NTIS
NIOSH-TR-006-73

PB 221 130

SUMMARY FINAL REPORT

An Experimental Study of the Pressure Losses in Converging Flow Fittings Used in Exhaust Systems

College of Engineering
The Ohio State University
Columbus

SUMMARY FINAL REPORT

AN EXPERIMENTAL STUDY OF THE PRESSURE LOSSES IN CONVERGING FLOW FITTINGS USED IN EXHAUST SYSTEMS

by

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The Ohio State Research Foundation

April, 1973

The project upon which this report is based was performed pursuant to Contract No. HSM 099-71-28 with the National Institute for Occupational Safety and Health, Department of Health, Education, and Welfare.

BIBLIOGRAPHIC DATA SHEET	1. Report No. NIOSH-TR-006-1973	2.	3. Recipient's Accession No. PB 221 130
4. Title and Subtitle An Experimental Study Of The Pressure Losses In Converging Flow Fittings Used In Exhaust Systems			5. Report Date April 1973 6.
7. Author(s) Charles F. Sepsy and Donald B. Pies			8. Performing Organization Rept. No.
9. Performing Organization Name and Address The Ohio State Research Foundation College of Engineering The Ohio State University Columbus, Ohio			10. Project/Task/Work Unit No. 11. Contract/Grant No. HSM 099-71-28
12. Sponsoring Organization Name and Address National Institute For Occupational Safety and Health Parklawn Building 5600 Fishers Lane Rockville, Maryland 20852			13. Type of Report & Period Covered Summary Final 14.

15. Supplementary Notes

N/A

16. Abstracts

An investigation was conducted to make pressure drop design data available for commercially marketed converging flow fittings used in industrial ventilation exhaust systems. The investigation included an experimental study and an analytical study. Forty-nine fittings over a wide range of sizes were studied in the experimental phase. The recommended geometry of a converging flow fitting consists of a tapered mainstream with a branch entry angle of thirty or forty-five degrees. The analytical study consisted of developing semi-empirical equations which would be applicable to fittings with tapered mainstreams and thirty, forty-five, or ninety degree branch angles for all combinations of branch, upstream, and downstream diameters.

17. Key Words and Document Analysis. 17a. Descriptors

Exhaust systems, Experimental design, ventilation, nozzles, fittings, statistical study, pressure measurements, pressure reductions, flow rate, reliability, velocity measurement

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group 13/01

18. Availability Statement	19. Security Class (This Report)	21. No. of Pages
Available to the public.	UNCLASSIFIED	52
	20. Security Class (This Page) UNCLASSIFIED	22. Price $3.00/$0.95

FORM NTIS-35 (REV. 3-72) THIS FORM MAY BE REPRODUCED USCOMM-DC 14952-P72

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NOMENCLATURE

Symbol	Description	Dimensions
A_b or AB	cross-sectional area of branch	in. sq.
A_d or AD	cross-sectional area of downstream	in. sq.
A_u or AU	cross-sectional area of upstream	in. sq.
CB	branch loss coefficient	
CB_t	theoretical main loss coefficient	
CM	main loss coefficient	
CM_t	theoretical main loss coefficient	
D_b or DB	diameter of branch	in.
D_d or DD	diameter of downstream	in.
D_u or DU	diameter of upstream	in.
ΔCB	empirical branch loss coefficient correction term	
ΔCM	empirical main loss coefficient correction term	
ΔP_{tbd}	total pressure drop between branch and downstream	in. of H_2O
ΔP_{tud}	total pressure drop between upstream and downstream	in. of H_2O
Q_b or QB	volume flow rate in branch	cfm
Q_d or QD	volume flow rate in downstream	cfm
Q_u or QU	volume flow rate in upstream	cfm
θ	branch angle	
V_b or VB	mean velocity in branch	fpm
V_d or VD	mean velocity in downstream	fpm
V_u or VU	mean velocity in upstream	fpm

INTRODUCTION

There has been a recent demand for pressure drop design data for converging flow fittings used in industrial ventilation exhaust systems. A thorough literature survey showed that existing pressure drop data was sketchy and of questionable reliability.

An investigation was conducted to make pressure drop design data available for commercially marketed converging flow fittings. The investigation included an experimental study and an analytical study. Forty-nine fittings over a wide range of sizes were studied in the experimental phase. The recommended geometry of a converging flow fitting[1] consists of a tapered mainstream with a branch entry angle of thirty or forty-five degrees (see Figure I). The analytical study consisted of developing semi-empirical equations which would be applicable to fittings with tapered mainstreams and thirty, forty-five, or ninety degree branch angles for all combinations of branch, upstream, and downstream diameters.

It was observed that pressure drop design data for converging flow fittings must be expressed in terms of pressure

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[1] Industrial Ventilation, A Manual of Recommended Practice. 1968. Lansing, Michigan: American Conference of Governmental Industrial Hygienists.

drop from upstream to downstream and from branch to downstream where the locations of the upstream, downstream, and branch sections are shown in Figure I. Two dimensionless pressure drop parameters were defined as

$$CB = \Delta P_{tbd}/(V_d/4005)^2 \qquad (1)$$

$$CM = \Delta P_{tud}/(V_d/4005)^2 \qquad (2)$$

where

CB = branch loss coefficient, dimensionless

CM = main loss coefficient, dimensionless

ΔP_{tbd} = total pressure drop at standard conditions from branch to downstream sections, inches of water

ΔP_{tud} = total pressure drop at standard conditions from upstream to downstream sections, inches of water

V_d = mean velocity at the downstream section, fpm

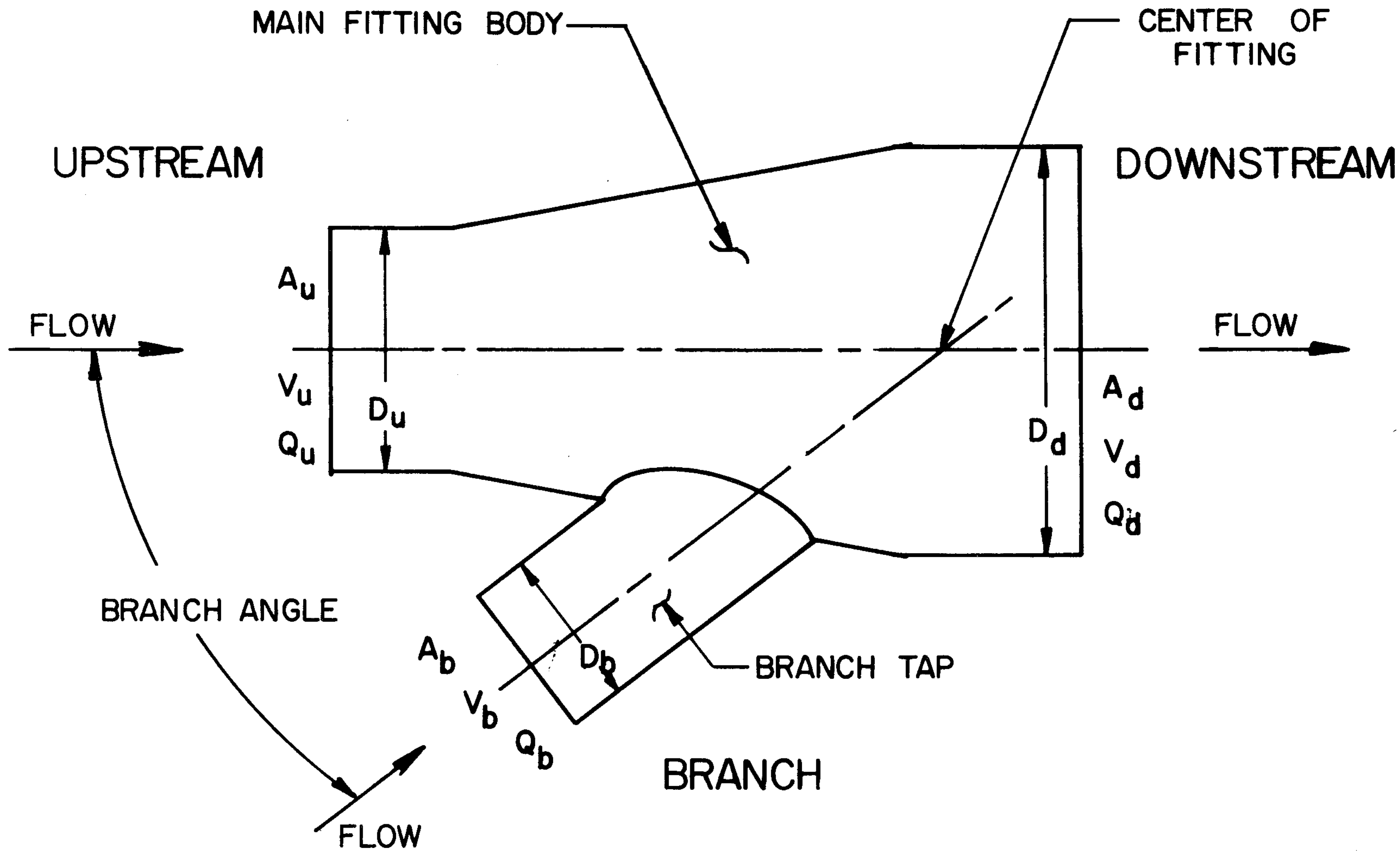


FIGURE I DEFINITION OF PARAMETERS FOR A TYPICAL FITTING

EXPERIMENTAL PROGRAM

Branch and main loss coefficients were determined experimentally for forty-nine different fittings. Both CB and CM were observed to be functions of the ratio of branch to upstream volume flow rate, and each of the fittings studied required a plot of CB versus Q_b/Q_u and CM versus Q_b/Q_u. Branch and upstream diameters varied from three to fourteen inches and the downstream diameter varied from four to sixteen inches. With the exception of three fittings, branch angles were thirty, forty-five, or ninety degrees. Branch velocities ranged from 1000 to 6000 feet per minute, upstream velocities ranged from 1000 to 5000 feet per minute, and the branch to upstream velocity ratio varied from seventy-five hundredths to six. The choice of the combination of take-off diameters was representative of diameter combinations used in practice. Only standard production line fittings were studied in order to assure that data was established for commercial fittings and not laboratory-controlled fittings.

A schematic of the test apparatus is shown in Figure II. Velocity heads and static pressures were measured by Dwyer pitot-static tubes. Pressure readings were taken with Ellison and Meriam inclined manometers with readability to one-hundredth of an inch of water.

All data were corrected to standard density and the friction losses between the measuring stations and the center of the fitting were subtracted from measured pressure drops. Subtracting friction losses standardized the data on a "no-length" basis.

Approximately thirty data points were run per fitting over the range of velocities and velocity ratios previously set forth. The data scatter band was roughly ±3 percent for the branch loss coefficient and ±4 percent for the main loss coefficient.

A detailed description of the experimental study is presented in References 1 and 2.

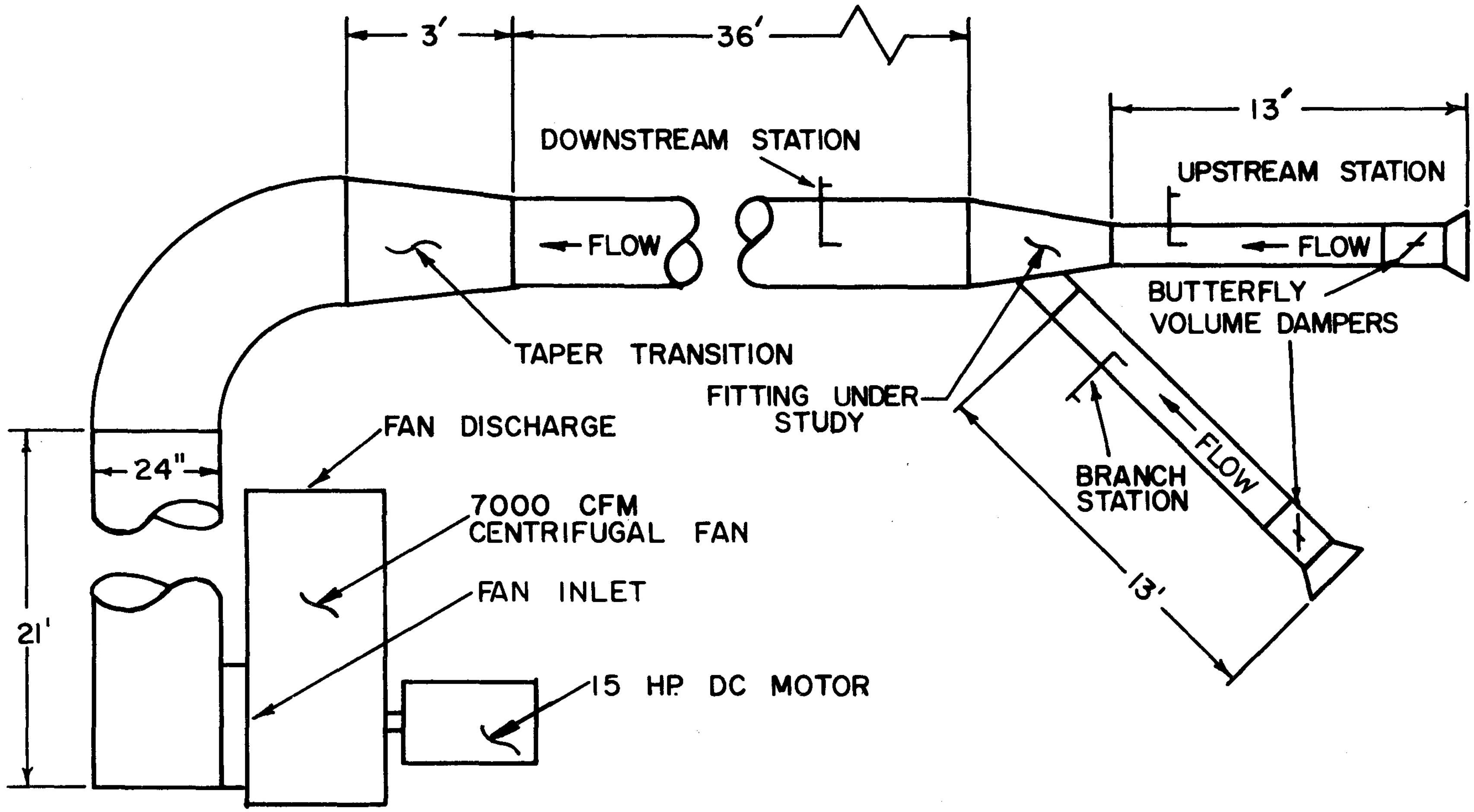


FIGURE II SCHEMATIC DIAGRAM OF TEST APPARATUS

ANALYTICAL EQUATIONS

Analytical equations were needed in order to determine branch and main loss coefficients for fittings not covered in the experimental study. These equations took the form of a theoretical approximation of CB and CM plus an empirical correction term. The semi-empirical analytical equations were

$$CB = CB_t + \Delta CB \quad (3)$$

$$CM = CM_t + \Delta CM \quad (4)$$

CB_t and CM_t were dimensionless theoretical expressions based on a momentum-mass balance which gave first approximations of the branch and main loss coefficients. These theoretical expressions were

$$CB_t = 1.0 + \left(\frac{A_d}{A_b}\frac{Q_b}{Q_d}\right)^2 - 2\frac{A_d}{A_u}\left(\frac{Q_u}{Q_d}\right)^2 - 2\frac{A_d}{A_b}\left(\frac{Q_b}{Q_d}\right)^2 \cos\theta \quad (5)$$

$$CM_t = 1.0 + \left(\frac{A_d}{A_u}\frac{Q_u}{Q_d}\right)^2 - 2\frac{A_d}{A_u}\left(\frac{Q_u}{Q_d}\right)^2 - 2\frac{A_d}{A_b}\left(\frac{Q_b}{Q_d}\right)^2 \cos\theta \quad (6)$$

where Q_b/Q_d and Q_u/Q_d could be put in terms of Q_b/Q_u by

$$Q_b/Q_d = \frac{Q_b/Q_u}{1.0 + Q_b/Q_u} \quad \text{and}$$

$$Q_u/Q_d = \frac{1.0}{1.0 + Q_b/Q_u}$$

The empirical correction terms, ΔCB and ΔCM, were given by the following expressions depending on the branch angle and on downstream diameter for fittings with ninety degree branch angles.

For branch angle = 30°:

$$\Delta CB = \beta_1 Q_b/Q_u + \beta_0 \tag{7}$$

where, $A_r = \dfrac{A_b/A_d}{A_u/A_d} (A_b/A_d + A_u/A_d)$

$$\beta_1 = \frac{0.0111}{A_r - 0.462} \text{ for } A_r \geq 0.56$$

$$\beta_1 = -2.71 A_r + 1.635 \text{ for } A_r < 0.56$$

$$\beta_0 = -1.694 A_u/A_d + 1.172$$

$$\Delta CM = 0.0556 CM_t^2 - 0.0106 CM_t - 0.116 \tag{8}$$

For branch angle = 45°:

$$\Delta CB = \beta_3 \frac{A_u/A_d}{A_b/A_d} Q_b/Q_u + \beta_2 \tag{9}$$

where, $A_{r1} = \dfrac{A_b}{A_d} (A_b/A_d + A_u/A_d)$

$$\beta_3 = -2.15 A_{r1} + 0.838 \text{ for } A_{r1} \leq 0.36$$

$$\beta_3 = -0.118 A_{r1} + 0.10 \text{ for } A_{r1} > 0.36$$

$$\beta_2 = 0.55 \text{ for } A_u/A_d < 0.6$$

$$\beta_2 = -0.03 \text{ for } A_u/A_d \geq 0.6$$

$$\Delta CM = 0.096 CM_t^2 - 0.41 A_u/A_d + 0.109 \tag{10}$$

For branch angle = 90°; downstream diameter $\geq$ 10 inches:

$$\Delta CB = \frac{6.61}{\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u}+2.78} + 0.178\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u}\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}-1.0\right) - 0.089\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}\right) - 1.91 \quad (11)$$

$$\Delta CM = 0.554\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u}\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}\right)^2 - 1.508\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u}\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}\right) + 0.971\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u} - 0.15 \quad (12)$$

For branch angle = 90°; downstream diameter < 10 inches:

$$\Delta CB = \beta_5 \frac{A_u/A_d}{A_b/A_d} Q_b/Q_u + \beta_4 \quad (13)$$

where, $A_{r1} = A_b/A_d\ (A_b/A_d + A_u/A_d)$

$\beta_5 = -1.483\ A_{r1} + 0.544$ for $A_{r1} < 0.4$

$\beta_5 = -0.133\ A_{r1} + 0.003$ for $A_{r1} > 0.4$

$\beta_4 = -0.912\ A_u/A_d + 0.845$

$$\Delta CM = 0.308\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u}\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}\right)^2 - 0.913\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u}\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}\right) + 0.628\frac{A_u/A_d}{A_b/A_d}\frac{Q_b}{Q_u} - 0.417\left(\frac{A_b}{A_d}+\frac{A_u}{A_d}\right) + C \quad (14)$$

where, $C = 0.53$ for $(A_b/A_d + A_u/A_d) \geq 1.2$

$C = 0.735$ for $(A_b/A_d + A_u/A_d) \leq 1.2$

It was observed that ΔCM was difficult to correlate for ninety degree branch angles over the entire range of downstream diameters investigated. It was also noted that ΔCM for ninety degree fittings with downstream diameters less than ten inches could, at best, only be given by an expression which gave approximate values of ΔCM. This ninety degree branch angle case for downstream diameters less than ten inches also showed ΔCM became quite unreliable for low and high values of Q_b/Q_u. It was decided that the curves for CM could be most accurately determined by making linear extrapolations from the analytical curves described over $0.6 \leq Q_b/Q_u \leq 2.4$ rather than describing CM over the entire range of Q_b/Q_u by the analytical expressions.

Table I lists the equation numbers pertaining to ΔCB and ΔCM for different branch angles and specifies the reliability restrictions based on comparison between the analytical equations and the experimental data. It was not felt appropriate to simply specify one uncertainty tolerance limit on the analytical branch and main loss coefficients for the general case. Reliability was observed to depend on A_b/A_d, A_u/A_d, branch angle, Q_b/Q_u, and downstream diameter. Nevertheless, the analytical equations were felt to give loss coefficients within roughly five to twenty percent of the actual values for production fittings.

TABLE I

EQUATION NUMBERS FOR ΔCB AND ΔCM

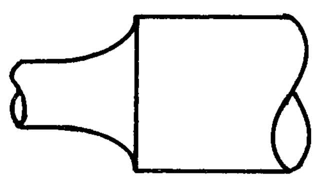
θ	ΔCB	ΔCM	Reliability Restrictions
30	7	8	
45	9	10	
90	11	12	ΔCB and ΔCM only for the downstream diameters $\geq$ 10 inches
90	13	14	ΔCB and ΔCM only for the downstream diameters < 10 inches, ΔCM only for $0.6 \leq Q_b/Q_u \leq 2.4$

CONCLUSIONS

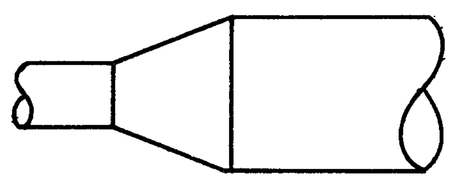
An analysis in Reference 1 studied the effects on the branch and main loss coefficients for variable branch angle. The branch, upstream, and downstream diameters were fixed and six branch angles were tried over the range from fifteen to ninety degrees. It was observed that as the branch angle increased, both the branch and main loss coefficients increased. A check was conducted to determine if the analytical branch and main loss coefficient equations (equations 3 and 4) could be used for angles other than thirty, forty-five, or ninety degrees without deriving new correction terms. Analytical branch and main loss coefficients were evaluated for branch angle equal to fifteen degrees with empirical corrections from equations 7 and 8. These values were compared with the experimental data for the fifteen degree branch angle fitting, but agreement was not felt close enough to deduce that the analytical expressions were valid for fifteen degree branch angles. The same check was made between the analytical equations (using correction terms from equations 9 and 10) and the experimental data for the sixty degree branch angle fitting. Significant deviations were also observed for this sixty degree branch angle case. It was felt the analytical expressions should not be used for branch angles other than thirty, forty-five, or ninety degrees unless new empirical correction terms were derived for the particular branch angle desired.

Observation of the generalized curves in the Appendix showed the following: the branch loss coefficient increased for decreasing A_b/A_d and/or increasing A_u/A_d for all branch angles; the main loss coefficient increased for increasing A_b/A_d and/or decreasing A_u/A_d for thirty and forty-five degree branch angles; and the main loss coefficient followed no definite trends for variable A_b/A_d and/or A_u/A_d for ninety degree branch angles.

Among the forty-nine fittings studied in the experimental investigation, four fittings had nozzle type reducers at the branch and/or upstream take-off. A nozzle type reducer is compared with a taper reducer in Figure III.



Nozzle Reducer



Taper Reducer

FIGURE III

For the four cases, branch diameter equaled four inches, upstream diameter equaled six inches, and the downstream diameter equaled eight inches. Further fitting descriptions and the respective fitting identification codes were: CON-T-1R-P, nozzle reducer branch, nozzle reducer upstream, ninety degree branch angle; T-1R-C, constant diameter branch, nozzle reducer upstream, ninety degree branch angle; L-1R-I, constant diameter branch, nozzle reducer upstream, forty-five degree branch angle; and CON-T-1RT-F, nozzle reducer branch, taper reducer mainstream, ninety degree branch angle. In general, when the fittings with nozzle type reducers were compared with the fittings with taper type reducers (using the same corresponding take-off diameters and branch angle), the loss coefficients were lower for fittings with the nozzle reducers. An attempt was made to extract a general trend between the loss coefficients of nozzle reducer fittings and the loss coefficients of taper reducer fittings. It was hoped this trend could be found because loss coefficients for nozzle reducer fittings could then be analytically determined since analytical expressions had already been derived for taper reducer fittings. Unfortunately, deviations between nozzle and taper reducer fitting loss coefficients were somewhat random for the four cases studied, and it was felt that several more nozzle reducer fittings must be tested before well defined trends could be established.

The concept of a negative loss coefficient might seem unfeasible because this would imply a total pressure increase in the direction of flow and a violation of conservation of energy. However, occurrence of a negative branch loss coefficient is seen when the upstream flow rate is high enough compared to the branch flow rate that the upstream flow can add sufficient energy to the flow between the branch and downstream to cause an increase in total pressure. The same argument holds for a negative main loss coefficient where the branch flow rate is great enough compared to the up-stream flow rate that the branch flow adds sufficient energy to the mainstream flow to cause an increase in total pressure between the upstream and downstream.

EXAMPLE

The following information is given for a converging flow fitting:

Q_b = 600 cfm

Q_u = 400 cfm

D_b = 6"

D_u = 9"

D_d = 10"

branch angle = 45°

density of the air = 0.068 lbm/ft^3

Find the total and static pressure drops for the branch to downstream and upstream to downstream sections.

Q_b/Q_u =1.5; A_b/A_d = 0.36; A_u/A_d = 0.81

From Figure A-21, CB = 2.2; from Figure A-22, CM = -0.72

$Q_d = Q_b + Q_u$ = 1000 cfm

A_d = 78.6 in^2

$V_d = Q_d/A_d$ = 1832 fpm

From equations 1 and 2, the total pressure drops for the branch to downstream and upstream to downstream at standard density (0.075 lbm/ft^3) are:

$$\left[\Delta P_{tbd}\right] \text{std} = CB \left(\frac{V_d}{4005}\right)^2 = 0.46 \text{ in. } H_2O$$

$$\left[\Delta P_{tud}\right] \text{std} = CM \left(\frac{V_d}{4005}\right)^2 = -0.151 \text{ in. } H_2O$$

Correcting pressure drops for the density equal to 0.068 lbm/ft^3:

$$\Delta P_{tbd} = (0.068/0.075) \left[P_{tbd}\right] \text{std} = 0.417 \text{ in. } H_2O$$

$$\Delta P_{tud} = (0.068/0.075) \left[P_{tud}\right] \text{std} = -0.136 \text{ in. } H_2O$$

Now, expressions will be derived for determining the static pressure drop. Since total pressure is defined as the sum of velocity head and static pressure, the branch and main loss coefficients may be expressed as:

$$CB = \frac{(H_{vb} - H_{vd}) + (P_b - P_d)}{(V_d/4005)^2}$$

$$CM = \frac{(H_{vu} - H_{vd}) + (P_u - P_d)}{(V_d/4005)^2}$$

Also, at standard density,

$$H_{vb} = (V_b/4005)^2 \ , \quad H_{vu} = (V_u/4005)^2 \ , \quad H_{vd} = (V_d/4005)^2 \ ,$$

giving

$$CB = \left(\frac{V_b}{V_d}\right)^2 - 1 + \frac{P_b - P_d}{(V_d/4005)^2}$$

$$CM = \left(\frac{V_u}{V_d}\right)^2 - 1 + \frac{P_u - P_d}{(V_d/4005)^2}$$

and knowing $V_b/V_d = (A_d/A_b)(Q_b/Q_d)$, $V_u/V_d = (A_d/A_u)(Q_u/Q_d)$,

$$Q_b/Q_d = \frac{Q_b/Q_u}{1.0 + Q_b/Q_u} \ , \quad Qu/Qd = \frac{1.0}{1.0 + Qb/Qu}$$

the static pressure drops are given (at standard density) by

$$[P_b - P_d]_{std} = (V_d/4005)^2 \left\{ 1.0 + CB - \left(\frac{Q_b/Q_u}{A_b/A_d(1 + Q_b/Q_u)} \right)^2 \right\} . \tag{15}$$

$$[P_u - P_d]_{std} = (V_d/4005)^2 \left\{ 1.0 + CM - \left(\frac{1.0}{A_u/A_d(1 + Q_b/Q_u)} \right)^2 \right\} \tag{16}$$

Substituting numerical values from this example into equations 15 and 16 gives

$$[P_b - P_d]_{std} = \left(\frac{1832}{4005}\right)^2 \left\{1.0 + 2.2 - \left(\frac{1.5}{0.36(1 + 1.5)}\right)^2\right\}$$

$$= 0.088 \text{ in. } H_2O$$

$$[P_u - P_d]_{std} = \left(\frac{1832}{4005}\right)^2 \left\{1.0 + (-0.72) - \left(\frac{1.0}{0.81(1 + 1.5)}\right)^2\right\}$$

$$= 0.008 \text{ in. } H_2O$$

Correcting pressure drops for density equal to 0.068 lbm/ft^3:

$$P_b - P_d = \frac{0.068}{0.075} [P_b - P_d]_{std} = 0.081 \text{ in. } H_2O$$

$$P_u - P_d = \frac{0.068}{0.075} [P_u - P_d]_{std} = 0.007 \text{ in. } H_2O$$

∴ Total pressure drops:

$\Delta P_{tbd} = 0.417$ in. H_2O

$\Delta P_{tud} = -0.136$ in. H_2O

Static pressure drops:

$P_b - P_d = 0.081$ in. H_2O

$P_u - P_d = 0.007$ in. H_2O

LIST OF REFERENCES

1. Sepsy, C.F., Lauvray, T.L., An Experimental Study of the Pressure Losses in Converging Flow Fittings Used in Exhaust Systems. Phase Report Number One. (Contract No. HSM 099-71-28 with the National Institute for Occupational Safety and Health, H.E.W.). The Ohio State Research Foundation. Dec., 1971.

2. Sepsy, C.F., Pies, D.B., An Experimental Study of the Pressure Losses in Converging Flow Fittings Used in Exhaust Systems. Phase Report Number Two. (Contract No. HSM 099-71-28 with the National Institute for Occupational Safety and Health, H.E.W.). The Ohio State Research Foundation. June, 1972.

3. Sepsy, C.F., Pies, D.B., An Experimental Study of the Pressure Losses in Converging Flow Fittings Used in Exhaust Systems. Final Report. (Contract No. HSM 099-71-28 with the National Institute for Occupational Safety and Health, H.E.W.). The Ohio State Research Foundation. Dec., 1972.

APPENDIX

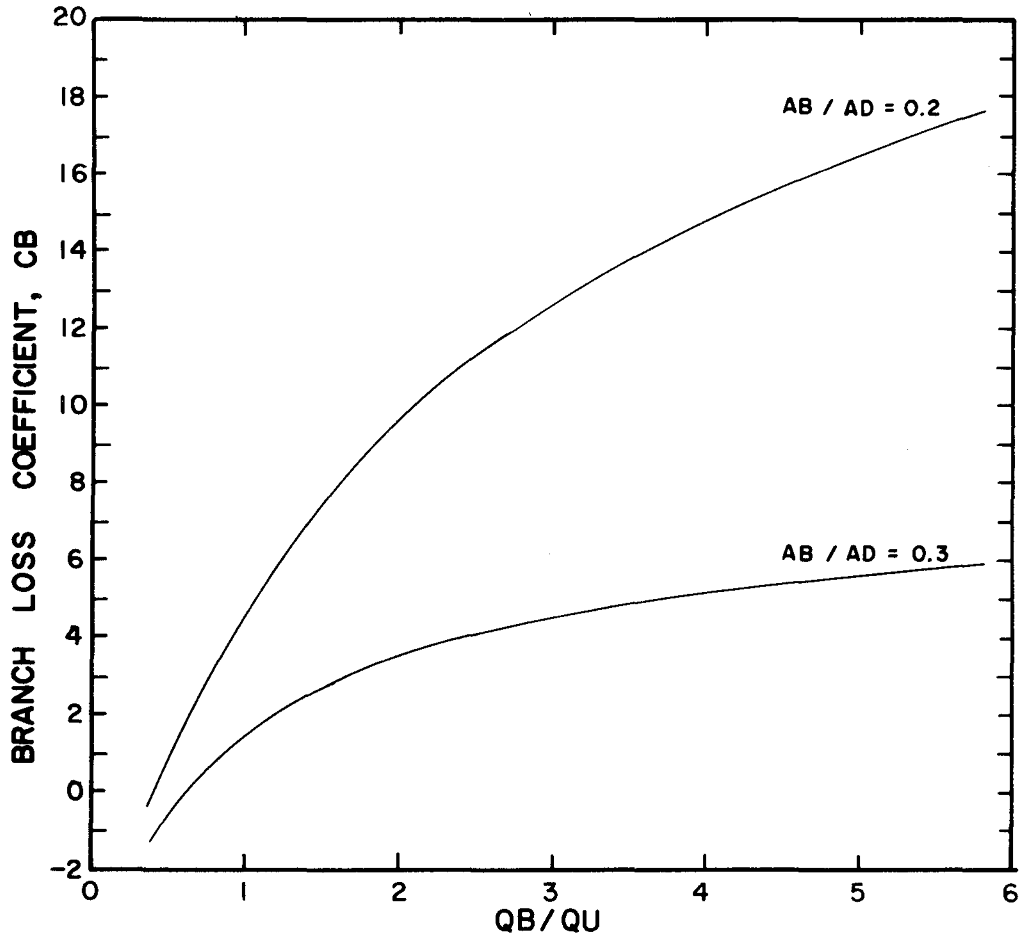


FIGURE A-1 BRANCH ANGLE=30°, AU/AD=0.3

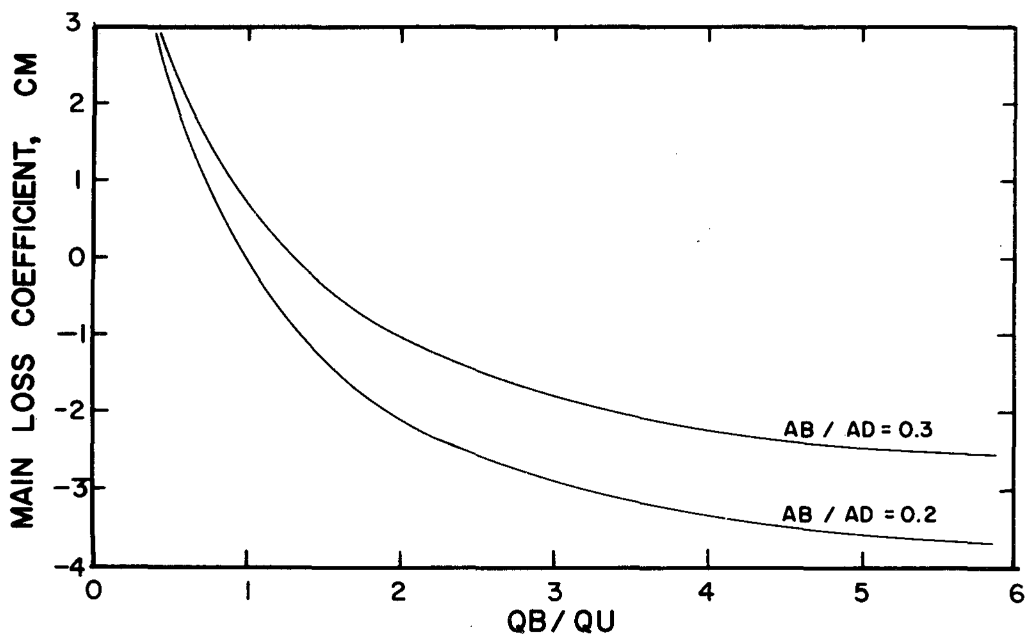


FIGURE A-2 BRANCH ANGLE=30°, AU / AD=0.3

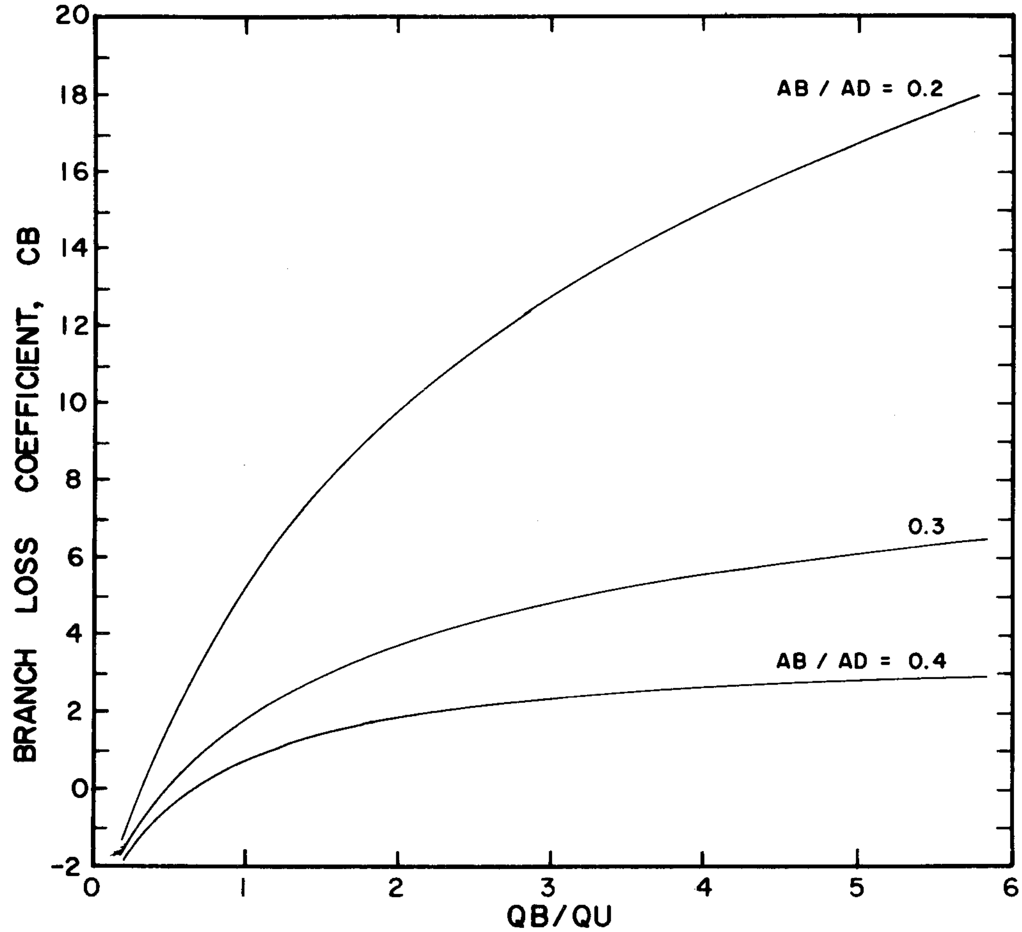


FIGURE A-3 BRANCH ANGLE=30°, AU/AD=0.4

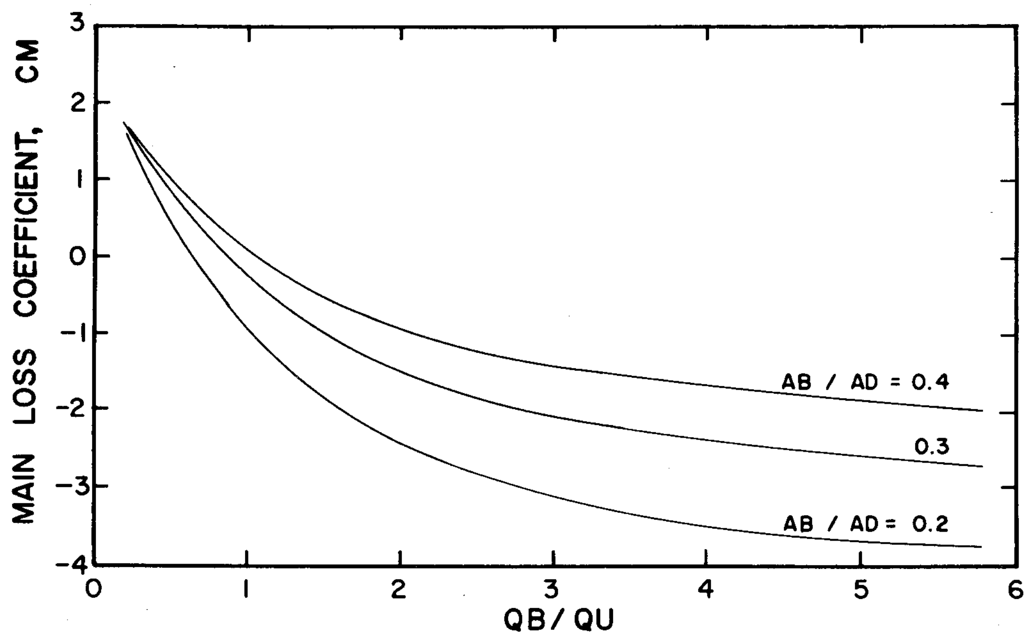


FIGURE A-4 BRANCH ANGLE=30°, AU/AD=0.4

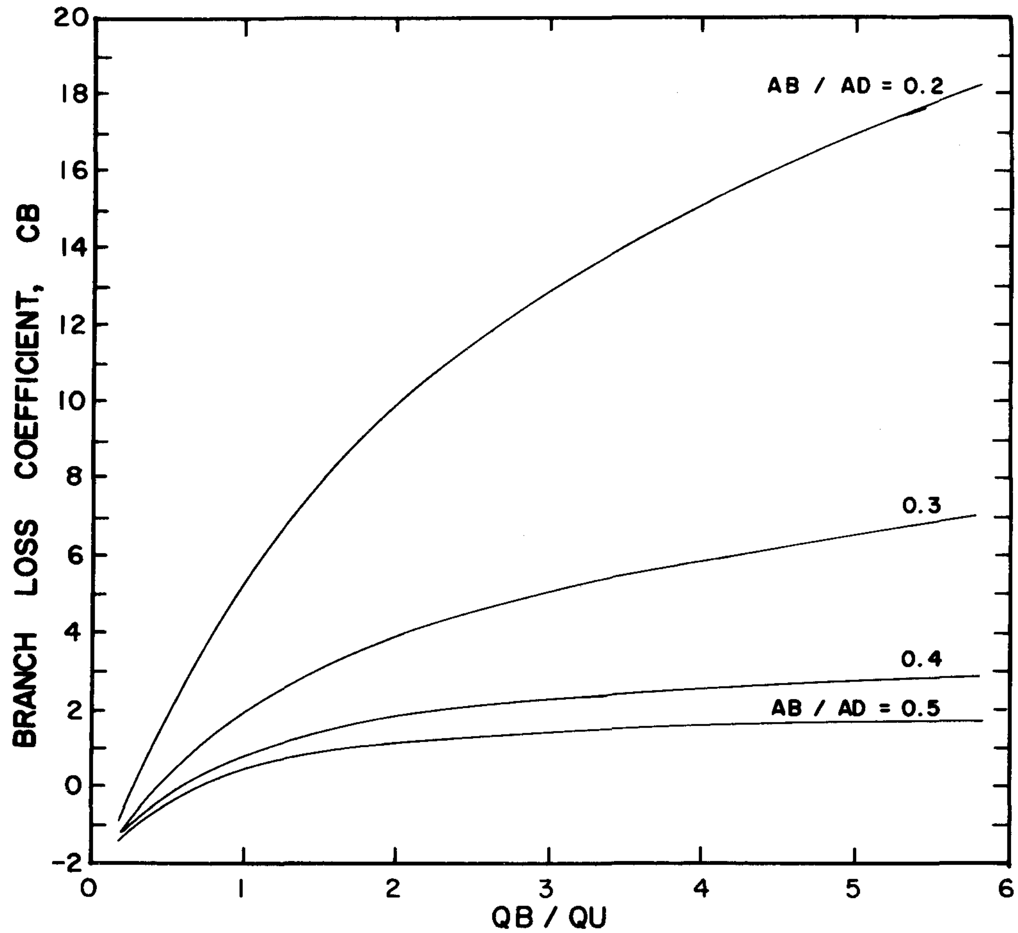


FIGURE A-5 BRANCH ANGLE=30°, AU/AD= 0.5

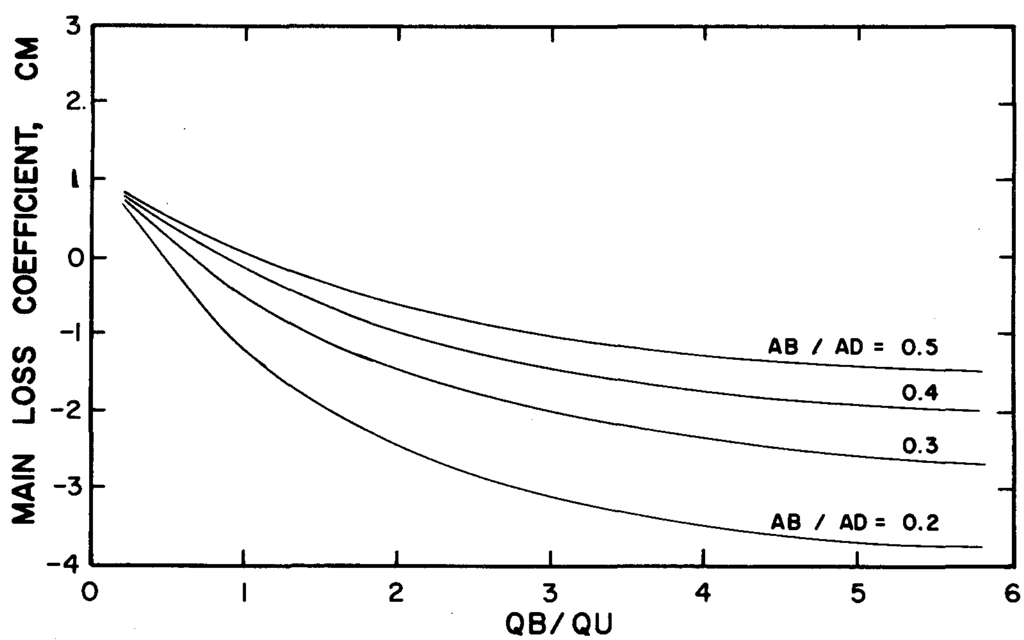


FIGURE A-6 BRANCH ANGLE=30°, AU/AD=0.5

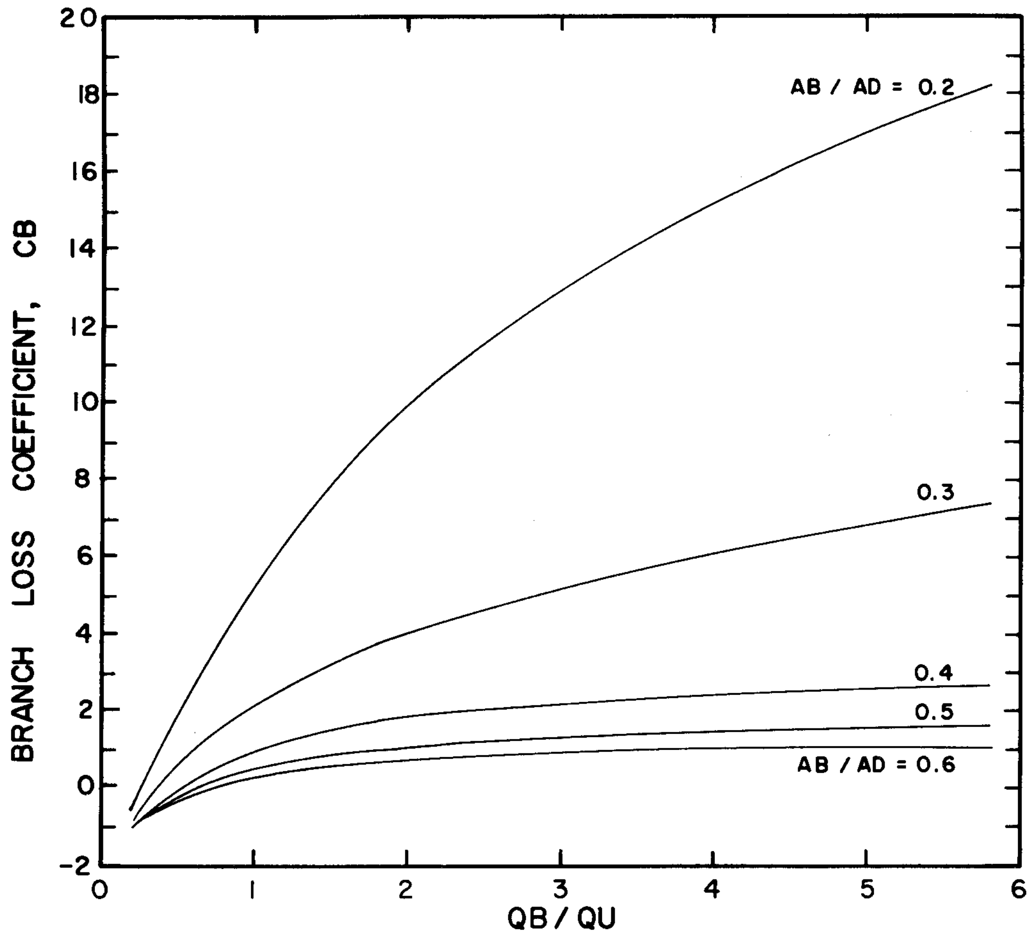


FIGURE A-7 BRANCH ANGLE=30°, AU/AD=0.6

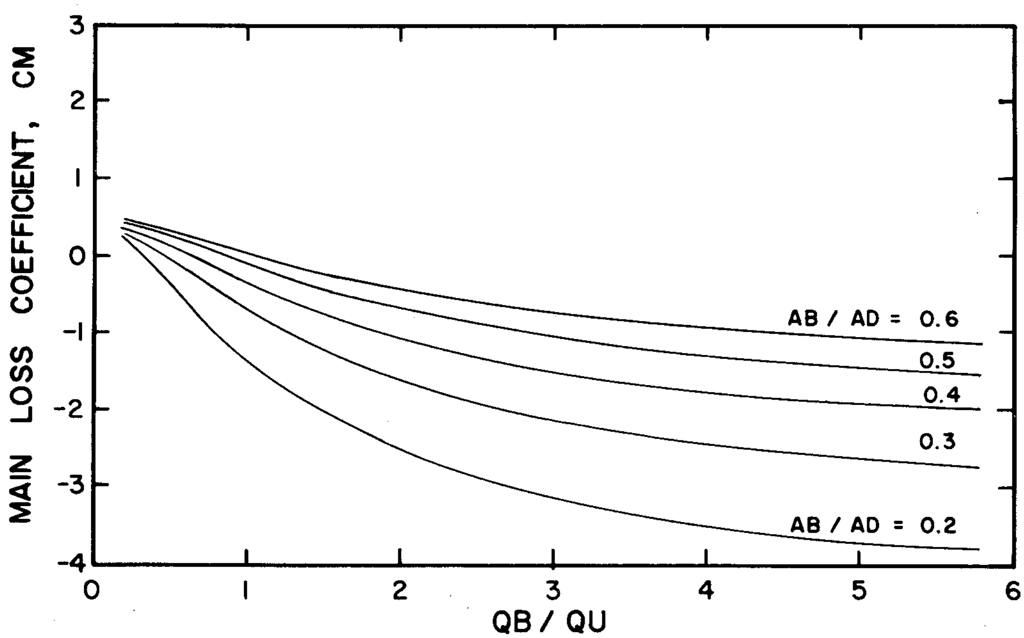


FIGURE A-8 BRANCH ANGLE=30°, AU/AD=0.6

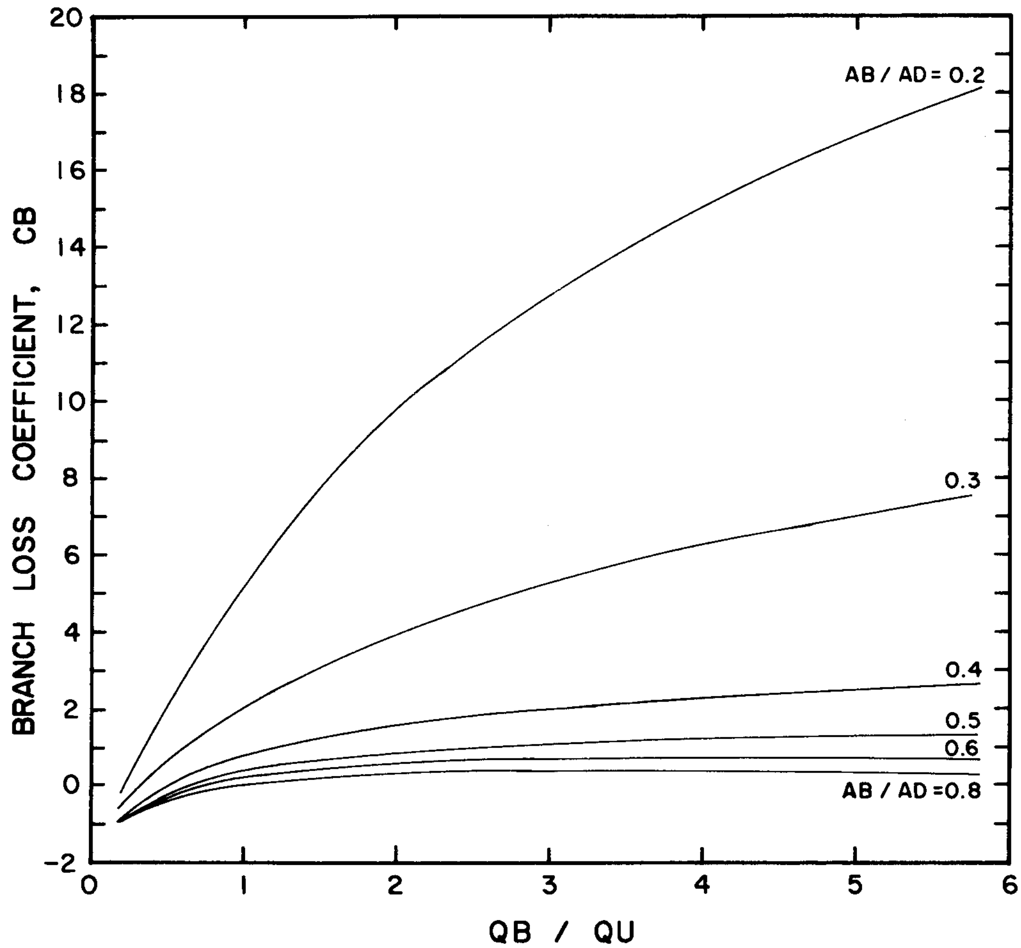


FIGURE A-9 BRANCH ANGLE = 30°, AU / AD = 0.8

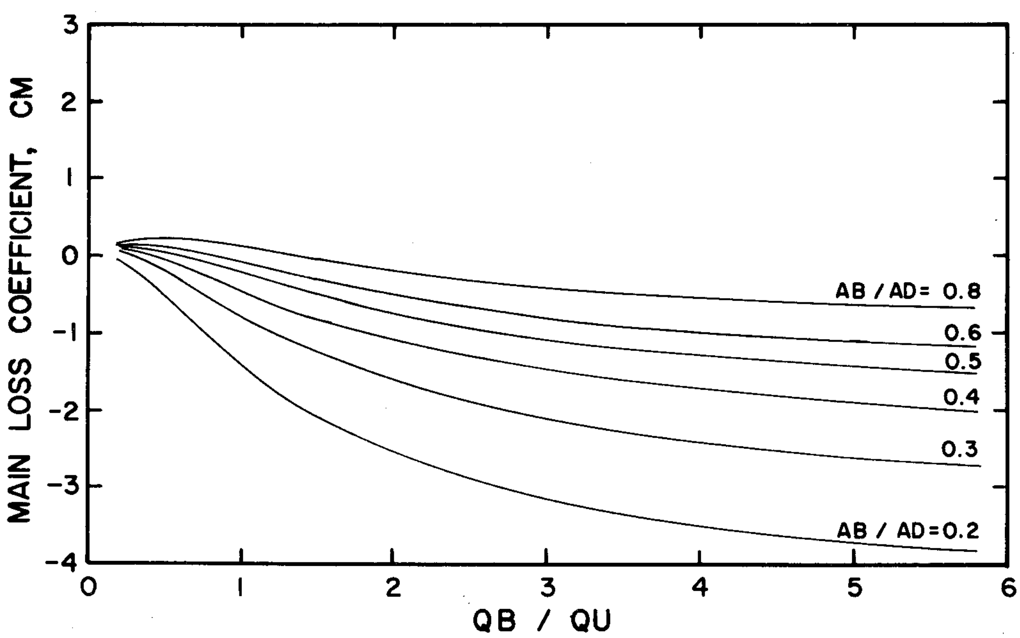


FIGURE A-10 BRANCH ANGLE = 30°, AU / AD = 0.8

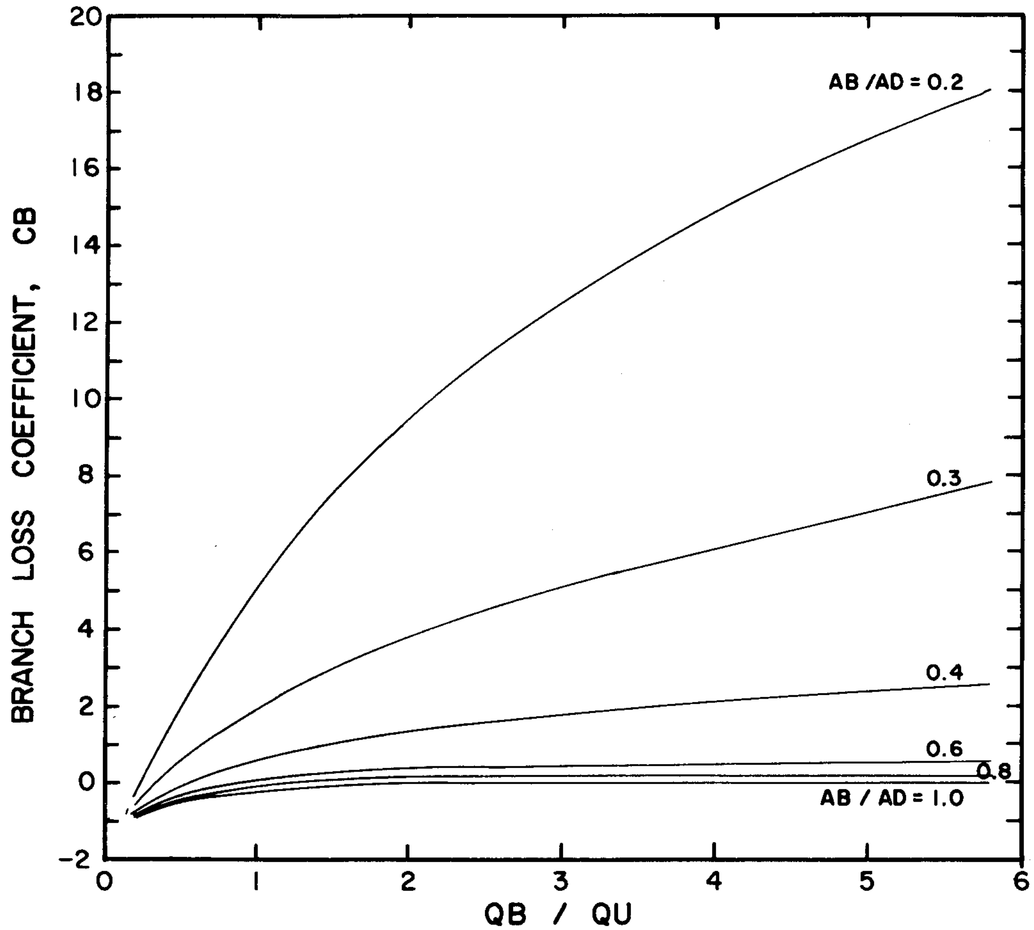


FIGURE A-11 BRANCH ANGLE = 30°, AU / AD = 1.0

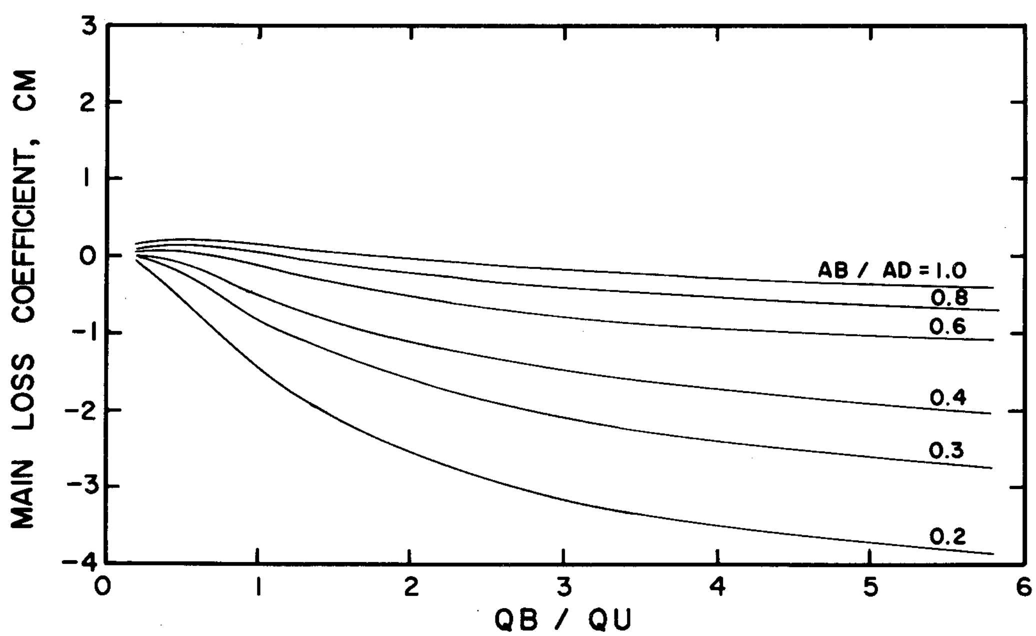


FIGURE A-12 BRANCH ANGLE = 30°, AU / AD = 1.0

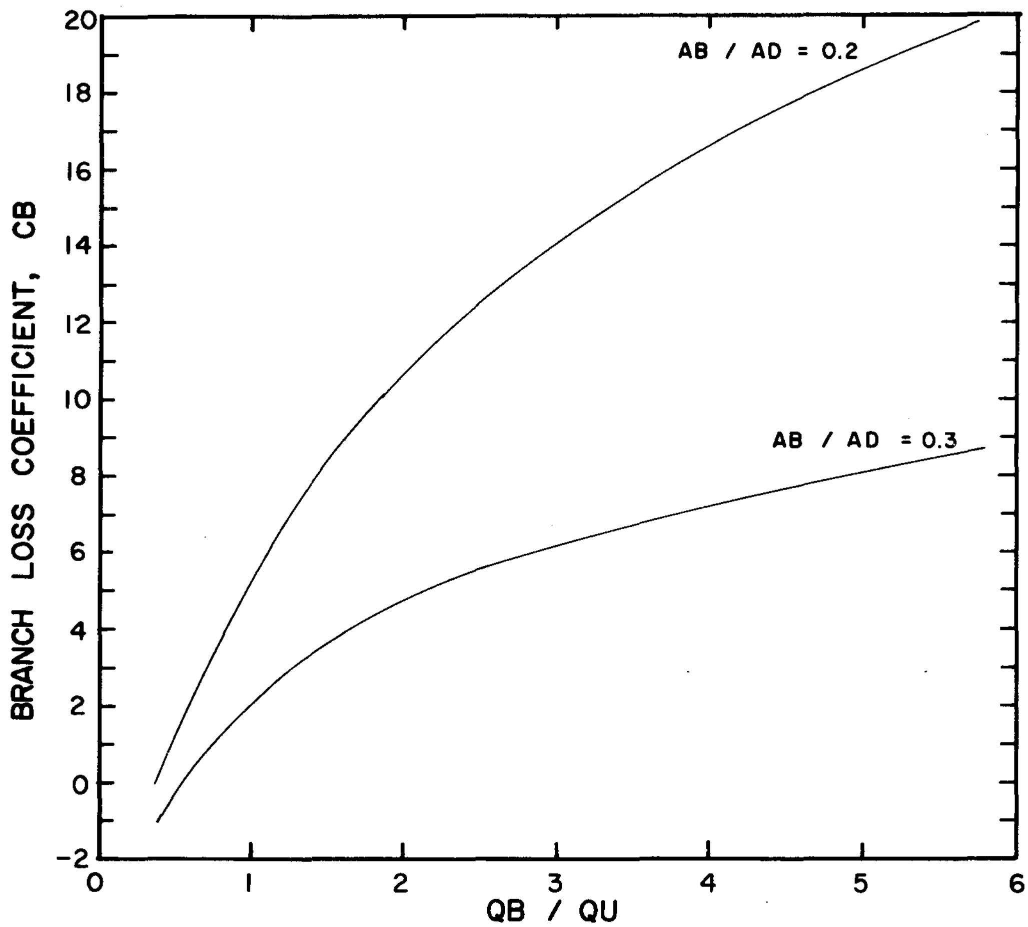


FIGURE A-13 BRANCH ANGLE = 45°, AU / AD = 0.3

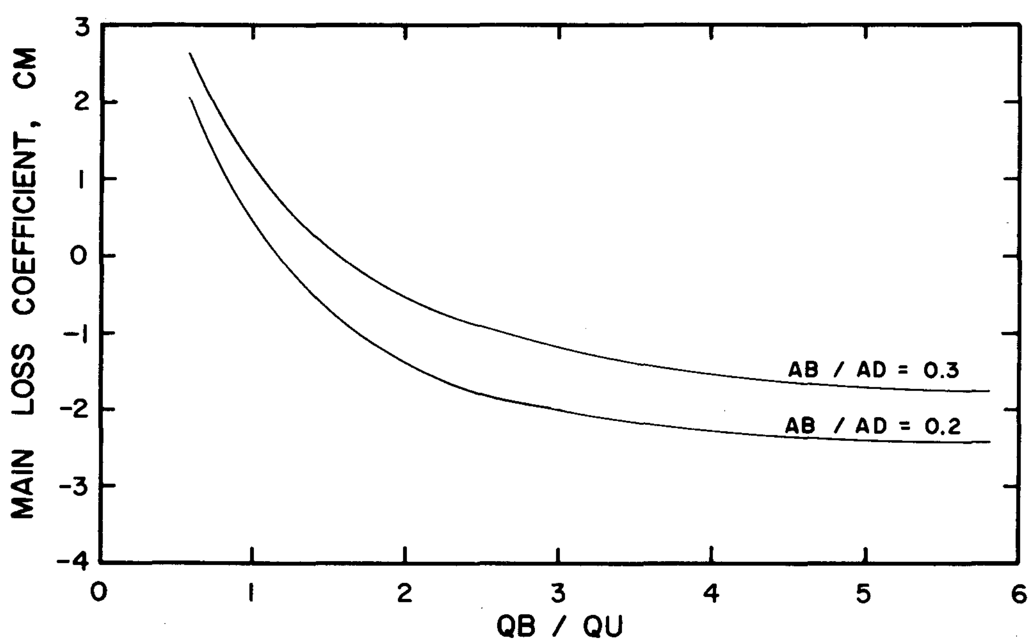


FIGURE A-14 BRANCH ANGLE = 45°, AU / AD = 0.3

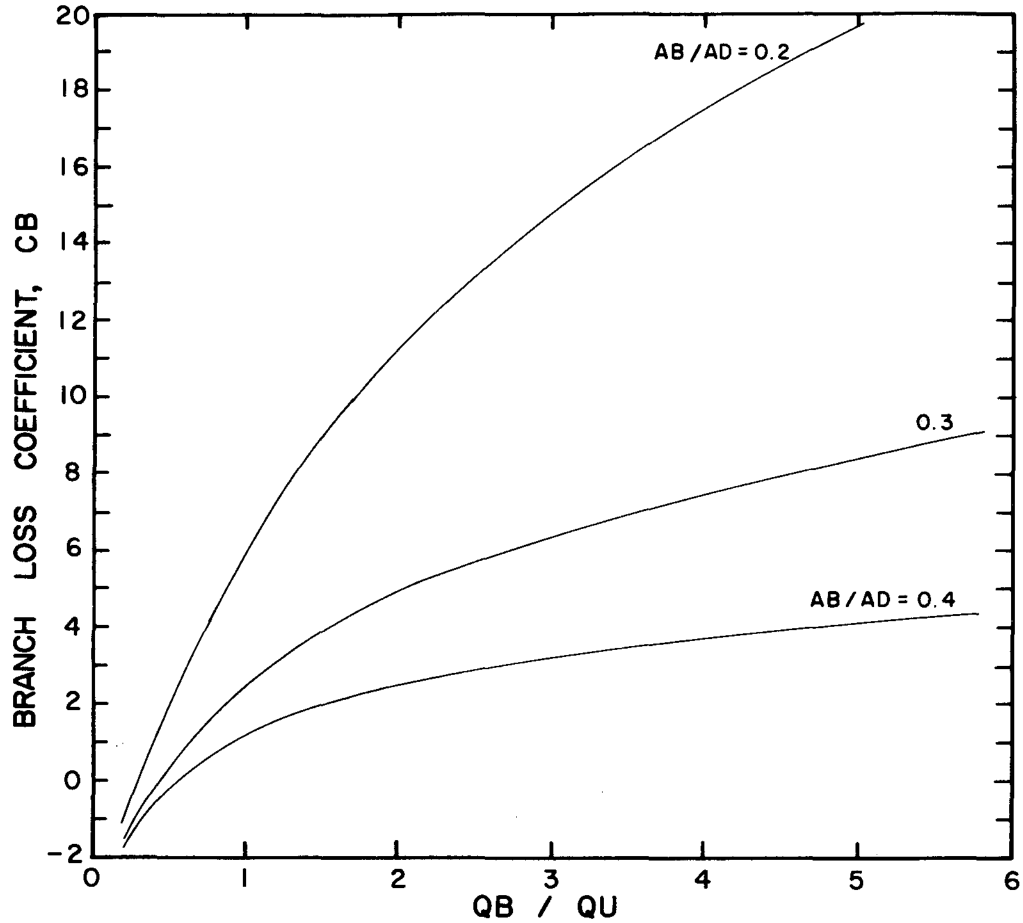


FIGURE A-15 BRANCH ANGLE=45°, AU / AD=0.4

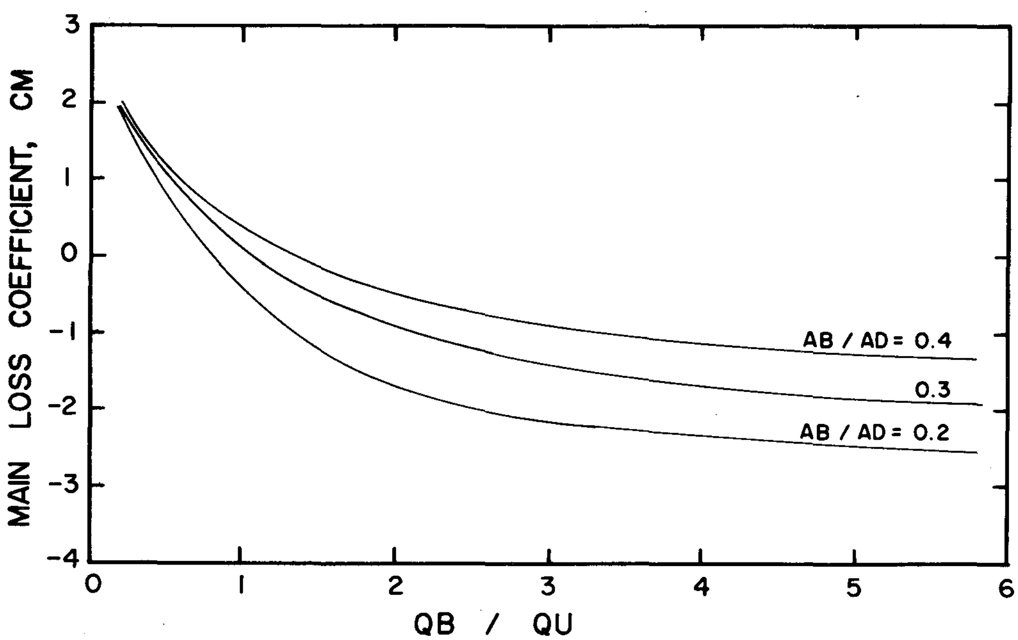


FIGURE A-16 BRANCH ANGLE=45°, AU / AD = 0.4

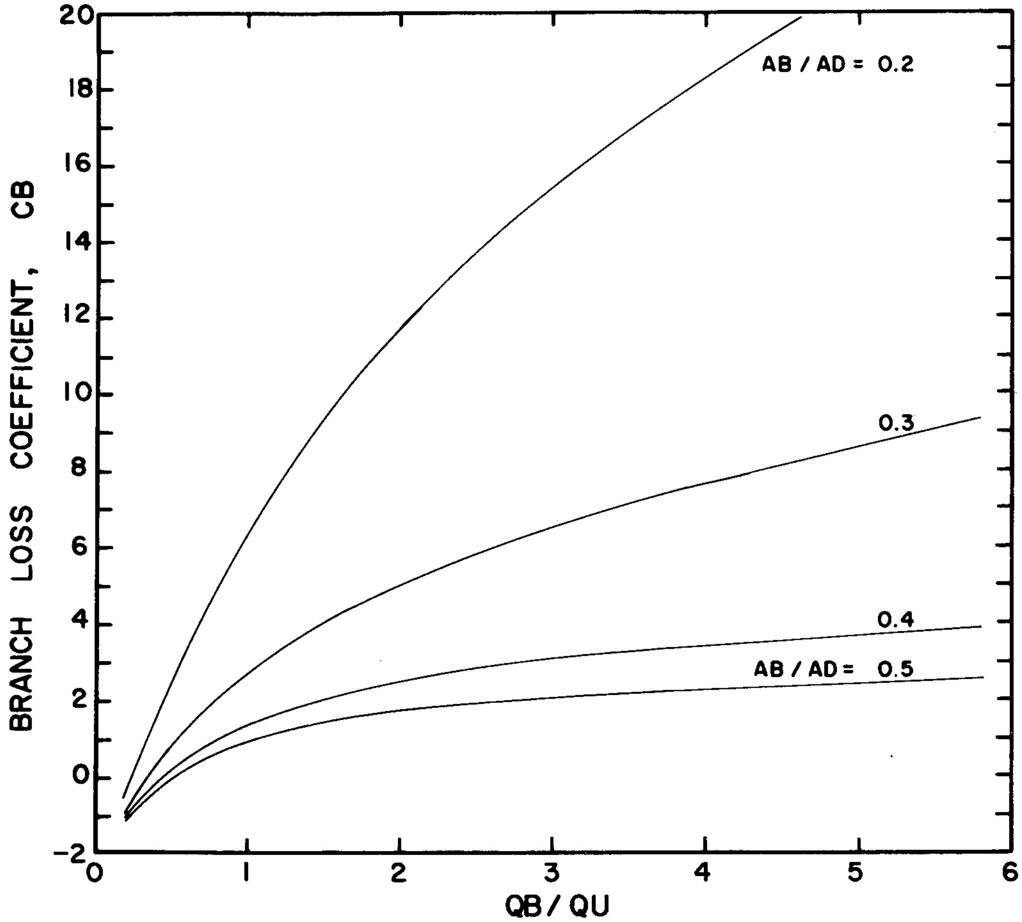


FIGURE A-17 BRANCH ANGLE = 45°, AU / AD = 0.5

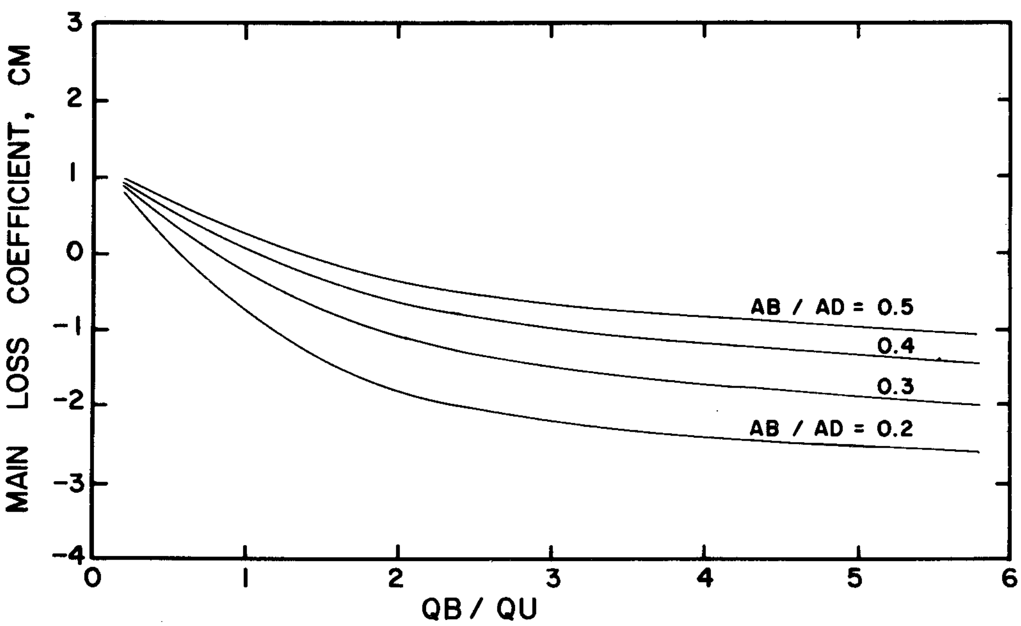


FIGURE A-18 BRANCH ANGLE = 45°, AU / AD = 0.5

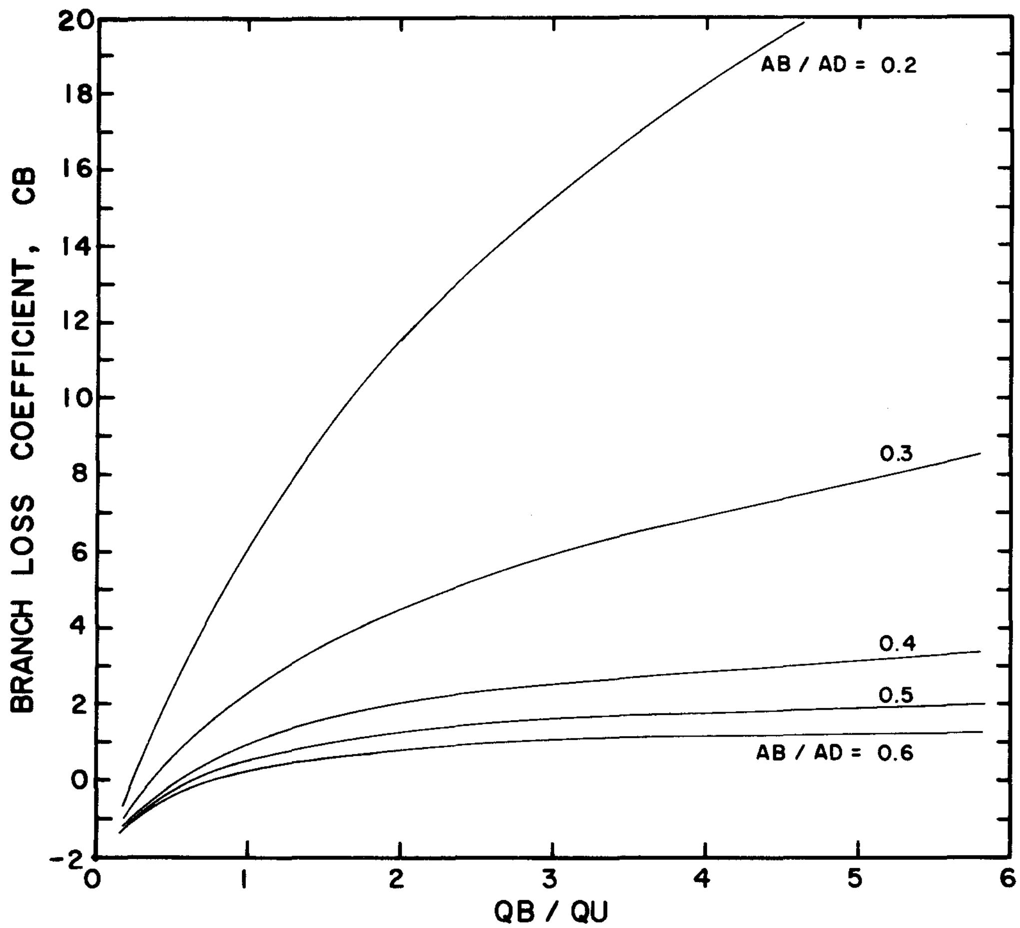


FIGURE A-19 BRANCH ANGLE = 45°, AU / AD = 0.6

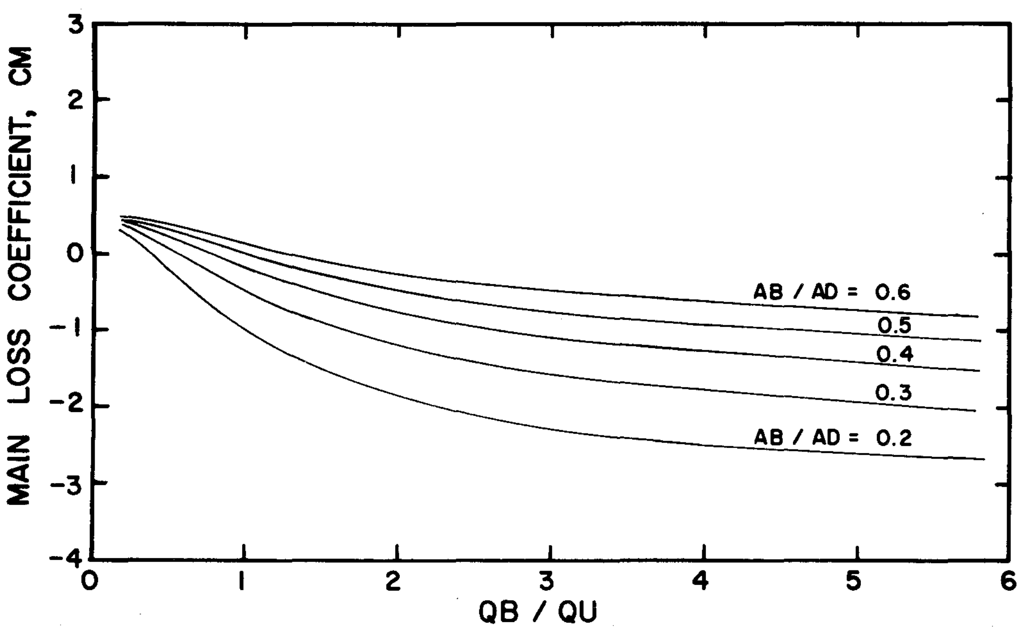


FIGURE A-20 BRANCH ANGLE = 45°, AU / AD = 0.6

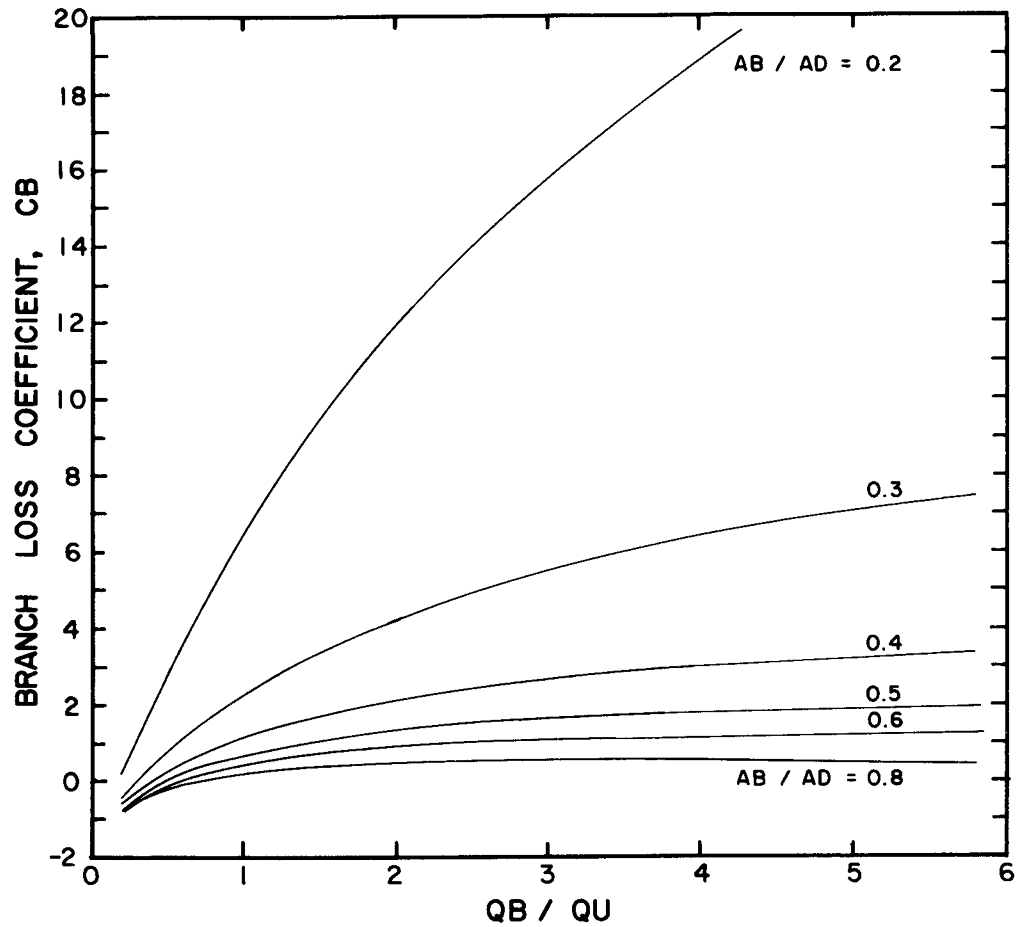


FIGURE A-21 BRANCH ANGLE = 45°, AU / AD = 0.8

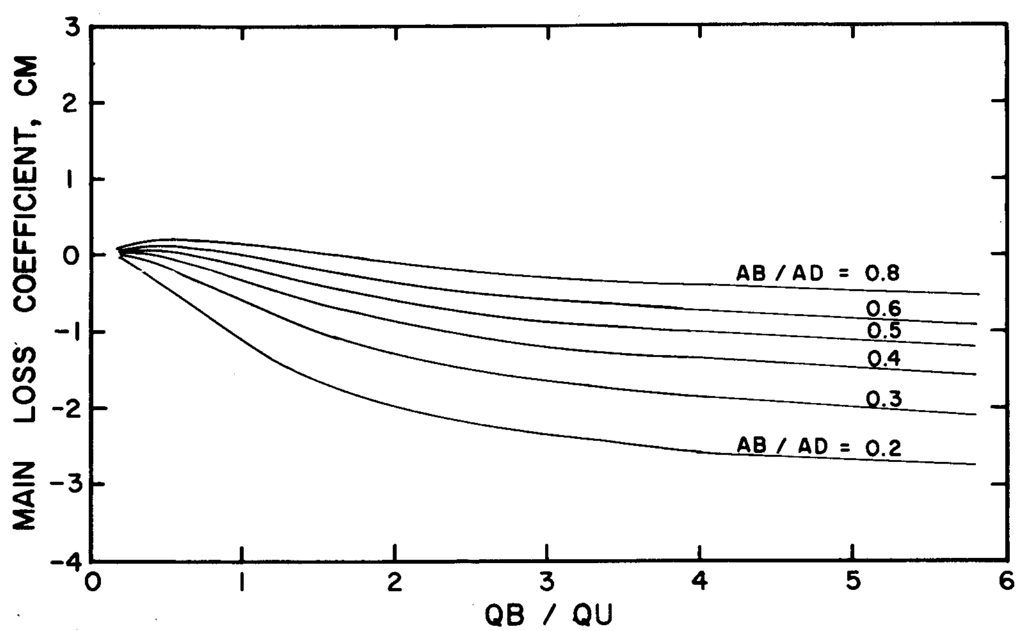


FIGURE A-22 BRANCH ANGLE = 45°, AU / AD = 0.8

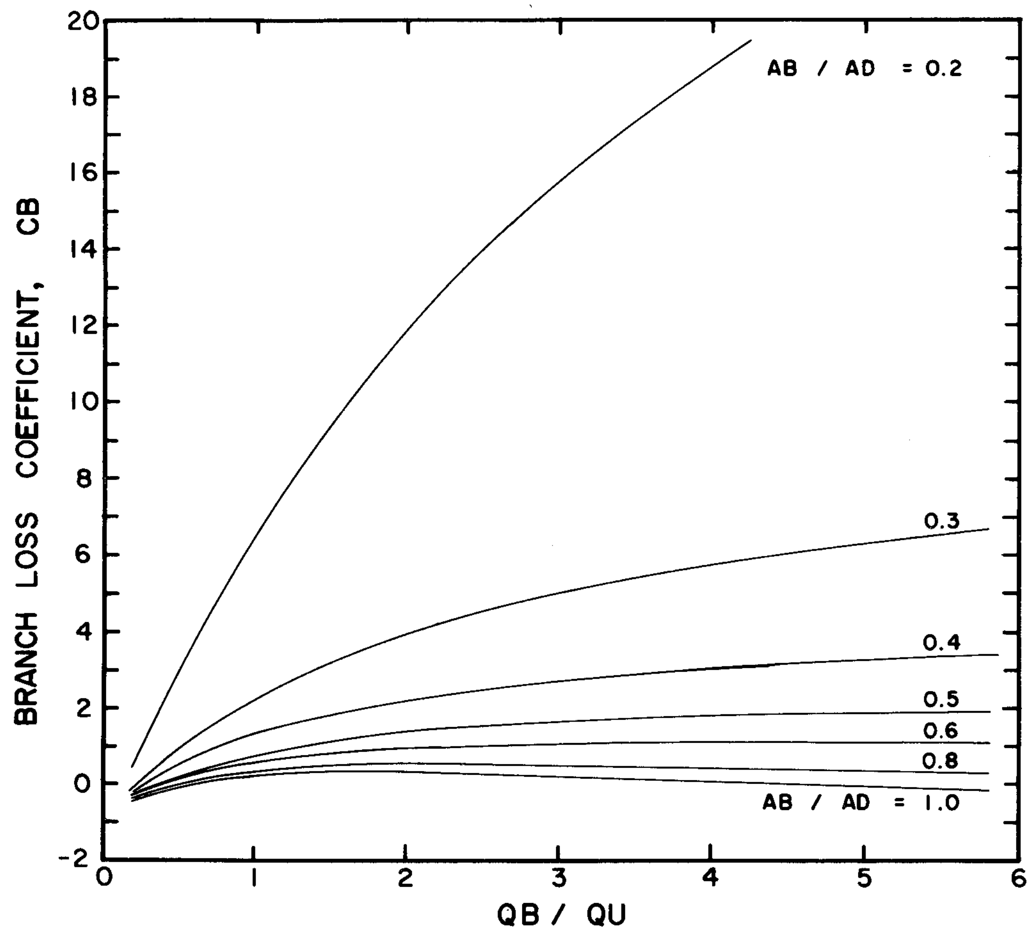


FIGURE A-23 BRANCH ANGLE = 45°, AU / AD = 1.0

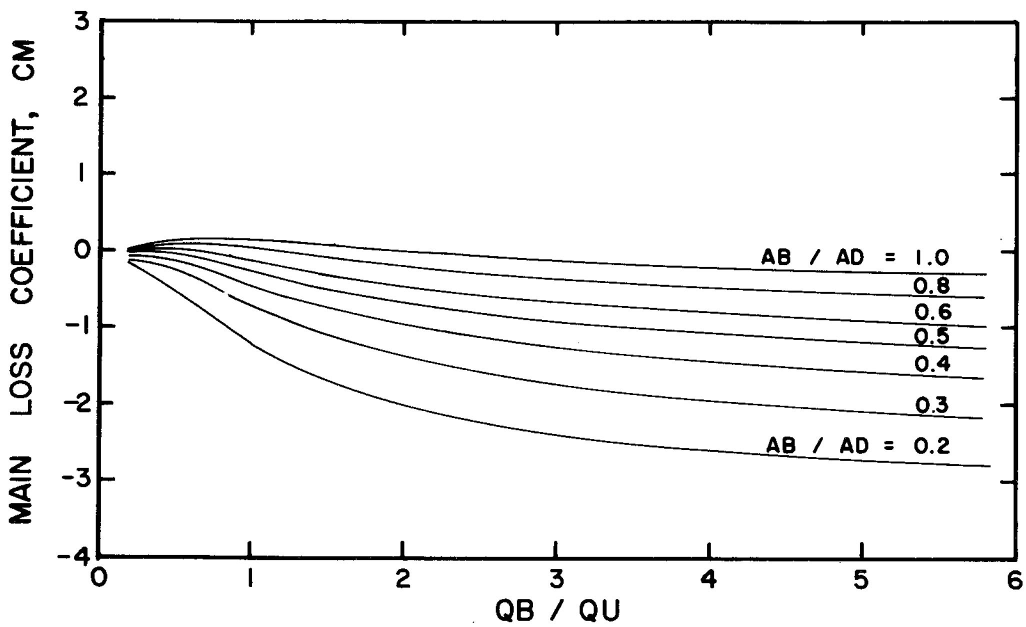


FIGURE A-24 BRANCH ANGLE = 45°, AU / AD = 1.0

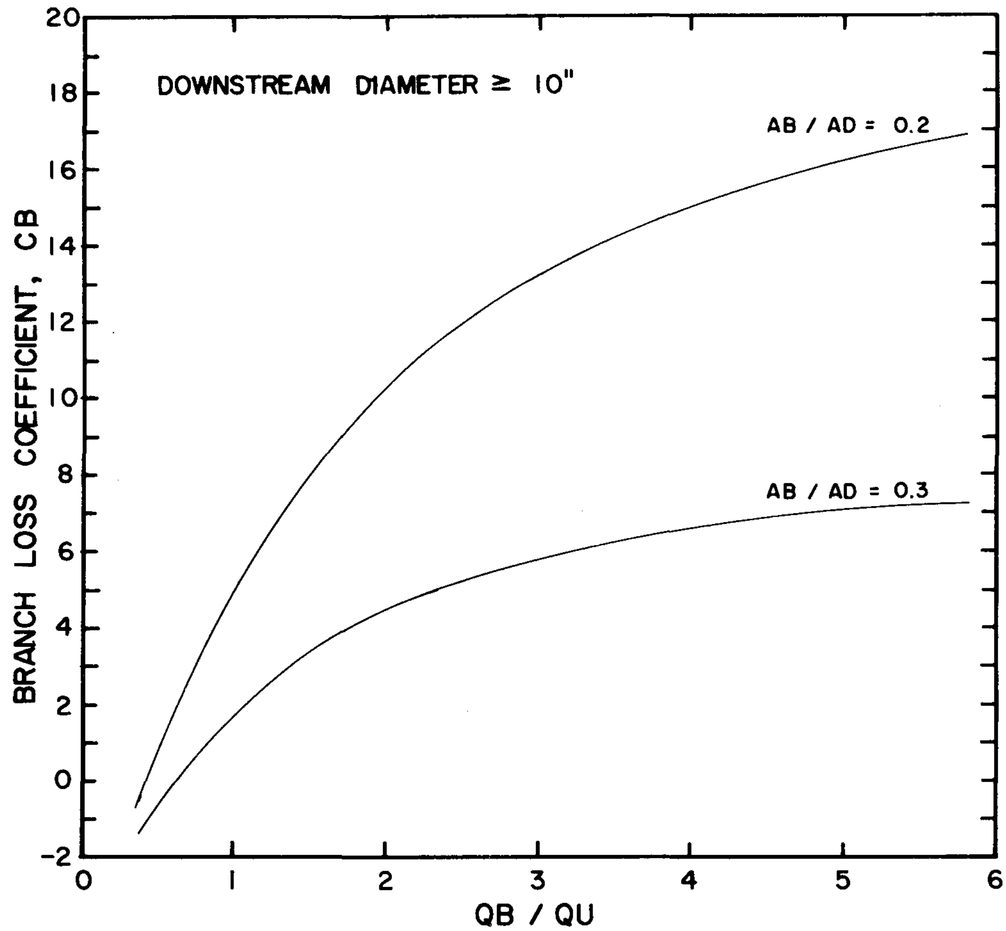


FIGURE A-25 BRANCH ANGLE = 90°, AU / AD = 0.3

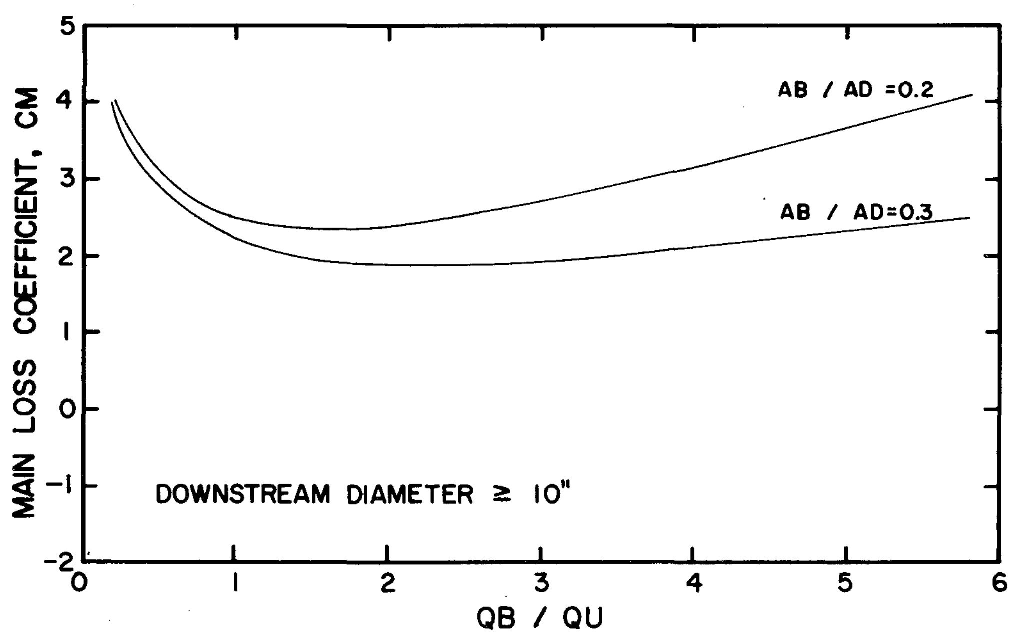


FIGURE A-26 BRANCH ANGLE = 90°, AU / AD = 0.3

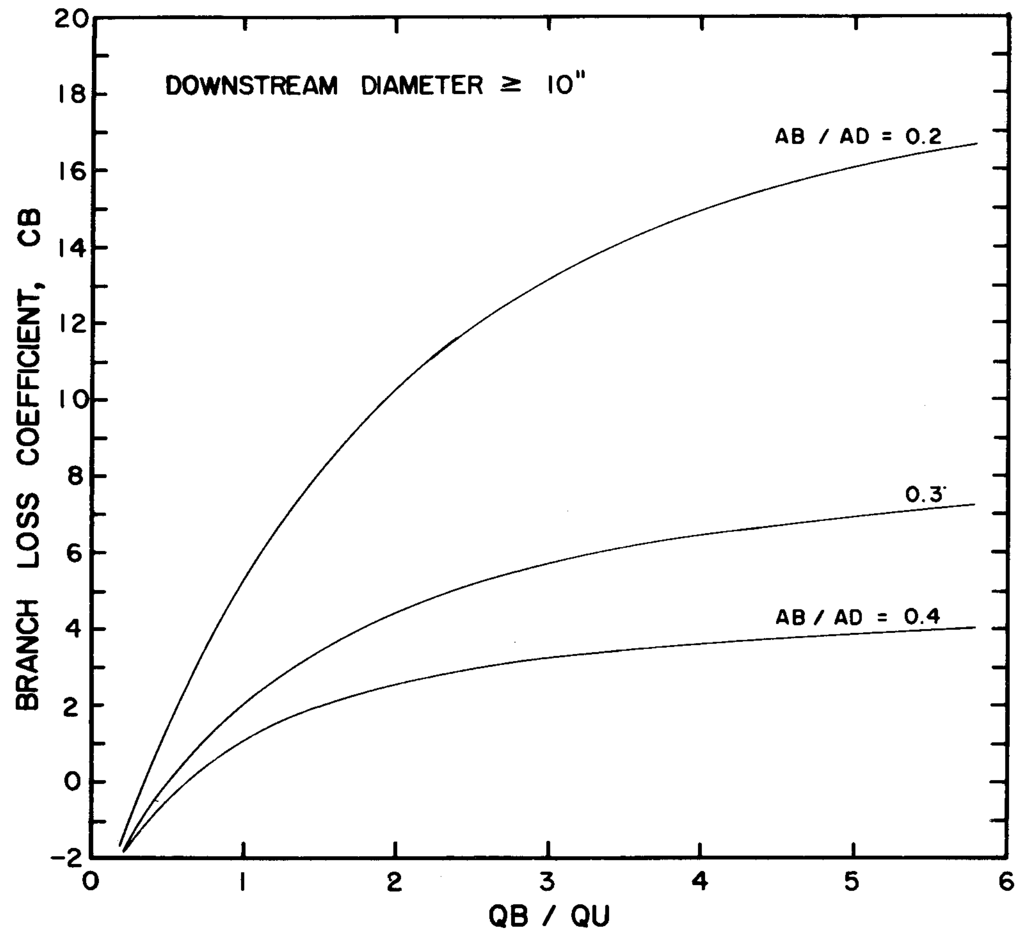


FIGURE A-27 BRANCH ANGLE = 90°, AU / AD = 0.4

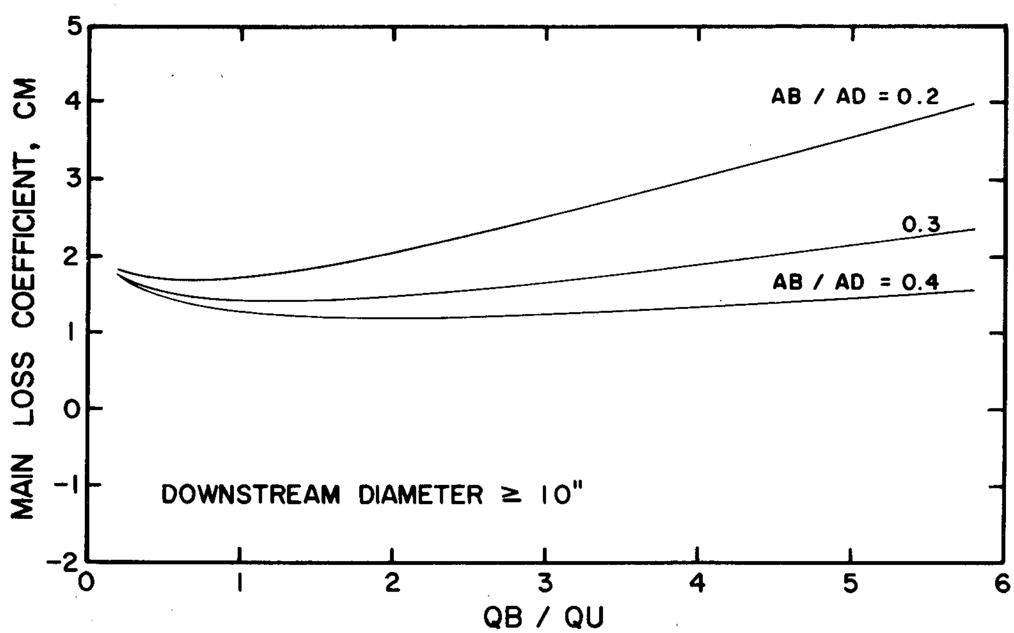


FIGURE A-28 BRANCH ANGLE = 90°, AU / AD = 0.4

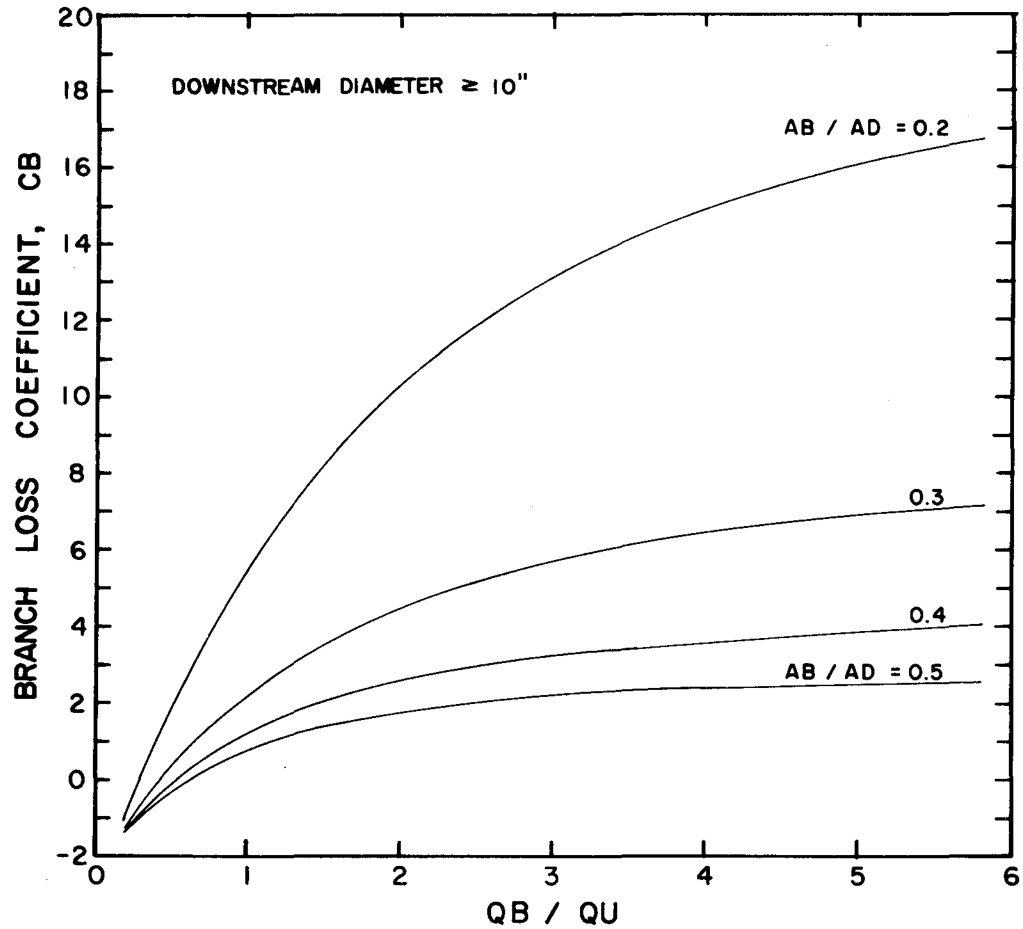


FIGURE A-29 BRANCH ANGLE=90°, AU / AD = 0.5

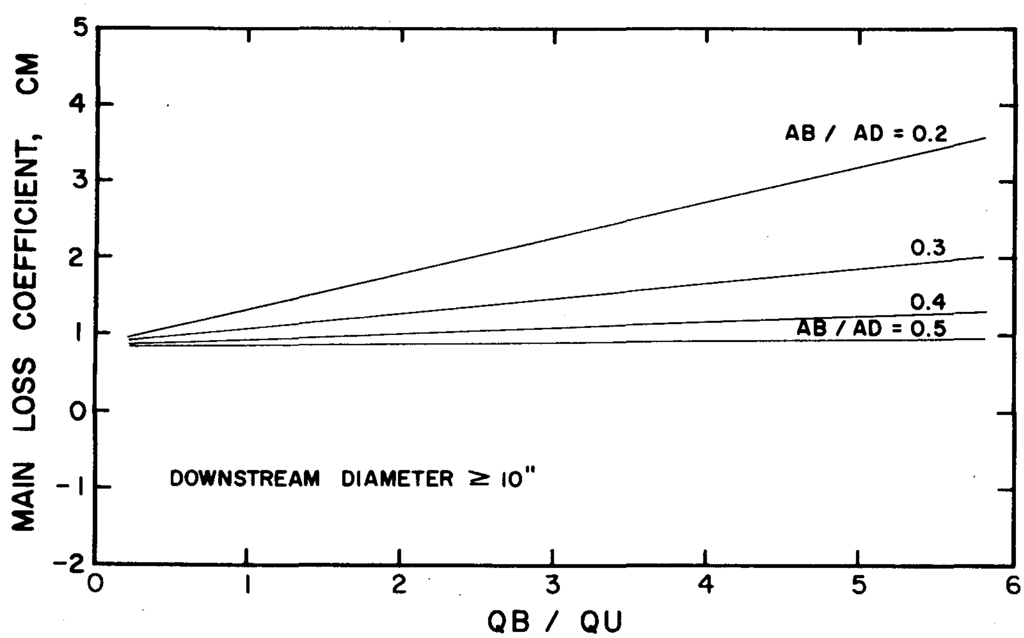


FIGURE A-30 BRANCH ANGLE=90°, AU / AD = 0.5

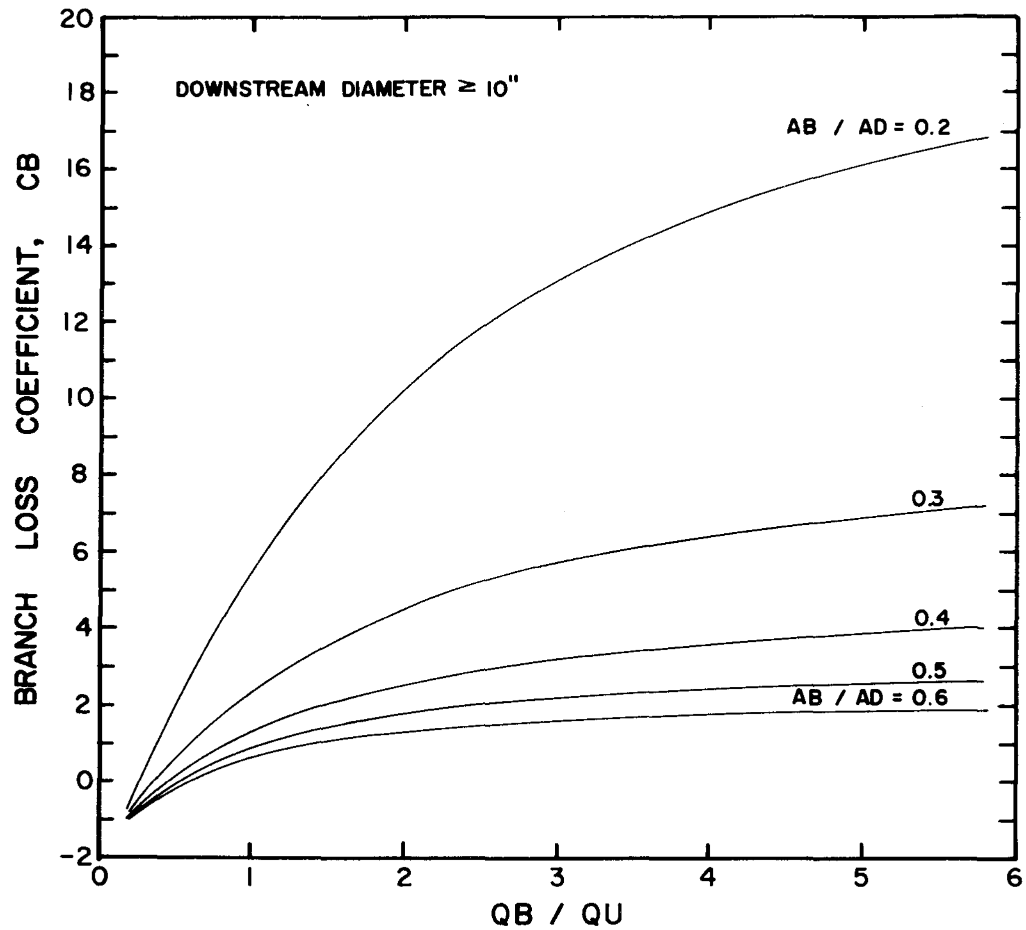


FIGURE A-31 BRANCH ANGLE = 90°, AU / AD = 0.6

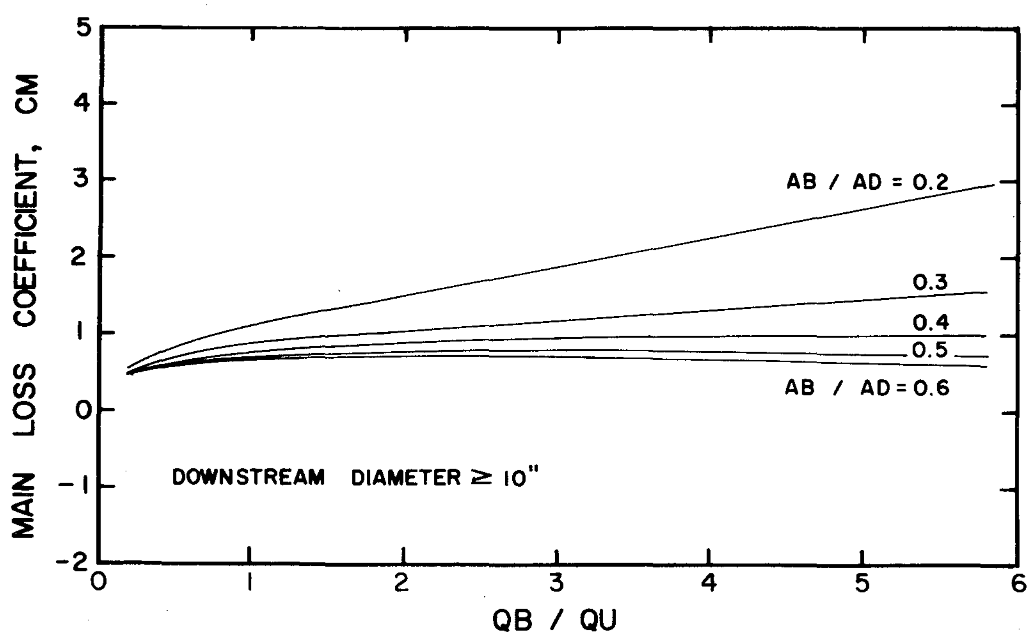


FIGURE A-32 BRANCH ANGLE = 90°, AU / AD = 0.6

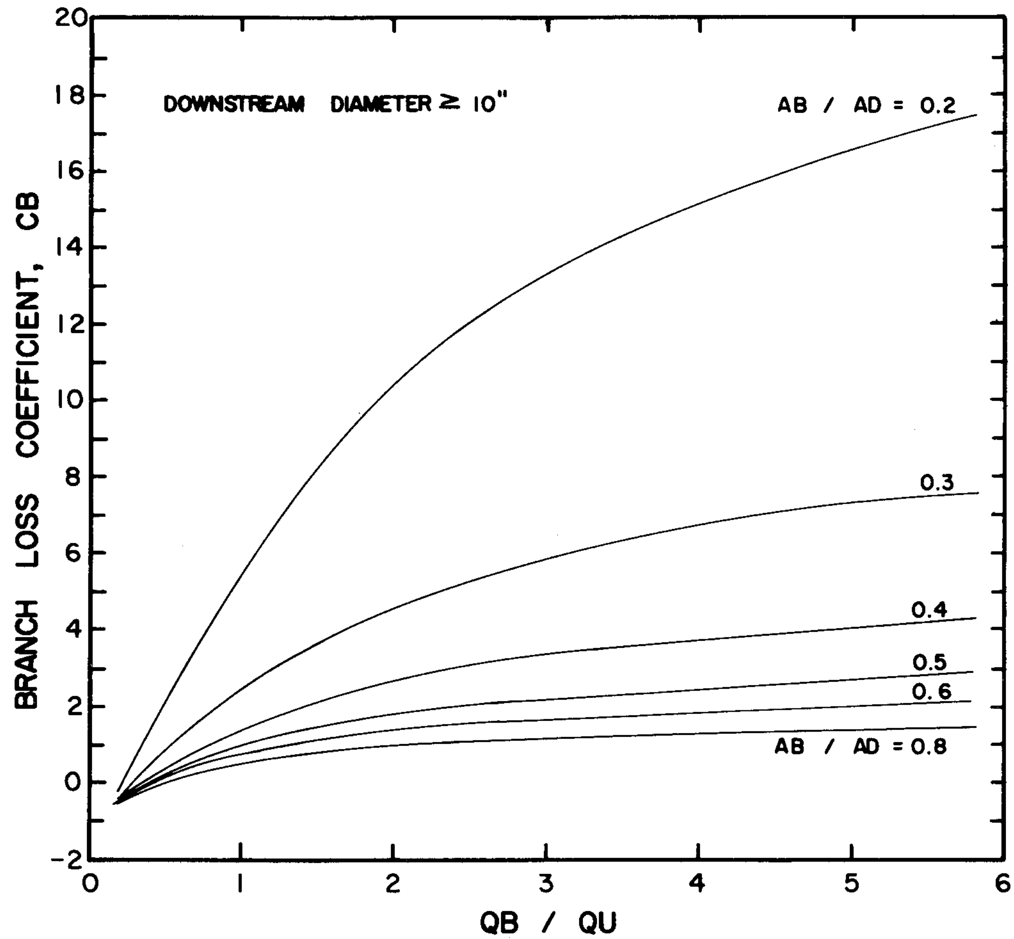


FIGURE A-33 BRANCH ANGLE = 90°, AU / AD = 0.8

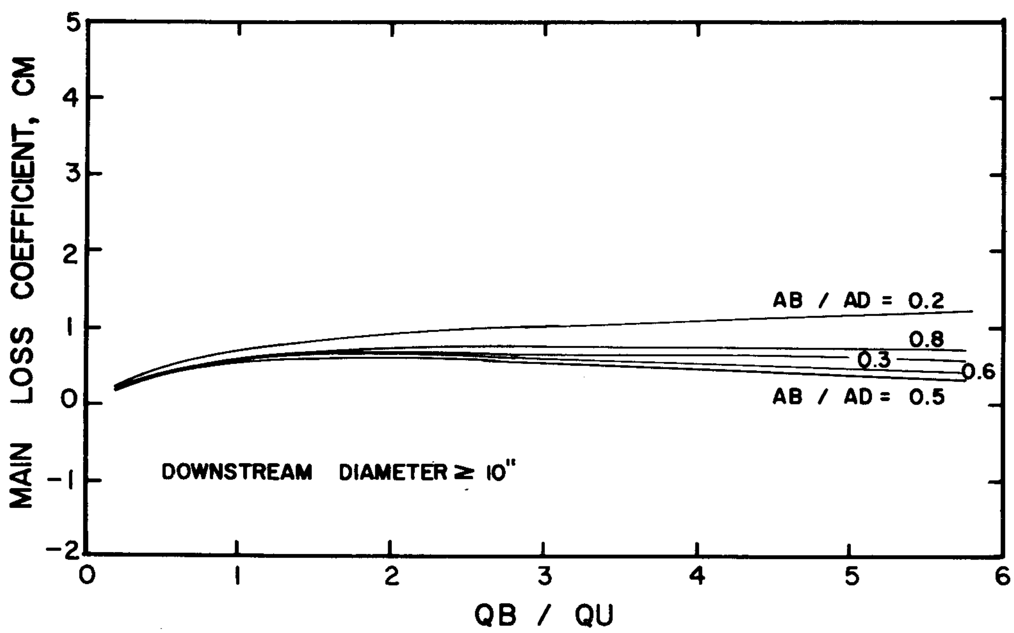


FIGURE A-34 BRANCH ANGLE = 90°, AU / AD = 0.8

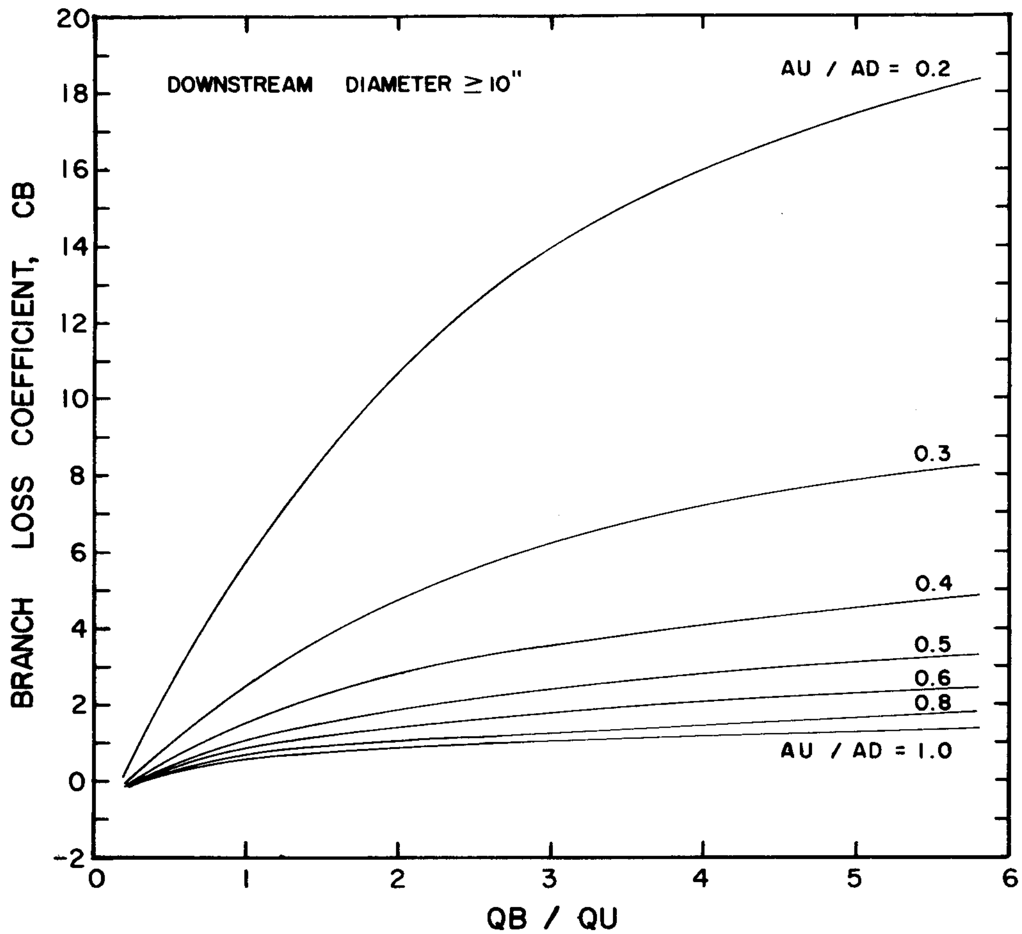


FIGURE A-35 BRANCH ANGLE = 90°, AU / AD = 1.0

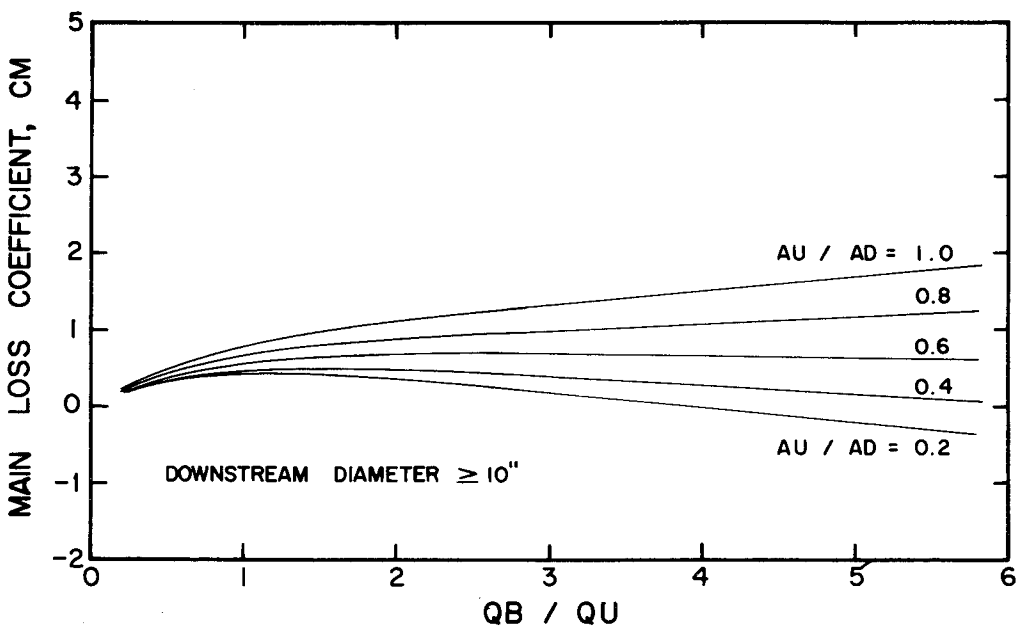


FIGURE A-36 BRANCH ANGLE = 90°, AU / AD = 1.0

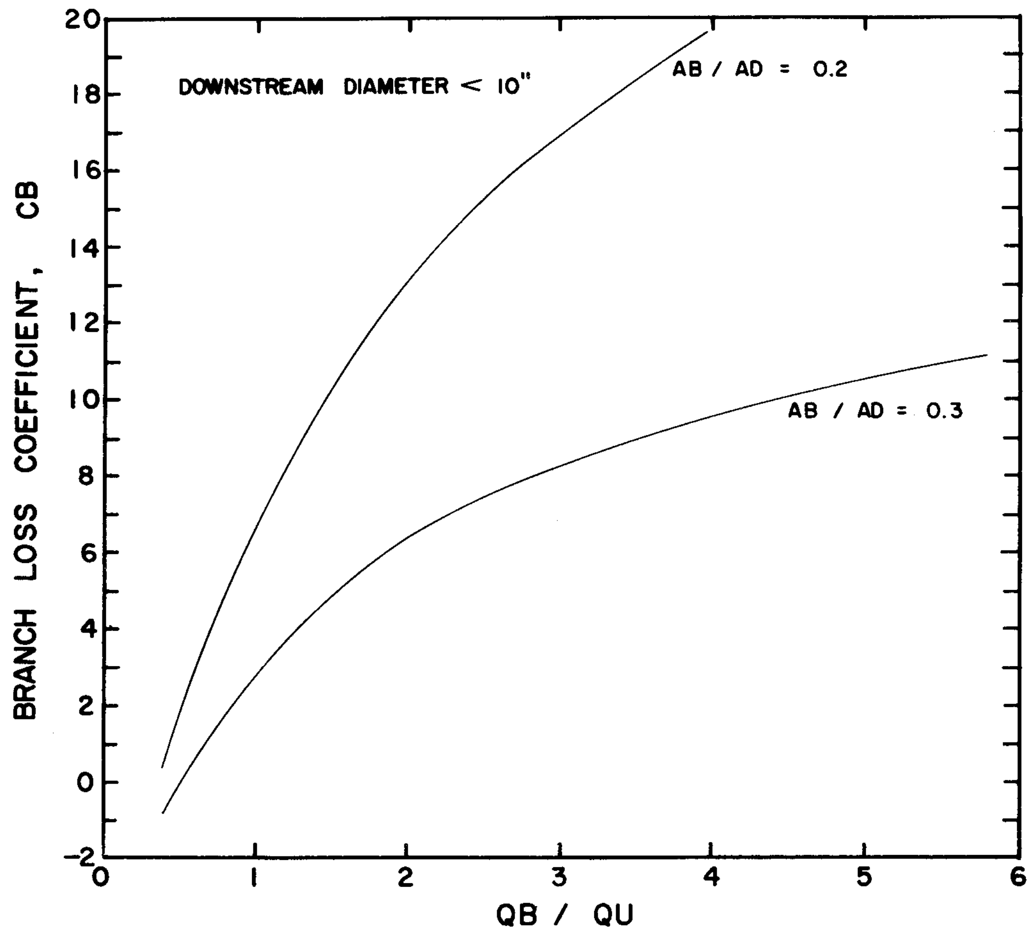


FIGURE A-37 BRANCH ANGLE = 90°, AU / AD = 0.3

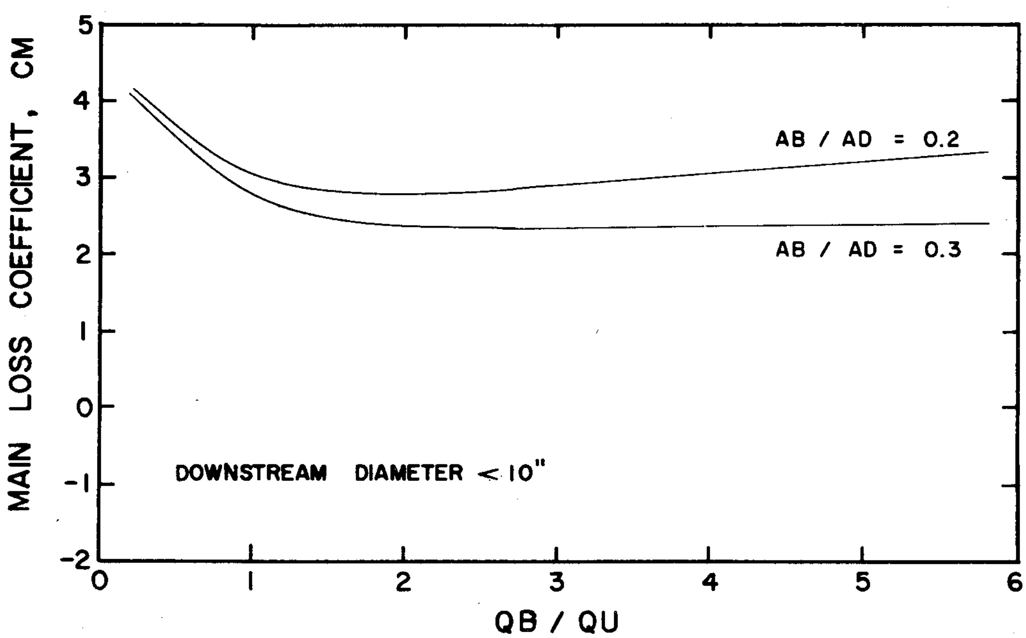


FIGURE A-38 BRANCH ANGLE = 90°, AU / AD = 0.3

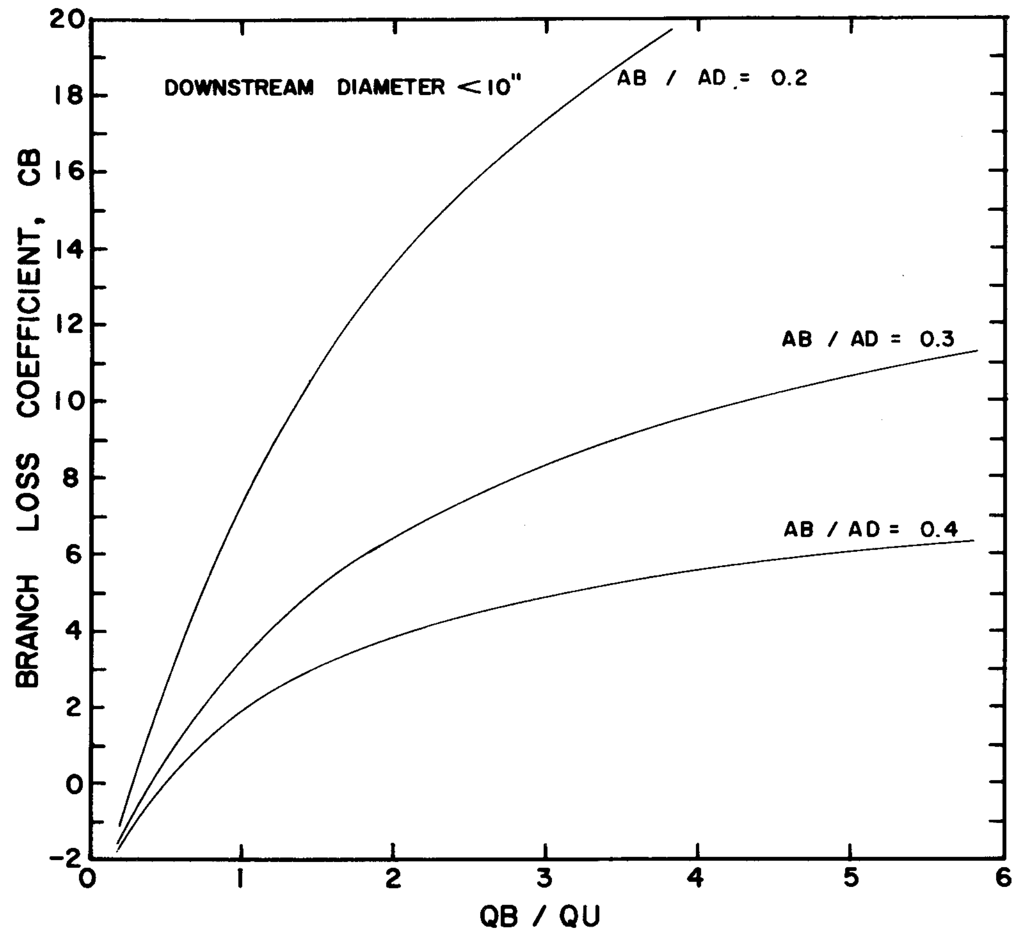


FIGURE A-39 BRANCH ANGLE = 90°, AU / AD = 0.4

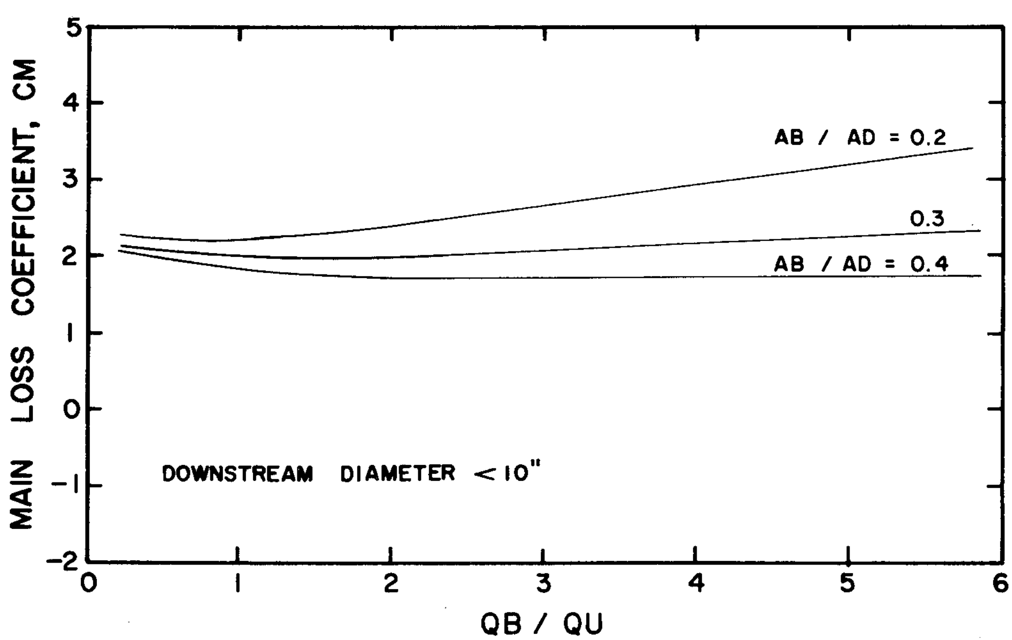


FIGURE A-40 BRANCH ANGLE = 90°, AU / AD = 0.4

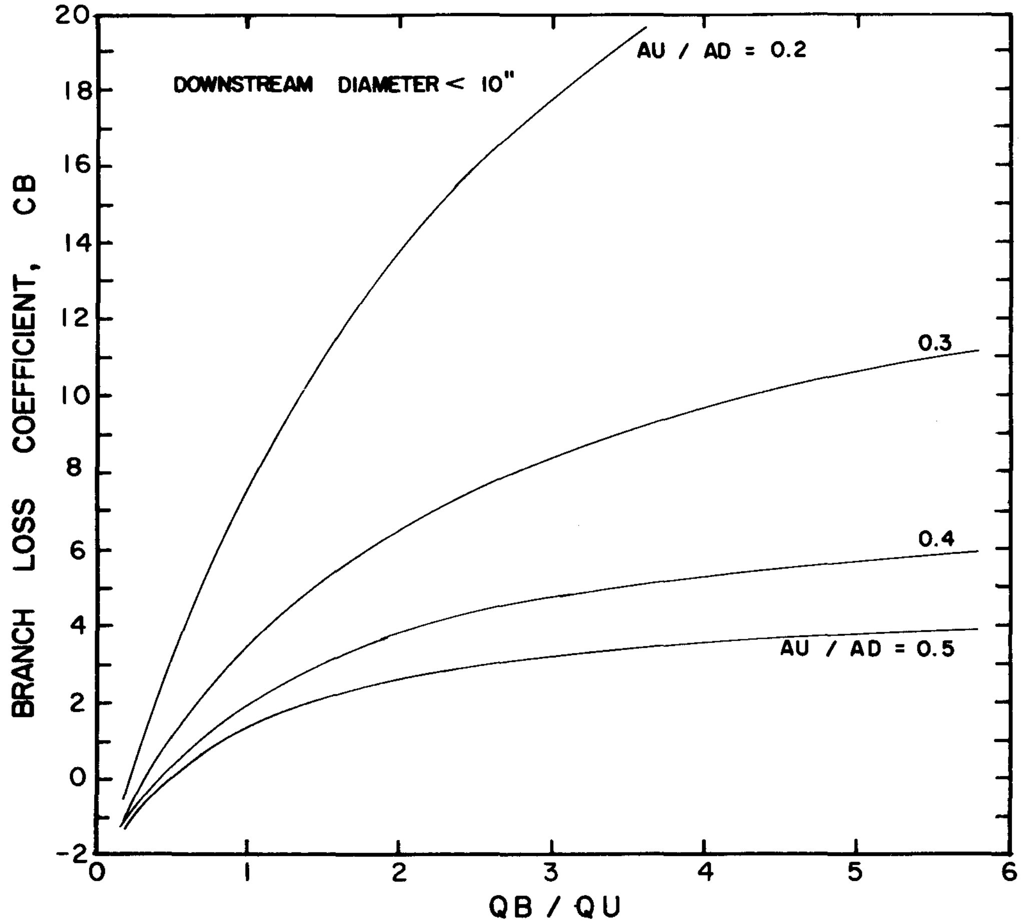


FIGURE A-41 BRANCH ANGLE = 90°, AU / AD = 0.5

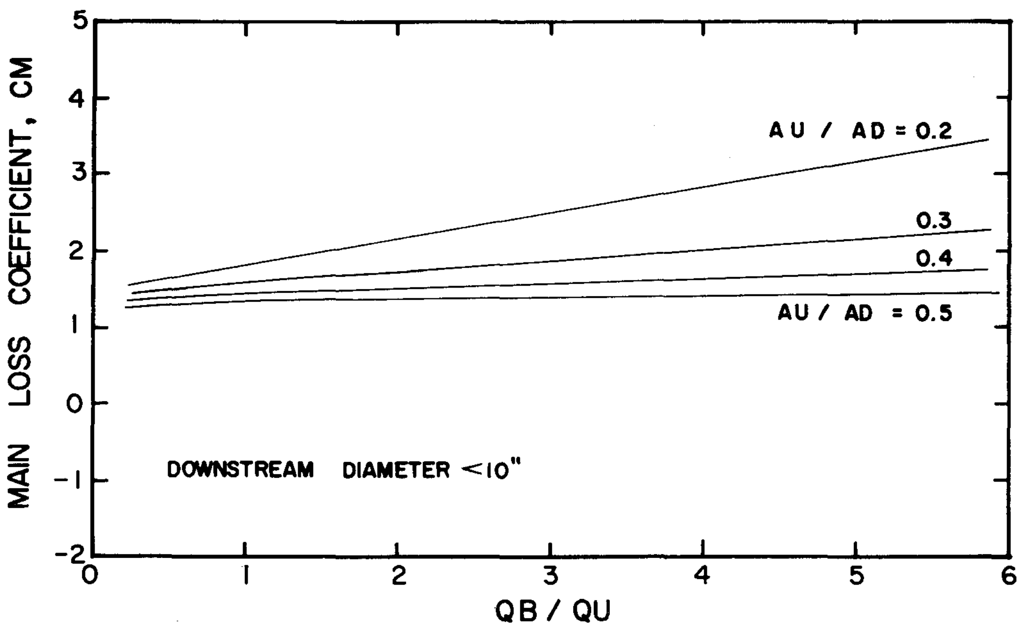


FIGURE A-42 BRANCH ANGLE = 90°, AU / AD = 0.5

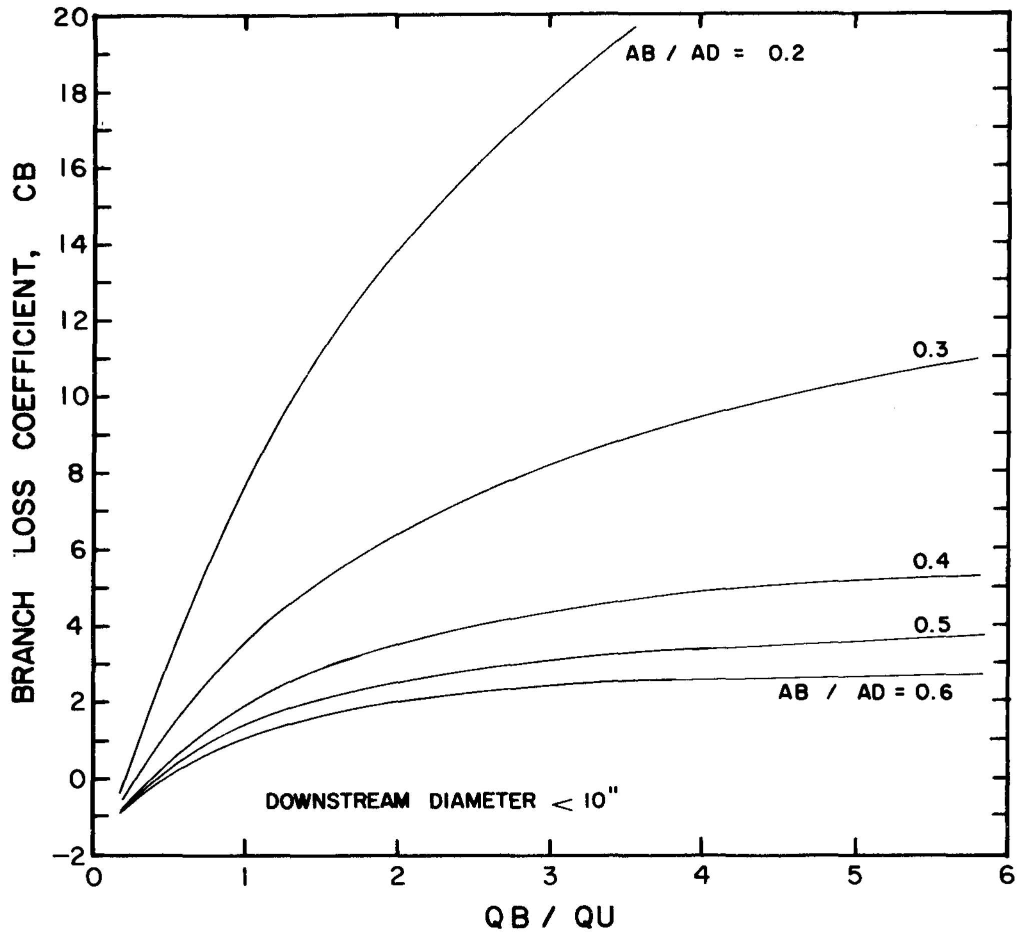


FIGURE A-43 BRANCH ANGLE = 90°, AU / AD = 0.6

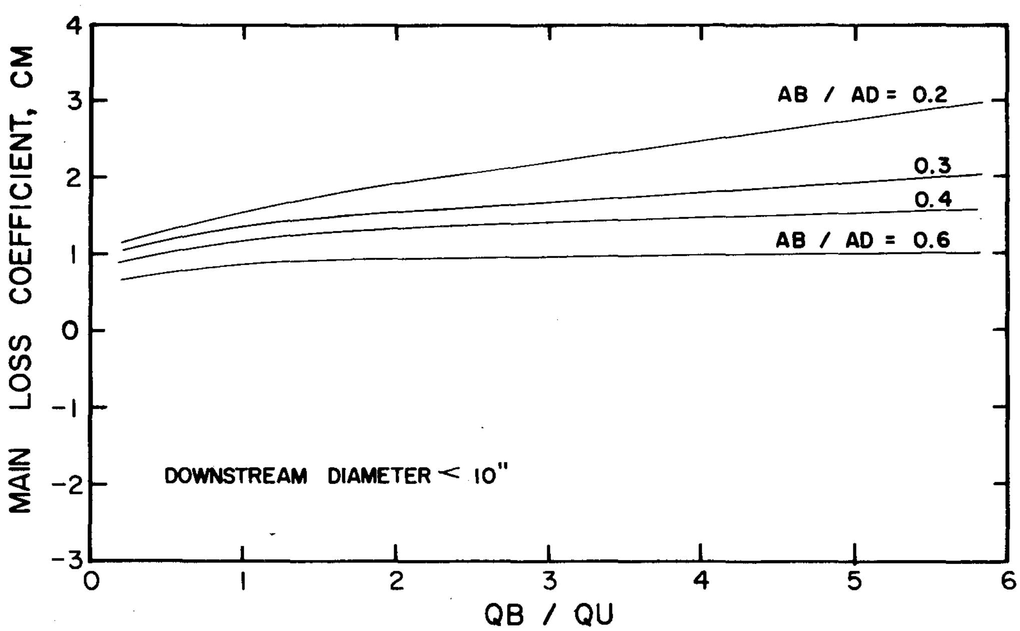


FIGURE A-44 BRANCH ANGLE = 90°, AU / AD = 0.6

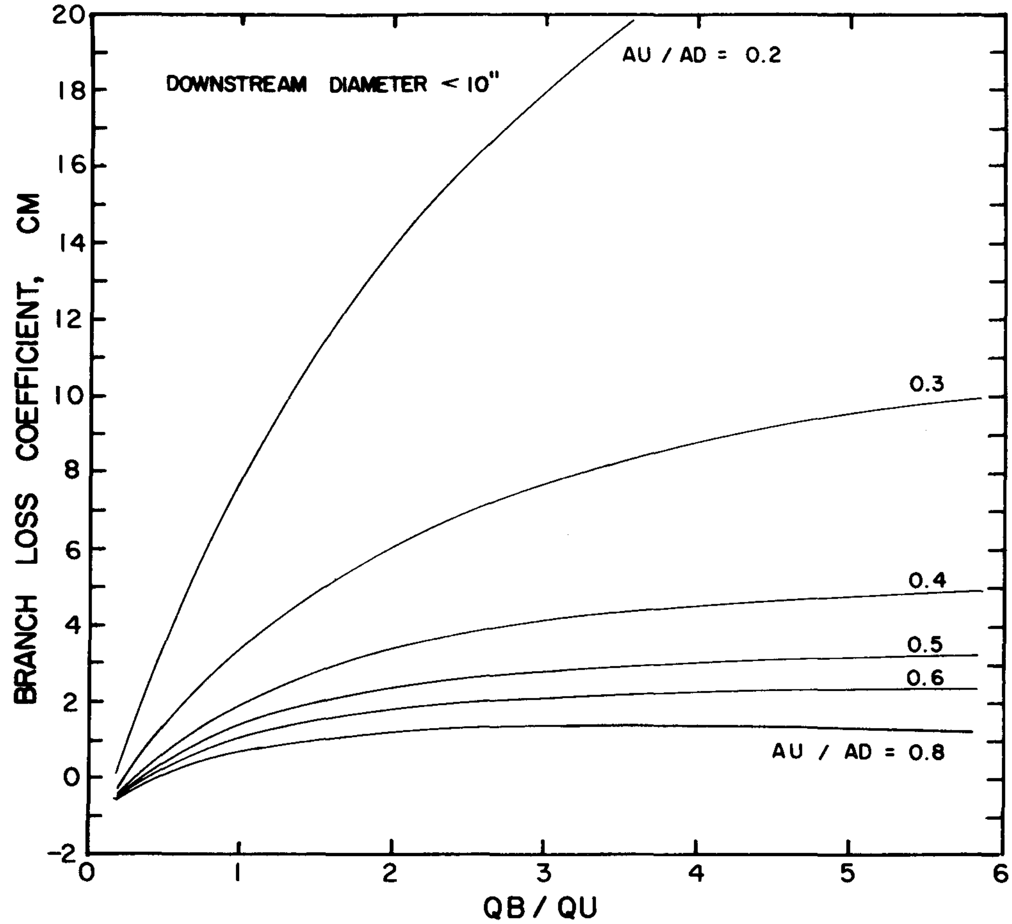


FIGURE A-45 BRANCH ANGLE = 90°, AU/AD = 0.8

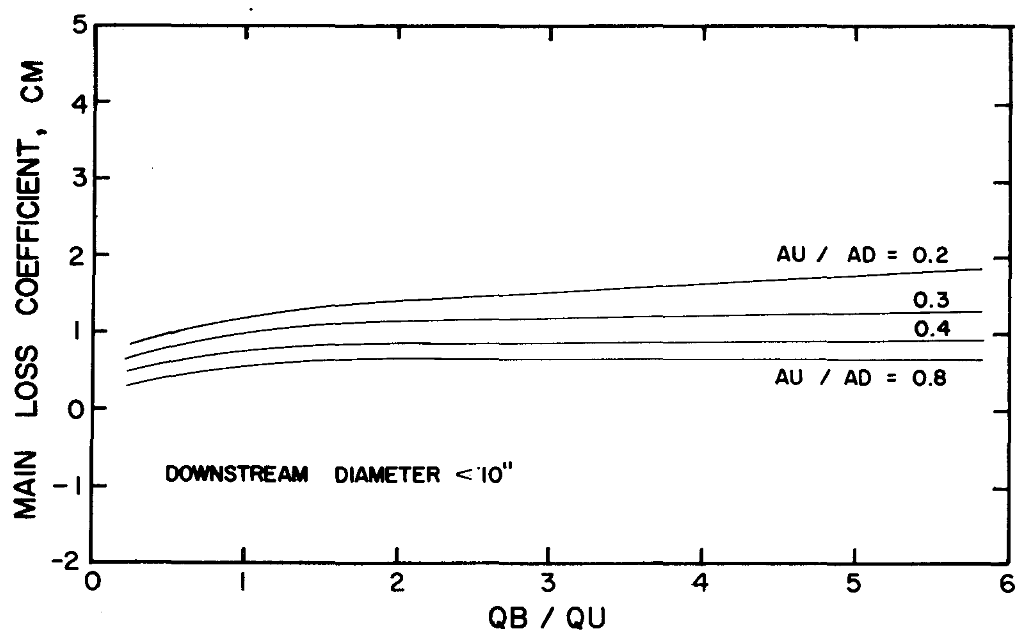


FIGURE A-46 BRANCH ANGLE = 90°, AU/AD = 0.8

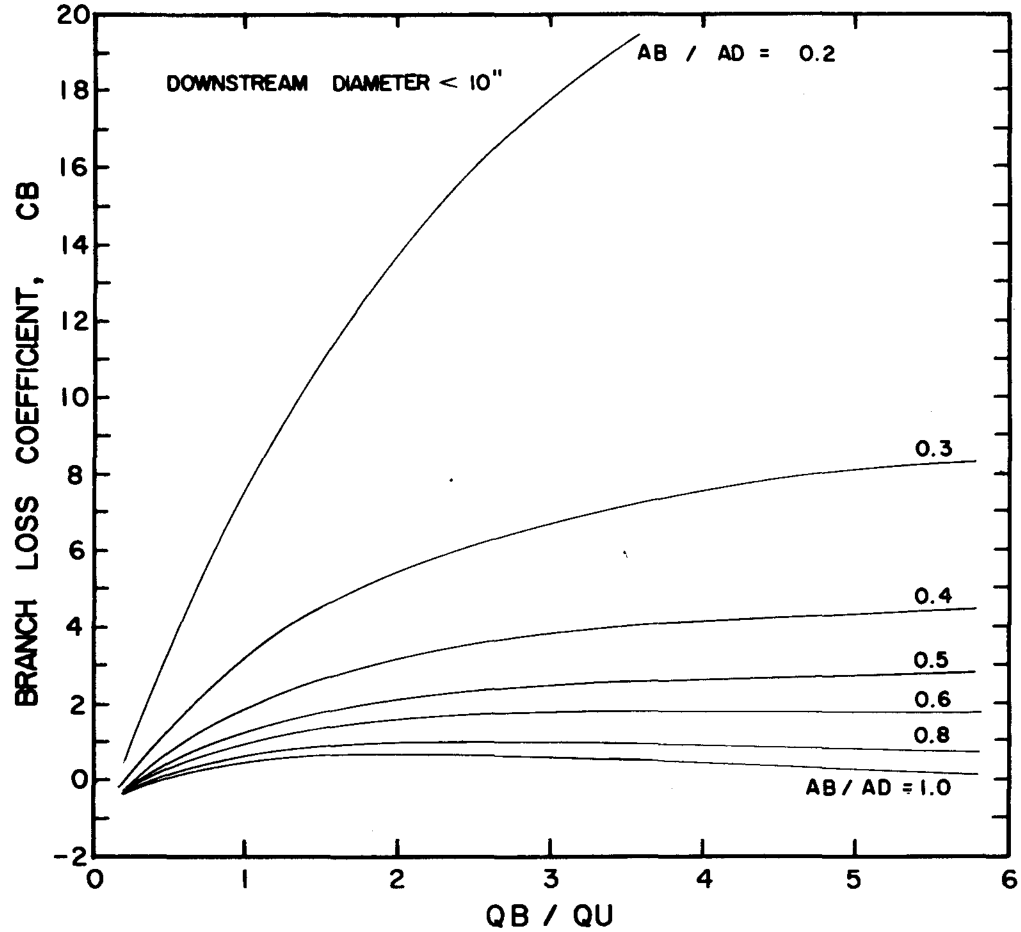


FIGURE A-47 BRANCH ANGLE = 90°, AU / AD = 1.0

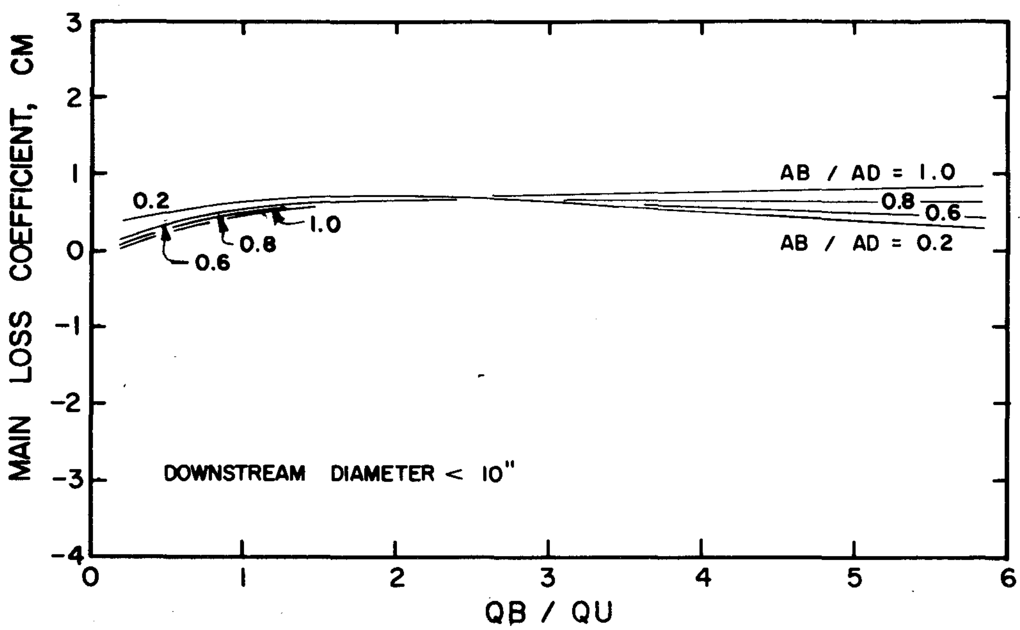


FIGURE A-48 BRANCH ANGLE = 90°, AU / AD = 1.0