WADC TECHNICAL REPORT 55-192

STUDIES ON THERMAL STRESSES
FOR
AIRCRAFT STRUCTURES EXPOSED TO TRANSIENT EXTERNAL HEATING

VOLUME I

EVALUATION OF THE THERMAL RESPONSE, FORCE AND MOMENT IN A PLATE

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Wright Air Development Center
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United States Air Force
Wright-Patterson Air Force Base, Ohio

FOREWORD

This report was prepared by J. E. Mahlmeister, T. Ishimoto, and A. Ambrosio of the Department of Engineering, University of California, Los Angeles, under Contract No. AF 33(616)-293. The contract was initiated under Project No. 1350, "Effects of Atomic Weapons on Aircraft Systems," and was administered by the Aircraft Laboratory, Directorate of Laboratories, Wright Air Development Center, with Lt. Joseph W. Saylor, Jr. acting as Project Engineer.

Alphonso Ambrosio directed and was technically responsible for the research described in this report and Walter C. Hurty acted as the representative of the Chairman of the Department, L.M.K. Boelter.

The authors wish to acknowledge the assistance of J. Schwartz, J. Snow, J. Barnes, and I. Grossman in the preparation of the graphs for this report.

ABSTRACT

This report is one of a series of analytical studies of aircraft structures exposed to transient heating. The present study reports on the response characteristics of the front surface temperature and the front-back temperature difference across a finite plate as well as the "thermal force" and "thermal moment" which exists as a result of the heating. The results are given in graphical form for use in future studies.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

for DANIEL D. McKEE
Colonel, USAF
Chief, Aircraft Laboratory
Directorate of Laboratories

CONTENTS

LIST OF FIGURES

NOMENCLATURE

a	=	Thermal diffusivity $(k/\rho C_p)$	ft^2/hr
b	=	Plate thickness	ft
Bi	=	Biot modulus	dimensionless
C_p	=	Heat capacity	Btu/lb °F
E	=	Modulus of elasticity	lb/in^2
h_c	=	Unit thermal conductance	Btu/hr ft^2 °F
I	=	Integral $\left(\int_0^\infty \frac{q}{q_m}\, dt^+\right)$	
k	=	Thermal conductivity	Btu/hr ft^2 °F/ft
M_T	=	Thermal moment	lb in/in
N_T	=	Thermal force	lb/in
q	=	Rate of heat flow per unit area into plate	Btu/hr ft^2
Q	=	Total heat absorbed by plate	Btu/ft^2
T	=	Temperature	°F
t	=	Time	sec or hr
Z	=	Cartesian coordinate (Z' refers to distance from back surface)	ft
α	=	Coefficient of linear thermal expansion	$°F^{-1}$
β	=	Heat transfer parameter $(b/\sqrt{a\eta})$	dimensionless
Δ	=	Difference	
η	=	Reference time (time for the input function to maximize)	sec or hr
ν	=	Poisson's ratio	
ρ	=	Weight density	lb/ft^3

Subscripts

T = Thermal

m = maximum

ref = reference

∞ = ambient

Superscript

$+$ = dimensionless

INTRODUCTION

Previous studies[1-5]* concerning the effects of heating aircraft structures have indicated that excessive temperatures and stresses can occur. The combination of temperatures and stresses can greatly increase aerodynamic drag due to large deflections and cause permanent deformations in the skins of wings and control surfaces.

Studies[3,5] of the heated plate equations originally developed by A. Nadai[4] have shown the necessity of evaluating the so-called "Thermal Force" and "Thermal Moment" resulting from restrained thermal expansions and temperature distributions, respectively. These quantities are the essential factors which combine the heat transfer and thermal stress investigations. The heat transfer investigation[2] resulted in an analytical determination of the thermal response of a finite plate exposed to transient heating.

A numerical evaluation of the thermal force and moment is presented in this study using the results of the uniformly irradiated finite plate of reference 2. In addition, the front surface temperature rise and the front to back surface temperature difference are reported in terms of dimensionless parameters. It is visualized that these results will be utilized in future thermal stress evaluation of aircraft structures.

*Numbers in superscripts indicate references in the bibliography at the end of the report.

HEAT TRANSFER SYSTEM

The idealized heat transfer system of reference 2 is shown in Figure 1. It consists of a uniformly irradiated plate with a constant thermal conductance (h_c) on the lower side and an insulated boundary on the other. The transient heating function $q(t)$ is shown in Figure 2. In order to present the results in dimensionless form, the following definitions were employed:

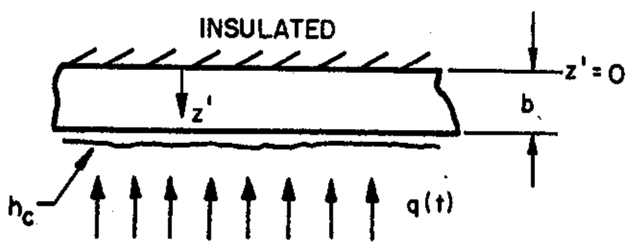


FIGURE 1 COORDINATE SYSTEM FOR UNIFORMLY IRRADIATED FINITE PLATE

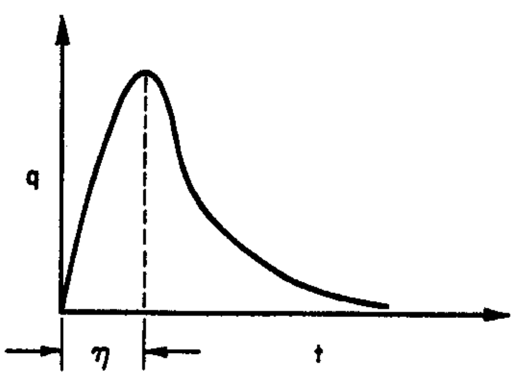


FIGURE 2 TRANSIENT HEATING FUNCTION

$$Z' \equiv \frac{z'}{b}, \qquad (1)$$

$$t^{+} \equiv \frac{t}{\eta}, \qquad (2)$$

$$T^{+} \equiv \frac{T - T_{\infty}}{\Delta T_{ref}}, \qquad (3)$$

$$\Delta T_{ref} \equiv \frac{Q}{\rho C_p b}, \qquad (4)$$

$$I \equiv \int_0^{\infty} \frac{q}{q_m} dt^{+}, \qquad (5)$$

$$Q \equiv \int_0^{\infty} q\, dt, \qquad (6)$$

$$Bi \equiv \tau \beta^2 = \frac{h_c b}{k}, \qquad (7)$$

$$\tau \equiv \frac{h_c \eta}{\rho C_p b}, \qquad (8)$$

and

$$\beta \equiv \frac{b}{\sqrt{a \eta}}, \qquad (9)$$

In terms of the dimensionless quantities defined above, the heat conduction equation is written as:

$$\frac{\partial^2 T^+}{\partial Z'^2} = \beta^2 \frac{\partial T^+}{\partial t^+} \tag{10}$$

with the following initial and boundary conditions:

$$\begin{aligned} &\text{when:} \quad t^+ = 0, \quad T^+ = 0; \\ &\text{at:} \quad Z' = 0, \quad \frac{\partial T^+}{\partial Z'} = 0; \\ &\text{and at:} \quad Z' = 1, \quad \frac{1}{\beta^2}\frac{\partial T^+}{\partial Z'} = \frac{q^+(t^+)}{I} - \tau T^+ \end{aligned} \tag{11}$$

The solution to equations (10) and (11) is:[2]

$$T^+(Z', t^+) = \int_0^{t^+} \frac{q^+(\lambda)}{I} \sum_{N=1}^{\infty} 2 \left[\frac{\cos V_N Z'}{\cos V_N} \frac{\exp\left[-\frac{V_N^2}{\beta^2}(t^+ - \lambda)\right]}{\left[1 + \frac{Bi}{V_N^2}(1 + Bi)\right]} \right] d\lambda \tag{12}$$

where

$$\tan V_N = \frac{Bi}{V_N}$$

This solution was evaluated for the front surface temperature rise and the temperature difference across the plate utilizing the heating function shown schematically in Figure 2. The front surface temperature is expressed as:

$$T^+(1, t^+) = \int_0^{t^+} \frac{q^+(\lambda)}{I} \sum_{N=1}^{\infty} 2 \left[\frac{\exp\left[-\frac{V_N^2}{\beta^2}(t^+ - \lambda)\right]}{1 + \frac{Bi}{V_N^2}(1 + Bi)} \right] d\lambda \tag{13}$$

The temperature difference across the plate (front surface temperature minus back surface temperature) is:

$$T^+(1,t^+) - T^+(0,t^+) = \int_0^{t^+} \frac{q^+(\lambda)}{I} \sum_{N=1}^{\infty} 2\left[\frac{1-\dfrac{1}{\cos \gamma_N}}{1+\dfrac{Bi}{\gamma_N^2}(1+Bi)}\right] exp\left[-\frac{\gamma_N^2}{\beta^2}(t^+-\lambda)\right] d\lambda \quad (14)$$

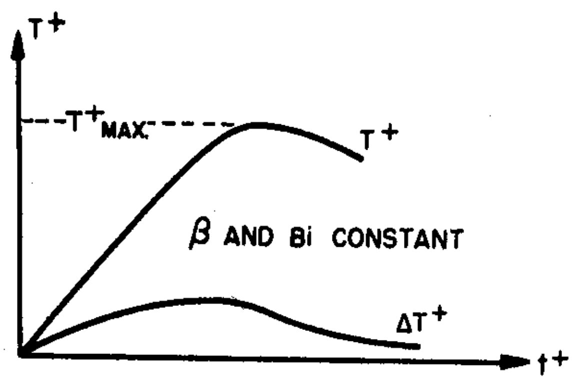


FIGURE 3 SCHEMATIC TEMPERATURE – TIME RESPONSE FOR A FINITE PLATE

Each temperature response evaluation was made for given values of the heat transfer parameters, Bi and β, as shown schematically in Figure 3. These curves are presented in the appendix for a range of Bi and β.

THE THERMAL FORCE AND MOMENT

The Thermal Force and Moment were developed as logical connecting parameters between the isotropic heated plate equations and the heat conduction solutions. These have been defined as:[3,5]

$$N_T \equiv \frac{1}{1-\nu} \int E\alpha\,(T - T_\infty)\,dZ \qquad (15)$$

and

$$M_T \equiv \frac{1}{1-\nu} \int E\alpha\,(T - T_\infty)\,Z\,dZ \qquad (16)$$

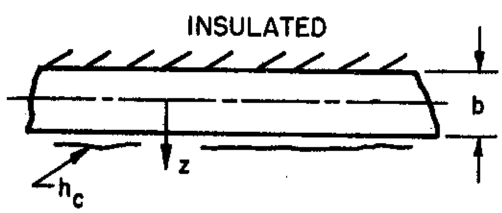


FIGURE 4 COORDINATE SYSTEM FOR HEATED PLATE EQUATIONS

When the mechanical properties of the material can be considered constant across the plate thickness, the neutral axis occurs at the plate center. This coordinate system is shown in Figure 4.

In terms of this coordinate system with the origin at the plate center, equations (15) and (16) are normalized to:

$$N_T^+ \equiv \frac{(1-\nu)\,N_T}{E\alpha\,\Delta T_{ref}\,b} = \int_{-1/2}^{+1/2} T^+\,dZ \qquad (17)$$

and

$$M_T^+ \equiv \frac{(1-\nu)\,M_T}{E\alpha\,\Delta T_{ref}\,b^2} = \int_{-1/2}^{+1/2} T^+ Z\,dZ \qquad (18)$$

The dimensionless thermal moment, M_T^+ , and thermal force, N_T^+, are functions of the heat transfer parameters Bi and β. Typical plots of these functions are shown schematically in Figures 5 and 6. These curves are presented in the appendix for the range of heat transfer parameters considered.

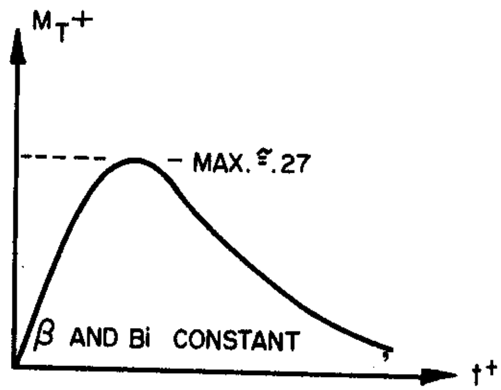


FIGURE 5 DIMENSIONLESS THERMAL MOMENT

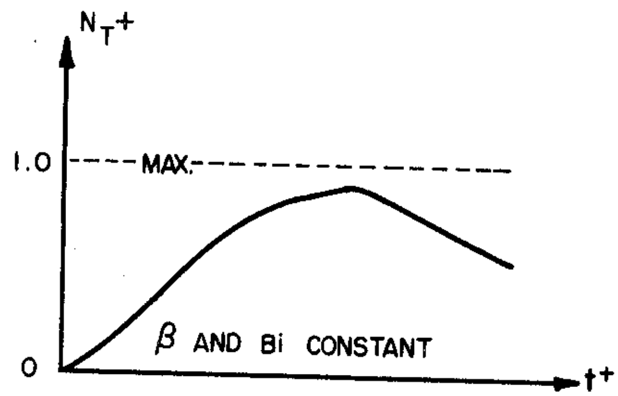


FIGURE 6 DIMENSIONLESS THERMAL FORCE

DISCUSSION OF RESULTS

Comparison of thermal force and moment curves with temperature curves show that N_T^+ and M_T^+ are similar to T^+ and ΔT^+, respectively. The maximum value of $N_T^+ = 1.0$ corresponds to the case of no convective cooling. This is the limiting case where all the input energy remains in the structure. The peak values of N_T^+ occurs approximately in the range of $t^+ = 1.0 - 6.0$ and for the case of no cooling occurs at the end of the input. The dimensionless thermal moment was found to peak at short times ($t^+ = 1.0 - 2.0$) with a maximum value of approximately 0.27 for the range of heat transfer parameters (Bi, β) considered. The sequence of events, for a plate exposed to transient heating is as follows: (1) The plate is subjected to a maximum moment with a relatively small thermal force; (2) then a large thermal force occurs with a small moment; and (3) the thermal force and moments then decay as elapsed time increases.

In order to illustrate the utility of these curves for the determination of the response characteristics an illustrative problem will be given. The following quantities must be assumed or determined from other analyses:

Properties

η = 3.00 sec = 8.33×10^{-4} hr

Q = 44 Btu/ft^2

h_c = 42 Btu/hr ft^2 °F

b = 3/16 in. = 0.0156 ft.

ρ = 173 lb/ft^3

C_p = 0.23 Btu/lb °F

k = 66.7 Btu/hr ft °F

$$a = \frac{k}{\rho C_p} = 1.67 \text{ ft}^2/\text{hr}$$

$E\alpha$ = 130 psi/°F

ν = 0.33

From equation (9)

$$\beta = \frac{b}{\sqrt{a\eta}} = \frac{0.0156}{\sqrt{1.67 \times 8.33 \times 10^{-4}}} = 0.42 \cong 0.4;$$

From equation (7)

$$Bi = \tau\beta^2 = \frac{h_c b}{k} = \frac{42 \times 0.0156}{66.7} = 0.01;$$

and from equation (2)

$$t = \eta t^+ = 3.00\, t^+.$$

Equation (4) gives the reference temperature

$$\Delta T_{ref} = \frac{Q}{\rho C_p b} = \frac{44}{173 \times 0.23 \times 0.0156} = 70.8\ ^\circ\mathrm{F} \quad \text{(above ambient)}$$

The actual thermal force and moment can be calculated from equations (17) and (18) as:

$$N_T = \frac{E\alpha\ \Delta T_{ref}\, b}{(1-\nu)} N_T^+ = \frac{E\alpha Q}{(1-\nu)\rho\ C_p} N_T^+$$

$$N_T = \frac{130 \times 70.8 \times .187}{(1-0.33)} N_T^+ = \underline{\underline{2460\ N_T^+}}$$

and

$$M_T = \frac{E\alpha\,\Delta T_{ref}\, b^2}{1-\nu} M_T^+ = \frac{E\alpha Qb}{(1-\nu)\ \rho\ C_p} M_T^+$$

$$M_T = \frac{130 \times 70.8\ (3/16)^2}{(1-0.33)} M_T^+ = \underline{\underline{460\ M_T^+}}$$

Reference to Figures A-1, A-4, A-7, and A-10 in the appendix indicates that maximum values of the dimensionless quantities and their associated dimensionless times are as follows:

Quantity	*Maximum Dimensionless Value*	*Dimensionless Time(t^+)*	*Value*
Front Surface Temperature (Figure A-1)	0.77	5.5	54.5 °F
Front-Back Temperature Difference (Figure A-4)	0.035	1.0	2.5 °F
Thermal Force (Figure A-7)	0.75	5.0 - 6.0	1844 lb/in
Thermal Moment (Figure A-10)	0.0031	1.0	1.43 lb in/in

Inspection of the above table shows that for the particular example, the thermal force is the predominating factor, the moment being quite small.

CONCLUSIONS

In summary, the results indicate the following:

1. The uniformly irradiated plate is subjected to a combination of thermal moment and force at each instant due to the transient temperature distribution.

2. The maximum thermal moment precedes the maximum thermal force with both quantities decaying as time progresses.

3. The maximum possible values of N_T^+ and M_T^+ are 1.0 and 0.27 respectively for the range of variables under consideration.

REFERENCES

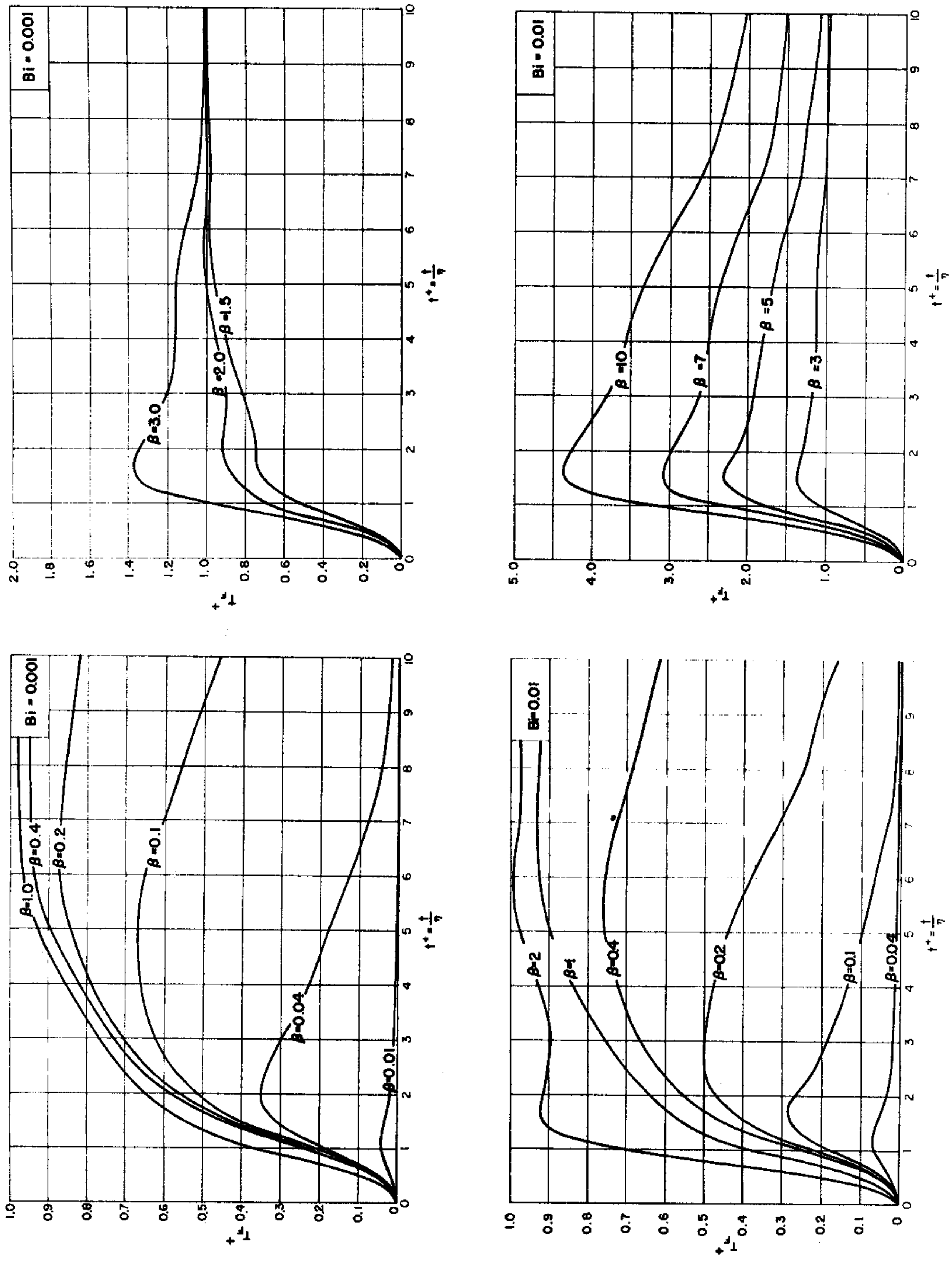
1. Allied Research, *Time Dependent Thermo-Elastic Studies of Thin Skinned Construction Used in Modern Aircraft,* Document No. ARA - M- 5174, June, 1954.
2. Ambrosio, A. and Ishimoto, T., "Analytical Studies of Aircraft Structures Exposed to Transient External Heating," Volume II, *Thermal Response of a Finite Plate and the "Thin" Plate Criterion,* WADC TR 54-579, Department of Engineering, University of California, Los Angeles, November, 1954.
3. Tsien, H. S., "Similarity Laws for Stressing Heated Wings," *Journal of Aero. Sci. 20,* 1-11 (1953).
4. Nadai, A., *Elastiche Platten,* (Elastic Plates), Julius Springer Verlag, Berlin, Germany, 326, 1925.
5. Zizicas, G. A., *Transient Thermal Stresses in Thin Isotropic Elastic Plates,* Department of Engineering Report No. 52-7, University of California, Los Angeles, April, 1952.

APPENDIX

The appendix contains a series of graphs for the front surface temperature, T_F^+, the front-back temperature difference, ΔT^+, thermal force, N_T^+, and thermal moment, M_T^+, as a function of time t^+. The range of parameters for which the numerical results are applicable are as follows:

$$Bi = 0.001 - 1.0$$
$$\beta = 0.01 - 20$$

The Index for the Specific Graphs



Bi = 0.001
β=1.0
β=0.4
β=0.2
β=0.1
β=0.04
β=0.01
Bi = 0.001
β=3.0
β=2.0
β=1.5
Bi=0.01
β=2
β=1
β=0.4
β=0.2
β=0.1
β=0.04
Bi = 0.01
β=10
β=7
β=5
β=3
$t^{+} = \frac{t}{\eta}$
T^{+}

FIGURE A-I

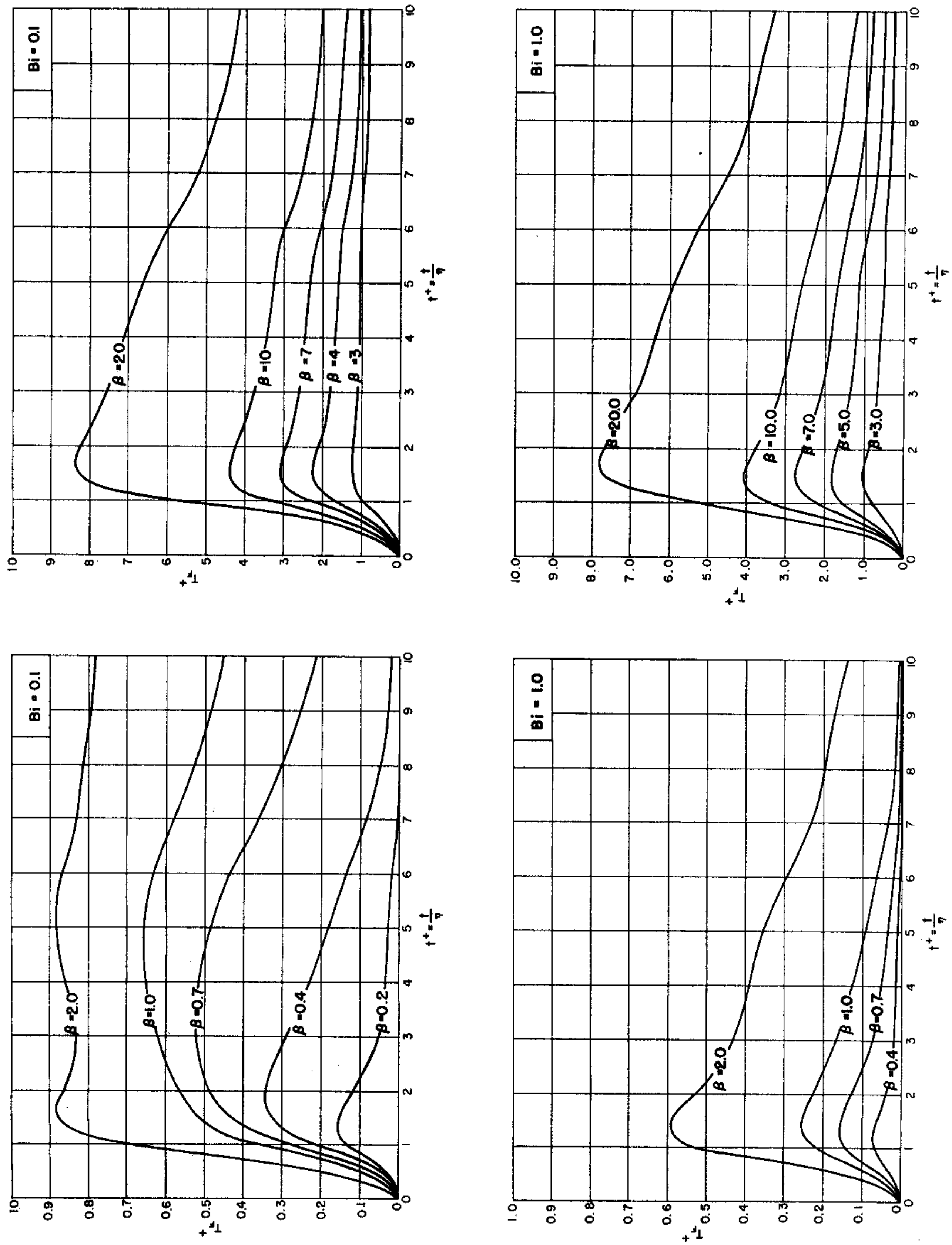
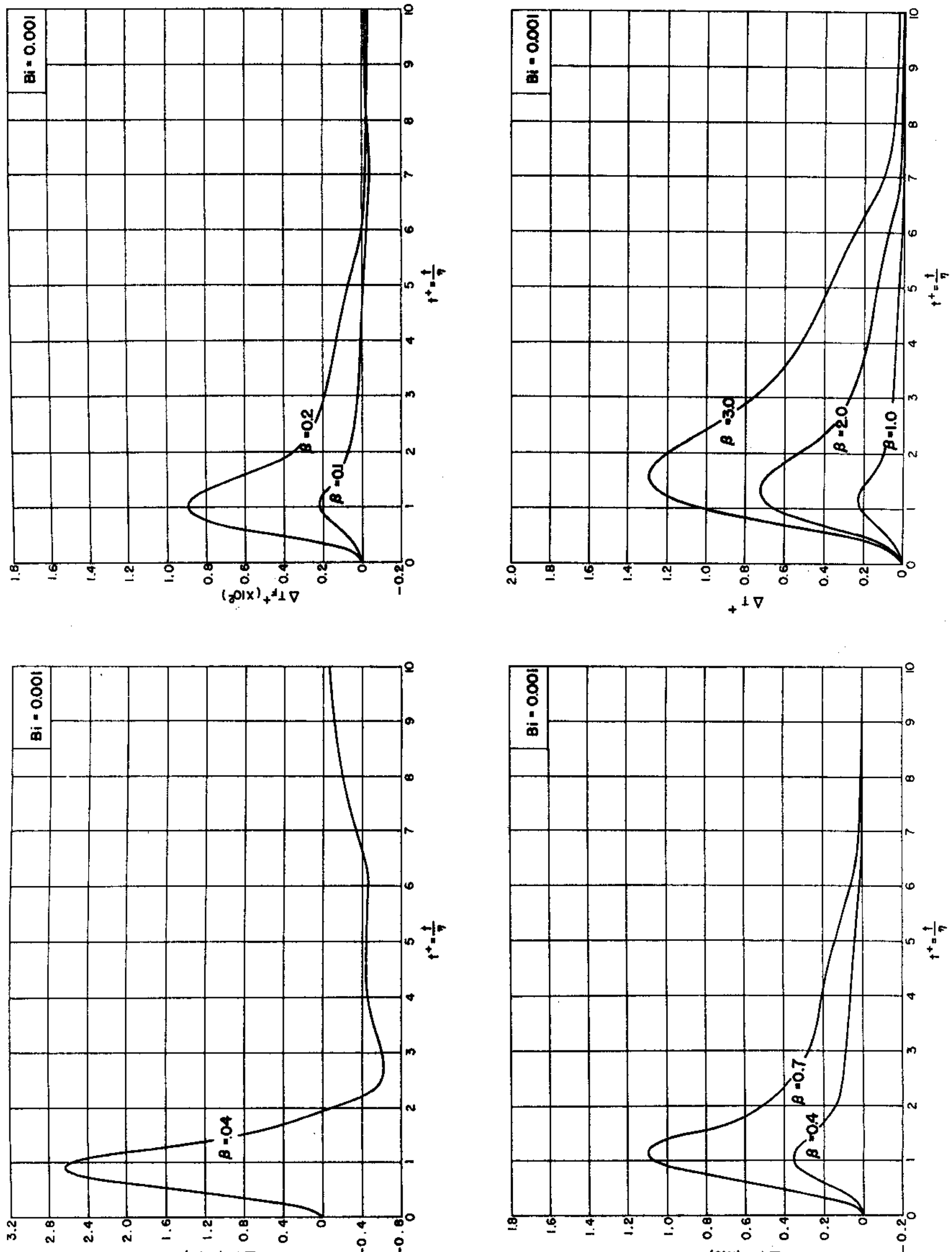

Bi = 0.1
β =20
β =10
β =7
β =4
β =3
Bi = 1.0
β =20.0
β =10.0
β =7.0
β =5.0
β =3.0
Bi = 0.1
β =2.0
β =1.0
β =0.7
β =0.4
β =0.2
Bi = 1.0
β =2.0
β =1.0
β =0.7
β =0.4

FIGURE A-2



Bi = 0.001
β = 0.2
β = 0.1
β = 0.4
β = 0.7
β = 3.0
β = 2.0
β = 1.0
$\Delta T^+ (\times 10)$
$\Delta T^+ (\times 10^4)$
$\Delta T^+ (\times 10^6)$
ΔT^+
$t^+ = \frac{t}{\eta}$

FIGURE A - 3

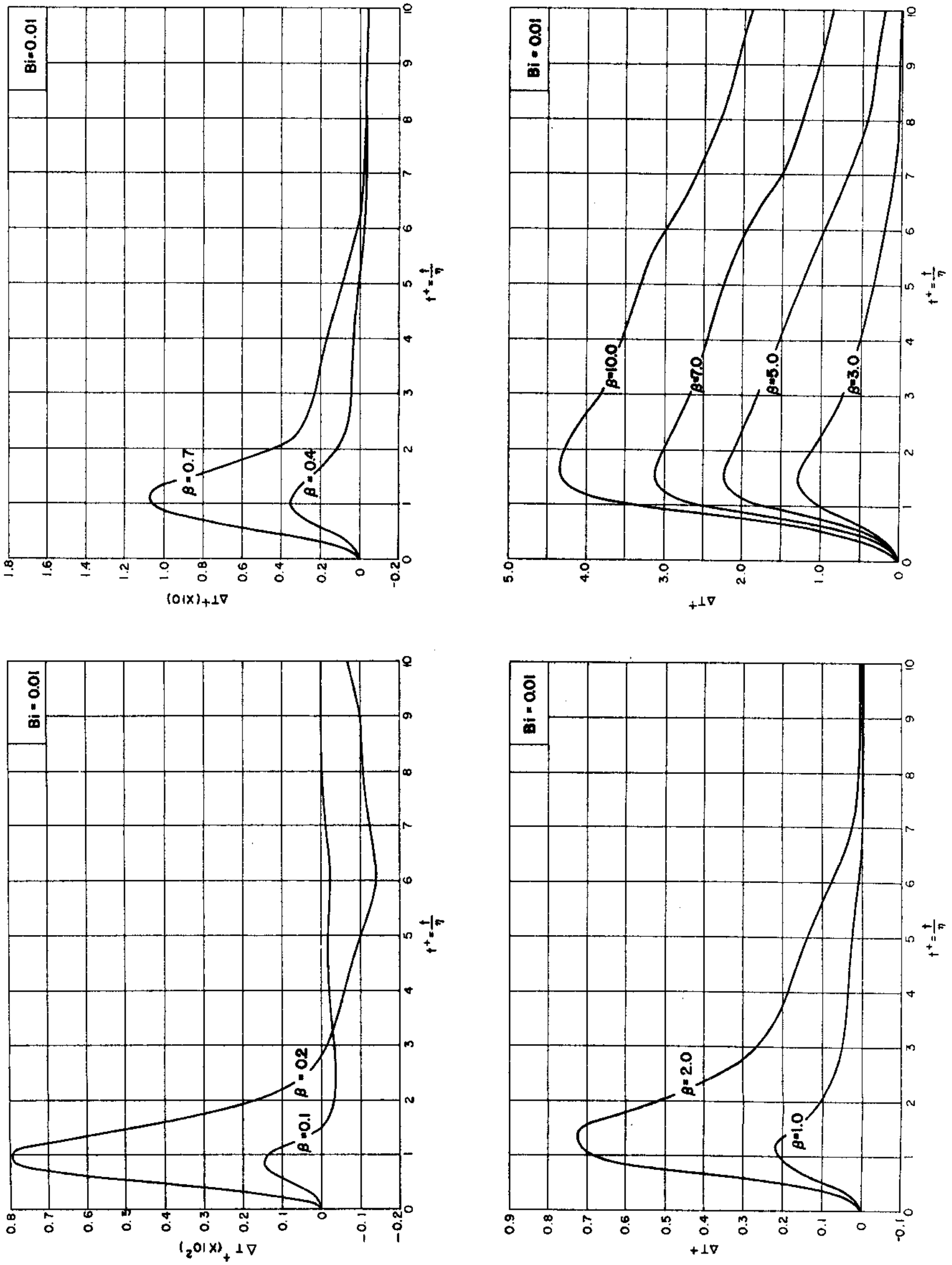
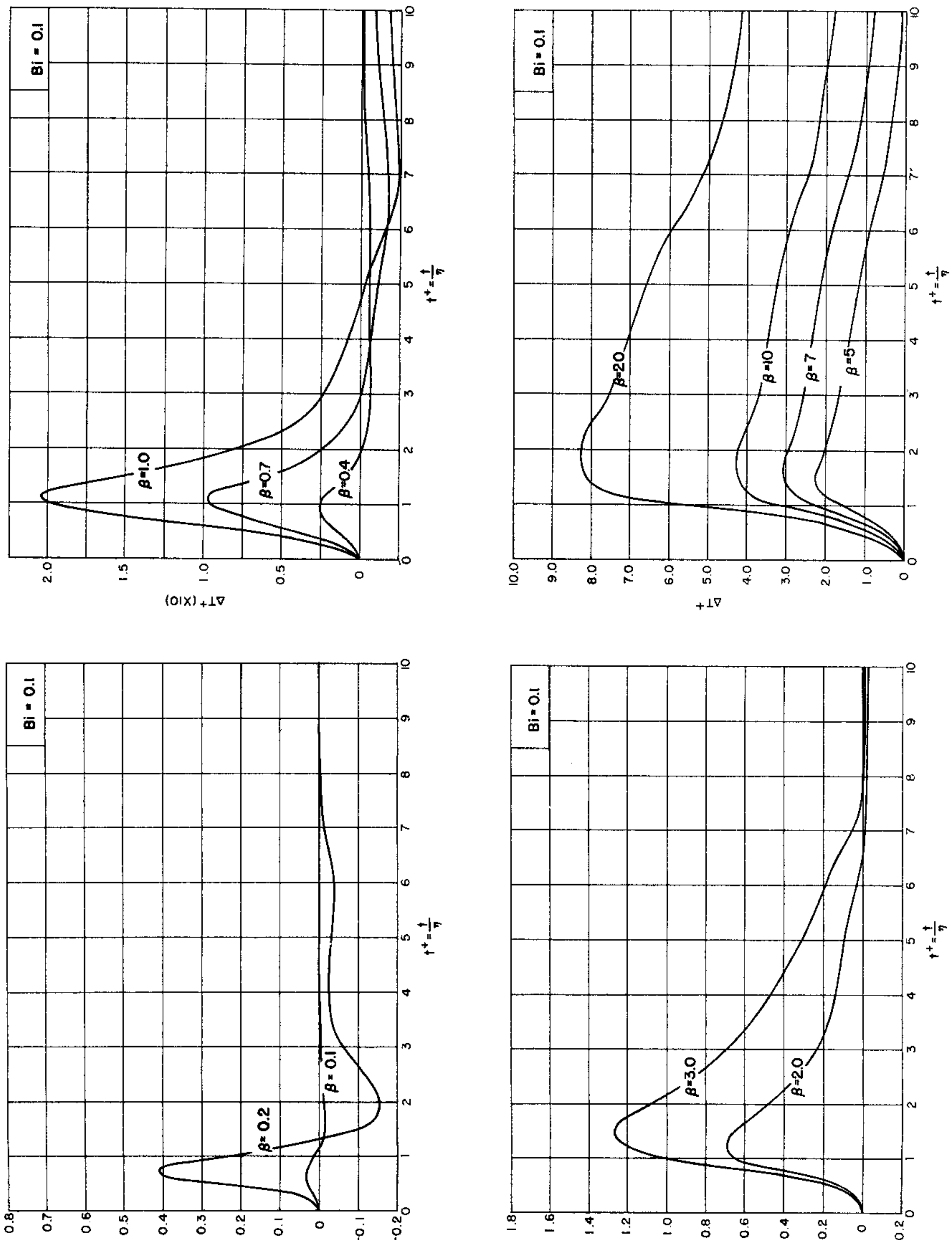

Bi = 0.01
β = 0.7
β = 0.4
ΔT+(X10)
t+ = t/η
Bi = 0.01
β = 10.0
β = 7.0
β = 5.0
β = 3.0
ΔT+
t+ = t/η
Bi = 0.01
β = 0.2
β = 0.1
ΔT+(X10²)
t+ = t/η
Bi = 0.01
β = 2.0
β = 1.0
ΔT+
t+ = t/η

FIGURE A-4



Bi = 0.1
β = 0.2
β = 0.1
$\Delta T^+ (\times 10^2)$
$t^+ = \frac{t}{\eta}$
β = 1.0
β = 0.7
β = 0.4
$\Delta T^+ (\times 10)$
β = 3.0
β = 2.0
ΔT^+
β = 20
β = 10
β = 7
β = 5

FIGURE A - 5

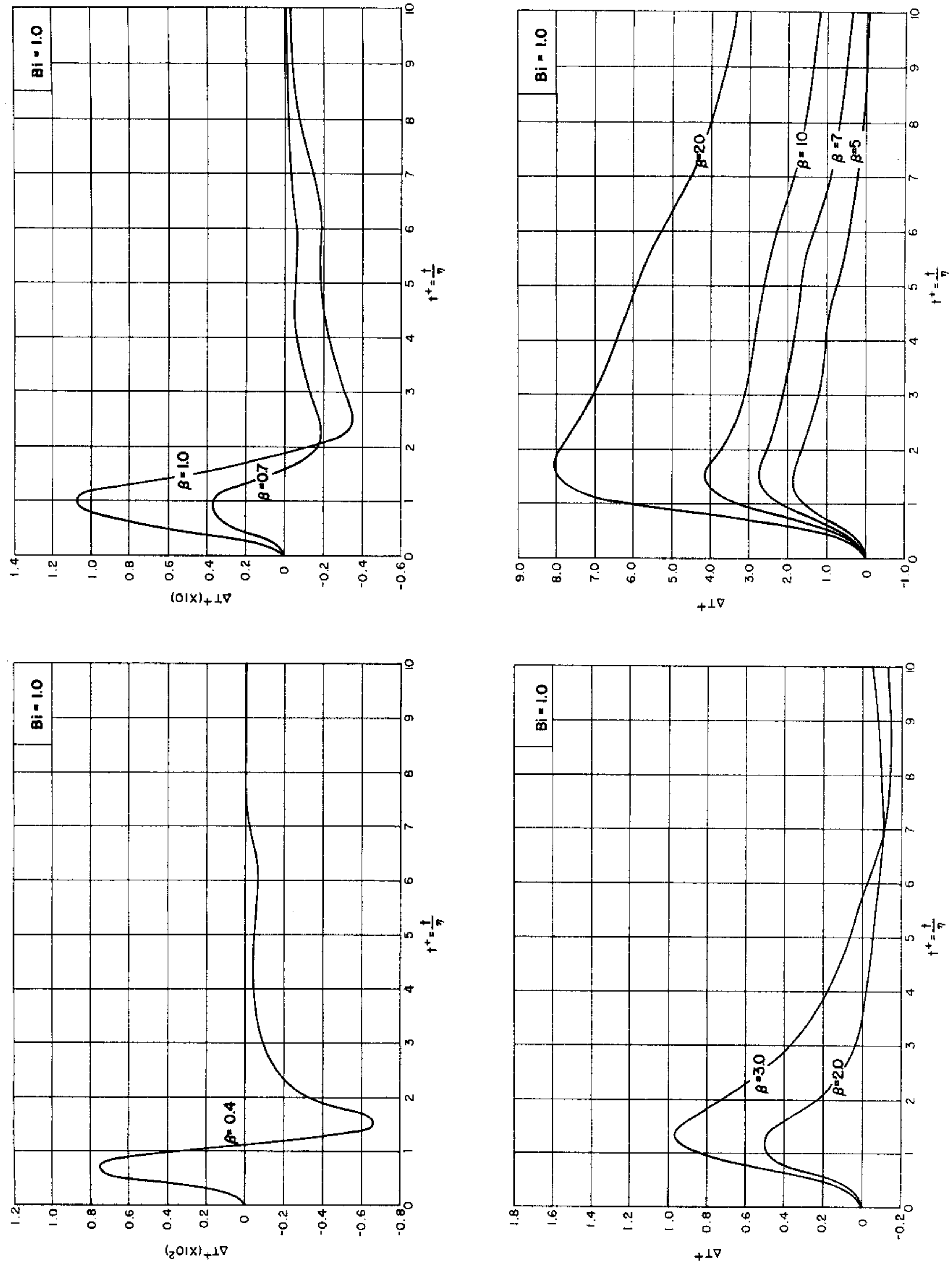

Bi = 1.0
β = 1.0
β = 0.7
ΔT+(X10)
Bi = 1.0
β = 20
β = 10
β = 7
β = 5
ΔT+
Bi = 1.0
β = 0.4
ΔT+(X10²)
Bi = 1.0
β = 3.0
β = 2.0
ΔT+
t+ = t/η

FIGURE A-6

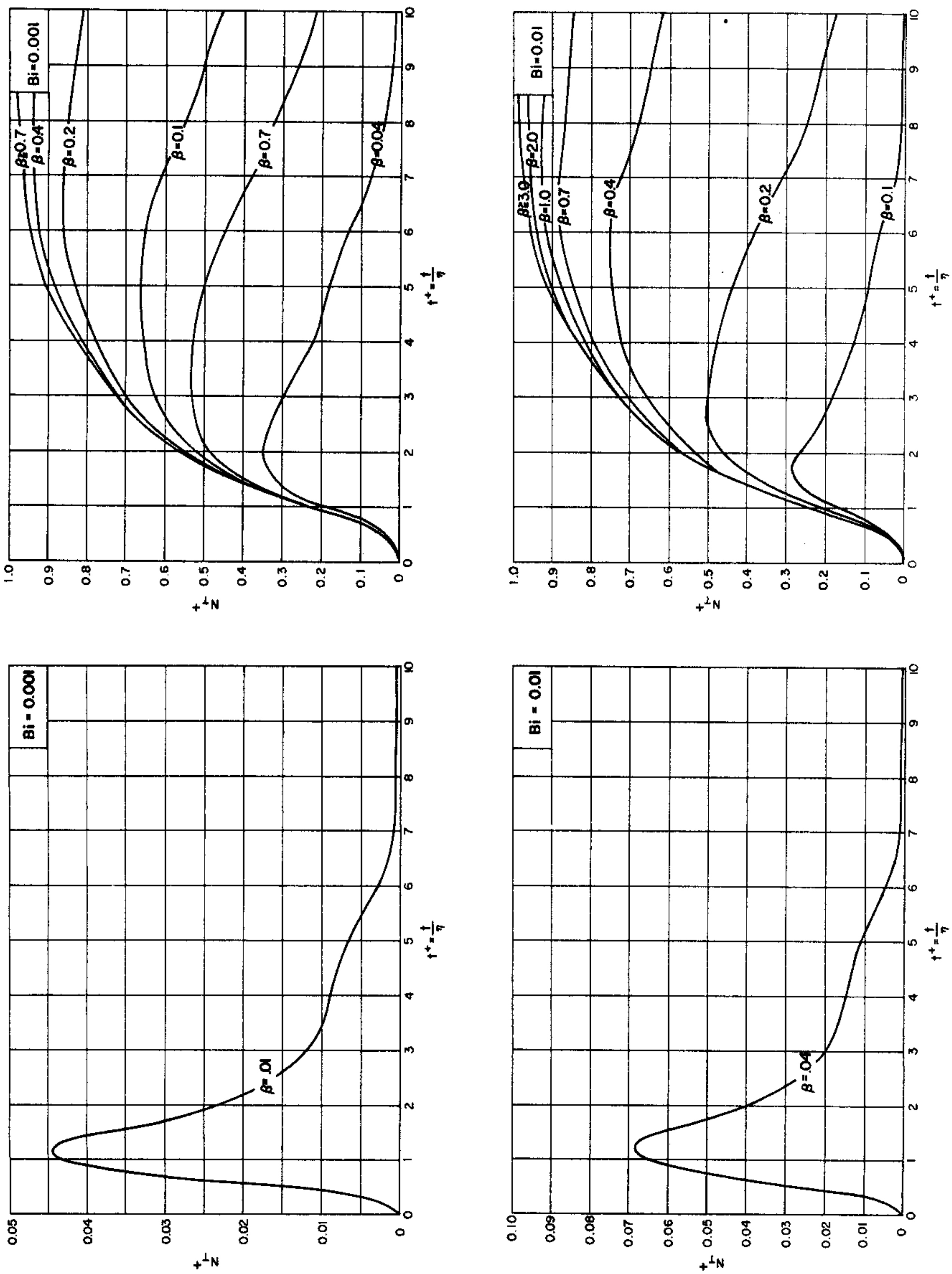

Bi = 0.001
β = .01
Bi = 0.01
β = 0.04
Bi=0.001
β=0.7
β=0.4
β=0.2
β=0.1
β=0.7
β=0.04
Bi=0.01
β=3.0
β=2.0
β=1.0
β=0.7
β=0.4
β=0.2
β=0.1
N_T^+
$t^+ = \frac{t}{\eta}$

FIGURE A - 7

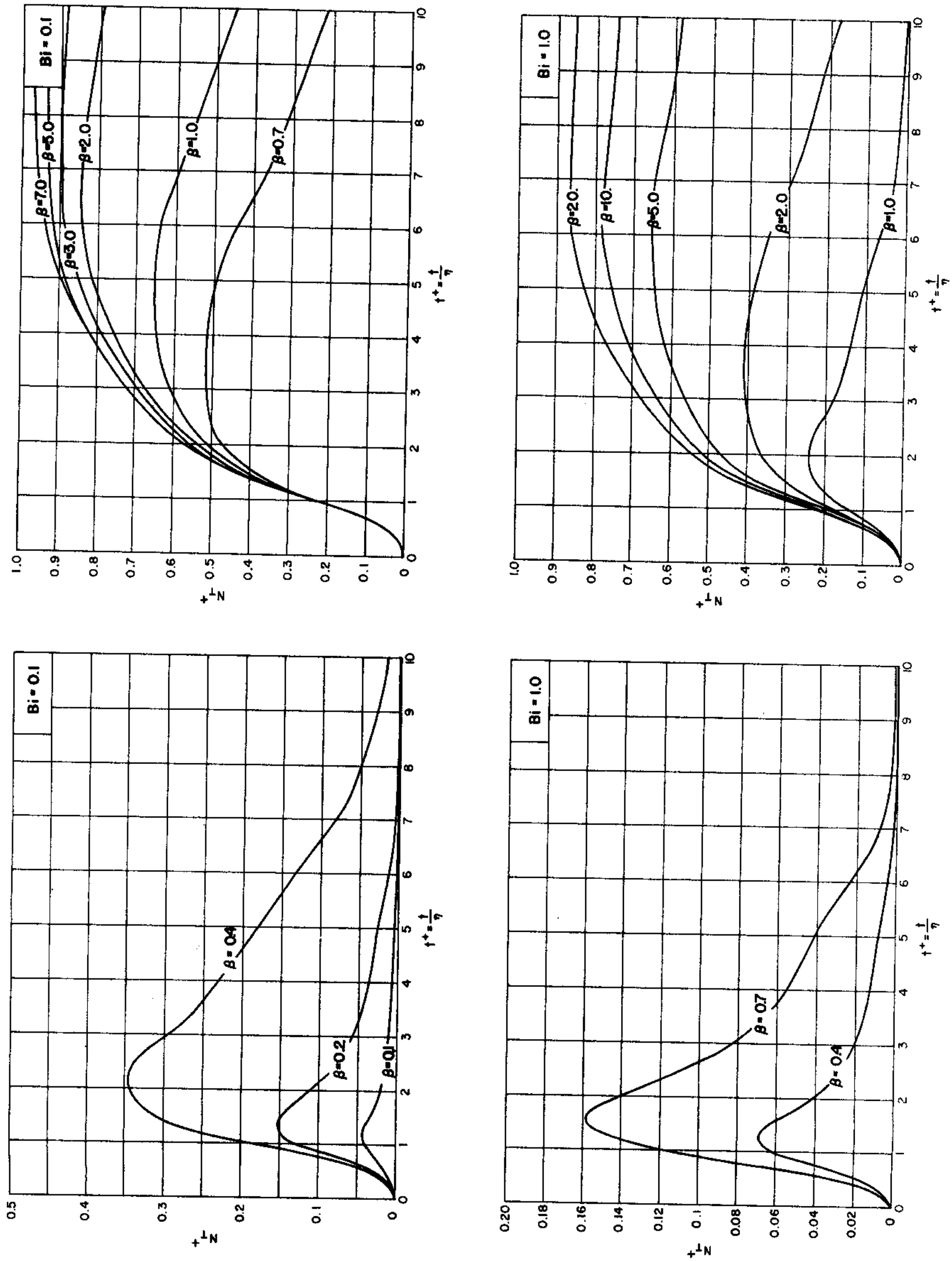

Bi = 0.1
β=7.0
β=5.0
β=3.0
β=2.0
β=1.0
β=0.7
Bi = 1.0
β=20.
β=10.
β=5.0
β=2.0
β=1.0
β=0.4
β=0.2
β=0.1
β=0.7
β=0.4
N_T^+
$t^+ = \frac{t}{\eta}$

FIGURE A - 8

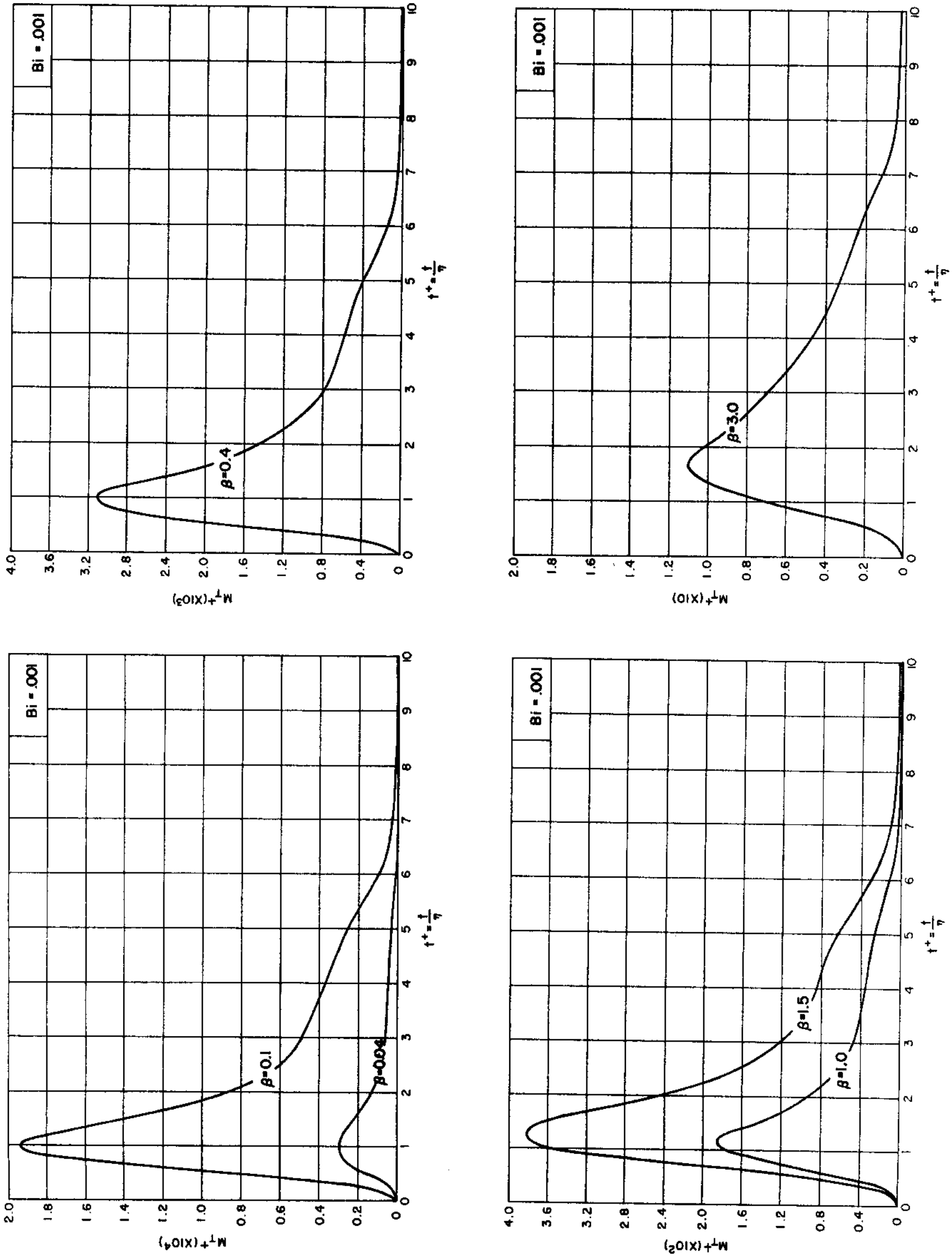
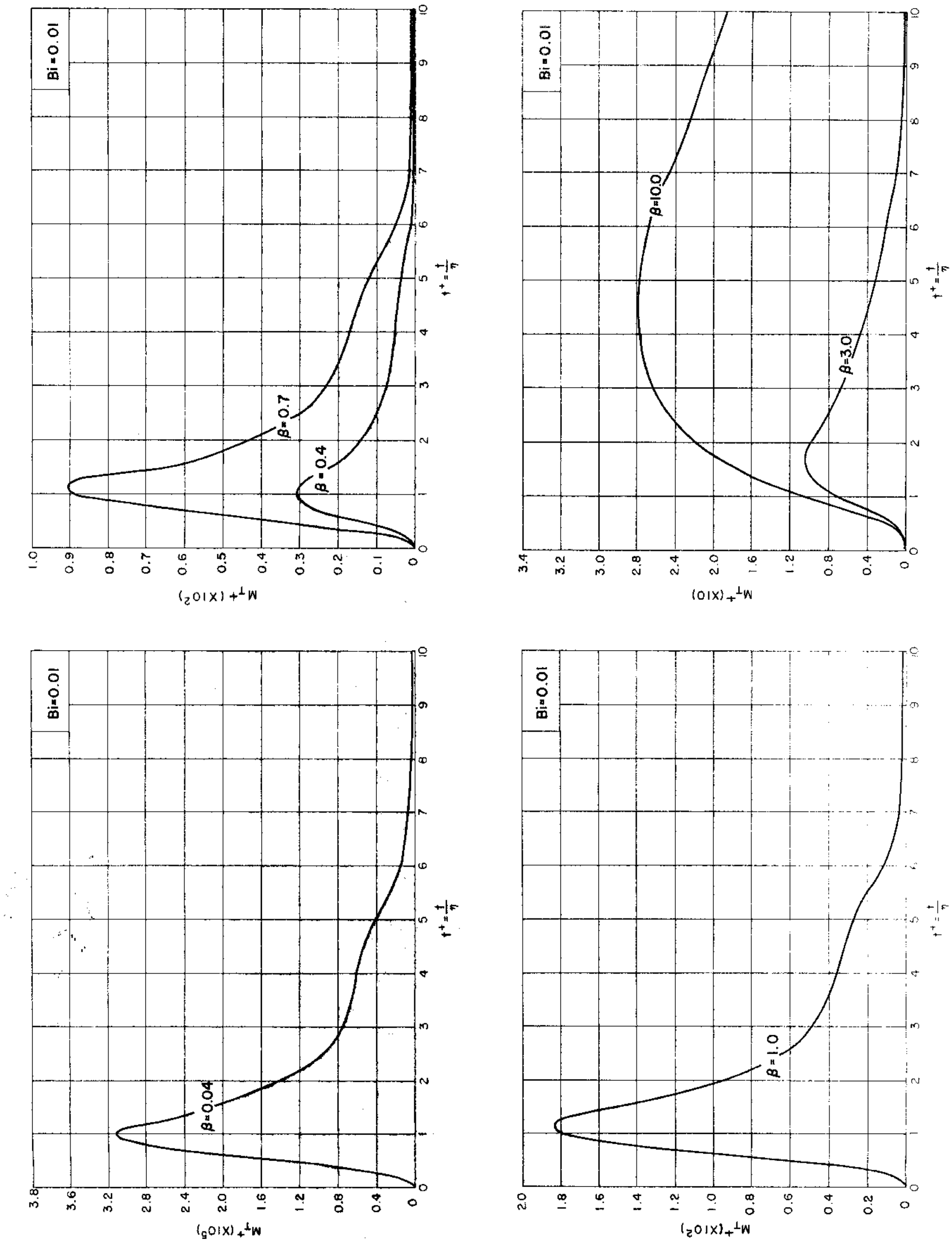

Bi = .001
β=0.4
$M_T{}^+ (X10^3)$
Bi = .001
β=3.0
$M_T{}^+ (X10)$
Bi = .001
β=0.1
β=0.04
$M_T{}^+ (X10^4)$
Bi = .001
β=1.5
β=1.0
$M_T{}^+ (X10^2)$
$t^+ = \frac{t}{\eta}$

FIGURE A-9



Bi = 0.01
β = 0.7
β = 0.4
M_T^+ (X10²)
$t^+ = \frac{t}{\eta}$
Bi = 0.01
β = 10.0
β = 3.0
M_T^+ (X10)
$t^+ = \frac{t}{\eta}$
Bi = 0.01
β = 0.04
M_T^+ (X10⁵)
$t^+ = \frac{t}{\eta}$
Bi = 0.01
β = 1.0
M_T^+ (X10²)
$t^+ = \frac{t}{\eta}$

FIGURE A-10

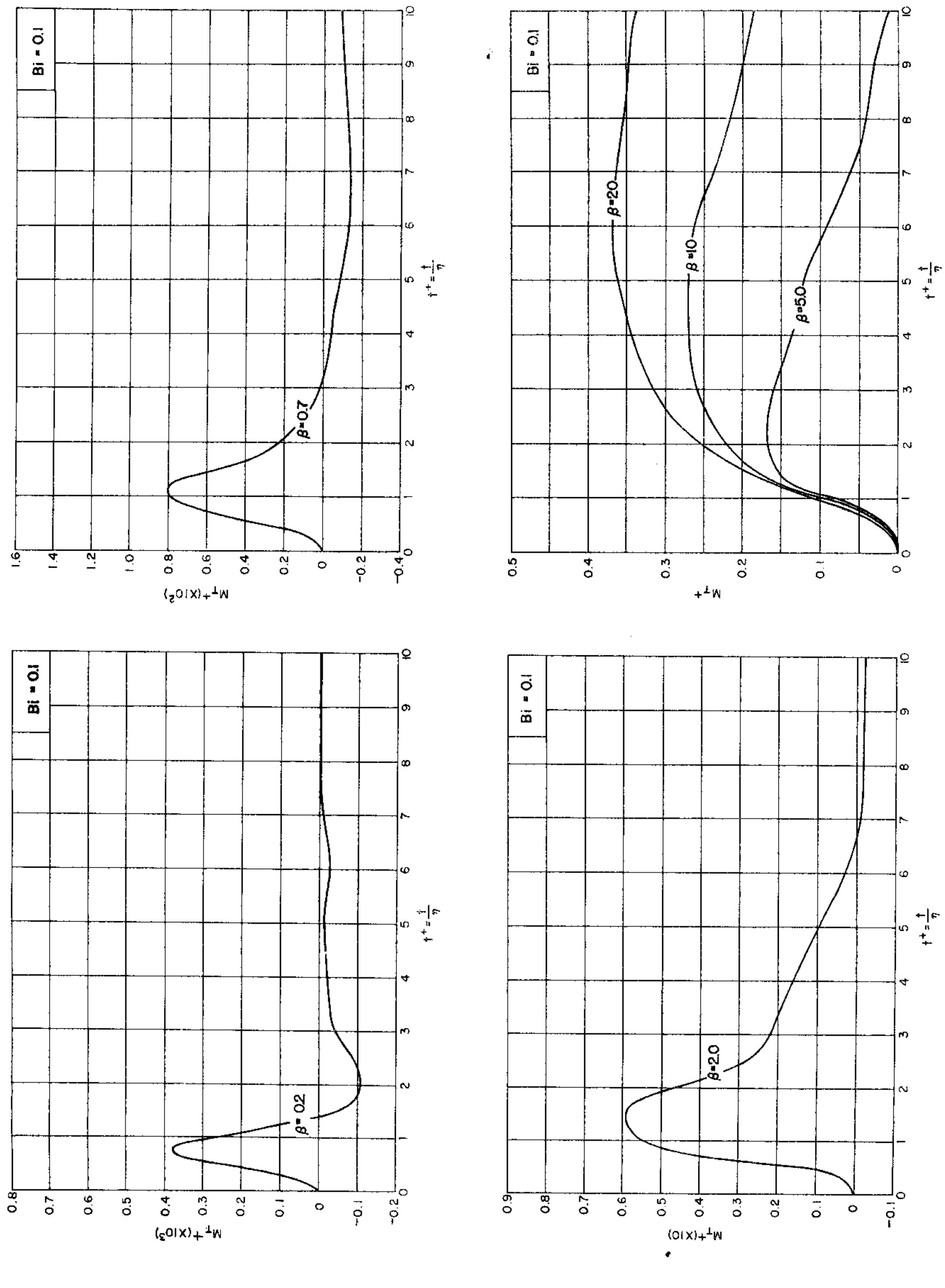
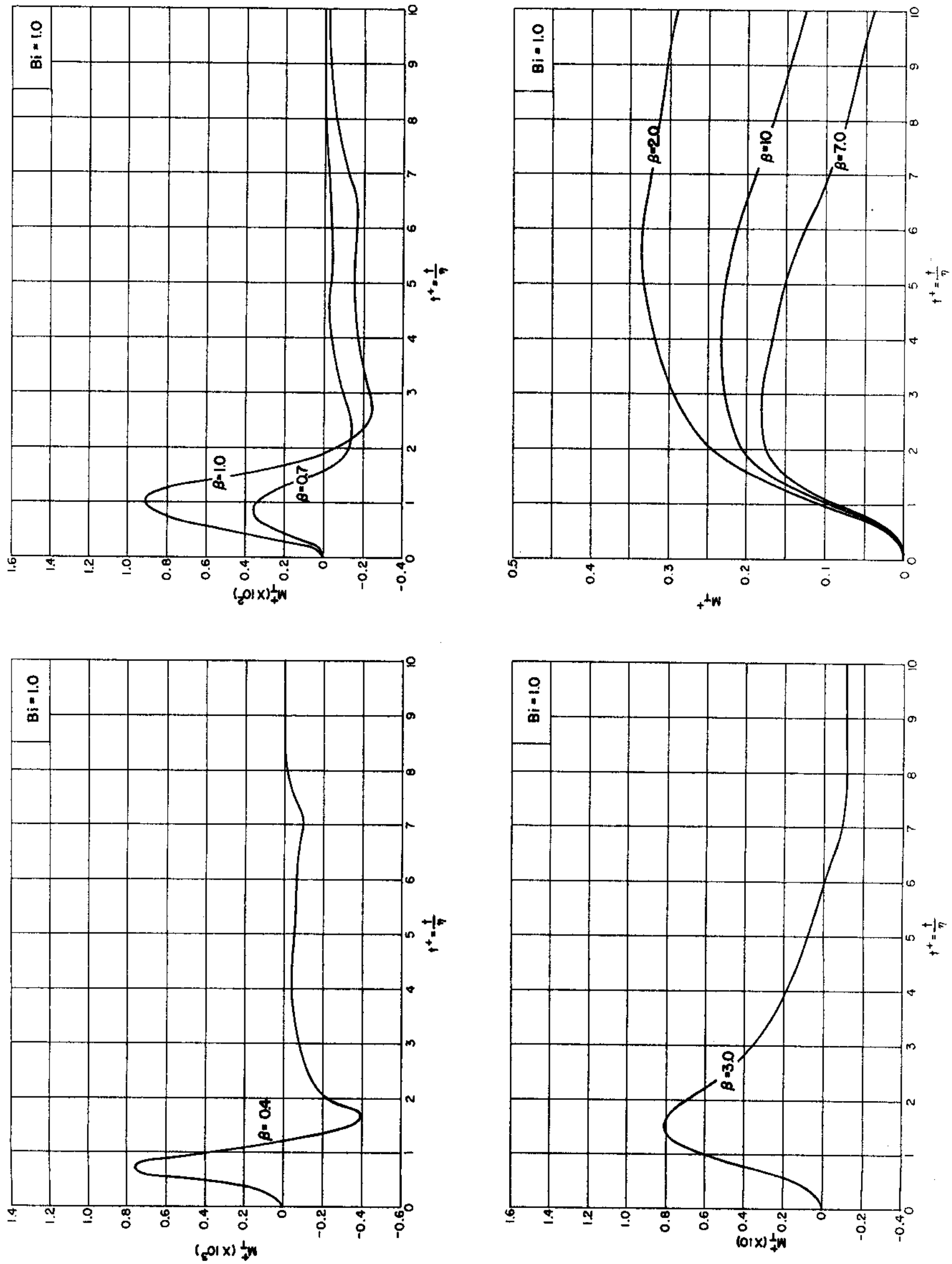

Bi = 0.1
β = 0.2
$M_T+(\times 10^3)$
$t^+ = \frac{t}{\eta}$
Bi = 0.1
β = 0.7
$M_T+(\times 10^2)$
$t^+ = \frac{t}{\eta}$
Bi = 0.1
β = 2.0
$M_T+(\times 10)$
$t^+ = \frac{t}{\eta}$
Bi = 0.1
β = 5.0
β = 10
β = 20
M_T+
$t^+ = \frac{t}{\eta}$

FIGURE A-11



Bi = 1.0
β = 1.0
β = 0.7
$M_T^+ (X10^2)$
$t^+ = \frac{t}{\eta}$
Bi = 1.0
β = 2.0
β = 10
β = 7.0
M_T^+
$t^+ = \frac{t}{\eta}$
Bi = 1.0
β = 0.4
$M_T^+ (X10^3)$
$t^+ = \frac{t}{\eta}$
Bi = 1.0
β = 3.0
$M_T^+ (X10)$
$t^+ = \frac{t}{\eta}$

FIGURE A-12

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