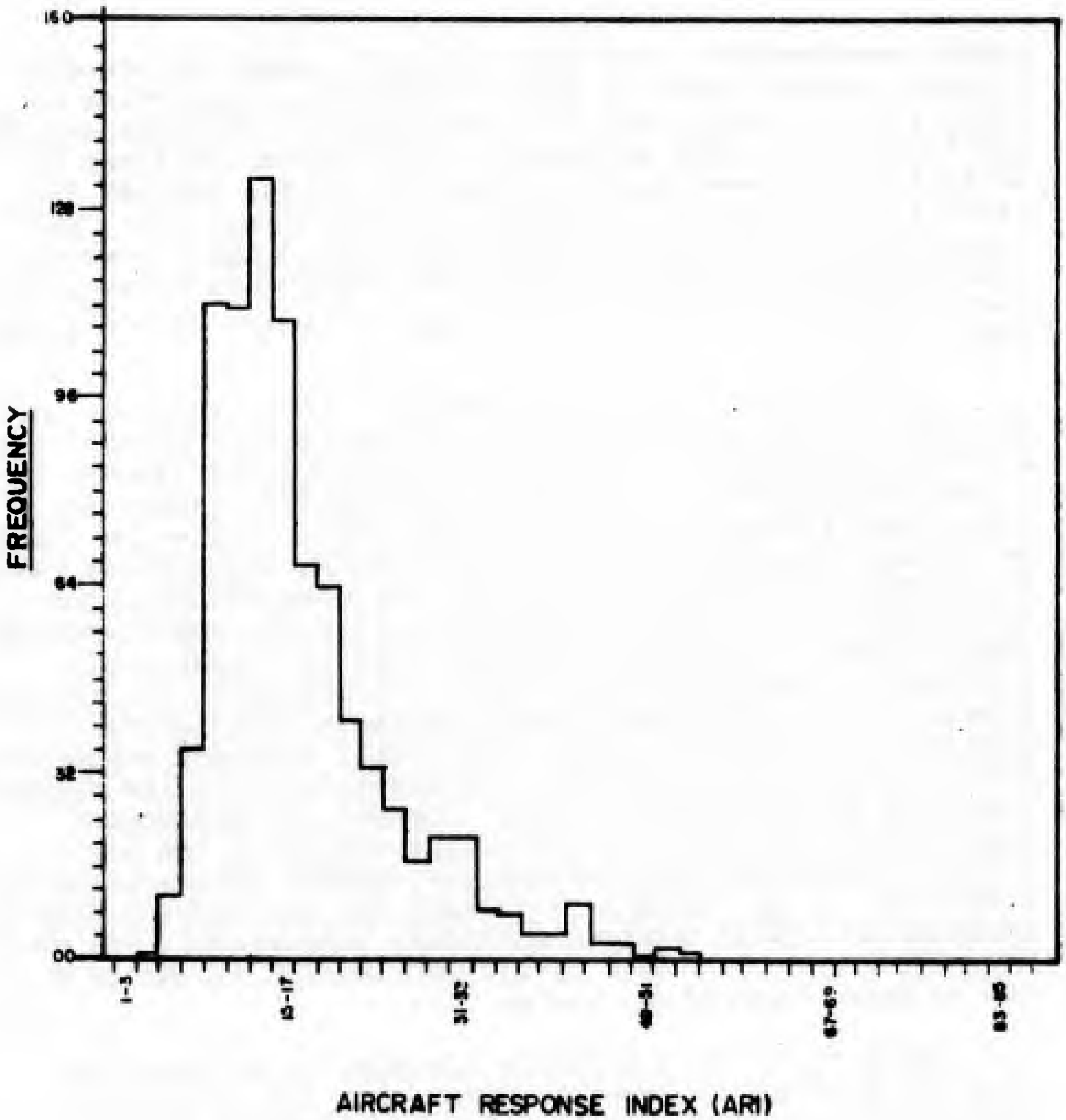



**FIGURE - 9 SEGMENTAL HISTOGRAM**

$ARI^{C}_{B-52}$

tested wavelengths. The RRIs and ARIs, based on overall profile lengths used in this analysis, are presented in Table 1. A combined ARI for each aircraft was also computed and included in this analysis. This ARI was obtained by using the root-mean square method to combine the ARI for pilot station, center of gravity, and tail section. The results of this analysis are not presented here, however, there appeared to be no significant difference between the rank orders when the overall $RRI_{400}$, $ARI^{C}_{F-4C}$, and $ARI^{C}_{B-52G}$ were compared.

As indicated previously, Figure 2 shows that, on an overall basis, there is a moderate correlation between the ARIs and the $RRI_{400}$. Therefore, the $RRI_{400}$ is assumed to be a fair indicator of the potential overall roughness for a particular runway. This relatively poor correlation (based on 24 data points) may be a result of the simplifying assumptions built into the TAXI Code or the compounding interrelationships of the varying wavelengths and amplitudes and their effect on aircraft response. Until a method of analysis is developed which accurately compares all pertinent runway profile variables with an improved simulation of aircraft response, including individual aircraft variables such as speed, gross weight, and configuration, the system used will be of limited value. However, as subsequent examination will show, the proposed system is the best analysis available considering the current state-of-the-art. Therefore, in an attempt to account for the varying aircraft profile data (ARIs used as secondary indicators), the decision was made to use all four cutoff wavelengths in analysis of the proposed evaluation system.

While there is a moderate correlation between the overall RRIs and the overall ARIs which can be further developed into an evaluation system and runway roughness standards, from an operational point of view we cannot be satisfied with just an overall evaluation of runway roughness. To allow for correction of roughness problems, the evaluation system must provide not only the magnitude of roughness, but also the specific portions of the runway which are considered to be rough (i.e., exceed a roughness standard). Therefore, this study was not carried into areas of research indicated previously, but was aimed at using the research accomplished to date to produce an evaluation system responsive to the needs of the operational USAF organizations.

After analysis of the overall RRIs and ARIs, it was determined that the most feasible and practical methodology was a segmental approach to runway roughness evaluation. The runway profile was subdivided into segments as shown in Figure 6. These segments must be small enough to isolate the rough areas which the overall RRIs and ARIs were unable to identify. A length of 500 feet (152 m) was selected for each segment with an overlap of 250 feet (76 m) for each iteration of segmental analysis. Segments of this length, including the overlap feature, would identify the specific rough areas along the profile. Additionally, it was possible that the 500-foot (152 m) segments would be long enough to identify profile roughness by both RRI and ARI in the same segment. This last requirement has been included because of problems introduced into the analysis technique by delayed aircraft response to runway roughness, i.e., the vertical accelerations experienced in the aircraft due to runway roughness may be felt at some point down the runway from where the aircraft actually transversed the rough area.

The evaluation procedure should include both a statistical and visual analysis of the filtered profiles and vertical acceleration data. The visual analysis alone was found to be an inadequate approach because the filtered profiles and acceleration data did not agree closely enough to provide an adequate starting point for the analysis. Additionally, visual analysis does not provide sufficient limitation of the areas of roughness for formulation of an economically feasible repair plan. However, the visual inspection technique can and should be used as a check on the results produced by the statistical analysis.

To begin the statistical analysis of the segmented profiles, the $RRI_{400}$, combined $ARI_{F-4C}$ and combined $ARI_{B-52G}$ segmental values were computed. Histograms presenting these results are shown in Figures 7, 8, and 9. The histograms are skewed to the right and introduce a slight bias, as previously discussed. However, at this point, two assumptions were made with regard to the segmental values, i.e., the parent population of the 500-foot (152 m) segmental values is assumed to be normal, and the mean and standard deviations of the sample are assumed to be representative of the population.

Based on a review of Figures 7, 8, and 9, and taking into account statistical theory of a normal population, arbitrary statistical limits were placed on the data. These limits have been defined as the Runway Roughness Standards against which profile segments may be evaluated on a relative basis (see Table 2). As shown in Figure 7, the upper limit of the category in which segments are defined as smooth

SMOOTH ——→| —— TRANSITIONAL ——→| —— ROUGH ——→

| | | |
|---|---|---|
| $ARI^{C}_{F4}$ | 0.648 | 0.788 |
| $ARI^{P}_{F4}$ | 0.491 | 0.614 |
| $ARI^{CG}_{F4}$ | 0.318 | 0.384 |
| $ARI^{T}_{F4}$ | 0.965 | 1.173 |
| $ARI^{C}_{B528}$ | 0.243 | 0.308 |
| $ARI^{P}_{B528}$ | 0.273 | 0.346 |
| $ARI^{CG}_{B528}$ | 0.0903 | 0.113 |
| $ARI^{T}_{B528}$ | 0.3093 | 0.396 |
| $RRI_{400}$ | 0.390 | 0.507 |
| $RRI_{200}$ | 0.265 | 0.333 |
| $RRI_{100}$ | 0.180 | 0.225 |
| $RRI_{50}$ | 0.116 | 0.142 |

TABLE 2 STANDARDS FOR EVALUATION

theoretically include 80 percent of the population. The next higher category is defined as transitional with limits set to statistically include 15 percent of the population. The 5 percent of the population which encompasses the highest RRIs is included in a category which is defined, quite arbitrarily, as rough. As can be seen on Figure 7, the boundary points between the categories are in areas of visual breaks in the data which also helped to determine the arbitrary limits. While the arbitrary nature of these categories is acknowledged, there is presently no more appropriate definition of roughness which can be applied to the evaluation of runway roughness. The categories presented here will provide a relative comparison of runway roughness until a better methodology is developed.

The combined $ARI_{F-4C}$ and combined $ARI_{B-52G}$ values obtained from a segmental analysis were also statistically developed into categories in the same manner as the RRIs. The limiting values for these categories are also presented in Table 2. The segmental RRIs and combined ARIs were compared as shown in Table 3 and Appendix B. There is no significant correlation between rough areas identified by the RRI and those identified by the combined ARIs. It is also obvious that the rough areas identified by the combined $ARI_{F-4C}$ are not necessarily the same as those identified by the combined $ARI_{B52G}$. This is a further indication that the type of aircraft transversing a runway profile is an important factor in defining runway roughness. Therefore, while the RRI and ARI do not directly correlate a particular profile segment, the ARI can be used, as discussed later in this report, to evaluate proposed changes to runway profiles for correcting runway roughness identified by the RRI.

Values of RRI based on profile segments were next computed for cutoff wavelengths of 200 feet, 100 feet, and 50 feet (61 m, 30.5 m, and 15.25 m). These values were compared to the combined $ARI_{F-4C}$ and combined $ARI_{B-52-G}$ as before. This comparison is also presented in Table 3 and Appendix B. Again, no direct correlation could be found between roughness based on profile and roughness based on aircraft response. Based on these and previous findings, an evaluation methodology was conceived, using the segmental RRI with associated runway roughness standards to identify roughness areas. The combined $ARI_{F-4C}$ and combined $ARI_{B-52G}$ would then be used to test the feasibility of correction of the roughness areas through physical modifications to the runway profile. An outline of the evaluation methodology developed is included as Appendix A to this report.

| | | RRI ALONE | RRI / $ARI^C_{F4}$ $ARI^C_{B52}$ | RRI / $ARI^C_{F4}$ | RRI / $ARI^C_{B52}$ | $ARI^C_{F4}$ $ARI^C_{B52}$ | $ARI^C_{F4}$ | $ARI^C_{B52}$ |
|---|---|---|---|---|---|---|---|---|
| | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (7) |
| $RRI_{400}$ | 16.7 | 5.6 | 5.6 | 2.6 | 2.8 | 3.1 | 7.5 | 5.1 |
| $RRI_{200}$ | 18.2 | 4.2 | 6.5 | 3.1 | 3.6 | 1.6 | 6.5 | 4.5 |
| $RRI_{100}$ | 17.8 | 4.5 | 6.5 | 4 0 | 2.9 | 2.2 | 6.1 | 4.8 |
| $RRI_{60}$ | 17.1 | 6.7 | 4 5 | 3.5 | 2.5 | 3.9 | 6.9 | 5.8 |
| $ARI^C_{F4}$ | 18.7 | | | | | | | |
| $ARI^C_{B52}$ | 16 5 | | | | | | | |

TABLE 3

PERCENTAGE COMPARISON OF TRANSITIONAL AND ROUGH SEGMENTS

**% OF $RRI_x$ ALONE**

| | |
|---|---|
| $RRI_{400}$ — | 4.2 |
| $RRI_{200}$ — | 3.3 |
| $RRI_{100}$ — | 1.4 |
| $RRI_{50}$ — | 5.1 |

**% OF COMBINATION OF TWO $RRI_x$**

| | |
|---|---|
| $RRI_{400}$ AND $RRI_{200}$ — | 2.0 |
| $RRI_{400}$ AND $RRI_{100}$ — | 0.2 |
| $RRI_{400}$ AND $RRI_{50}$ — | 0.0 |
| $RRI_{200}$ AND $RRI_{100}$ — | 2.0 |
| RRI[illegible] AND $RRI_{50}$ — | 0.5 |
| $RRI_{100}$ AND $RRI_{50}$ - | 2.4 |

**% OF COMBINATIONS OF THREE $RRI_x$**

| | |
|---|---|
| $RRI_{400}$ $RRI_{200}$ AND $RRI_{100}$ — | 2.1 |
| $RRI_{400}$ $RRI_{200}$ AND $RRI_{50}$ — | 0.0 |
| $RRI_{400}$ $RRI_{100}$ AND $RRI_{50}$ — | 0.6 |
| $RRI_{200}$ $RRI_{100}$ AND $RRI_{50}$ — | 1.3 |

**% OF COMBINATIONS OF FOUR $RRI_x$**

| | |
|---|---|
| $RRI_{400}$ $RRI_{200}$ $RRI_{100}$ AND $RRI_{50}$ — | 7.2 |

## TABLE 3 (cont)

## PERCENTAGE COMPARISON OF TRANSITIONAL AND ROUGH SEGMENTS

NOTES: (1) Percentage of segments shown transitional or rough by a respective index.

(2) Percentage of segments shown transitional or rough by a single indicator.

(3) Percentage of segments shown transitional or rough combined by $REI_x$, $ARI^C_{F4}$ and $ARI^C_{B52}$.

(4) Percentage of segments shown transitional or rough by $REI_x$ and $ARI^C_{F4}$ combined.

(5) Percentage of segments shown transitional or rough by $REI_x$ and $ARI^C_{B52}$ combined.

(6) Percentage of segments shown transitional or rough by $ARI^C_{F4}$ and $ARI^C_{B52}$ combined.

(7) Percentage of segments shown rough by $ARI^C_{B52}$ or $ARI^C_{F4}$.

In order to use this methodology, a procedure has been developed using actual runway profiles as test cases. The runway profiles are obtained through use of the LASER profilometer and the data, which were automatically recorded on magnetic tape, are checked for consistency in the field through the use of a UNIVAC 1050-II computer at the base receiving the runway roughness evaluation survey. After the consistency of the data has been verified, the magnetic tapes are returned to the AFCEC to be compiled by a computer into a usable form for analysis. A computer check is also made at this point for abnormalities in the profile elevations. When this is completed, a computer plot of the runway profile is obtained. The profile is then filtered and segmental RRIs calculated. The profile is then run on the computer TAXI code for the primary and secondary mission aircraft (if characteristics are available) for the airbase being evaluated (F-4C and B-52G aircraft were used in this work, however, the TAXI code has been loaded with characteristics of the primary weapons systems in the USAF inventory) and segmental ARIs are developed. The segmental RRIs and ARIs are reviewed in conjunction with a visual inspection of the filtered profile plot and aircraft vertical acceleration data. The segments of the runway profile which are within the marginal and rough categories based on segmental RRI are identified by the computer and these are compared against the visual inspection of the data. A decision is then made, based on engineering judgment and field experience, as to which areas of roughness on the profile should be considered for modification. The profile segments which include the selected areas are then plotted by the computer on an expanded vertical scale. This plot is used to identify the elevations of a "smoothed" profile which is selected by the engineer in an attempt to correct the roughness problem. The revised profile is then rerun on the computer and new segmental RRIs and combined ARIs calculated for the mission aircraft. The new values are examined to determine if the "smoothed" profile has provided significant improvement in the aircraft response data and placed the runway segments in the "smooth" Runway Roughness Standard category. This procedure can be applied to all identified rough areas of the runway profile at one time, or each identified rough area can be evaluated individually at the engineer's discretion.

After completion of the profile evaluation, the feasibility of actually accomplishing reconstruction of the runway to conform to the elevations of the "smoothed" profile is investigated. If the modifications are justified, based on physical conditions existing in the field, structural and economic constraints, the final modified profile is plotted by the computer for use by the design engineer.

The Runway Roughness Evaluation Report will be published in two parts. Part 1 will provide the results of the analysis including the existing profiles, segmental values, and identification of areas identified as being relatively rough (i.e., classify as Transitional or Rough when evaluated against the Runway Roughness Standards). If the appropriate Major Command decides the economics, safety, and operational considerations of the situation warrant further study of the problem, Part II will be completed and released. Part II of the study will include the profile "modifications" analysis, proposed new profile (computer plot and elevation data) and possible construction techniques. The division of the report in this manner is intended to preclude expenditure of engineer manhours and computer time to develop the proposed modifications until justified by a request from the parent Major Command.

## SECTION III

## DISCUSSION AND CONCLUSIONS

As shown in this report, the method developed to analyze runway profiles is a highly simplified procedure to describe or quantify a very complicated problem. The assumptions and simplifications included in the aircraft simulation by the TAXI Code, combined with the assumption of normality in the segmental RRIs and combined ARIs somewhat limit the overall utility of the method. This limitation must be considered in all evaluations by this method. Identification of portions of a runway profile as Transitional or Rough on a relative basis must be compared to locations of roughness included in aircrew complaints, especially those from aircrews with considerable operational experience on the runway under study.

It has been demonstrated that if these limitations are given sufficient weight in conjunction with runway profile evaluations, the methodology presented here can be used effectively with a good probability of success.

It is also obvious, based on the evaluation work accomplished to date using this methodology, that the analysis procedure must be used by an experienced engineer who can weigh the results against reality and the limitation of the procedure.

## SECTION IV

## RECOMMENDATIONS

Based on work accomplished to date, the following recommendations are provided to stimulate further research into runway roughness evaluation methodology and development of improved roughness standards.

1. The selection of suitable wavelength cutoff values for various aircraft must be given a high priority for further research. As the cutoff wavelength is one of the most basic concepts included in the present methodology, accurate identification of appropriate cutoff values is vital.

2. The effect of gross weight, configuration, and speed on aircraft response to runway roughness is significant. The combination of those characteristics which will produce the most critical response to runway roughness must be determined for each type of aircraft.

3. The vertical accelerations experienced in various aircraft are not necessarily the same for each aircraft trafficking a rough portion of a runway profile. The level of response considered to be rough must be identified for each type of aircraft.

4. Other methodology, beyond the scope of this report, such as comparison of profile slopes or changes in profile slope on the actual profile or the filtered profile must be investigated to determine whether a correlation with aircraft response can be used for a more direct and accurate evaluation of runway roughness.

5. A methodology must be developed to differentiate among the expected responses of various aircraft based solely on the runway profile and pinpoint the location of the runway roughness. This methodology will assure operations personnel that aircraft response has been considered in roughness evaluation.

## REFERENCES


1. Baum, Neal P. and Trudy Ann Stough, "Evaluation of Inertia and LASER Profilometer Systems," Air Force Weapons Laboratory Technical Report No. AFWL-TR-74-289 (FAA-RD-74-188) April 1975.

2. Sonnenburg, Paul N., "Analysis of Airfield Runway Roughness Criteria," Federal Aviation Administration Research and Development Report No. FAA-RD-75-110, November 1976.

3. Discussions between Capt Dannie Burk, AFCEC and Anthony G. Gerardi, Air Force Flight Dynamics Laboratory.

4. Discussions between Capt Dannie Burk, AFCEC and Paul N. Sonnenburg, US Army Construction Engineering Research Laboratory (CERL).

5. Gerardi, Anthony G. and Adolph K. Lohwasser, "Computer Program Volume I, Program Development, Air Force Weapons Laboratory Technical Report No. AFWL-TR-73-109, Vol I, Aug 1973.

6. Gerardi, Anthony G. and Adolph K. Lohwasser, "Computer Program for the Prediction of Aircraft Response to Runway Roughness," Volume II, User's Manual, Air Force Weapons Laboratory Technical Report No. AFWL-TR-73-109, Vol II, July 1973.

## APPENDIX A

## ANALYSIS AND SURVEY WORK FLOW

1. Field Survey

a. Obtain airfield layout plan and survey line dimensions and location.

b. Acquisition of runway profile elevations on 6-inch horizontal increments through use of the Inertial or LASER profilometer.

c. Field check of data on magnetic tape for completeness through UNIVAC 1050-II computer system.

2. Compile Computer Input Data

a. Review profile elevation data for abnormalities.

b. Check survey line lengths to ensure all sections are included and total profile length is correct.

3. Run Computer Program to Filter Profiles

a. Cutoff wavelengths of 50, 100, 200, and 400 feet used.

b. Runway profile and filtered profile plotted by computer.

4. Statistical Development of RRI by Computer

a. Overall analysis

b. Segmental analysis

5. Comparison of Generated RRIs Against Runway Roughness Standards

a. Quantification and location of roughness.

b. Generated RRIs and standards based on cutoff wavelengths of 50, 100, 200, and 400 feet.

6. Aircraft Simulation Run on TAXI Computer Code

a. Primary and secondary mission aircraft for runway.

b. ARIs generated for mission aircraft.

c. Quantification of aircraft vertical acceleration response.

d. Overall length of profile analysis.

e. Segmental analysis.

f. Roughness defined by RRI analysis reviewed in light of ARI values.

7. Graphic Profile Modification

a. Areas identified as rough by RRIs are "smoothed" by modifying profile.

b. Modified profile filtered by computer.

c. RRIs generated based on modified profile.

8. Aircraft Simulation on Modified Profile

a. Same mission aircraft as before.

b. New ARIs generated for overall profile length and segmental analysis.

9. Reevaluation of Modified Profile

a. Comparison of RRIs against Runway Roughness Standards and RRIs from original profile.

b. Comparison of ARIs against original ARIs.

c. Determine if modified profile resulted in improved RRI values and aircraft response.

10. Review of Feasibility of Profile Modifications

a. Physical feasibility.

b. Economical feasibility.

c. Political ramifications.

d. Justification.

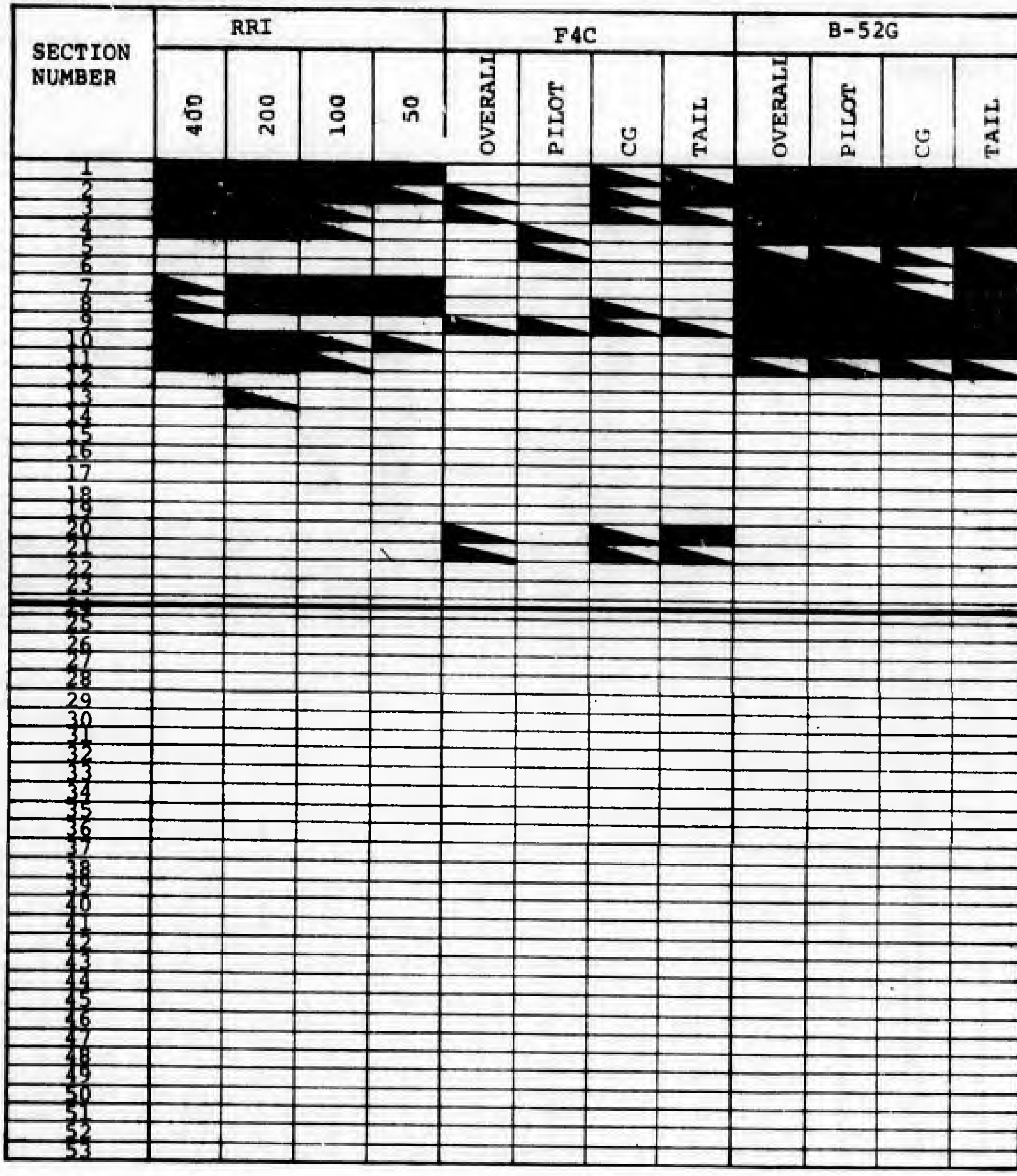
APPENDIX B

SEGMENTAL COMPARISON

OF

RUNWAYS STUDIED

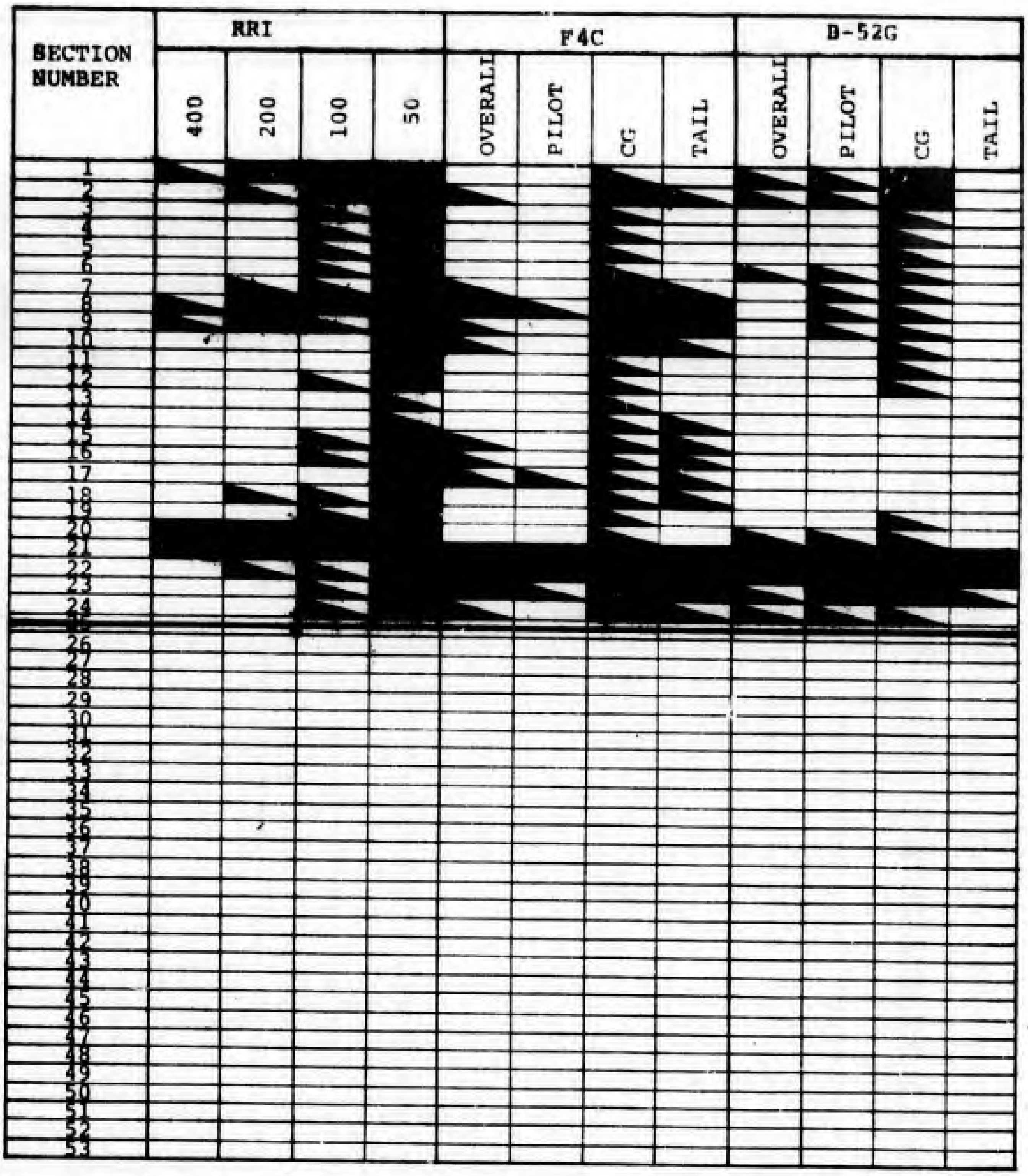
ALBANY RW 19 ℄

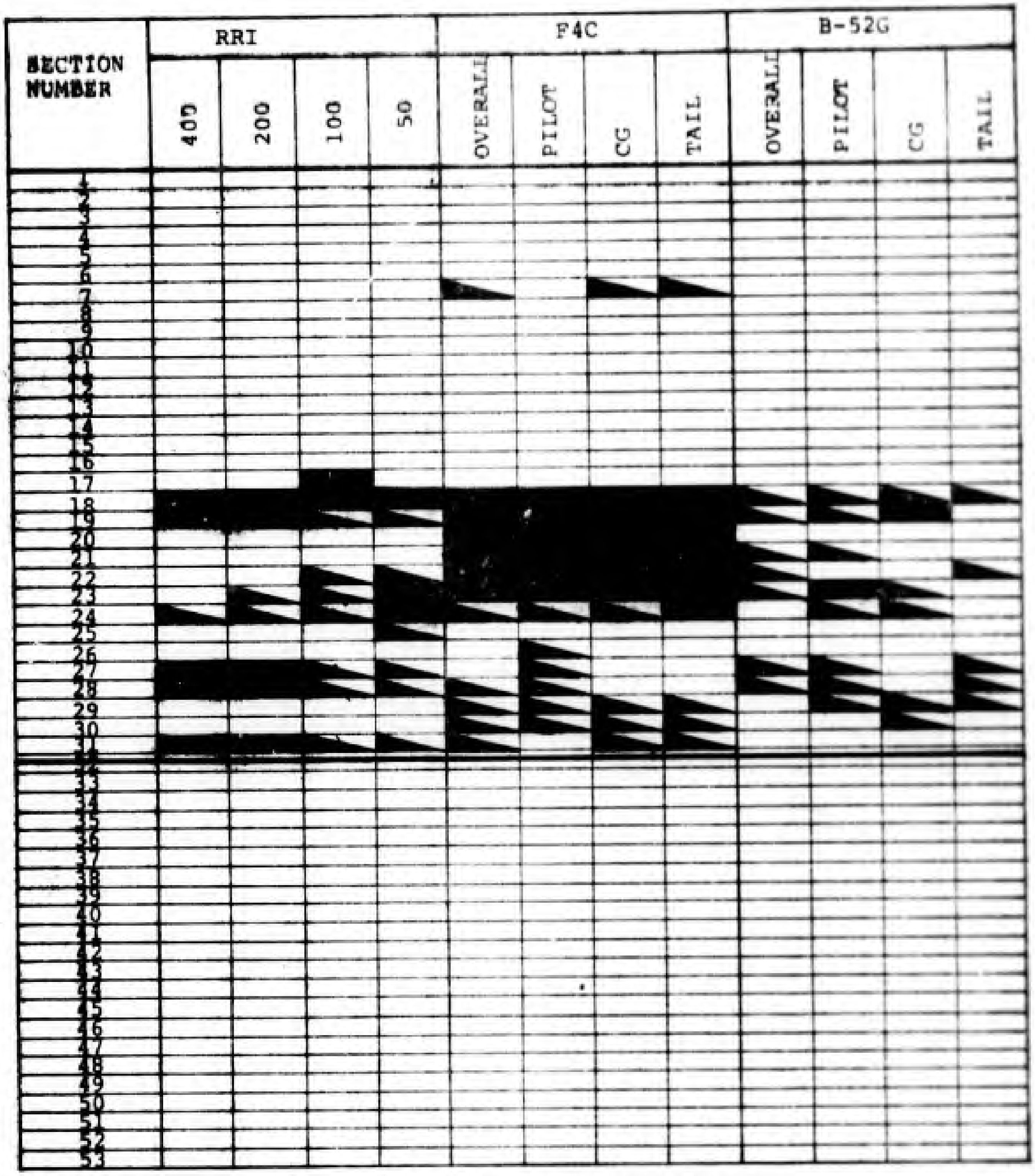



- TRANSITIONAL

- ROUGH

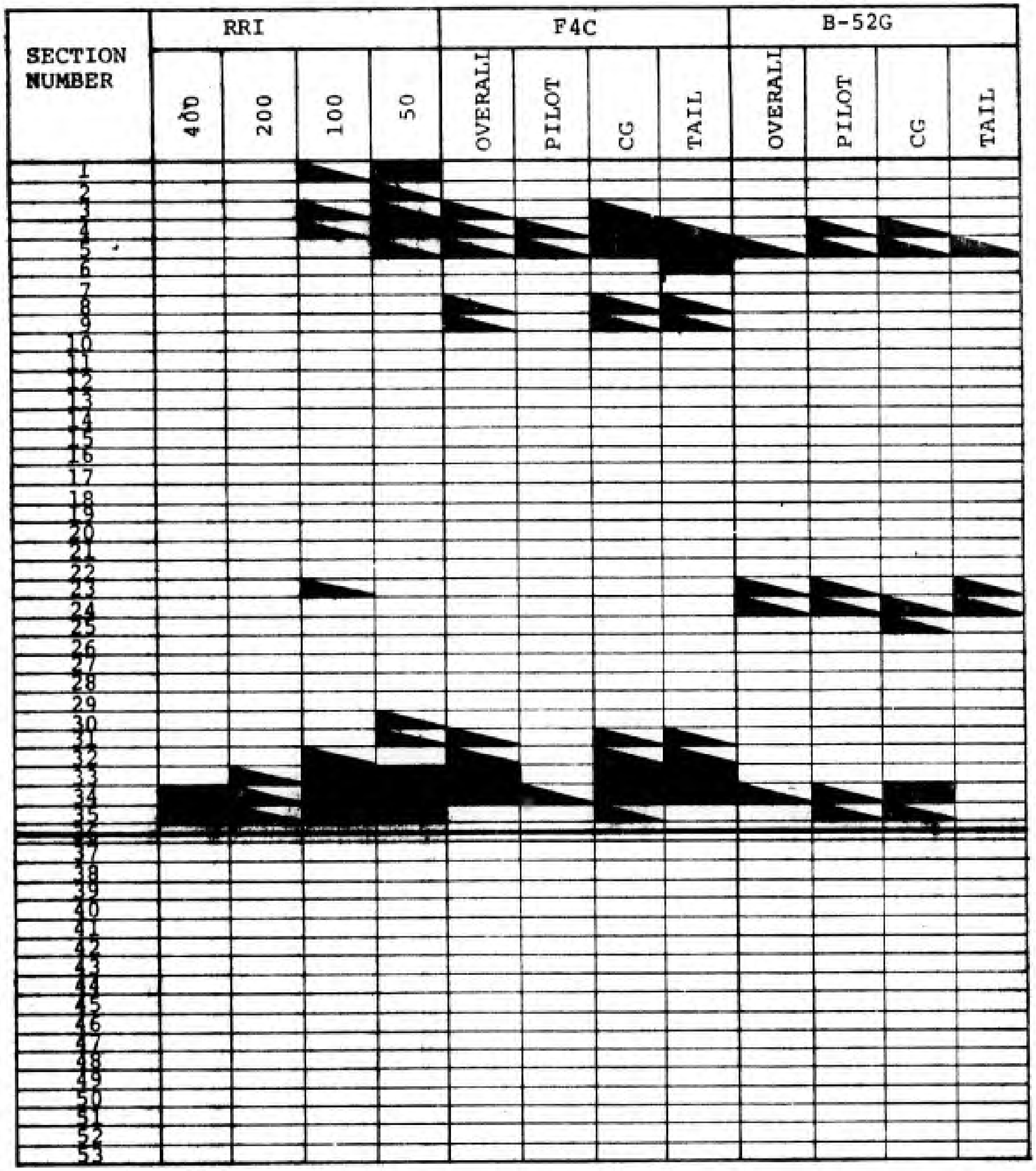
ASHVILLE RW 16 $C_L$



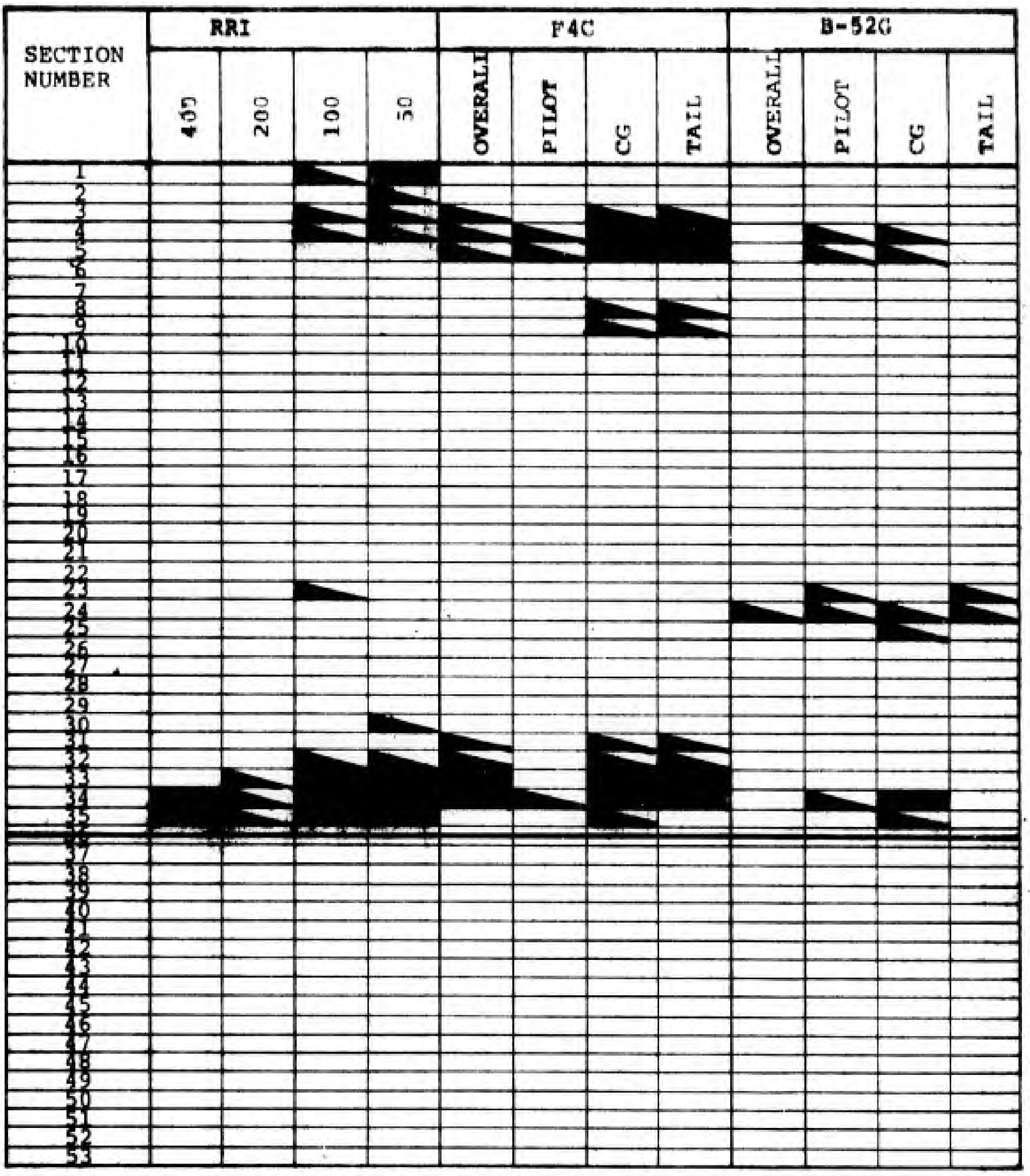

SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53

| SECTION NUMBER | RRI | | | | F4C | | | | B-52G | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 400 | 200 | 100 | 50 | OVERALL | PILOT | CG | TAIL | OVERALL | PILOT | CG | TAIL |
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | |
| 18 | | | | | | | | | | | | |
| 19 | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | |
| 21 | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | |
| 23 | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | |
| 26 | | | | | | | | | | | | |
| 27 | | | | | | | | | | | | |
| 28 | | | | | | | | | | | | |
| 29 | | | | | | | | | | | | |
| 30 | | | | | | | | | | | | |
| 31 | | | | | | | | | | | | |
| 32 | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | |
| 35 | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | |
| 39 | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | |
| 42 | | | | | | | | | | | | |
| 43 | | | | | | | | | | | | |
| 44 | | | | | | | | | | | | |
| 45 | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | |
| 48 | | | | | | | | | | | | |
| 49 | | | | | | | | | | | | |
| 50 | | | | | | | | | | | | |
| 51 | | | | | | | | | | | | |
| 52 | | | | | | | | | | | | |
| 53 | | | | | | | | | | | | |

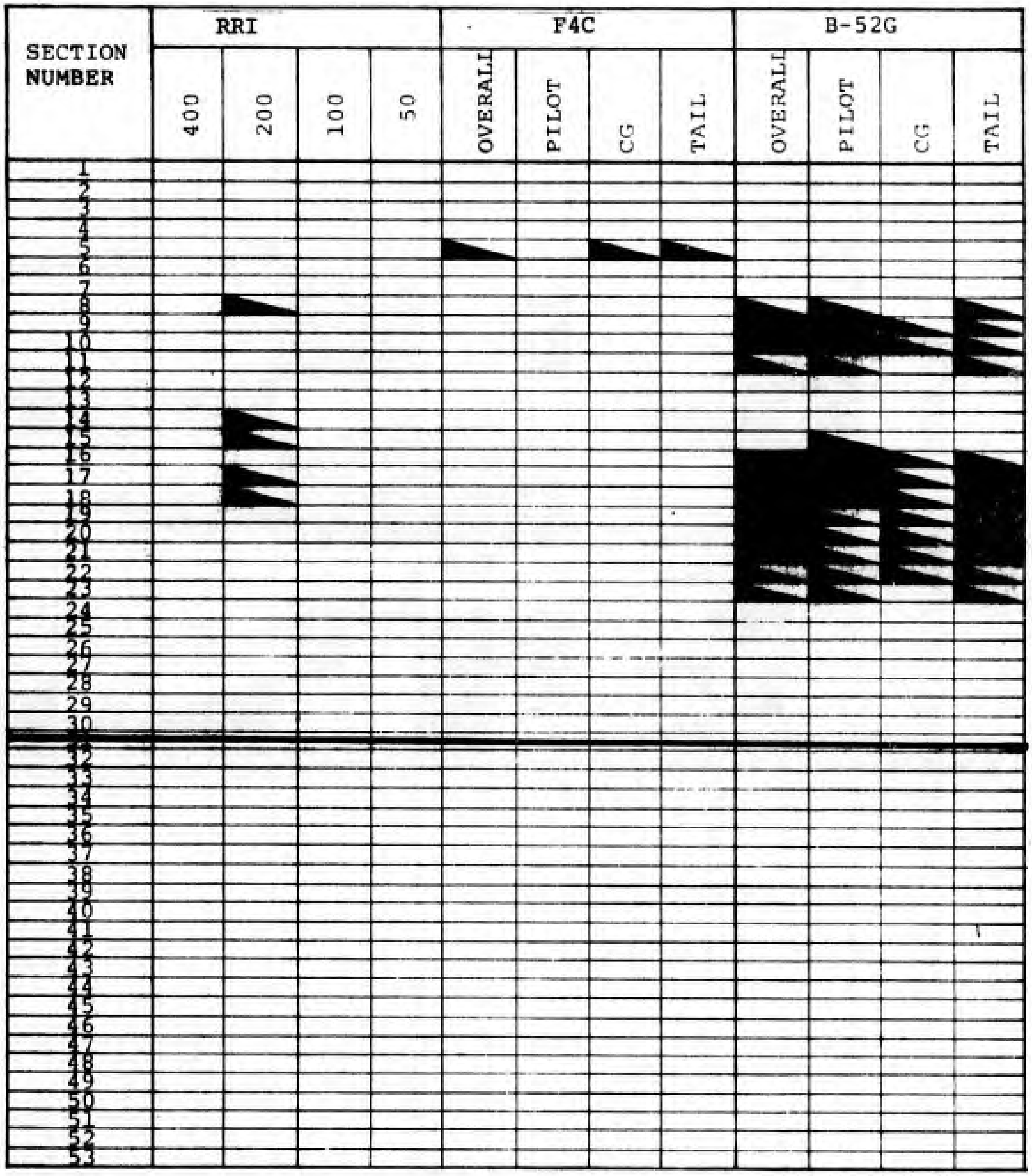
CHARLESTON RW 15 $C_L$ OLD



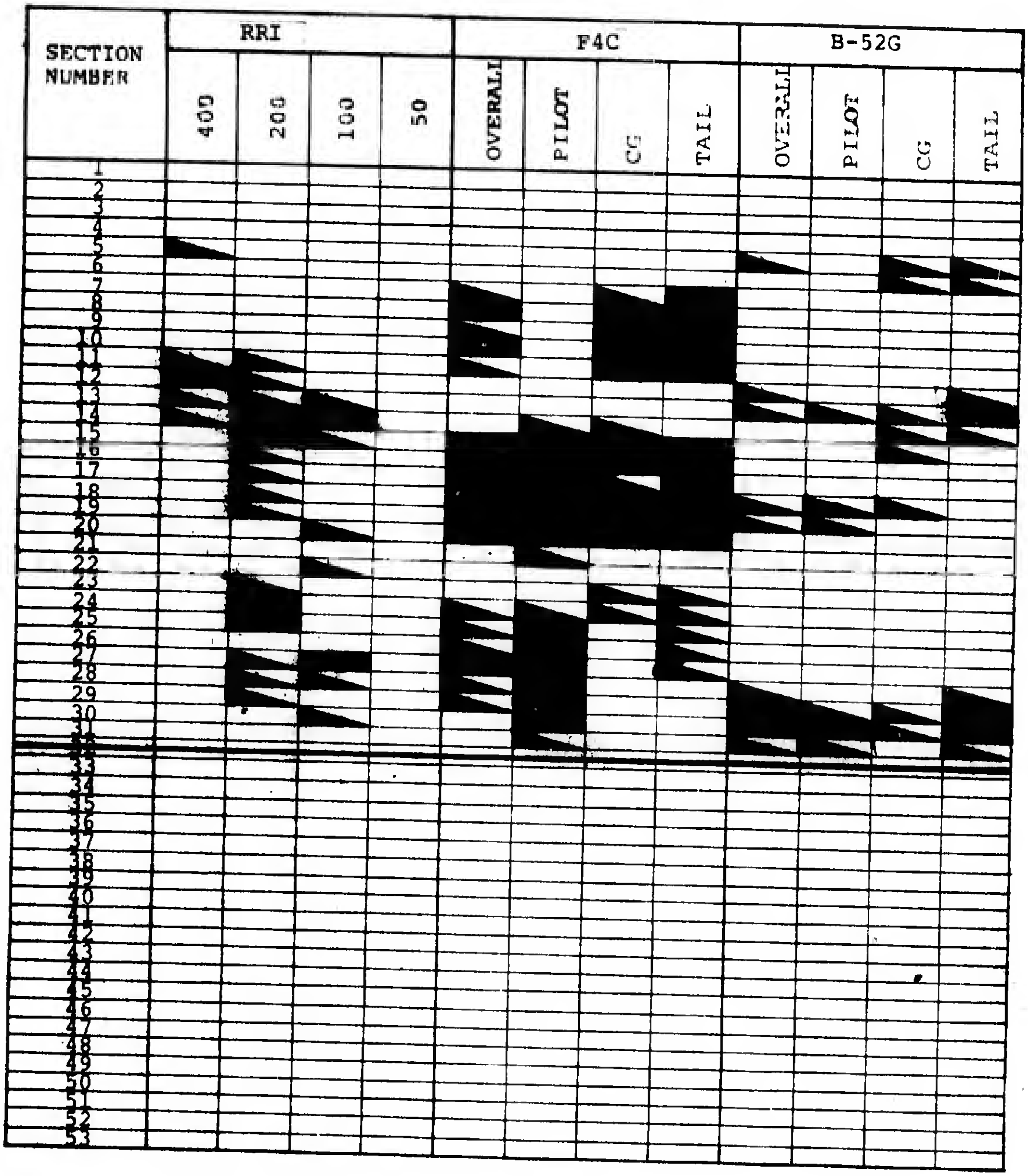
CHARLESTON $C_L$



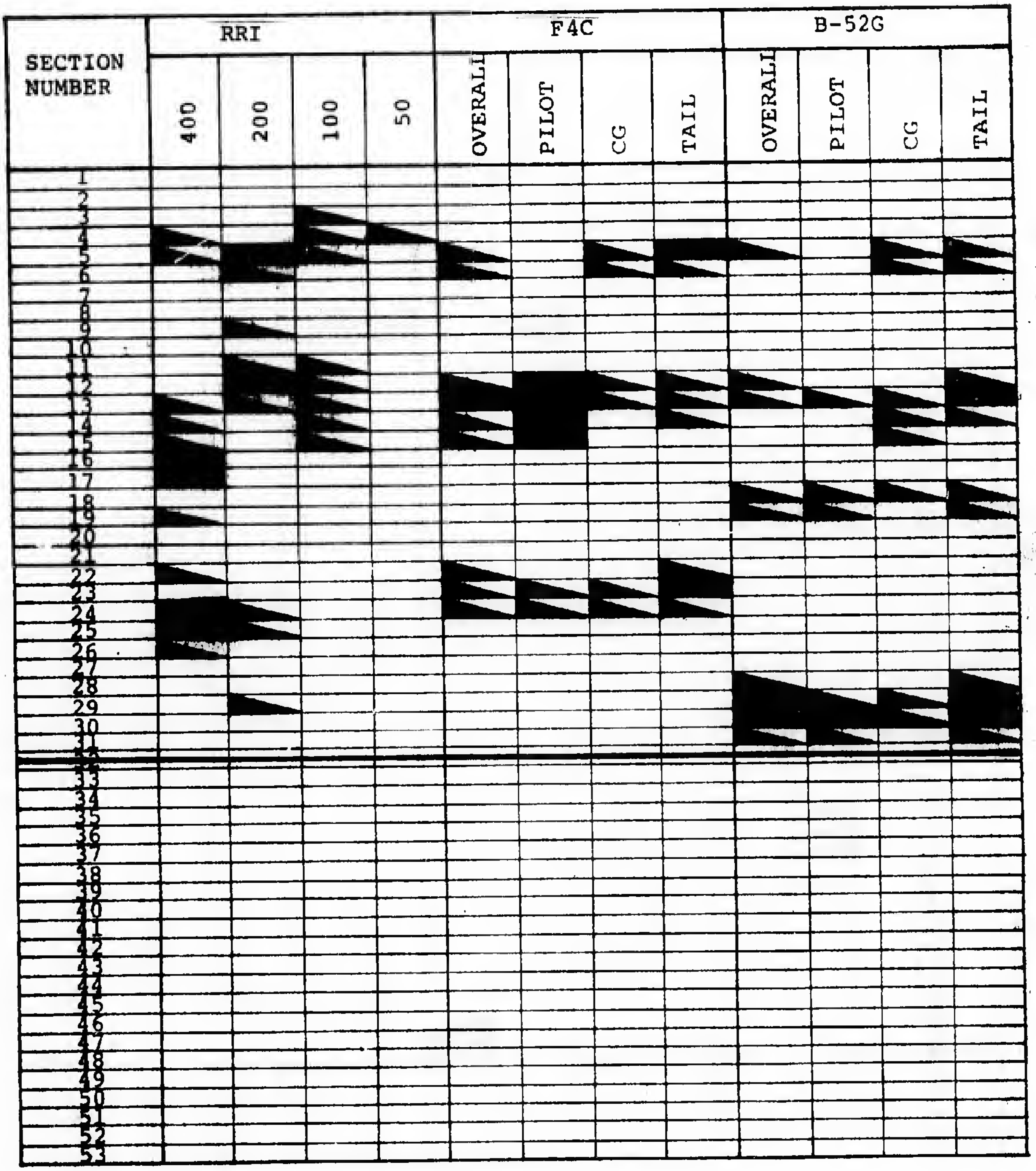
CRAIG RW 32R (EM007)



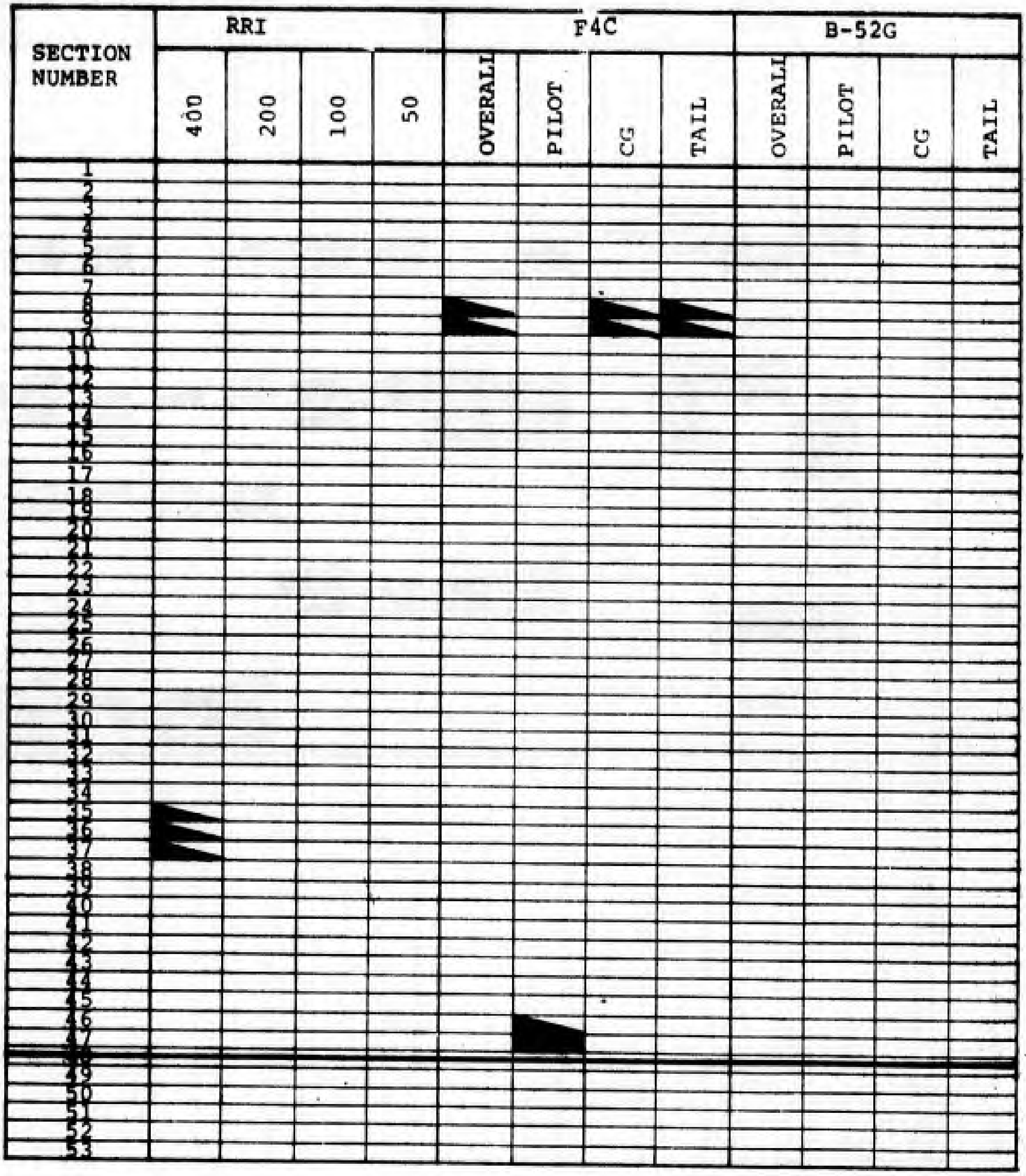
CRAIG RW 32R (EM010)



CRAIG RW 32R (EM013)



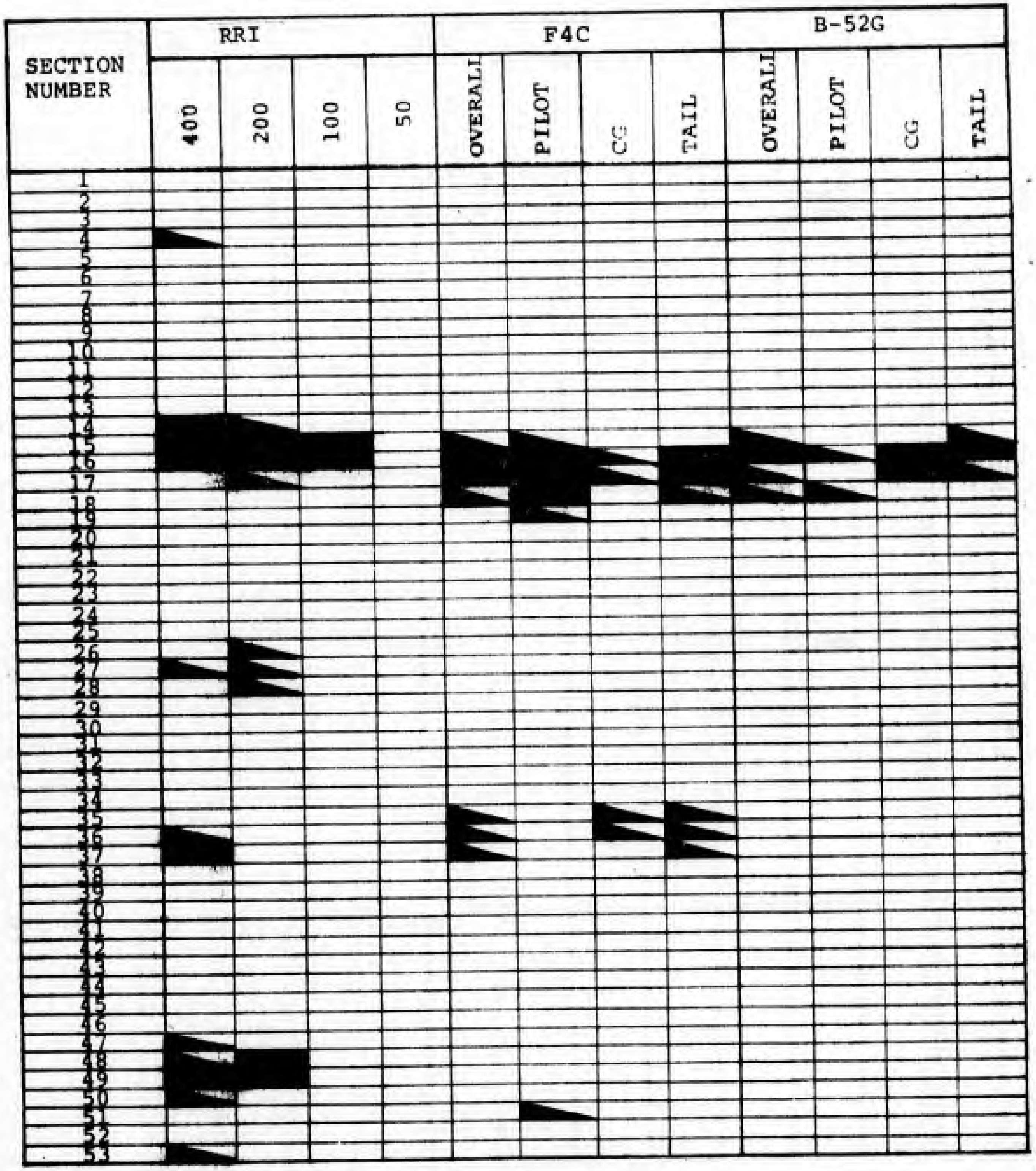
DAL/FTW RW 17 $C_L$



## DOBBINS RW 11/29

| SECTION NUMBER | RRI | | | | F4C | | | | B-52G | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 400 | 200 | 100 | 50 | OVERALL | PILOT | CG | TAIL | OVERALL | PILOT | CG | TAIL |
| 1 | | | | | | | | | | | | |
| 2 | ■ | | | | | | | | | | | |
| 3 | ■ | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 16 | | | | | ■ | | ■ | ■ | | | | |
| 17 | | | | | | | | | | | | |
| 18 | | | | | | | | | | | | |
| 19 | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | |
| 21 | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | |
| 23 | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | |
| 26 | ■ | | | | | | | | | | | |
| 27 | | | | | | | | | | | | |
| 28 | | | | | | | | | | | | |
| 29 | | | | | | | | | | | | |
| 30 | | | | | | | | | | | | |
| 31 | | | | | | | | | | | | |
| 32 | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | |
| 35 | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | |
| 39 | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | |
| 42 | | | | | | | | | | | | |
| 43 | | | | | | | | | | | | |
| 44 | | | | | | | | | | | | |
| 45 | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | |
| 48 | | | | | | | | | | | | |
| 49 | | | | | | | | | | | | |
| 50 | | | | | | | | | | | | |
| 51 | | | | | | | | | | | | |
| 52 | | | | | | | | | | | | |
| 53 | | | | | | | | | | | | |

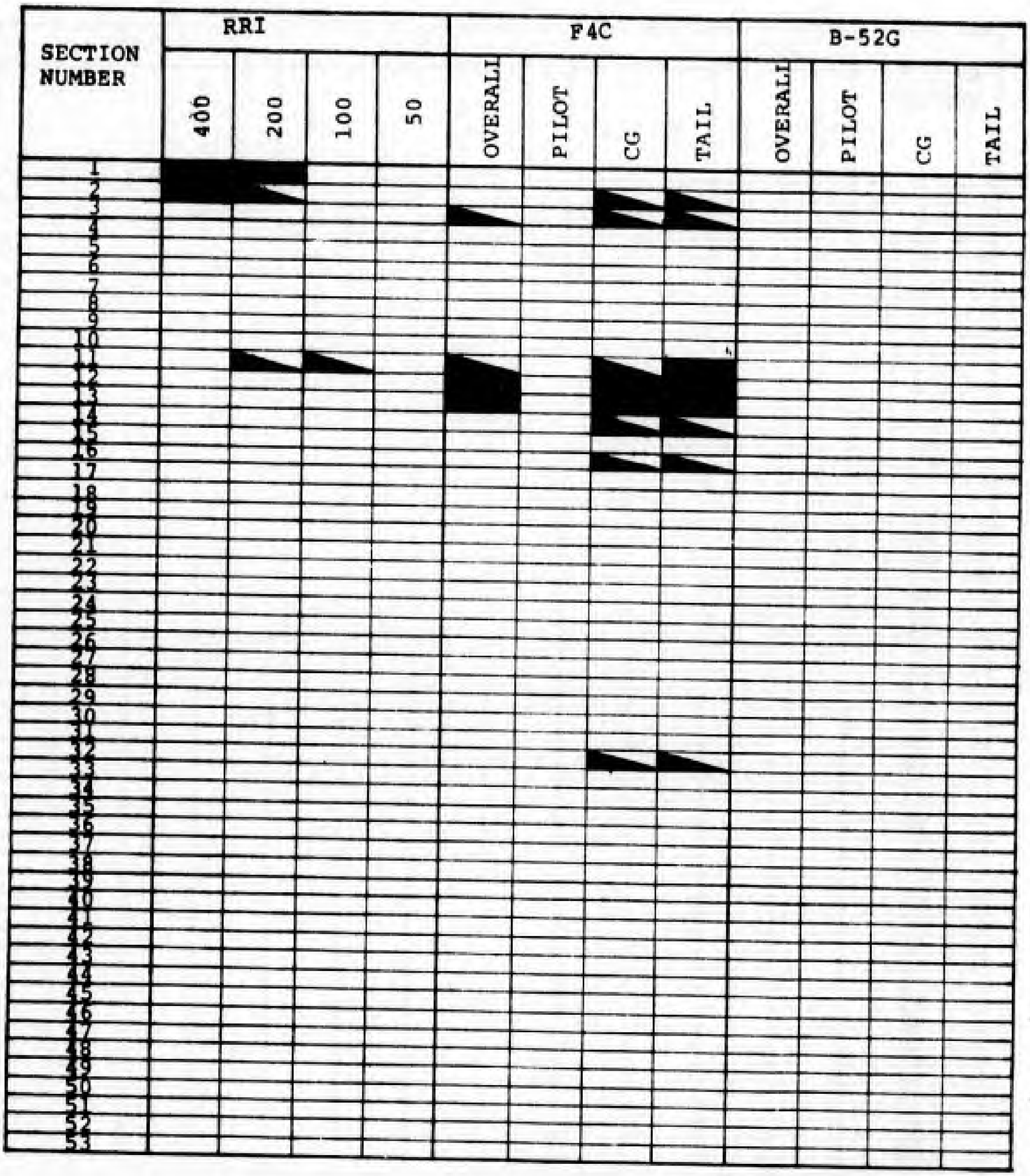
DYESS


SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53

EDWARDS RW 04 ℄

| SECTION NUMBER | RRI | | | | F4C | | | | B-52G | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 400 | 200 | 100 | 50 | OVERALL | PILOT | CG | TAIL | OVERALL | PILOT | CG | TAIL |
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | |
| 18 | | | | | | | | | | | | |
| 19 | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | |
| 21 | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | |
| 23 | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | |
| 26 | | | | | | | | | | | | |
| 27 | | | | | | | | | | | | |
| 28 | | | | | | | | | | | | |
| 29 | | | | | | | | | | | | |
| 30 | | | | | | | | | | | | |
| 31 | | | | | | | | | | | | |
| 32 | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | |
| 35 | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | |
| 39 | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | |
| 42 | | | | | | | | | | | | |
| 43 | | | | | | | | | | | | |
| 44 | | | | | | | | | | | | |
| 45 | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | |
| 48 | | | | | | | | | | | | |
| 49 | | | | | | | | | | | | |
| 50 | | | | | | | | | | | | |
| 51 | | | | | | | | | | | | |
| 52 | | | | | | | | | | | | |
| 53 | | | | | | | | | | | | |

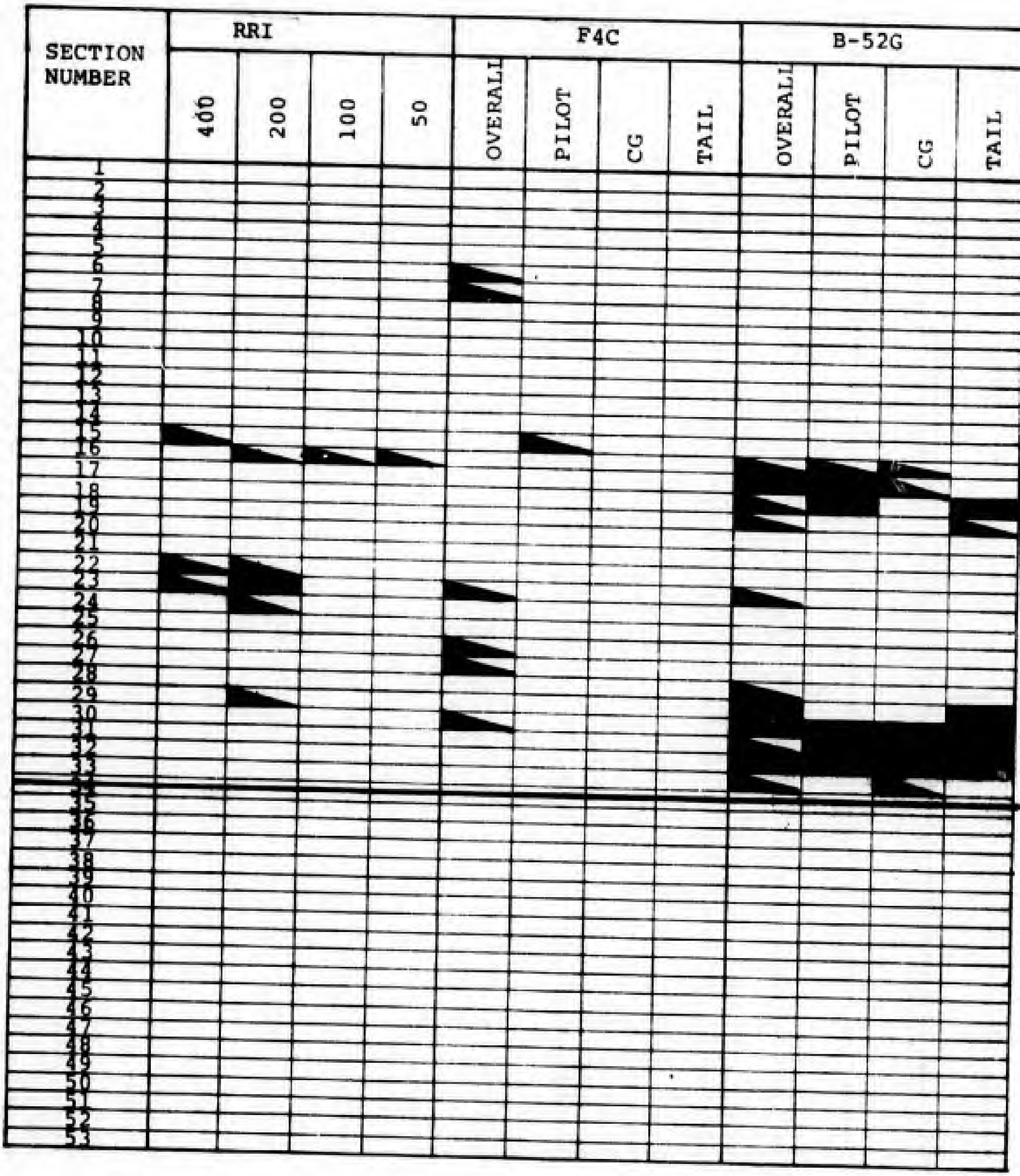
## ELLSWORTH RW 12/30 26 ℄



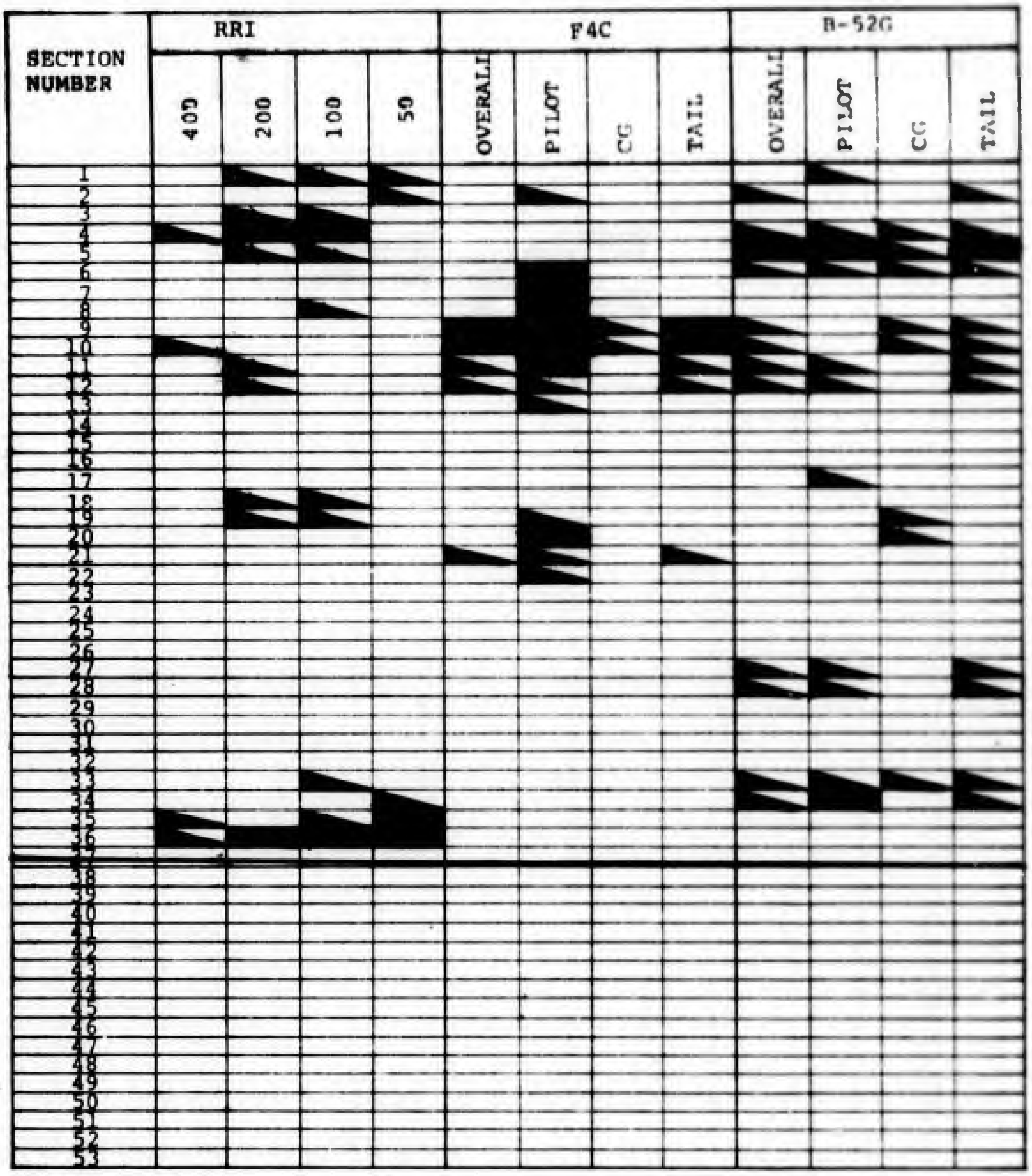
## GRAND FORKS RW 35

| SECTION NUMBER | RRI | | | | F4C | | | | B-52G | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 400 | 200 | 100 | 50 | OVERALL | PILOT | CG | TAIL | OVERALL | PILOT | CG | TAIL |
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | |
| 15 | | | | | | | | | | | | |
| 16 | | | | | | | | | | | | |
| 17 | | | | | | | | | | | | |
| 18 | | | | | | | | | | | | |
| 19 | | | | | | | | | | | | |
| 20 | | | | | | | | | | | | |
| 21 | | | | | | | | | | | | |
| 22 | | | | | | | | | | | | |
| 23 | | | | | | | | | | | | |
| 24 | | | | | | | | | | | | |
| 25 | | | | | | | | | | | | |
| 26 | | | | | | | | | | | | |
| 27 | | | | | | | | | | | | |
| 28 | | | | | | | | | | | | |
| 29 | | | | | | | | | | | | |
| 30 | | | | | | | | | | | | |
| 31 | | | | | | | | | | | | |
| 32 | | | | | | | | | | | | |
| 33 | | | | | | | | | | | | |
| 34 | | | | | | | | | | | | |
| 35 | | | | | | | | | | | | |
| 36 | | | | | | | | | | | | |
| 37 | | | | | | | | | | | | |
| 38 | | | | | | | | | | | | |
| 39 | | | | | | | | | | | | |
| 40 | | | | | | | | | | | | |
| 41 | | | | | | | | | | | | |
| 42 | | | | | | | | | | | | |
| 43 | | | | | | | | | | | | |
| 44 | | | | | | | | | | | | |
| 45 | | | | | | | | | | | | |
| 46 | | | | | | | | | | | | |
| 47 | | | | | | | | | | | | |
| 48 | | | | | | | | | | | | |
| 49 | | | | | | | | | | | | |
| 50 | | | | | | | | | | | | |
| 51 | | | | | | | | | | | | |
| 52 | | | | | | | | | | | | |
| 53 | | | | | | | | | | | | |

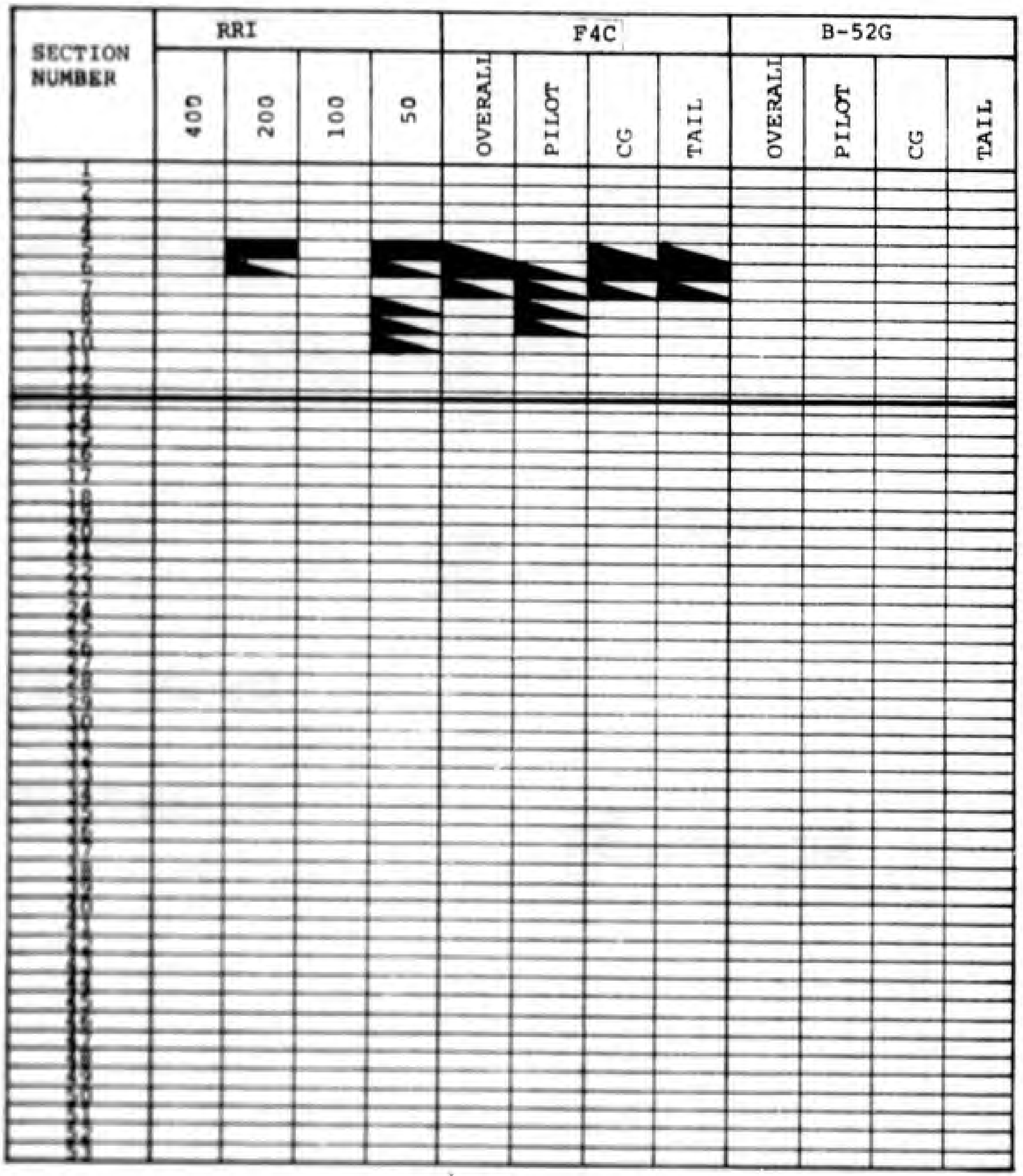
KIRTLAND RW 17



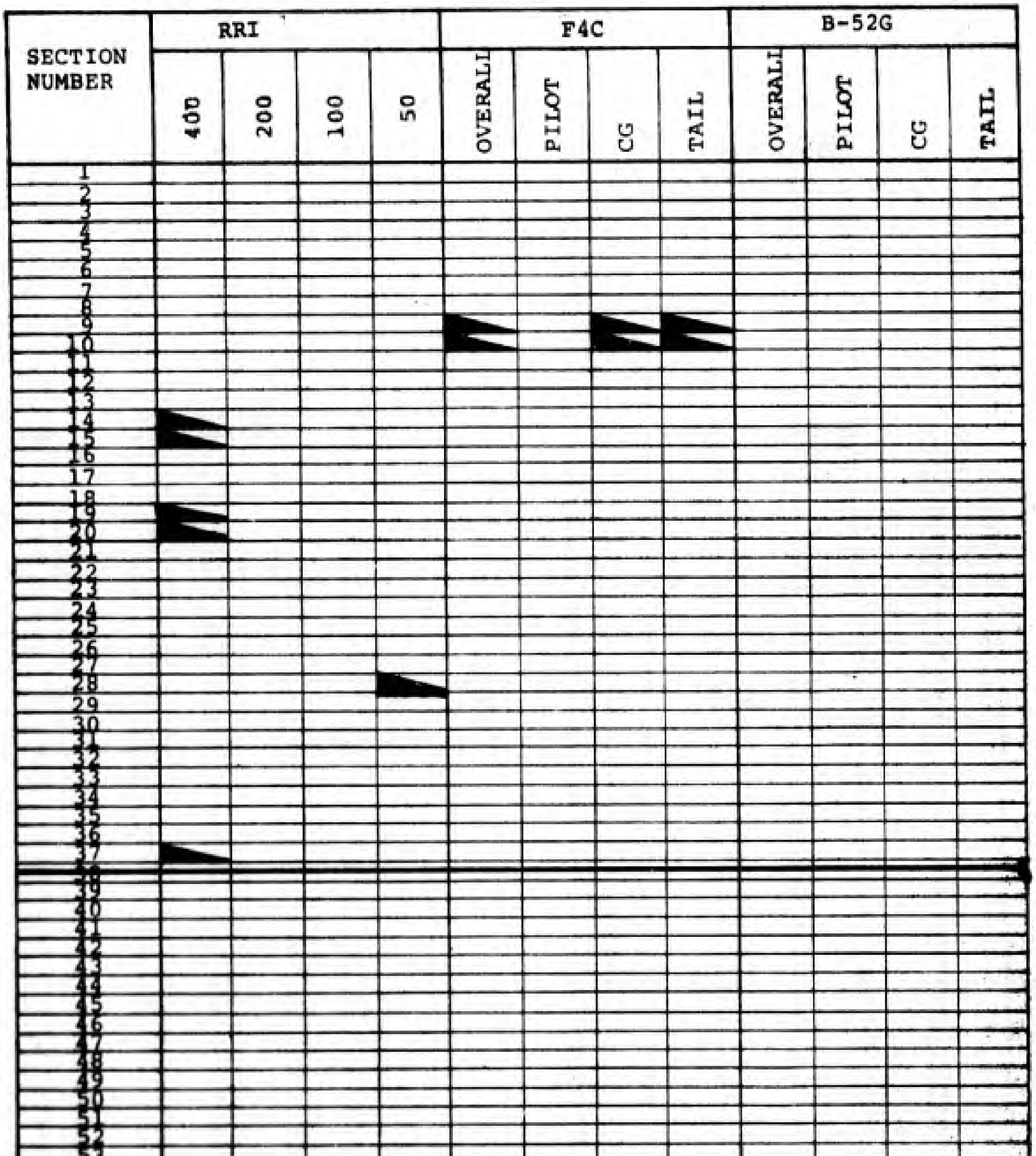
NEWARK RW 22L 36



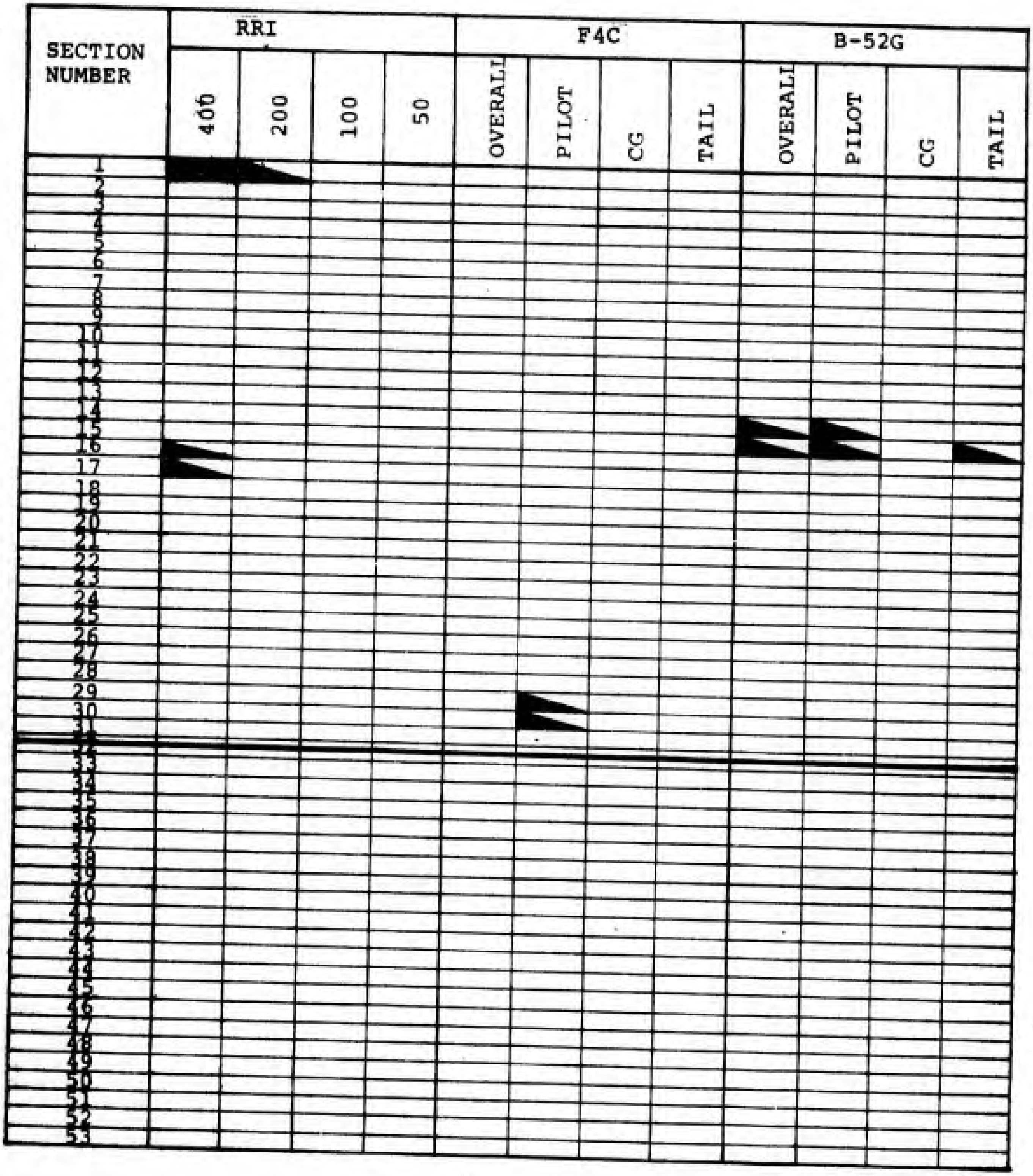
NEW YORK RW 13R $C_L$



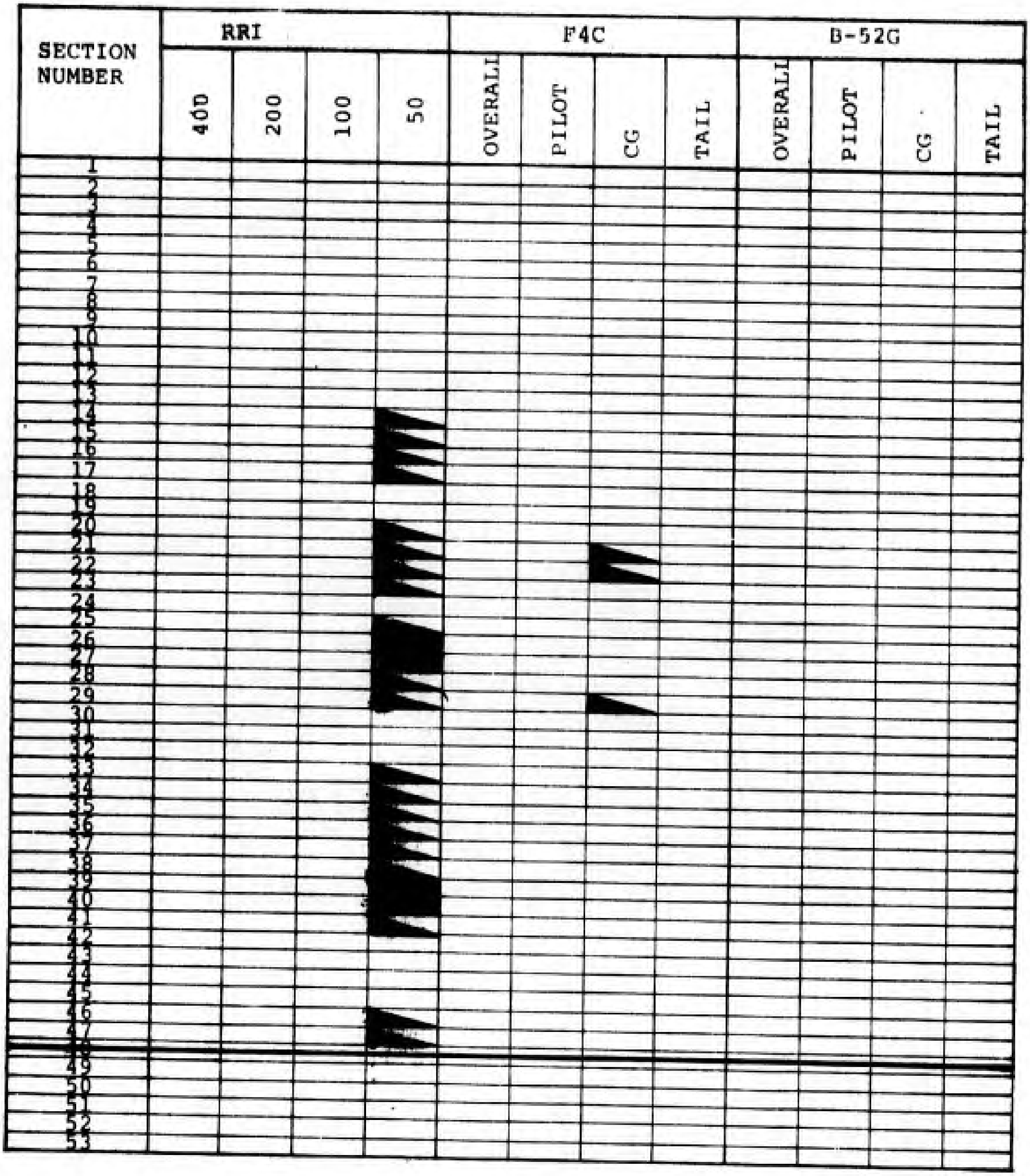
OFFUTT RW 12 ℄


SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53

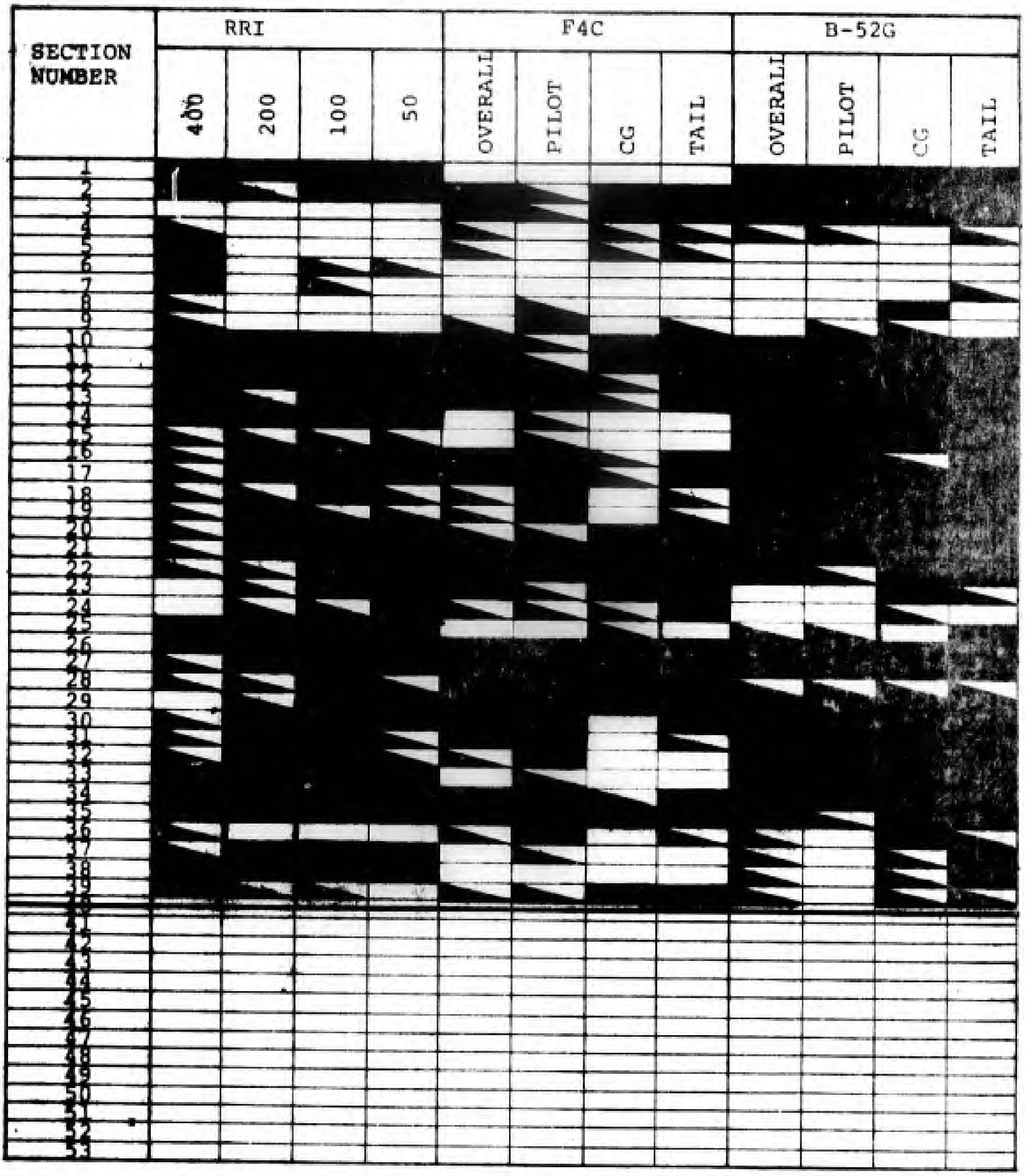
O'HARE RW 22L ℄


SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53

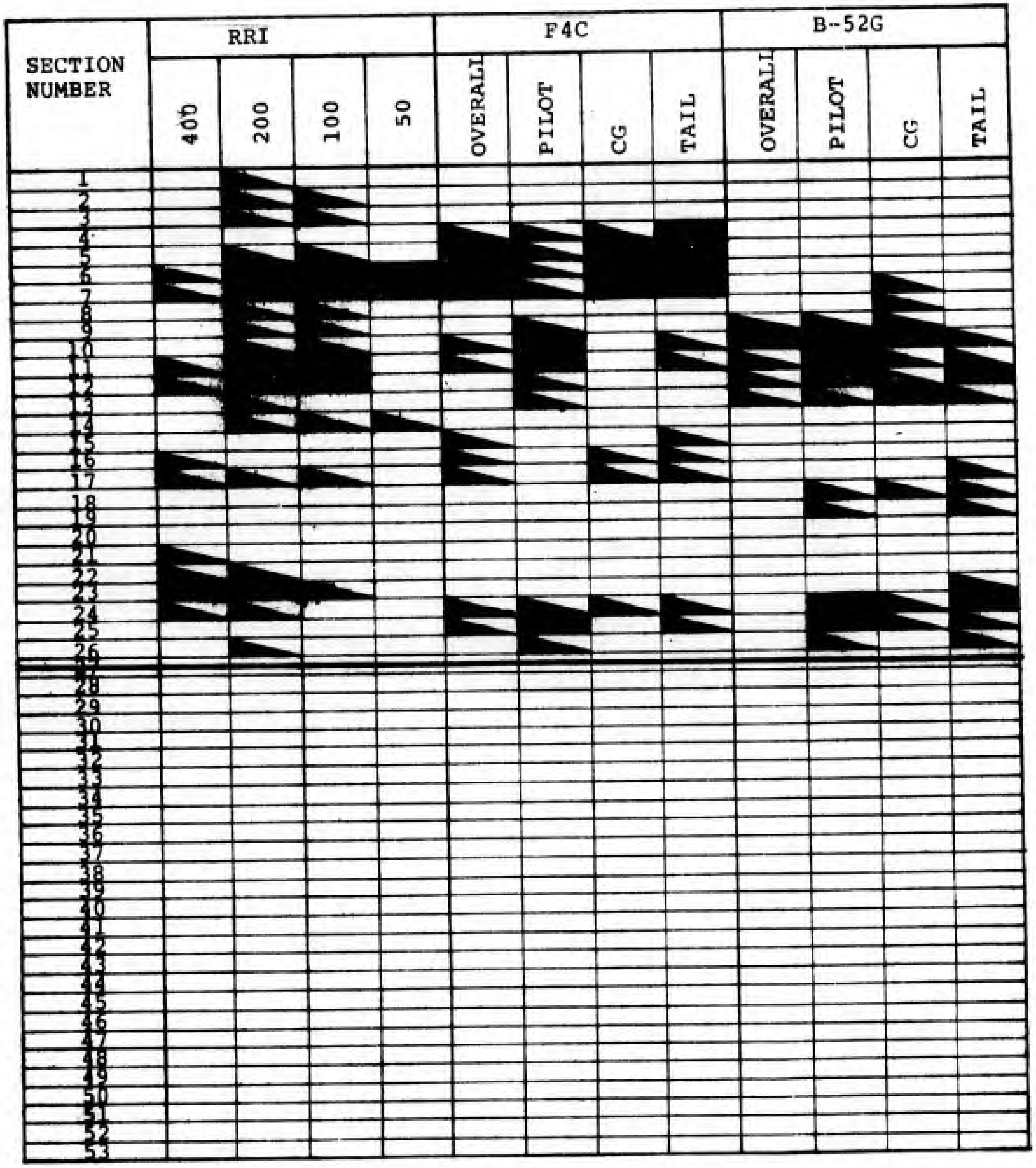
PALMDALE 07 ℄


SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53

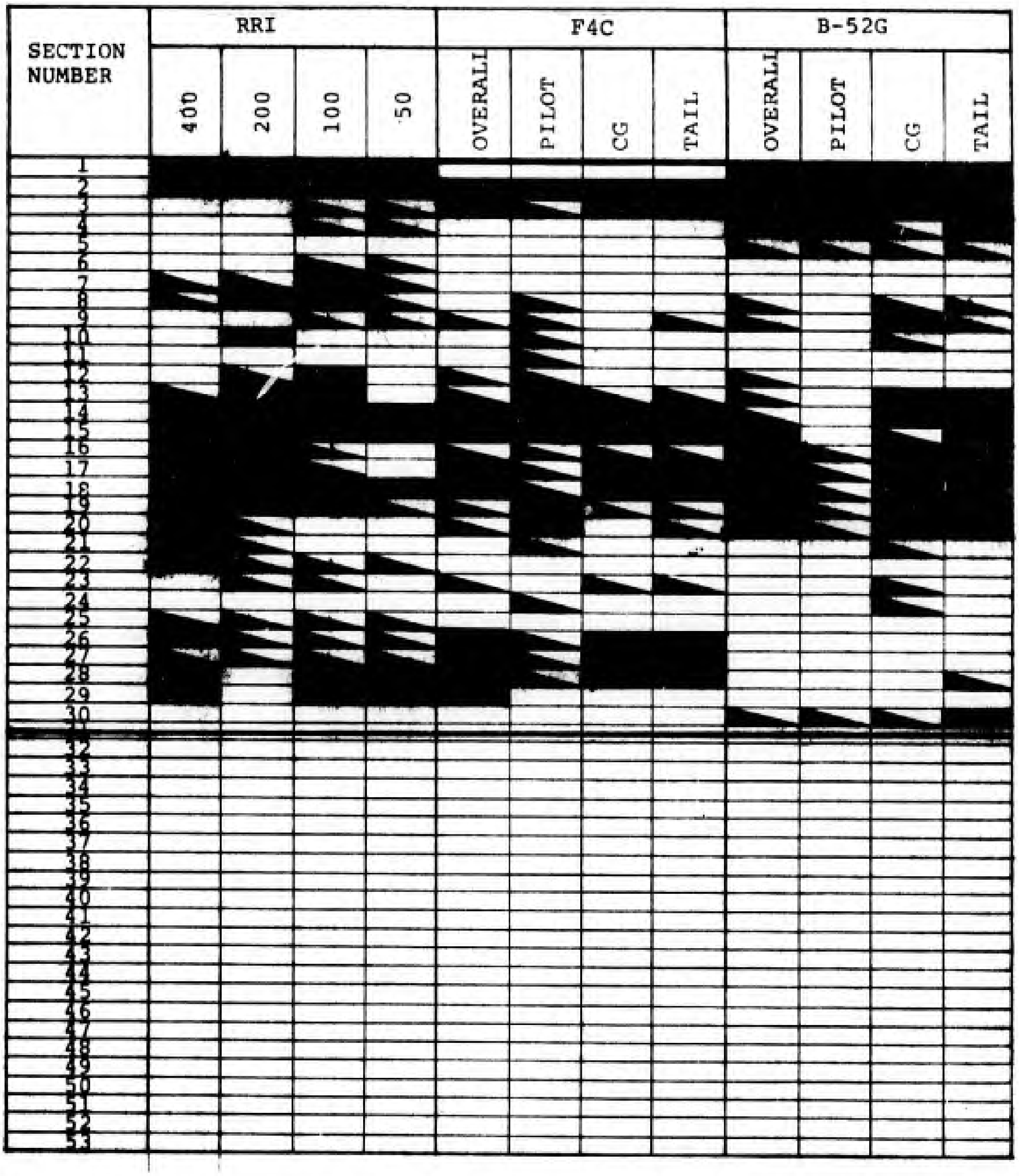
THULE


SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53

WASHINGTON NATL RW 09



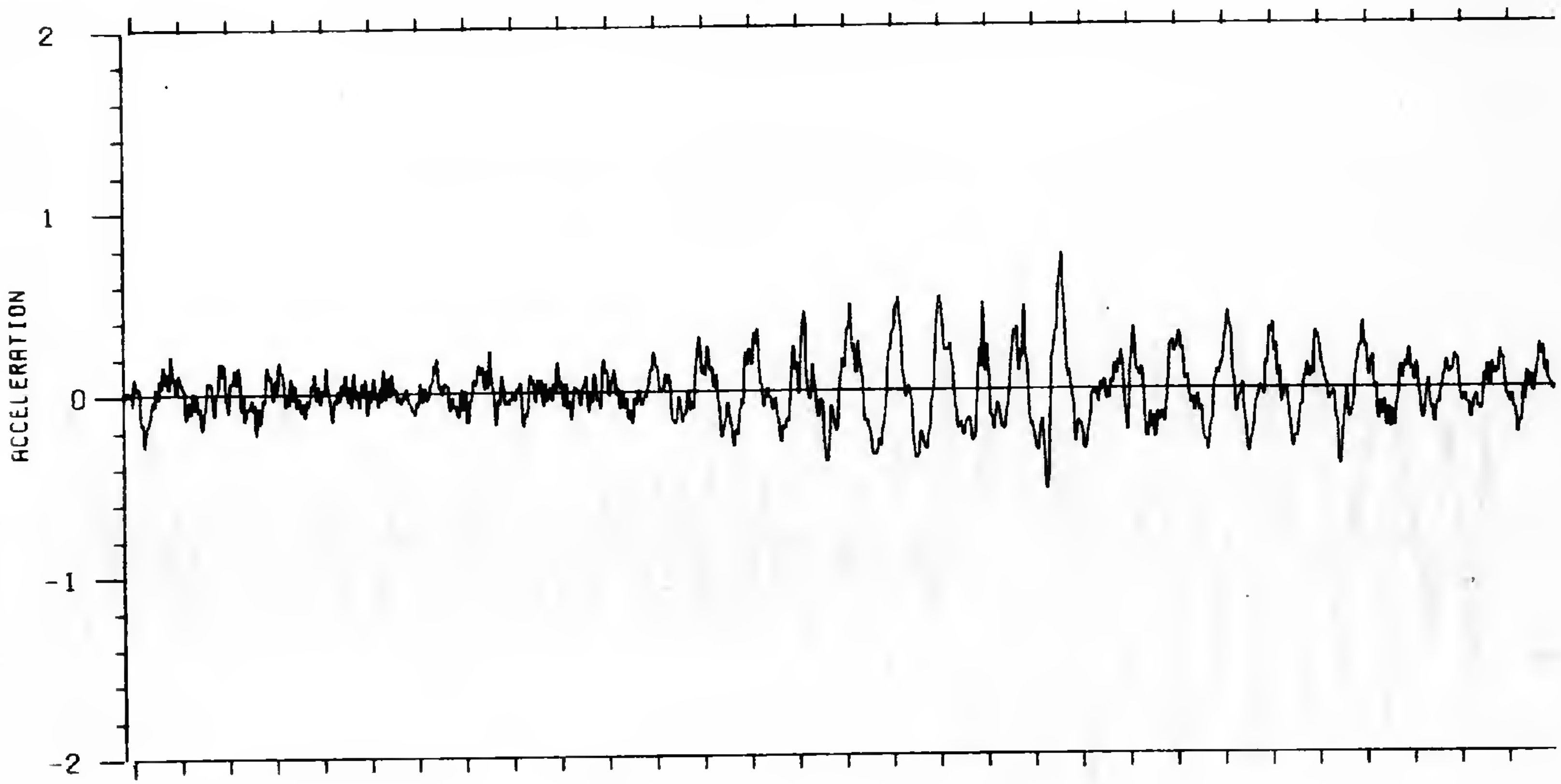
NORFOLK


SECTION NUMBER
RRI
400
200
100
50
F4C
OVERALL
PILOT
CG
TAIL
B-52G
OVERALL
PILOT
CG
TAIL
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53

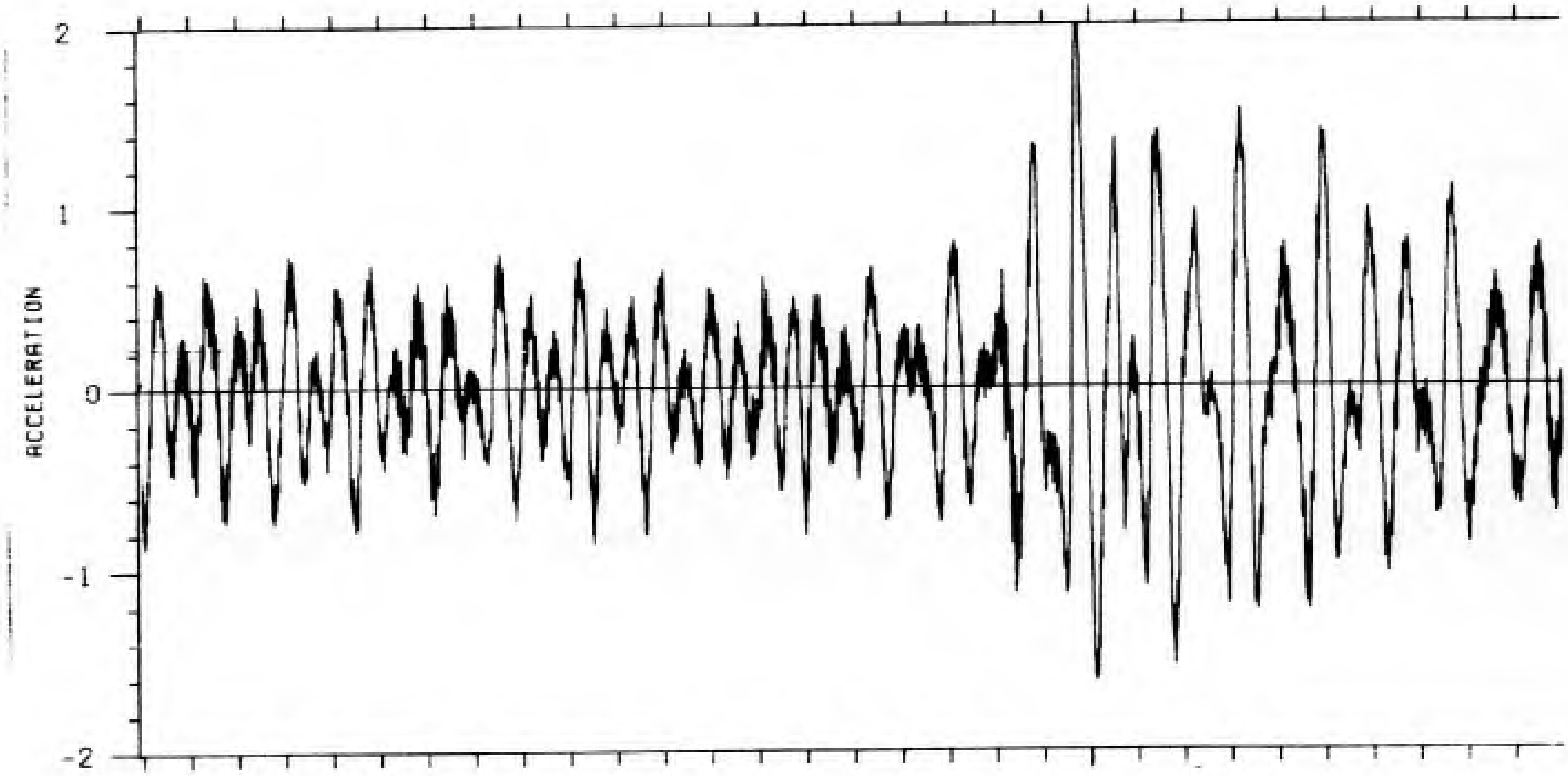
APPENDIX C

TYPICAL AIRCRAFT RESPONSE

FROM TAXI




TYPICAL B-52 PILOT STATION AIRCRAFT RESPONSE




TYPICAL F-4 PILOT STATION AIRCRAFT RESPONSE

## GLOSSARY OF TERMS

| | |
|---|---|
| ARI | Aircraft Response Index |
| $ARI^{P}_{B-52G}$ | Aircraft Response Index at Pilot station for B-52G aircraft. |
| $ARI^{CG}_{F-4C}$ | Aircraft Response Index at Center of Gravity for F-4C aircraft. |
| $ARI^{T}_{C-5}$ | Aircraft Response Index at Tail Section for C-5 aircraft. |
| $ARI^{C}_{C-141}$ | Mathematical Combination of Aircraft Response Indices at Pilot, Center of Gravity, and Tail Stations for C-141 aircraft. |
| RMS | Root Mean Square. |
| RRI | Runway Roughness Index. |
| $RRI_{400}$ | Runway Roughness Index based on cutoff wavelength of 400 feet. (Also 200, 100, and 50 feet.) |
| TAXI | Computer program used to simulate aircraft response to runway profile. |

## INITIAL DISTRIBUTION

| | |
|---|---|
| HQ USAF/PREE | 1 |
| HQ USAF/PREM | 1 |
| HQ AAC/DEM | 1 |
| HQ ADCOM/DEM | 1 |
| HQ AFLC/DEM | 1 |
| HQ AFRES/DEM | 1 |
| HQ AFSC/DEM | 1 |
| ANG/DE | 1 |
| HQ ATC/DEM | 1 |
| HQ MAC/DEM | 1 |
| HQ PACAF/DEM | 1 |
| HQ SAC/DEM | 1 |
| HQ TAC/DEM | 1 |
| HQ USAFE/DEM | 1 |
| HQ USAF/DFCEM | 1 |
| DET 1, HQ ADTC/CN | 2 |
| AFIT/DET | 5 |
| DDC/TCA | 12 |
| AUL | 1 |
| AFCEC/DEM | 25 |
| | 60 |