THE BEHAVIOR OF ALLUVIAL FANS

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Craig Douglas Malcovish
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CRAIG DOUGLAS MALCOVISH

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MASTER OF SCIENCE

ABSTRACT

An alluvial fan is a stream deposit whose surface forms a cone-shaped segment radiating downslope from the point where the stream channel emerges from a mountainous area. Recent highway and pipeline construction has necessitated the crossing of numerous alluvial fans in northern mountainous regions such as Alaska and the MacKenzie Valley in the Northwest Territories. A hydraulic model study was conducted in order to examine the behavior of fans in these areas and to assess changes in their behavior due to engineering interference from bridge crossings, subsurface pipeline crossings, and removal of the nose of the fan surface.

Many of the geomorphic features and processes initially observed on model fans agreed well with reported field observations from other researchers. Changes in normal depositional patterns took place when interference conditions were then applied to model fans.

Initial constriction of the flow through guide banks at bridge crossings caused the build-up of a new conical shaped segment directly below the crossing. Upstream channel backfilling was induced and lateral channel shifting above the guide banks resulted. Increasing the length of the guide banks reduced the rate of deposition within them but did not completely prevent lateral shifting.

Removal of the nose of the fan initially resulted in downcutting of a steep, incised channel and the formation of a new fan segment below the existing surface. Channel incision was limited, however, to a depth at which the channel and the developing segment reached a graded condition. Subsequent aggradation occurred within the channel and the fan surface was regraded to its natural form.

Scour at subsurface pipeline crossings was not considered to be of serious consequence to fans in general.

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TABLE OF CONTENTS

CHAPTER I

INTRODUCTION

Page

CHAPTER II

THE GEOMORPHOLOGY OF ALLUVIAL FANS

CHAPTER III

HYDRAULIC PROCESSES ON ALLUVIAL FANS

CHAPTER IV

LABORATORY OBSERVATIONS

CHAPTER V

CONCLUSIONS

CHAPTER VI

RECOMMENDATIONS

APPENDIX A

MODEL DETAILS

APPENDIX B

TESTING PROGRAM

APPENDIX C

TEST RESULTS (ALLUVIAL FAN DEVELOPMENT)

APPENDIX D

TEST RESULTS (RIVER TRAINING WORKS)

APPENDIX E

TEST RESULTS (FAN DISSECTION)

APPENDIX F

GRAPHS AND FIGURES

APPENDIX G

ALASKA DATA

LIST OF FIGURES

Figure

LIST OF PLATES

Plate

LIST OF PHOTOGRAPHS

Photograph

LIST OF TABLES

LIST OF SYMBOLS

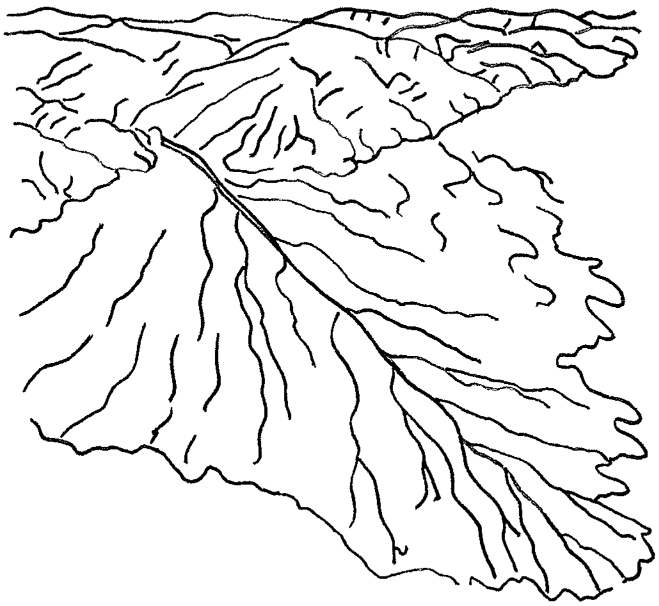
Symbol	Definition
A_f	Fan area
Ad	Drainage basin area
c	Ratio of fan area to drainage basin area of 1 square mile
cfs	Cubic feet per second
d	Depth of flow
D	Particle size
G	Sediment yield
H	Maximum drainage basin relief
n	Channel roughness
n'	Slope of the regression line
Q	Discharge
Q_s	Sediment load
S	Slope of energy grade line
S_d	Drainage basin slope
S_f	Fan slope
v	Velocity
w	Width
τ	Tractive force
τ_c	Critical tractive force
γ	Density of flow

CHAPTER I

INTRODUCTION

1.1 Introduction

An alluvial fan is a stream deposit whose surface forms a cone-shaped segment, radiating downslope from the point where the stream channel emerges from a mountainous area (Bull, 1964 a; FIGURE 1.1).



A simple alluvial fan (Bull, 1968)

FIGURE 1.1

Alluvial fans are distinct landforms that are a part of a complex erosional-depositional system. Readily erodible sediments are transported by stream flow from an upland source area and deposited at a point where the stream suddenly debouches onto a gentler sloping plain. Streams link the erosional and depositional segments of the system and are the dominant influence on alluvial fan morphology.

1.2 Previous Work

1.2.1 Areas of Study

The occurrence of alluvial fans has been reported from all continents. However, due to recurring problems of flash flooding and land subsidence in densely populated areas, arid and semi-arid regions of the southwestern United States have been the focal point for extensive study of alluvial fans in North America. (cf. Eckis, 1928; Buwalda, 1951; Blissenbach, 1954; Bull, 1962, 1964; Lustig, 1965; Melton, 1965; Denny, 1965; Hooke, 1967, 1968).

Due principally to their less conspicuous development and lack of accessibility, alluvial fans in cold temperate, mountainous regions have received very little attention in North American literature. Studies are limited to an account of a small group of fans near Aklavik, N.W.T. (Legget et al 1966), the work of Anderson and Hussey (1962) at Franklin Bluffs, Alaska, and investigations of fans in south central British Columbia (Ryder, 1970, 1971) and the Alberta Rockies (McPherson and Hirst, 1971).

1.2.2 Scope

The conclusions presented in previous literature have concentrated upon aspects of:

(1) The morphometry of alluvial fans and their relationship with drainage basin characteristics. (Bull, 1964 a; Melton, 1965; Hooke, 1968; Ryder, 1971).

(2) The causes and processes of alluvial fan deposition.

(Eckis, 1928; Buwalda, 1951; Bull, 1964 b; Lustig, 1965; Hooke, 1967; Ryder, 1970).

1.3 Current Problems Associated with Alluvial Fans

The locations of many current problems associated with alluvial fans are the high mountain valleys of Alaska and the Northwest Territories. Increasing demands for petroleum resources have resulted in extensive studies of proposed routes for the Alaska and MacKenzie Valley Pipelines. Furthermore, highways are to be constructed along these routes to provide a suitable means of access.

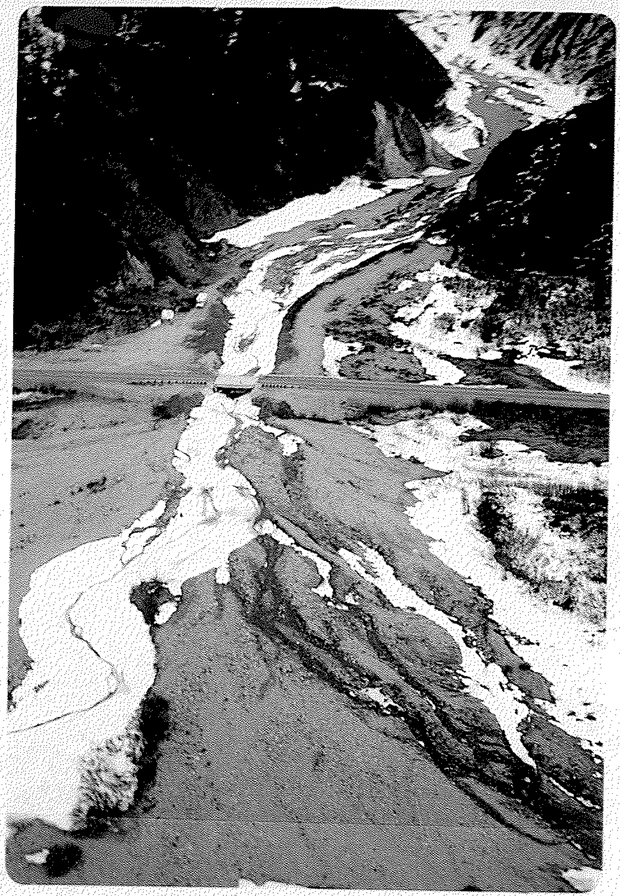
The problems of highway and pipeline design are complicated by the fact that the proposed routes must cross numerous alluvial fans. Consequently, many subsurface pipeline crossings and hydraulic bridge crossings are required. In addition to river and floodplain crossings, protective works such as dikes and guidebanks are often utilized to provide a means of stabilizing erodible stream channel banks during periods of peak flows.

PHOTOGRAPHS 1 and 2 illustrate typical bridge crossings on alluvial fans in Alaska.

1.4 Justification for Further Study

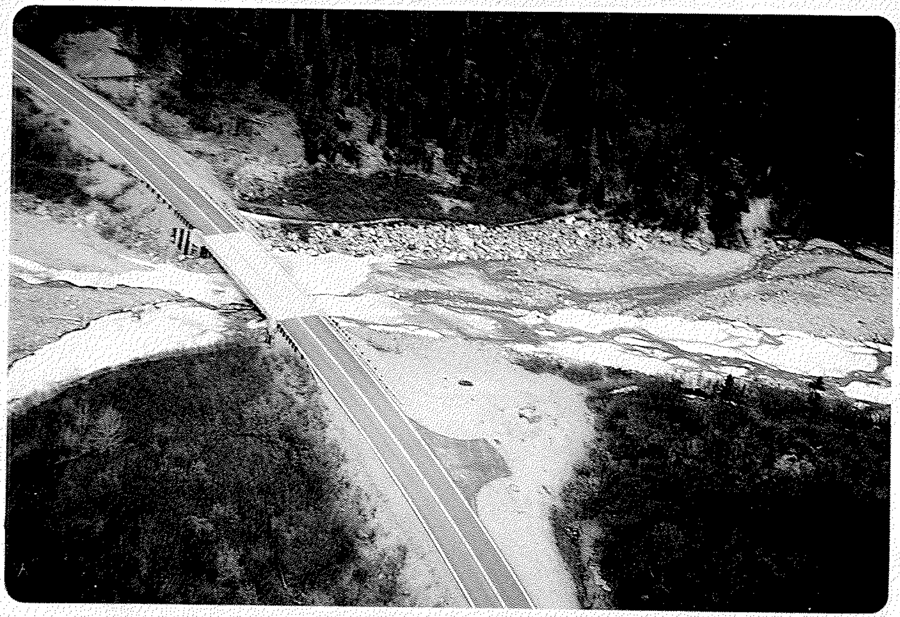
The necessity for further study of alluvial fans in these northern regions becomes apparent if one considers the areas and scope of previous work.

Many of the features and processes noted in previous literature are similar to those on fans along the Alaska and MacKenzie Valley Pipelines.



Floyd Creek Bridge Crossing

PHOTOGRAPH 1



Darling Creek Bridge Crossing

PHOTOGRAPH 2

However, it appears probable that many of the conclusions reached may be applicable specifically to fans within arid and semi-arid regions, and not to fans in general.

Studies conducted on both natural and laboratory fans have not considered any effects of engineering interference upon alluvial fan development. Therefore, further study of the hydraulic processes affected by subsequent alterations to the natural fan surface may aid in establishing necessary parameters for the design of river crossings along these routes.

1.5 Purpose of Study

The purpose of this study is:

(1) To evaluate the hydraulic processes and resultant geomorphic features occurring on alluvial fans in cold temperate, high mountain regions.

(2) To evaluate changes in alluvial fan behavior due to:

  a) hydraulic bridge crossings
  b) subsurface pipeline crossings
  c) fan dissection (removal of the nose of the fan)

(3) To assess the consequences of the construction of bridge and pipeline crossings on fans in Alaska.

1.6 Future Thesis Chapters

The conclusions reached in this study will be based upon a review of previous North American literature and a concurrent hydraulic model study.

The literature review will summarize the fundamental geomorphic features, interrelationships with drainage basin parameters, and hydraulic processes presented in earlier studies.

The hydraulic model study will check on these fundamental characteristics and identify any other aspects of alluvial fan behavior that might have been overlooked in previous literature. The model study will then focus upon observations made of the changes in fan behavior due to the application of various engineering interference conditions.

1.7 Hydraulic Model Study

1.7.1 Basis of Interpretation

Exact modeling of a specific fan cannot at present be used to obtain quantitative data, because scaling relationships for sediment transport by stream and debris flows are not sufficiently well known. Consequently, fans built in the laboratory are treated as small fans in their own right, not as scale models of natural fans.

Most of the empirical relationships for sediment transport by streams are based upon experimental flume studies and not from actual stream channel measurements. Leopold and Maddock (1953) pointed out that sediment transported by a stream can be divided into suspended load and bed load, but depending upon flow conditions, sediment may be entrained as suspended load or at some other time be transported as bed load. No satisfactory method for determining the relative proportions of each has been found at present. The situation for debris flows becomes even more difficult to assess because of variable fluctuations in the density of flow.

As a result, the scaling of flows is restricted to an overall gross scaling relationship between sediment size and discharge. The processes of sorting and deposition and the features that resulted are assumed to be similar to those in nature, and will thus be used as a basis of interpretation of field data from Alaska.

1.7.2 Model Setup

Specific details concerning layout, scaling, operation and instrumentation of the model are found in Appendix A.

1.7.3 Testing Program

The testing program consisted of three phases. These were:

(1) Alluvial Fan Development.

(2) River Training Works.

(3) Fan Dissection.

Specific details of each phase of the program are found in Appendix B.

CHAPTER II

THE GEOMORPHOLOGY OF ALLUVIAL FANS

2.1 Introduction

This chapter deals with the relevant aspects of fan morphology presented in previous literature.

Knowledge of the geomorphology of alluvial fans provides information concerning their past erosional and depositional behavior.

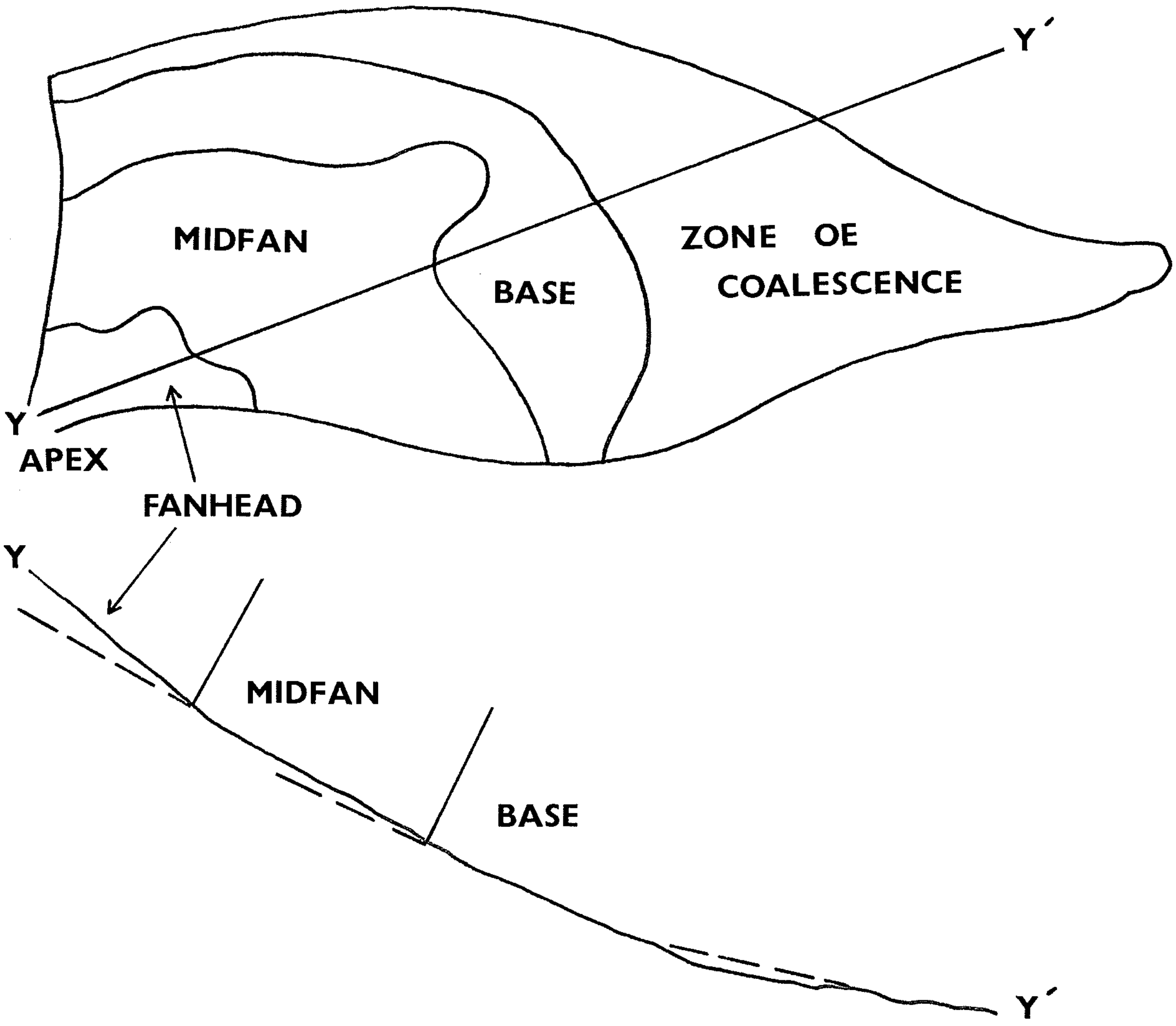
2.2 Depositional Features

2.2.1 Definitions and General Features

The apex of an alluvial fan is located at the point where the stream emerges from the mountains. It is the point of highest elevation of the fan. The fanhead refers to the area adjacent to the apex and midfan denotes the area located between the fanhead and outer, lower margins or base of the fan (Blissenbach, 1954).

A compound alluvial fan results from the lateral coalescence of many fans. This feature is also termed a piedmont plain (Bull, 1964 a).

Bull (1964 a) describes a radial profile as a topographic profile along a radial line on the fan surface, extending from the apex to the base of the fan, and a cross-fan profile as a topographic profile roughly parallel to the mountain front. FIGURE 2.1 diagramatically illustrates the zones of an alluvial fan and a radial profile through it.



Zones of an alluvial fan with a radial profile through it (Modified after Bull, 1964 a)

FIGURE 2.1

2.2.2 Radial Profiles

Changes in fan slope are observed in the radial profiles of most fans. Radial profiles are gently concave upwards (Bull, 1964 a). Blissenbach (1954) noted that the steepest angle of dip on an alluvial fan is encountered close to its apex, and the angles of dip gradually become flatter when proceeding in the downfan direction.

Radial profiles are not smooth curves. Instead, profiles are comprised of several segments, each having essentially a constant slope. The surfaces of these segments form bands of approximately uniform slope which are concentric about the fan apex (Bull, 1964 a).

On most of the fans Bull (1964 a) studied, the slope of the upper fan segment and of the valley upstream from it, were similar. It was concluded that the area of deposition on the fan and stream channel upslope from it, maintained a uniform and common gradient. The fan segments resulted from changes in stream channel gradients which caused deposition on gentler slopes. Hooke (1967) reported that upper fan segments were also graded to the slope of the lower segment.

2.2.3 Cross-Fan Profiles

Cross-fan profiles illustrate the convex nature of alluvial fan deposits. By noting the downslope decrease in convexity of a series of cross-fan profiles, Bull (1964 a) showed that alluvial fans were part of a gently sloping cone.

It was also noted that the predominance of stream channels within thirty degrees of the medial position, on a cross fan profile, indicates that more deposition occurs in this area than in areas located further from the medial position.

2.2.4 Alluvial Fan Deposits

Bull (1964 b) suggested that alluvial fan deposits can be differentiated into three groups:

(1) Water-laid sediments consist either of sheets of sand and silt deposited by braided streams, or of sand and gravel deposited in the beds of stream channels. These deposits are generally well sorted.

(2) Mudflow deposits consist of cobbles and boulders embedded in a matrix of fine sands and silts that have abrupt, well defined margins along the sides and downslope edges of the deposit. These sediments are poorly sorted and have lobate tongues extending from sheet-like deposits.

(3) Intermediate deposits have characteristics between those of water-laid sediments and mudflow deposits. They have no sharply defined margins and tend to blend with the soil.

Many researchers recognized the predominance of mudflow (or debris flow) deposits in fanhead regions (Bull, 1964; Lustig, 1965; Eckis, 1928; Hooke, 1967; Ryder, 1970; McPherson and Hirst, 1970). Water-laid sediments were generally noted to be characteristic of midfan and base areas.

Hooke (1967) also observed the presence of "sieve deposits" on both laboratory and natural fans studied. These deposits were described as lobes of coarse-grained material in which the finer fraction had been removed by means of the winnowing action of water passing over them.

2.2.5 Sedimentary Structure

Alluvial fan deposits are laid down in beds approximately parallel to the surface of a fan. Thus the surface angles of alluvial fans are repeated within fan strata (Blissenbach, 1954).

Both Ryder (1970) and Blissenbach (1954) observed the occurrence of distinct beds of mudflow deposits that made contact with stream deposits of comparable thickness. These stream deposits occurred as well-sorted gravel lenses, as opposed to mudflow deposits, which showed no internal stratification.

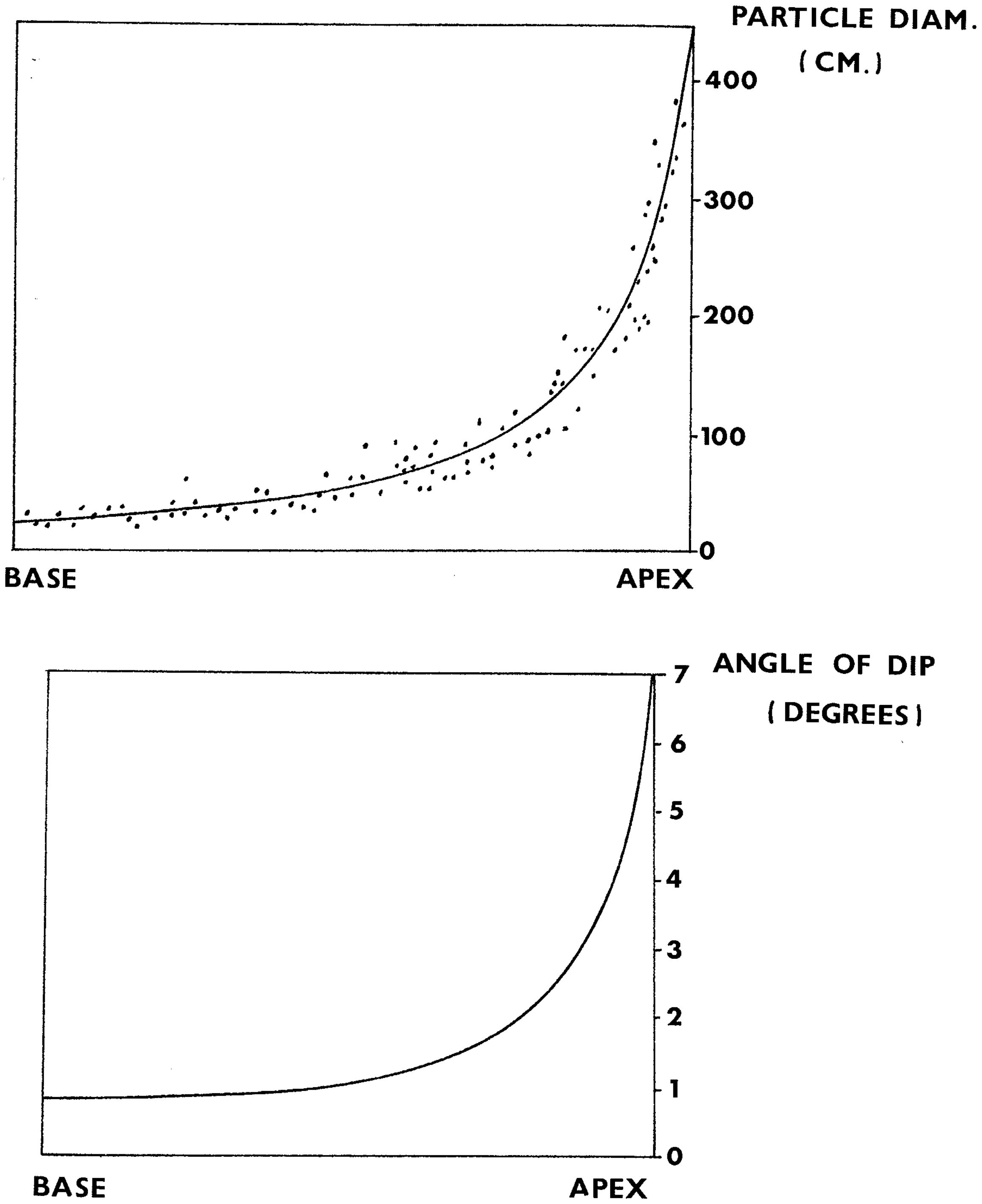
Transverse or cross-fan sections reveal beds that are limited in extent. Such cut and fill structures are common in most fans. These structures resulted from frequent stream channel entrenchment and subsequent backfilling by mudflow deposition (Bull, 1964 a; Blissenbach, 1954; Ryder, 1970).

2.2.6 Particle Sizes and Particle Size Distribution

Most earlier studies have acknowledged a general relationship between decreasing particle size and overall reduction in fan slope in a downfall direction (Eckis, 1928; Melton, 1965; Legget et al, 1966; Hooke, 1967). Blissenbach (1952, 1954) observed that the rate of change in maximum particle size along a radial profile is approximately equal to the rate of change in fan surface slope. FIGURE 2.2 shows Blissenbach's findings.

Channel entrenchment tends to distort trends in particle size distribution; due to the transportation of entire loads of sediment to downslope areas deficient in coarse material (Bull, 1968).

Particle size distribution ranges are greater on fan surfaces than along stream channel beds. Stream bed sediments contain considerably lower percentages of finer material (Bull, 1968; McPherson and Hirst, 1970).



Distributions of maximum particle sizes and angles of dip along a radial profile on an alluvial fan of the Santa Catalina Mountains, Arizona (Modified from Blissenbach, 1952)

FIGURE 2.2

2.2.7 Sorting

Blissenbach (1954) stated that the sorting of alluvial fan deposits may be regarded as a function of:

(1) The range in sediment sizes within the drainage basin.

(2) The type of transporting and depositing agent.

(3) The distance of transport.

Considerable variation in the degree of sorting exists on alluvial fan deposits. Due to mass transport effects debris flows are unable to produce a high degree of sorting. On the other hand, water flows are able to rework and selectively deposit their sediment load, resulting in a high degree of sorting.

2.3 Stream Channels

Stream channels on alluvial fans may be braided, straight, or meandering and are commonly found on the highest parts of the fan surface (Bull, 1964 a).

In fanhead and upper midfan regions, most researchers note that stream channels are frequently entrenched (Bull, 1964 a; Buwalda, 1951; Denny, 1965; Melton, 1965; Lustig, 1965; Hooke, 1967; Ryder, 1970; Eckis, 1928). Eckis described this feature as a "fanhead trench". Bull pointed out that fanhead trenches are usually of a meandering nature and that the trenches of ephemeral streams are narrow while the trenches of intermittent streams are wide. Once entrenchment of a channel has begun natural levees of debris flow (mudflow) deposits are a common feature, particularly on the lower bank.

Most fanhead trenches tend to become shallower as they proceed downfan. Hooke (1967) defined the point where an incised channel emerges with the fan surface as the "intersection point". Ryder (1970) concluded that fanhead trenching indicated the development of lower stream channel gradients across the upper fan areas and deposition below the "intersection point" would reduce the overall gradient.

Fan surfaces below the intersection point are characterized by shallow, braided or discontinuous channels. Braided channels are characteristic of water flows and commonly change position during periods of flow (Bull, 1964 a). The lower points of these channels have been noted by McPherson and Hirst (1970) to be on a level with or slightly higher than the adjacent fan surfaces.

The processes of deposition and erosion identified with the various types of stream channels will be discussed in Chapter III.

2.4 Interrelationships Between Fan and Drainage Basin Parameters

2.4.1 General Statement

Previous workers such as Bull (1962, 1964); Melton (1965); Denny (1965); Hooke (1968) and Ryder (1971), have developed quantitative relationships between fan characteristics of area and slope and certain features of drainage basin morphometry.

The overall similarity of these relationships has been interpreted as indicating that a steady-state or equilibrium condition does exist within a landscape and that alluvial fan characteristics are sensitive to changes in the drainage basin.

2.4.2 Basin Morphometry and Fan Area

With increasing drainage area, the area of an alluvial fan increases. Logarithmic plots of fan area, A_f, against drainage basin area, A_d, (Bull, 1964 a; Denny, 1965; Hooke, 1968) have resulted in the empirical relationship;

$$A_f = c\ A_d^{\,n'}$$

where the co-efficient c is the area of a fan with a one square mile drainage area and the exponent n' is the slope of the regression line.

Because considerable regional variations in values for c and n have been observed, Hooke (1968) outlined several factors which influence these values. The primary factor influencing c is the ratio of depositional area to the erosional area within a watershed. Variations of c within a watershed are due to lithogic variations of the basins which affect sediment yield. Both Hooke (1968) and Bull (1964 a) observed that fans with a predominately coarse-grained source area (cobbles, boulders and very little fine material) were much smaller than fans with a fine-grained source area; (abundant supply of sands and silts). Observed values for n' of less than unity implied that larger drainage basins supply less sediment per square mile than smaller basins. This was attributed to the storage of debris in lower order alluvial channels and on valley side-slopes of larger drainage basins.

2.4.3 Basin Morphometry and Fan Slope

Previous studies have concluded that fan slope is controlled by debris calibre and by the nature and size of the debris transporting processes.

Eckis (1928) and Melton (1965) showed that fan slope decreases with increasing fan area. It follows that slope must also decrease with increasing drainage basin area. This relationship has been shown by Bull, (1964 a), Hooke (1968) and Ryder (1971). The decrease in fan slope was attributed by Hooke (1968), to proportionately higher discharges being emitted from larger watersheds. Fans built in the laboratory with lower discharges had steeper slopes than those built with higher discharges. Increasing the discharge generally resulted in regrading of a fan to a lower slope.

Hooke (1968) suggested that source area lithology can influence fan slope by controlling the debris sizes, the nature of the depositional processes and the sediment concentrations of flows. The influence of debris size was illustrated on laboratory fans by distinct breaks in slope at points where the transition from coarse deposits to finer deposits occurred. Ryder (1971) observed that slopes were generally steeper for gravel fans than for silt fans.

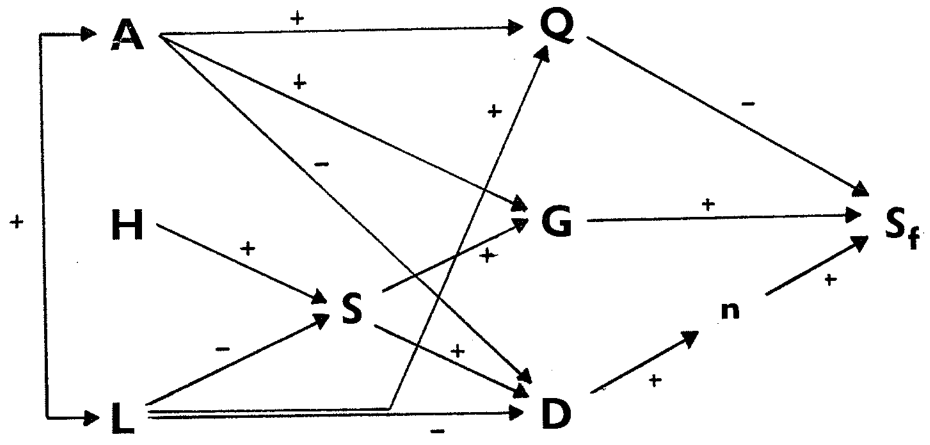
Laboratory fans on which the depositional processes were either mudflow or debris flow deposition were approximately five degrees steeper than fans constructed primarily by fluvial conditions under otherwise equivalent conditions. Comparable effects were also observed on the natural fans studied (Hooke, 1968).

Flows with higher sediment concentrations built steeper fans in the laboratory. A similar result was found by Bull (1964 a) in the San Joaquin Valley. Fans draining source areas underlain by mudstone and shale were generally steeper than those underlain by sandstone deposits. This was attributed to greater erodibility of the mudstone and shale. Ryder (1971) compared slopes of "paraglacial" fans in south central British Columbia to those in the southwestern United States and observed that the slopes of "paraglacial" fans were generally steeper for a comparable drainage basin. It was noted that higher sediment concentrations, due to abundant supplies of glacial drift, appeared to be the most likely cause.

Melton (1965) suggested that increased debris concentration in regions of high elevation or in northern latitudes gives rise to steeper slopes.

Relationships between overall drainage basin slope, (defined as the slope of a straight line from the fanhead to the highest point in a drainage basin), relative relief and fan slope were not acknowledged by Hooke (1968). Instead, it was concluded that these parameters were approximately proportional to the channel gradient in the drainage basin and that a correlation existed between this channel slope and fan slope. Melton (1965) and Ryder (1971), however, reported significant relationships between relative relief ratio H/A_d (where H is the maximum relief in a drainage basin and A_d is the basin area), drainage basin slope, and fan slope; through processes of stream and mudflow deposition. As the basin ruggedness increased (basin slope and relative relief), the proportion of mudflow relative to fluvial deposition increased. Therefore, fan slope also increased.

Ryder (1971) summarized the postulated interrelationships between drainage basin parameters, stream characteristics, and fan slope. This is shown in FIGURE 2.3.



Basin Parameters		Stream Parameters		Fan Slope
A–	basin area	**Q**–	discharge	
H–	basin height	**G**–	sediment yield	S_f
S–	basin slope	**D**–	debris size	
L–	basin length	**n** –	channel roughness	

Summary of postulated interrelationships between drainage basin parameters, stream characteristics and fan slope (Ryder, 1971)
FIGURE 2.3

CHAPTER III

HYDRAULIC PROCESSES ON ALLUVIAL FANS

3.1 Introduction

This chapter will review the fundamental depositional and erosional processes discussed in previous literature. Knowledge of these fundamental processes provides a basis for forecasting probably developments in future fan behavior.

3.2 General Statement on Alluvial Fan Deposition

Streams emerging from steep mountain canyons are commonly loaded with large amounts of sediment. At the alluvial fan, a pronounced tendency for deposition is immediately developed. Deposition is not caused by abrupt decreases in stream gradient, however. The slopes of upper fan regions have been commonly noted to be approximately the same as the stream channel farther upstream (Bull, 1964 a).

Bull (1968) attributed fan deposition to changes in the hydraulic geometry of flow, once it is no longer confined within a single channel. Stream discharge is equal to the product of the mean width (w), mean depth (d), and velocity of flow (v). $Q = wdv$. Once the flow spreads out, an increase in width must be accompanied by a decrease in depth. Although a decrease in depth causes an increase in velocity this is offset by volume reduction. The overall effect is a loss of transportive power.

3.3 Sediment Transport

3.3.1 Modes of Deposition

Most researchers have acknowledged that debris flow and water flows constitute the modes of transportation and subsequent deposition on an alluvial fan (Bull, 1964; Lustig, 1965; Melton, 1965; Hooke, 1967; Ryder, 1970).

Debris flows and water flows are differentiated by the nature of their sediment loads. Debris flows have much higher densities and viscosities than water flows (Sharp and Nobles, 1953). Hooke (1967) suggested that waterflows are able to vary their sediment load by erosion and deposition, whereas debris flows could only selectively deposit their largest particles. Although both modes resulted from water entraining loose sediments, a point existed where sediment entrainment became irreversible. Therefore, a water flow could not evolve from a debris flow.

Blissenbach (1954) categorized debris flow and waterflow (or fluvial) deposition in terms of their depositional relationship on a fan surface:

(1) Sheetfloods are primarily debris flows which spread out in a sheet-like form, covering a large extent of the fan surface.

(2) Streams are characteristic of continual water flows which deposit sediment along a main channel or at the base of the fan by means of a number of braided channels.

(3) Streamfloods are characteristic of either debris flows or water flows and deposit sediment along adjacent floodplains.

3.3.2 Factors controlling the Mode of Deposition

The mode of deposition on an alluvial fan is dependent upon the particular runoff regime.

Ryder (1970) attributed fluvial deposition to relatively equable flows originating from larger drainage basins of high elevation. In this case, channels are maintained free of loose debris and minor blockages. Permanency of stream flow is related to a summer water supply from continued snowmelt. McPherson and Hirst (1970) concluded that fluvial deposition may be the dominant process in constructing alluvial fans in cold temperate, high mountain regions.

On the other hand, Ryder (1970) noted that great and rapid changes in the discharge of snowmelt streams and their intermittent or ephemeral nature within smaller drainage basins, more likely resulted in the production of debris flows. In this case, weathered debris is accumulated within stream channels, giving rise to temporary damming and resultant surges in discharge. Bull (1968) added that steep basin slopes, having an insufficient vegetation cover to prevent accelerated erosion would also contribute to debris flow production during periods of rapid runoff. Most studies also attributed the irregular and torrential nature of precipitation within arid regions as a dominant factor in the greater occurrence of debris flows.

3.3.3 Competence

The competence of the transporting medium is an important factor in determining the downfan extent of deposition on an alluvial fan.

Lustig (1965) and Hooke (1967) used tractive force as a measure of the competence of the largest particles within debris flows. Tractive force is expressed as $\tau = \gamma dS$, where τ is the shear exerted on the upper layer of the channel bed material, γ is the specific weight of the transporting medium, d is the depth of the flow, and S is the slope of the energy gradient.

Individual particles cease to move when the tractive force τ_o no longer exceeds the critical value τ_c, or:

$$\tau_o = \gamma dS \leq \tau_c$$

Laboratory observations suggested that this condition results from a decrease in either hydraulic gradient (= fan slope), or flow depth, as the flow moves downfan and spreads out (Hooke, 1967).

Lustig (1965) modified the tractive force theory in order to be able to estimate the competence of past flows from field data at numerous locations on the fan surface. Maximum particle size and fan slopes were substituted for values of d and S, respectively. The value for density of flow was omitted since values on the fan surface can vary considerably during the downfan progress of the flow. Thus, the distribution of the dS products was mapped and the resulting isopleths were interpreted as reflecting the competence of transport. By assuming that competence decreases in the direction of flow, Lustig (1965) concluded that orthogonals to these isopleths delineated paths of sediment transport.

Large boulders were observed in areas of negligible slope and, therefore, negligible competency. Lustig (1965) pointed out that this apparent anomaly reflected upon a mass transport mechanism attended by the buoyancy and momentum effects of debris flows.

3.4 Channels and Deposition

3.4.1 Changing Loci of Deposition

Most individual flows cover only a small part of an alluvial fan. During formation of a fan, the stream channel shifts repeatedly, both along the contours and radial lines of a fan (Bull, 1968).

Deposition during a single event on an alluvial fan is localized. Over a sufficient period of time, however, shifting of the locus of deposition on laboratory fans resulted in relatively uniform deposition over the entire fan surface. As a result, lower fan areas are aggrading, but at a slower rate than the fanhead (Hooke, 1967).

Hooke (1967) related the average radial position of the intersection point to the relative importance of debris flows and water flows in fan aggradation. Fluvial deposition predominates below the intersection point whereas overbank debris flow deposition predominates above the intersection point. On laboratory fans, Hooke (1967) observed that the intersection point would migrate towards the apex as the previous channel was backfilled by debris flows. Subsequent water flows then eroded a new channel laterally offset from the previous course. Bull (1968) also noted that lateral migration of the area of deposition occurred when deposition had raised the fan surface sufficiently to cause shifting of the stream channel to a lower part of the fan. Hooke (1967) attributed such shifting to uniform deposition and noted that diversion of the channel near the fanhead distributes debris flow sediments over the upper fan surface and results in rapid shifting of the intersection point. Consequently, minor changes in stream channel position near the apex cause large changes in channel position at the base of the fan. Bull (1968) and Lustig (1965) stated that deposition below the zone of bankfull deposition (i.e. intersection point) occurs in transitory locations which depend upon the migration of braided channels.

3.4.2 Causes of Channel Entrenchment

A number of opinions have been expressed with regard to the causes of channel entrenchment on alluvial fans. Lustig (1965) related estimated tractive forces of debris flows and water flows to channel trenching. It was suggested that a climatic change in modern fan processes resulted in greater occurrences of high density flows such as debris flows. These flows in turn, produced degradation by reason of their greater tractive force. Debris flows were able to erode the floors of channels by removing bed material too large to be transported by water flows. Abandoned channels of higher elevations and greater estimated tractive force values within active channels (as opposed to values on the fan surface) were cited as two principal field illustrations of this hypothesis.

Hooke (1967) and Ryder (1970) suggested that fanhead incision was the natural result of an alteration between debris flows and water flows. Channel backfilling by debris flows did not necessarily result in the diversion of subsequent flows. Once the peak flows had passed, the level of flow commonly receded and the stream followed its original course. By reason of their ability to transport on a lower slope, subsequent water flows incised a channel out of the sediment deposited earlier by debris flows. This process was repeatedly observed on laboratory fans. Hooke (1967) also noted that fanhead incision occurred on laboratory fans when the locus of deposition shifted to a place that had not received sediment for several episodes. The slope towards these topographic lows was greater than the overall slope of the fan. Entrenchment due to this process was temporary, lasting only until the low area was built up to the same level as the rest of the fan. Hooke (1967) concluded that entrenchment only resulted when debris flows were alternated with water flows. When water flows were used alone, the flow was unable to transport the material armouring the channel bed.

3.4.3 Depositional Significance of Channel Entrenchment

Channel trenching is an important process in enlarging fans in arid regions, because the loci of deposition are shifted sufficiently far downslope to permit flows to deposit on areas of a fan that would otherwise receive sediment only during times of major flooding (Bull, 1968).

Bull (1964 b) noted that a greater proportion of debris flows will reach a fan during periods when a stream channel is entrenched upstream from the fan, than when it is not. A narrow entrenched channel allows mudflows to maintain a sufficient depth of flow to overcome the critical tractive force of the channel and reach the fan. Buwalda (1951) also suggested that in such cases, waterfloods as well as mudflows are able to transport coarser rock debris than they could transport on the relatively smooth surface of the fan. It was concluded that frequent entrenchment is the controlling factor in transporting coarse sediments to the middle or lower fan areas.

Hooke (1967) summarized the depositional relation between uniform deposition and channel entrenchment by stating, "if deposition is uniform over the fan surface, then debris flows must periodically exceed channel depth and deposit sediment near the fanhead. If the depth of incision is so great as to prevent overbank deposition, then subsequent deposition farther downfan results in backfilling of the channel above the intersection point. The depth of incision is decreased until overbank deposition near the fanhead proceeds at the same rate as deposition elsewhere on the fan. Alternatively, if overbank deposition at the fanhead occurs frequently, then the depth of incision increases until the depositional rates are the same."

3.5 Base Level Dissection

Lowering of the local base level by active downcutting of a trunk channel results in degradation of tributary stream channels on alluvial fans. The fan surface is usually divided into two specific areas which remain as terraces. Dissection of the fan in this manner was recognized by Blissenbach (1954) and Ryder (1970).

This process is primarily dependent upon the lowering of the trunk river, although the rate at which fan dissection proceeds is dependent upon the erosive nature of the tributary stream (Ryder, 1970).

Erosion by the fan building stream is initiated at the base of the fan and migrates towards the apex. Blissenbach (1954) noted that until graded conditions are reached, the fanhead and midfan areas undergo dissection while a depositional tendency prevails farther downfan near the trunk channel.

During the initial stages of dissection the lowest part of the stream is steepened below a marked break in slope, where the dissected gulley and fan surface intersect. This break in slope migrates upstream until the slope is again similar to that of the fan (Ryder, 1970).

CHAPTER IV

LABORATORY OBSERVATIONS

4.1 Introduction

This chapter discusses the hydraulic processes and resultant geomorphic features that were observed for each phase of the testing program outlined in TABLE B.1. Many of the observations presented herein will be used to examine fan behavior in northern mountainous regions.

4.2 Alluvial Fan Development

4.2.1 Introduction

During this phase of the testing program, model alluvial fans were constructed for varying flow conditions and changes in the type of sediment used. The test results are given in APPENDIX C.

4.2.2 Sediment Transport

The volume of sediment injected into the upper end of the trough served to maintain a continuous supply of sediment for streamflow transport. The rate of transport for each particular discharge interval was not measureable because only a fraction of the total volume injected was removed from the trough and deposited on the fan.

The characteristics of the sediment load were reflected by the magnitude of the prevailing discharge. These are outlined in TABLE 4.1.

TABLE 4.1

Characteristics of the sediment load

Discharge	Total Sediment Load	Characteristics
0.020 cfs	bed load and suspended load	murky flows consisting of large pebbles and sand particles rolling along the channel bed (PHOTOGRAPH 3)
0.010 cfs	bed load	clearwater flows consisting of small pebbles and sand particles rolling along the channel bed
0.005 cfs	bed load	clearwater flows consisting of sand particles winnowed out from among larger pebbles comprising the channel bed

Sediment transport at 0.020 cfs

PHOTOGRAPH 3

4.2.3 Uniform Deposition

Model fans were representative of an aggrading depositional system. During a single event, deposition was localized and thus one part of the fan was built slightly higher than the surrounding conical surface. Test results indicated that when observed over a period of several events, lateral channel shifting resulted in deposition of a relatively uniform layer of sediment over the entire fan surface and in symmetrical areal fan growth.

4.2.4 Channels and Deposition

Changes in stream channel patterns corresponded with changes in the applied discharge and the corresponding composition of the sediment load. During higher flows (0.010 and 0.020 cfs), channel instability was induced by the high observed rate of bed load movement. Streams within the trough as well as on the fan surface were characterized by shallow braided and split channels. Local bed load deposition frequently resulted in the formation of channel bars. Bars consisted of coarse particles which could not be transported under local consitions existing in the particular reaches and of the finer material trapped among these coarser particles.

Braided channels transported sediment to lower areas of the fan surface. When these areas had been raised to or slightly above the general level of the rest of the fan surface, channels were backfilled sufficiently to induce lateral shifting of the flow. Abandoned channels testified to the abrupt changes in the locus of the deposition. (PHOTOGRAPH 4)

Abandoned channels

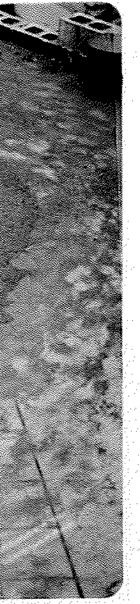
PHOTOGRAPH 4

Periodically, capture of braided channels within an incised channel occurred when the flow proceeded laterally in the direction of an area that had not received sediment for a period of time. The slopes towards such topographic lows were greater than the slope of the fan under prevailing discharge conditions. Thus, a narrow channel, with depths greater than those normally observed for braided channels, was eroded through the existing fanhead deposits. Eroded sediments were transported farther downfan and deposited in a sheet-like manner below the intersection of the incised channel with the lower fan surface. This process was responsible for the presence of coarse sediments at greater distances from the apex than was normally observed through transport by braided channels.

Incision, however, was only temporary. Bed load passing through the channel eventually resulted in the backfilling to the level of the adjacent area. At this point, flows reverted back to a braided channel pattern.

Base flows (0.005 cfs) were characterized by a meandering channel within the trough and on the upper areas of the fan. The concentration of the flow within a single channel did not result in significant lowering of the channel however, because the flows were unable to remove the larger particles armouring the channel bed. Paving originated within the trough and proceeded downstream with time. (PHOTOGRAPH 5). Deposition of the fine sands winnowed out of the upper reaches corresponded with the transition of the meandering channel to a braided or fan shaped channel pattern on lower slopes at the base of the fan.

PLATE 4.1 illustrates the typical behavior of model alluvial fan stream channels during a single runoff (hydrograph) event.

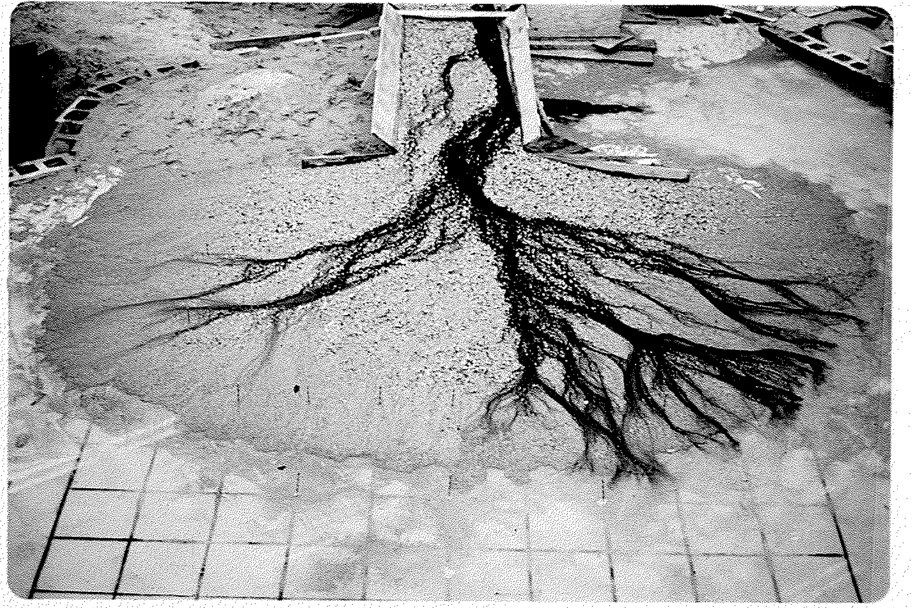


IN.

CFS, T = 55 MIN.

INCREASED CHANNEL BRAIDING AT Q = 0.010 CFS, T = 50 MIN.

PHOTOGRAPH 6B



CHANNEL SHIFTING AT Q = 0.020 CFS, T = 60 MIN.

PHOTOGRAPH 6D

PLATE 4.1

CHANNEL DEVELOPMENTS DURING A HYDROGRAPH

Channel location at Q = 0.005 cfs, T = 40 min.

PHOTOGRAPH 6A

Increased channel braiding at Q = 0.010 cfs, T = 50 min.

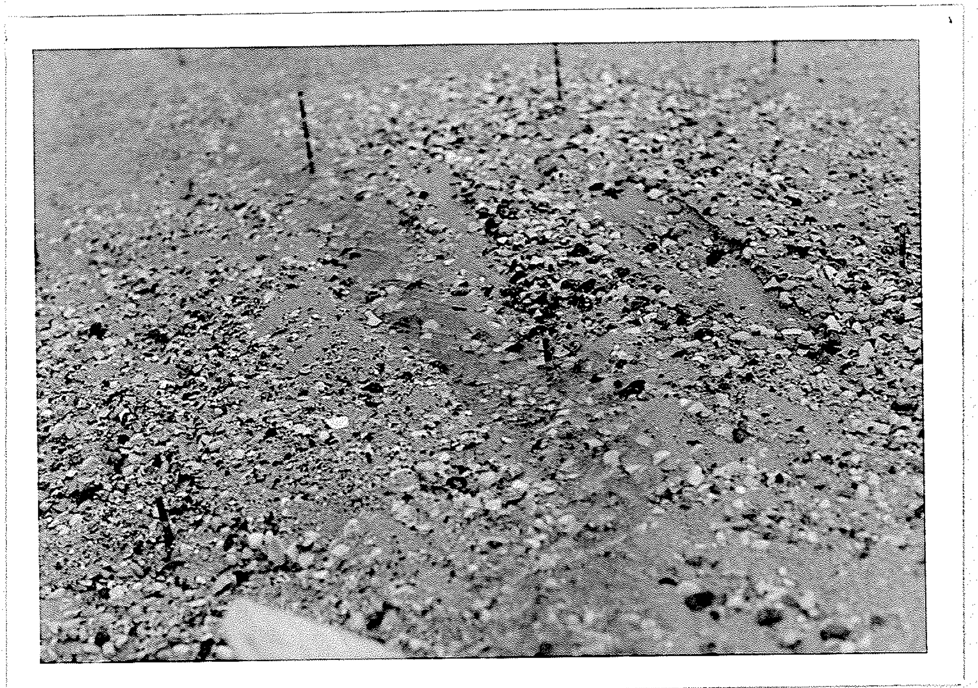
PHOTOGRAPH 6B

Channel shifting and temporary entrenchment at Q = 0.010 cfs, T = 55 min.

PHOTOGRAPH 6C

Channel shifting at Q = 0.020 cfs, T = 60 min.

PHOTOGRAPH 6D



The beginning of channel paving at 0.005 cfs

PHOTOGRAPH 5

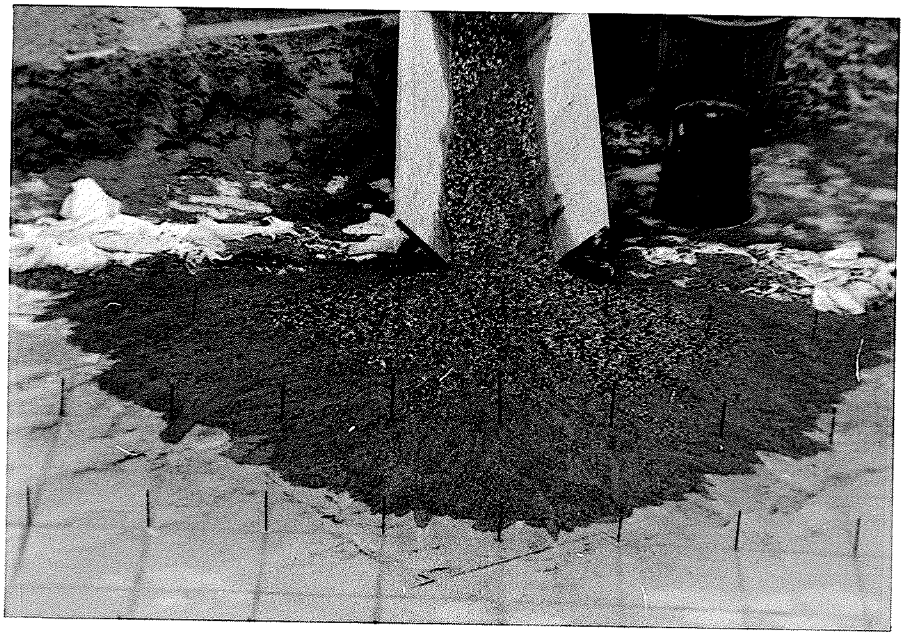
4.2.5 Hydraulic Geometry of Stream Channels

Stream channel properties of width, depth and velocity could not be measured on model fans. The difficulties in measurement were due to the shallowness of the channels that were formed and by the instantaneous changes in the direction of flow that occurred.

In spite of the lack of actual measurements, relative changes in depth and width were observed as the flow proceeded in a downfan direction. In general, channel depths decreased while channel widths increased for a given discharge. At high flows, braiding resulted in the division of the flow into numerous shallower channels. At low flows, decreases in depth and increase in width were accounted for by the effects of upstream channel paving and downstream channel braiding.

4.2.6 Fan Morphology

Test results generally indicated that radial profiles were distinguished by fan segments of uniform slope. Decreases in the local slopes of these segments were associated with changes from coarse, poorly-sorted sediments of the upper segment slopes to finer, well-sorted sediments on the lower slopes (PHOTOGRAPH 7).



Fan segmentation

PHOTOGRAPH 7

Slope changes between adjacent fan segments were affected by the nature of the applied discharges. Fans constructed by hydrographs exhibited a gradual slope change whereas fans constructed by constant discharge exhibited abrupt slope changes.

4.2.7 Effects of Discharge on Fan Slope

Fan slope adjustments to changes in the magnitude of the applied discharge were not measurable on model fans. Measurements along a fixed radial profile did not consistently represent a true indication of slope changes because lateral channel shifting was frequent.

4.2.8 Effects of Downstream Flooding on Fan Morphology

A distinct change in alluvial fan development occurred when a high downstream water level was used to simulate the flooding of a major trunk channel. The presence of backwater resulted in changes in the rate of areal growth and the normal characteristics of radial fan profiles.

Areal growth was reduced. Since deposition occurred over a smaller fan area, the overall fan slope (defined as the slope of a straight line along a radial profile from the apex to the nose) was much greater. TABLE 4.2 summarizes these observed differences in fan development.

TABLE 4.2

Comparison of fan development

Condition	Time of test min.	Discharge cfs	Fan area sq. ft.	Overall fan slope
No downstream flooding	140	0.010 (constant)	38.32	0.076
Downstream flooding	120	0.010 (constant)	12.48	0.103

Radial profiles did not slope gently to the floor of the model but exhibited a distinct slope discontinuity at the nose of the fan. The height of the fan at this point corresponded to the height of the backwater.

Thus an almost vertical edge gave the fan a delta-like appearance (PHOTOGRAPH 8).

Slope discontinuity at the nose of the fan

PHOTOGRAPH 8

4.2.9 Fans Constructed with Mortar Sand

The previously discussed observations in this chapter dealt with alluvial fans constructed with gravel. Fans constructed with mortar sand (PHOTOGRAPH 9a) exhibited none of the characteristics found on gravel fans (PHOTOGRAPH 9b). No distinct channels existed. Instead, flows on the fan and within the trough were poorly defined and almost sheet-like in appearance; areal growth was much greater than that for gravel fans and no distinct downfan changes in particle sizes were observed. As a result radial profiles were not concave but were almost straight lines.

A fan constructed with mortar sand

PHOTOGRAPH 9a

A fan constructed with gravel

PHOTOGRAPH 9b

On the basis of the above observations mortar sand was judged to be too fine and not graded well enough to be a realistic sediment for use in further fan construction.

4.3 River Training Works

4.3.1 Introduction

During this phase of the testing program, bridge crossings were located on the fan surface. Guide banks were placed upstream of these crossings in order to prevent lateral shifting of the main flow channel and subsequent erosion of the roadway embankment (for details of these works, see FIGURES F.3, F.4, and F.5). The test results are given in APPENDIX D.

4.3.2 Channels and Deposition

The overall effects of these works on depositional fan behavior were similar for all of the various types of guide banks tested.

During high discharges (0.010 and 0.020 cfs), initial downcutting of the channel bed resulted in convergence of braided channels in the trough into a single oscillating flow channel within the guide banks. Scour was induced by abrupt deflections in the direction of flow at the nose of the guide banks.

The restrictions on lateral shifting resulted in a change in depositional pattern. Downstream from the bridge crossing, aggradation occurred since the stream was free to braid and shift its channel laterally. Deposition of the bed load resulted in the formation of a distinct conical fan segment radiating outwards from the crossing

(PHOTOGRAPH 11). This zone of deposition served as a hinge point for further upstream aggradation. Once the lower fan areas had been built up sufficiently, initial downcutting that had taken place was offset by subsequent deposition in the form of islands or bars within the guide banks. Radial profiles illustrated the upfan migration of backfilled deposits. Erosion of the roadway embankments resulted when further backfilling gave rise to temporary diversion of the main flow channel in front of the guide banks. As a result, areas above and adjacent to the roadway were built up sufficiently to cause further diversion of the flow back through the lower areas within the guide banks.

A reduction in discharge to 0.005 cfs marked a return to a meandering channel in the upper reaches. The channel was eroded into the previously backfilled sand deposits until channel armouring took place.

Channel behavior under interference by bridge crossings is illustrated in PLATE 4.2.

Fan segmentation below the bridge crossing

PHOTOGRAPH 11

min.

min.

Channel downcutting at Q = 0.020 cfs, T = 60 min.

PHOTOGRAPH 10c

Return to a single channel at Q = 0.005 cfs, T = 90 min.

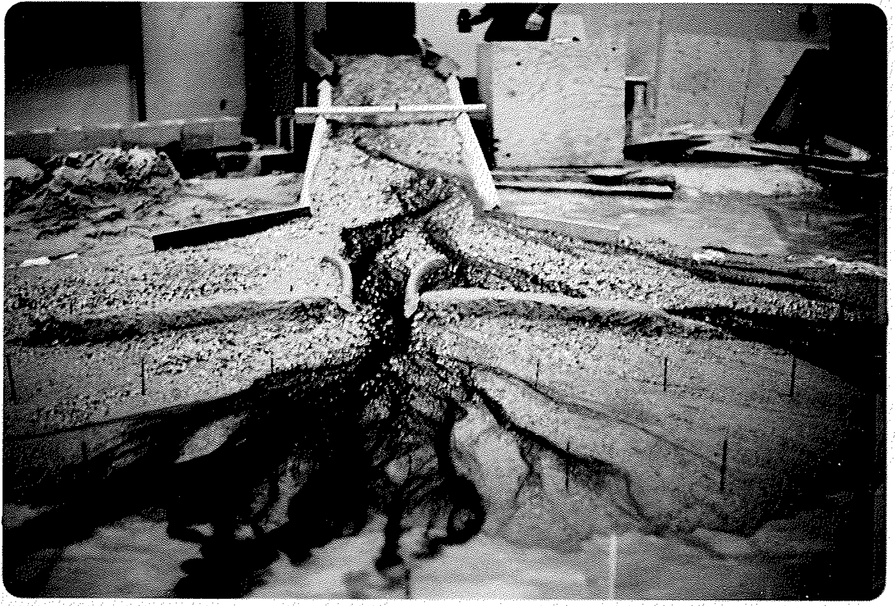
PHOTOGRAPH 10f

PLATE 4.2

CHANNEL DEVELOPMENTS DUE TO BRIDGE CROSSING INTERFERENCE

CHANNEL LOCATION AT Q = 0.005 CFS, T = 40 MIN.

PHOTOGRAPH 10A



CHANNEL BRAIDING AT Q = 0.010 CFS, T = 50 MIN.

PHOTOGRAPH 10B

DIVERSION OF MAIN FLOW CHANNEL TOWARDS EMBANKMENTS AT Q = 0.020 CFS, T = 63 MIN.

PHOTOGRAPH 10D

CHANNEL SHIFTING AT Q = 0.010 CFS, T = 80 MIN.

PHOTOGRAPH 10E

RET

4.3.3 Rates of Deposition

Increasing the lengths (and curvature) of the guide banks reduced the rate of vertical sediment deposition within them. This was attributable to deeper initial channel scouring and, therefore, greater retention of flows within the longer guide banks.

The rates of deposition for each bridge detail are comparatively illustrated by PLATES 4.3 to 4.5.

4.4 Fan Dissection

4.4.1 Introduction

This phase of the testing program involved the removal of the nose of the fan prior to operation of the model (FIGURE F.7). The test results are given in APPENDIX E.

4.4.2 Depositional Signifigance

Removal of the nose of the fan resulted in initial downcutting of a steeply sloping and incised stream channel. The eroded fan deposits were selectively re-deposited as a new fan segment directly below the incised channel. Another resultant feature was the division of the upper fan surface into two areas which remained as terraces.

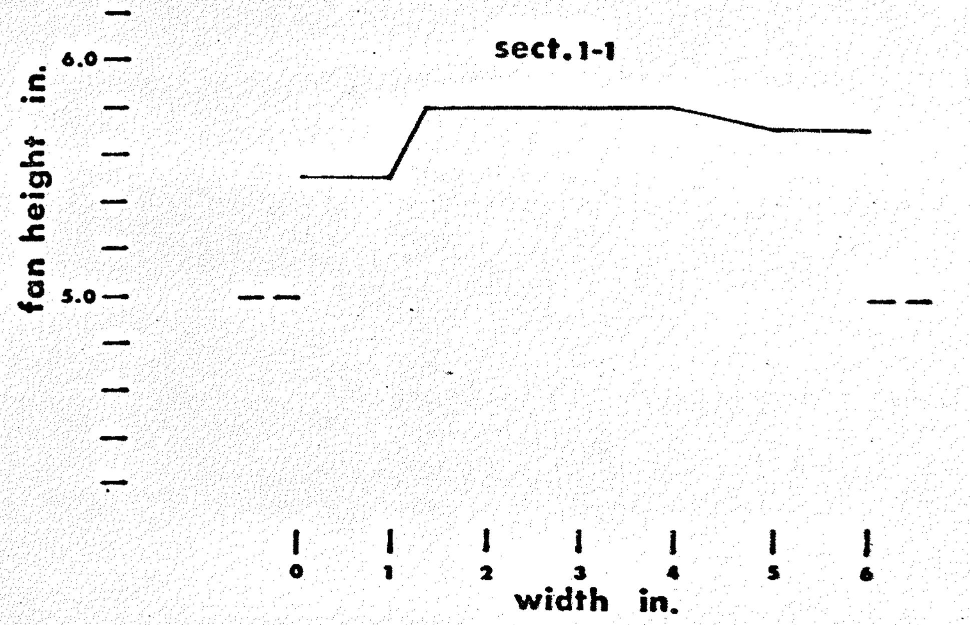
Test results indicated however, that higher applied flows increased the depth of channel incision only until the stream channel and the rebuilding fan segment reached a graded or uniform slope condition. After that, bed load deposition occurring within the channel resulted in raising of the channel bed and the transition from a single channel to laterally shifting braided channels. Braided channels widened the terraced area through bank erosion and aggraded the rebuilding fan segment so that a uniform slope would be maintained. A reduction in applied discharge marked the return to a paved meandering channel. Armouring in the upstream reaches resulted in additional areal growth at the base of the rebuilding fan segment.

Guide banks initially placed at the apex of the fan were not useful in restricting channel shifting, as the flows often shifted around them.

PLATE 4.6 illustrates the processes that resulted in fan rebuilding.

CROSS SECTION I - I AT T = 60 MIN. (2ND HYDROGRAPH)

PHOTOGRAPH 12c



CROSS SECTION I - I

FIGURE 4.2c

PLATE 4.3

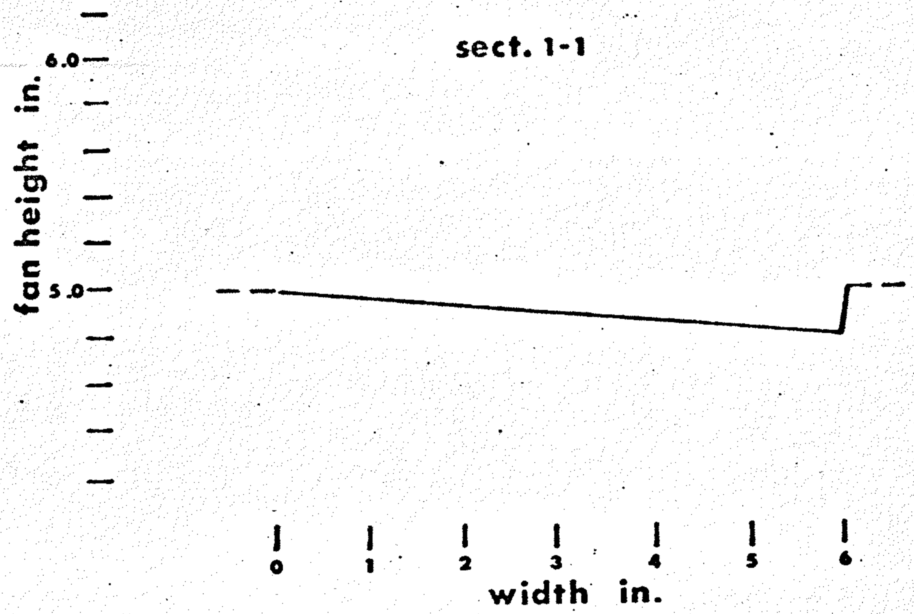
CROSS SECTION DEVELOPMENTS FOR BRIDGE DETAIL NO.1

(LOOKING DOWNSTREAM)

KEY : GUIDE BANK BASE — —

CROSS SECTION I - I AT T = 40 MIN.

PHOTOGRAPH 12A

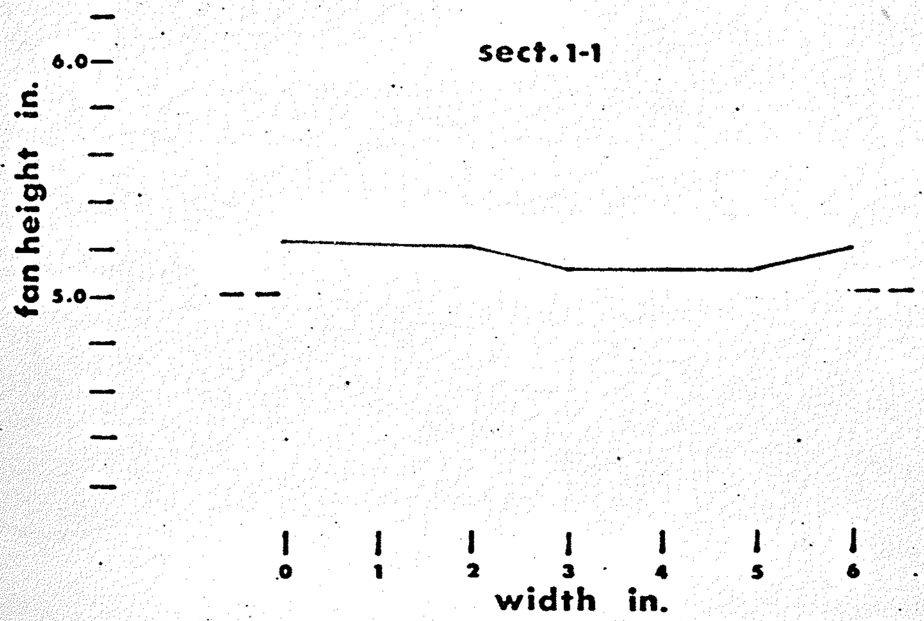


CROSS SECTION I - I

FIGURE 4.2A

CROSS SECTION I - I AT T = 60 MIN.

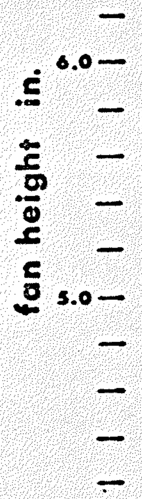
PHOTOGRAPH 12B

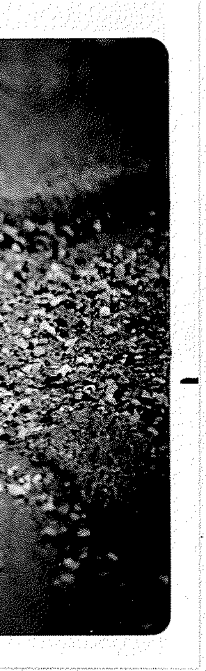


CROSS SECTION I - I

FIGURE 4.2B

C

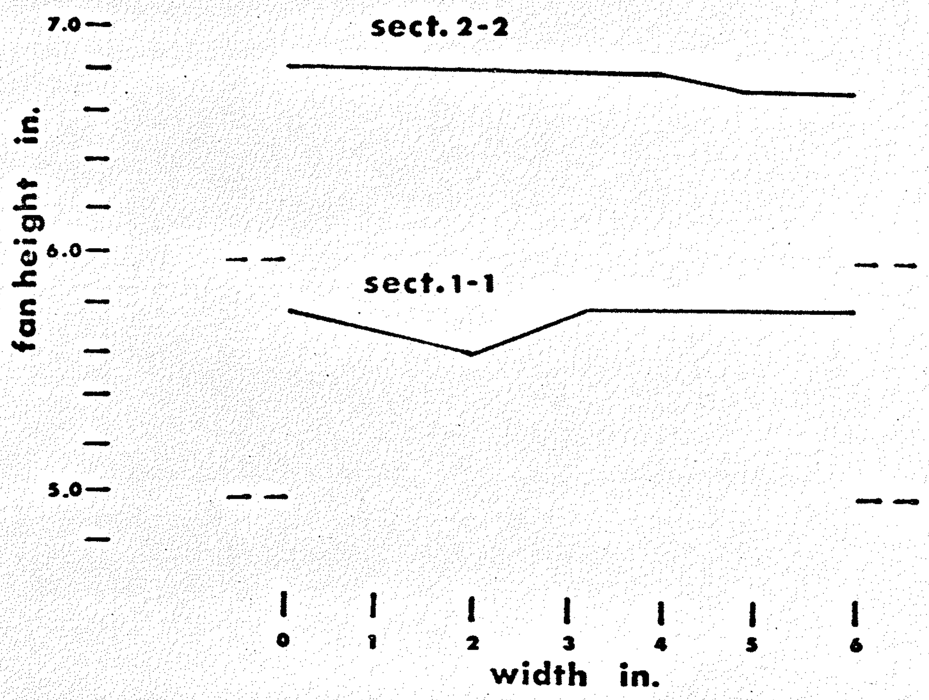




IN.

CROSS SECTIONS 1 - 1 AND 2 - 2 AT T = 60 MIN. (2ND HYDROGRAPH)

PHOTOGRAPH 13c



CROSS SECTIONS 1 - 1 AND 2 - 2

FIGURE 4.1c

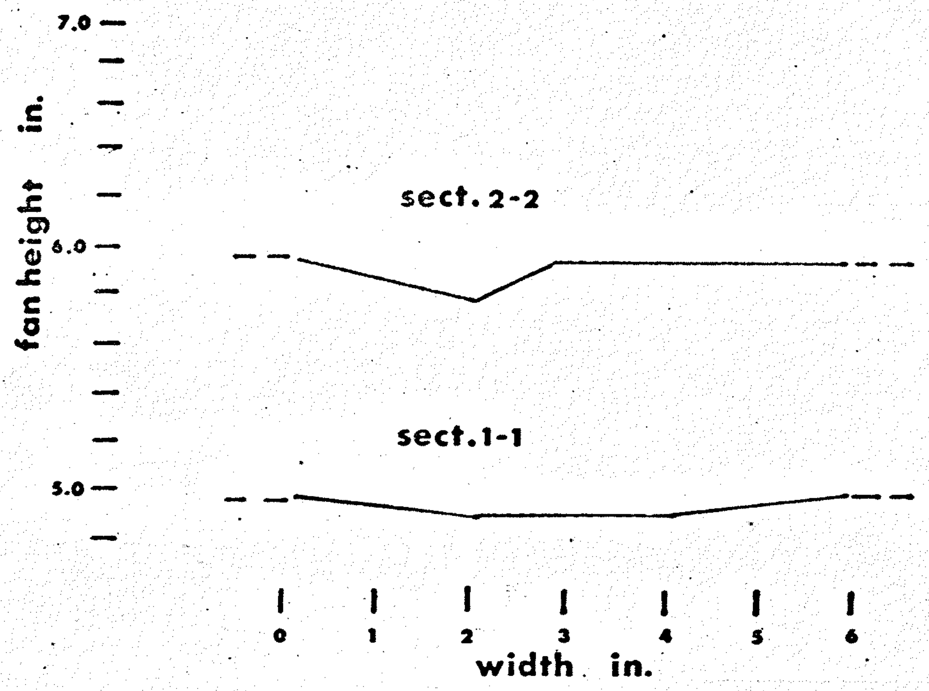
PLATE 4.4

CROSS SECTION DEVELOPMENTS FOR BRIDGE DETAIL NO. 2
(LOOKING DOWNSTREAM)

KEY: GUIDE BANK BASE ‒ ‒

Cross sections 1 - 1 and 2 - 2 at T = 40 min.

PHOTOGRAPH 13A

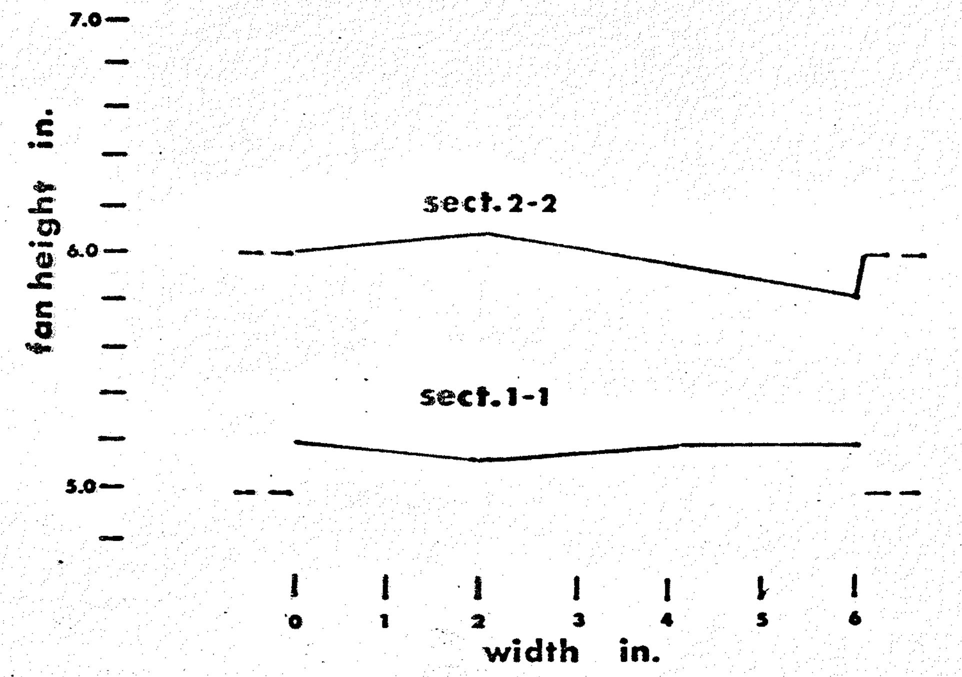


Cross sections 1 - 1 and 2 - 2

FIGURE 4.1A

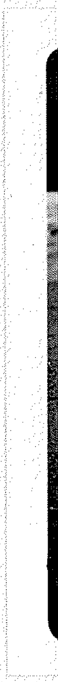
Cross sections 1 - 1 and 2 - 2 at T = 50 min.

PHOTOGRAPH 13B

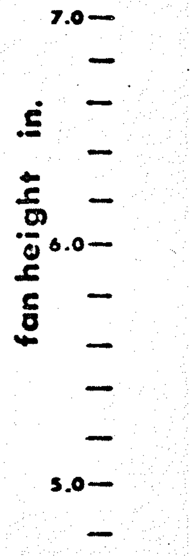


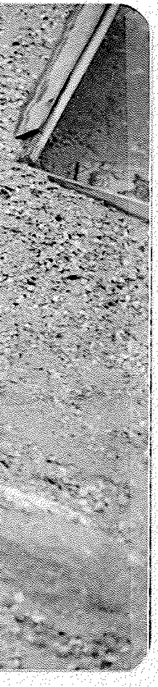
Cross sections 1 - 1 and 2 - 2

FIGURE 4.1B



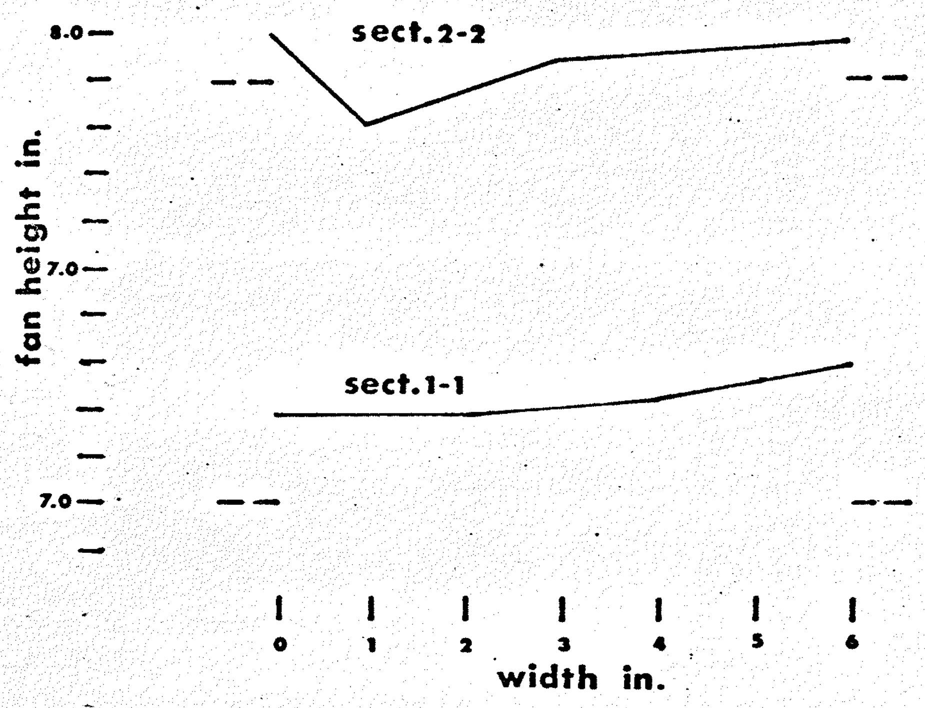
Cross se





Cross sections I - I and 2 - 2 at T = 60 min.

PHOTOGRAPH 14c



Cross sections I - I and 2 - 2

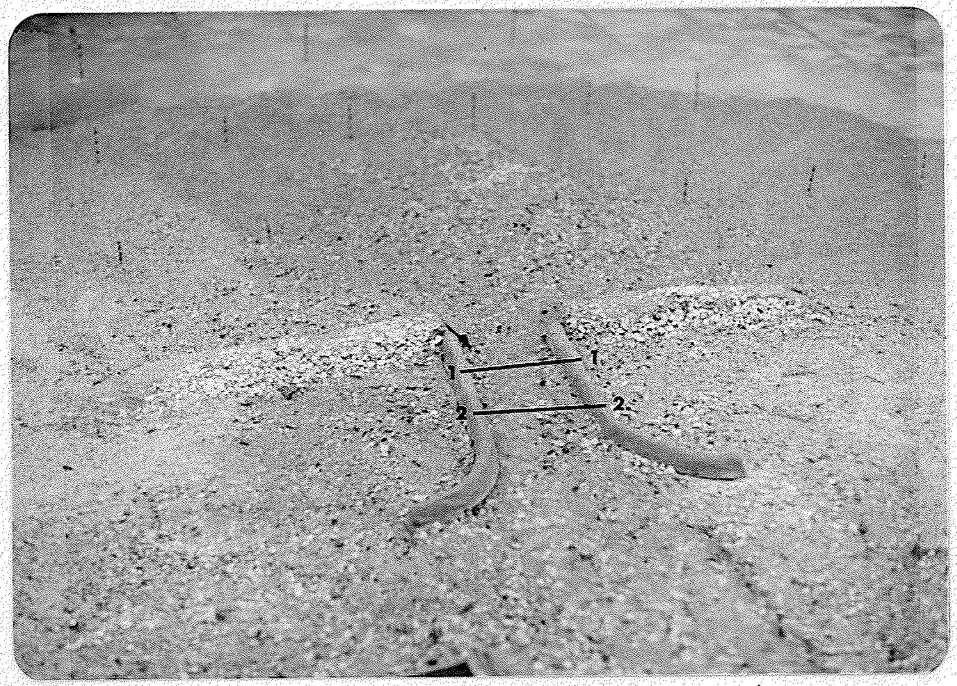
FIGURE 4.3c

PLATE 4.5

CROSS SECTION DEVELOPMENTS FOR BRIDGE DETAIL NO. 3

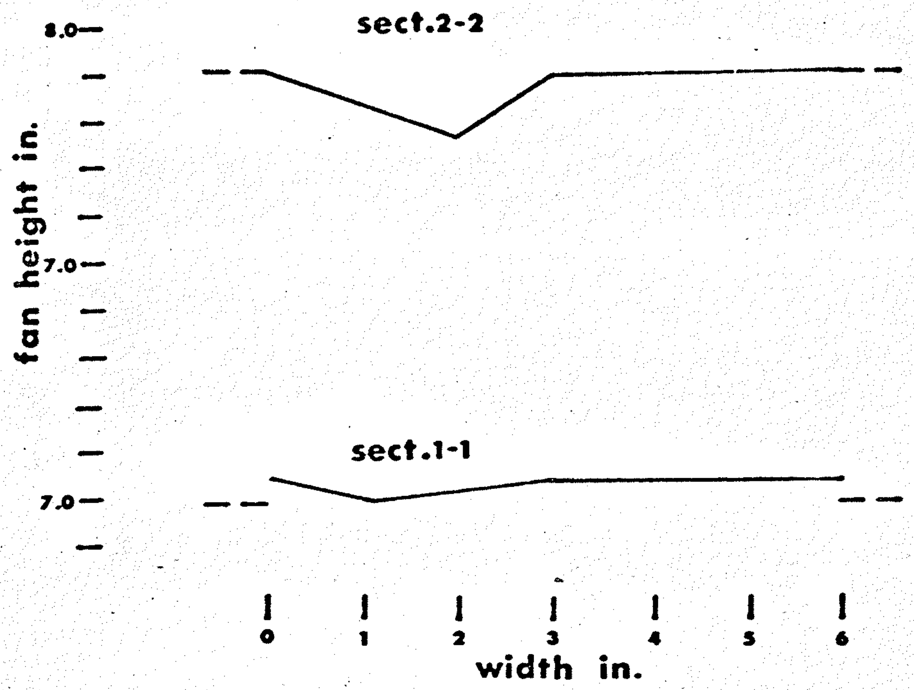
(LOOKING DOWNSTREAM)

KEY: GUIDE BANK BASE – –



CROSS SECTIONS 1 - 1 AND 2 - 2 AT T = 40 MIN.

PHOTOGRAPH 14A

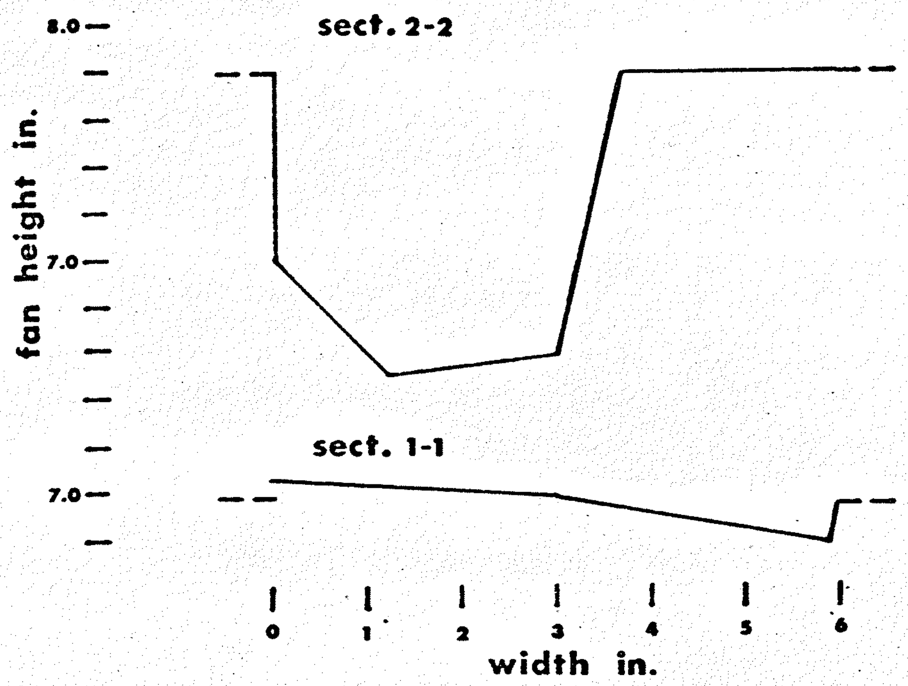


CROSS SECTIONS 1 - 1 AND 2 - 2

FIGURE 4.3A

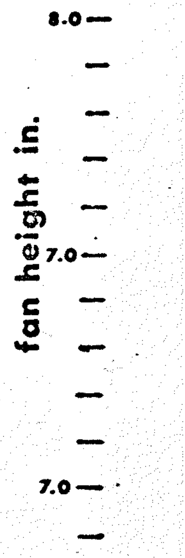
CROSS SECTIONS 1 - 1 AND 2 - 2 AT T = 50 MIN.

PHOTOGRAPH 14B



CROSS SECTIONS 1 - 1 AND 2 - 2

FIGURE 4.3B



05 cfs, T = 40 min.

Further downcutting and fan segment growth at Q = 0.010 cfs, T = 50 min.

PHOTOGRAPH 15B

Braiding and deposition on fan segment at Q = 0.005 cfs, T = 120 min.

PHOTOGRAPH 15E

Channel braiding at Q = 0.020 cfs, T = 60 min.

PHOTOGRAPH 15C

PLATE 4.6

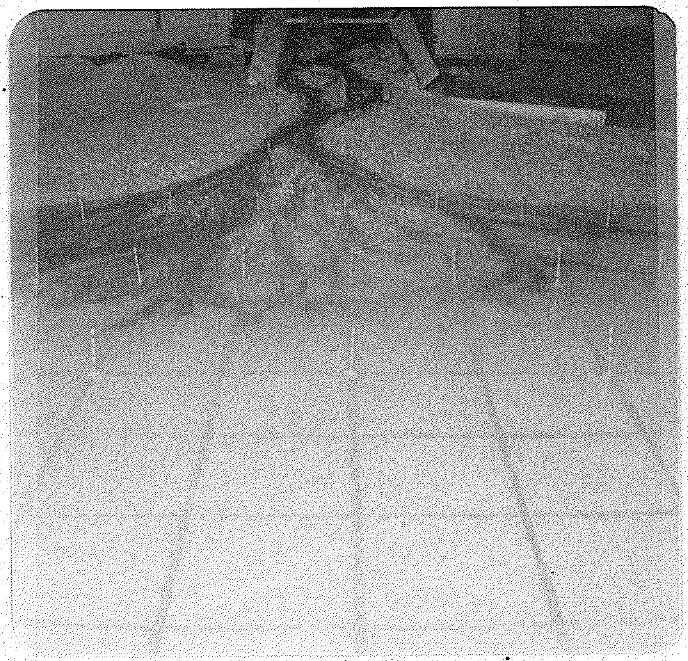
FAN REBUILDING AFTER REMOVAL OF THE NOSE

INITIAL DOWNCUTTING AND FORMATION OF A NEW SEGMENT AT Q = 0.005 CFS, T = 40 MIN.

PHOTOGRAPH 15A

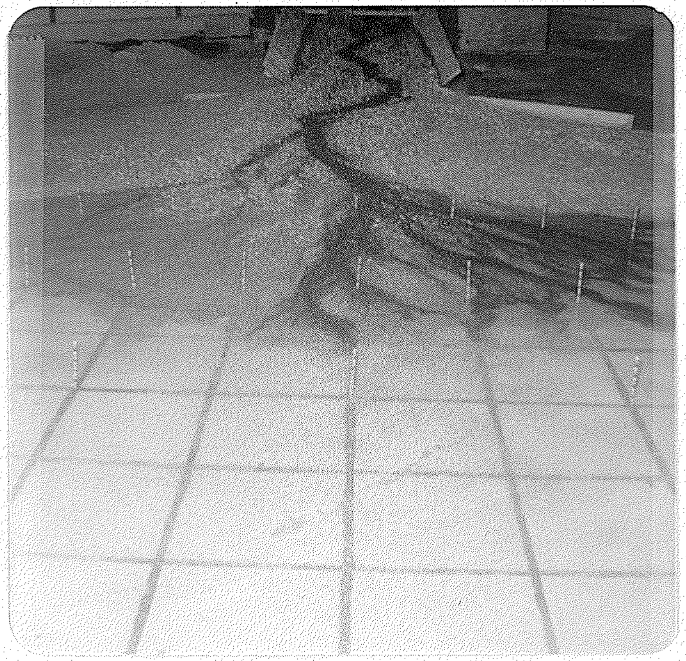
FURTHER DOWNCUTTING AND FAN SEGMENT GROWTH AT Q = 0.010 CFS, T = 50 MIN.

PHOTOGRAPH 15B



CHANNEL SHIFTING AT Q = 0.010 CFS, T = 80 MIN.

PHOTOGRAPH 15D



BRAIDING AND DEPOSITION ON FAN SEGMENT AT Q = 0.005 CFS, T = 120 MIN.

PHOTOGRAPH 15E

CHAPTER V

CONCLUSIONS

5.1 Similarity of Model Fans to Natural Fans

Laboratory fan morphology processes agreed well with those observed in previous literature. Similarity was evident for fan segmentation, the relationship between concave radial profiles and particle size distributions, sorting, uniform deposition and fan symmetry.

Observations conflicting with those in previous literature were related to the relative importance of debris flows in stream channel development and fan morphology; most notably permanent channel entrenchment. However, reference to field data of bed material from Alaska, indicated the predominance of coarse gravels and a lack of a high percentage of fine silts. Model fans were also constructed of non-cohesive sand and gravel. Therefore, the hydraulic processes occurring on fans in northern mountainous regions are similar to those on model fans. Debris flows and permanent channel entrenchment, which are characteristic of fans constructed in predominantly arid and semi-arid regions were not reproduced in the model.

5.2 Factors Affecting Channel Development on Alluvial Fans in Alaska

Discharge (Q), sediment load (Q_s) and particle size (D) are characteristics of the hydrology, geology and relief of the drainage basin.

They are imposed on stream channels and are essentially independent of the stream channel system. High flows are characterized by large sediment loads and large particle sizes in transport whereas low flows are characterized by small sediment loads and small particle sizes in transport. The hydraulic factors which are dependent are channel depth (d) and width (w). These are mutually adjusted with changes in the discharge, sediment load and particle sizes in transport. The factor which is neither dependent nor independent is slope (S).

The relationships between these factors are exhibited on model fans through changes from a single meandering channel pattern on steep upper fan areas, at low flows, to braided channel patterns at high flows.

Braided channels do not develop without an appreciable bed load and corresponding high discharges. The explanation appears to be the movement of bed load exceeding local competence and consequent coarse sediment deposition within the channel, causing the diversion of flow from one channel into a number of channels, or the deposition of channel bars and the development of islands.

Braiding at high flows indicates channel cross-sectional shape adjustments of width and depth. Relatively deeper and narrower single-thread channels are observed at low flows whereas increases in discharge and bed load result in observed reductions in channel depth and increases in channel width, in accordance with the erodible nature of the channel banks.

Changes in local fan or channel slopes are not attributable to channel braiding. Channels may be braided on either higher or lower fan slopes, or both, depending upon the flow conditions. On the other hand, a strong tendency for temporarily incised channels to flow towards topographic lows, where the local slope of the fan is steeper than in other areas, indicates channel adjustments to slope.

5.3 Changes in Alluvial Fan Behavior Due to Engineering Interference

(1) Bridge crossings (guide banks)

Constricting high flows through guide banks and bridge crossings results in initial downcutting of upstream braided channels into a major flow channel; which in turn, alters the deposition pattern normally observed on natural fan surfaces. Rather than long term uniform deposition over lower fan areas, deposition is localized in an area directly downstream of the bridge crossing. High rates of subsequent bed load deposition cause areas within these crossings to backfill. Any further backfilling results in a substantial increase in the amount of sediment deposition upstream of bridge crossings and a tendency for lateral channel shifting towards the roadway embankments.

(2) Subsurface pipeline crossings

Due to the effects of channel armouring at low flows and high rates of local bed load deposition with stream channels at high flows, degradation is not significant. Consequently, subsurface pipeline crossings have little or no effect upon normal fan behavior.

A possible exception occurs when a stream channel is trapped between the edge of the fan surface and an adjacent valley wall. In this case, channel scouring lowers the bed sufficiently to erode the pipeline crossing.

(3) Removal of the nose of the fan

Removal of the nose of the fan results in downcutting of a steep, incised stream channel and the development of a new fan segment. Degradation continues until the rebuilding fan segment and the incised channel reach a graded or uniform slope condition. A graded condition is maintained through subsequent aggradation of the incised channel at high flows while the resultant laterally shifting braided channels erode the incised channel banks. Repeated runoff events, (periods of high flows), will eventually result in regrading of the fan surface to its natural form.

5.4 Use of the Manning Flow Equation for the Design of Bridge and Pipeline Crossings

Use of the Manning flow equation to forecast the water surface elevation or stage for a given stream channel cross-section and design discharge requires the accurate determination of channel roughness. Friction losses due to roughness in a natural stream depend upon the size and gradation of the sediments comprising the channel bed and on the shape, size and spacing of the irregularities within the boundaries of flow. Substantial increases in the amount and sizes of bed load in transport during high flows, make it difficult to assess a constant value for roughness; simply by reason of their tendencies for changes in channel shape and bed material. Due to the presence of large boulders within these channels, turbulence develops a high energy dissipation that also results in significant changes in the water surface profile. Therefore, the Manning equation will not give reliable results.

5.5 The Consequences of Bridge and Pipeline Construction Across Alluvial Fans in Alaska

The effects of highly unstable alluvial fan stream channels upon bridge crossings largely depends upon the location of the crossing in relation to the fan surface. In areas where the fan is constricted between steep valley walls, lateral channel shifting may be limited through the use of guide banks or dikes which tie into the valley walls. However, in cases where bridge crossings are located on wider and lower areas of the fan surface, river training works do not appear to be a permanent solution. Lateral channel shifting upstream of these works may result in washout of the roadway embankment.

In the case of subsurface pipeline crossings, an opposite situation exists. Pipelines may be scoured out if streams are constricted sufficiently to induce degradation. On lower and wider areas of the fan, degradation is not an important factor.

5.6 Limitations of Testing

Alluvial fans constructed in the laboratory were useful in studying qualitative relationships between stream channels and their depositional significance. However, no quantitative relationships for the hydraulics of stream channels on alluvial fans were able to be developed because of limitations to the sizes and rapidity of shifting of the streams that were formed.

Due to the crude method used, the rates of sediment injection were highly variable throughout the testing program. Although the rate of injection did not entirely govern the amount of sediment being transported, a more accurate means of injection would eliminate any possible discrepencies with natural fan and channel development.

Since the available time for testing was limited by other research requirements, not all of the aspects of river training were studied. These will be outlined in the following chapter.

CHAPTER VI

RECOMMENDATIONS

6.1 Laboratory Research

It is recommended that further laboratory research should be conducted on additional aspects of river training for pipeline and bridge crossings.

With bridge crossings, guide bank designs may be modified by:

(1) increasing the curvature of the nose of the guide banks.

(2) increasing the lengths of guide banks so that they tie into valley walls.

(3) placing additional guide banks downstream of the crossings.

For pipeline crossings, training works may be used to assess the best locations for sag points. Retaining structures parallel to the pipeline could also be assessed.

6.2 Field Research

It is recommended that field research should be extensively conducted on alluvial fan stream channels. The accumulation of field data from a large number of streams would enable the development of quantitative relationships between channel width, depths, velocities, slope and discharge, such as those developed by Leopold and Maddock (1953). These relationships would result in a reasonable alternative to the problem of attempting to assign a roughness value for the Manning equation.

The rates of aggradation and/or degradation could be assessed for existing crossings and a comparison made between results from a concurrent model study, and the field data. This could lead to additional improvements upon current methods of river training.

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APPENDIX A

MODEL DETAILS

MODEL DETAILS

A.1 Basic Principles

The construction of small alluvial fans in the laboratory resulted from the simulation of a steeply sloping mountain stream that debouches onto a valley floor of lesser slope.

A.2 Model Layout

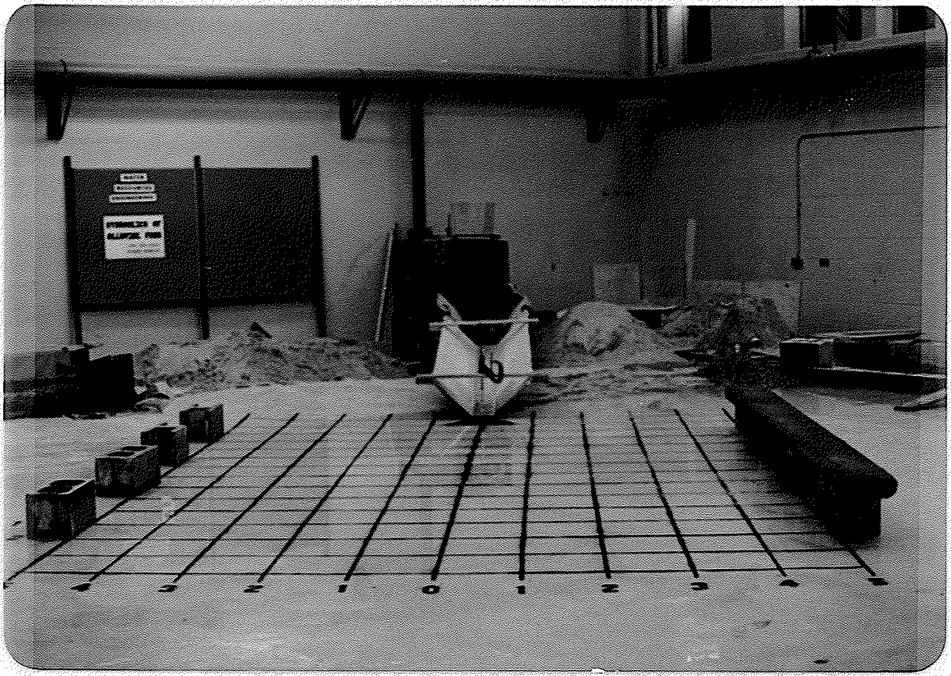
The model layout shown in PHOTOGRAPHS 16 and 17, was located on the lower floor of the hydraulics laboratory and consisted of the following:

(1) Concrete Floor - a four inch thick concrete floor simulated the valley floor and provided an approximate 20ft x 30ft working area for fan construction. The far end of the floor was sloped towards a drain which returned the water to the sump.

(2) Trough - A 3/4 inch plywood trough simulated the mountain stream. The trough was 10 feet long and trapezoidal in shape; having a top width of 20 inches, bottom width of 6 inches and 1 to 1 side slopes. A metal plate was used to provide a smooth transition between the trough and floor.

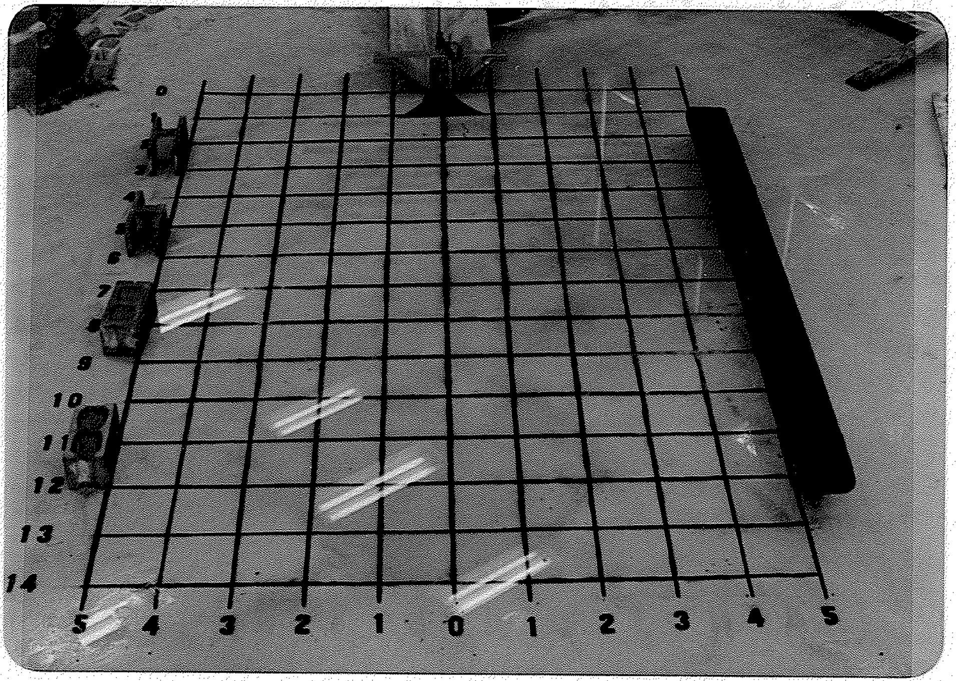
(3) Weir Box - a 6 ft x 2.5 ft metal weir box contained a water inlet valve and a built-in 90° V-notch weir. Water was pumped into the weir box through a 6 inch diameter water main leading from the sump. A metal extension was added to the front of the weir box in order to provide a flexible connection for the trough.

(4) Grid - With the trough in place a 14 ft x 10 ft grid was painted on the concrete floor; so that the centre line of



Model layout

PHOTOGRAPH 16



Closeup of grid

PHOTOGRAPH 17

the grid was in line with the centre line of the trough. The grid was divided into 1 foot squares with both the horizontal and vertical lines numbered for easier observations.

(5) Color-coded rods - Steel 1/8 inch diameter rods, color coded in calibrations of 2/10 inch, were positioned at specific points on the grid. Taller rods (8 inch) were placed near the mouth of the trough (where larger fan heights were expected), while 6 inch rods were placed elsewhere. Rods were spaced at 2 foot intervals in the vertical direction and 1 foot intervals in the horizontal direction.

(6) Sediment - The sediments used for testing were piled in adjacent areas beside the trough. The sediments were locally supplied calcareous aggregates. The grain size analyses are given in FIGURES F.1 and F.2.

(7) Bridge Crossings - The bridge crossings used consisted of a roadway embankment and a set of guide banks. (For details see FIGURES F.3, F.4, and F.5). The guide banks were constructed of plasticene while the roadway embankments were made of the same sediments used for testing. A stone or rip-rap protection was placed on the upstream sides of the roadway.

A.3 Model Scaling

The only scaling relationship used was an approximate overall gross scaling relationship between sediment size and discharge. Discharges were chosen by trial and error procedure until the model was judged to be performing adequately.

Trough slopes being dimensionless, were chosen from topographic maps of alluvial fans in Alaska. The size of the trough was chosen to allow streamflows to form their own channel within the injected sediments. No scaling relationship was used for the bridge crossings because their relative sizes were not considered critical to the nature of the study.

A.4 Operation and Instrumentation

(1) Discharge - Tests were conducted with both constant discharges and repeated standard hydrographs (FIGURE F.6). Each applied discharge for the standard hydrograph was run for a specific time interval rather than as simultaneous values. The time intervals used were chosen to approximate a steeper rising limb and a lesser sloped recession limb as would normally be found for natural flows.

Discharges were regulated by means of the inlet valve and the rated 90° V-notch weir.

Q model	Height of water (weirbox)
0.005 cfs.	0.361 ft.
0.010 cfs.	0.386 ft.
0.020 cfs.	0.421 ft.

(2) Sediment Injection - a motorized hopper was initially used to inject sediment into the trough; so that the rate of input could be regulated with the applied discharge. This method was found to be inadequate, however, as the quantities of dry sand initially used had to be re-used as wet sand. As a result, sediment was injected by hand. The rate of injection was increased or decreased as consistently as possible with the respective increase or decrease in discharge. The amount of sediment injected during a particular discharge interval was measured

by means of a 2 ft x 2 ft x 2 ft wooden box. By recording initial and final depths, the volume of sediment and thus the weight of sediment was determined.

(3) Depths - The color coded rods placed in the concrete floor provided permanent station measurements of fan depths. A calibrated brass rod was also used to record any additional measurements required.

(4) Bridge Locations - Each of the bridge details used was located at the farthest downstream point on the fan at which a reasonably well-defined channel was found. The crossings were placed perpendicular to the direction of flow. Prior to each application, a standard hydrograph was run on the model in order to regrade the fan surface of previous tests.

A.5 Miscellaneous Observations and Measurements

A number of additional observations were noted during the operation of the model. Sediment sorting, sediment transport by streams and their depositional patterns were visually assessed. Observations of channel patterns, lateral channel shifting and areal fan growth were mapped after each particular discharge interval. To aid in these observations, purple dye was placed in the streams and photographs were used to provide a permanent visual record.

APPENDIX B

TESTING PROGRAM

Phase	Test No.	Trough Slope	Sediment Used	Process	Additional remarks	Test results reference
Alluvial fan development	1	0.115	gravel	constant Q = .01 cfs and constant sediment input	——	Appendix C
	2		mortar sand	constant Q = .01 cfs and constant sediment input	——	
	3		gravel	constant Q - .01 cfs and constant sediment input	high water level downstream to simulate trunk river in-flood	
	4		gravel	series of repeated standard hydrographs and corresponding variations in sediment input	——	
River training works	5	0.115	gravel	series of repeated standard hydrographs and corresponding variations in sediment input	bridge detail No. 1 placed on fan surface	Appendix D
	6				bridge detail No. 2 placed on fan surface	
	7				bridge detail No. 3 placed on fan surface	
Fan dissection	8	0.115	gravel	series of repeat standard hydrographs and corresponding variations in sediment input	nose of fan removed and channel guide banks located in trough	Appendix E

Testing program

TABLE B.1

APPENDIX C

TEST RESULTS

(ALLUVIAL FAN DEVELOPMENT)

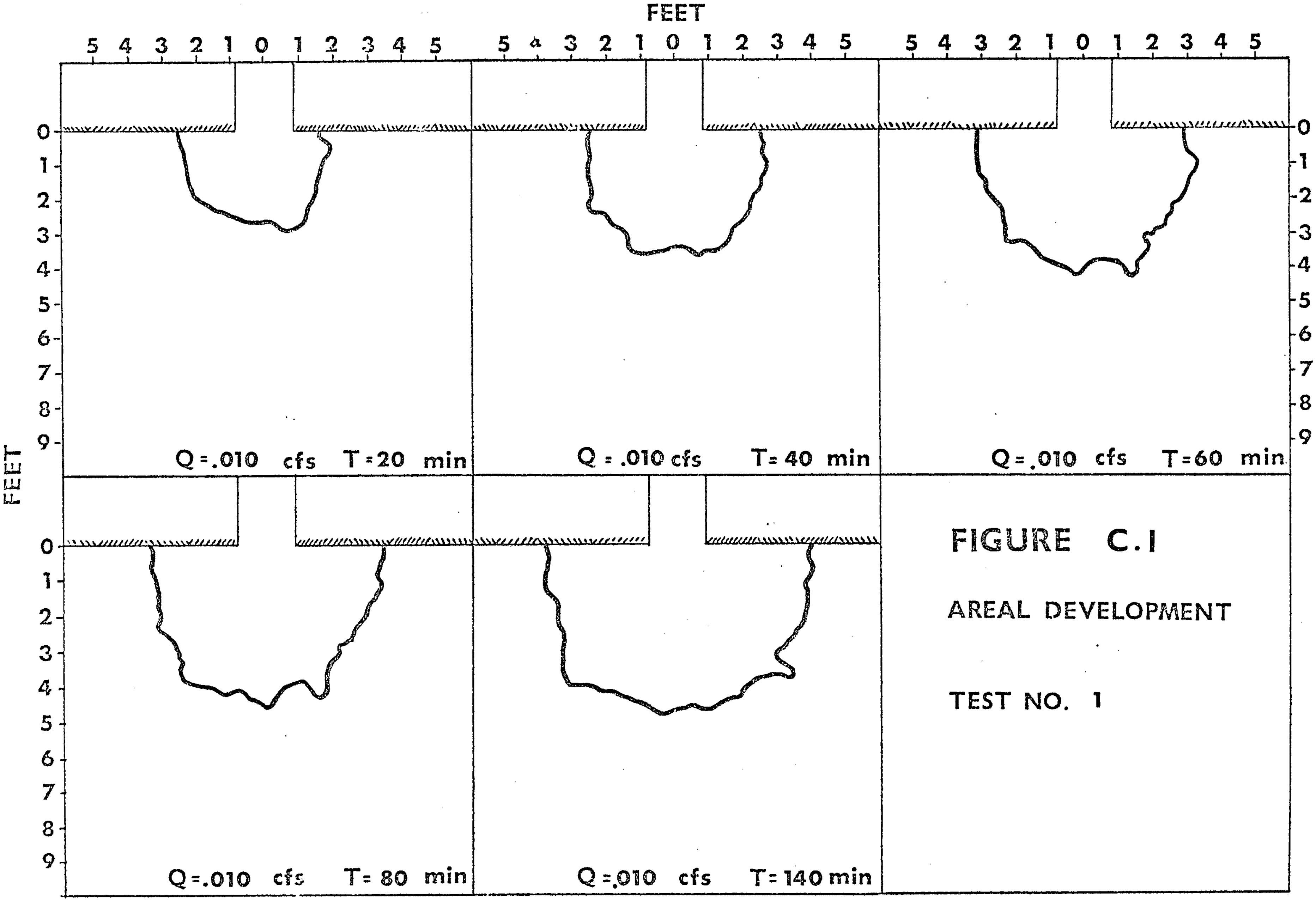


FIGURE C.1

AREAL DEVELOPMENT

TEST NO. 1

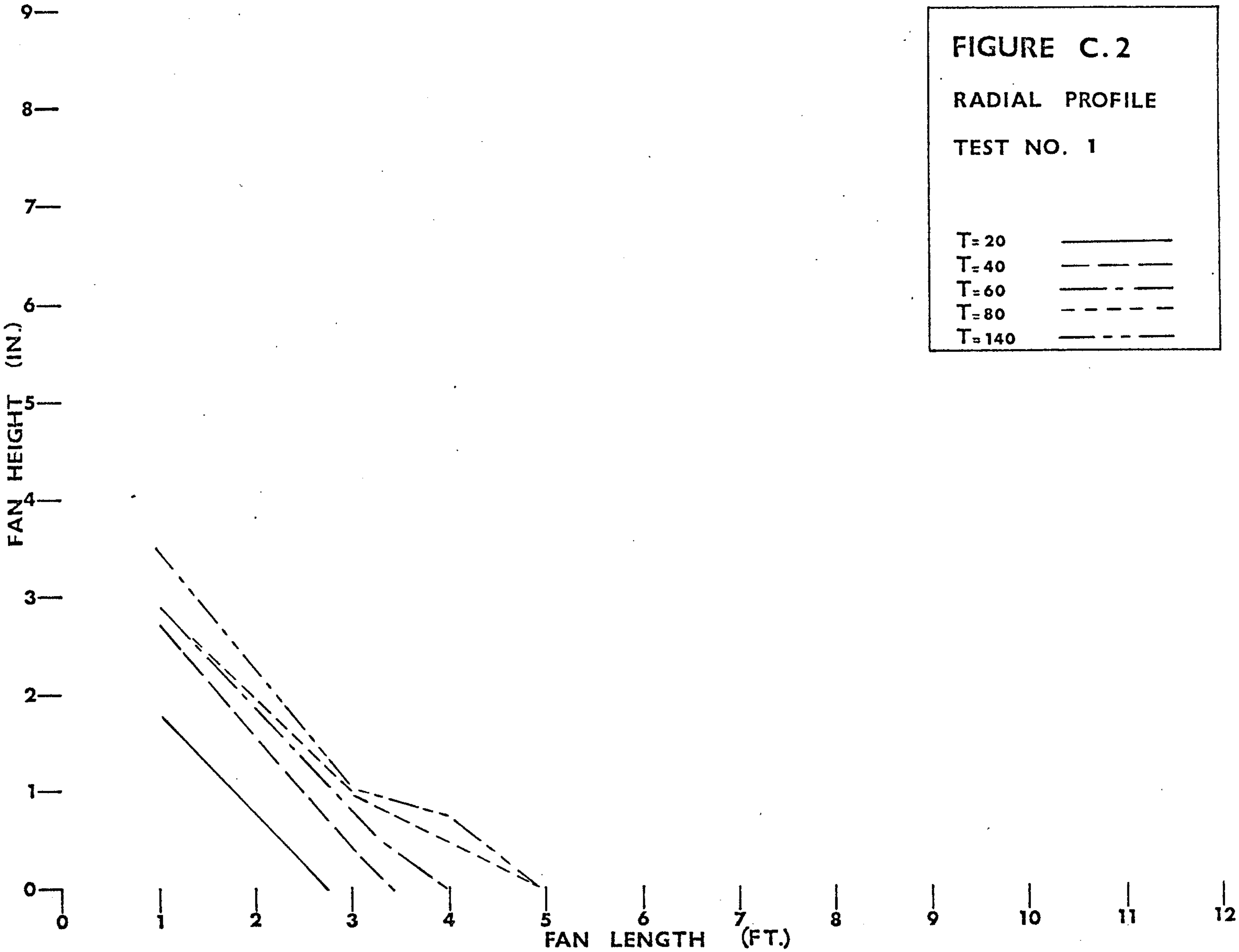


FIGURE C.2

RADIAL PROFILE

TEST NO. 1

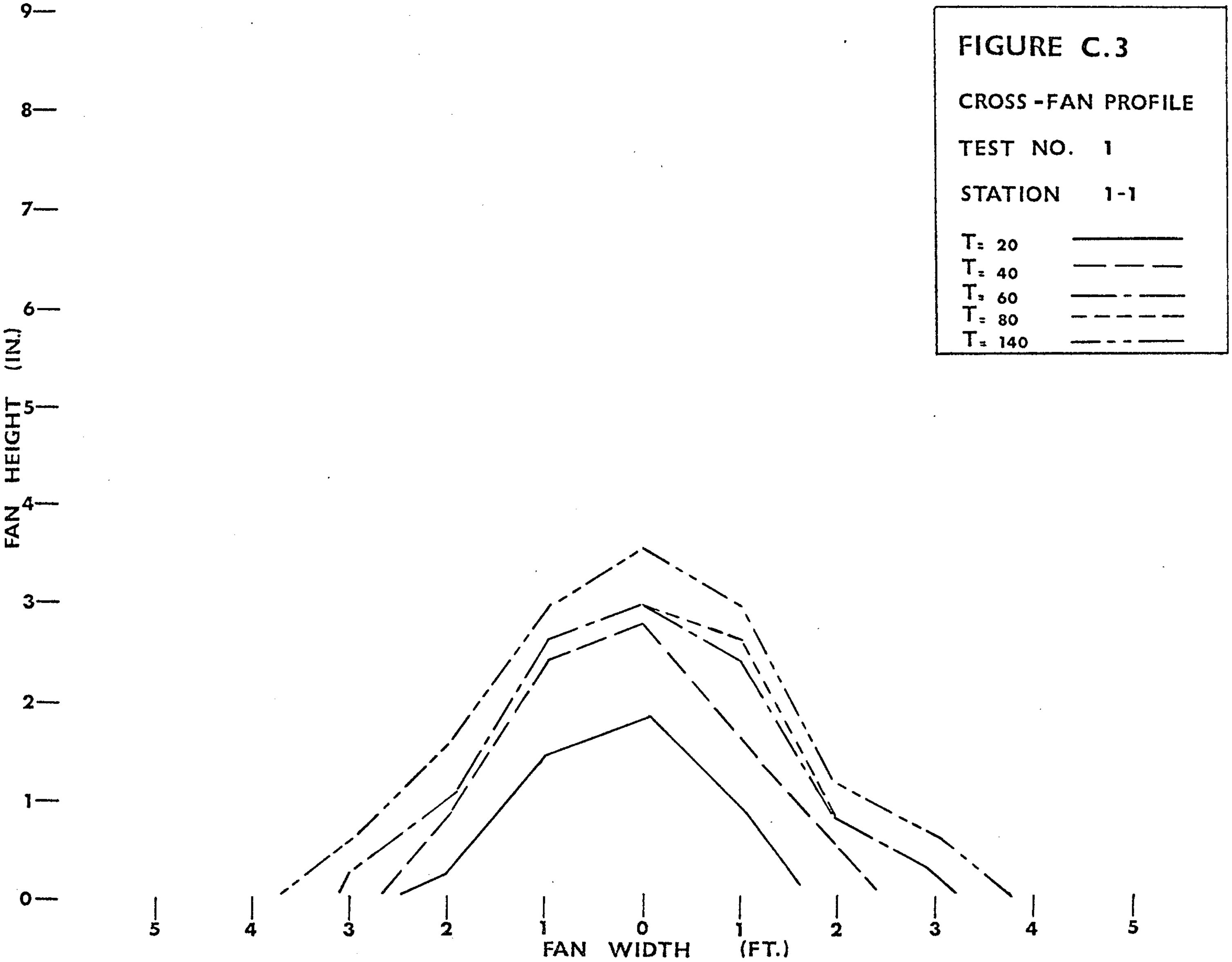


FIGURE C.3

CROSS-FAN PROFILE

TEST NO. 1

STATION 1-1

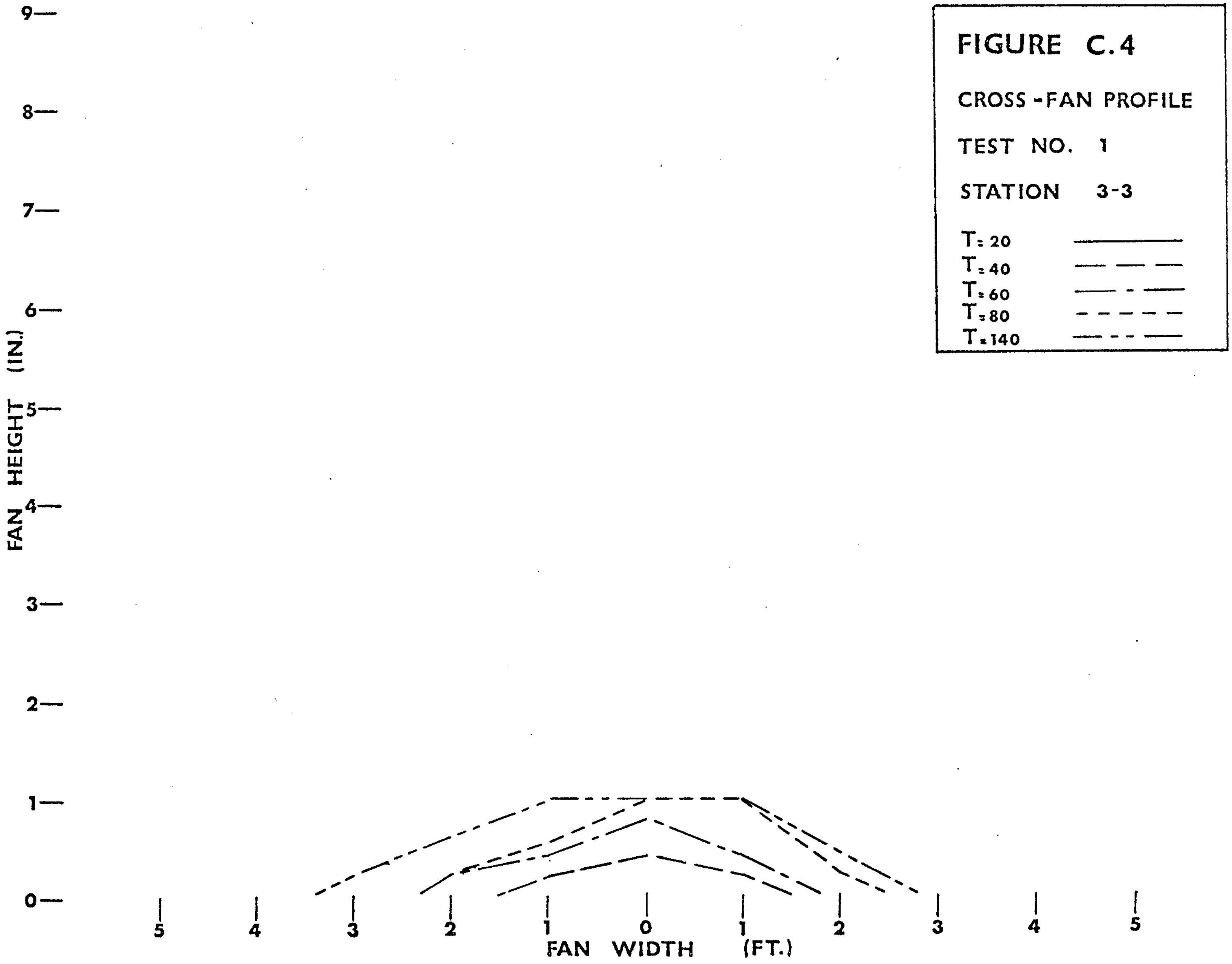


FIGURE C.4

CROSS-FAN PROFILE

TEST NO. 1

STATION 3-3

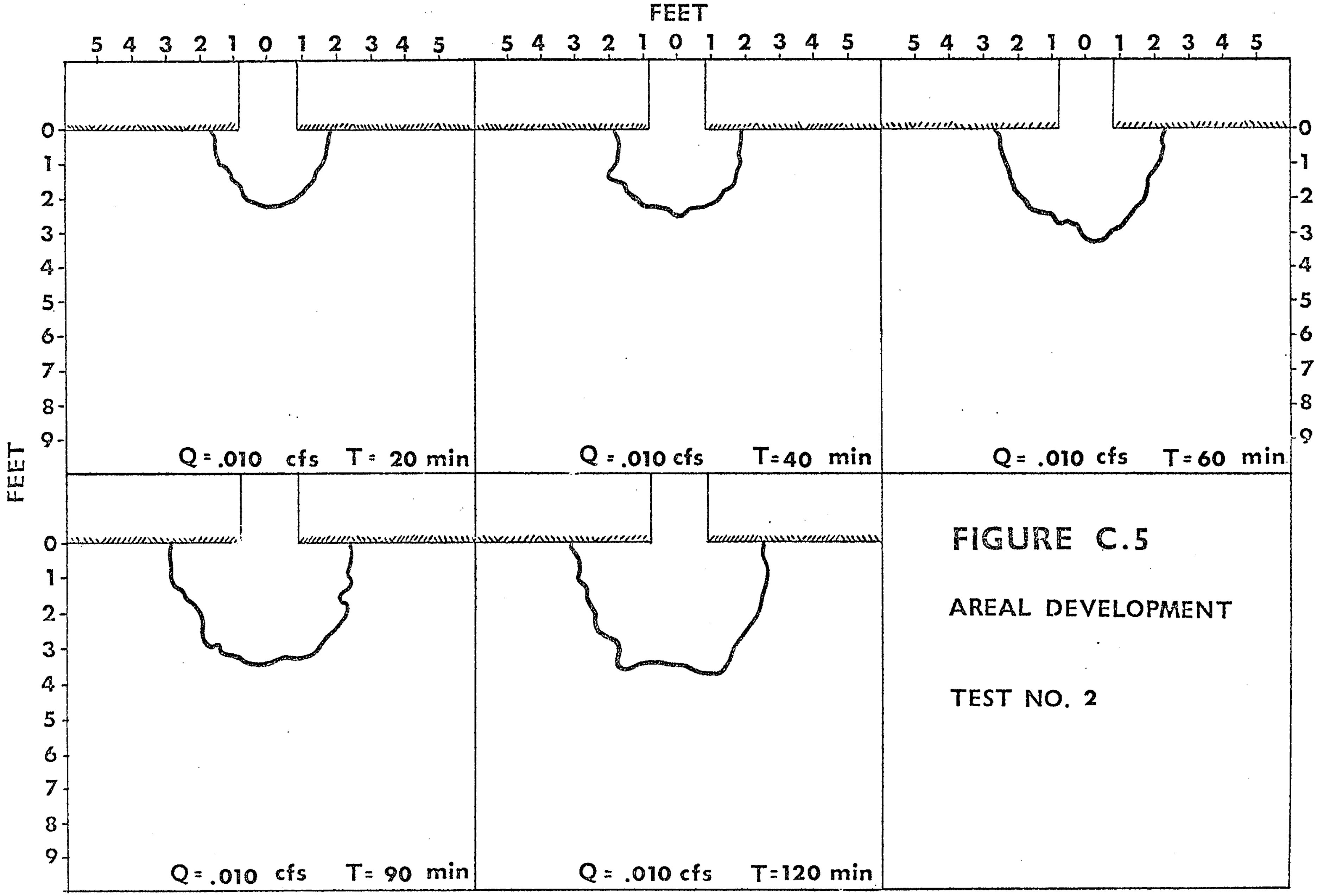


FIGURE C.5

AREAL DEVELOPMENT

TEST NO. 2

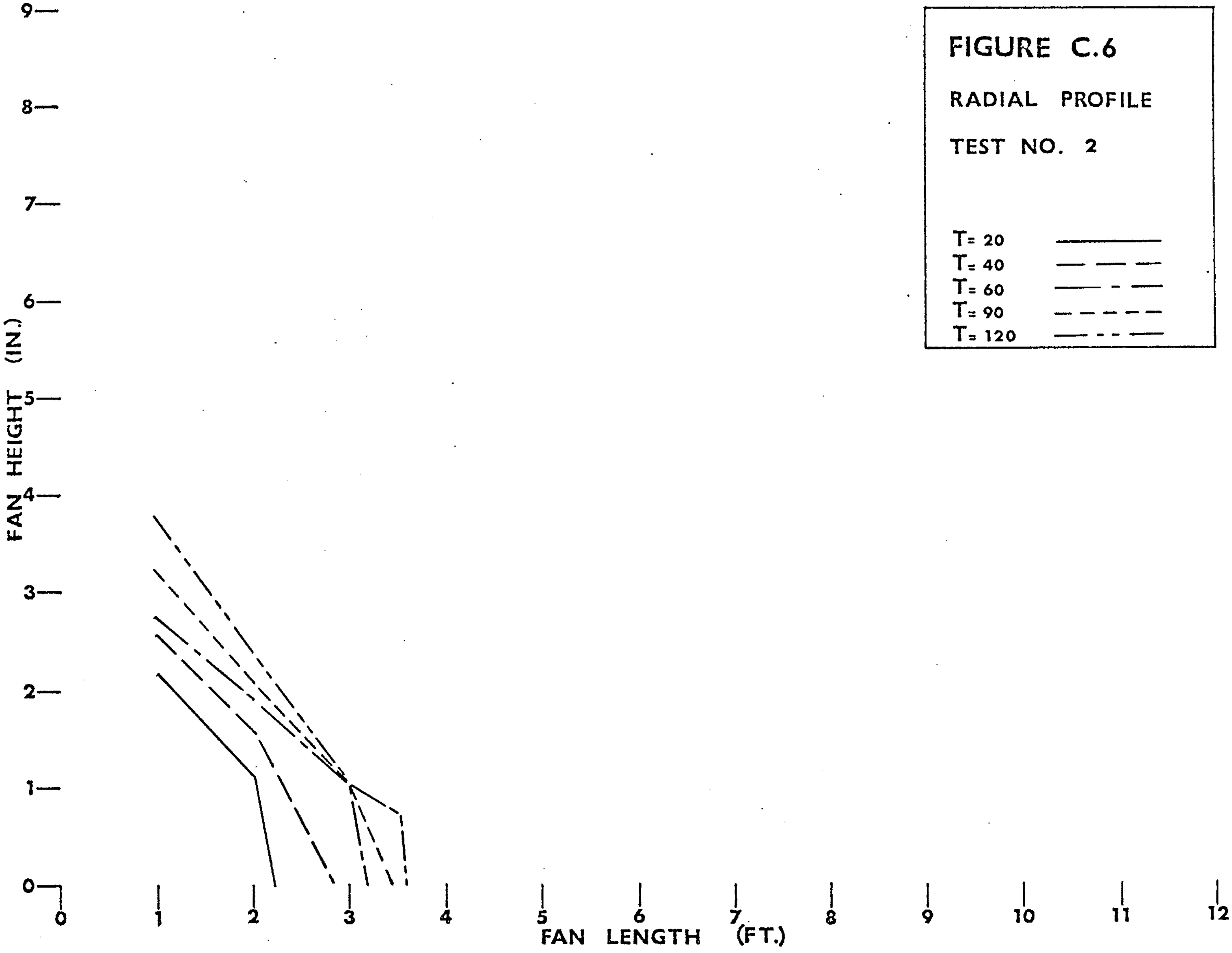


FIGURE C.6

RADIAL PROFILE

TEST NO. 2

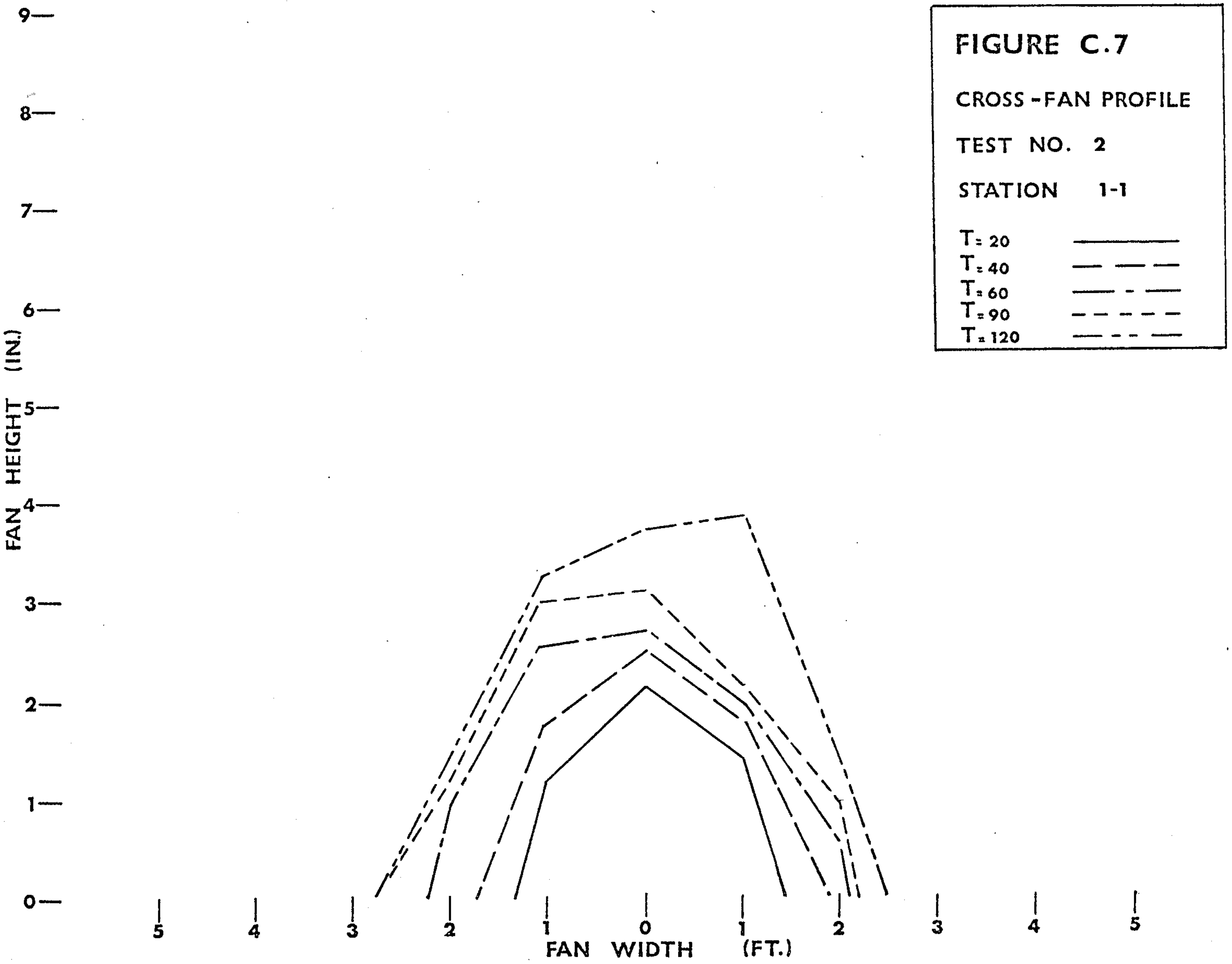


FIGURE C.7

CROSS-FAN PROFILE

TEST NO. 2

STATION 1-1

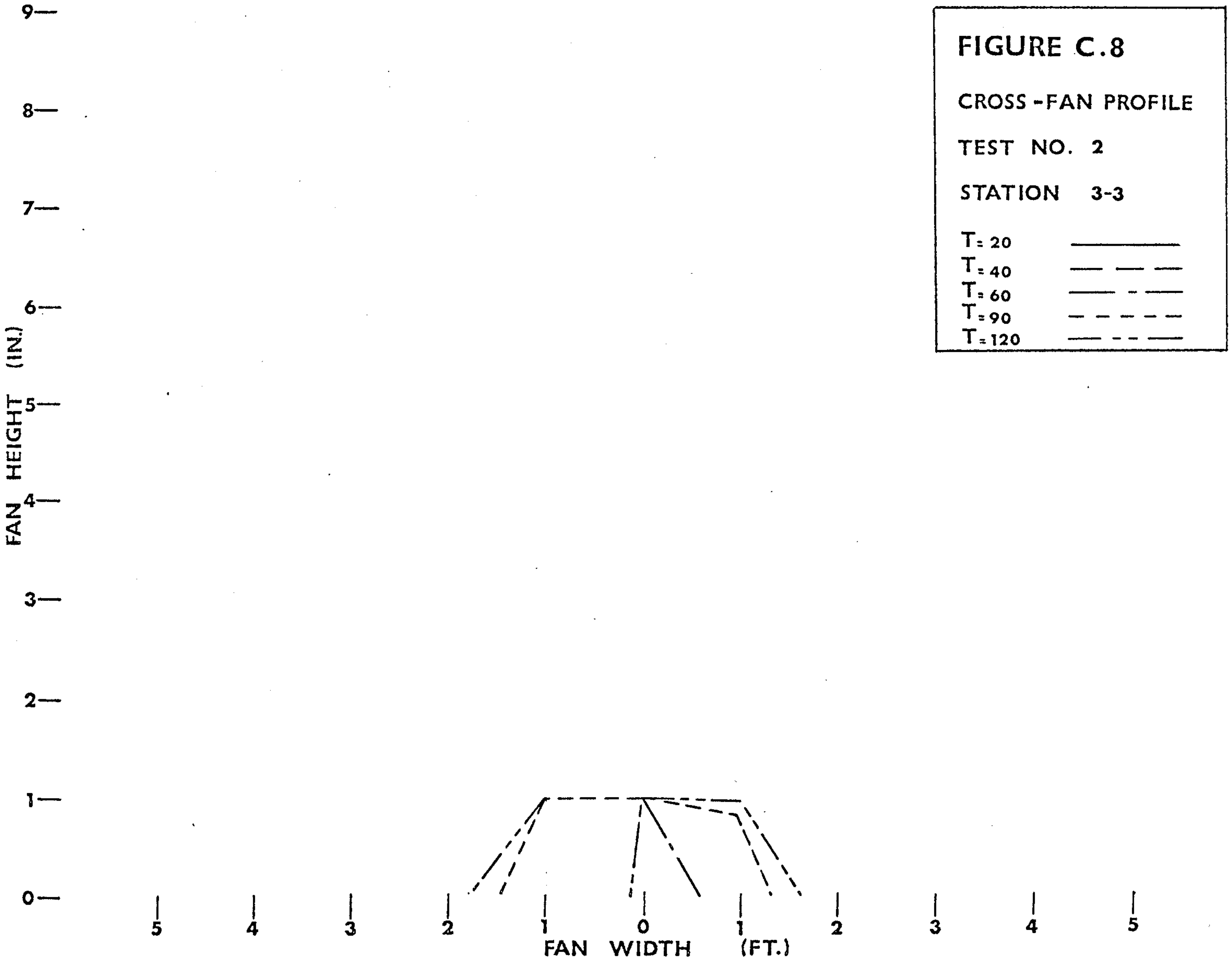


FIGURE C.8

CROSS-FAN PROFILE

TEST NO. 2

STATION 3-3

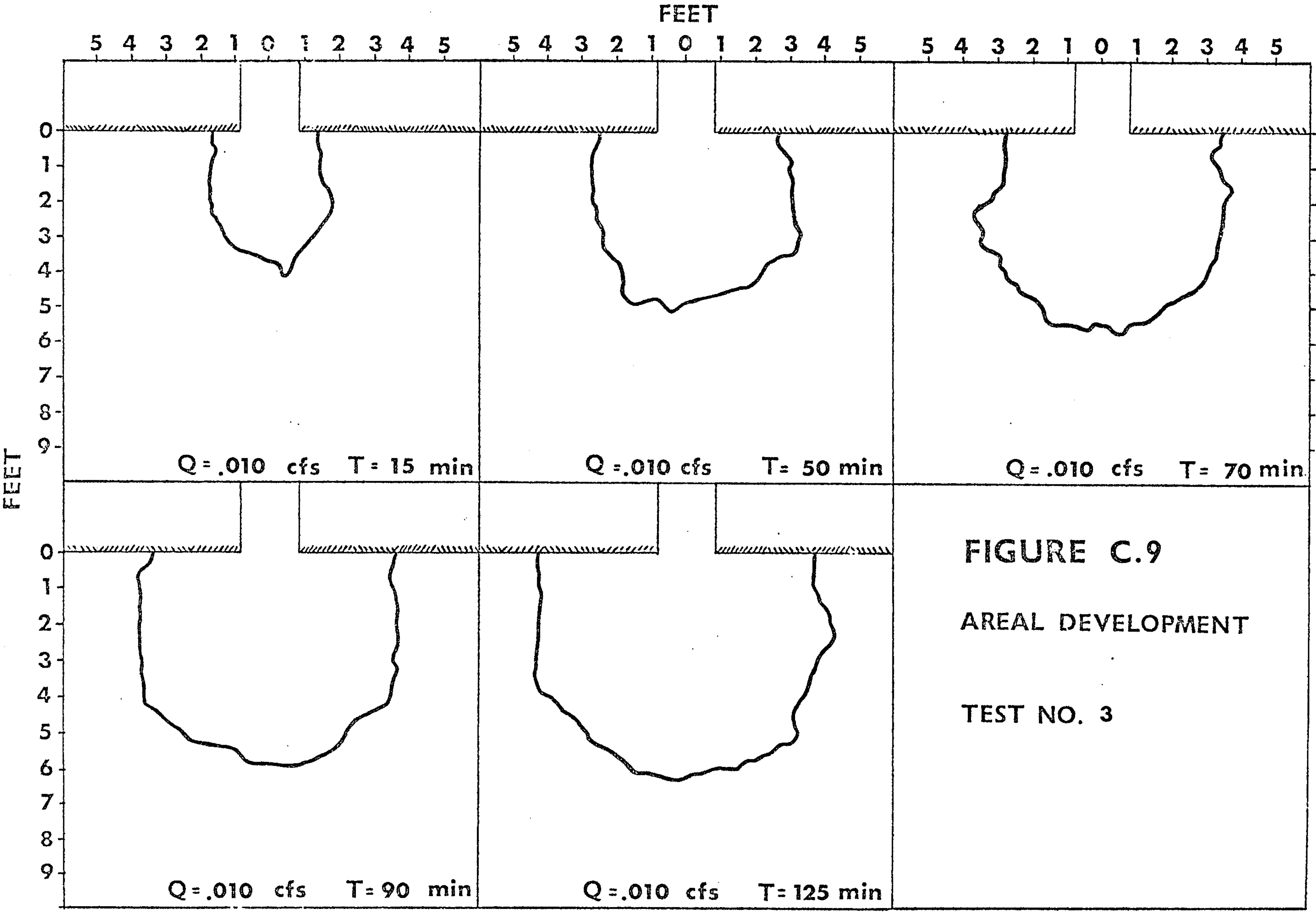


FIGURE C.9

AREAL DEVELOPMENT

TEST NO. 3

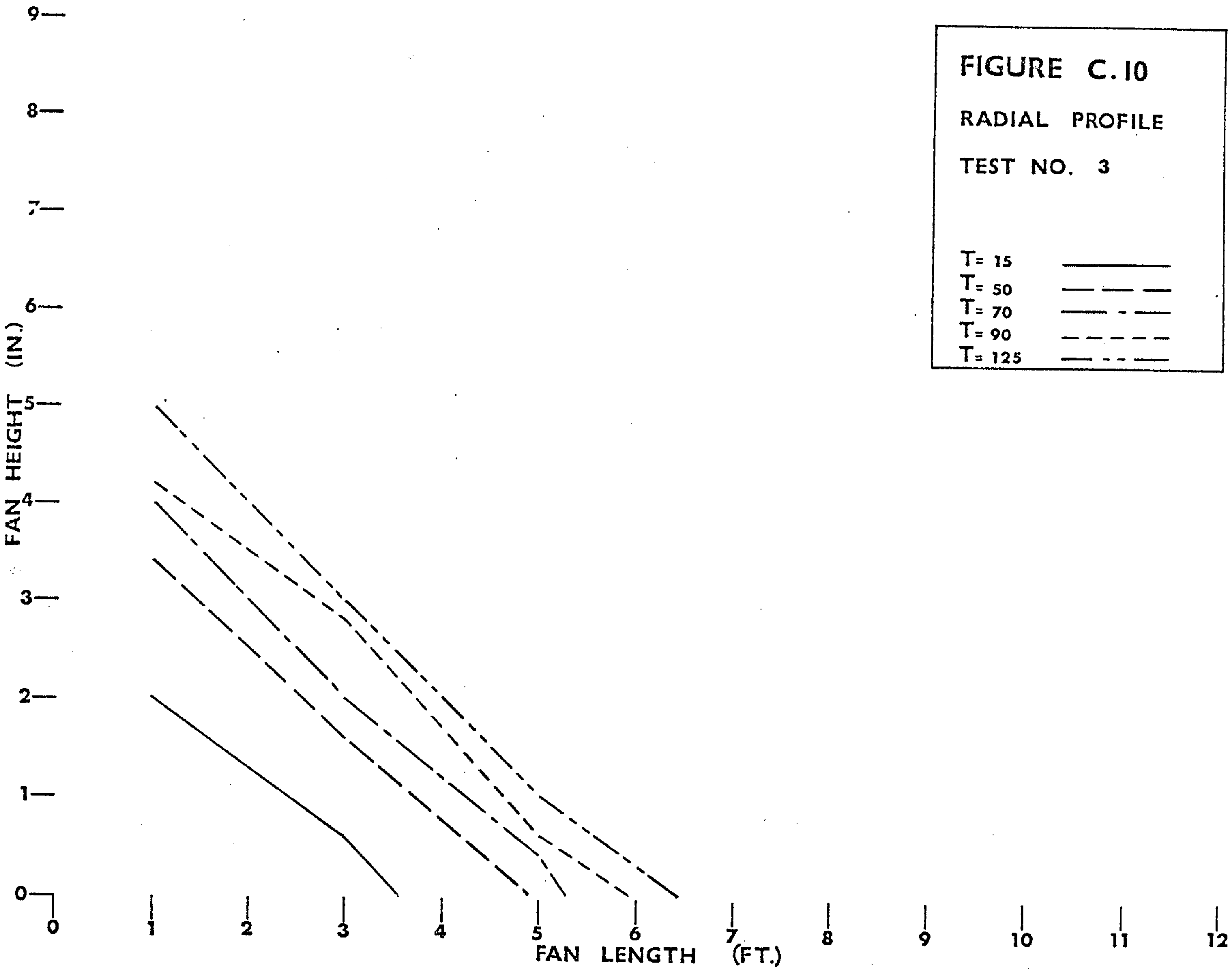


FIGURE C.10

RADIAL PROFILE

TEST NO. 3

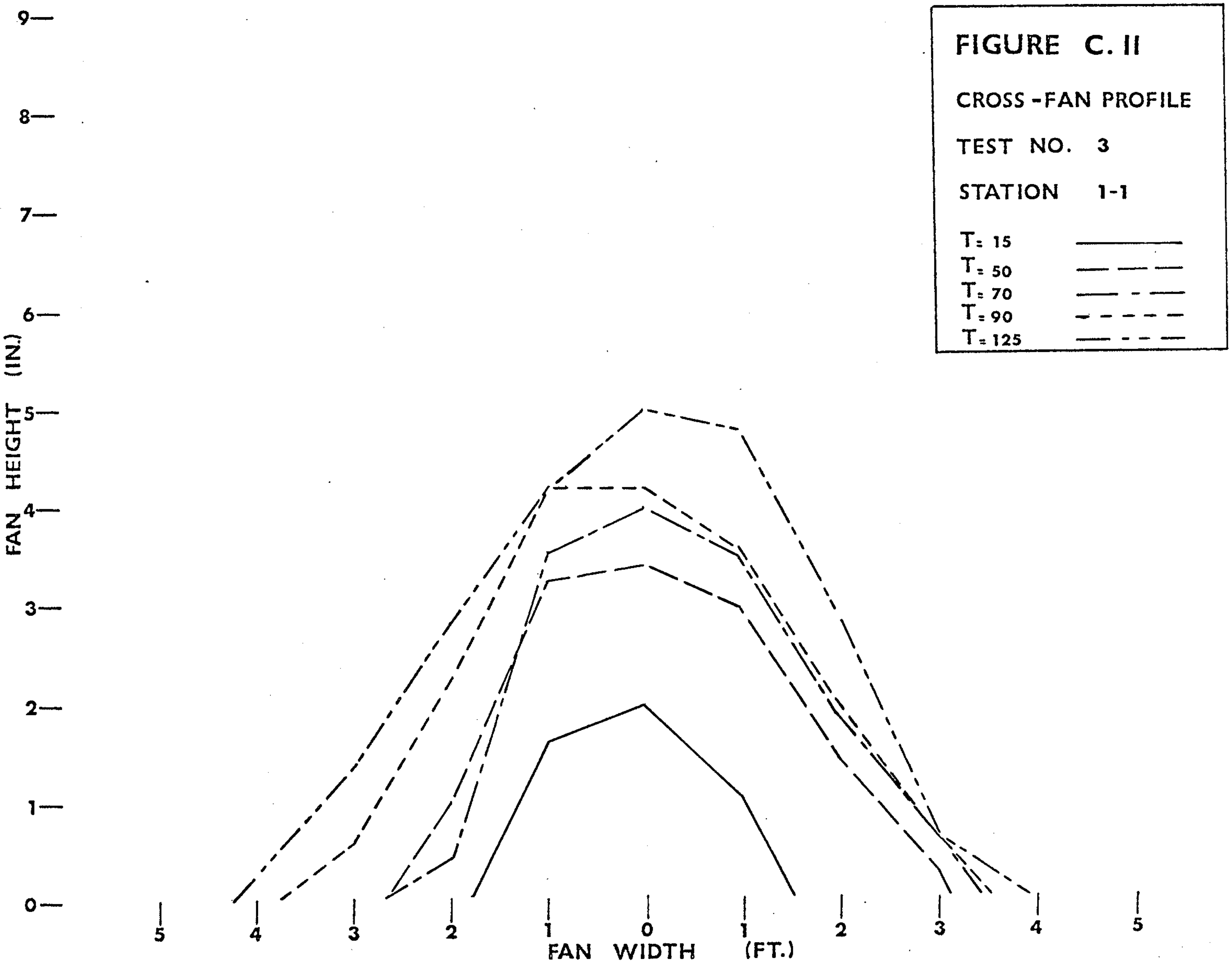


FIGURE C. II

CROSS-FAN PROFILE

TEST NO. 3

STATION 1-1

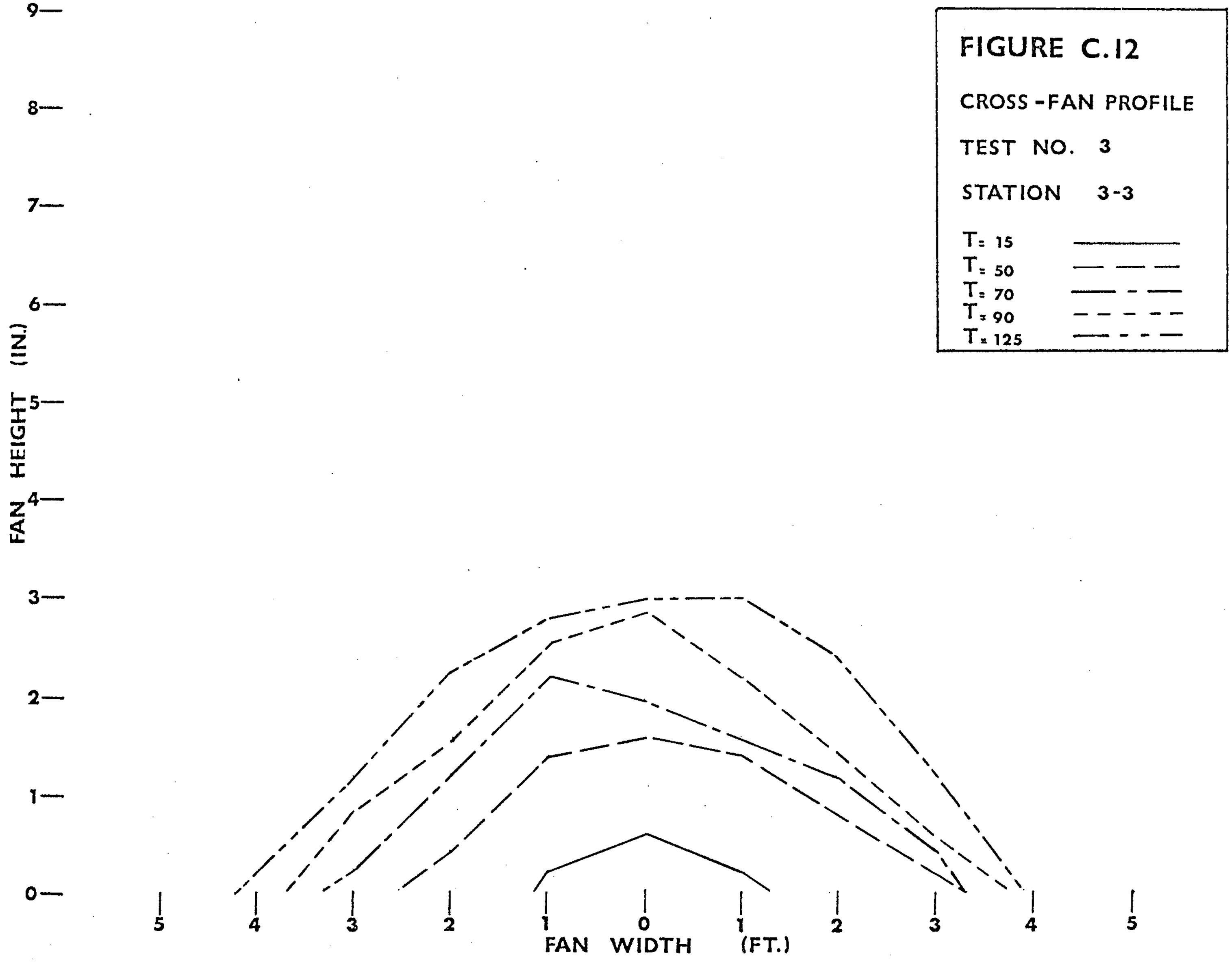


FIGURE C.12

CROSS-FAN PROFILE

TEST NO. 3

STATION 3-3

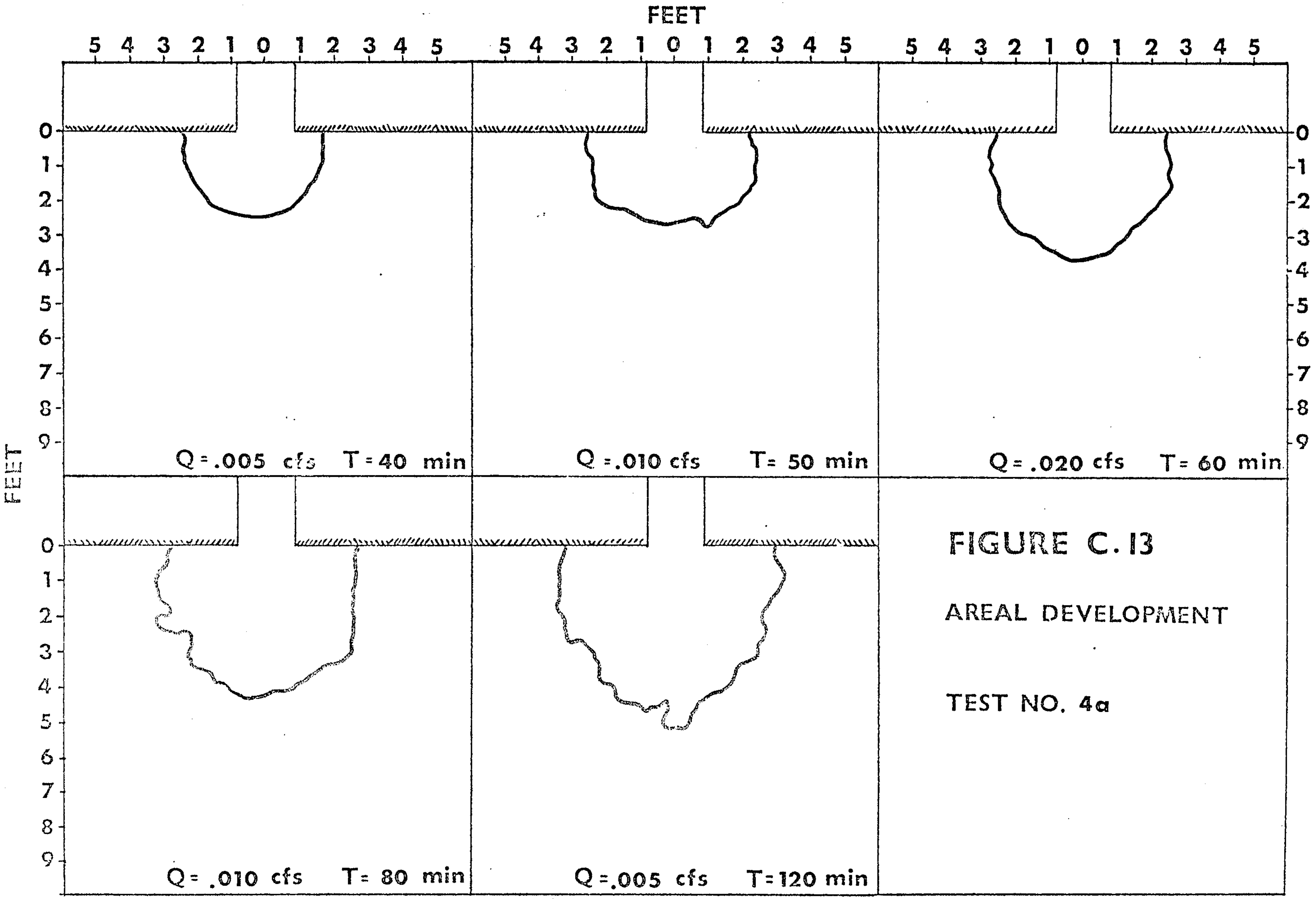


FIGURE C.13

AREAL DEVELOPMENT

TEST NO. 4a

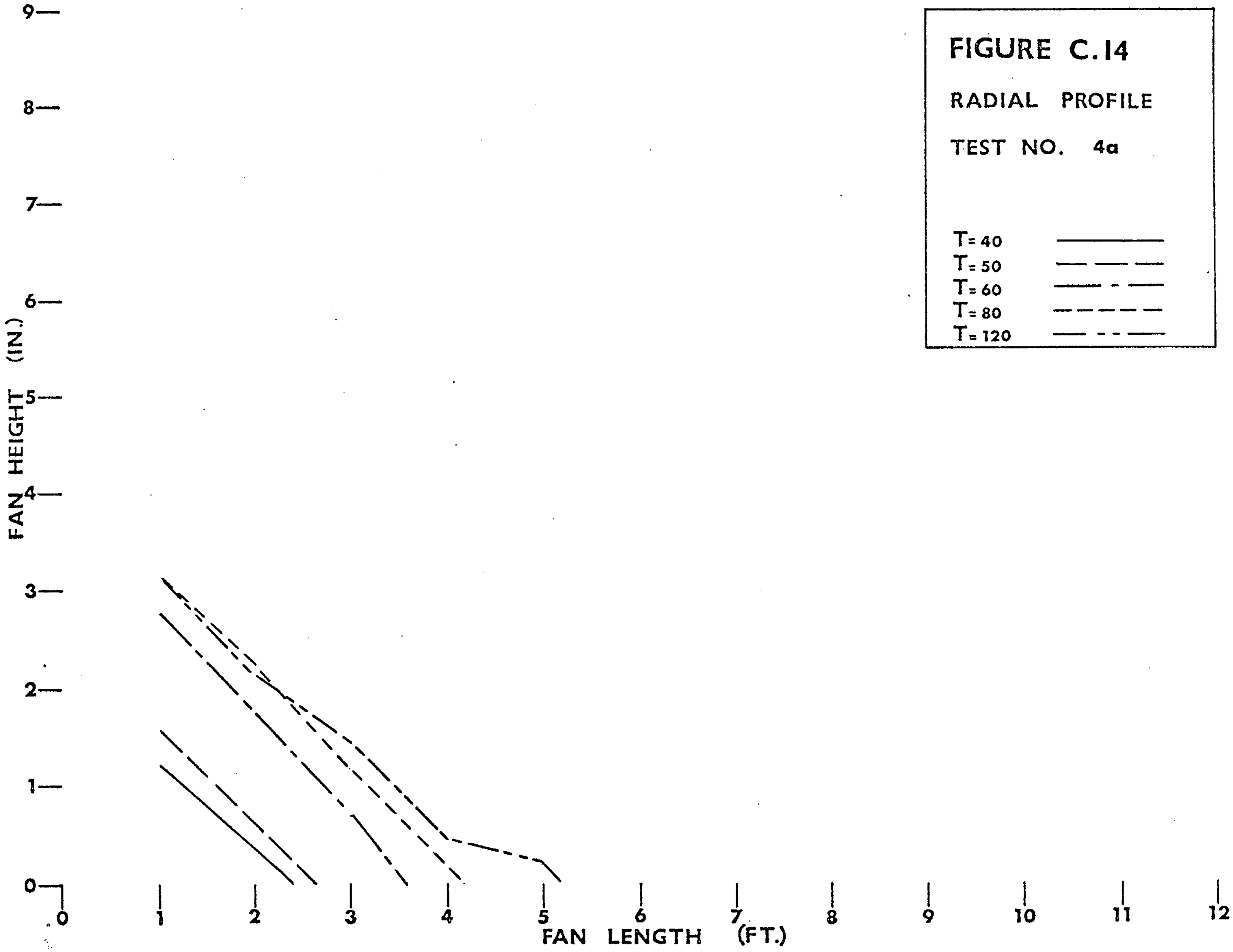


FIGURE C.14

RADIAL PROFILE

TEST NO. 4a

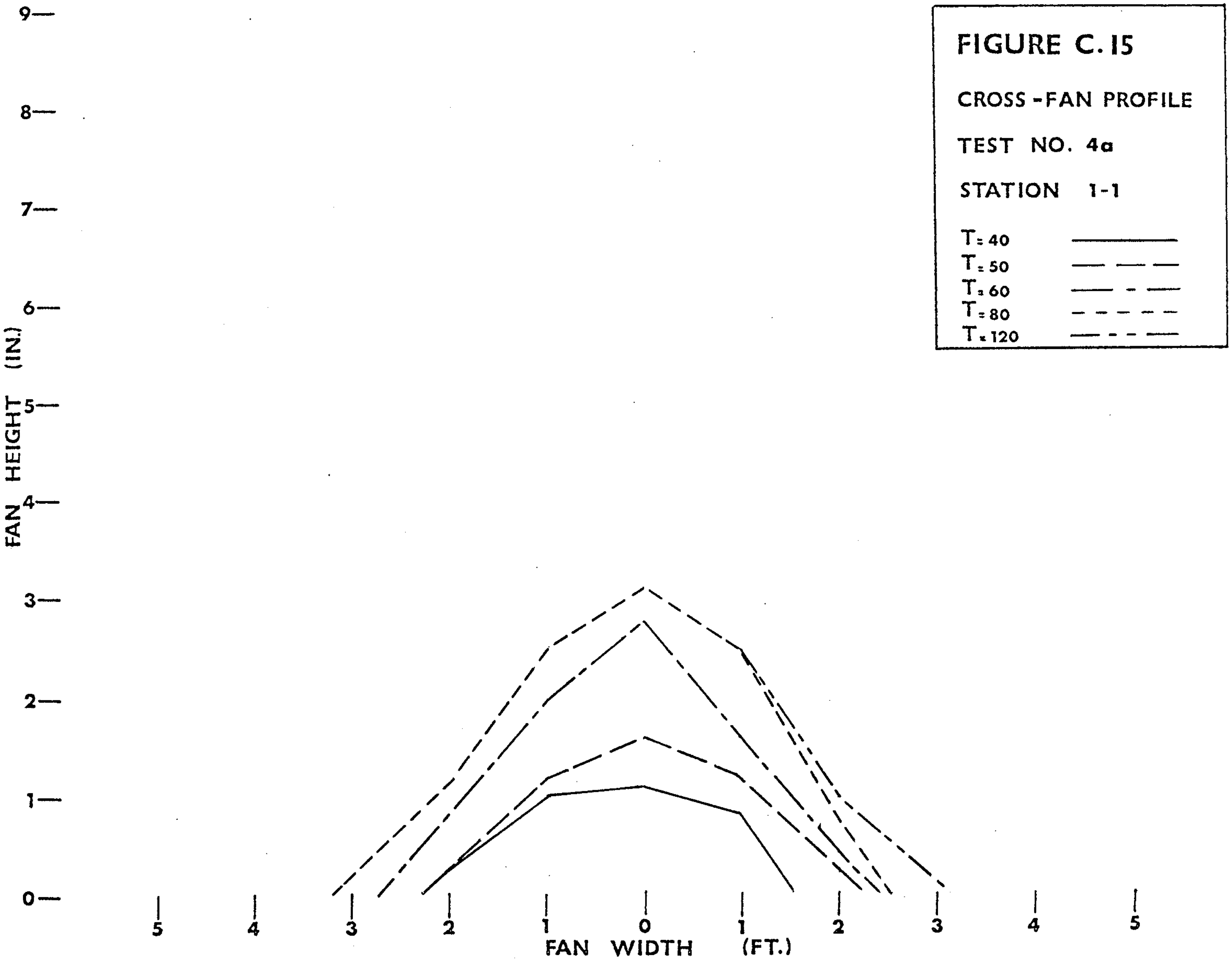


FIGURE C. 15

CROSS - FAN PROFILE

TEST NO. 4a

STATION 1-1

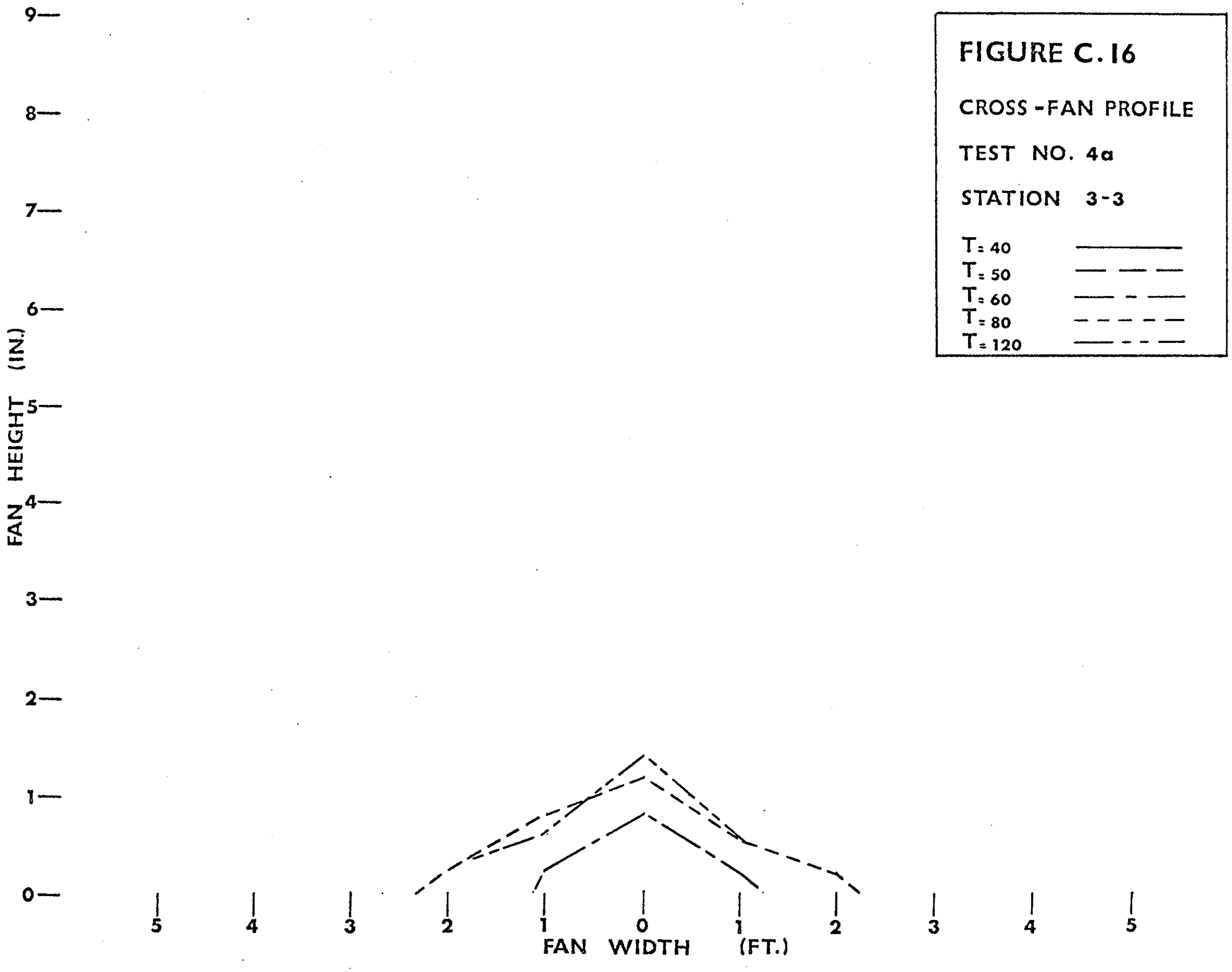


FIGURE C.16

CROSS-FAN PROFILE

TEST NO. 4a

STATION 3-3

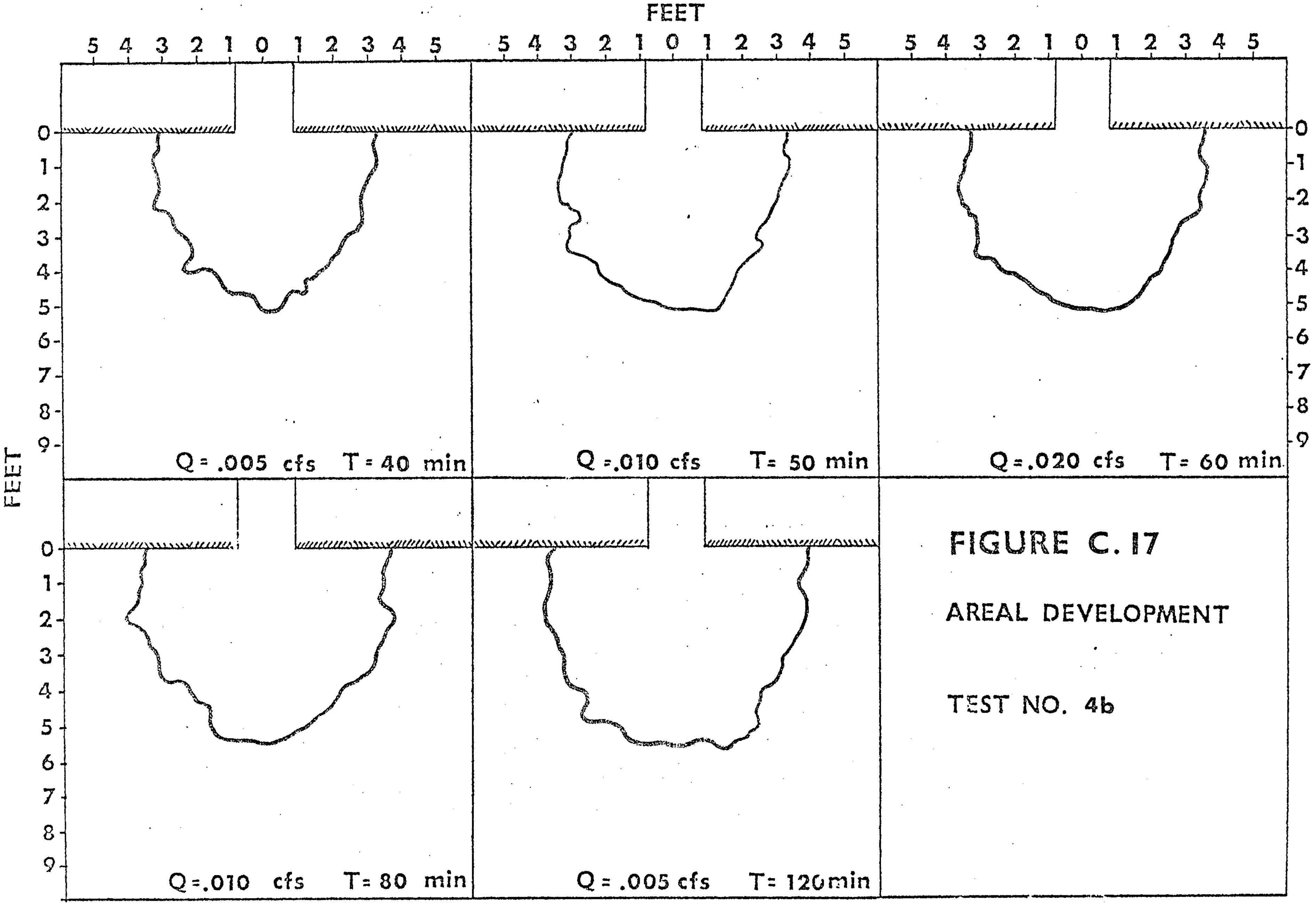


FIGURE C. 17

AREAL DEVELOPMENT

TEST NO. 4b

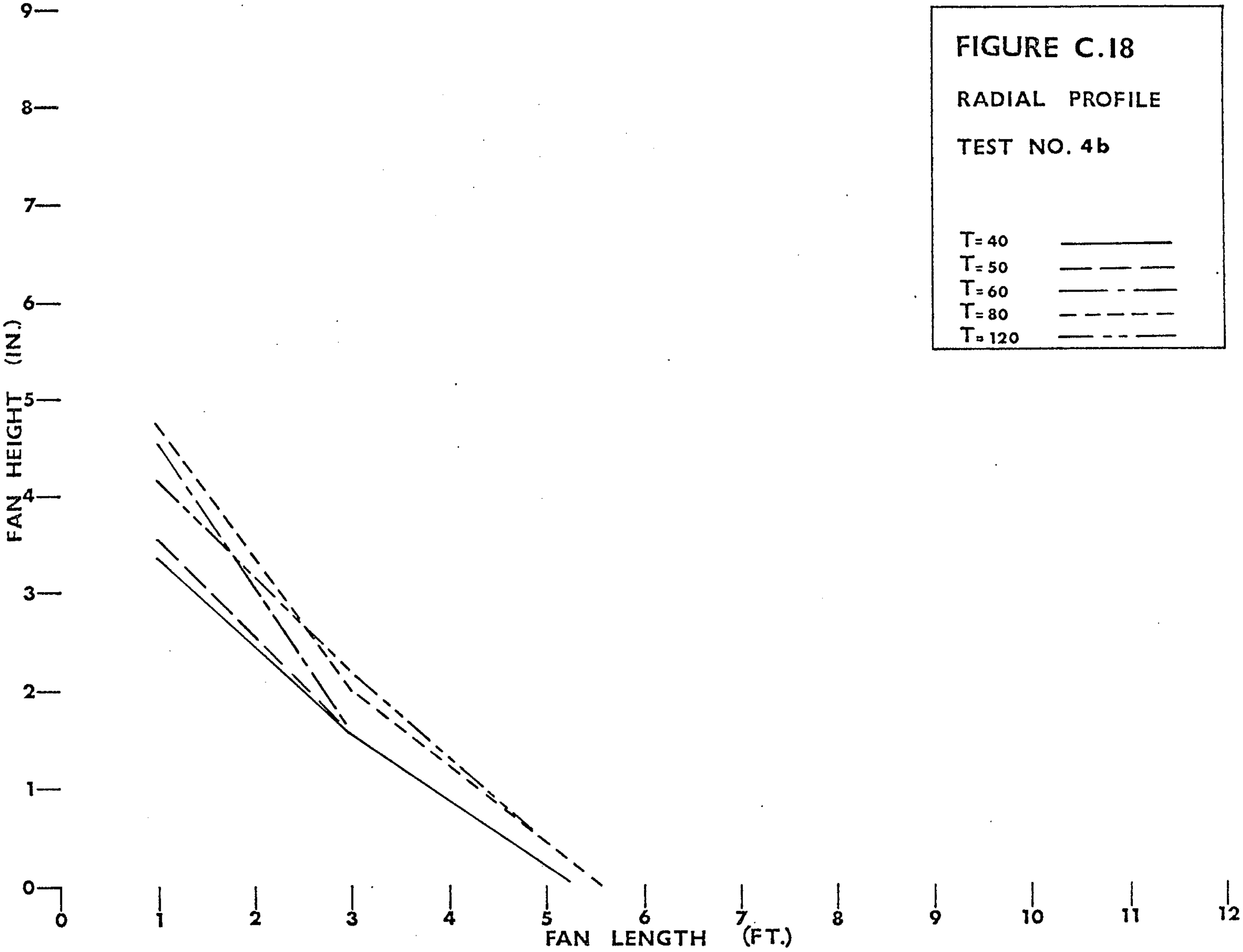


FIGURE C.18

RADIAL PROFILE

TEST NO. 4b

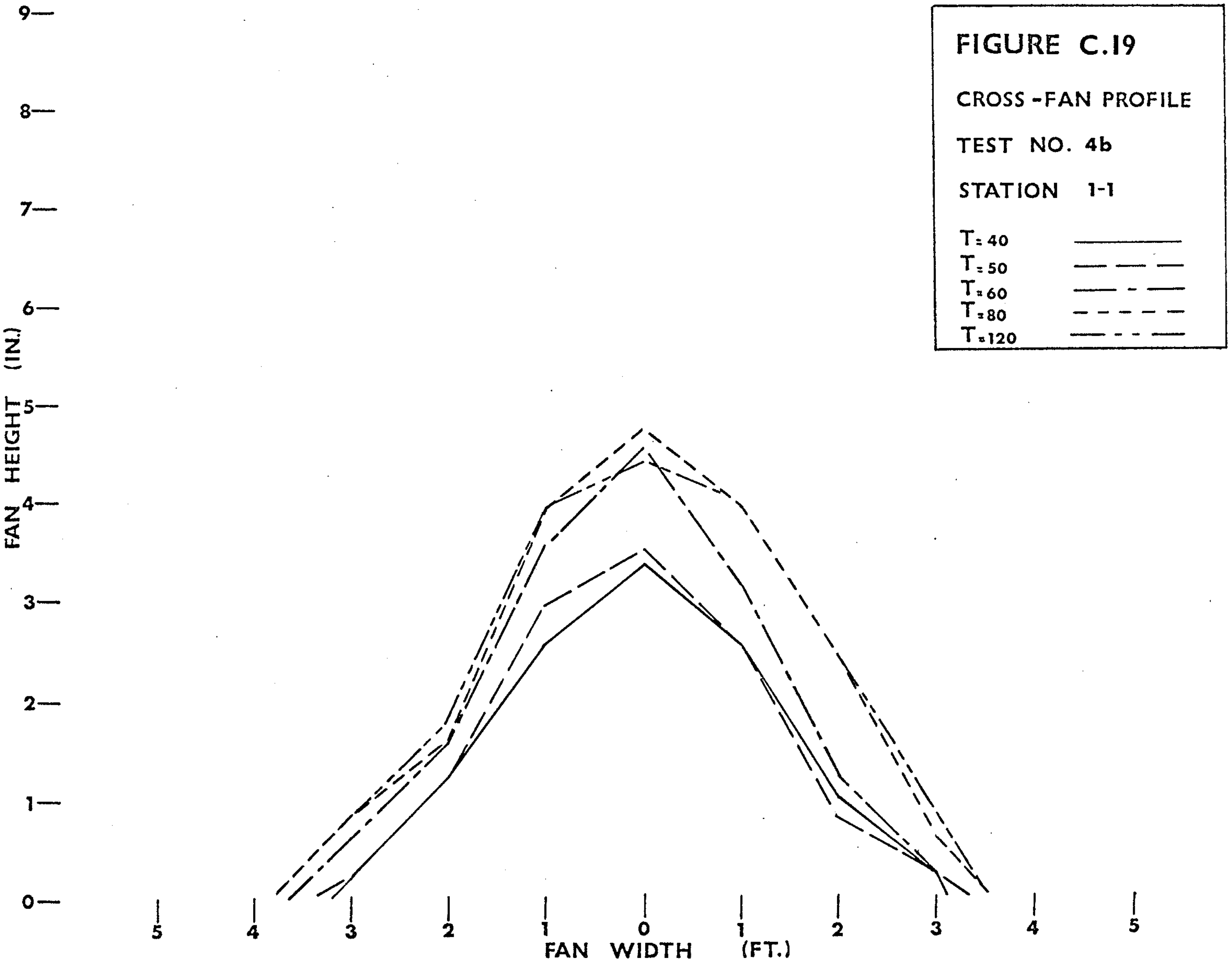


FIGURE C.19

CROSS-FAN PROFILE

TEST NO. 4b

STATION 1-1

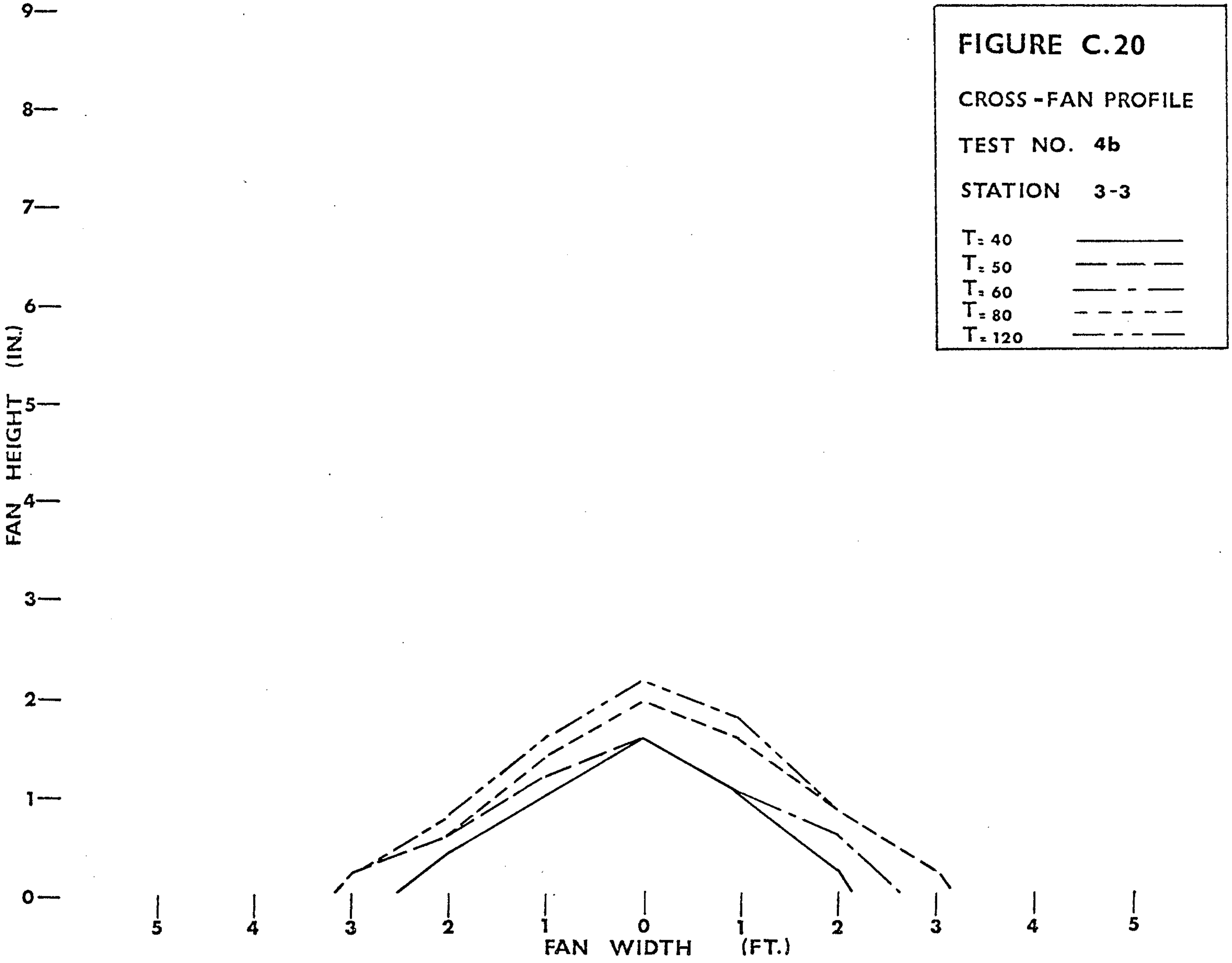


FIGURE C.20
CROSS-FAN PROFILE
TEST NO. 4b
STATION 3-3
T= 40
T= 50
T= 60
T= 80
T= 120
FAN HEIGHT (IN.)
0
1
2
3
4
5
6
7
8
9
5
4
3
2
1
0
1
2
3
4
5
FAN WIDTH (FT.)

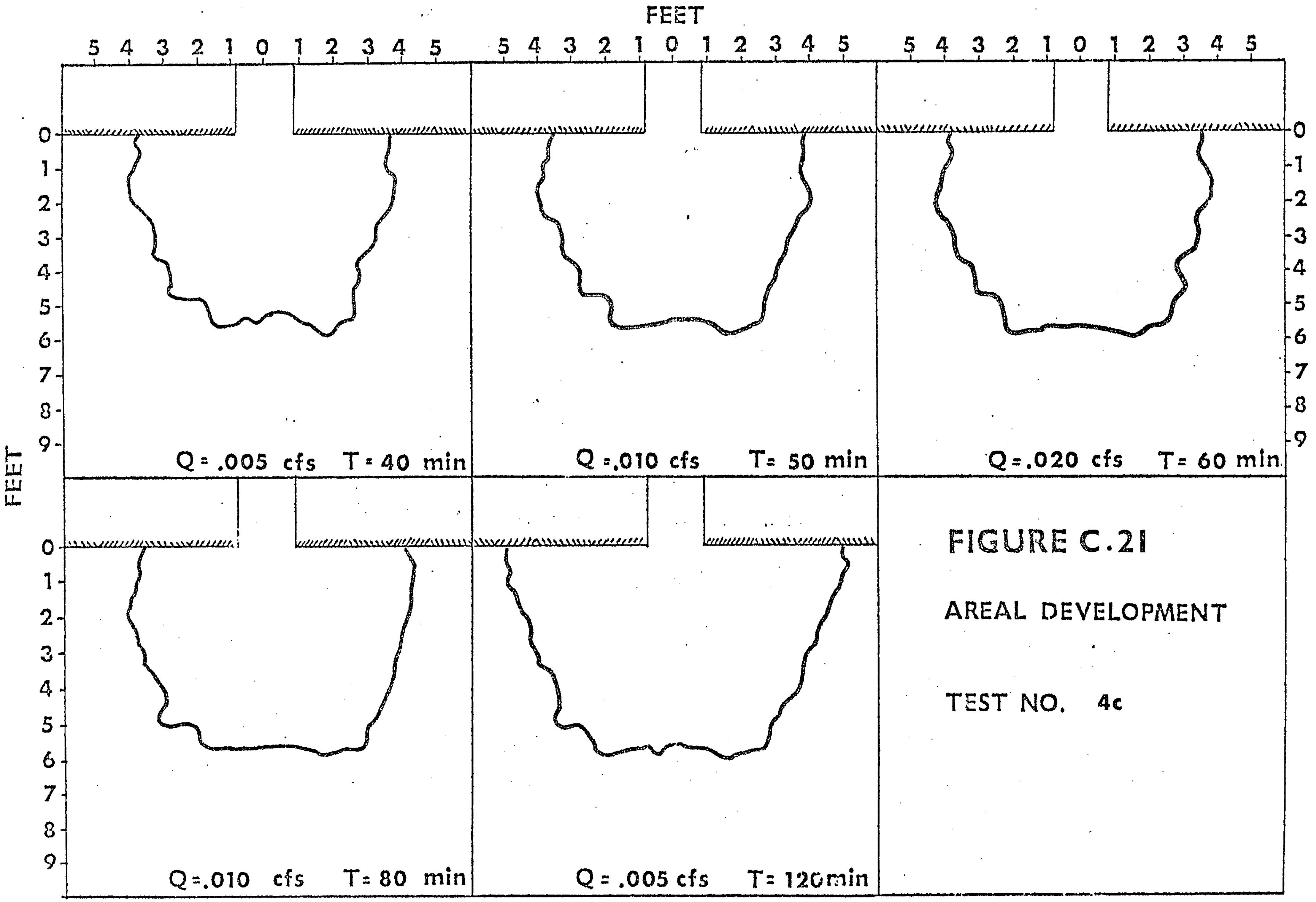


FIGURE C.21

AREAL DEVELOPMENT

TEST NO. 4c

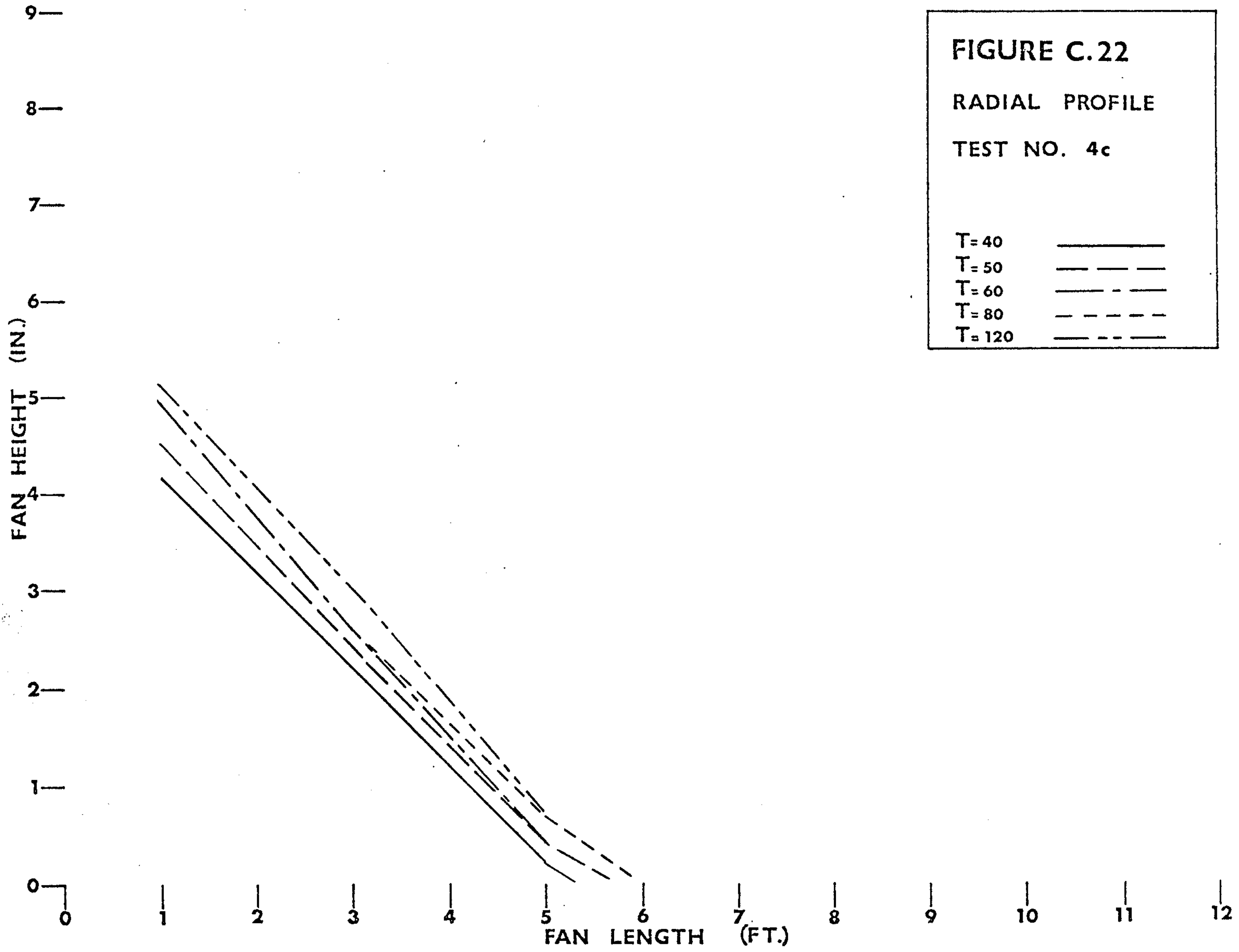


FIGURE C.22

RADIAL PROFILE

TEST NO. 4c

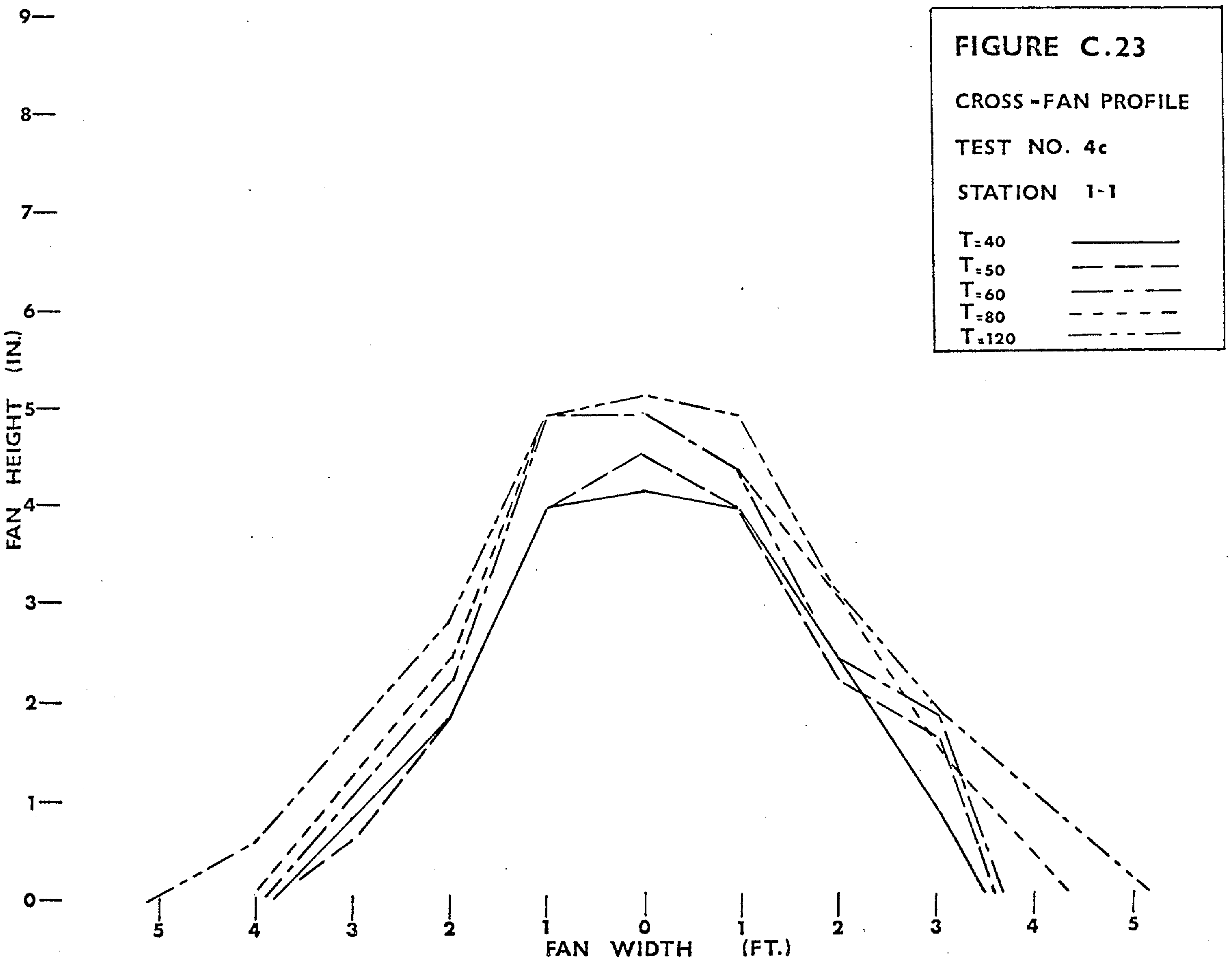


FIGURE C.23

CROSS-FAN PROFILE

TEST NO. 4c

STATION 1-1

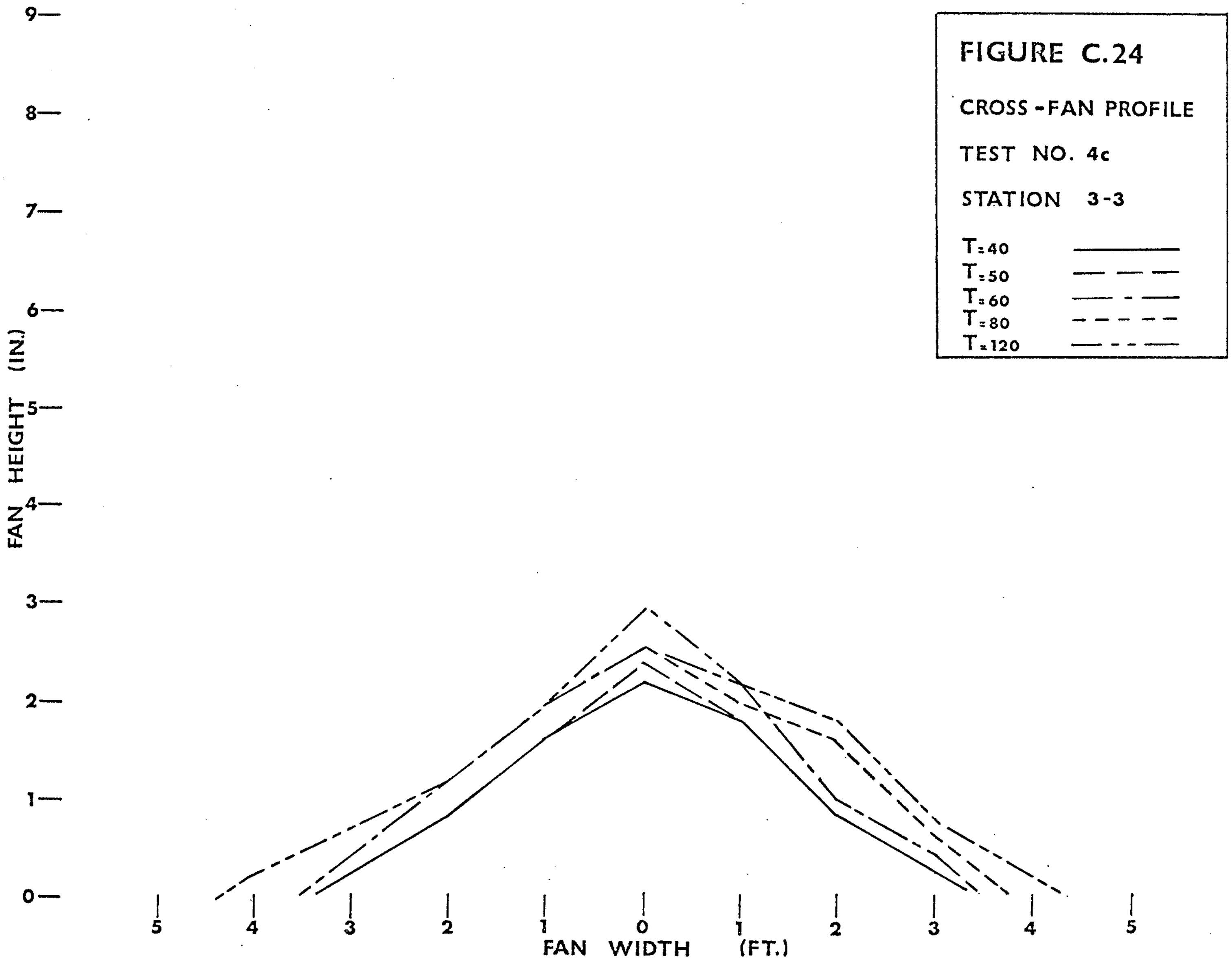


FIGURE C.24

CROSS-FAN PROFILE

TEST NO. 4c

STATION 3-3

APPENDIX D

TEST RESULTS

(RIVER TRAINING WORKS)

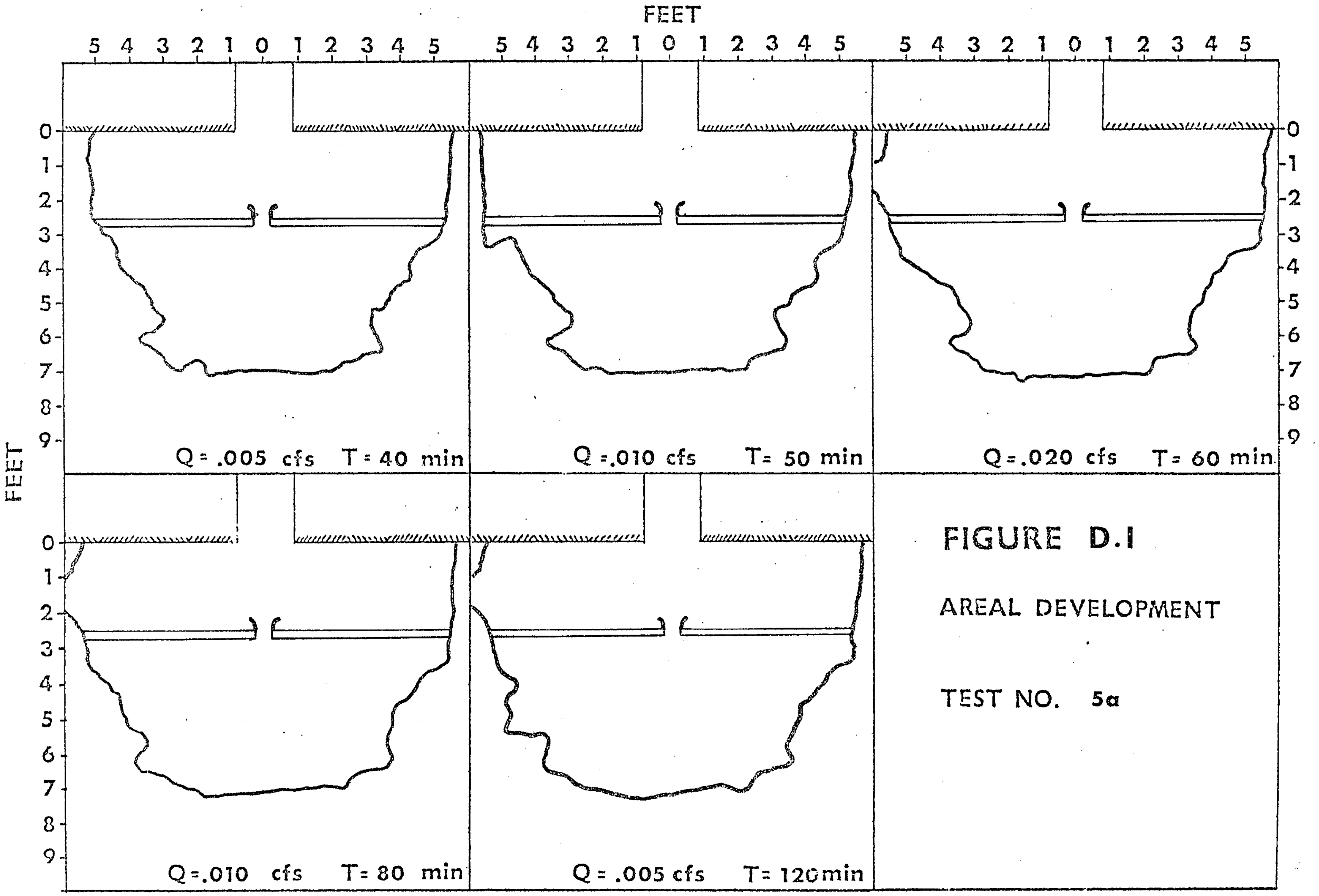


FIGURE D.I

AREAL DEVELOPMENT

TEST NO. 5a

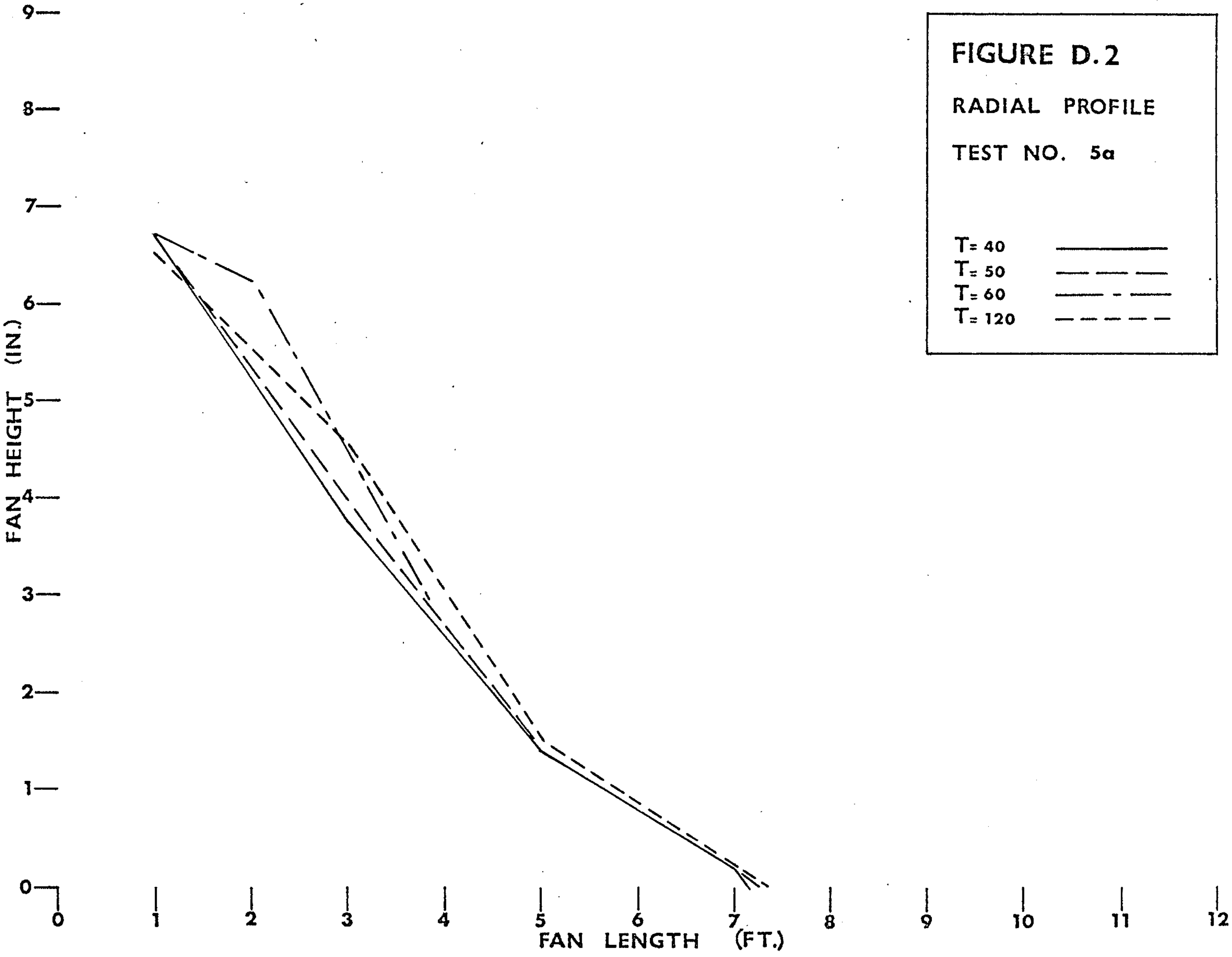


FIGURE D.2

RADIAL PROFILE

TEST NO. 5a

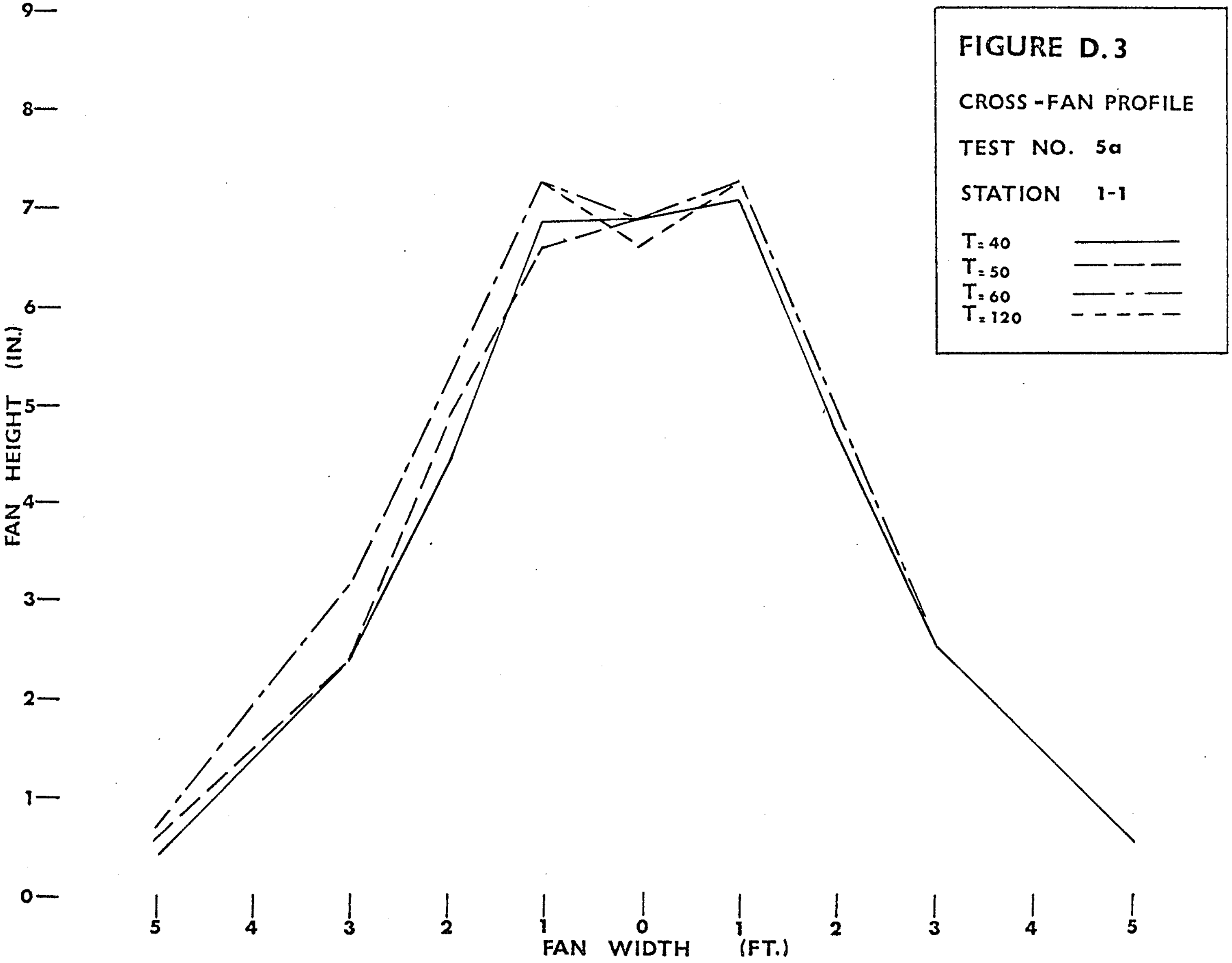


FIGURE D.3

CROSS-FAN PROFILE

TEST NO. 5a

STATION 1-1

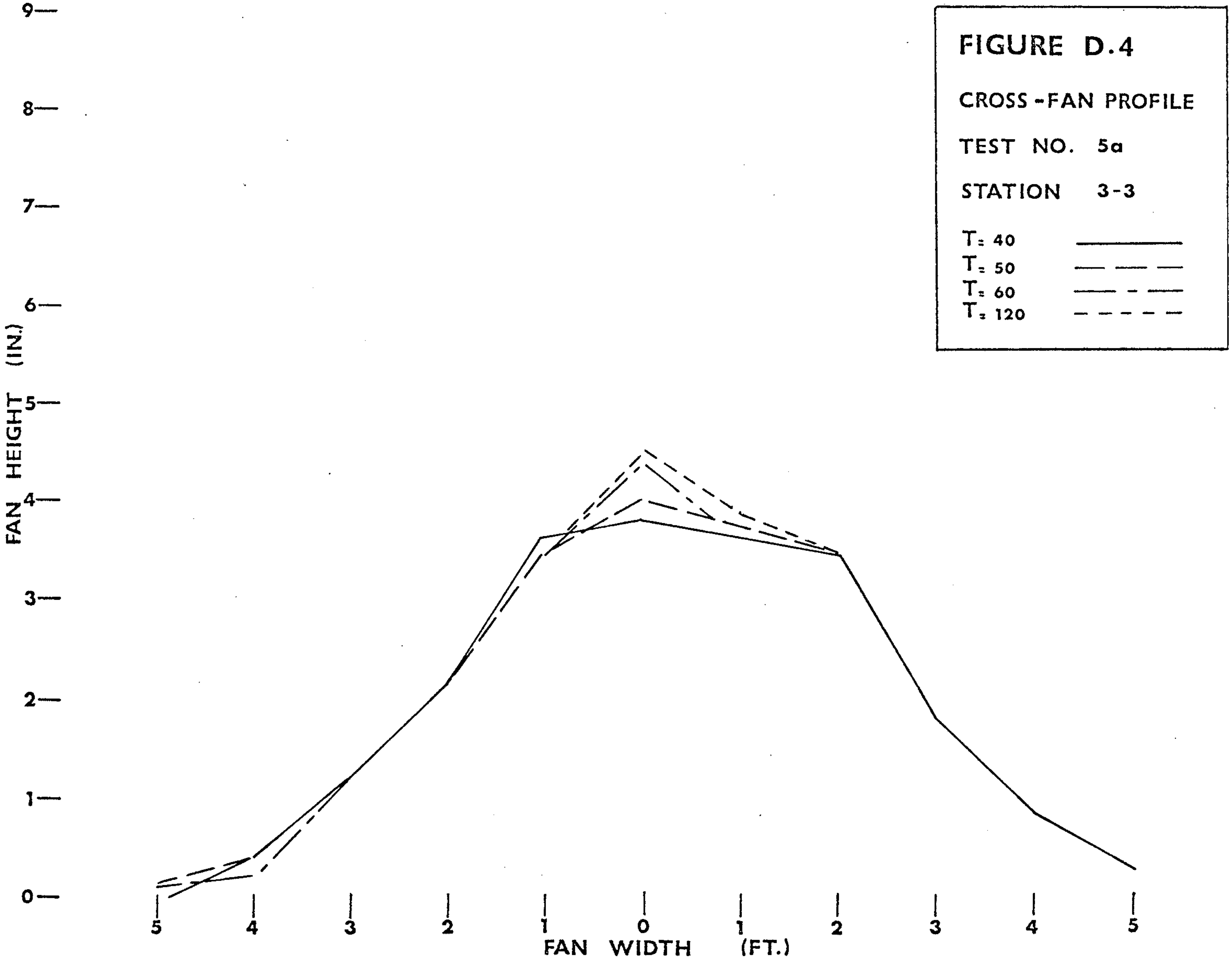


FIGURE D.4

CROSS-FAN PROFILE

TEST NO. 5a

STATION 3-3

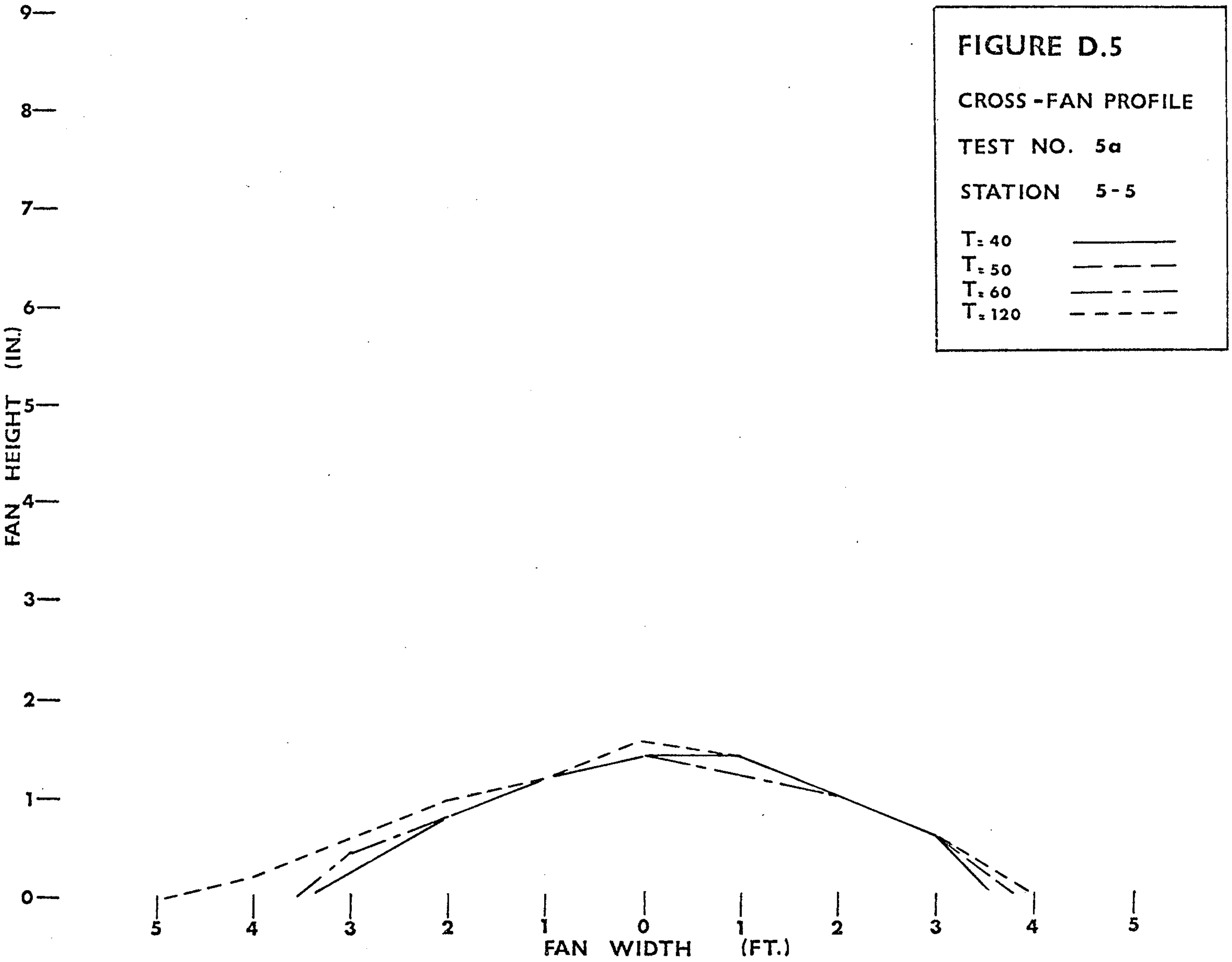


FIGURE D.5

CROSS-FAN PROFILE

TEST NO. 5a

STATION 5-5

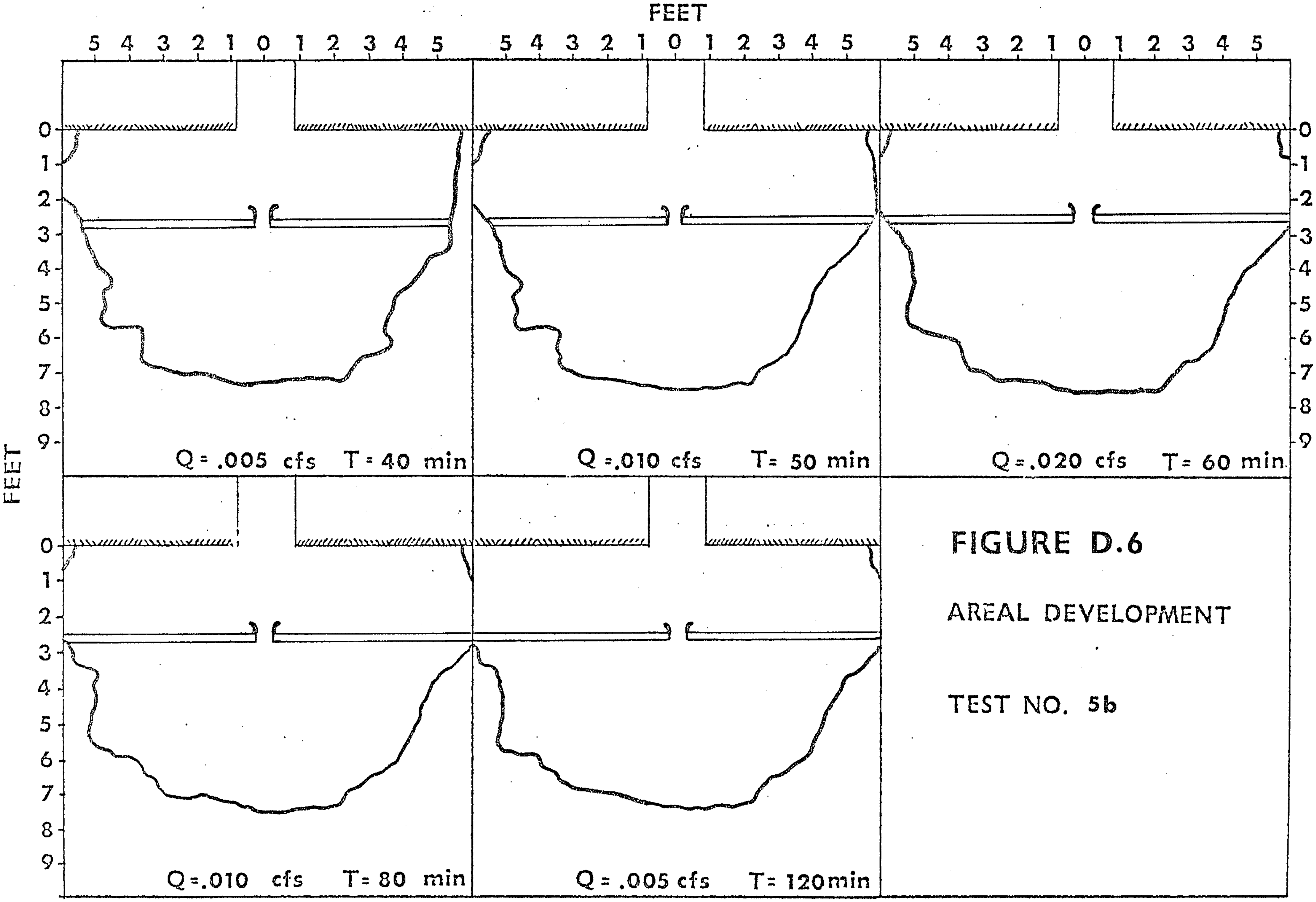


FIGURE D.6

AREAL DEVELOPMENT

TEST NO. 5b

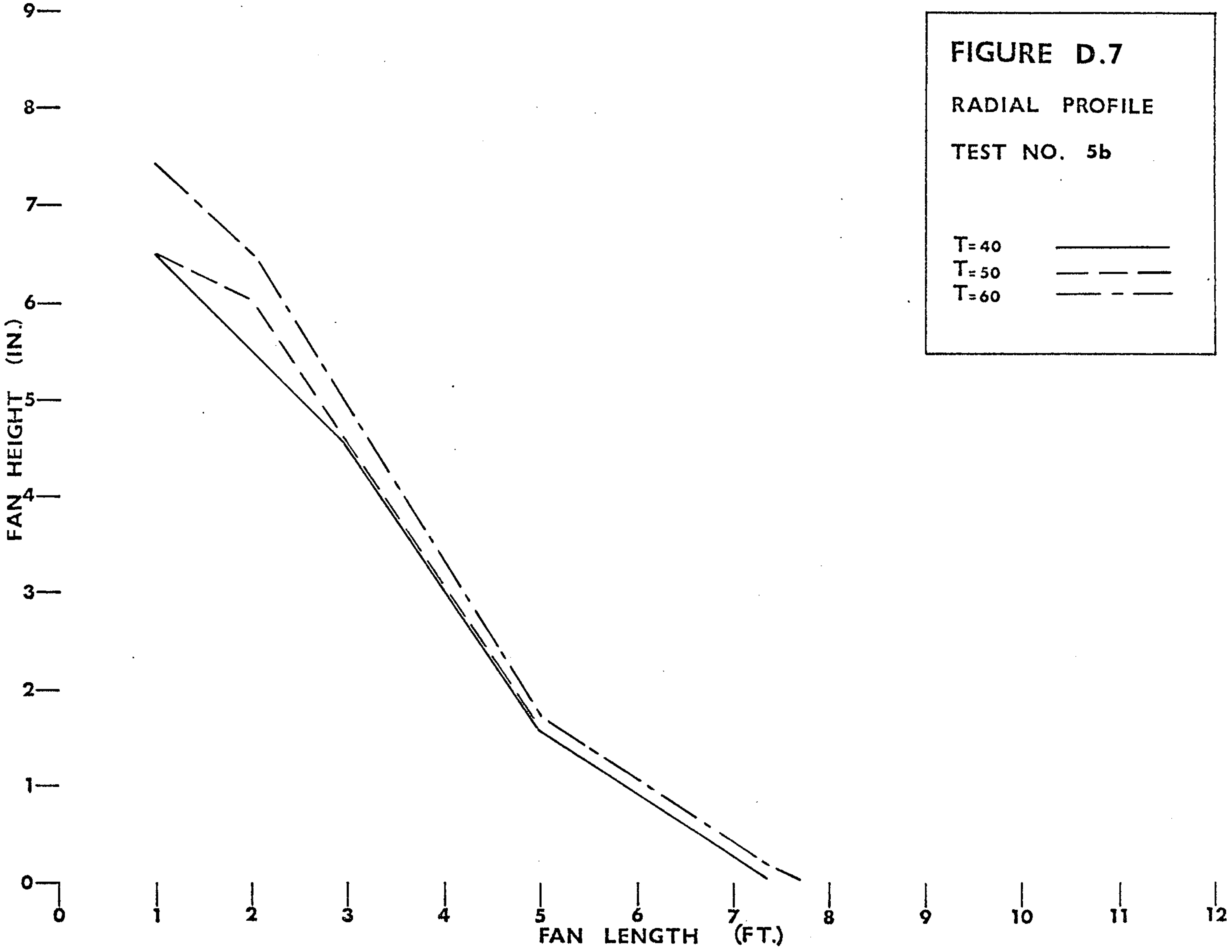


FIGURE D.7

RADIAL PROFILE

TEST NO. 5b

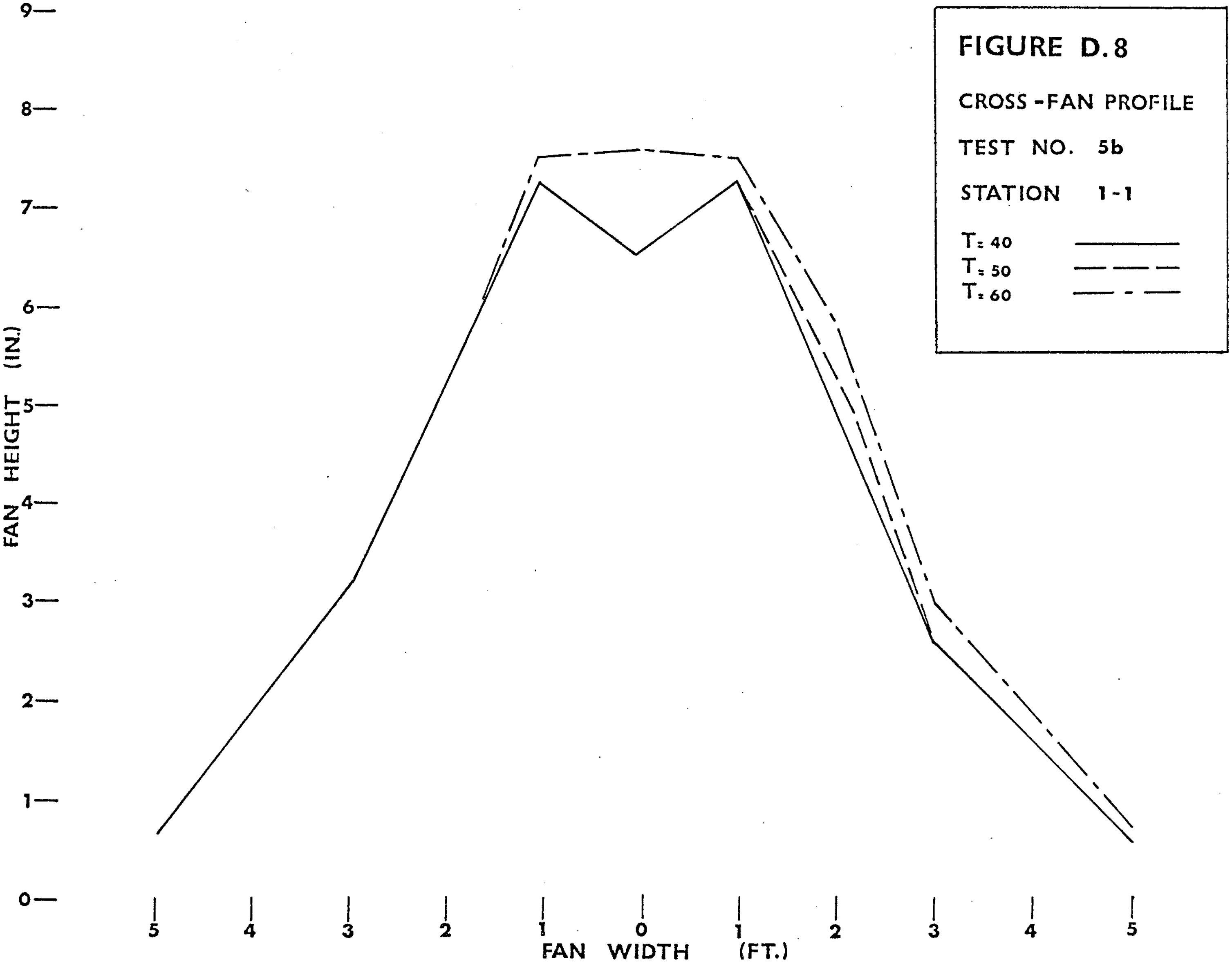


FIGURE D.8

CROSS-FAN PROFILE

TEST NO. 5b

STATION 1-1

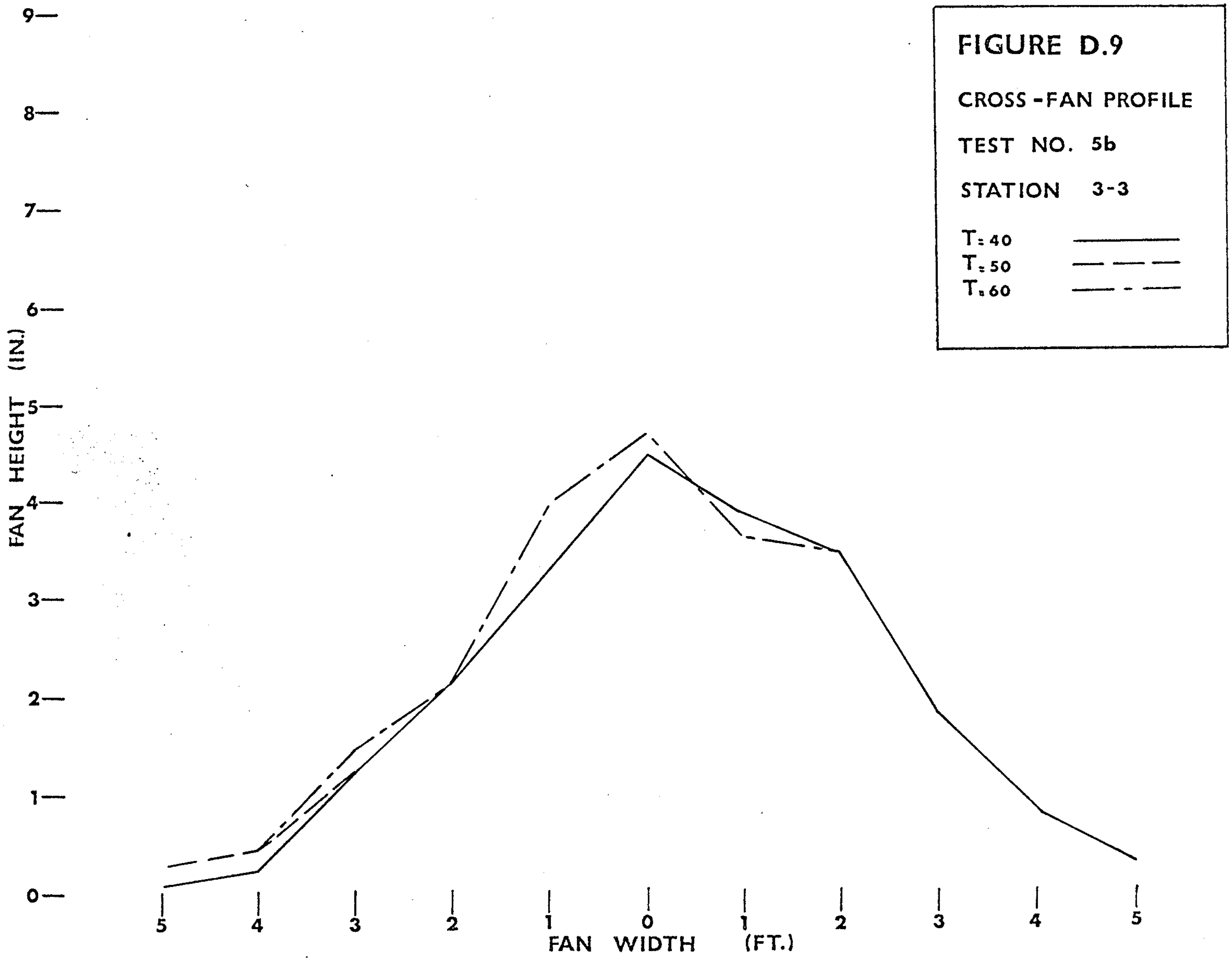


FIGURE D.9

CROSS-FAN PROFILE

TEST NO. 5b

STATION 3-3

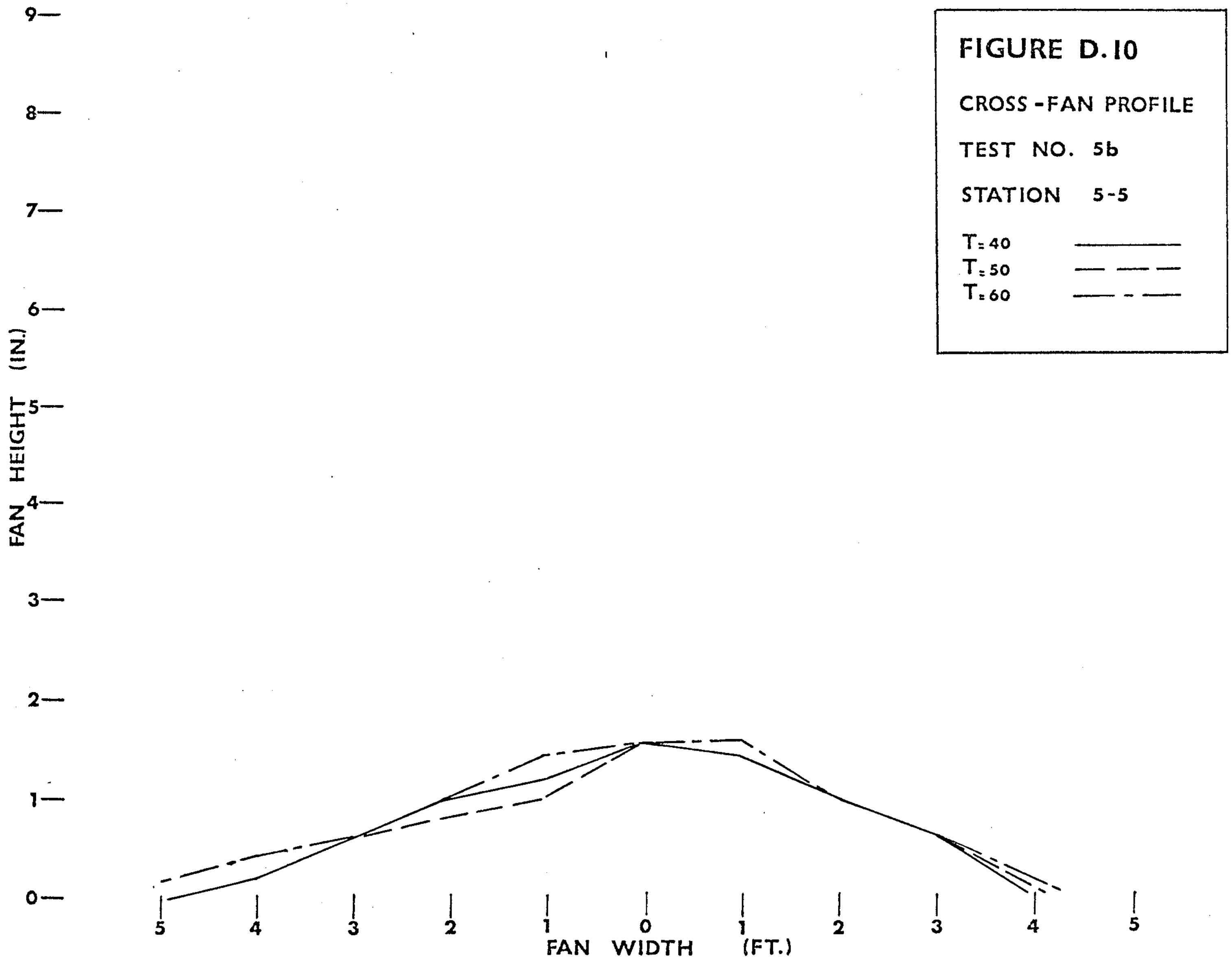


FIGURE D.10

CROSS-FAN PROFILE

TEST NO. 5b

STATION 5-5

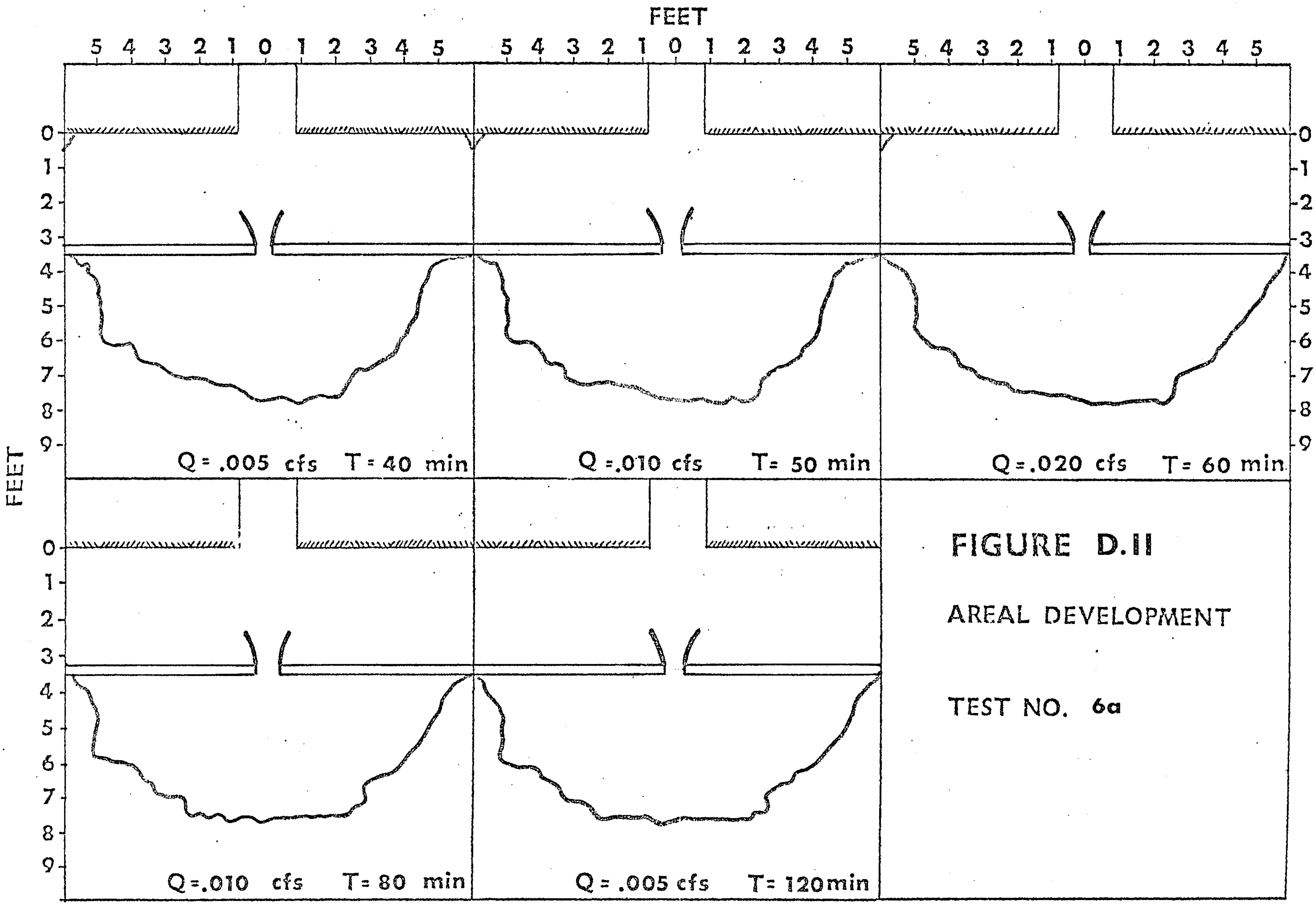


FIGURE D.II

AREAL DEVELOPMENT

TEST NO. 6a

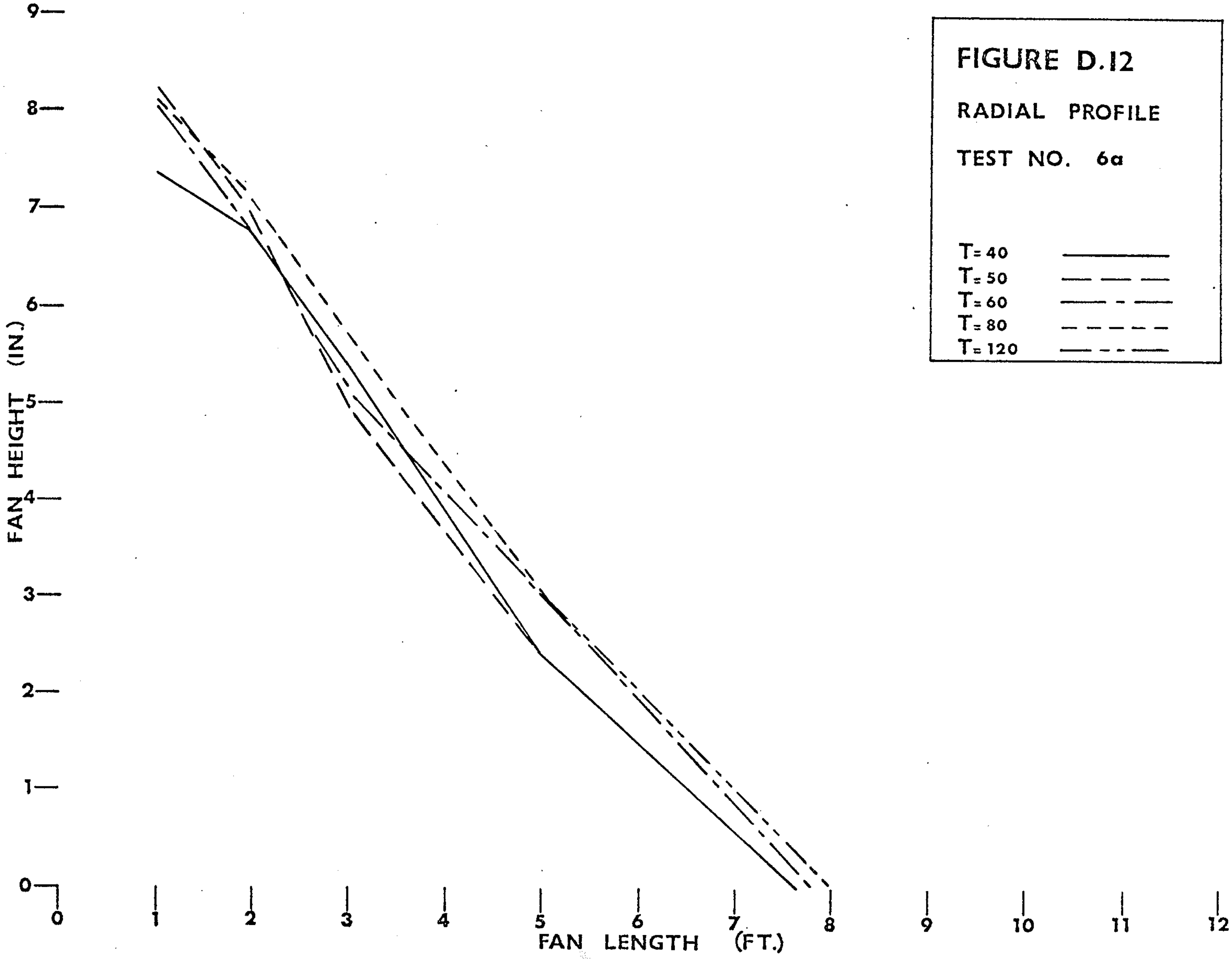


FIGURE D.12

RADIAL PROFILE

TEST NO. 6a

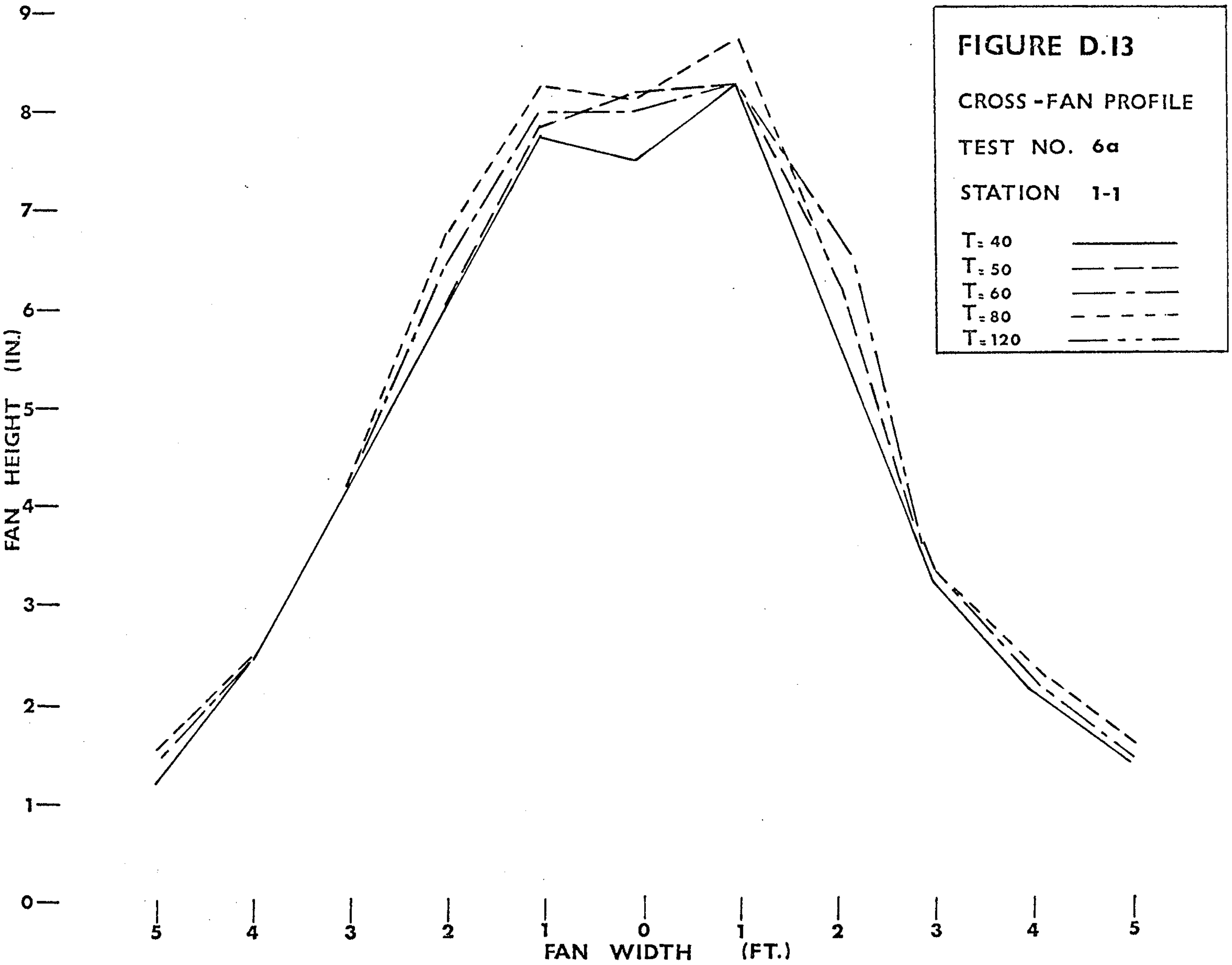


FIGURE D.13

CROSS-FAN PROFILE

TEST NO. 6a

STATION 1-1

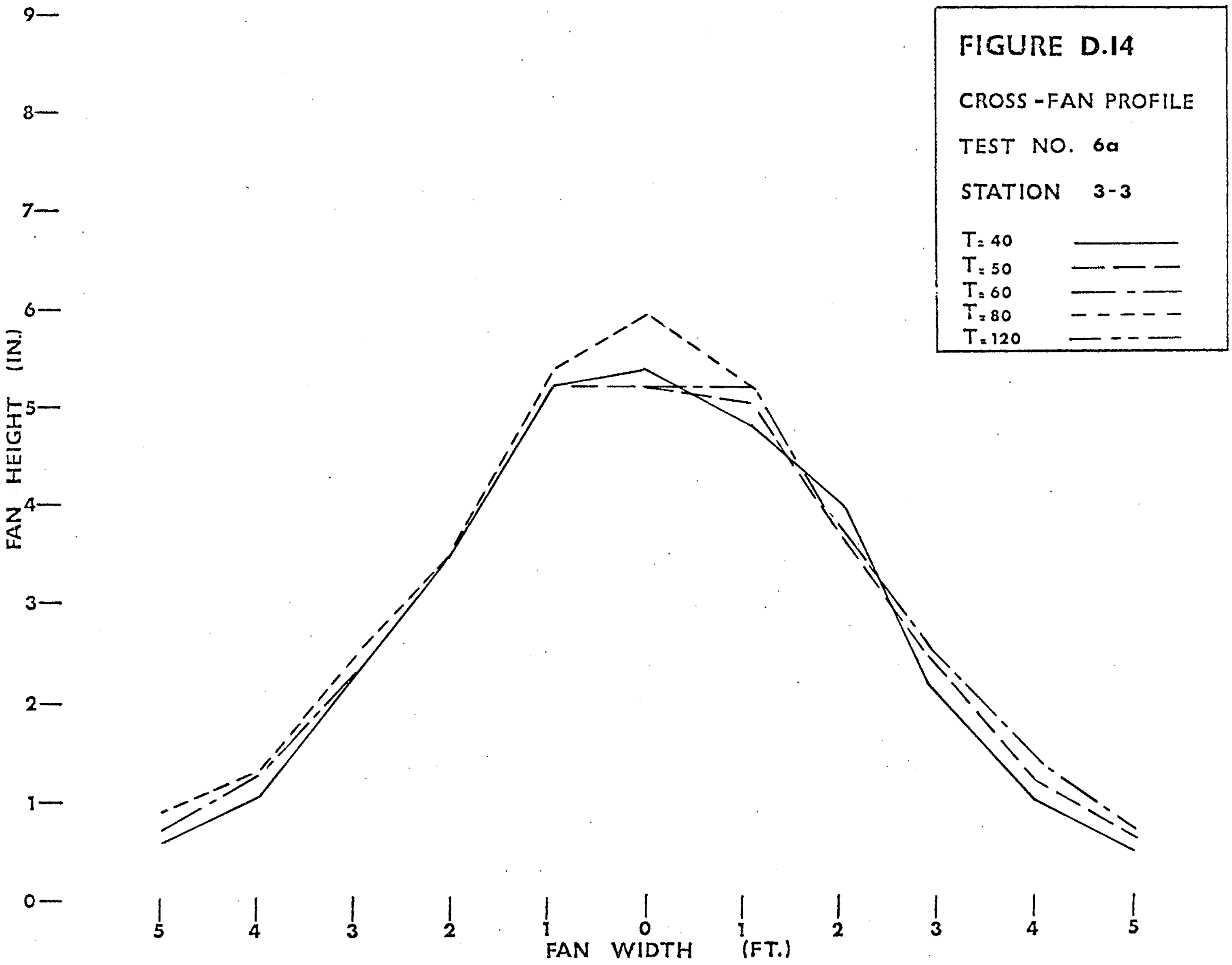


FIGURE D.14

CROSS-FAN PROFILE

TEST NO. 6a

STATION 3-3

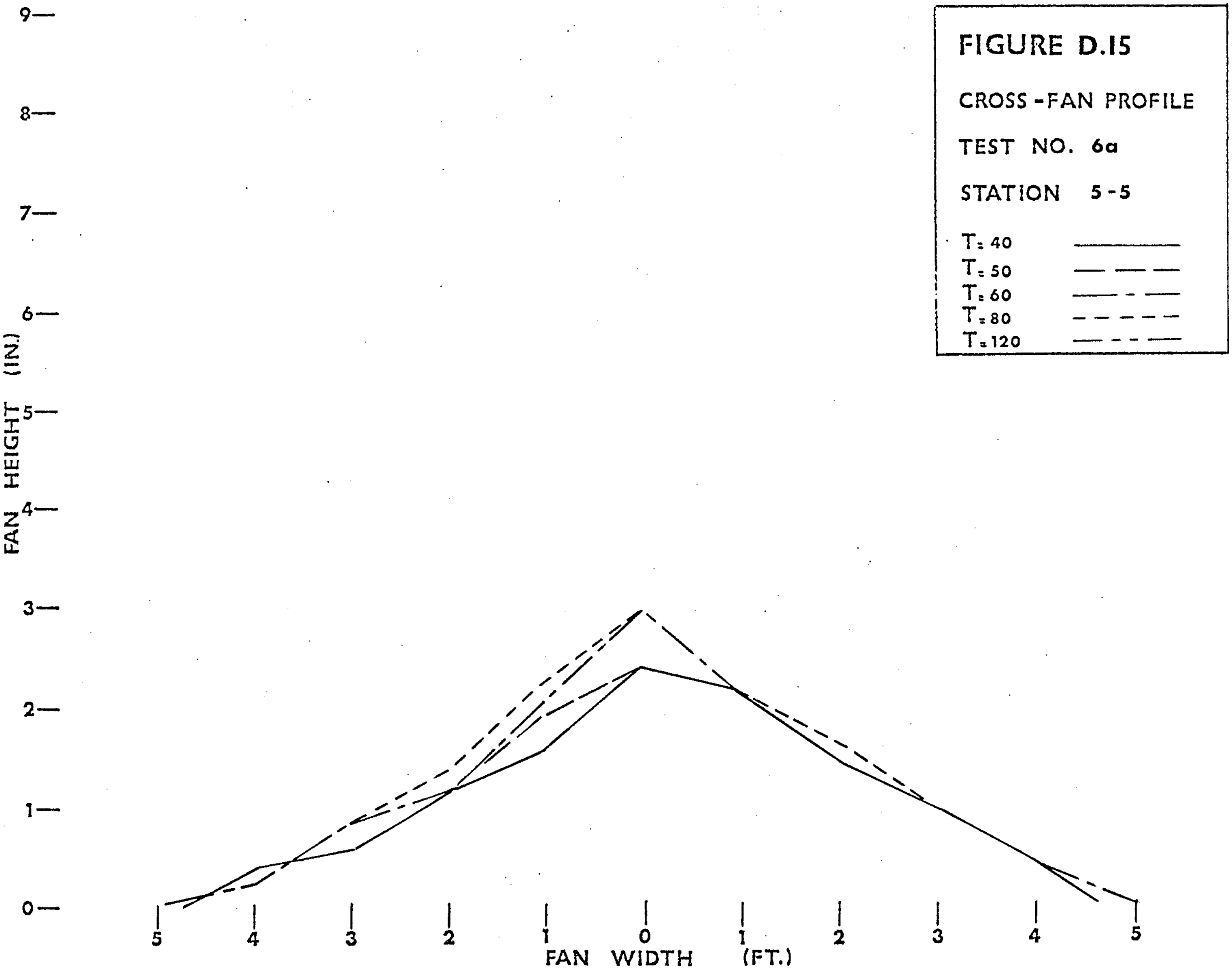


FIGURE D.15

CROSS-FAN PROFILE

TEST NO. 6a

STATION 5-5

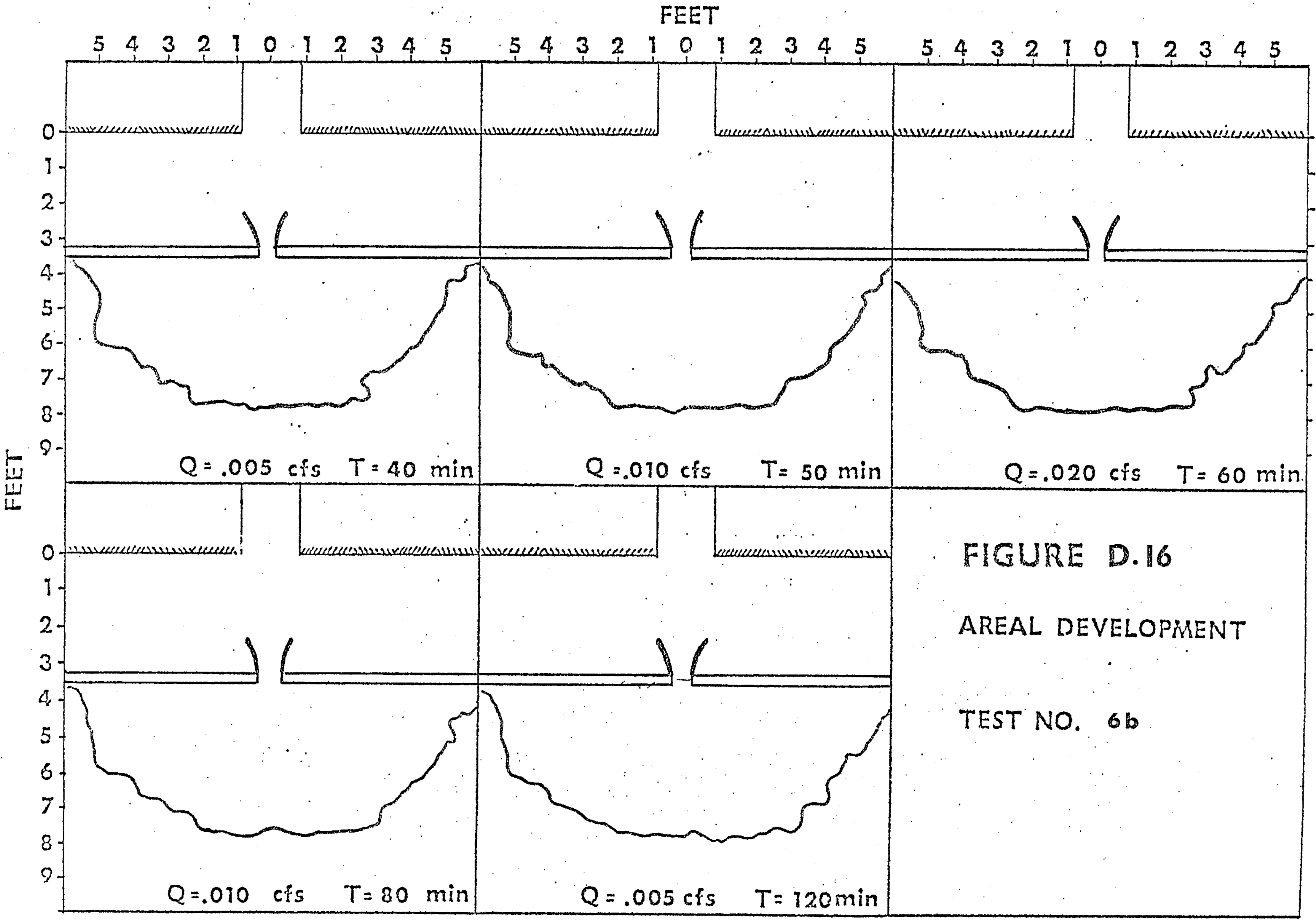


FIGURE D.16

AREAL DEVELOPMENT

TEST NO. 6b

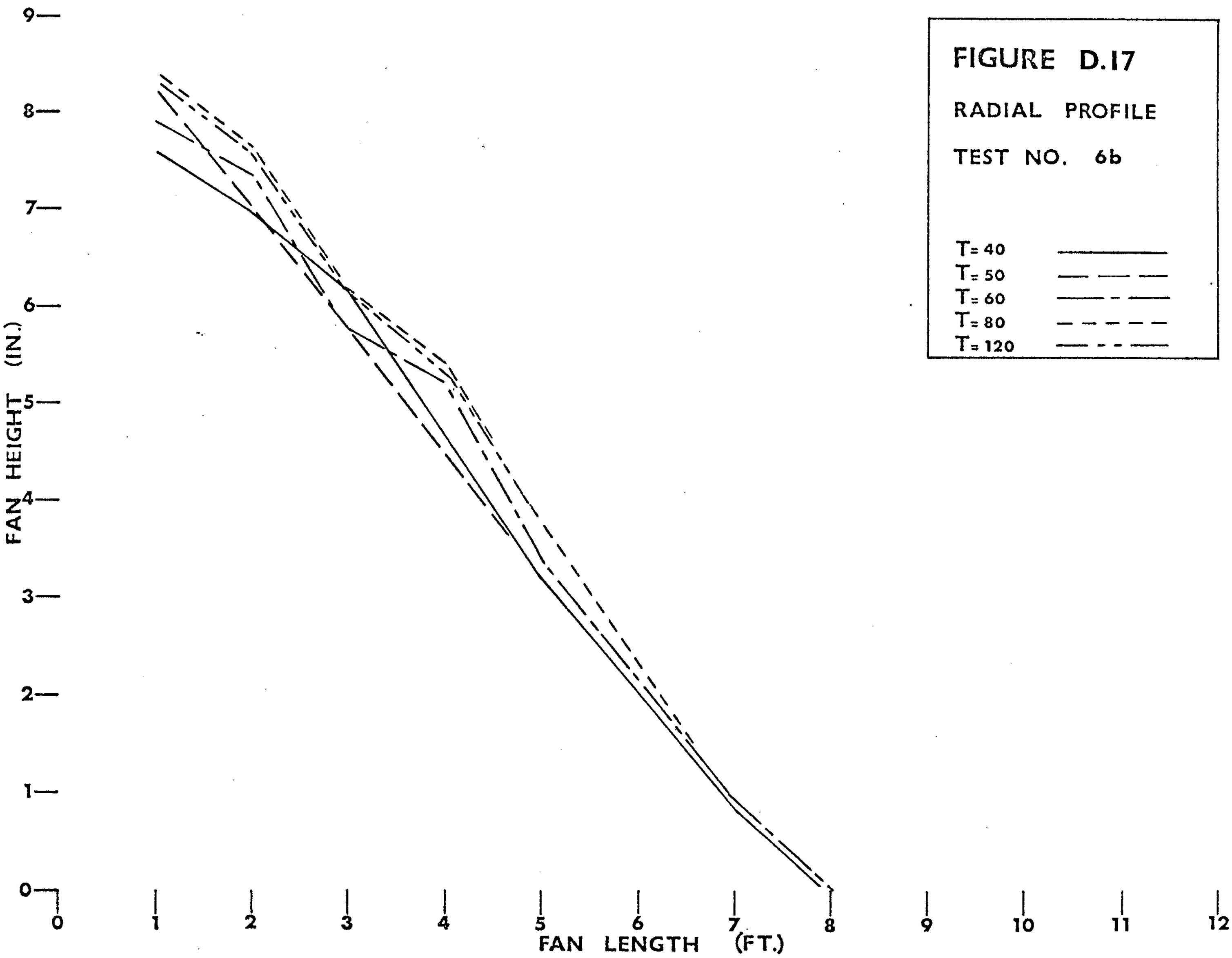


FIGURE D.17
RADIAL PROFILE
TEST NO. 6b
T= 40
T= 50
T= 60
T= 80
T= 120
FAN HEIGHT (IN.)
0
1
2
3
4
5
6
7
8
9
FAN LENGTH (FT.)
0
1
2
3
4
5
6
7
8
9
10
11
12

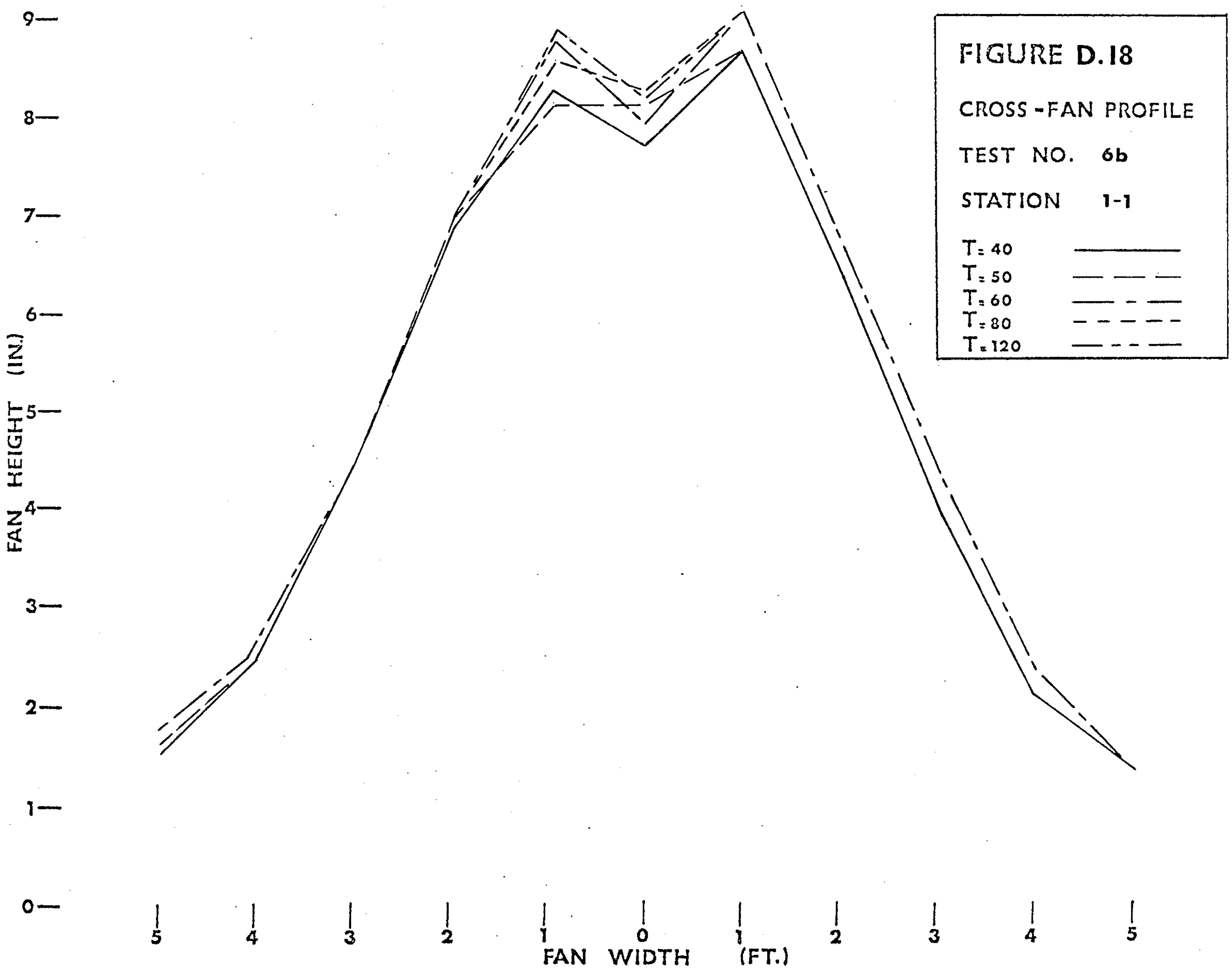


FIGURE D.18

CROSS-FAN PROFILE

TEST NO. 6b

STATION 1-1

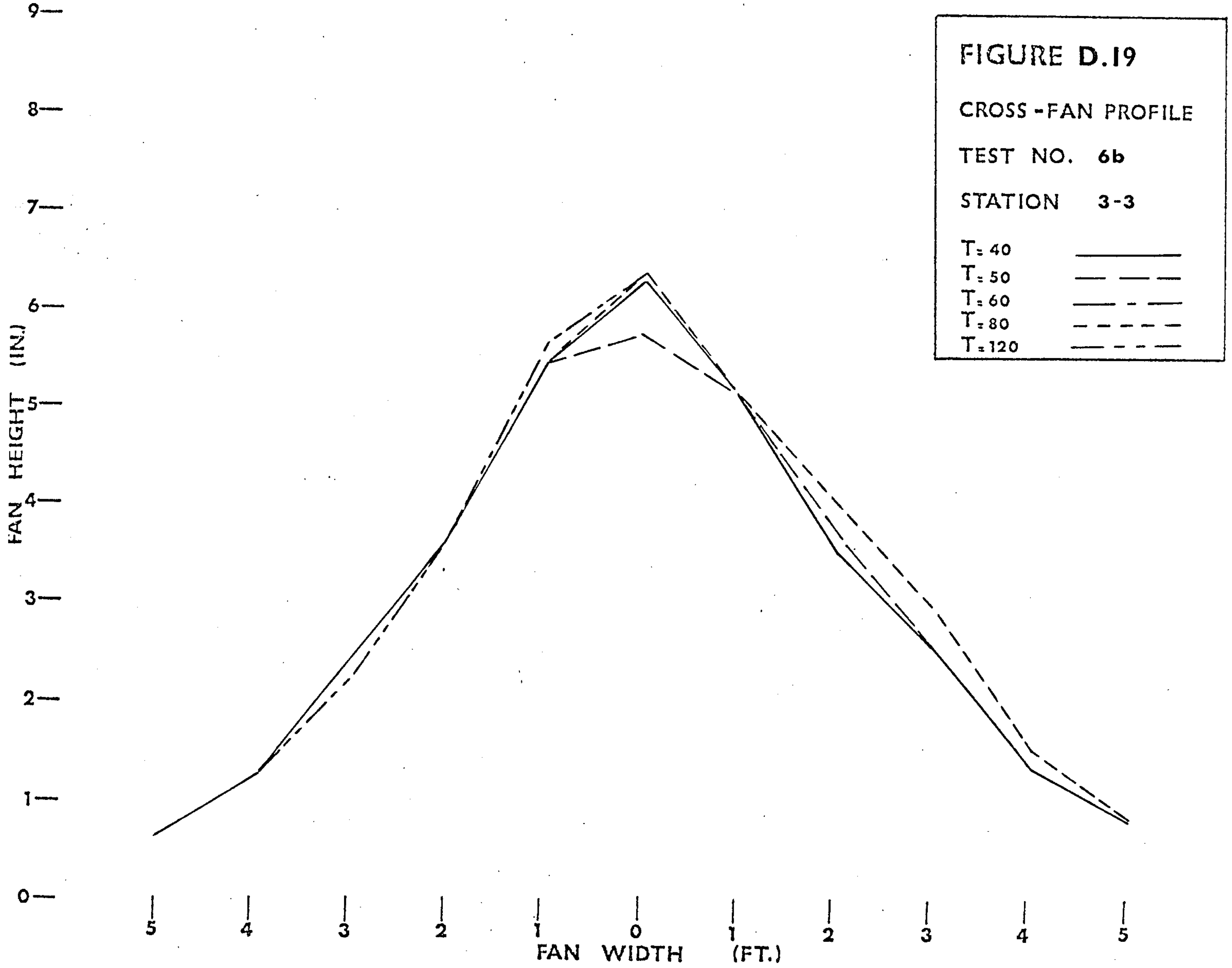


FIGURE D.19

CROSS-FAN PROFILE

TEST NO. 6b

STATION 3-3

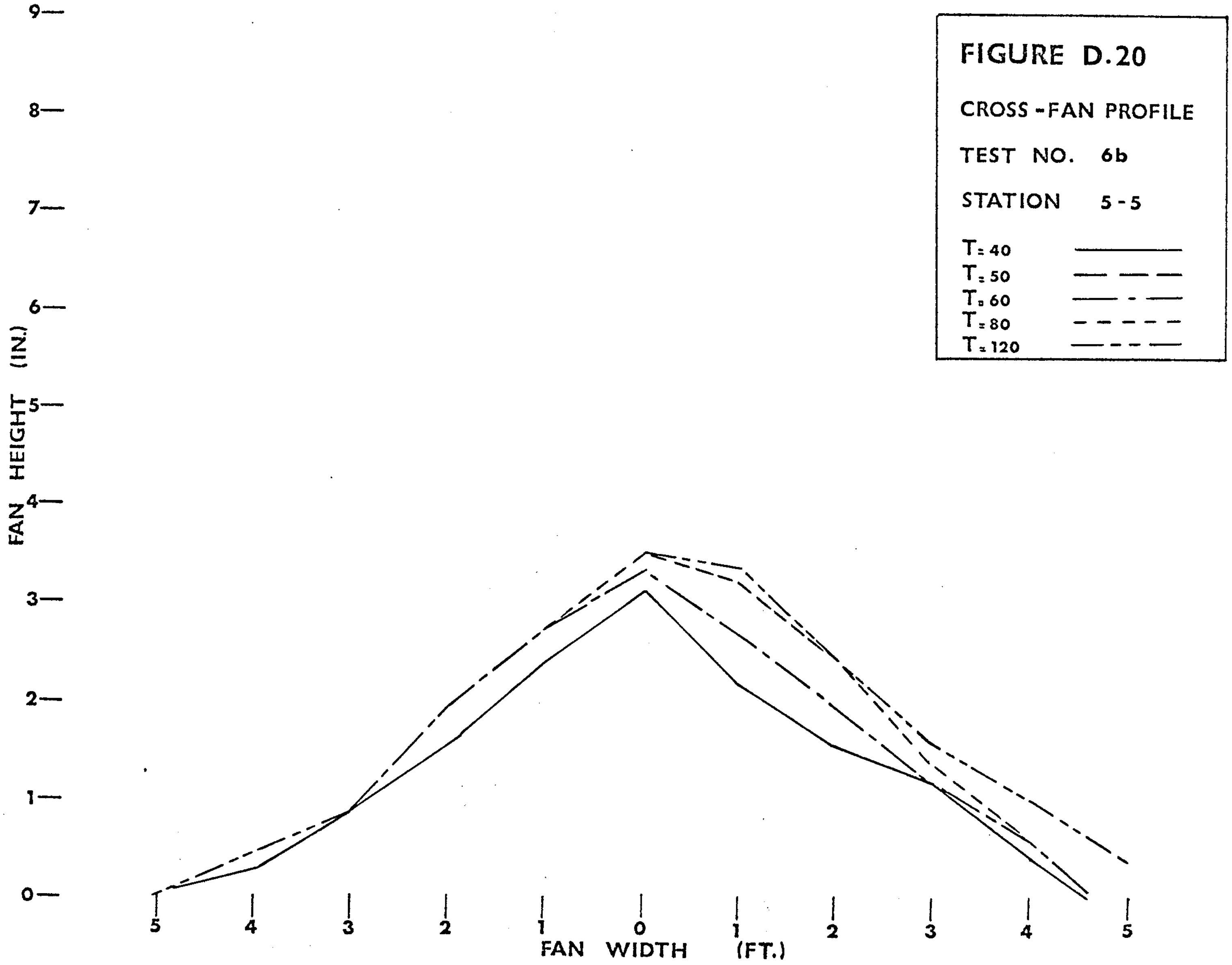


FIGURE D.20

CROSS-FAN PROFILE

TEST NO. 6b

STATION 5-5

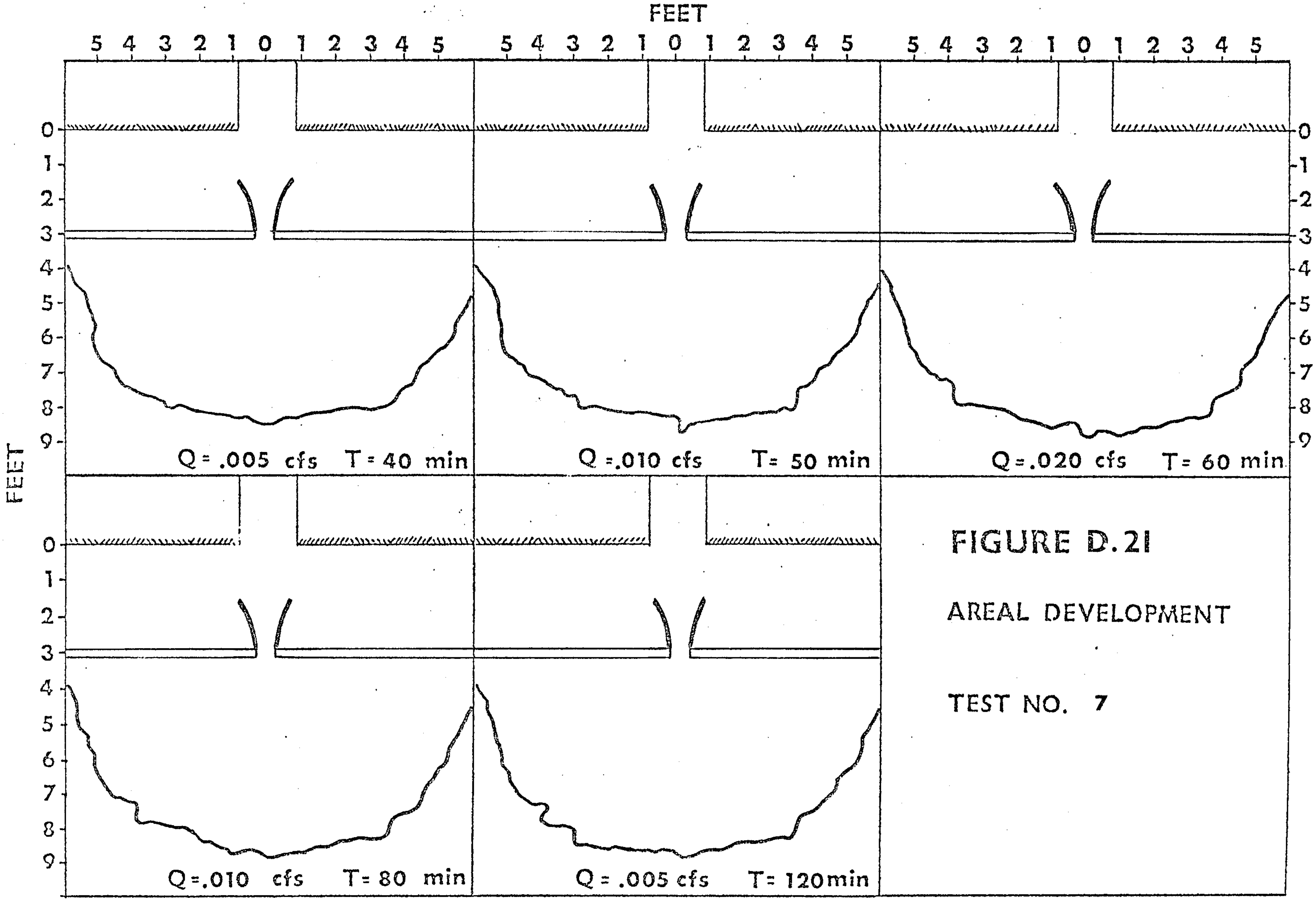


FIGURE D.21

AREAL DEVELOPMENT

TEST NO. 7

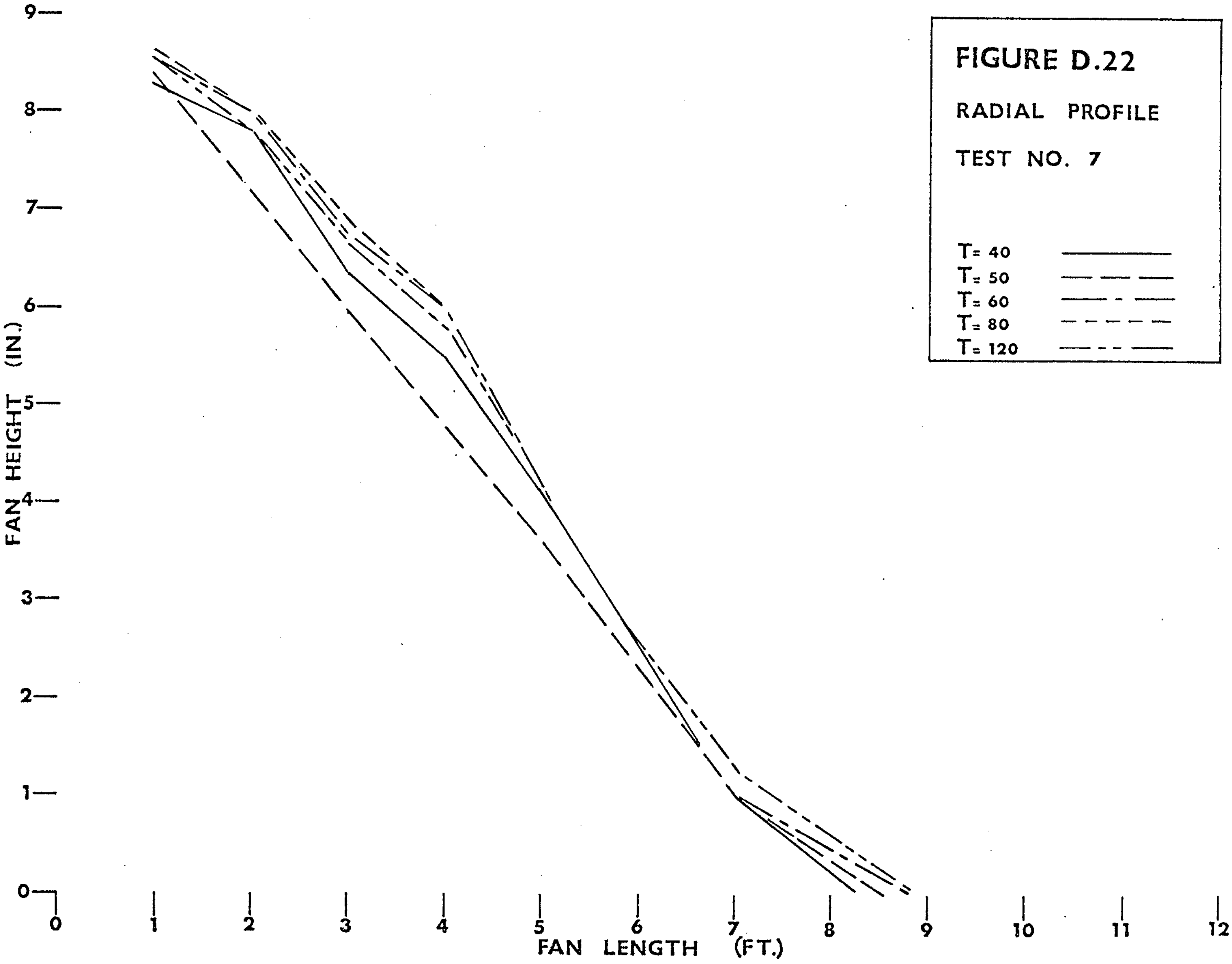


FIGURE D.22

RADIAL PROFILE

TEST NO. 7

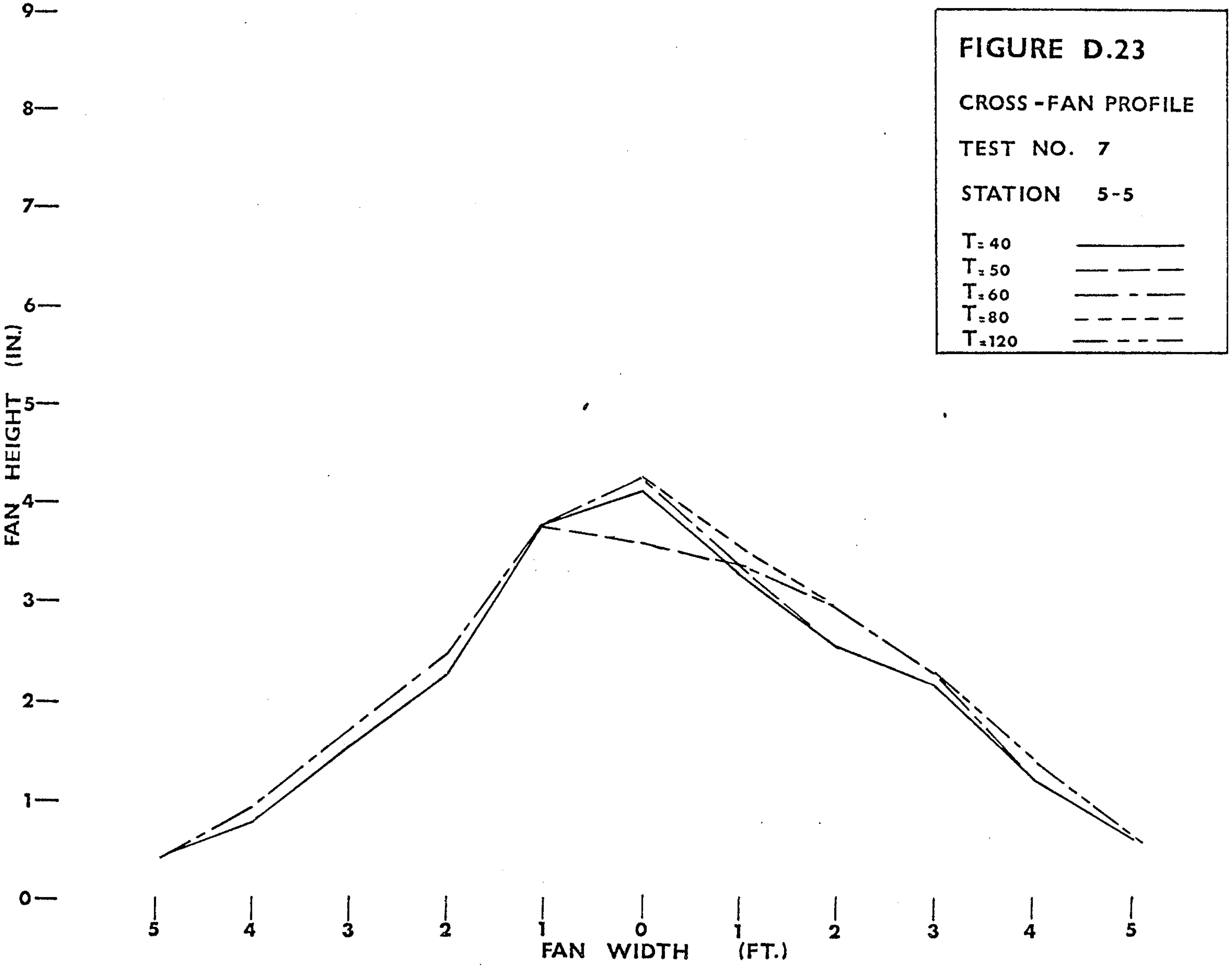


FIGURE D.23

CROSS-FAN PROFILE

TEST NO. 7

STATION 5-5

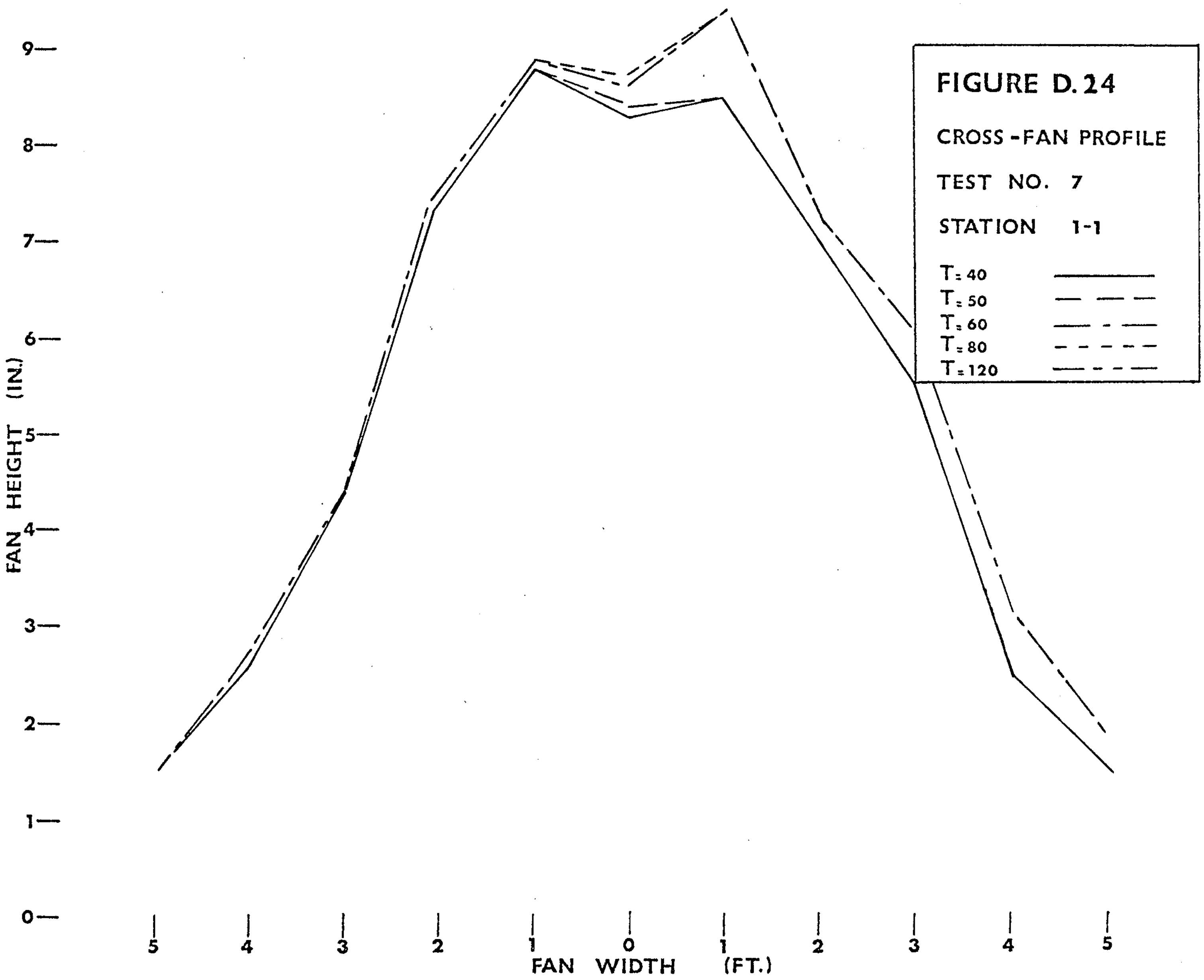


FIGURE D.24

CROSS-FAN PROFILE

TEST NO. 7

STATION 1-1

APPENDIX E

TEST RESULTS

(FAN DISSECTION)

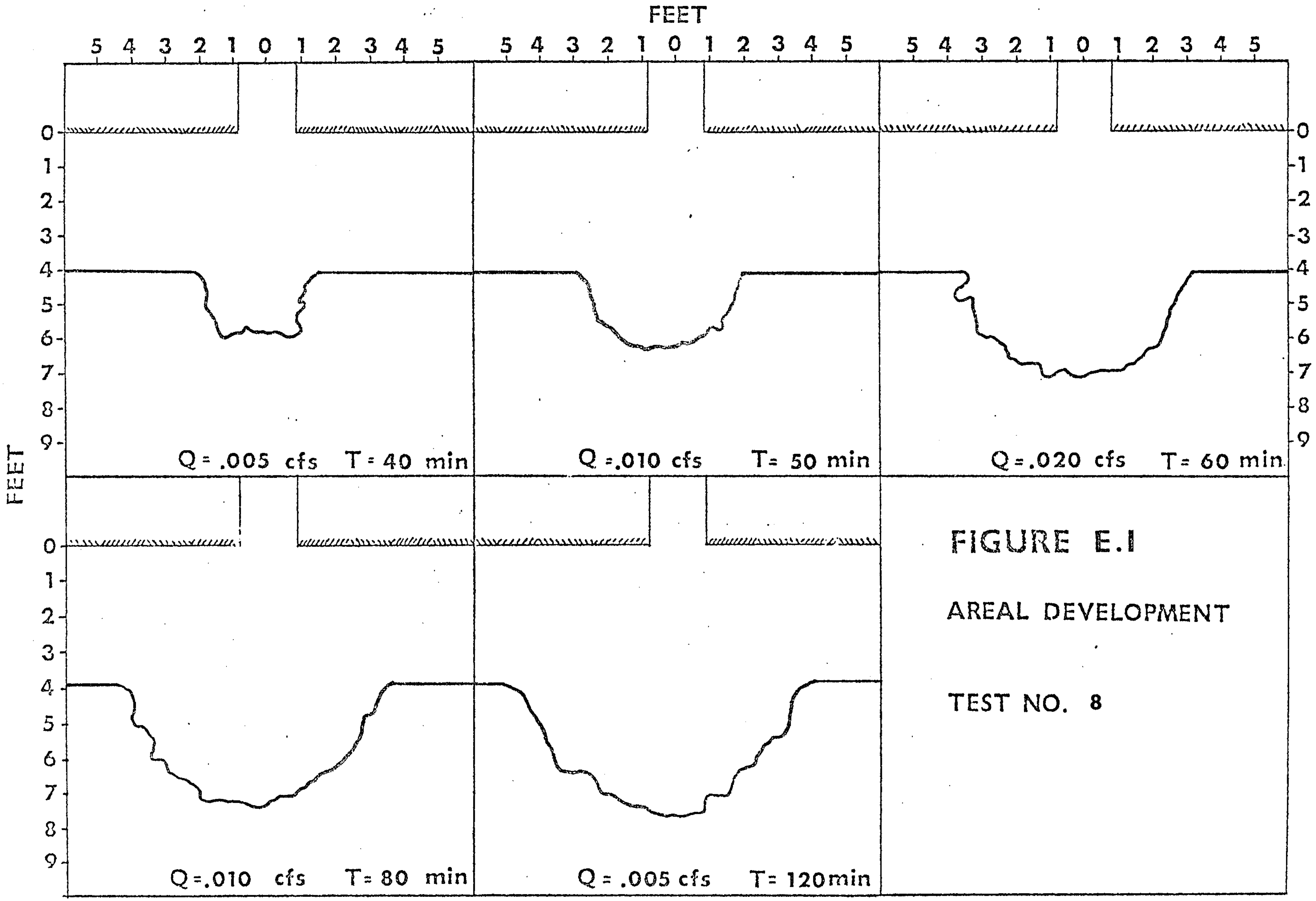


FIGURE E.1

AREAL DEVELOPMENT

TEST NO. 8

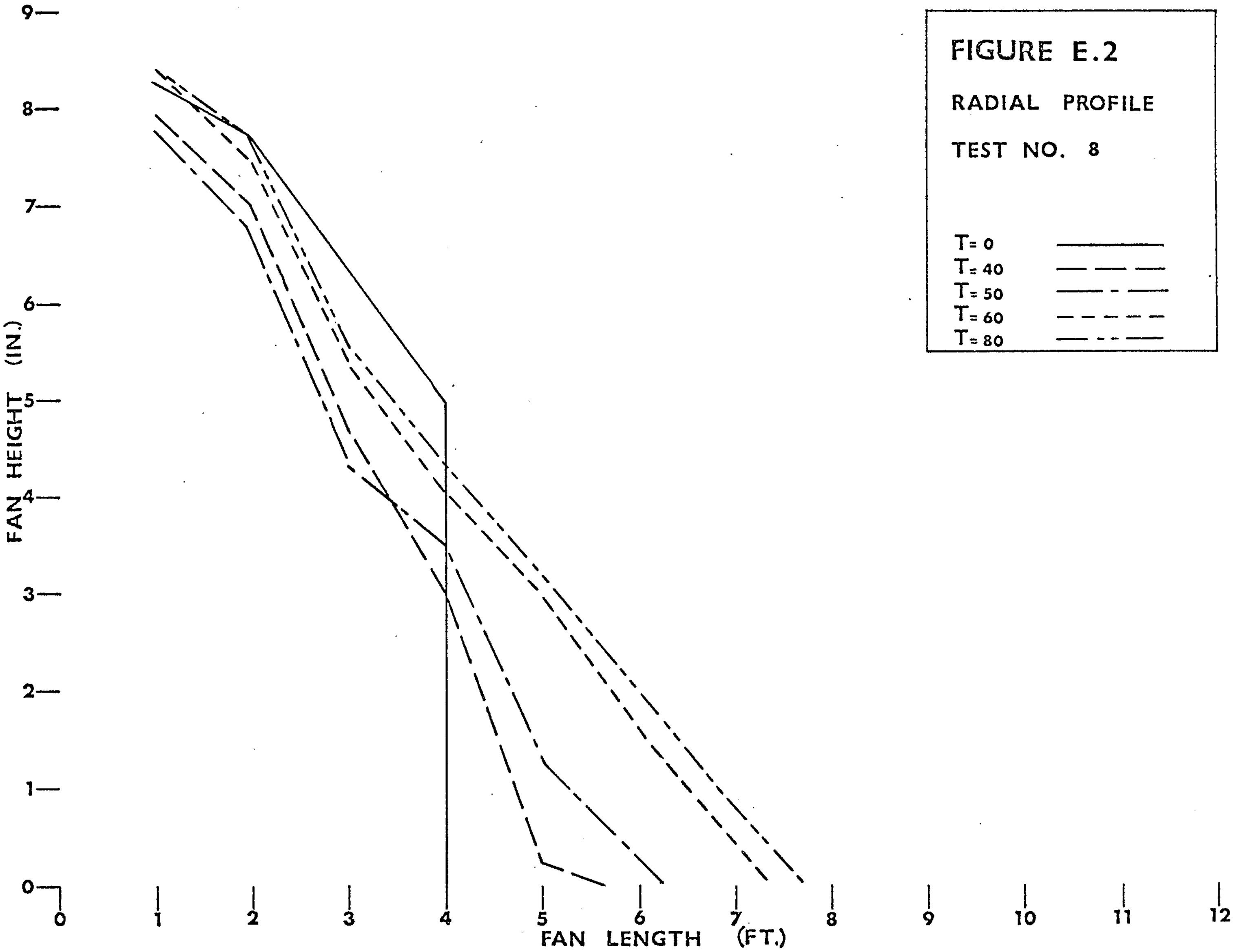


FIGURE E.2

RADIAL PROFILE

TEST NO. 8

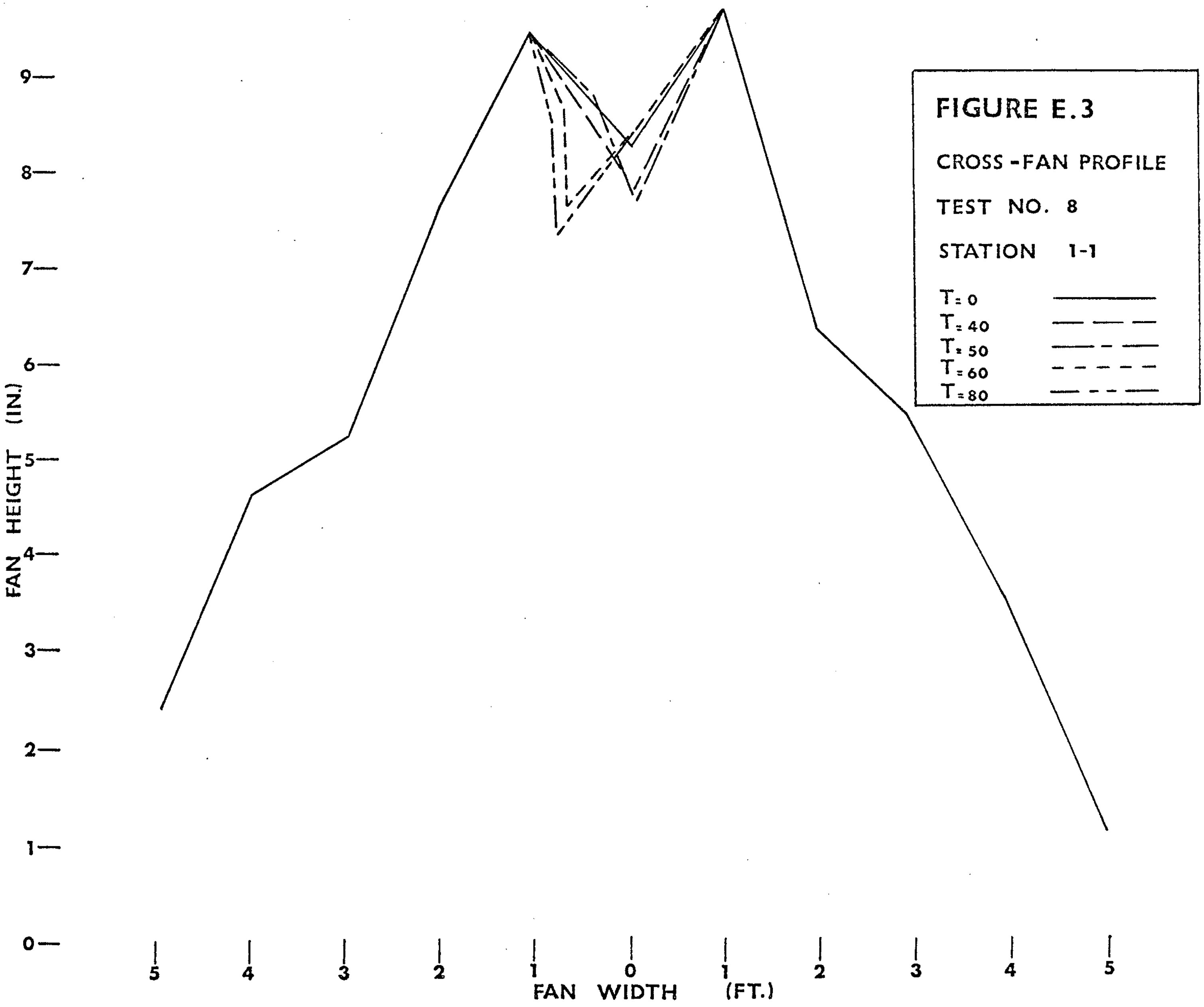


FIGURE E.3

CROSS-FAN PROFILE

TEST NO. 8

STATION 1-1

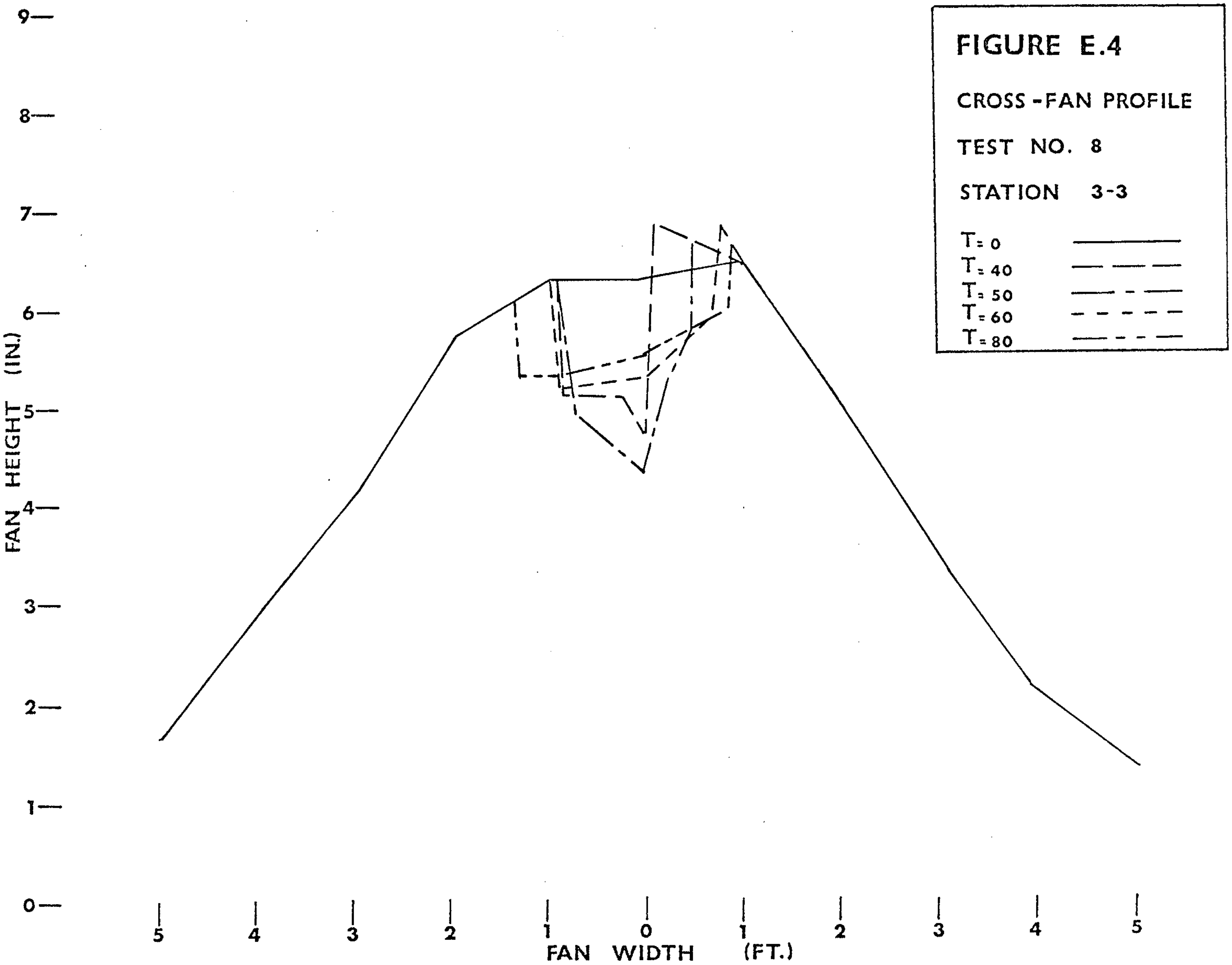


FIGURE E.4

CROSS-FAN PROFILE

TEST NO. 8

STATION 3-3

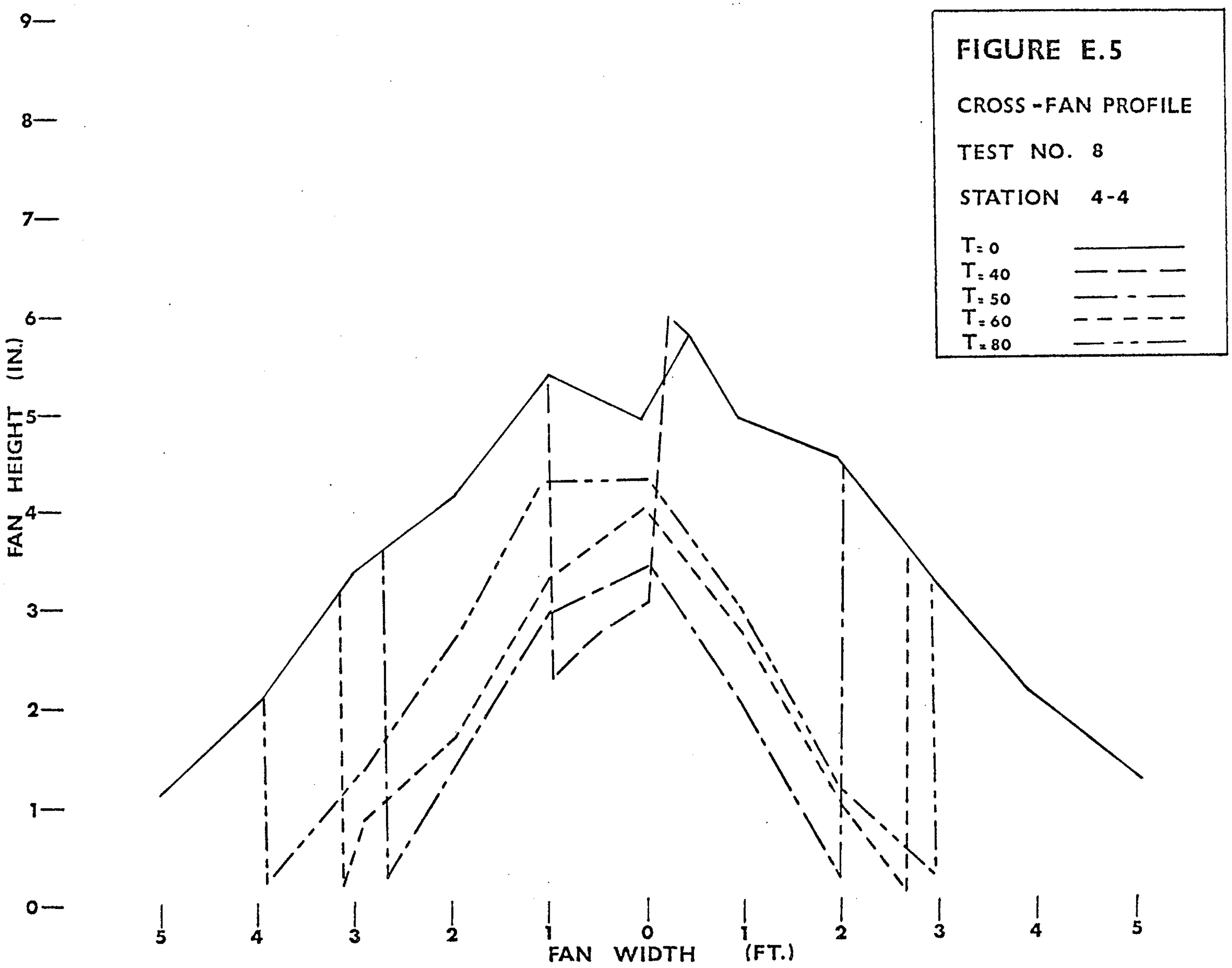


FIGURE E.5

CROSS - FAN PROFILE

TEST NO. 8

STATION 4-4

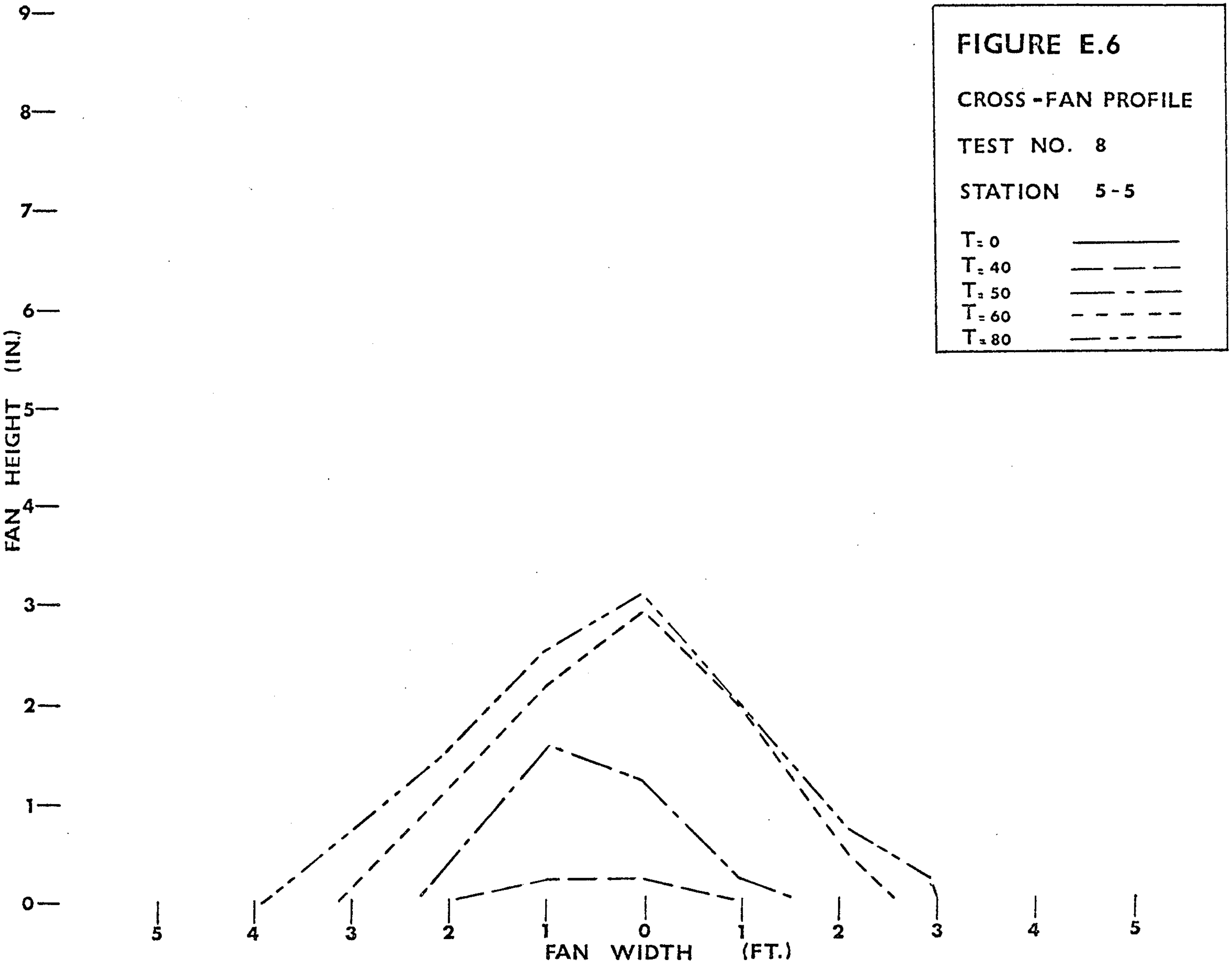


FIGURE E.6

CROSS-FAN PROFILE

TEST NO. 8

STATION 5-5

APPENDIX F

GRAPHS AND FIGURES

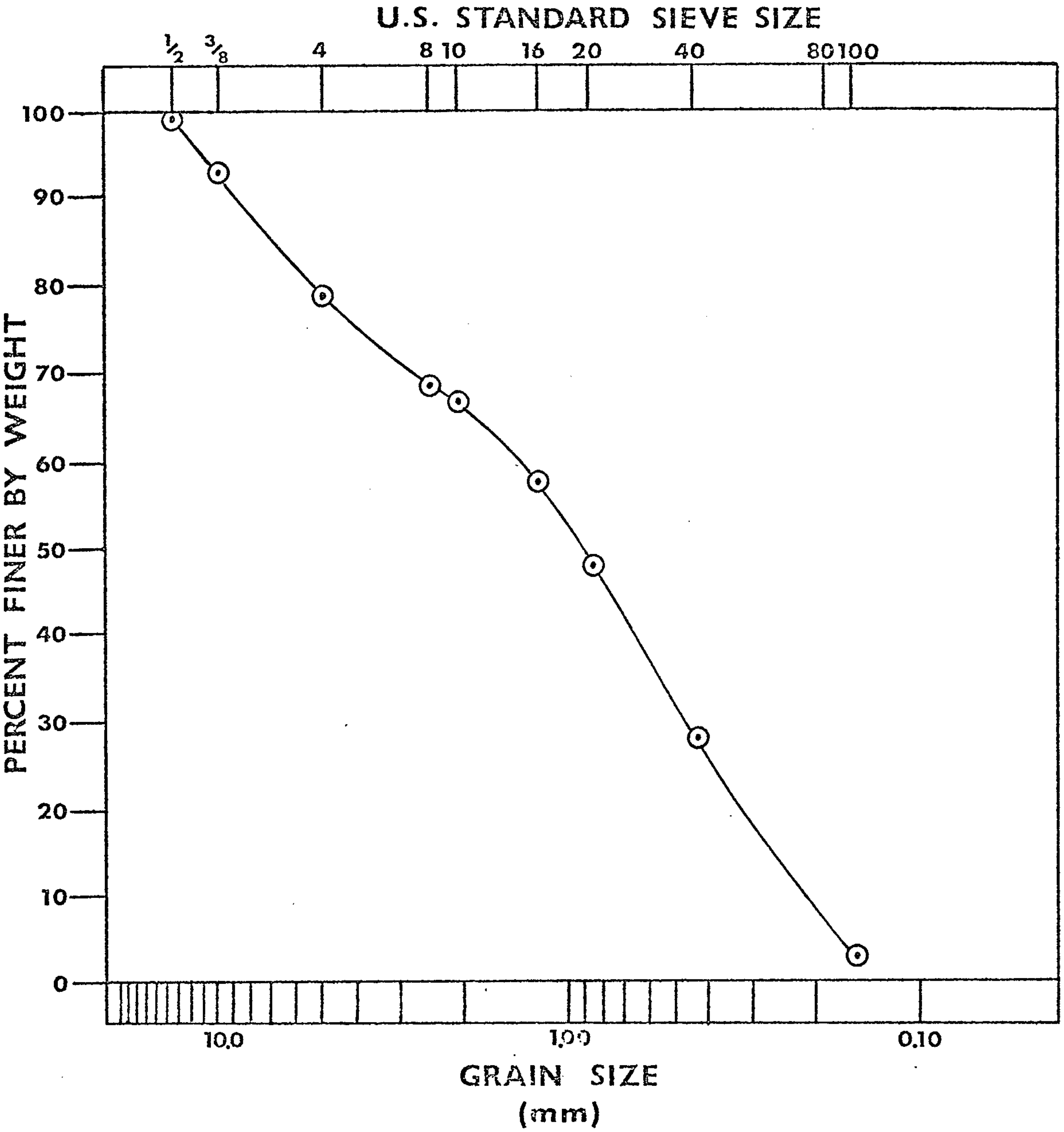


FIGURE F.1
GRAIN SIZE DISTRIBUTION

GRAVEL

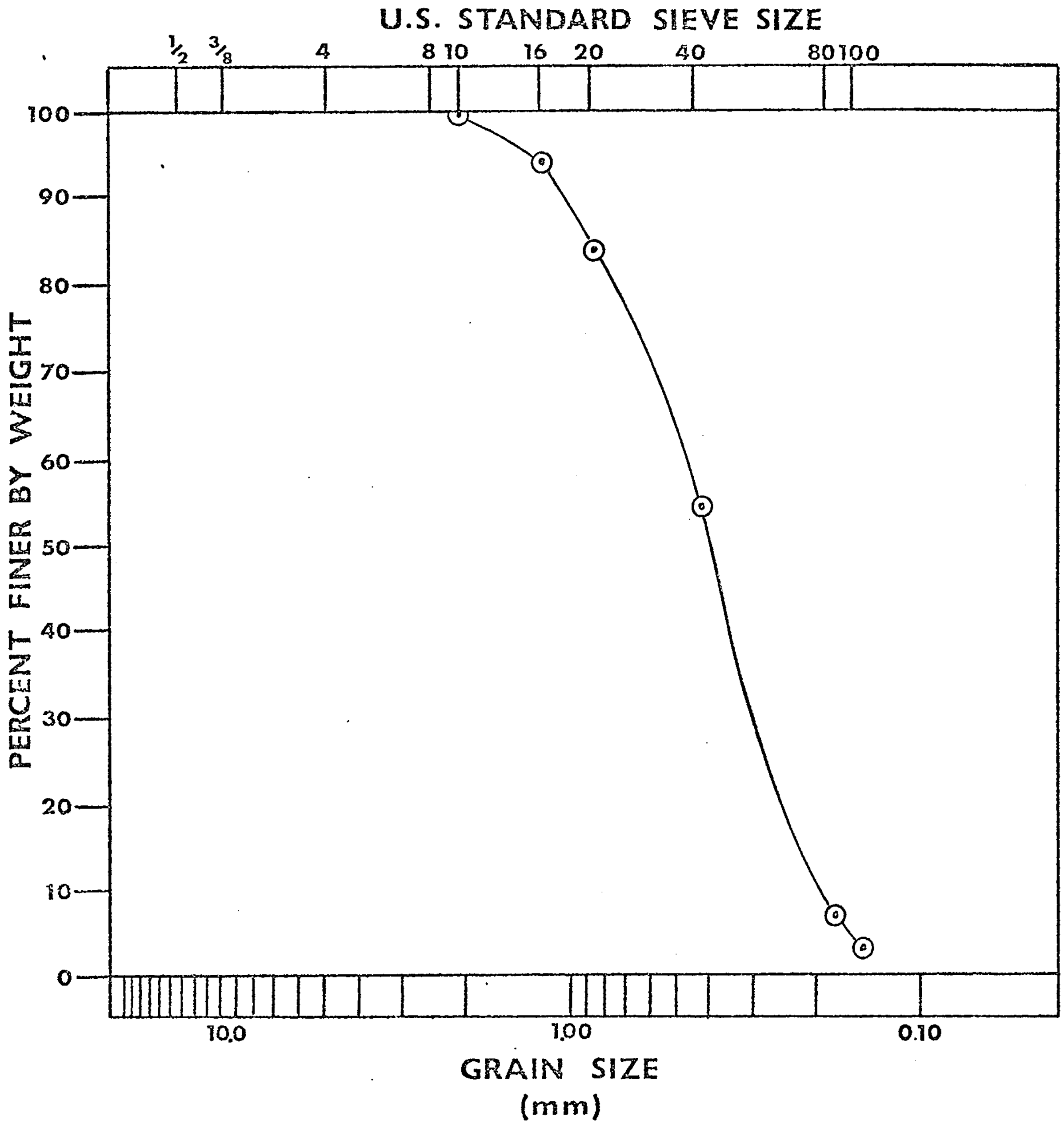
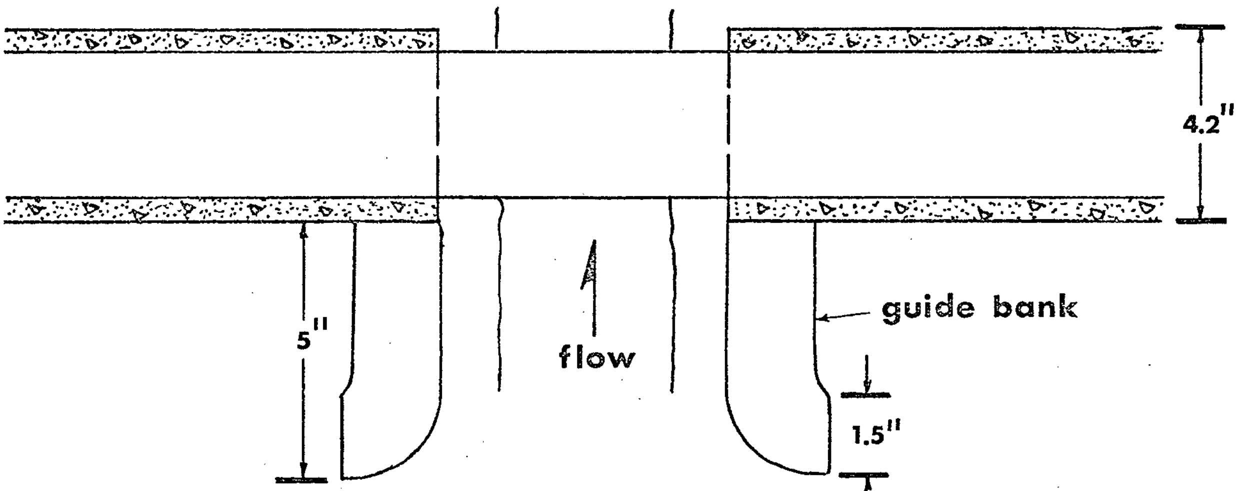
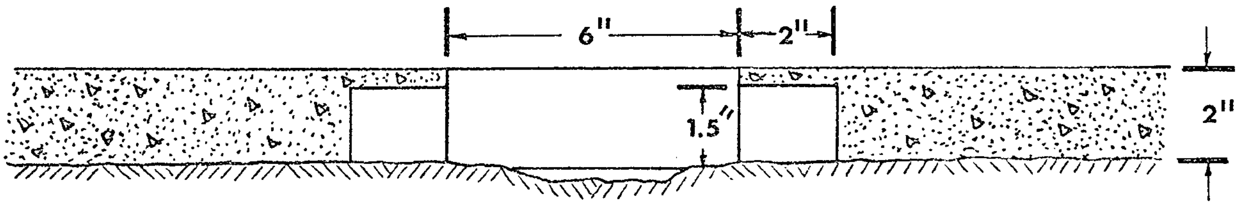


FIGURE F. 2
GRAIN SIZE DISTRIBUTION

MORTAR SAND



PLAN



ELEVATION

FIGURE F.3
BRIDGE DETAIL NO. I

SCALE : 4to1

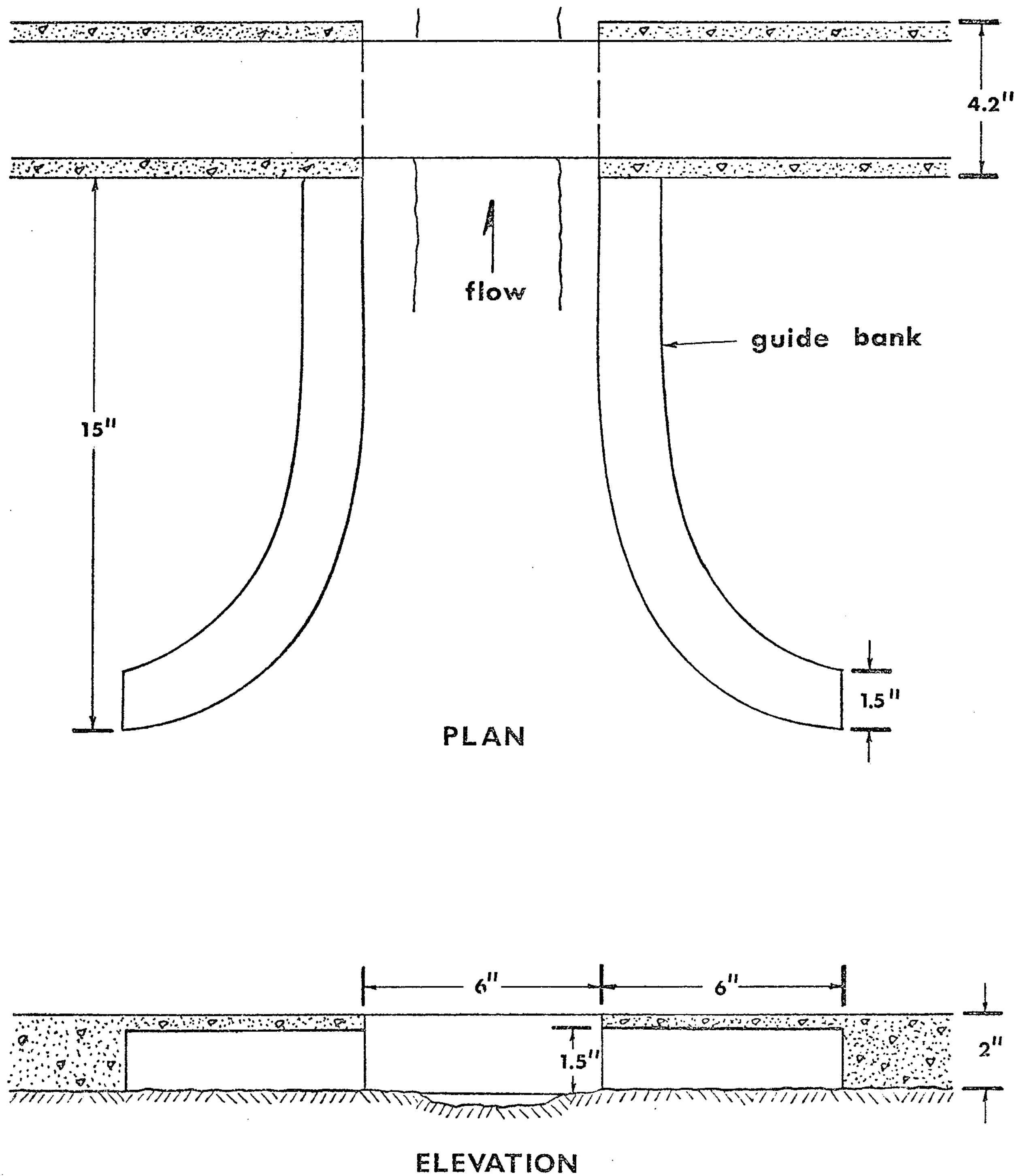


FIGURE F.4

BRIDGE DETAIL NO. 2

SCALE : 4to1

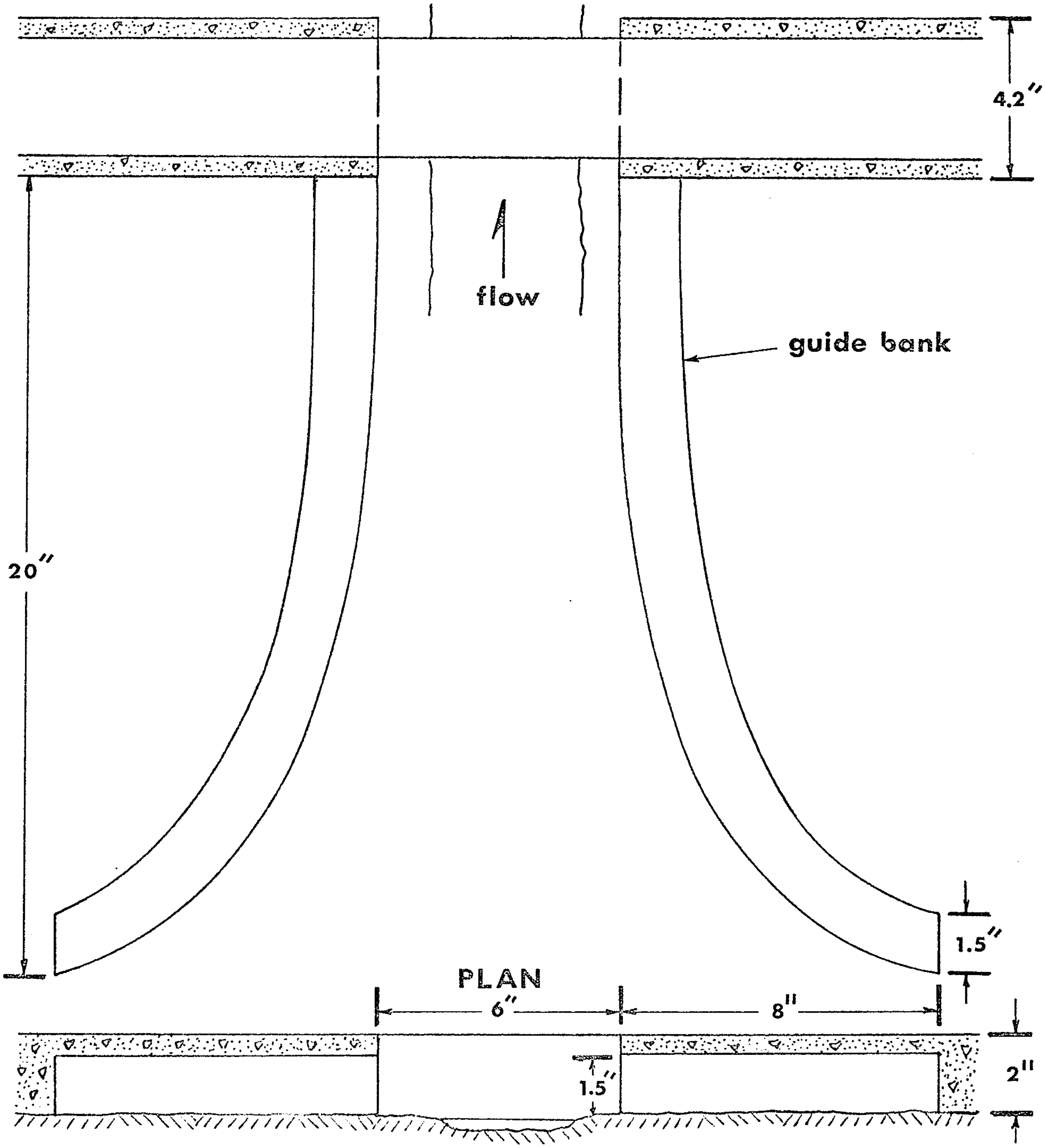


FIGURE F.5

BRIDGE DETAIL NO. 3

SCALE: 4 to 1

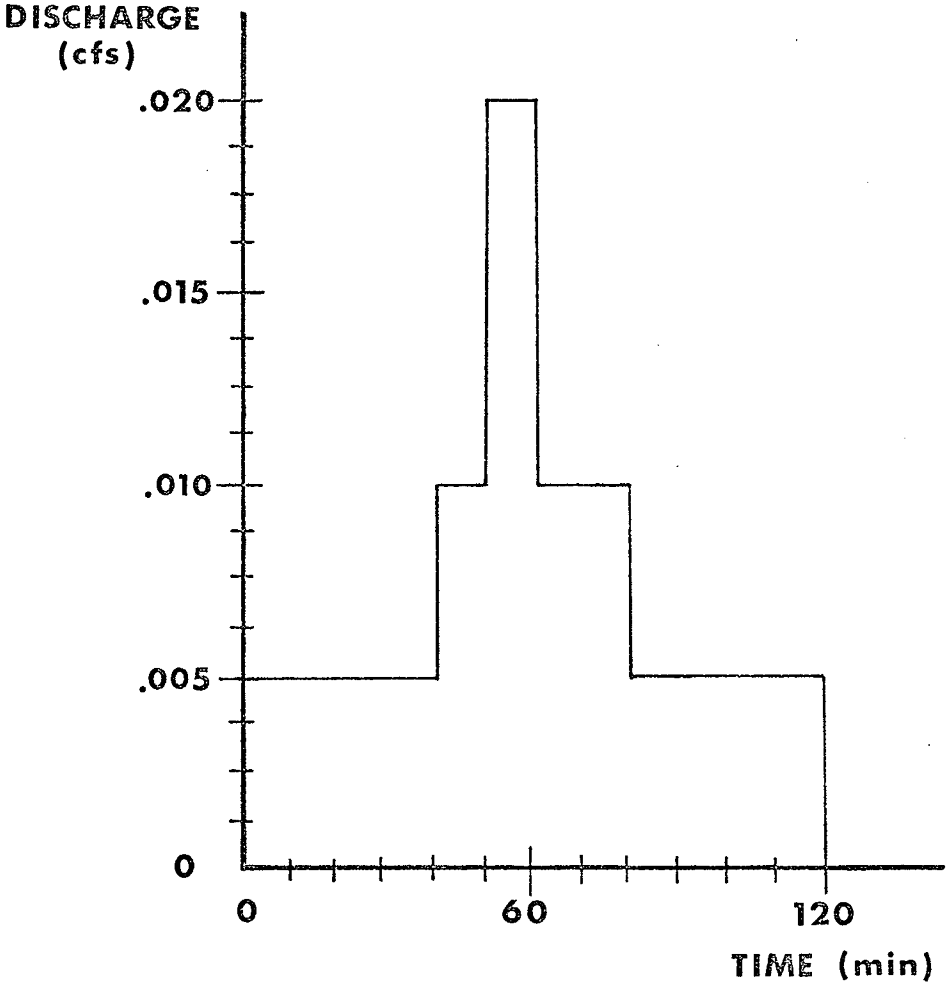


FIGURE F.6
STANDARD HYDROGRAPH

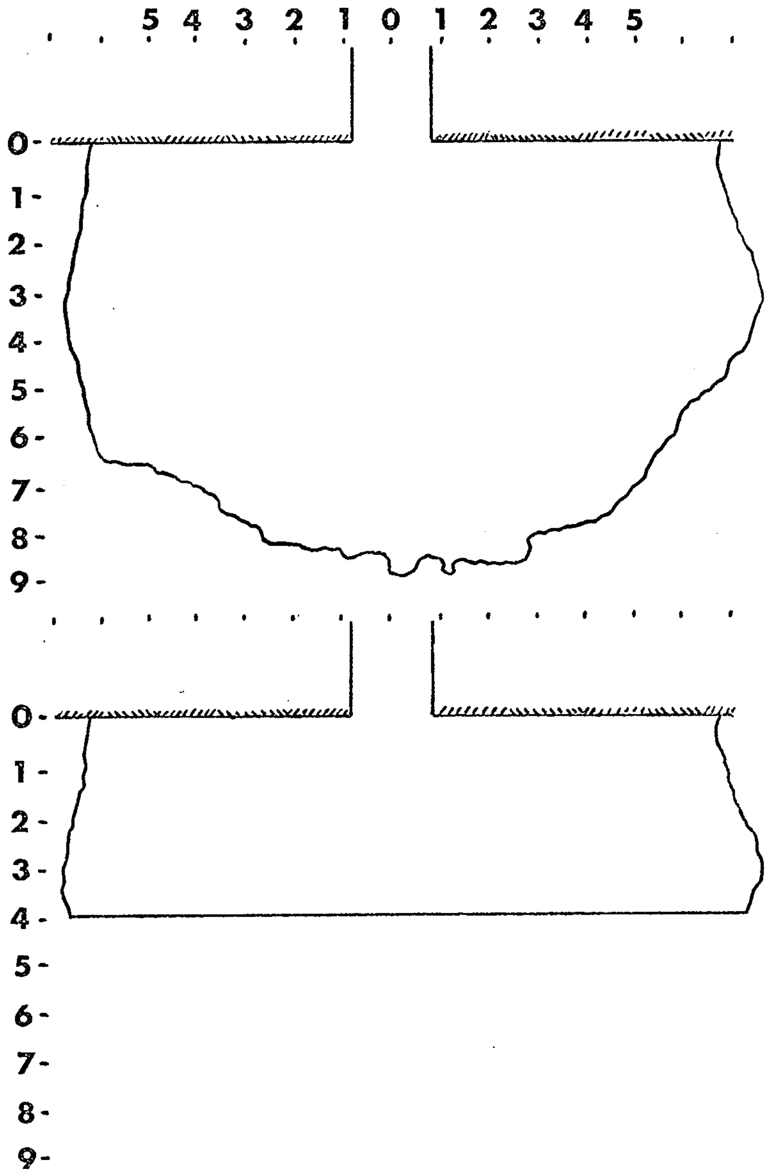


FIGURE F.7

PLAN VIEW OF THE ALLUVIAL FAN PRIOR TO AND AFTER REMOVAL OF THE NOSE (TEST NO. 8)

APPENDIX G

ALASKA DATA

DRILL HOLE LOGS

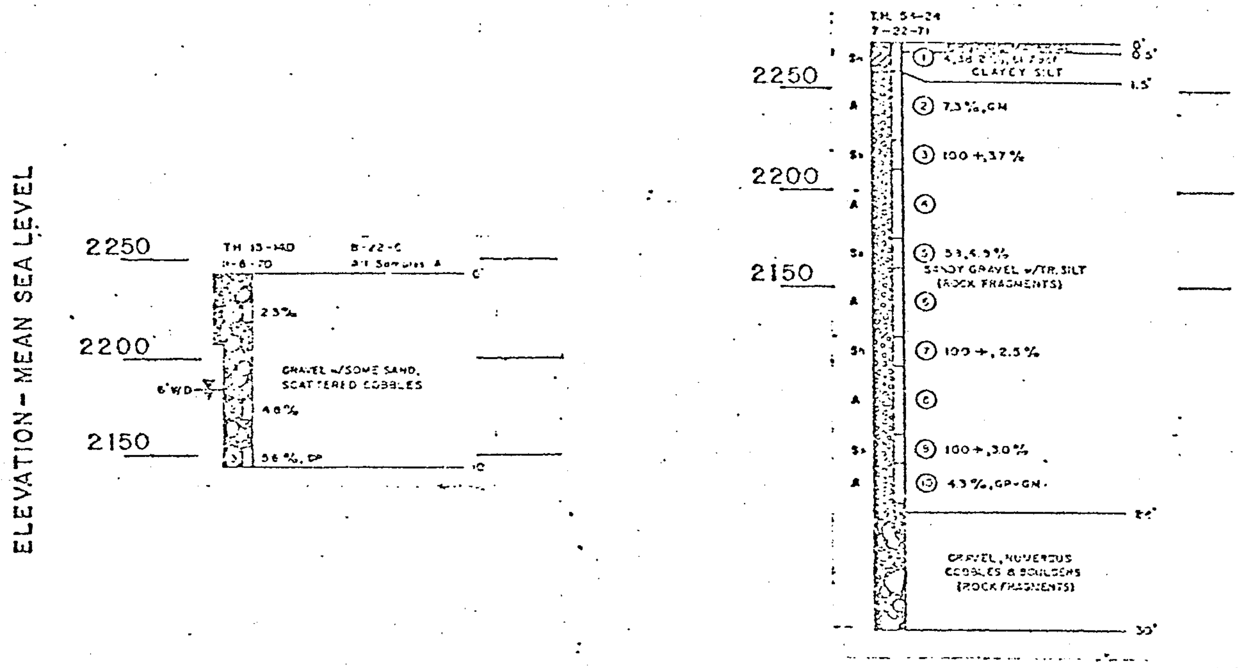
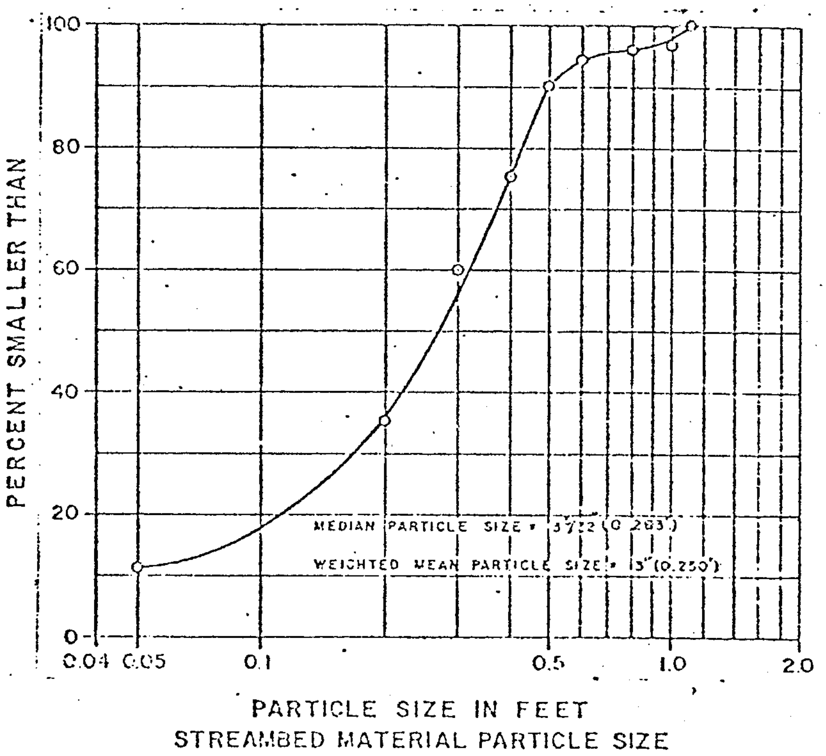


FIGURE G.1

DRILL HOLE LOG - CREEK NO. 1

PHOTOGRAPH NOT AVAILABLE



FIGUREG.2

GRAIN SIZE DISTRIBUTION - CREEK NO. 1

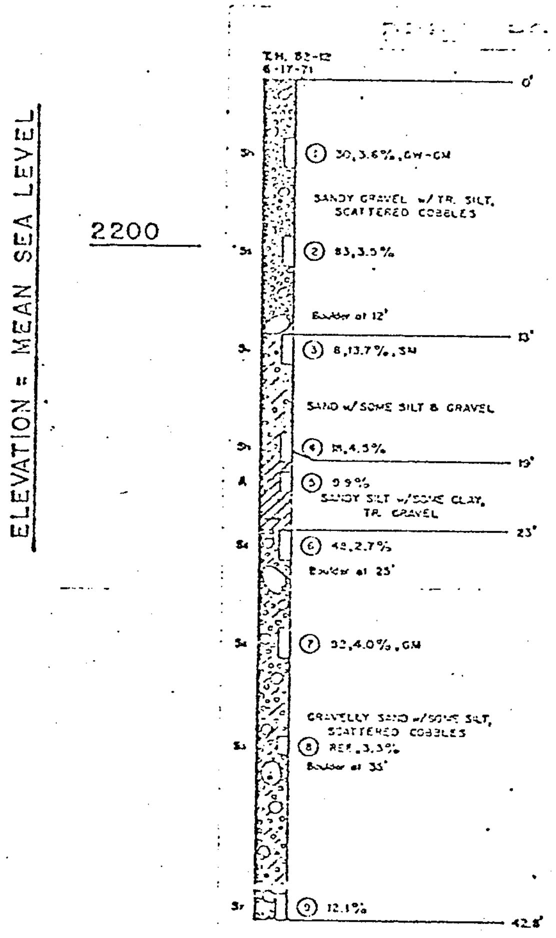
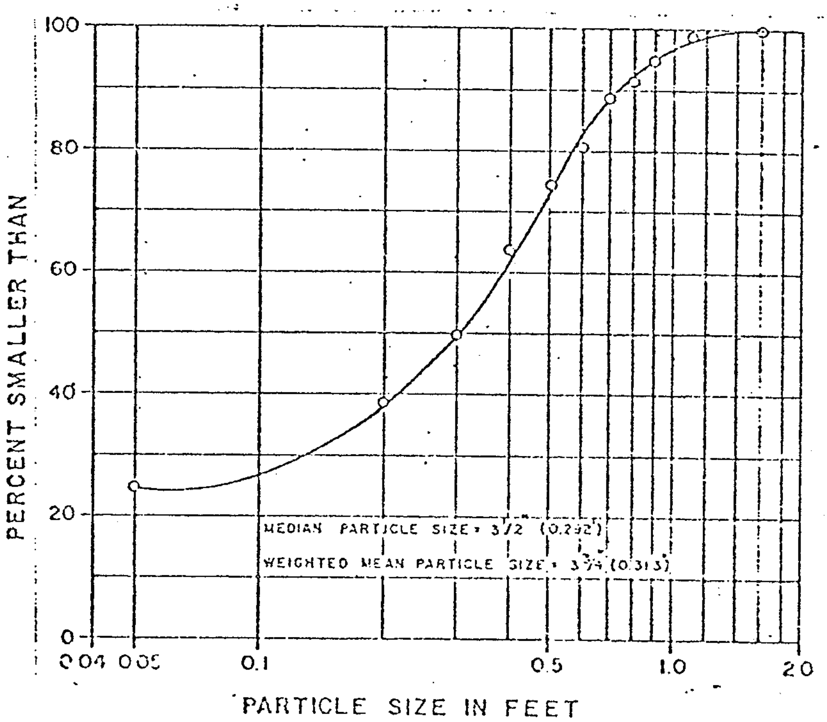


FIGURE G.3

DRILL HOLE LOG – CREEK NO. 2

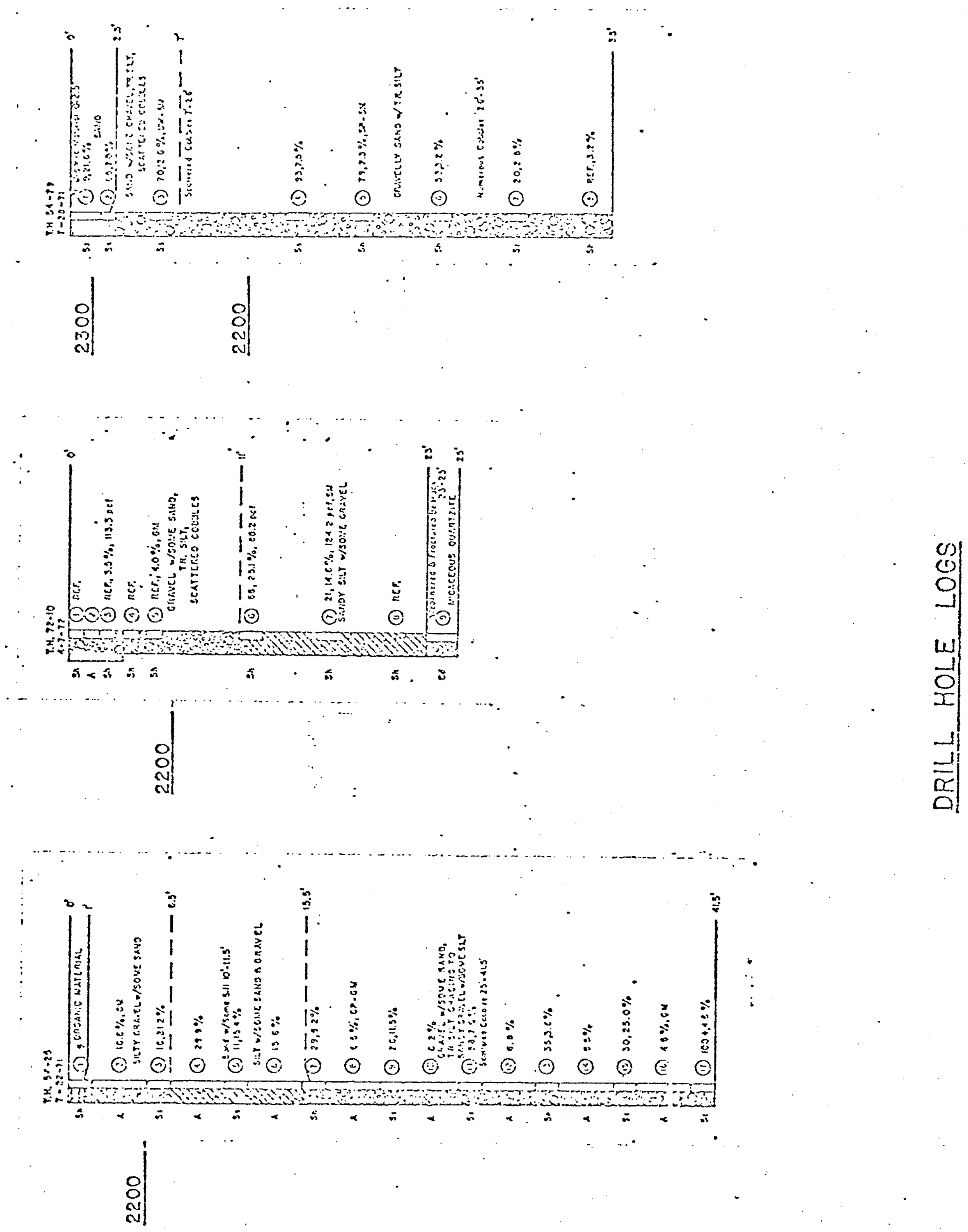
PHOTOGRAPH NOT AVAILABLE



STREAMBED MATERIAL PARTICLE SIZE

FIGURE G.4

GRAIN SIZE DISTRIBUTION – CREEK NO. 2

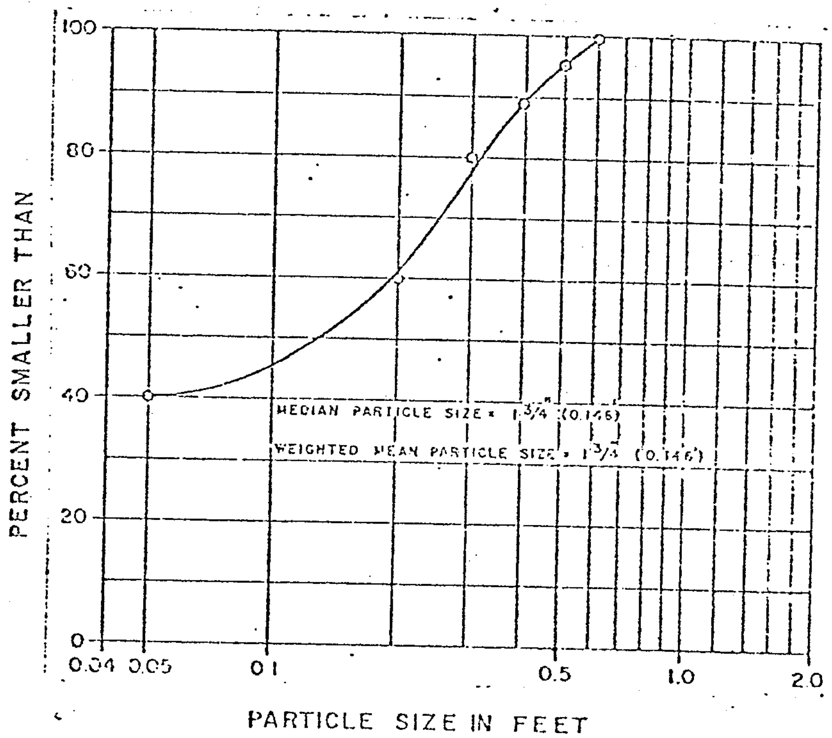


ELEVATION = MEAN SEA LEVEL

FIGURE G.5

DRILL HOLE LOG – CREEK NO. 3

PHOTOGRAPH NOT AVAILABLE



STREAMBED MATERIAL PARTICLE SIZE

FIGURE G.6

GRAIN SIZE DISTRIBUTION – CREEK NO. 3