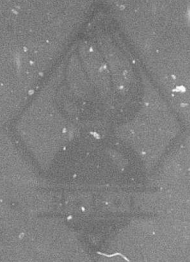


TR-1421

SOME THEORETICAL NOTES
ON THE DETACHED LEVER ESCAPEMENT

December 1963



U.S. ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
WASHINGTON, D.C. 20315

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**SOME THEORETICAL NOTES
ON THE DETACHED-LEVER ESCAPEMENT**

by
David R. Haley

December 1968



U S ARMY MATERIEL COMMAND
HARRY DIAMOND LABORATORIES
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ABSTRACT

This report presents a continuation of the first detailed mathematical analysis made on a detached-lever escapement timing device. The model studied was based on the T5K1 pin-lever escapement, designed primarily for ordnance applications. Although good quantitative results evolved from the original study, subsequent work suggested that the model was not capable of simulating certain characteristics of the detached-lever escapement. For example, this type escapement often had a torque sensitivity characteristic (frequency vs driving torque) that was concave upward.

Further mathematical analysis has resulted in minor but apparently significant changes to the original model, indicating the feasibility of predicting the performance of an escapement more accurately. Also, this analysis—though probably incomplete—now indicates that certain basic characteristics of timers can be changed without changing the basic mechanism.

CONTENTS

	Page No.
ABSTRACT.....	3
1. INTRODUCTION.....	7
2. ESCAPEMENT.....	7
2.1 Equations of Motion.....	7
2.2 Modifications to Equations of Motion.....	10
2.3 Method of Solution.....	17
2.4 Escape Wheel Torque T_a	20
3. ELEMENTARY PARAMETRIC STUDIES USING ESCAPEMENT MODEL.....	20
3.1 Side-Thrust Effects.....	20
3.2 Variation in Coefficient of Friction During Unlocking.....	21
3.3 Variations in Pallet-Lever Inertia and Escape-Wheel Inertia.....	22
3.4 Effect of Ratio D/R_1	22
3.5 The Angle β^*	22
3.6 Escape Wheel to Pallet-Lever Center Distance.....	23
3.7 Escape-Wheel Tooth Geometry.....	23
3.8 Hairspring and Balance Inertia Studies.....	24
4. DISCUSSION AND CONCLUSIONS.....	24
APPENDIX A	50 - 54
APPENDIX B.....	55 - 117
DISTRIBUTION.....	119-123

ILLUSTRATIONS

Figure

1. Pin-lever escapement.....	26
2. Experimental and theoretical beat rate curves for T5E1 escapement.....	27
3. Diagrams showing events during forward half-cycle.....	28
4. Escapement geometry.....	29
5-24. Theoretical beat rate curves for T5E1 escapement.....	30-49
A-1 Sample BALCYC deck format.....	51

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1. INTRODUCTION

Under HDL contract DA-49-186-AMC-176(D), Minnix¹ derived the first detailed mathematical analysis of a detached-lever escapement timing device (fig. 1). The work reported herein is intended to expand that analysis to a more useful model.

Although Minnix used the T5E1 pin-lever escapement as his model, his analysis was generalized to the extent of requiring only minor modifications to describe jeweled lever, folded lever, attached lever, and torsional oscillator escapements. That analysis was programmed for digital solution on an IBM 1620 computer, with numerical results that indicated the feasibility of predicting the escapement performance with an accuracy theretofore unattainable.

Despite that good quantitative results were obtained from the Minnix analysis, prior work by Overman and Bettwy² exhibited empirical characteristics of the detached-lever escapement that were not simulated with the model studied. HDL's experimental results show that this type of escapement may have a torque sensitivity curve (beat rate versus main-spring torque) that is concave upward. Note curve (a) in figure 2, which plots data on a T5E1 escapement; also note that the Minnix model¹ shows a definite increase in beat rate as illustrated by curve (b) in figure 2.

An expansion of the Minnix analysis was therefore begun at HDL, which lead to some minor but apparently significant changes to the original model. These changes have been incorporated into a digital computer program (appx A & B) at these laboratories, based on the original analysis. The results of the further analysis are encouraging, in that (1) the performance of an escapement can be predicted with greater accuracy and (2) certain basic characteristics of timers can be changed without changing the basic mechanism.

2. ESCAPEMENT

2.1 Equations of Motion

The motion cycle of a detached lever escapement is divided into 12 phases, illustrated schematically for the "forward" half cycle in figure 3. Here, β represents displacement of the balance, measured positive counterclockwise and taken to be zero when the impulse pin

¹ Minnix R. B., "The Development of a Mathematical Model of the Detached Lever Escapement," Virginia Military Institute Research Laboratory, 1968.

² Overman, D. L. and Bettwy, D. S., "Experimental Mechanical Timer with Detached Lever Escapement and Digital Readout System," HDL Tech Memo 65-44, 1965.

lies on the line of centers of the balance and lever staff; θ , the lever displacement, is measured positive counterclockwise, and taken to be $P/2$ (fig. 4) when $\beta = 0$; and the escape wheel displacement ϵ , is measured positive clockwise from an arbitrary initial line. The event not shown in figure 3 is the fifth in the sequence, in which the pallet lever is locked by the escape wheel while the balance is at an intermediate position. The catchup phase occurs between the time when unlocking ends and the pallet pin reengages the escape wheel tooth.

Several major assumptions were made by Minnix in his derivation of the equations of motion, both to simplify the analysis and to determine which of the many parameters involved in the design of the escapement are germane to its performance. Many of the original assumptions have been weeded from the model; those remaining that appear to be of greatest relevance are included below.

- (1) An effective geometry is defined so that
 - (a) pallet pins and impulse pins have zero diameter,
 - (b) there is no draw angle on the escape wheel teeth,
 - (c) there is no lever fork, and
 - (d) unlocking ends when $\beta = 0$;
- (2) The balance equilibrium position is at $\beta = 0$, that is, it is here that the hairspring exerts no torque;
- (3) The hairspring is linear (has a linear force-deflection curve);
- (4) Collisions are instantaneous and perfectly elastic;
- (5) Friction due to gravity at all pivots is negligible;
- (6) The energy transmission from escape wheel to balance during impulse incurs no losses.

It is in order to achieve (1 d) that certain other modifications to the geometry are assumed as described by Minnix (ch 3).¹

Under these assumptions, the following equations of motion for the balance are derived, assuming $\beta = \beta_m > 0$, $\dot{\beta} = 0$ at $t = 0$. This assumption obviously has no effect on the motion; it is made for convenience in describing the motion of the various phases. For a detailed derivation of these equations, see description by Minnix¹ (ch 5) or appx A.

Free Motion: $\beta_1 \leq \beta \leq \beta_m$.

$$I_B \ddot{\beta} + (K-L)\beta = 0. \quad (1)$$

Here

I_B is the inertia of the balance,

1. Minnix, R. B., op. cit.

K is the hairspring deflection constant,
L is a friction loss term due to the "side thrust" effect of the hairspring.

Unlocking: $\beta_2 = 0 < \beta < \beta_1$.

$$I_1 \ddot{\beta} + \frac{1}{2} \dot{I}_1 \dot{\beta} + (K-L)\beta = T_f. \quad (2)$$

Here $I_1 = I_B + X^2 I_L$,

I_L is the inertia of the pallet,

X is the lever arm ratio between balance and pallet lever,

T_f is the frictional torque in the negative sense arising from the drag of the entrance pallet pin on the locking face of the escape wheel tooth.

Catchup: $\beta_3 < \beta < \beta_2 = 0$.

$$I_1 \ddot{\beta} + \frac{1}{2} \dot{I}_1 \dot{\beta} + (K+L)\beta = 0, \quad (3)$$

$$I_E \ddot{c} = -T_a. \quad (4)$$

Here

I_E is escape wheel inertia, and

T_a is applied torque at escape wheel.

Note that since the equations are independent during this phase, and since (3) seems analytically intractable, we must rely on an iterative procedure to determine β_3 .

Impulse: $\beta_4 < \beta < \beta_3$.

$$I_2 \ddot{\beta} + \frac{1}{2} \dot{I}_2 \dot{\beta} + (K+L)\beta = XZT_a. \quad (5)$$

Here

$$I_2 = I_B + X^2 I_L + X^2 Z^2 I_E, \text{ and}$$

Z is the lever arm ratio between escape wheel and pallet lever.

Free Motion: $\beta_6 \leq \beta \leq \beta_4$.

$$I_B \ddot{\beta} + (K+L)\beta = 0. \quad (6)$$

Of the assumptions involved in the derivation of these equations, we shall accept all but the last part of the first and the second. A detailed study of the effect of the second part of the first assumption, the fifth, and the sixth will be reported in a subsequent paper.

2.2 Modifications to Equations of Motion

Consider the second assumption—that the hairspring exerts no torque on the balance when $\beta = 0$. This seems to be the design aim of all escapements of this type. But a cursory examination of even a rather large escapement indicates that the attainment in practice of such a goal is probably tedious. Thus the effect of variation of the equilibrium position is studied parametrically.

Assume that the hairspring exerts no torque on the balance staff when $\beta = \beta^*$. β^* is then known as the angle by which the escapement is "out of beat." The equations of motion then become:

Free Motion: $\beta_1 \leq \beta \leq \beta_m$.

$$I_B \ddot{\beta} + (K-L)(\beta - \beta^*) = 0. \quad (7)$$

Unlocking: $\beta_2 \leq \beta \leq \beta_1$.

$$I_1 \ddot{\beta} + \frac{1}{2} \dot{I}_1 \dot{\beta} + (K-L)(\beta - \beta^*) = T_f \quad (8)$$

Catchup: $\beta_3 \leq \beta \leq \beta_2$.

$$I_1 \ddot{\beta} + \frac{1}{2} \dot{I}_1 \dot{\beta} + (K+L)(\beta - \beta^*) = 0, \quad (9)$$

$$I_E \ddot{\epsilon} = -T_a.$$

Impulse: $\beta_4 \leq \beta \leq \beta_3$.

$$I_2 \ddot{\beta} + \frac{1}{2} \dot{I}_2 \dot{\beta} + (K+L)(\beta - \beta^*) = XZT_a \quad (10)$$

Free Motion: $\beta_a \leq \beta \leq \beta_4$.

$$I_B \ddot{\beta} + (K+I) (\beta - \beta^*) = 0. \quad (11)$$

If $\beta^* = 0$, these equations reduce to the previous equations of motion.

It will be shown subsequently that the timekeeping characteristics of an escapement are rather sensitive to changes in β^* .

As is explained in chapter 3 of reference 1, to achieve the assumption of unlocking at $\beta = \beta_2 = 0$, an "effective geometry" is defined with virtually all geometric parameters modified slightly to an "effective" value. The definitions of geometric parameters are to be found in figure 4. We define the effective value of each parameter as its actual value with the following exceptions. The notation is that of Minnix.

$$R_{ppe} = 0. \quad (12)$$

$$R_{ee} = R_e + R_{pp}, \quad (13)$$

$$R_{2e} = R_2 + R_{pp} \quad (14)$$

We now follow Minnix's analysis exactly except to note that at unlocking $\beta = \beta_2 \neq 0$; but β_2 is now computed just as the other values, by using the relation between β and ρ , ρ_2 being known geometrically.

We have

$$\beta_2 = \cos^{-1} \left(\frac{R_{pe}^2 + S^2 - R_{1e}^2}{2R_{pe}S} \right) \quad (15)$$

and

$$\beta_2 = \sin^{-1} \left(\frac{D}{R_I} \sin \left(\frac{P}{2} - \rho_2 \right) \right) - \left(\frac{P}{2} - \rho_2 \right), \quad (16)$$

exactly the same formulae as before but geometrically more accurate due to the change in the effective geometry.

Similarly, by the symmetry of the pallet lever cycle,

$$\rho_{11} = P - \rho_2 \quad (17)$$

and

$$\beta_8 = \sin^{-1} \left\{ \frac{D}{R_I} \sin \left(\frac{P}{2} - \rho_8 \right) \right\} - \left(\frac{P}{2} - \rho_8 \right). \quad (18)$$

To define the motion of the escapement subject to these equations, we must also recompute the initial velocities for each phase. We make use of the conservation of energy laws and the assumption of instantaneous, completely elastic collisions (thus conserving momentum).

Phase 1: The initial energy in this phase is entirely stored in the hairspring and the only dissipative effect is that of side thrust friction. Hence, equating energy at each end of the phase,

$$\begin{aligned} \frac{1}{2} K (\beta_m - \beta^*)^2 &= \frac{1}{2} K (\beta_1 - \beta^*)^2 + \frac{1}{2} I_B \dot{\beta}_{1b}^2 \\ + \int_{\beta_1}^{\beta_m} L(\beta - \beta^*) d\beta &= \frac{1}{2} K (\beta_1 - \beta^*)^2 + \frac{1}{2} I_B \dot{\beta}_{1b}^2 \\ + \frac{1}{2} L [(\beta_m - \beta^*)^2 - (\beta_1 - \beta^*)^2] & \end{aligned} \quad (19)$$

so that

$$\dot{\beta}_{1b}^2 = \frac{K-L}{I_B} [(\beta_m - \beta^*)^2 - (\beta_1 - \beta^*)^2]. \quad (20)$$

The notation used here is followed throughout. Namely, when a collision occurs at balance amplitude β_j , $\dot{\beta}_{jb}$ denotes the balance velocity at the instant before collision, $\dot{\beta}_{ja}$ the balance velocity at the instant after collision. Also, we denote by I_{1j} the value of the coupled variable inertia I_1 when $\beta = \beta_j$. For example, $I_{27} = I_2 \{\beta_7\}$.

Phase 2: By the assumption of an instantaneous and perfectly elastic collision at the beginning of unlocking, we have, by conservation of momentum,

$$I_B \dot{\beta}_{1b} = I_{11} \dot{\beta}_{1a},$$

so that

$$\dot{\beta}_{1a} = \frac{I_B}{I_{11}} \dot{\beta}_{1b} = \frac{-I_B}{I_{11}} \left\{ \frac{K-L}{I_B} [(\beta_m - \beta^*)^2 - (\beta_1 - \beta^*)^2] \right\}^{\frac{1}{2}} \quad (21)$$

During this phase, energy is lost due to side-thrust friction and unlocking friction. Thus,

$$\begin{aligned} \frac{1}{2} K (\beta_1 - \beta^*)^2 + \frac{1}{2} I_{11} \dot{\beta}_{1a}^2 &= \frac{1}{2} I_{12} \dot{\beta}_2^2 \\ + \frac{1}{2} K (\beta_2 - \beta^*)^2 + \int_{\beta_2}^{\beta_1} L(\beta - \beta^*) d\beta &+ \int_{\beta_2}^{\beta_1} T_f d\beta. \end{aligned} \quad (22)$$

Minnix¹ (appx C) has exhibited a function U such that

$$T_f = T_f(\beta) = \mu T_a U(\beta).$$

For convenience, we define

$$I_U = \int_{\beta_2}^{\beta_1} U(\beta) d\beta. \quad (23)$$

Then (22) becomes

$$\begin{aligned} \frac{1}{2} K (\beta_1 - \beta^*)^2 + \frac{1}{2} I_{11} \dot{\beta}_1^2 a = \frac{1}{2} I_{12} \dot{\beta}_2^2 + \frac{1}{2} K (\beta_2 - \beta^*)^2 \\ + \frac{1}{2} L [(\beta_1 - \beta^*)^2 - (\beta_2 - \beta^*)^2] + \mu T_a I_U, \end{aligned} \quad (24)$$

so that

$$\dot{\beta}_2^2 = \frac{1}{I_{12}} \left\{ (K-L) [(\beta_1 - \beta^*)^2 - (\beta_2 - \beta^*)^2] + I_{11} \dot{\beta}_1^2 a - 2\mu T_a I_U \right\}.$$

Phase 3: Once $\dot{\beta}_2$ is known, β_3 can be found by the method described in the next section (2.3).

After this, expressions for $\dot{\beta}_{3b}$ and $\dot{\beta}_{3a}$ can be derived. Assume that $\beta_4 \leq \beta^* \leq \beta_2$.

In phase 3, only the side-thrust effect dissipates energy, so conservation laws guarantee that

$$\begin{aligned} \frac{1}{2} I_{12} \dot{\beta}_2^2 + \frac{1}{2} K (\beta_2 - \beta^*)^2 = \frac{1}{2} K (\beta_3 - \beta^*)^2 + \frac{1}{2} I_{13} \dot{\beta}_{3b}^2 + \int_{\beta_3}^{\beta_2} L |\beta - \beta^*| d\beta \\ = \frac{1}{2} K (\beta_3 - \beta^*)^2 + \frac{1}{2} I_{13} \dot{\beta}_{3b}^2 + \frac{1}{2} L [(\beta_2 - \beta^*)^2 - \text{sgn}(\beta_3 - \beta^*) (\beta_3 - \beta^*)^2], \end{aligned} \quad (26)$$

so that

$$\dot{\beta}_{3b}^2 = \frac{1}{I_{13}} \left\{ I_{12} \dot{\beta}_2^2 + K [(\beta_2 - \beta^*)^2 - (\beta_3 - \beta^*)^2] - L [(\beta_2 - \beta^*)^2 - \text{sgn}(\beta_3 - \beta^*) (\beta_3 - \beta^*)^2] \right\} \quad (27)$$

Phase 4: As before, by assuming instantaneous and elastic collisions from conservation of momentum

$$\dot{\beta}_{3a} = (I_{13} \dot{\beta}_{3b} + X_3 Z_3 I_E \dot{\epsilon}_{3b}) / I_{23} \quad (28)$$

¹ Minnix, R. B., op. cit.

Here $X_3 = X(\beta_3)$, $Z_3 = Z(\beta_3)$. During this phase, energy is carried away by side thrust losses and added to the system through impulse. Hence,

$$\begin{aligned} \frac{1}{2} K(\beta_3 - \beta^*)^2 + \frac{1}{2} I_{23} \dot{\beta}_{3a}^2 &= \frac{1}{2} K(\beta_4 - \beta^*)^2 \\ + \frac{1}{2} I_{24} \dot{\beta}_4^2 + \int_{\beta_4}^{\beta_3} L|\beta - \beta^*| d\beta + \int_{\beta_4}^{\beta_3} (-T_a) X Z d\beta. \end{aligned} \quad (29)$$

(The torque is applied opposed to ϵ .) No. $\therefore Z = \frac{d\epsilon}{d\beta}$ in this half cycle, so

$$\int_{\beta_4}^{\beta_3} X Z d\beta = \epsilon_3 - \epsilon_4. \quad (30)$$

Further,

$$\int_{\beta_4}^{\beta_3} L|\beta - \beta^*| d\beta = \frac{1}{2} L \left[\text{sgn}(\beta_3 - \beta^*) (\beta_3 - \beta^*)^2 + (\beta_4 - \beta^*)^2 \right] \quad (31)$$

Hence, (29) becomes

$$\begin{aligned} \frac{1}{2} K(\beta_3 - \beta^*)^2 + \frac{1}{2} I_{23} \dot{\beta}_{3a}^2 &= \frac{1}{2} K(\beta_4 - \beta^*)^2 + \frac{1}{2} I_{24} \dot{\beta}_4^2 \\ + \frac{1}{2} L \left[(\beta_4 - \beta^*)^2 + \text{sgn}(\beta_3 - \beta^*) (\beta_3 - \beta^*)^2 \right] + T_a (\epsilon_4 - \epsilon_3). \end{aligned} \quad (32)$$

Solving for $\dot{\beta}_4^2$, we have

$$\begin{aligned} \dot{\beta}_4^2 &= \frac{1}{I_{24}} \left\{ I_{23} \dot{\beta}_{3a}^2 + K \left[(\beta_3 - \beta^*)^2 - (\beta_4 - \beta^*)^2 \right] \right. \\ &\quad \left. - L \left[(\beta_4 - \beta^*)^2 + \text{sgn}(\beta_3 - \beta^*) (\beta_3 - \beta^*)^2 \right] + 2T_a (\epsilon_3 - \epsilon_4) \right\} \end{aligned} \quad (33)$$

Phases 5 and 6: Here, only side-thrust friction induces losses. The equation of energy balance is

$$\begin{aligned} \frac{1}{2} K(\beta_4 - \beta^*)^2 + \frac{1}{2} I_B \dot{\beta}_4^2 &= \frac{1}{2} K(\beta_6 - \beta^*)^2 - \int_{\beta_6}^{\beta_4} L(\beta - \beta^*) d\beta \\ &= \frac{1}{2} K(\beta_6 - \beta^*)^2 - \frac{1}{2} L \left[(\beta_4 - \beta^*)^2 - (\beta_6 - \beta^*)^2 \right], \end{aligned} \quad (34)$$

implying

$$(\beta_6 - \beta^*)^2 = (\beta_4 - \beta^*)^2 + \frac{I_B \dot{\beta}_4^2}{K+L}. \quad (35)$$

Phase 7: As only side-thrust phenomena affect the energy balance, it follows that

$$\begin{aligned} \frac{1}{2} K (\beta_8 - \beta^*)^2 &= \frac{1}{2} K (\beta_7 - \beta^*)^2 + \frac{1}{2} I_B \dot{\beta}_{7b}^2 - \int_{\beta_8}^{\beta_7} L(\beta - \beta^*) d\beta \\ &= \frac{1}{2} K (\beta_7 - \beta^*)^2 + \frac{1}{2} I_B \dot{\beta}_{7b}^2 - \frac{1}{2} L \left[(\beta_7 - \beta^*)^2 - (\beta_8 - \beta^*)^2 \right], \end{aligned} \quad (36)$$

or

$$\dot{\beta}_{7b}^2 = \frac{K-L}{I_B} \left\{ (\beta_8 - \beta^*)^2 - (\beta_7 - \beta^*)^2 \right\}. \quad (37)$$

Phase 8: By conservation of momentum,

$$I_{17} \dot{\beta}_{7a} = I_B \dot{\beta}_{7b},$$

or, noting $I_{17} = I_{11}$,

$$\dot{\beta}_{7a} = \frac{I_B}{I_{11}} \left\{ \frac{K-L}{I_B} \left[(\beta_8 - \beta^*)^2 - (\beta_7 - \beta^*)^2 \right] \right\}^{\frac{1}{2}} \quad (38)$$

Applying conservation of energy principles and noting losses and contributions of energy,

$$\begin{aligned} \frac{1}{2} K (\beta_7 - \beta^*)^2 + \frac{1}{2} I_{17} \dot{\beta}_{7a}^2 &= \frac{1}{2} I_{18} \dot{\beta}_8^2 + \frac{1}{2} K (\beta_8 - \beta^*)^2 \\ - \int_{\beta_7}^{\beta_8} L(\beta - \beta^*) d\beta - \int_{\beta_7}^{\beta_8} T_f d\beta &= \frac{1}{2} I_{18} \dot{\beta}_8^2 + \frac{1}{2} K (\beta_8 - \beta^*)^2 \\ - \frac{1}{2} L \left[(\beta_8 - \beta^*)^2 - (\beta_7 - \beta^*)^2 \right] + \mu I_U T_a, \end{aligned} \quad (39)$$

implying

$$\dot{\beta}_8^2 = \frac{1}{I_{18}} \left\{ (K-L) \left[(\beta_7 - \beta^*)^2 - (\beta_8 - \beta^*)^2 \right] - 2\mu I_U T_a + I_{17} \dot{\beta}_{7a}^2 \right\}. \quad (40)$$

Phase 9: By the principles used in the eight previous phases, it may be concluded that

$$\begin{aligned} \frac{1}{2} I_{18} \dot{\beta}_8^2 + \frac{1}{2} K (\beta_8 - \beta^*)^2 &= \frac{1}{2} K (\beta_9 - \beta^*)^2 + \frac{1}{2} I_{19} \dot{\beta}_{9b}^2 \\ + \int_{\beta_8}^{\beta_9} L|\beta - \beta^*| d\beta &= \frac{1}{2} K (\beta_9 - \beta^*)^2 + \frac{1}{2} I_{19} \dot{\beta}_{9b}^2 \\ + \frac{1}{2} L \left[(\beta_9 - \beta^*)^2 + \text{sgn} (\beta_9 - \beta^*) (\beta_9 - \beta^*)^2 \right]. \end{aligned} \quad (41)$$

Therefore,

$$\dot{\beta}_{9b} = \frac{1}{I_{19}} \left\{ I_{18} \dot{\beta}_a^2 + K \left[(\beta_a - \beta^*)^2 - (\beta_9 - \beta^*)^2 \right] - L \left[(\beta_9 - \beta^*)^2 + \text{sgn} (\beta_9 - \beta^*) (\beta_9 - \beta^*)^2 \right] \right\}. \quad (42)$$

Phase 10: By the usual methods,

$$\dot{\beta}_{9a} = \frac{1}{I_{29}} \left\{ I_{19} \dot{\beta}_{9b} - X_9 Z_9 I_E \dot{\epsilon}_{9b} \right\}. \quad (43)$$

Looking at the energy balance,

$$\begin{aligned} \frac{1}{2} K (\beta_9 - \beta^*)^2 + \frac{1}{2} I_{29} \dot{\beta}_{9a}^2 &= \frac{1}{2} K (\beta_{10} - \beta^*)^2 + \frac{1}{2} I_{2,10} \dot{\beta}_{10}^2 \\ &+ \int_{\beta_9}^{\beta_{10}} L |\beta - \beta^*| d\beta - \int_{\beta_9}^{\beta_{10}} XZT_a d\beta. \end{aligned} \quad (44)$$

But in this half cycle, since $XZ = -\frac{d\epsilon}{d\beta}$, we have

$$\int_{\beta_9}^{\beta_{10}} XZT_a d\beta = -T_a (\epsilon_9 - \epsilon_{10}); \quad (45)$$

further,

$$\int_{\beta_9}^{\beta_{10}} L |\beta - \beta^*| d\beta = \frac{1}{2} L \left[(\beta_{10} - \beta^*)^2 - \text{sgn} (\beta_9 - \beta^*) (\beta_9 - \beta^*)^2 \right]. \quad (46)$$

Therefore, (44) becomes

$$\begin{aligned} \frac{1}{2} K (\beta_9 - \beta^*)^2 + \frac{1}{2} I_{29} \dot{\beta}_{9a}^2 &= \frac{1}{2} K (\beta_{10} - \beta^*)^2 + \frac{1}{2} I_{2,10} \dot{\beta}_{10}^2 \\ &+ \frac{1}{2} L \left[(\beta_{10} - \beta^*)^2 - \text{sgn} (\beta_9 - \beta^*) (\beta_9 - \beta^*)^2 \right] + T_a (\epsilon_9 - \epsilon_{10}), \end{aligned} \quad (47)$$

which yields

$$\begin{aligned} \dot{\beta}_{10}^2 &= \frac{1}{I_{2,10}} \left\{ I_{29} \dot{\beta}_{9a}^2 + K \left[(\beta_9 - \beta^*)^2 - (\beta_{10} - \beta^*)^2 \right] \right. \\ &\quad \left. - L \left[(\beta_{10} - \beta^*)^2 - \text{sgn} (\beta_9 - \beta^*) (\beta_9 - \beta^*)^2 \right] - 2T_a (\epsilon_9 - \epsilon_{10}) \right\}. \end{aligned} \quad (48)$$

Phases 11 and 12: By use of another equilibrium condition, the following simpler expression can be obtained for $\dot{\beta}_{10}^2$.

$$\begin{aligned} \frac{1}{2} K (\beta_{10} - \beta^*)^2 + \frac{1}{2} I_B \dot{\beta}_{10}^2 &= \frac{1}{2} K (\beta_m - \beta^*)^2 + \int_{\beta_{10}}^{\beta_m} L(\beta - \beta^*) d\beta \\ &= \frac{1}{2} K (\beta_m - \beta^*)^2 + \frac{1}{2} L [(\beta_m - \beta^*)^2 - (\beta_{10} - \beta^*)^2], \end{aligned} \quad (49)$$

so

$$\dot{\beta}_{10}^2 = \frac{K+L}{I_B} [(\beta_m - \beta^*)^2 - (\beta_{10} - \beta^*)^2], \quad (50)$$

and we have all the necessary initial conditions.

2.3 Method of Solution

Since the displacement β of the balance is not explicitly desired as a function of time, we solve for the time expended in each phase. To do this, regardless of the apparent diversity of equations of motion, only three general forms need be considered. This approach is due primarily to Bloom.¹

In phases 1, 5, 6, 7, 11, and 12, the equation of motion is of the form

$$I\ddot{\beta} + c(\beta - \beta^*) = 0,$$

the harmonic oscillator equation, readily solved explicitly.

In phases 2, 4, 8, 10, the equation can be written in the form

$$I(\beta)\ddot{\beta} + \frac{1}{2}\dot{I}(\beta)\dot{\beta} + c(\beta - \beta^*) = F(\beta) \quad (51)$$

Let $v = \dot{\beta}$ and denote by a prime, differentiation with respect to β (that is, $\frac{df}{d\beta} = f'$).

Then

$$\ddot{\beta} = v \frac{dv}{d\beta} = vv'$$

¹Calculations derived by H. M. Bloom, IDL staff member, on a detached lever escapement system (1968).

and (51) becomes

$$Ivv' + \frac{1}{2} v^2 I' + c(\beta - \beta^*) = F(\beta). \quad (52)$$

Upon the substitution $g = v^2$, so that $g' = 2vv'$, (52) reduces to

$$\frac{1}{2} Ig' + \frac{1}{2} I'g + c(\beta - \beta^*) = F(\beta), \quad (53)$$

or

$$(Ig)' = 2(F(\beta) - c(\beta - \beta^*)). \quad (54)$$

For the given phase under consideration, let β_0 and β denote the initial and final balance displacements. Then, integrating (54) to a given displacement, we have

$$\int_{\beta_0}^{\beta} \frac{d}{d\xi} (I(\xi)g(\xi)) d\xi = 2 \int_{\beta_0}^{\beta} [F(\xi) - c(\xi - \beta^*)] d\xi, \quad (55)$$

or

$$I(\beta)g(\beta) = I(\beta_0)g(\beta_0) + 2 \int_{\beta_0}^{\beta} F(\xi) d\xi + c[(\beta_0 - \beta^*)^2 - (\beta - \beta^*)^2]. \quad (56)$$

Define

$$H(\beta) = 2 \int_{\beta_0}^{\beta} F(\xi) d\xi, \quad (57)$$

and

$$C_0 = I(\beta_0)g(\beta_0) + c(\beta_0 - \beta^*)^2. \quad (58)$$

Now we have

$$g(\beta) = v^2(\beta) = \dot{\beta}^2 = \frac{1}{I(\beta)} [H(\beta) - c(\beta - \beta^*)^2 + C_0]. \quad (59)$$

Thus,

$$\frac{d\beta}{dt} = \pm \left\{ \frac{1}{I(\beta)} [H(\beta) - c(\beta - \beta^*)^2 + C_0] \right\}^{\frac{1}{2}}. \quad (60)$$

The apparent ambiguity of sign does not in fact exist, for $\dot{\beta} \leq 0$ in phases 1-6 and $\dot{\beta} \geq 0$ in phases 7-12. For typographical convenience,

we now consider only the positive root. Separating variables and integrating, we have, if t_0 and t_f denote initial and final times for the phase,

$$t_f - t_0 = \int_{t_0}^{t_f} dt = \int_{t_0}^{t_f} \frac{\sqrt{I(\xi)} \dot{\xi} dt}{\sqrt{H(\xi) + C(\xi - \beta^*)^2 + C_0}} \\ = \int_{\beta_0}^{\beta_f} \frac{\sqrt{I(\xi)} d\xi}{\sqrt{H(\xi) + C(\xi - \beta^*)^2 + C_0}}. \quad (61)$$

The integral on the right in (61) can be evaluated easily by standard quadrature techniques. Thus, the problem is solved for these phases.

The analysis for phases 3 and 9 proceeds in much the same way, in that after noting $F(\beta) \approx 0$, we have

$$t_f - t_0 = \int_{\beta_0}^{\beta_f} \left[\frac{I(\xi)}{C(\xi - \beta^*)^2 + C_0} \right]^{\frac{1}{2}} d\xi. \quad (62)$$

In this case, however, we do not know β_f ($=\beta_3$ or β_9); but we can solve for β_f and t_f simultaneously by an iterative procedure. In these phases the escape wheel turns freely under the influence of the mainspring torque alone, as described by

$$\text{or} \quad I_E \ddot{\epsilon} = -T_a, \\ \epsilon(t) = \epsilon_0 - \left(T_a / 2I_E \right) t^2, \quad (63)$$

where

$$\epsilon(t_0) = \epsilon_0,$$

$$\dot{\epsilon}(t_0) = 0.$$

We also have (Minnix, ch 4)¹ a coupling equation of the form

$$\epsilon(\beta) = f_c(\beta),$$

valid when the pallet pin and escape wheel tooth are in contact. Using these equations, it is possible to iterate to a solution for the desired quantities.

¹ Minnix, R. B., op. cit.

2.4 Escape Wheel Torque T_a

The assumption that the escape wheel torque T_a is constant was made because we are interested only in equilibrium conditions. A major objective of this study is to determine what changes the beat rate of an escapement, thus rendering the mechanism inaccurate. It is clear that, apart from transient conditions, beat rate at constant torque must be constant. Hence, by assuming T_a to be constant, we can find the corresponding steady-state beat rate and thus determine the way this rate varies with torque.

3. ELEMENTARY PARAMETRIC STUDIES USING ESCAPEMENT MODEL

An elementary study was made next of the effect on the escapement's performance of the variation of several geometric and dynamic parameters of its design. Since constancy of beat rate is of prime importance for a good mechanism, we shall look at the changes effected in the plot of beat rate versus escape wheel torque.

Most of the ensuing beat rate curves will have end points corresponding to balance amplitudes of 60 and 330 deg, with corresponding range of escape-wheel torques lying generally between 200 and 14,000 dyne-cm. It is believed that under normal operating conditions, the mainspring of the T5E1 escapement supplies a torque at the escape wheel of between 1000 and 6000 dyne-cm.

3.1 Side-Thrust Effects

Shinkle¹ seems to have first noted that, in addition to exerting a torque on the balance staff, the hairspring of an escapement must also exert a "side-thrust" force perpendicular to the staff with the resulting friction acting to oppose balance motion.

To assume that the magnitude of this frictional torque is linearly dependent on balance displacement is consistent with the assumption of hairspring linearity, as is the assumption that the torque is zero when $\beta = \beta^*$.

Minnix, in some of his early work with Overman, determined that the coefficient of side-thrust friction should have the value $L = 13.83$ dyne-cm/radian for the T5E1 escapement. This was an empirical determination and its accuracy is unknown.

¹Shinkle, J. M., "Detached Lever Escapement Study," Sandia Corp Report SC-RR-65-57 (1965).

The plots in figure 5 show, as has been observed by Shinkle, that beat rate is markedly dependent upon this coefficient. This may be somewhat surprising at first in view of the ratio of L to the spring constant K ($K=921.9$ dyne-cm/radian for the T5E1). But an examination of the various energy losses incurred by the escapement shows that side-thrust losses constitute one of the major loss mechanisms.

Notice should be taken of the type of change in the beat-rate curve brought about by a change in L . Primarily, as L grows larger, the beat rate curve shifts downward and higher torque is required to drive the escapement at a given balance amplitude, the downward shift being more pronounced at lower torques (amplitudes). A characteristic, which is readily observed here and can be seen to permeate all of the curves presented herein, is that all the curves seem to be asymptotic at high torques to a curve qualitatively rather similar to a log-log plot. This phenomenon will become even clearer in later figures.

It can be noted that a hairspring can never really have a side-thrust coefficient of zero. However, it is also clear that the use of a torsion wire as balance spring would correspond to $L=0$. Thus, figure 5 lends credence to the thesis that a torsional oscillator should make an excellent timing mechanism.

3.2 Variation in Coefficient of Friction During Unlocking

In most ways, side-thrust losses are quite similar to other frictional losses. And indeed, I can be derived as a function of balance staff geometry and the coefficient of friction, μ , which was not done in this study.

Since the coefficient of friction varies widely among different surfaces and materials, it is almost meaningless to talk of a nominal value. The actual value can be determined only by experimentation. But it is meaningful and informative to study, as in the previous section, the effect of changes in μ during the unlocking phase (see eq 22) on timekeeping characteristics. Figure 6 shows that the results are quite similar to those exhibited in figure 5, as might be expected.

It will be shown later that once μ and L are known, certain geometric parameters can be varied to counteract the effect of lower beat rate at lower torque. Indeed, it will be shown that we can flatten the curve considerably in the middle and toward the right, and raise it essentially as high as desired on the left, thus generating a curve quite flat overall.

3.3 Variations in Pallet-Lever Inertia and Escape-Wheel Inertia

It is deemed that the graphs representing parametric variations in beat rate for changes in pallet lever and escape wheel inertias (fig. 7 and 8, respectively) are self-explanatory and represent nothing except that which might be expected—that a "heavier" mechanism runs more slowly. The similarity of these curves to those generated in frictional studies (fig. 5 and 6) seems rather remarkable.

3.4 Effect of Ratio D/R_I

The first of the geometric parameters are considered next. The distance D from balance staff center to pallet staff center and the impulse radius R_I are not considered separately, but only their ratio since it is only this ratio that enters into the analytical formulation of the model.

Of the quantities examined, this ratio seems to be the least critical to escapement performance. This seems a little surprising, not only because all other geometry seems quite significant, but this ratio determines in large part the lever arm for energy transmission from mainspring to balance. Figure 9 shows just how insensitive the mechanism is to variations in D/R_I .

3.5 The Angle β^*

As mentioned, it is only natural to study the response of a mechanism to changes in β^* . In such a study, some quite interesting phenomena are to be observed, as seen in figure 10 for the nominal T5E1 configuration. Here, as before, β^* denotes the hairspring equilibrium position.

First, as β^* increases, so does the beat rate for any given torque—that is, the whole curve shifts up or down with β^* . Second, as β^* increases, the beat rate curve attains a greater positive slope for balance amplitudes of about 90 deg or less ($T_b \approx 600$ dyne/cm). Third, and perhaps most important, as β^* increases, a large middle segment of the beat rate curve rises faster than the rest, thus destroying the nominal curve shape and monotonicity and generating a beat rate that may even decrease with increasing torque.

Note particularly that for $\beta^* = 2$ deg, the beat rate changes by less than 0.02 bps for escape wheel torques between 900 and 9000 dyne-cm. This represents a maximum deviation of about 0.04 percent over the normal operating range.

Also important here is that the asymptotic tendency of the beat rate curve is still present for high torques, even though we have shown how to change the basic shape of the plot.

3.6 Escape Wheel to Pallet-Lever Center Distance

Another geometric parameter S , the distance from escape-wheel staff center to pallet-lever staff center, is seen from figure 11 to have some considerable effect on the mechanism's torque sensitivity.

Three points about figure 11 seem worthy of mention. First, changes in S are seen to effect only rather slight changes in beat rate for high torques (amplitudes). Second, the family of curves tails off sharply at low torques as S decreases. Third and most salient, as S is increased past about 0.2400 in., the beat rate continues to increase at low torques; the beat rate actually decreases at higher torques, causing distinct curves within the family to intersect. Nothing even remotely suggesting that this phenomenon might occur has been observed elsewhere.

Noting the curves in figures 10 and 11, one might conjecture that if, say, $S=0.2420$ and $\beta^* = 1$ deg, a quite flat beat rate curve might be generated. That such is the case may be noted from figure 12.

3.7 Escape-Wheel Tooth Geometry

It might be expected that the shape of the escape wheel teeth would have a greater effect on the performance of an escapement than any other design parameter. This turns out to be hardly the case.

Recall from figure 4 the definitions of the radii R_1 and R_2 and the face angle γ . We shall leave the central angle defining the tooth unchanged so that, for a given value of the root radius R_0 , any two of the quantities R_1 , R_2 , and γ define the tooth completely. For the nominal T5E1 escapement, these quantities take on the values:

$$R_1 = 0.184 \text{ in.},$$

$$R_2 = 0.2019 \text{ in.}, \text{ and}$$

$$\gamma = 50 \text{ deg}$$

In figure 13, we see the effect of holding R_2 constant while γ varies and R_1 is changed dependently; no really significant change is effected. But in figure 14, R_1 is held constant, varying R_2 and γ and causing some noticeable torque sensitivity at the lower end.

It seems worthwhile to emphasize again the asymptotic tendency exhibited in figures 13 and 14.

3.8 Hairspring and Balance Inertia Studies

Since a mechanical escapement is essentially a linear oscillator of known natural frequency with some energy input to compensate for various losses, twice this natural frequency is a rather good approximation to the beat rate of the mechanisms. However, as shown, beat rate tends to vary with escape-wheel torque. In order to study how this torque sensitivity varies with beat rate, appropriate mechanisms were examined with the escapement model; the results are presented in figures 15 through 23.

Two points seem noteworthy here. First, for a given spring, it is seen that the higher inertia balances tend to yield less torque-sensitive designs. That is to say, the beat-rate curves are flatter. And second, the curve in figure 23 seems to have been obtained from the nominal curve (see fig. 24) by a shift to the right along itself, away from the steeper low torque area, thus tending to flatten the curve. The difference between the two mechanisms is that the hairspring constant, balance inertia, and side-thrust coefficient have each been doubled.

In figures 15-23, the natural beat rate of the balance is plotted for comparison and is labeled ω_n . It seems from these plots that the horizontal line corresponding to this natural beat rate is the asymptote mentioned previously.

4. DISCUSSION AND CONCLUSIONS

Assuming that our escapement model yields accurate results, the design of timing movements may be transferred from the domain of skilled craftsmen to an engineering atmosphere, at least for ordnance applications. We have discovered some of the design parameters to changes in which torque sensitivity seems very dependent; and there are some that seem to have little effect on this sensitivity. Use of this information and a little jiggling of computer cards, can yield the beat-rate curve presented in figure 24 very nearly flat, with no basic change to the T5E1 escapement. Apparently, under certain conditions, simple basic modifications to the T5E1 might predict even better results. For example, a stronger spring might be used to run the escapement at higher torques, thus moving the operating region to the flatter portion of the beat-rate curve.

But the model is incomplete and the validity of its predictions is really unknown. There are several obvious changes and additions

that need to be effected, including:

- (1) Provision for consideration of the escape tooth draw angle;
- (2) Capability to consider friction at the balance and pallet-lever pivots;
- (3) Provision for friction between pallet pin and escape-wheel tooth during impulse; and
- (4) Inclusion of lever fork geometry.

Although this report discusses the sensitivity of performance to changes in certain design parameters, no design changes are given for removing such sensitivities. And it would be in this area that this analysis would have its greatest value, allowing manufacturing tolerances to be relaxed and, hopefully, permitting the design of rugged, inexpensive, yet accurate timers. It is indicated, however, that the analysis in its present form is sufficient to determine, qualitatively at least, the effect of parameter variations throughout manufacturing tolerance ranges. As such, it should provide a valuable tool in setting such tolerances.

Assuming that a first step has been taken toward a means of transferring escapement design ability and responsibility from the artisan to the engineer, it is suggested that the following three additional steps are necessary to effect this transfer:

- (1) Incorporate into the model the further refinements mentioned above;
- (2) Initiate an extensive experimental program to determine the accuracy of the model; and,
- (3) Conduct a detailed study of the energy analysis derived by Minnix to devise methods of eliminating the undesirable characteristics discovered. For instance, is it possible to design a mechanism insensitive to side-thrust losses? Or to changes in S (fig 4)? Or to escape tooth geometry?

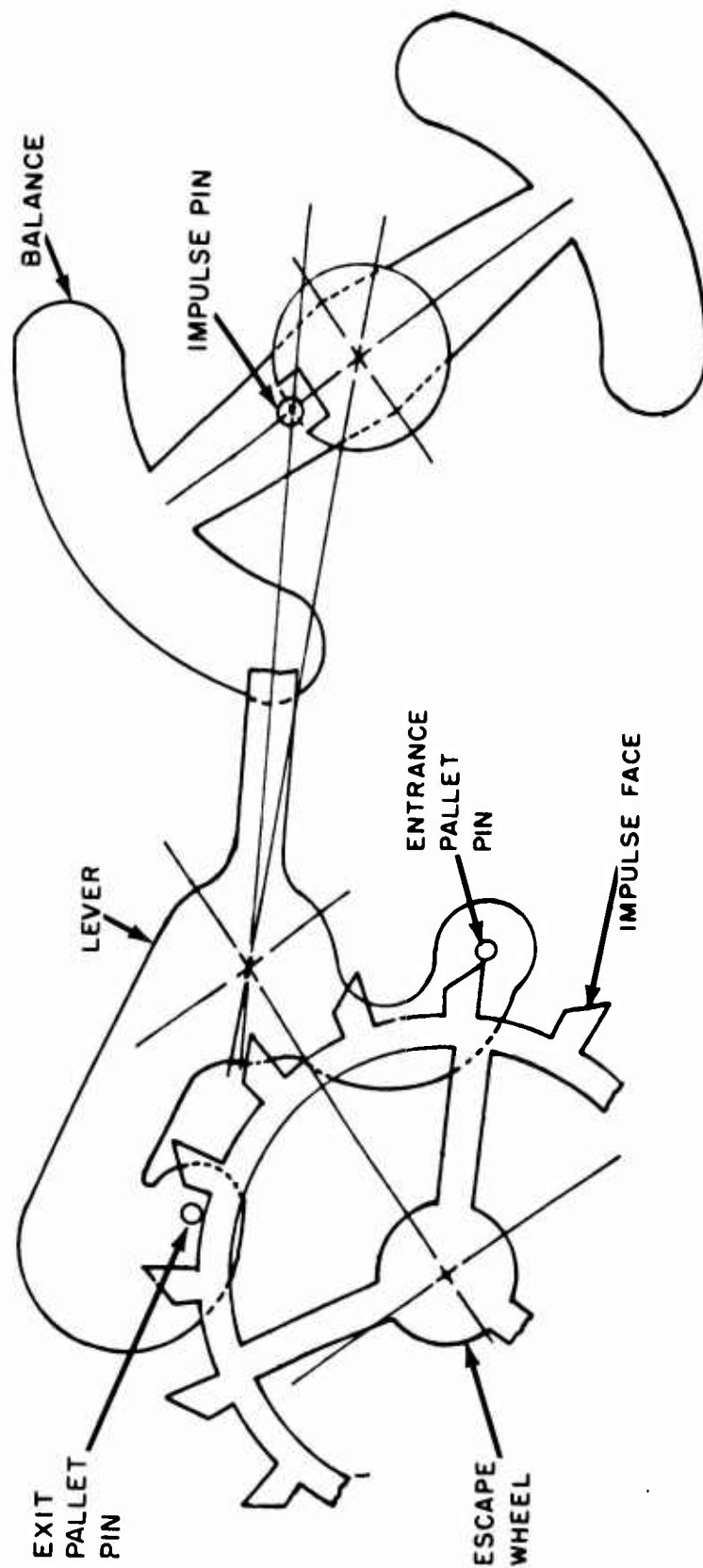


Figure 1. Pin-lever escapement.

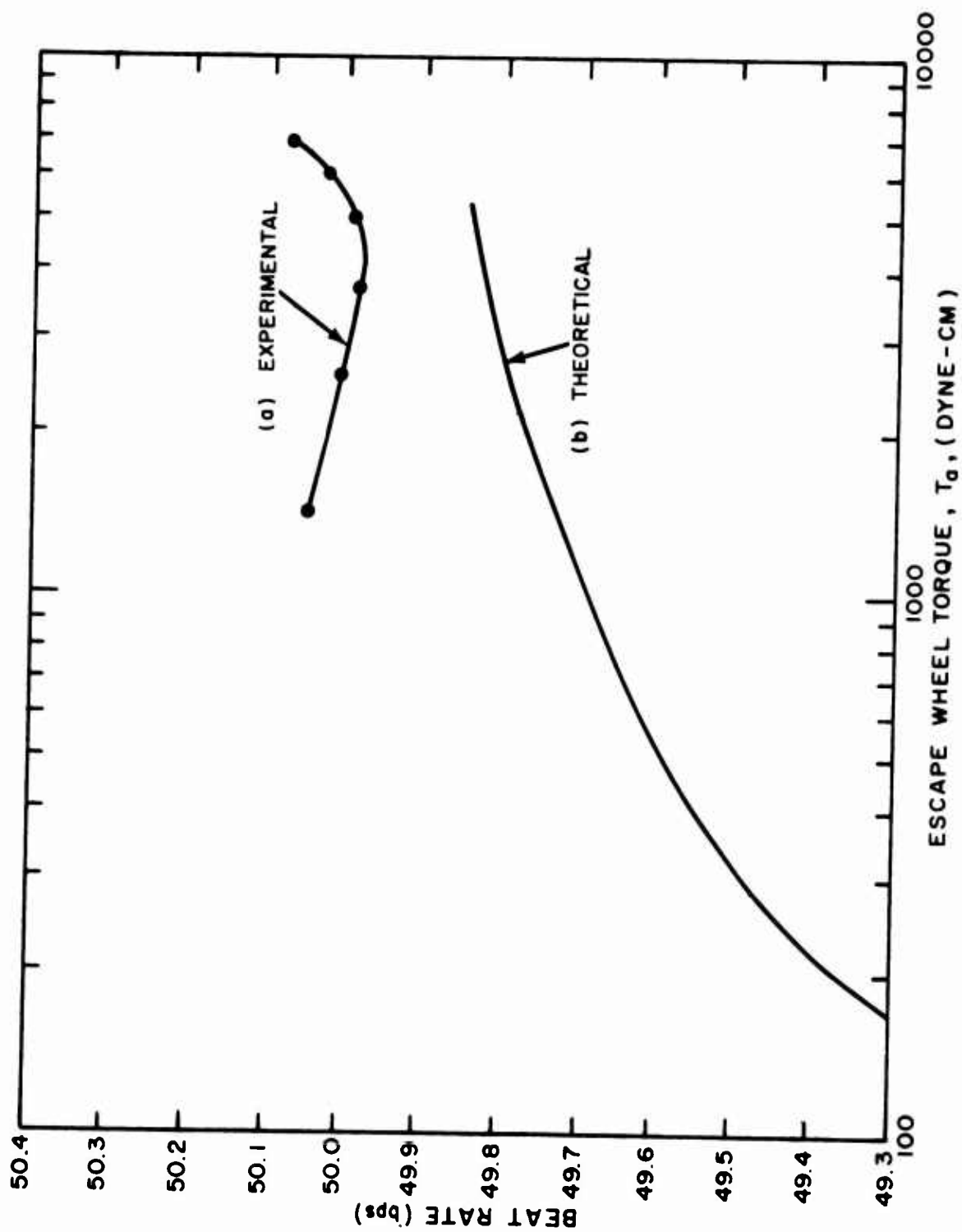


Figure 2. Experimental and theoretical beat rate curves for T5E1 escapement.

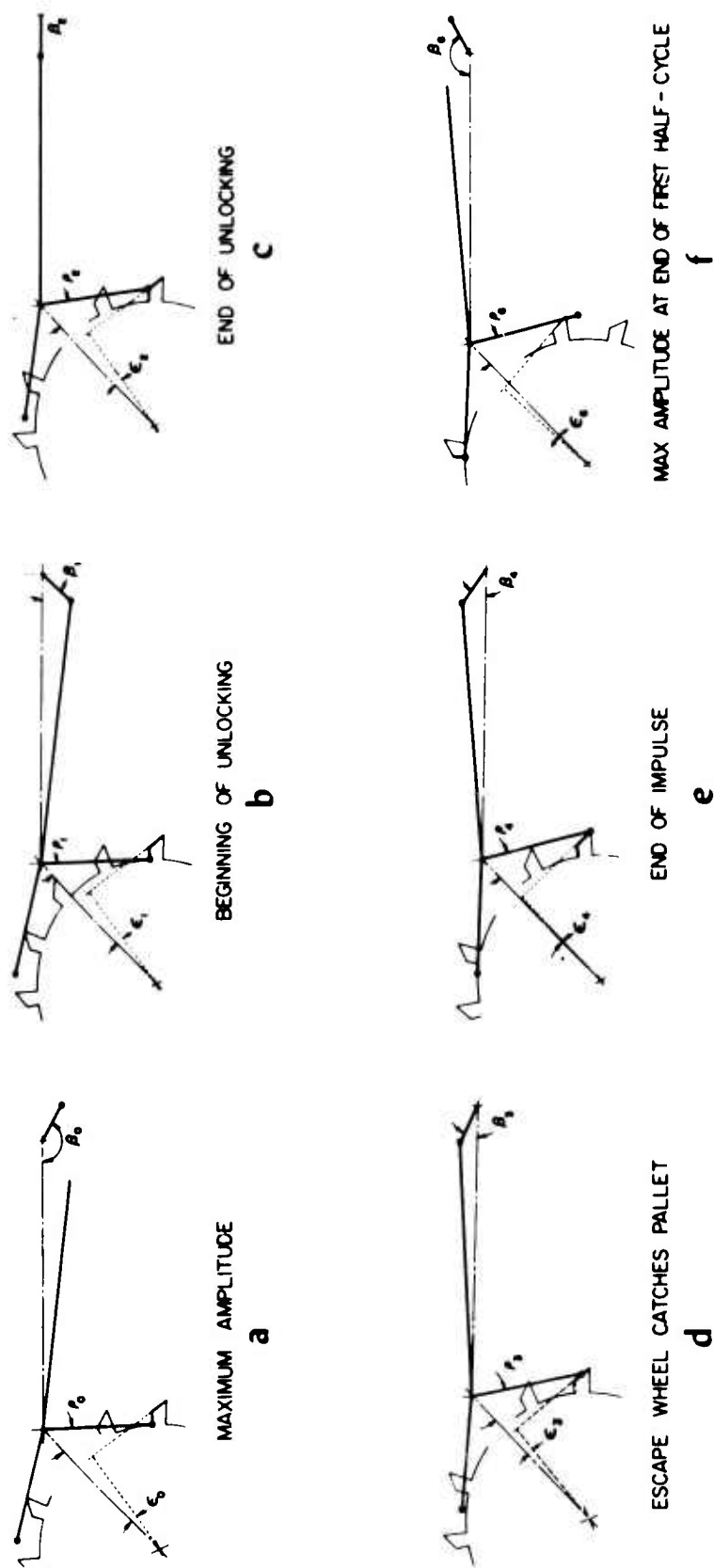


Figure 3. Diagrams showing events during forward half-cycle.

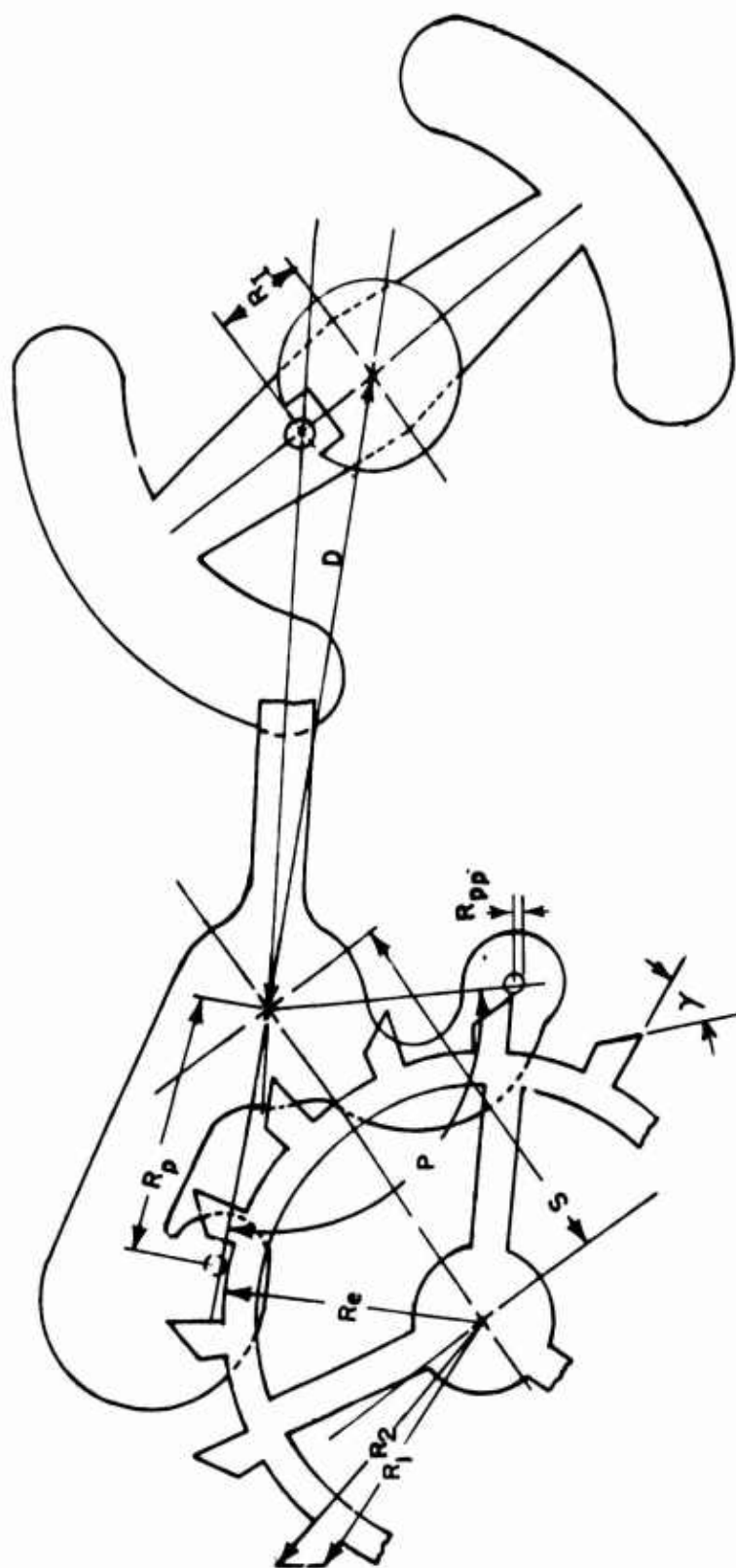


Figure 4. Escapement geometry.

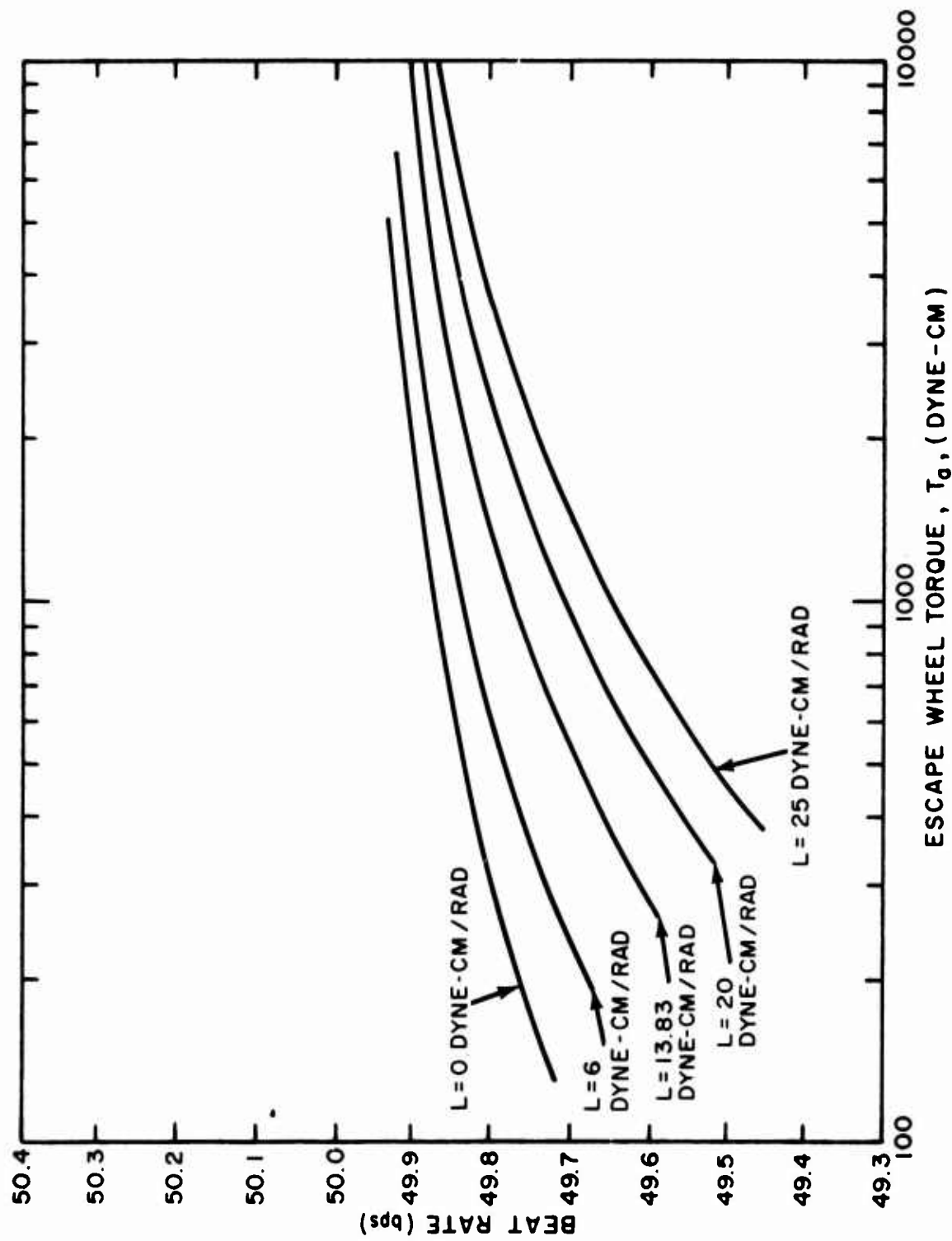


Figure 5. Theoretical beat rate curve for T5E1 escapement.

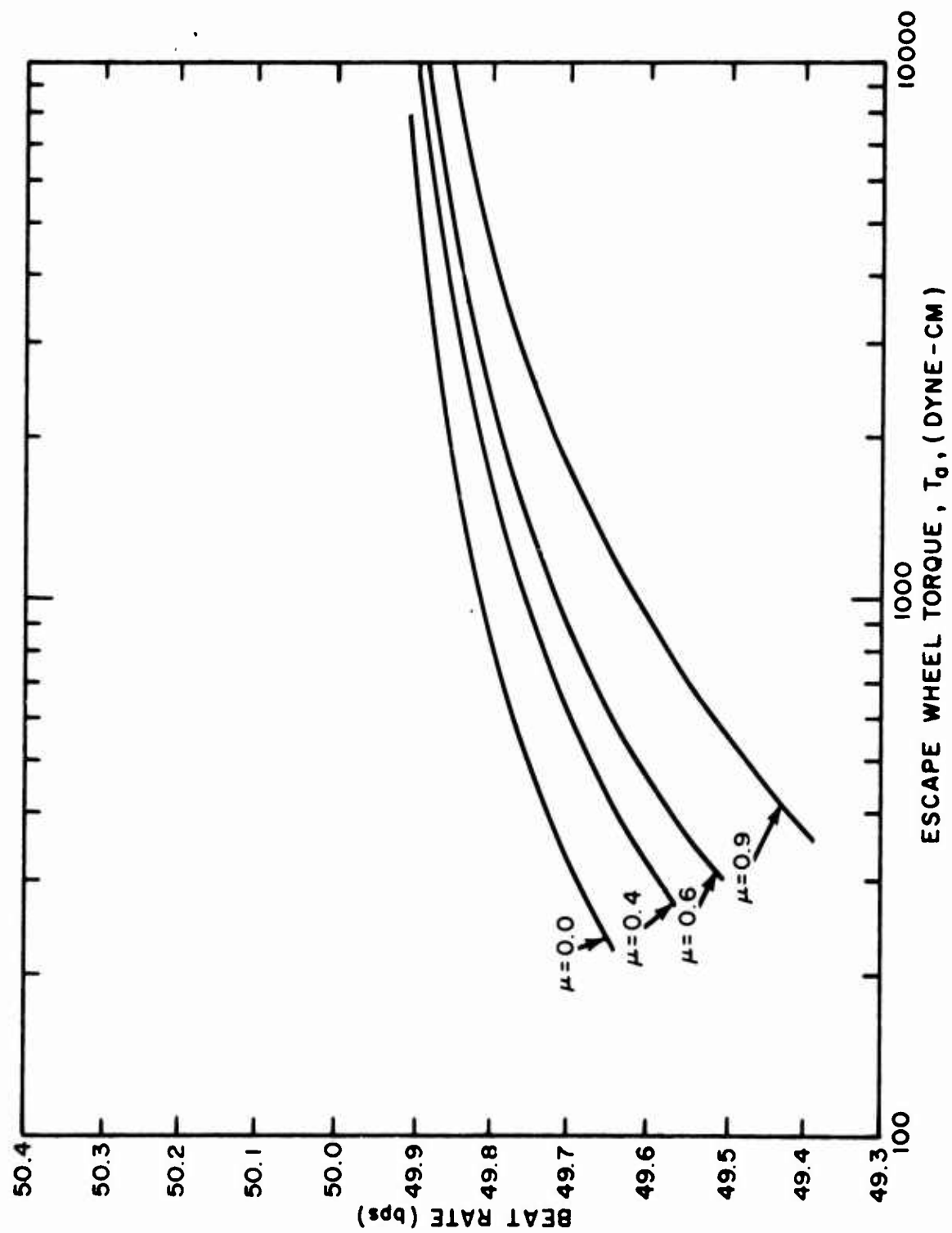


Figure 6. Theoretical beat rate curve for T5E1 escapement.

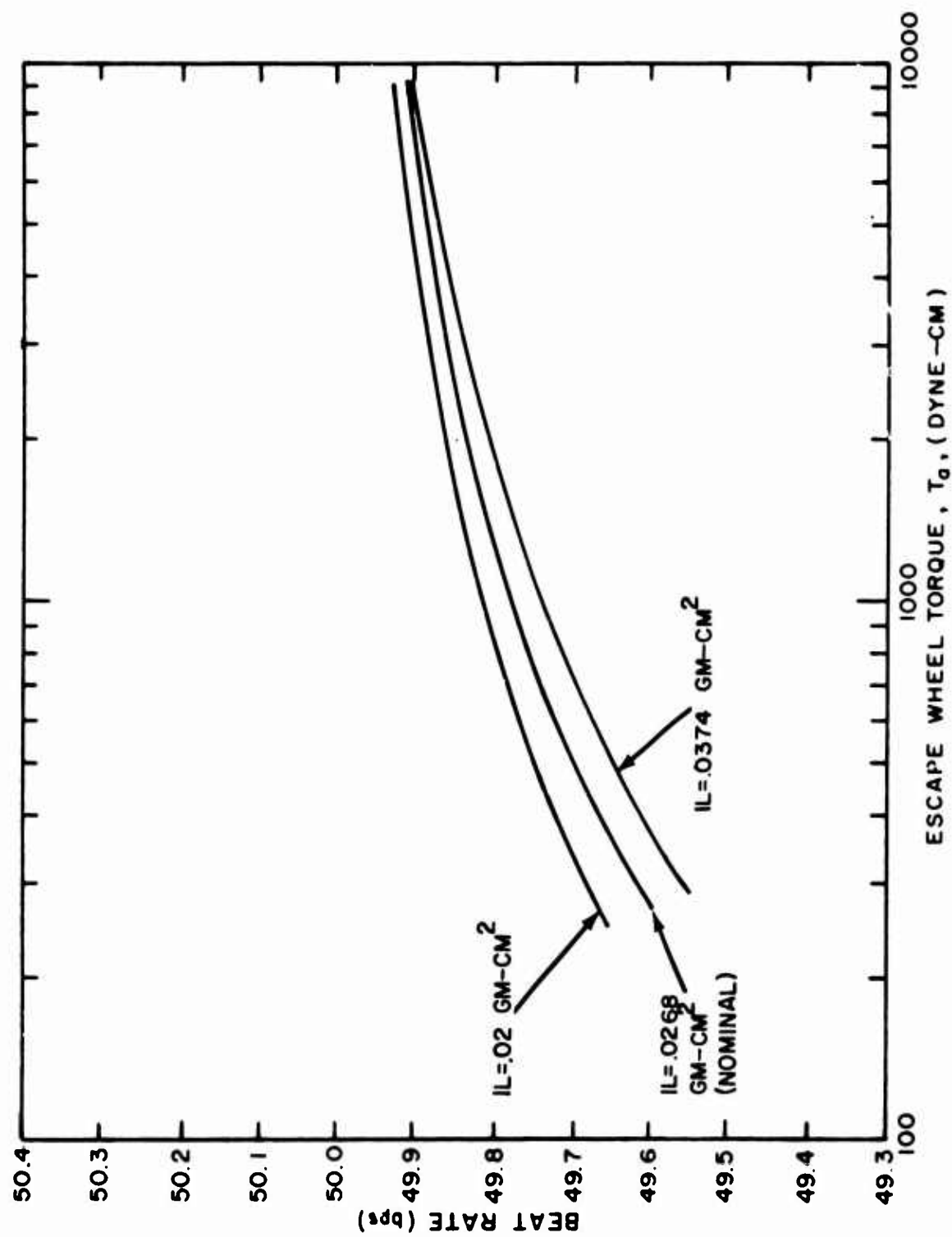


Figure 7. Theoretical beat rate curve for T5E1 escapement.

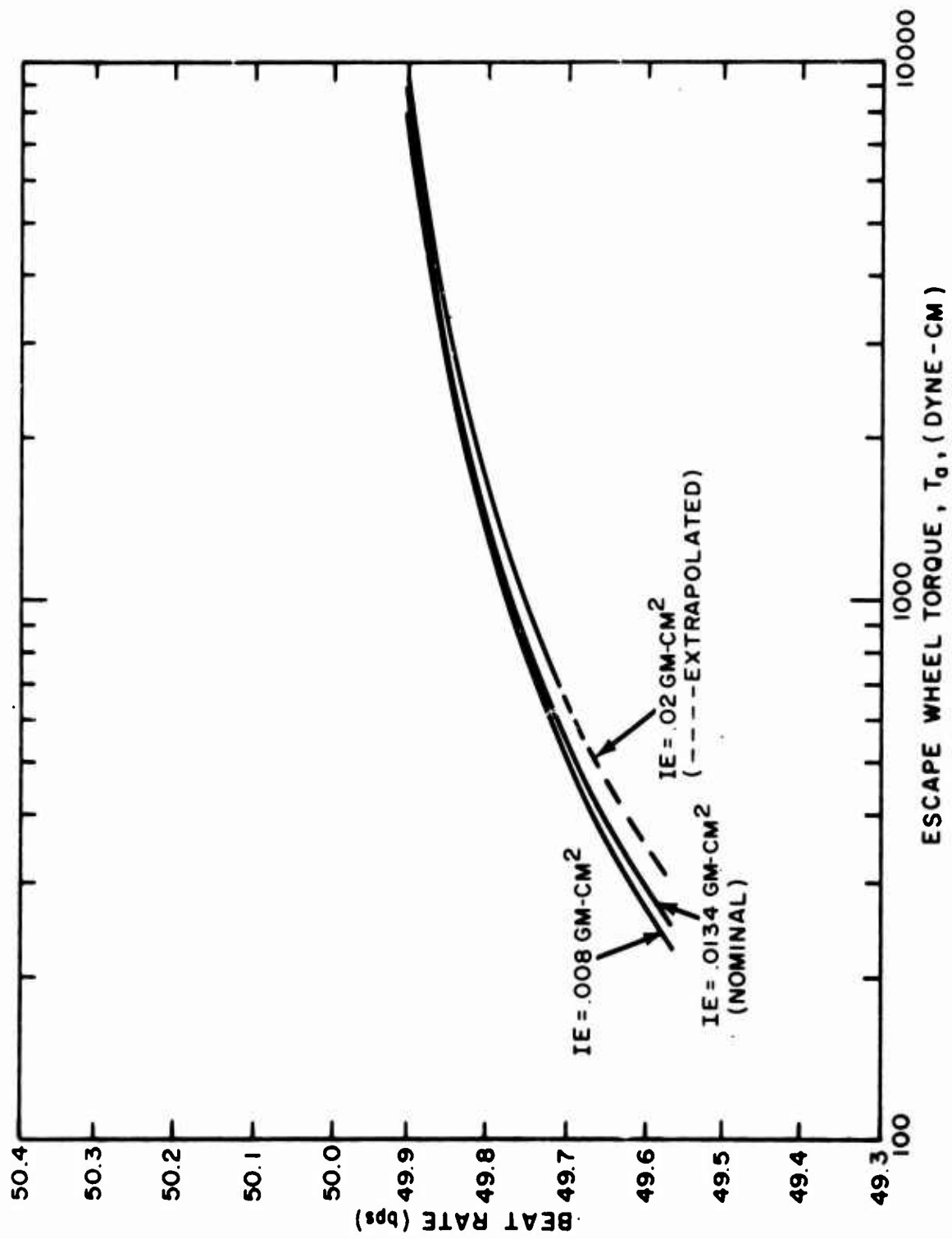


Figure 8. Theoretical beat rate curve for TSE1 escapement.

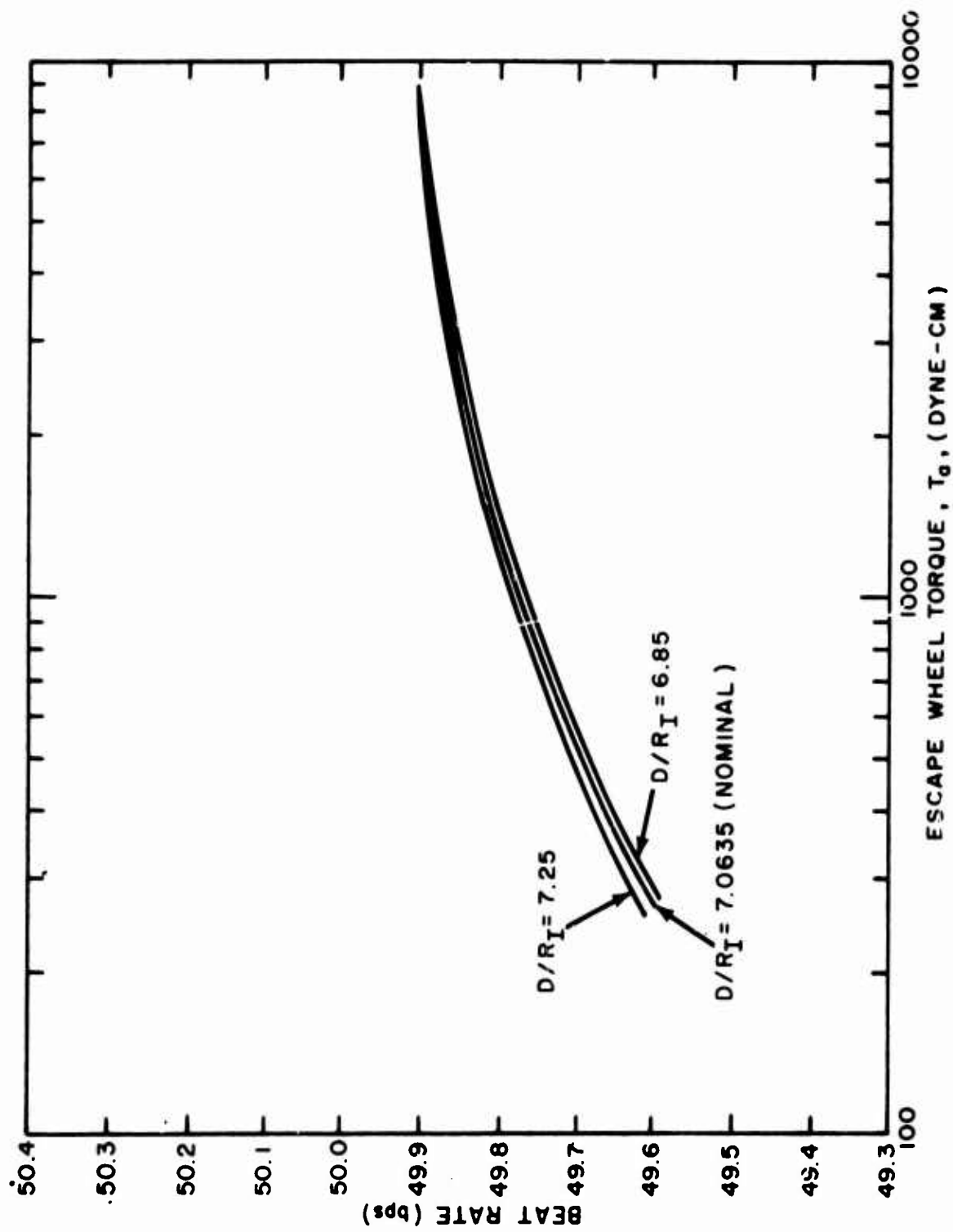
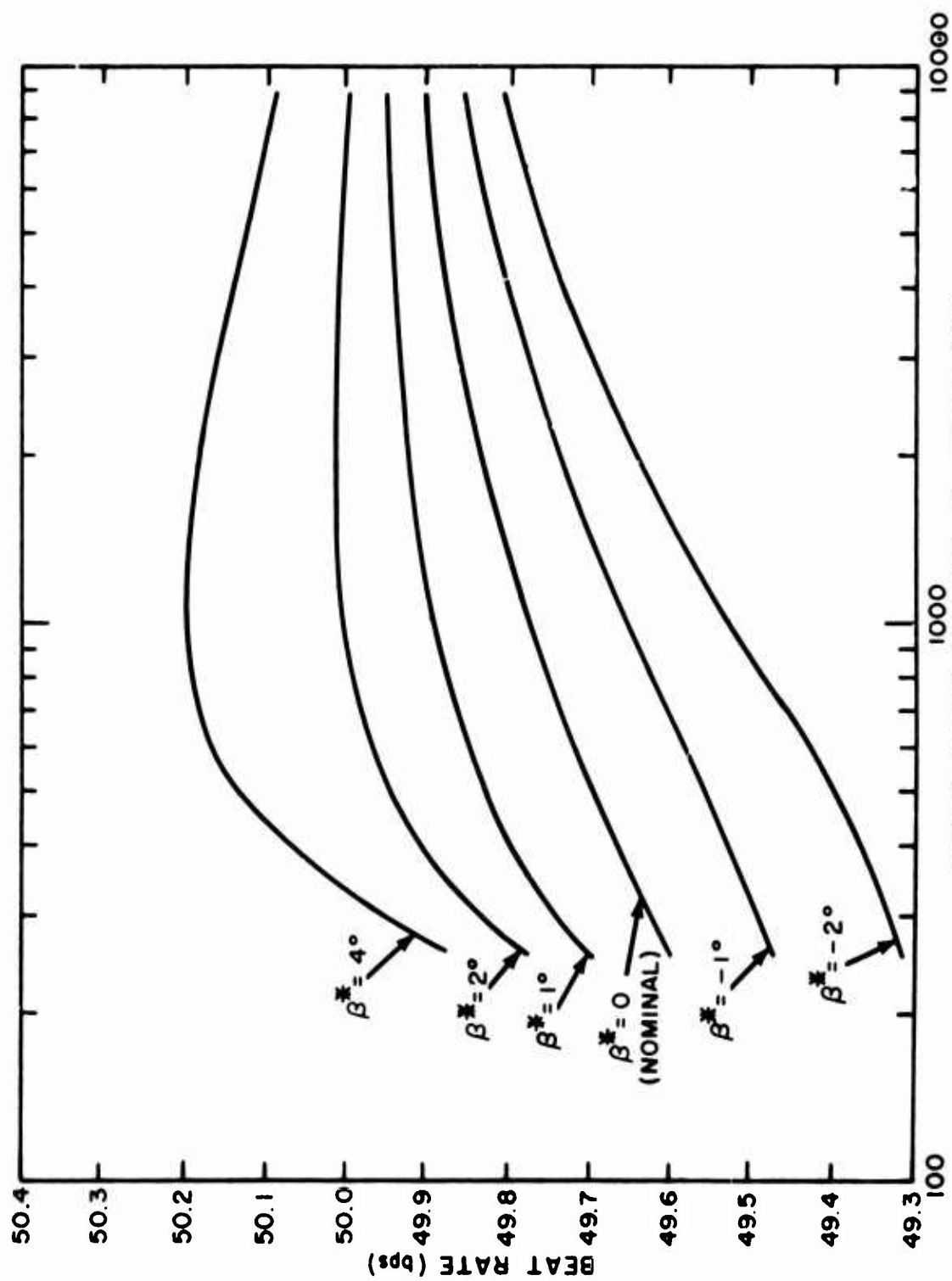


Figure 9. Theoretical beat rate curve for T5E1 escapement.



ESCAPE WHEEL TORQUE, T_0 , (DYNE-CM)

Figure 10. Theoretical beat rate curve for T5E1 escapement.

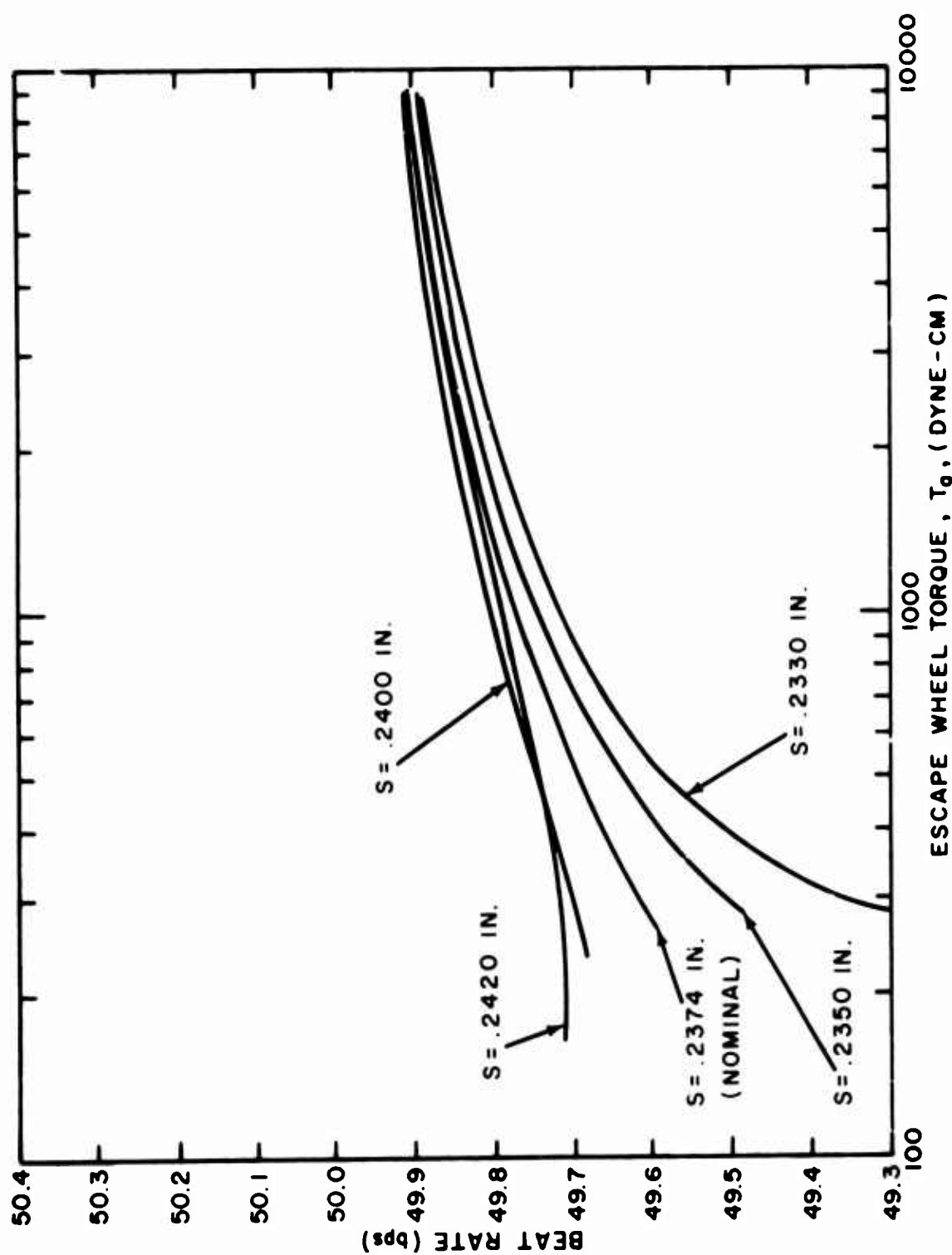


Figure 11. Theoretical beat rate curve for T5E1 escapement.

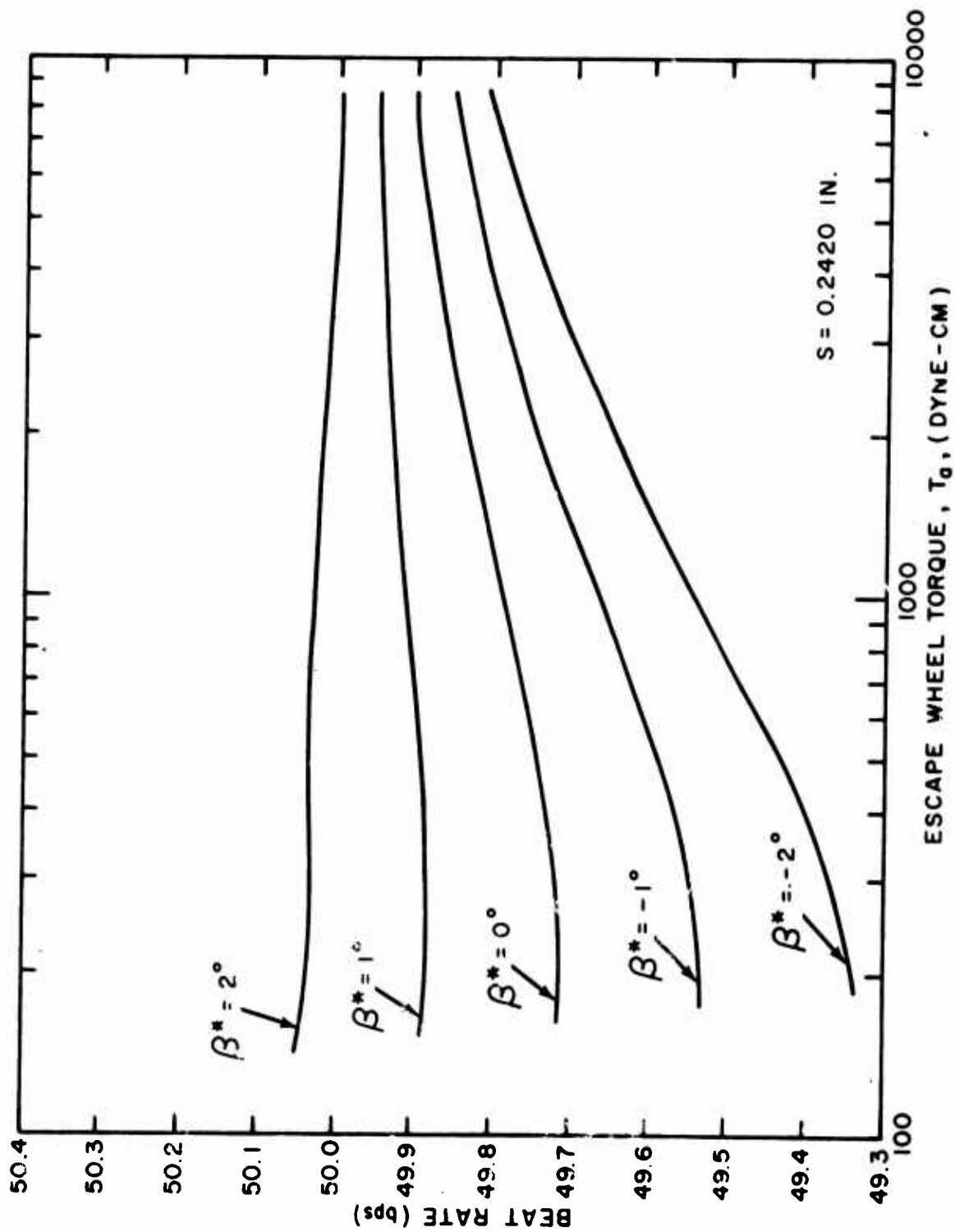


Figure 12. Theoretical beat rate curve for T5E1 escapement.

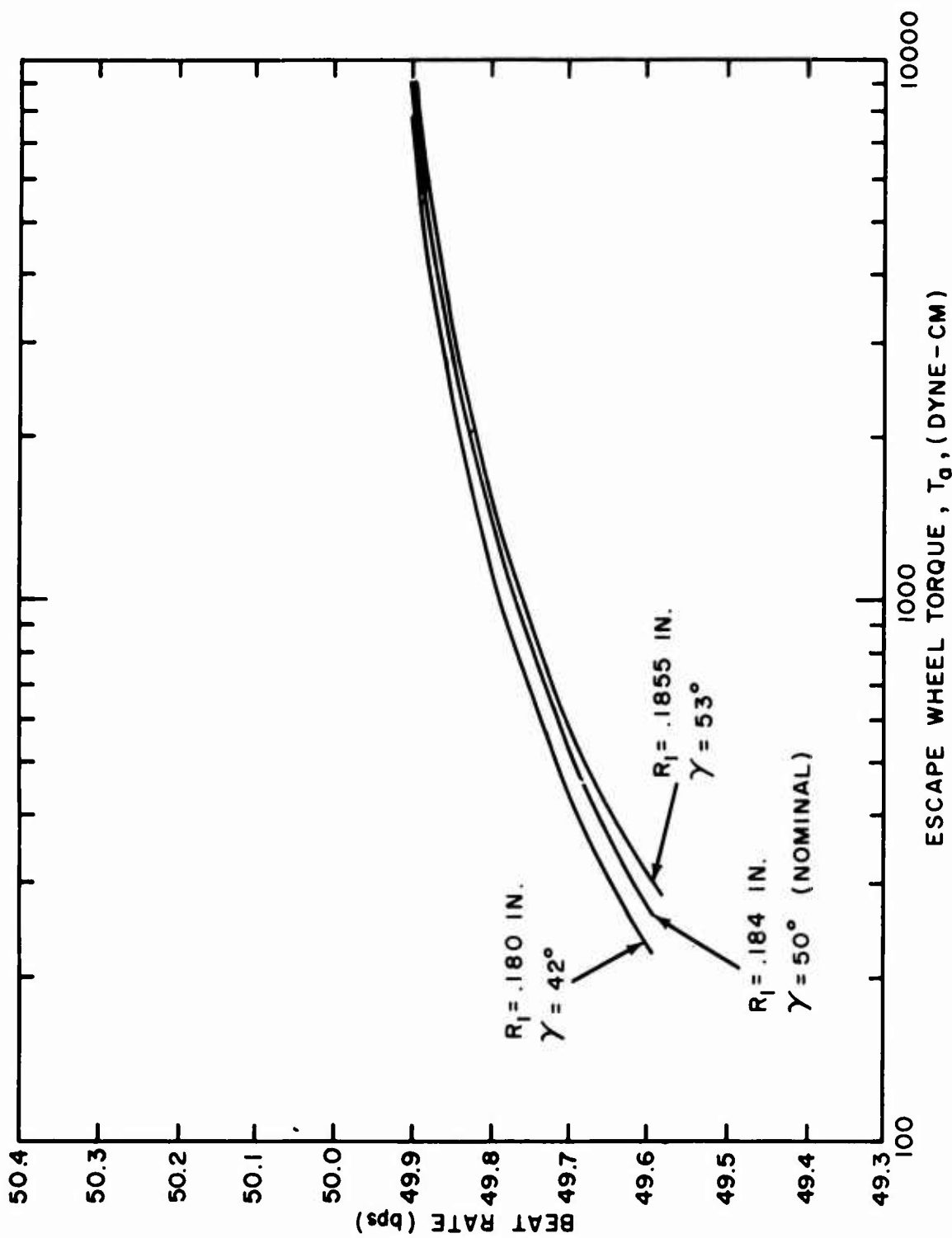


Figure 13. Theoretical beat rate curve for T5E1 escapement.

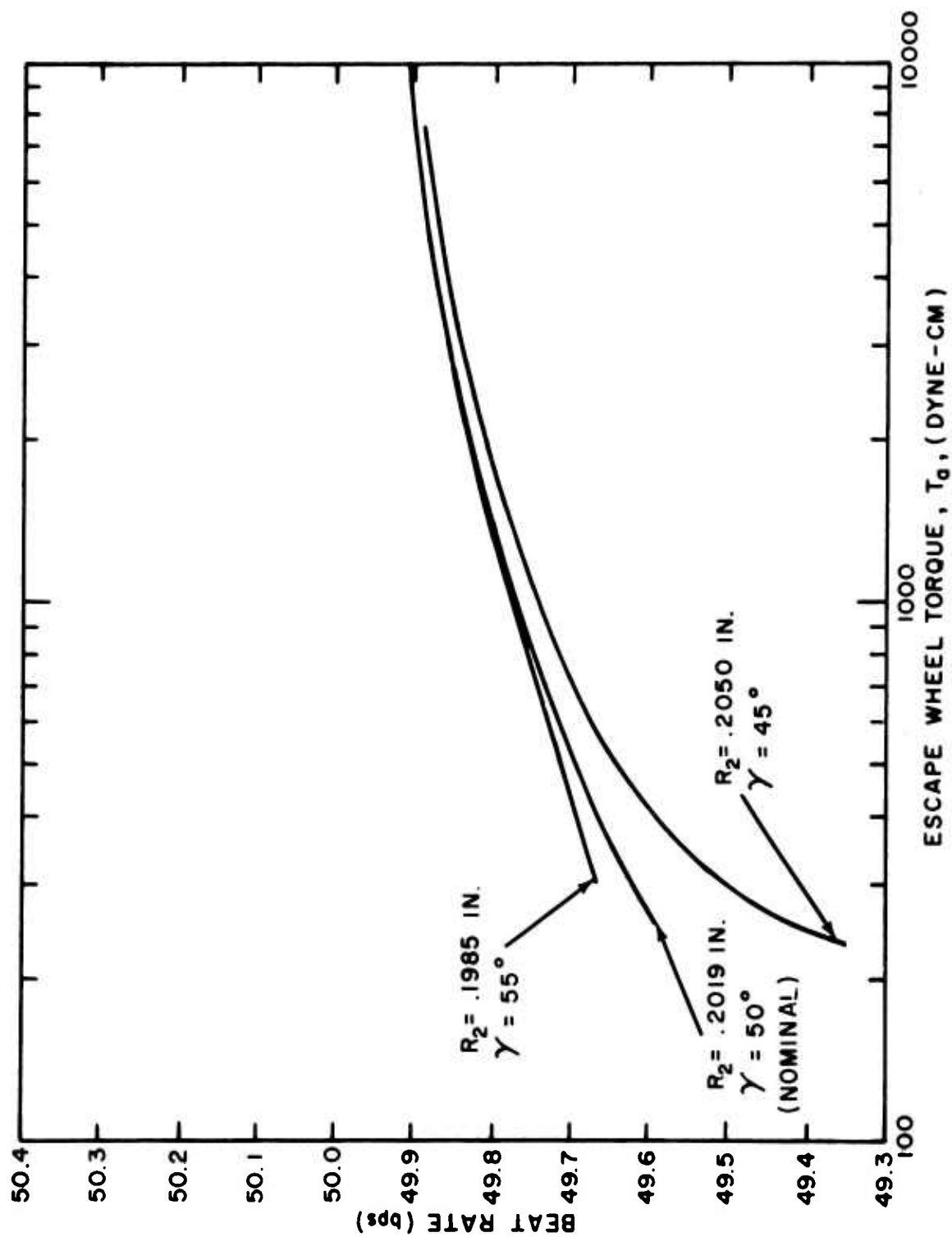


Figure 14. Theoretical beat rate curve for T5E1 escapement.

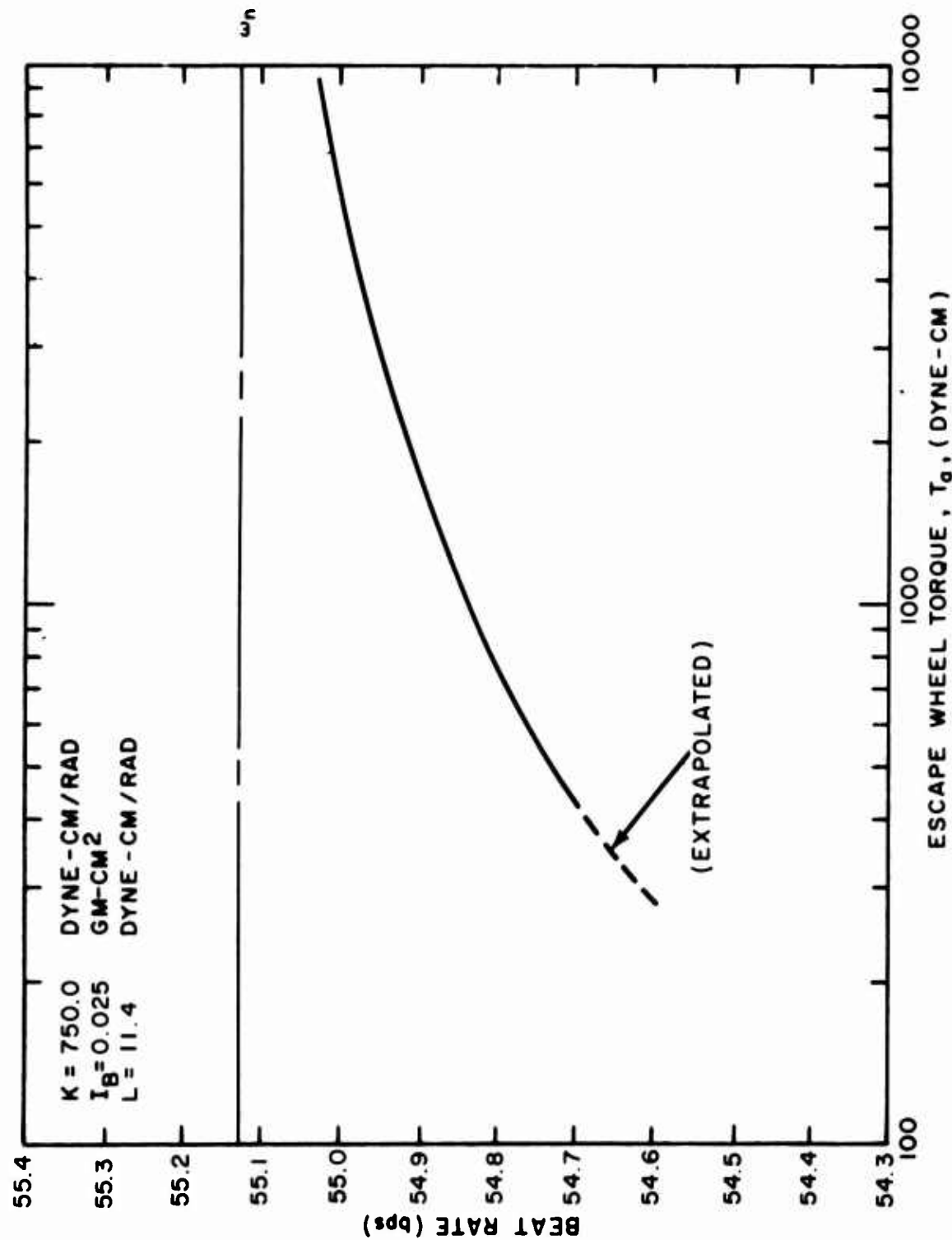


Figure 15. Theoretical beat rate curve for TSE1 escapement.

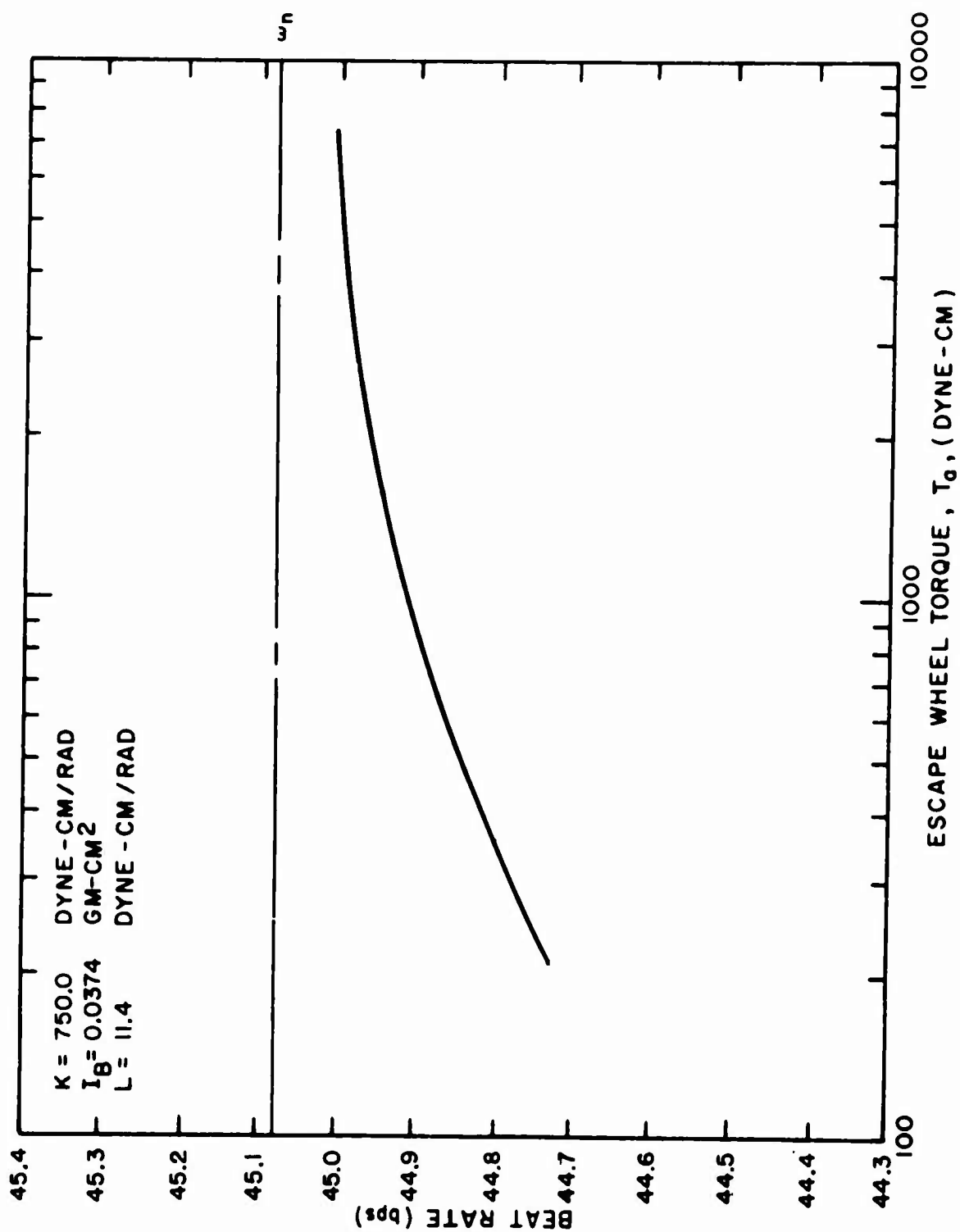


Figure 16. Theoretical beat rate curve for T5E1 escapement.

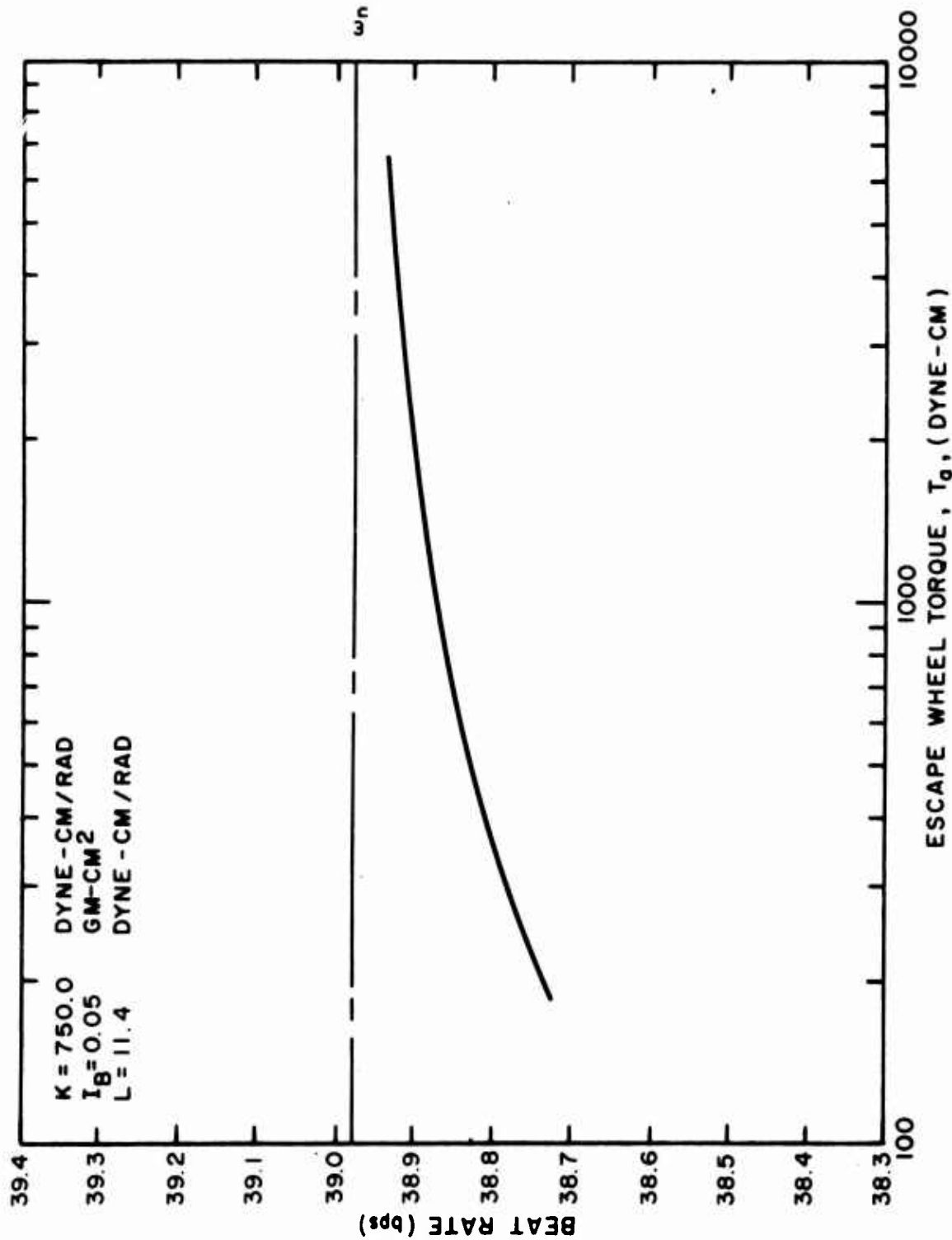


Figure 17. Theoretical beat rate curve for T5E1 escapement.

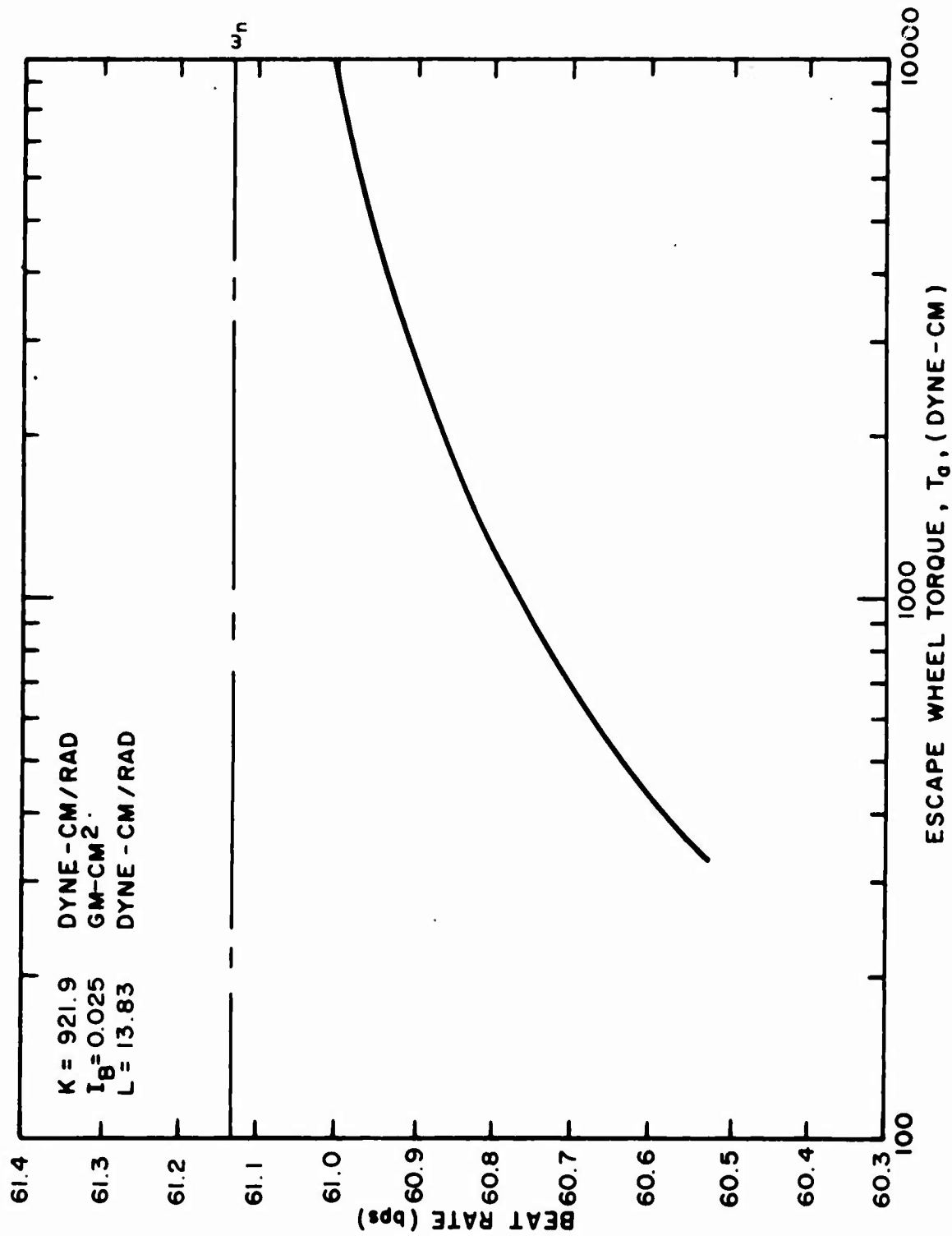


Figure 18. Theoretical beat rate curve for T5E1 escapement.

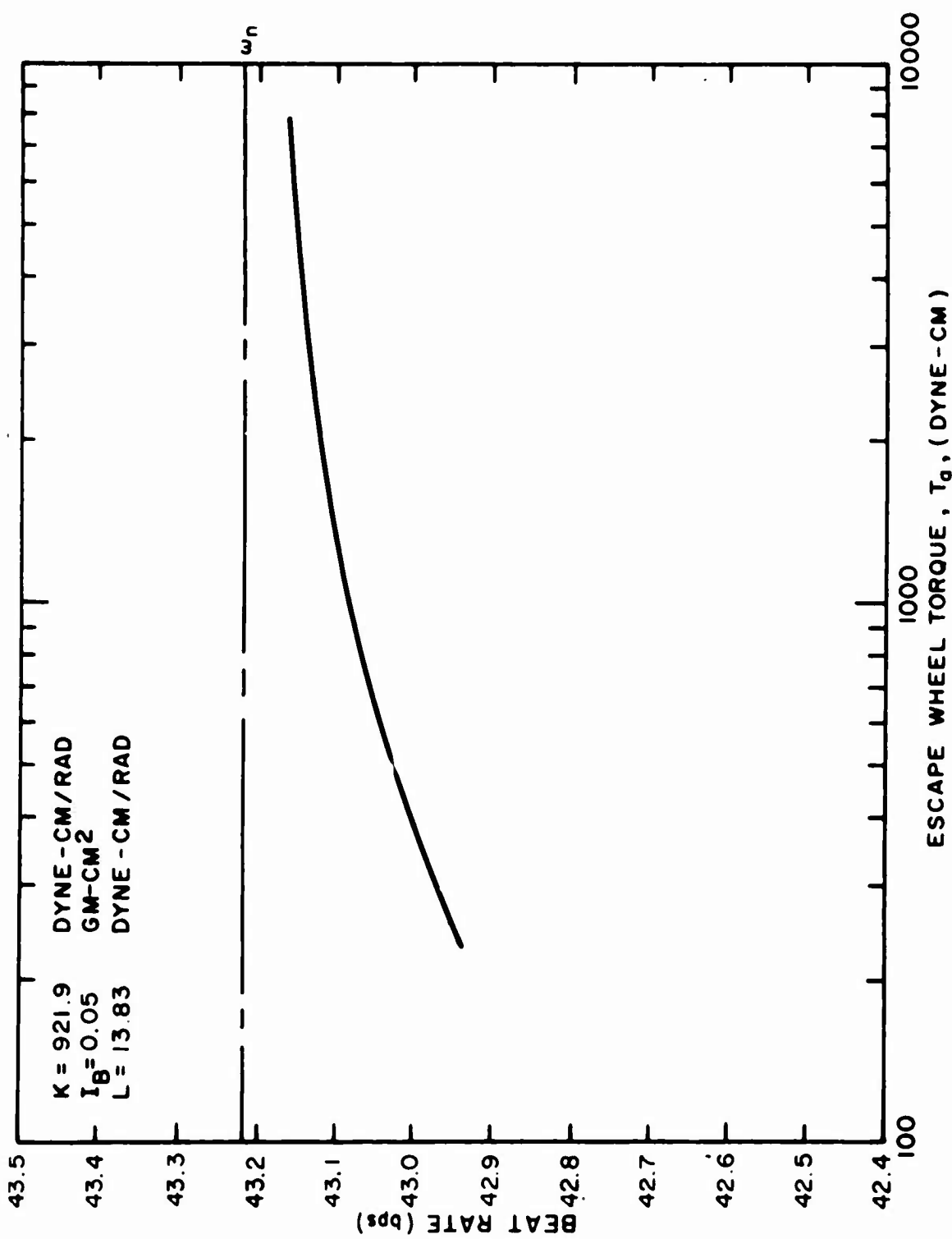


Figure 19. Theoretical beat rate curve for T5E1 escapement.

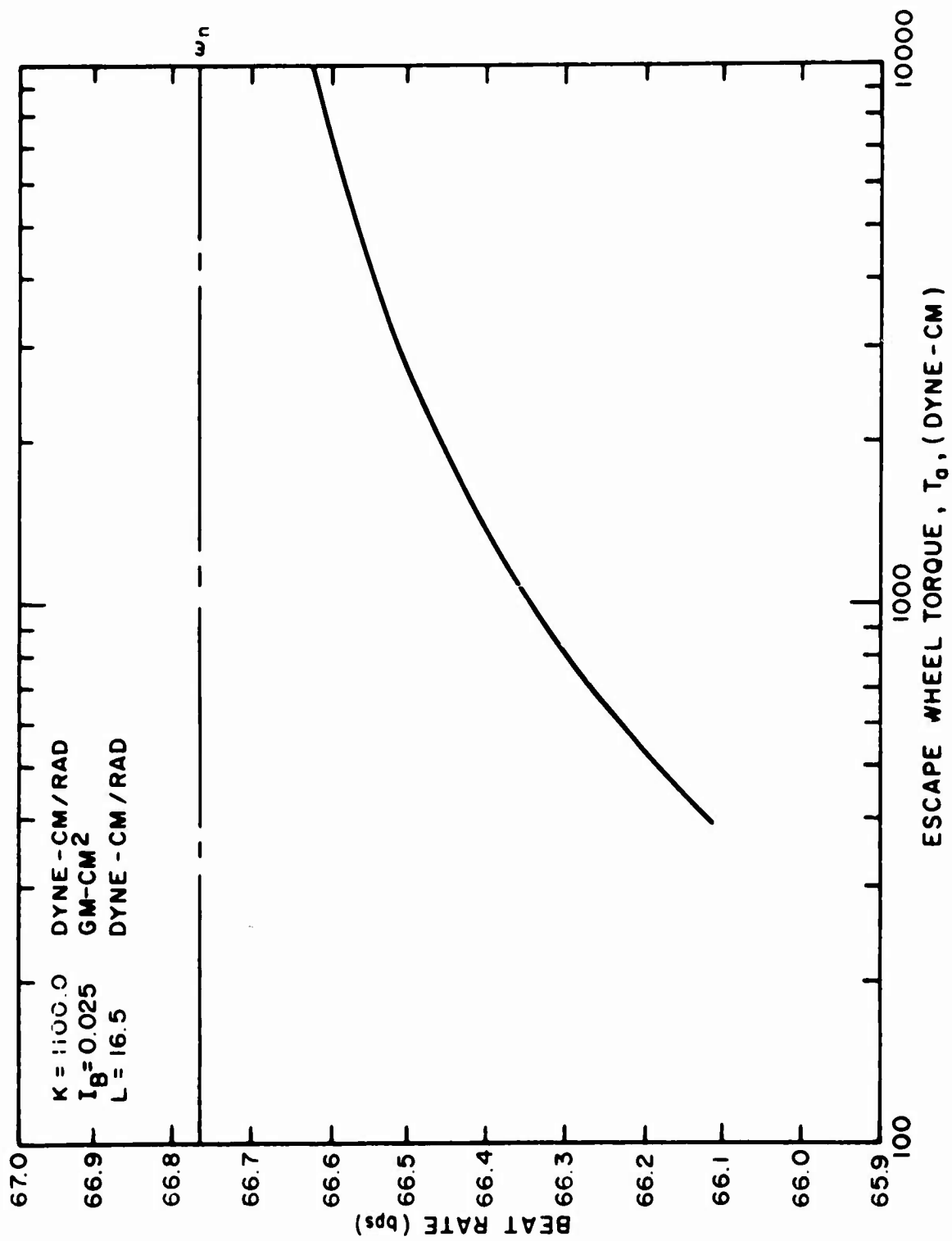


Figure 20. Theoretical beat rate curve for TSE1 escapement.

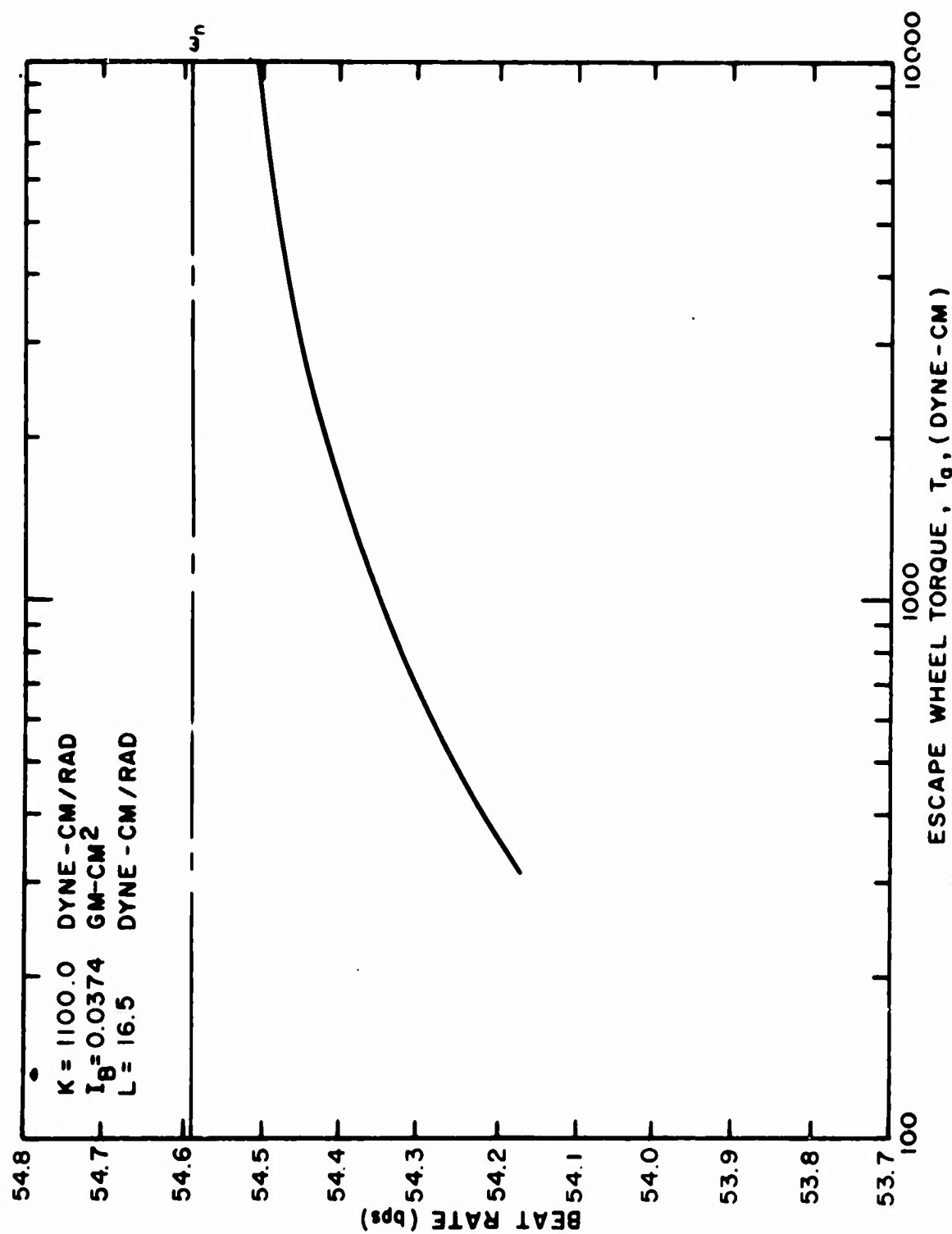


Figure 21. Theoretical beat rate curve for TSE1 escapement.

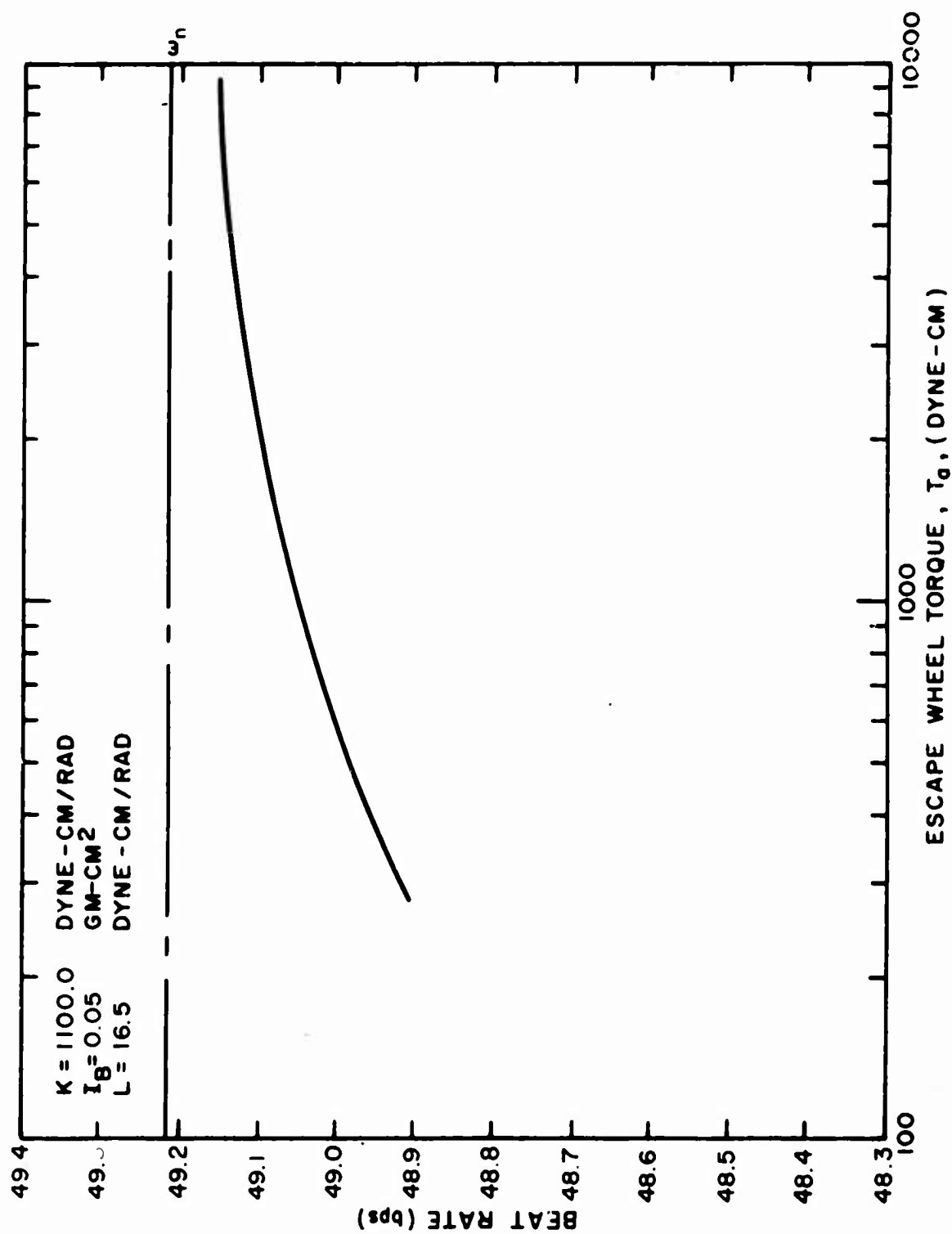


Figure 22. Theoretical beat rate curve for T5E1 escapement.

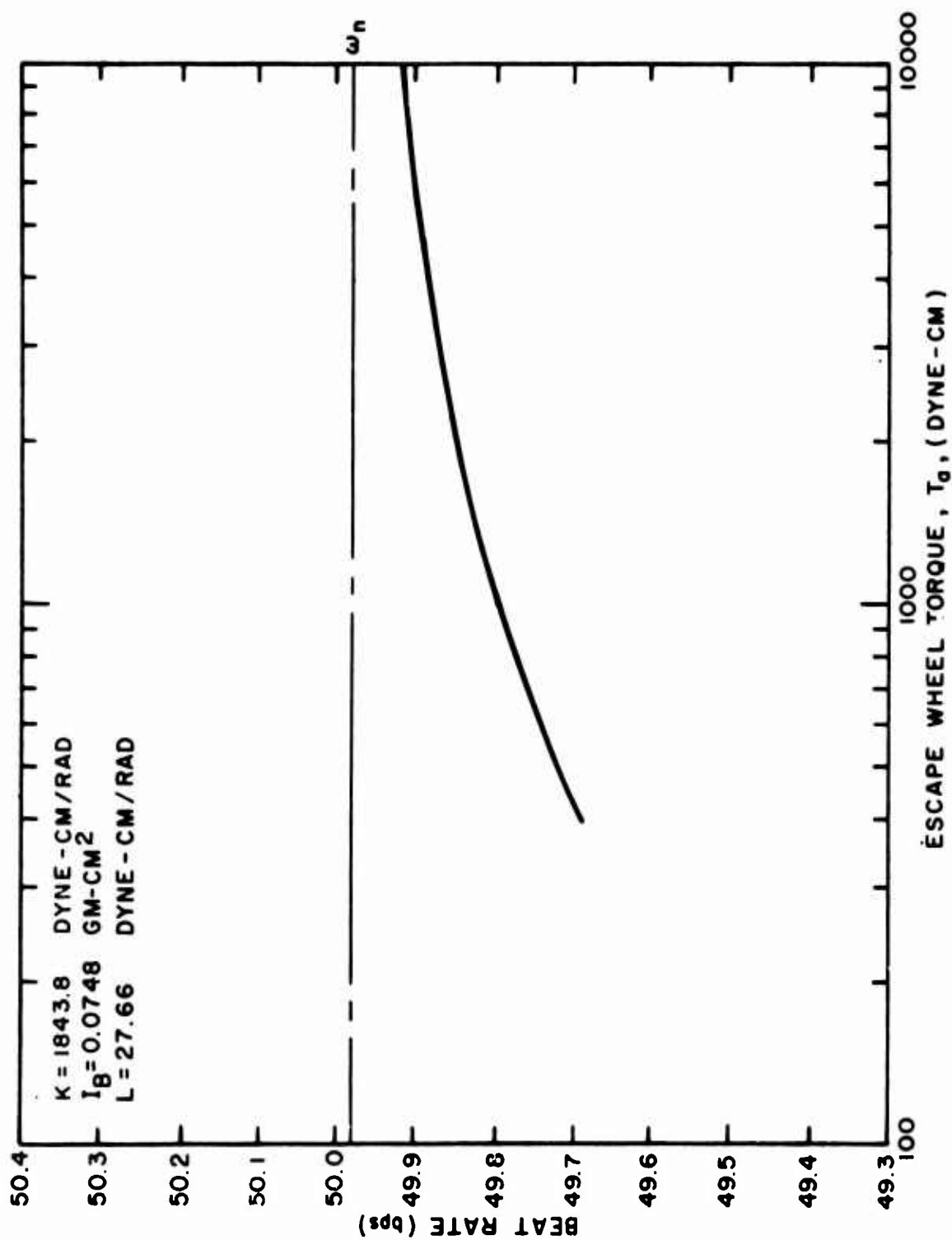


Figure 23. Theoretical beat rate curve for T5E1 escapement.

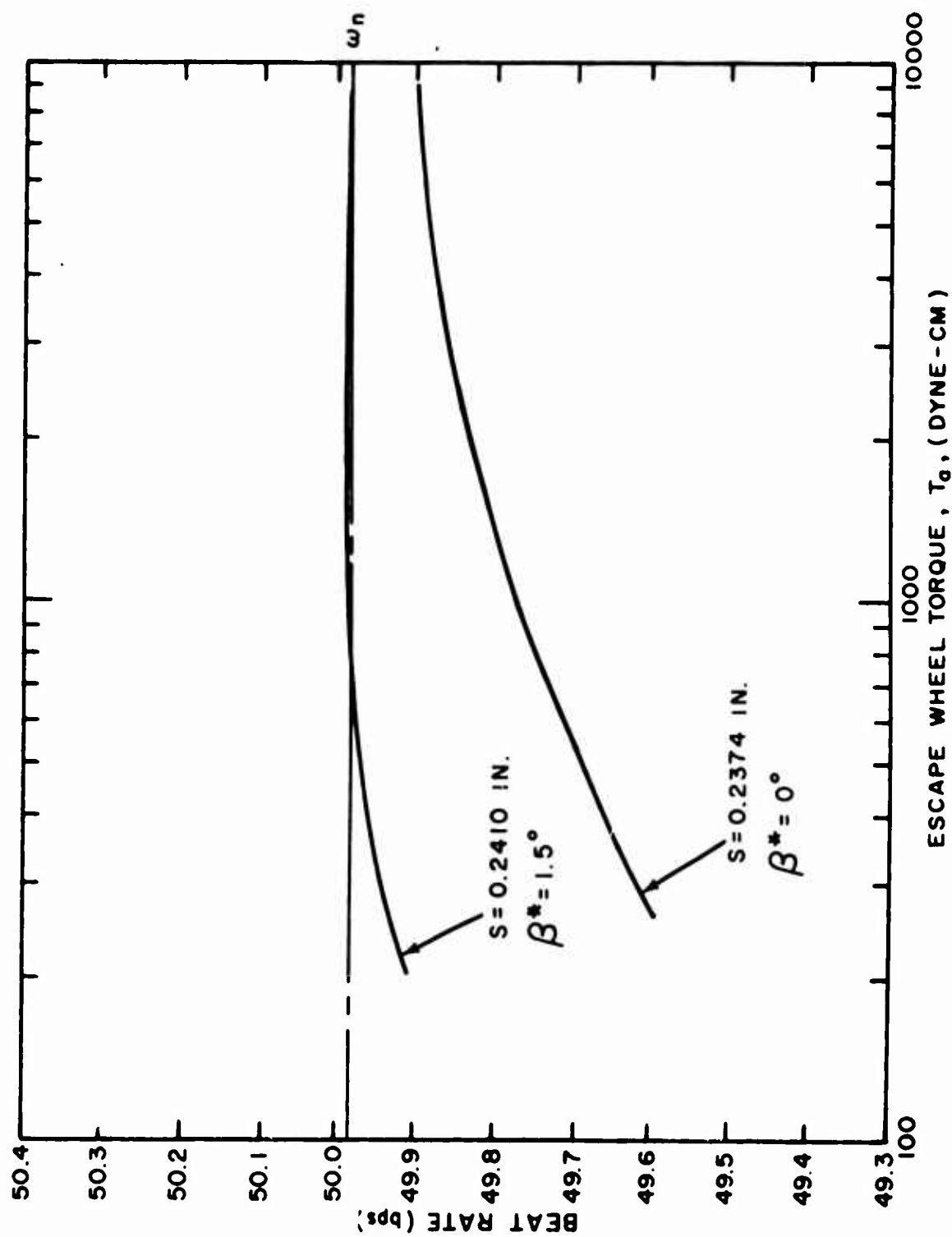


Figure 24. Theoretical beat rate curve for T5E1 escapement.

APPENDIX A

OPERATING INSTRUCTIONS FOR THE DIGITAL

COMPUTER PROGRAM BALCYC

51

1. Deck Setup

The deck is set up in the standard IBSYS format as illustrated in figure A-1.

2. Data Deck

Data are input via the NAME LIST facility of the IBSYS monitor. As usual, the first card of the data deck is a \$ DATA control card, \$ in column 1, DATA in columns 2-5. This is followed immediately by one or more case decks.

A case deck begins with a card with \$ DAT preceded and followed by one blank space. Data may begin on this same card, and each input item is referenced by a field of the form.

XXX = 527.903,

for instance, where XXX is an input variable name and 527.903 is the input value for XXX. The comma immediately following is mandatory. Blanks are not permitted within the field, but may be used at will between fields. See sample input deck.

Column 1 is ignored in all cards. Columns 2-80 are scanned for data.

Following are the inputs for the program:

ICND	= 0	, program sets nominal convergence criteria;
	≠ 0	, user supplies the following six convergence criteria.
ERR		Relative error in Simpson's Rule calculations (nominally 1.OE-7).
REL		Relative error in iteration for $\beta_3\beta_9$, (nominally 1.OE-7).
RELM		Relative error in calculation of T_a (nominally 1.OE-7).
N		Initial number of points for Simpson's Rule (nominally 11).
NMAX2		Maximum number of points for Simpson's Rule (nominally 1000).
MMAX		Maximum number of iterations for finding T_a (nominally 20).

(If ICND = 0, these criteria need not be input.)

IGEM = 0 Recalculate geometry.
 ≠ 0 Same geometry as previous case.

(Should be set to zero for first case in every run.)

RE R_e , escape wheel root radius.
 A,B Legs of triangle defining pallet geometry.
 RPP R_{pp} , pallet pin radius.
 BN Number of teeth on escape wheel.
 SN Number of escape-wheel teeth spanned by pallets.
 GAMMA γ , escape-wheel tooth face angle.
 S S, escape wheel-pallet center distance.
 DRI D/R_I , lever arm ratio.
 UBI $I_U = \int_{\beta_2}^{\beta_1} U(\beta) d\beta$. If known input; otherwise set to zero. Must be changed in each case where geometry changes.
 K K, hairspring constant.
 IB I_B , balance inertia.
 IL I_L , lever inertia.
 IE I_E , escape wheel inertia.
 L L, side thrust coefficient
 MU μ , coefficient of friction during unlocking.
 A1, A2, A3 An initial estimate for T_a is taken from these parameters,

$$T_a = A1(A2+L)\beta_m^2 + A3.$$

It has been found that, for the T5E1 mechanism, $A1 = 12$, $A2 = 16$, $A3 = 40$ are suitable values. (c.g.s. units).

JA number of values of β_m for this configuration (case).
 AMPL values of β_m for this case, JA in all.

R1		R_1 , escape tooth unlock radius.
R2		R_2 , escape wheel enter radius.
BSTAR		β^* , out of beat angle.
IWRITE	= 0,	no intermediate output;
	$\neq 0$,	intermediate output printed, usually of no value.

The symbol \$ must terminate each case. It may not be in column 1 of any card.

As many cases as desired may be run at one time. If certain parameters remain unchanged from case to case, they need not be re-input.

All error messages are deemed self-explanatory.

Any system of units is acceptable, as long as lengths are consistent within themselves and inertias follow the same units. For example, in the sample inputs, all lengths are in inches and all inertias in c.g.s. units. This is possible since all lengths go out as ratios. (Note that T_a will come out in torque units consistent with the system used, but will always be labeled dyne-cm.) All angles are input in degrees.

Sample output is seen in appendix B, and is deemed self-explanatory.

APPENDIX B
SOURCE PROGRAM LISTING
SAMPLE INPUT
SAMPLE OUTPUT

8
3108
SEVECUITE

310J08
MAP

175434-0.010.005300,HALEY

BLOG83

XEROX X ON 1138.7

310ETC BALCYC

RALCYC - EEN SOURCE STATEMENT - JENLSI -

DIMENSION AMPL(20),BETA(13),RWD(13),EPS(13),T(23),TAD(20),BDOOT(13),
J,TT(13)

REAL K,L,IB,IL,IE,MU,L,DOE

NAMELIST/DAT/ZIPARAM,ICOND,IGEDM,RE,A,B,RPP,BN,SN,GAMMA,S,DR1,UB1,
1 ERR,REL,P,LM,NO,NMAX,NMAX2,NMAX,K,IO,IL,IE,L,MU,AL,A2,JA,AMPL,
2R1,R2,IWRITE,IBSTAR,A3

INTEGER ALARM

COMMON DR1,P,RPE,S,BN,DE,K,L,IB,IL,IE,MU,SN

C THIS PROGRAM IS DESIGNED TO CALCULATE THE PERIOD OF A DETACHED
C LEVER ESCAPEMENT SYSTEM FOR ONE CYCLE FOR A GIVEN INITIAL AMPLITUDE
C OF THE ANGULAR DISPLACEMENT OF THE BALANCE. ALSO INCLUDED IS THE
C CALCULATION OF THE APPLIED TORQUE AS A FUNCTION OF THE AMPLITUDE.

C INPUT

C RE,GAMMA DEFINE GEOMETRY OF THE ESCAPE WHEEL AND TEETH
C A,B DESCRIBE SIZE AND LOCATION OF THE PALLET PINS WITH
C RESPECT TO THE LEVER STAFF

C RPP PALLET PIN DIAMETER

C BN NUMBER OF TEETH ON THE ESCAPE WHEEL

C SN NUMBER OF TEETH SPANNED BY THE PALLET PINS

C S SEPARATION BETWEEN THE LEVER STAFF AND THE ESCAPE WHEEL STAFF

C DR1 RATIO OF DISSEPARATION BETWEEN THE LEVER STAFF AND
C BALANCE STAFF) TO R1 (RADIUS OF THE IMPULSE PIN FROM
C THE BALANCE AXIS)

C AMPL VALUE OF INITIAL AMPLITUDE OF BETA(CAN HAVE JA CASES)

C K SPRING CONSTANT
(INPUT IS IN DEGREES)

C IB,IL,IE MOMENT OF INERTIA OF BALANCE,LEVER,AND ESCAPE WHEEL

C L TORQUE CONSTANT (TF=L*BETA)

C MU FRICTION CONSTANT

C ERR RELATIVE ERROR IN SIMPSON'S RULE CALCULATION

C REL RELATIVE ERROR IN CALCULATION OF BETA FOR PHASE3

C NO INITIAL NUMBER OF POINTS FOR SIMPSON'S RULE

C NMAX2 MAXIMUM NUMBER OF POINTS FOR SIMPSON'S RULE

C NMAX MAXIMUM NUMBER OF ITERATIONS FOR PHASE3

C IGEDM SET EQUAL TO ZERO FOR NEW CASES WITHIN A RUN : F

C ICOND IF ICOND IS EQUAL TO ZERO THEN THE PROGRAM CHOOSES

C S,DR1,SN,BN,A,B,RE,RPP,AND GAMMA HAVE NOT CHANGE

C ERR=REL=REL-1.E-7,MU=11,NMAX=NMAX-2,NMAX2=USOO

C ERR=REL=REL-1.E-7,MU=11,NMAX=NMAX-2,NMAX2=1000

C UB1 VALUE OF THE INTEGRAL OF U(BETA). IF SET EQUAL TO

C ZERO, THE PROGRAM WILL CALCULATE IT.

C AL,A2,A3 PARAMETERS FOR CALCULATING THE INITIAL GUESS OF YA

C IWRITE IF INTERESTED IN INTERMEDIATE PRINTOUT IN SUBROUTINES

C TORQ AND PHASE3,SET TWIRTY EQUAL TO NONZERO

C VALUE,OTHERWISE SET EQUAL TO ZERO

C BSTAR VALUE OF EQUILIBRIUM POSITION OF BETA-USUALLY ZERO

C VARIABLES

BALCYC - EFN SOURCE STATEMENT - JFN(S) -

```
C      BETA      ANGULAR DISPLACEMENT OF THE BALANCE
C      RHO       ANGULAR DISPLACEMENT OF THE LEVER
C      EPSILON  ANGULAR DISPLACEMENT OF THE ESCAPE WHEEL
C      TA       APPLIED TORQUE
C      T        PERIOD OF CYCLE

C      PI=3.1415927
C      PIA=182./PI
C      INPUT
C      XX=GAMMA
C      YY=BSTAR
C      GAMMA=C.
C      BSTAR=C.
C      READ(5,DAT)
C      IPARAM=C
C      IF(GAMMA.EQ.0.)GOTO500
C      GAMMA=GAMMA/PIA
C      GOTO 501
C      GAMMA=XX
C      500 CONTINUE
C      501 IF(BSTAR.EQ.0.) GOTO503
C      BSTAR=BSTAR/PIA
C      GOTO502
C      502 BSTAR=YY
C      503 CONTINUE
C      SET CONVERGENCE CRITERIA IF ICOND=0
C      IF(ICOND.NE.0) GO TO 40
C      ERR=1.E-7
C      REL=1.E-7
C      RELM=1.E-7
C      NO=11
C      NMAX=20
C      NMAX=20
C      NMAX=20
C      NMAX=1000
C      40 CONTINUE
C      CALCULATE GEOMETRY
C      IF(IGEOM.EQ.0) GO TO 89
C      CALL GEOM(RE,A,B,APP,GAMMA,R1,R2,REE,R1E,R2E,PHI,OMEGA,OMEGAE,Q,
C      1  LD,LDE,RP,RPE,BETA,RHO,EPS,EPD,RHOD)
C      89 CONTINUE
C      CALCULATION OF UBI
C      IF(UBI.NE.0.) GO TO 70
C      B1=BETA(1)
C      B2=BETA(2)
C      CALL UBICATERR,NMAX2,IWARN,B1,B2,UBI)
C      IF(IWARN.NE.0) WRITE(6,220)
C      WRITE INPUT
C      70 OMEGA=OMEGA*PIA
C      PHI=PHI*PIA
C      GAA=GAMMA*PIA
C      BSTAR=BSTAR*PIA
C      WRITE(6,301) RPP,RE,RP,R1,R2,LD,Q,OMEG ,RPE,REE,RPE,R1E,R2E,LDE,
C      1  QE,OMEG
C      P=P*PIA
C      WRITE(6,302) GAA ,SN,ON,SP,A,B,DRI,PHI,Y
C      30 30
```

07/30/68

BALCYC - EFM SOURCE STATEMENT - IFN(S) -

```

P=P/PIA
WRITE(5,303) K,L,B,I,L,E,MU,UBI,A1,A2
WRITE(6,304) ERR,REL,RELM,NO,NMAX,NMAX2,IPARAM,ICOND,IGCOM,
1  INKITE,BSTX ,A3
DO 10 J=1,JA
  BETAM=AMPL(J)*PI/180.
  TAO(J)=A*BETAM**2*(L+A2)*A3
  BETAI2)=BETAM
  C CALCULATE APPLIED TORQUE
  C ALSO BETAI3,BETA9
  TA=TAU(J)
  CALL TORQUEBETA,RHO,EPS,TA,BETAM,NMAX,REL,IMARN3,IMARN9,NMAX,RELM,
1  ALARM,T3,T9,BDOT,R1E,R2E,ER3,NMAX2,UBI,WRITE,BSTAR)
  TAO(J)=TA
  IF(IALARM.NE.O) WRITE(6,202)
  IF(IMARN3.NE.O) WRITE(6,203) IMARN3
  IF(IMARN9.NE.O) WRITE(6,225) IMARN9
  TT(3)=15
  TT(9)=T9
  C CALCULATE PERIOD FOR PHASE1 TYPE
  C INCLUDES PHASES 1,5,6,7,11,12
  DO 15 JJ=1,6
    NP=JJ
    IF(NP.EQ.1) GO TO 5
    NP=NP+3
    IF(JJ.GE.5) NP=NP+3
    BETAU=BETA(NP-1)
    P=BDOT(NP-1)
    EB=EPS(NP-1)
    EA=EPS(NP)
    GO TO 5
5 BETAD=BETAM
  RDOTO=C
  6 BETAF=BETA(NP)
  BDOTF=BDOT(NP)
  CALL PHASE1(BETAD,BDOTO,EB,EA,BETAF,TA,TP,BDOTF,NP,BSTAR)
  P=AINP)=BETAF
  BDOT(NP)=BDOTF
  15 TT(NP)=TP
  C CALCULATE PERIOD FOR PHASE2 TYPE
  C INCLUDES PHASES 2,4,8,10
  DO 30 JJ=2,10,2
    NP=JJ
    IF(NP.EQ.6) GO TO 30
    BETAD=BETA(NP-1)
    BETAF=BETA(NP)
    BDOTO=BDOT(NP-1)
    CALL PHASE2(BETAD,BETAF,BDOTO,VO,ERR,NMAX2,TA,TP,NP,ALARM,BSTAR)
    TT(NP)=TP
    IF(ALARM.EQ.O) GO TO 30
    WRITE(5,204) NP
  30 CONTINUE
  TT(J)=TT(1)
  DO 26 M=2,12
    26 TT(J)=TT(J)+TT(M)
  C WRITE OUTPUT

```

```

800IQ=2.
RM=AMPL(J)
RO=RHO*PIA
EO=EPS*PIA
WRITE(5,207) RM,RO,EO,800IQ
DO 8 M=1,12
  RV=BETA(M)*PIA
  R=RHO(M)*PIA
  E=EPS(M)*PIA
  80=ROOT(M)*PIA
  8 WRITE(5,208) M,BV,R,E,IT(M),80
10 CONTINUE
  WRITE(5,209)
  AVE=0.
  DO 25 J=1,JA
    25 AVE=2./T(J)*AVE
  AJ=JA
  BEAVE=AVE/AJ
  DO 20 J=1,JA
    BEAT=2./T(J)
    BRE=(BEAT-BEAVE)*100./BEAVE
    20 WRITE(5,210) AMPL(J),TAOT(J),T(J),BEAT,BRE
    GO TO 1
301 FORMAT(1H1,55X14HCLOCK GEOMETRY//16X3HPP,9X2HRE,10X2HRP,10X2HRL,
1 12X2HR2,10X1HL,11X1H0,11X5H0EGA/7H ACTUAL5X811X,F11.7),
2//12H EFFECTIVE 8(1X,F11.7)///)
302 FORMAT(12X5HGAMMA,8X4HSPAN,8X5HTEETH,8X1HS,11X1HP,10X1HA,11X1HB,
1 11X4HD/R1,8X3HPI/9X9F12.8)///)
303 FORMAT(56X10HPARAMETERS//14X1HS,11X1HL,11X2H18,11X2H1L,9X2H1E,10X
1 2HMU,10X3HUB1,10X2HA1,10X2HA2/8X13,8,6F12.8,2F12.6)///)
304 FORMAT(56X10HCONDITIONS//3X3HER,7X3HREL,8X4HREL,4X2HNO,17H NMAX
1 NMAX VMAX2,4X6HIPARAM,3X5HICOND,3X5HIGEDM,8H IWRITE,6X5HBSTAR,15
3X2HA3/3(1PE10,1),315,16,418,1PE20,8,OPF1,6)
202 FORMAT(1H1,51H THE APPLIED TORQUE DID NOT REACH THE DESIRED VALUE)
205 FORMAT(57H BETA9 FOR PHASE9 DID NOT CONVERGE TO THE DESIRED VALUE
1 13)
203 FORMAT(57H BETA3 FOR PHASE3 DID NOT CONVERGE TO THE DESIRED VALUE
1 13)
204 FORMAT(1H1,58H THE PERIOD HAS NOT CONVERGED PROPERLY FOR PHASE,14)
207 FORMAT(///7X6HPOSITION,15X4HBETA,16X3HHRD,17X7HEPSILON,13X6HPERIO
1D,13X4HDOOT///10X2H 0,8X3(2PE20,8),20X,1PE20,8)
208 FORMAT(1H1,8X13,8X3(2PE20,8))
209 FORMAT(1H1,5X9HAMPLITUDE,11X14HAPPLIED TORQUE,8X6HPERIOD,12X9HBEAT
1 RATE,10X15HBEAT RATE ERROR/28X7H0VNE-CM,15X3HSEC,13X9HBEATS/SEC,1
20X13HPERCENT(REL,1)///)
210 FORMAT(5(2PE20,8))
220 FORMAT(14H1THE INTEGRAL OF U(BETA) DID NOT CONVERGE)
END

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07/30/68

PAGE 7

50
S18FTC PM3

SUBROUTINE PHASE3(EPSO,ODOTO,NMAX,REL,TA,T,VP,IMARN,DEFS,BETAF,RHO

IEPS,R,LL,BETL,ERR,NMAX2,BETAO,IMRITE,BSTAR)

1 DIMENSION ET(100,2),PT(100,2),M(100,2),FEB(100,2),BO(100,2),B(2),

1 NZ(2), CO(2),DB(2),RH(100,2)

COMMON DRI,P,RPE,S,BN,QE,K,L,IB,IL,IE,MU,SN

REAL K,L,IB,IL,IE,MU,11,110

IMARN=0

IF(IMRITE,NE,0) WRITE(6,102)

SG=NP-4

NR=2

IF(NP-EQ,9) GO TO 6

CS=TA/(2.*IE)

NR=1

IF(1L-EQ,2) GO TO 6

C CALCULATE CONSTANTS

C2=K-L

C1=K+L

P12=6.2831854

RID=1./DRI

DDRI=RID*DDRI

RPE=RPES

SSQ=S+S

RPES=RPES

TPES=2.*RPES

ANG=3.1415927*(.5-2.*SN/BN)

RS=RPES*SSQ

P2=P/2.

C8=COS(BETAO)

XO=(C8-RID)/(DDRI-2.*C8)

110=IB*IL*XO*XO

13

C COMPUTE INITIAL CONDITIONS

6 NZ(NR)=0

DH(NR)=SIGN((BETL-ABS(BETAO))/10.,SG)

DELTA=DB(NR)/1000.

IM=1

RO(1,NR)=BETAO

CO(NR)=110*ODOTO+2*C2*BETAO+2-2.*C2*BSTAR*BETAO

C

C COMPUTE INTEGRAL

27 ITR=1

N1=1

N2=3

60 DO 12 J=N1,N2,N1

G=J-1

BE=G*DELTA+BO(IM,NR)

COSB=COS(BE)

SINH=SINH(BE)

X=(COSB-RID)/(DDRI-2.*COSB)

11=IB*X*X*IL

C=C2

IF(BE,LT,-BSTAR)C=C1

12 H(J)=SQRT(ABS(11/(CO(NR)-C*BE*BE+2.*C*BSTAR)))

IF(N1-EQ,2) GO TO 13

C=COSB

S=SINH

35

PH3 - EFN SOURCE STATEMENT - IFN(S) -			07/30/68	PAGE 9
BINR1=RE				
13	CALL STMPH,DELTA,N2,ERR,SUM,LP1			44
	IF(LEP,NE,0) GO TO 45			
	IF(LTH,EO,1) GO TO 45			
	IF(ABS(SUM)-SUM1,GT,100,ERR=ABS(SUM)) GO TO 45			
	SUM=115,ERR=SUM1/15.			
	GO TO 15			
45	JTR=2			
	SUM1=SUM			
	IF(N2,LT,NMAX2) GO TO 30			
	BINR1=BO(IH,NR)			
	IH=IM-1			
	IWARN=3			
	GO TO 70			
30	DO 23 J=1,N2			
	JJ=N2-J+1			
	J2=2-JJ-1			
23	M(J2)=H(JJ)			
	N1=2			
	N2=2*N2-1			
	DELTA=DELTA/2.			
	GO TO 50			
C	CALCULATE TIME AND EPS(I)			
15	IF(IM,EO,1) GO TO 16			
	FT(IM,NR)=SUM*FT(IM-1,NR)			
	GO TO 17			
16	FT(1,NR)=SUM			
17	ET(IM,NR)=EPSO-C5*FT(IM,NR)*FT(IM,NR)			
C	CALCULATE EPS(BETA)			
	UI=SB7(DRI-CB)			90
	RH(IM,NR)=P2-ATANUI			
	IF(INP,EO,9) GO TO 10			
	RP=SQRT(RS-TRPES*COS(RH(IM,NR)))			96 97
	R=RP			
	UI=QE/RE			
U2	(RP*RF+SSQ-RPESQ)/(2,SSQ*RF)			
FEB	(IM,NR)=ARSIN(UI)-ARSIN(U2)			98 99
	GO TO 20			
10	RR=SQRT(RS-TRPES*COS(IP-RH(IM,NR)))			104 105
	R=RR			
	U4=QE/RR			
U3	(RR*RR+SSQ-RPESQ)/(2,SSQ*RR)			
FEB	(IM,NR)=ABS(ANG+ARCCOS(U4))-ARSIN(U3)			106 107
20	IF(ABS(FEB(IM,NR)-ET(IM,NR)),LT,REL*ABS(ET(IM,NR))) GO TO 70			
	IF(ABS(DELTA),LT,1-E-B*ABS(B(NR))) GO TO 70			
	IF(IWRITE,NE,0) WRITE(6,101) IN,FT(IM,NR),B(NR),ET(IM,NR),FEB(IM,NR),DELTA,NZ(NR),IWARN			119
	IF(LTH,LE,NMAX) GO TO 72			
	IWARN=2			
	GO TO 70			
72	IF(FEB(IM,NR),GT,ET(IM,NR)) GO TO 75			
	IF(NZ(NR),EO,2) GO TO 75			
	DELTA=DN(NR)/2.			
85	IM=IM+1			
	BO(IM,NR)=B(NR)			
85	IF(ABS(BO(IM,NR)+2,DELTA),GT,8EYL) DELTA=SIGN(DELTA,ABS(BO(IM,NR)))			

07/30/68

P43 - EFN SOURCE STATEMENT - IEN(S) -

1 11/2,SG)

GO TO 27

75 JF(IM,ST,1) GO TO 80

IWARN=1

GO TO 73

80 NZ(NR)=2

D1=FEB(IM-1,NR)-ET(IM-1,NR)

D2=FEB(IM,NR)-ET(IM,NR)

DELTB--(B0(IM,NR)-B(NR))*D1/(2*(D1-D2))

DELTN=SIGN(DELTB,SG)

JELFEB(IM,NR),GT,ET(IM,NR)) GO TO 86

GO TO 95

70 TRANSIFT(IM,NR))

EPS=FEB(IM,NR)

DEPS--TA*Y/IE

BETAF=R(NR)

RHO=RH(IM,NR)

101 FORMAT(15,5(1PE15.5),215)

102 FORMAT(5H IM ,5XINT,14XSHB(NR),10X2HET,13X3HFEB,10X5HDELTB,9X2HNZ

1,6H IWARN)

RETURN

END

07/30/68

PAGE 13

3.
SIBFTC TORQI

07/30/66

TOROL - EFM SOURCE STATEMENT - JFN(5) -

SUBROUTINE TORQ(BETA,RHO,EPS,TA,BETAM,NMAX,REL,TWARN3,IWARN9,MHAX,

1 RELM,IALARM,I3,T9,BDOT,A1E,I2E,ERR,NMAX2,UB1,WRITE,BSTAR)

DIMENSION BETAI(13),RHOI(13),EPSI(13),T(100),F(100),BDOT(13)

COMMON DRI,P,RPE,S,BN,GE,K,L,I8,JL,JE,MU,SM

REAL L,K,I8,IL,IE,MU,I11,I12,I13,I14,I19,I29,I110,I210

1 I23,I24,I81

BST=BSSTAR

IALARM=2

LL=1

DEIL=ABS(BETA(4))

ICOUNT=0

IOLD=1

FACT=.3

J=1

C COMPUTE CONSTANTS

PI2=3.14159265

BIS=BETA(11)*BETA(11)

B1=BETA(11)

CALL FUNCT(B1,I1,I11,I2,X,Z,E,R)

BDIA=-(I8/I11)*SQRT((R-L)*((BETAM-BST)**2-(B1-BST)**2)/I8)

BDOT(11)=BDIA

B2=BETA(12)

B25=B2**2

CALL FUNCT(B2,I1,I12,I2,X,Z,E,R)

B4=BETA(4)

E4=EPS(4)

CALL FUNCT(B4,I2,I14,I24,X,Z,E4,R2E)

B1)=BETA(12)

E1)=EPS(10)

CALL FUNCT(B10,I3,I110,I210,X,Z,E10,R2E)

I011=I8/I11

AA=K*(I210/I8-I811)+L*(I210/I8-I811)

AB=K*(I111-(I24+I210)/I2)+L*(I811-(I24+I210)/I2)-2.1

AC=K*(I24/I8-I811)+L*(I24/I8-I811)

AD=BETA(11)*BETA(11)*AB

AE=BETAM*BETAM*AA/2.

AF=AE*AD

T(11)=TA

C ITERATE TO FIND TA

30 TA=T(J)

B025=((K-L)*((B1-BST)**2-(B2-BST)**2) + I11*B01A**2-2.*MU*YA

1 *UB1)/I12

B02=-SQRT(B025)

BDOT(12)=B02

E2=EPS(12)

B2=BETA(12)

CALL PHASE3(E2,B02,NMAX,REL,TA,TP,3,IWARN9,ED3N,B3,R3,E3,R,LL,BEYL

1 ,EAR,NMAX2,B2,WRITE,BSTAR)

T3=TP

RHO(3)=R3

EPS(3)=E3

BETAI(3)=B3

CALL FUNCT(B3,I2,I13,I23,X3,Z3,E3,R)

B03B5=(I12*B025+K*(I22-BST)**2-(B3-BST)**2)-L*((B2-BST)**2-

1 SIGM(L,B3-BST)*(B3-BST)**2)/I13

JOB - EFM SOURCE STATEMENT - IFN(S) -		07/30/68	PAGE 15
B03B--SQR(1003AS)			23
B03A=(113+8038+X3+23-16+ED38)/123			
IF(ABS(B03A).LT.ABS(B03B))B03A=B03B			
B00T(13)=B03A			
B04S=(11./124)+(12+803A+2+K+(183-BST)**2-(B4			-BST)**2)-
1 L=(184-BST)**2+SIGN(1.,B3-BST)*(B3-BST)**2+2.*TA*(E3-E4))			26
B04--SQR(1004S)			
B00T(14)=B04			
B08ST=(B		4-BST)**2+18+804S/(K+L)	27
B6=BST-SQR(B08ST)			
BETA(6)=B6			
B5=B6+D6			
B7=DETA(7)			
B078S=(K-L)*((186-BST)**2-(187-BST)**2)/18			28
B07A=(18/111)*SQR(B078S)			
B00T(7)=B07A			
B8=RETA(9)			
B08S=(1./112)*(K-L)*((187-BST)**2-(188-BST)**2)-2.*MU*UB1*TA*111			
1 B07A**2)			29
B08=SQR(B08S)			
B00T(8)=B08			
E8=EPS(8)			
CALL PHASE3(E8,B08,NMAX,REL,TA,TP,9,IMARN9,ED9B,B9,R9,E9,R,LL,BETL			30
1 ,ERR,NMAX2,B8,1WRITE,BSTAR)			
LL=2			
T9=TP			
RHO(9)=R9			
BETA(9)=B9			
EPS(9)=E9			33
CALL FJUNCT(B9,3,119,129,X9,Z9,E9,R)			
B078S=(1./119)*(112+800S+K*(188-BST)**2-(189-BST)**2)			
1 L=(188-BST)**2+SIGN(1.,B9-BST)*((B9-BST)**2)			35
B09B=SQR(B078S)			
B09A=(119+809B-X9+Z9+E9+R)/129			
IF(ABS(B09A).LT.ABS(B09B))B09A=B09B			
B00T(9)=B09A			
B01J5=(1./1210)*(K-L*(189-BST)**2-(190-BST)**2)+129+809A**2			
1 L=(190-BST)**2-SIGN(1.,B9-BST)*(B9-BST)**2)*2.*TA*(E9-E10))			
2			38
B01J=SQR(B01J5)			
B00T(11)=B01J			
B=AF*B5S*AC/2.			
3CC=-5*(123+803A+803A+803A+129+809A+809A+119+809BS)			
C2=804081		-EPS(3)*EPS(4)-EPS(9)*EPS(10)	
F(1)=15CC-B1/C			
IF(1WRITE=0) WRITE(6,101) J,T(J),F(J),B3,B9			
CHECK FOR CONVERGENCE			40
IF(F(J).LT.0.) GO TO 50			
ICOUNT=3			
IF(J.EQ.1) GO TO 70			
IF(ABS(F(J)-T(J)).LE.RELM*ABS(T(J))) GO TO 80			
IF(ABS(F(J)-F(J-1)).LE.RELM*ABS(F(J))) GO TO 80			
IF(ABS(T(J)-T(J-1)).LE.RELM*ABS(T(J))) GO TO 80			
T(J)=F(J)-F(J-1)*T(J)/(T(J)-T(J-1))			
F(J)=T(J)-F(J-1)*T(J)/(T(J)-T(J-1))			
IF(J.GE.NMAX) GO TO 90			
GO TO 75			

ICRQ1 - EFN SOURCE STATEMENT - IFN(S) -

50 IF(J,NE,1) GO TO 55

IF(I10,EQ,2) GO TO 58

TR=T(J)

FR=F(J)

T(J)=11.-FACT)*TR

I10=2

IEXP=1

GO TO 30

58 IF(F(J),LE,FR) GO TO 59

TNEM=(TR-T(J))*FR/(FR-F(J))+T(J)

TR=T(J)

FR=F(J)

T(J)=TNEM

GO TO 56

59 IEXP=IEXP+1

T(J)=11.-FACT*(IEXP)*TR

GO TO 56

56 ICOUNT=ICOUNT+1

IF(ICOUNT,GT,13) GO TO 90

GO TO 30

55 T(J)=T(J)+T(J-1))/2.

GO TO 55

70 T(J+1)=F(J)

75 J=J+1

IF(T(J),LT,0.) T(J)=T(J-1))/2.

GO TO 30

90 IALARM=1

80 TA=T(J)

C COMPUTES ENERGIES

TE=5*(BETAM*BETAM

C EQUIVALENT ESCAPEMENT ENERGY BALANCE

C ENERGY GAINS

FGCC=.5*(123*BD3A*BD3A-113*BD3BS)

FOT=TA*(EPS(3)-EPS(4))

RGCC=.5*(129*BD9A*BD9A-119*BD9BS)

RGI=TA*(EPS(9)-EPS(10))

C TOTAL ENERGY GAIN

TG=FGCC+FGI+RGCC+RGI

C ENERGY LOSSES

FLST=.5*(BETAM*BETAM*865)

FLUC=.5*(K-L)*(1.-1811)*(BETAM*BETAM-BIS)

FLUF=UBI *MU*TA

FLEL=((K+L)/2.)*(124/18-1.)*(865-BIS)

RLST=FLST

RLJC=.5*(K-L)*(1.-1811)*(865-BIS)

RLUF=FLUF

RLEL=((K+L)/2.)*(1210/10-1.)*(BETAM*BETAM-BIS)

C TOTAL ENERGY LOSSES

TL=FLST+RLST+FLUC+RLUC+FLEL+RLEL+FLUF+RLUF

C SYSTEM ENERGY BALANCE

C ENERGY LOSSES

FCC=TA*(EPS(2)-EPS(3))-FGCC

FLELP=FLEL+TA*(EPS(4)-EPS(5))

RLCC=TA*(EPS(8)-EPS(9))-RGCC

RLELP=RLEL+TA*(EPS(10)-EPS(11))

C TOTAL ENERGY LOSSES

07/30/68

IDENT - EFM SOURCE STATEMENT - JEN(S) -

TLP=FLST+RLST+FLUC+RLUC+FLUF+RLUF+FLCC+RLCC+FLCLP+RLCLP

ENERGY GAINS

FTGP=TA+PIZ/(2.00M)

RTGP=FTGP

TOTAL ENERGY GAINS

TGP=FTGP+RTGP

WRITE(S,119)

WRITE(S,121) TE,TE

WRITE(S,121)

WRITE(S,122) FGCC,FTGP

WRITE(S,123) FLST,RTGP

WRITE(S,124) FGCC

WRITE(S,125) RTGP

WRITE(S,126) TGTGP

WRITE(S,127)

WRITE(S,128) FLST,FLST

WRITE(S,129) FLUC,FLUC

WRITE(S,130) FLUF,FLUF

WRITE(S,131) FLCL,FLCL

WRITE(S,132) RLST,RLST

WRITE(S,133) RLUC,RLUC

WRITE(S,134) RLUF,RLUF

WRITE(S,135) RLCL,RLCL

WRITE(S,136) RLCC

WRITE(S,137) RLCLP

WRITE(S,138) TLTLP

119 FORMATTING, 114, 31MEQJIV ESCAPEMENT ENERGY BALANCE, 0X,

1 27MTOTAL SYSTEM ENERGY BALANCE, 7)

122 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 22MTOTAL ENERGY, F12.6, 7)

121 FORMATTING, 12MEGAIN, 25X, 12MEGAIN, 0X,

122 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

123 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

124 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

125 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

126 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

127 FORMATTING, 13MEGAIN, 26X, 13MEGAIN, 0X,

128 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

129 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

130 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

131 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

132 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

133 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

134 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

135 FORMATTING, 20MTOTAL ENERGY, F12.6, 5X,

1 20MTOTAL ENERGY, F12.6, 7)

[illegible]

07/30/68

50
S10FTC SIMP1

07/30/68

SIMPL - EFN SOURCE STATEMENT - IFN(S) -

```
SUBROUTINE SIMPL(F, DELTAB, N, ERR, SUM, LP)  
  DIMENSION F(100)
```

```
  TN=N  
  LP=0
```

```
  CF=F(5)-4.*F(4)+6.*F(3)-4.*F(2)+F(1)
```

```
  SUM=0.
```

```
  DO 7 J=1,N
```

```
    IF(J.NE.1.AND.J.NE.N) GO TO 5
```

```
    A=1.
```

```
    GO TO 7
```

```
  5 IF(MOD(J,2).EQ.1) GO TO 6
```

```
    A=6.
```

```
    GO TO 7
```

```
  6 A=2.
```

```
  7 SUM=SUM+A*F(J)
```

```
  SUM=SUM*DELTAB/3.
```

```
  E=ABS(DELTAB*TN*OF/180.)
```

```
  R=ABS(ERR*SUM)
```

```
  IF(E.LE.R) GO TO 10
```

```
  LP=1
```

```
  10 CONTINUE
```

```
  RETURN
```

```
  END
```

07/30/68

1.
SIBFTC FUNC1

```
SUBROUTINE FUNCT(BETA, ICASE, I1, I2, X, Z, EPS, R)
COMMON DR1, P, RPE, S, BN, QE, K, L, IB, IL, IE, MU, SM
REAL K, L, IB, IL, IE, MU, I1, I2
COSB=COS(BETA)
RID=1./ORI
ODRI=RID*ORI
X=(COSB-RID)/(ODRI-2.*COSB)
IL=ID*X*IL
IF(ICASE.EQ.1) GO TO 10
YE=SQRT(ABS(R*R-QE*QE))
IF(ICASE.EQ.2) GO TO 5
Z=(S/YE)*SIN(SN*3.1415927*Z./BN-EPS)-1.
GO TO 20
5 Z=1.+(S/YE)*SIN(EPS)
20 IZ=IL*X*Z*Z*IE
JJ=J*J
END
```

07/30/68

PAGE 27

3.
SIBFTC PHI

07/30/68

PH1 - EFM SOURCE STATEMENT - IFM(S) -

```

SUBROUTINE PHASE1(BETA0,BDOTO,EP5B,EP5A,BETAF,TA,T,BDOTE,NP,BSTAR)
COMMON DR1,P,PE,S1,BN,BE,KAL,IB,IL,IE,MU,SN
REAL K,L,IB,IL,IE,MU
EPLANG1=SQRT((PE**2+S**2-SRPE**2)*COS(ANG))
IF(NP.EQ.1.OR.NP.EQ.7) GO TO 5
M=SQRT((K*L)/IB)
BOIFF=BETAD-BSTAR
PHI0=ATAN(BDOTE/(M*BOIFF))
IF(NP.EQ.6.OR.NP.EQ.12) GO TO 7
C CALCULATION FOR PHASES 5 AND 11
AU=SQRT(BOIFF*BOIFF*(BDOTO/M)*(BDOTO/M))
SG=NP-5
RHO=P/2.-ATAN(SIN(BETA0)/(OR1-COS(BETA0)))
IF(NP.EQ.11) GO TO 30
R=FR(RHO)
ICASE=2
GO TO 20
30 ANG=P-RHO
R=FR(ANG)
ICASE=3
20 CALL FUNCT(BETA0,ICASE,DM,DM,X,Z,EP5B,R)
DEEM=X*Z
EP5D=-ABS(IDEFB*BDOTO)
CT=TA/(2.*IE)
T=EP5D/2.+SQRT(ABS(EP5D*EP5D/A.+CT*(EP5B-EP5A))))/CT
TI=PHI0/M
IF(TI.LE.T) GO TO 15
HETAF=SIGN(ACOS(SIN(T-PHI0)*BSTAR,SG)
BOOTE=SIGN(ACOS(SIN(M-T-PHI0),SG)
GO TO 3
15 T=T1
HETAF=SIGN(ACOS,SG)
BOUTE=2.
GO TO 10
C CALCULATION FOR PHASES 6 AND 12
7 BDOTE=D.
T=PHI0/M
GO TO 10
C CALCULATION FOR PHASES 1 AND 7
5 T=SQRT((B-K-L))*ARCCOS((BETAF-BSTAR)/(BETA0-BSTAR))
10 RETURN
END

```

2 3

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07/30/68

10
SIBFTC PH2

```
SUBROUTINE PHASE2(BETAO,BETAF,BDOTO,NO,ERR,VMAX2,TA,T,NP,ALARM,BST
  1AR)
  DIMENSION F(1001),M(1001),G(11)
  COMMON DRI,P,RPE,S,N,QE,K,L,B,IL,IE,MU,SN
  REAL K,L,B,IL,IE,MU,I,KL
  INTEGER ALARM
  PI=3.1415927
  RPE=SQ-RPE+RPE
  SSU=S+S
  AL=K*L
  IF(NP.EQ.2) KL=K-L
  RPE=SQ-RPE+S
  TAMU=TA*U
  TRPE=2.*RPE
  AID=1./DRI
  QD=1.*QD+DRI
  PI2=PI/2.
  ANG=2.*PI*SN/BN
  ALARM=2
  N=(70-1)/2+1
  IF(MOD(N,2).EQ.0) N=N+1
  ITR=1
  TN=N-1
  DELTAB=(BETAF-BETAO)/TN
  MII)=J.
  15 DELTF=DELTAB/4.
  DO 13 J=1,N
    TJ=J-2
    BETAS=BETAO+TJ*DELTAB
    IF(J.EQ.1) BETAS=BETAO
    DO 30 JK=1,5
      TK=JK-1
      NLTA=UETAS+TK*DELTF
      COSB=COS(BETA)
      RHO=P/2.-ATAN(SIN(BETAF)/(DRI-COSB))
      X=(COSB-RID)/(DDR)-2.*COSB)
      IF(NP.EQ.2.OR.NP.EQ.8) GO TO 7
      IF(NP.EQ.10) G. TO 5
      RF=SQRT(ABS( RPE+SSQ-TRPE+COS(RHO)))
      YE=SQRT(ABS(RF*RF-QE*QE))
      EPSF=ARSIN(QE/RF)-ARSIN((RF*RF+SSQ+WPESQ)/(2.*S*RF))
      Z=1.*S*SIN(EPSF)/YE
      GO TO 5
    5 RR=SQRT(ABS(RPE+SSQ-TRPE+COS(P-RHO)))
      YE=SQRT(ABS(RR*RR-QE*QE))
      EPSR=ARS(P/2-ANG*ARCS(COE/RR)-ARSIN((RR*RR+SSQ-RPESQ)/(2.*S*RR)))
      Z=(S*VE)*SIN(ANG-EPSR)-1.
    6 I=IB*XX*IL+X*XX*Z*IE
      GO TO 3
    7 I=IH*XX*IL
      U=K*RPES+SIN(4*H)/(RPESU+SSQ-TRPE+COS(RHO))
      TF=TAMJ*U
      FO=TF/KI
      GO TO 2
    3 FI=K*Z*TA
```

07/30/68

P42 - FEN SOURCE STATEMENT - (FENIS) -

```

FQ=FN/KL
2 G(JK)=FO
IF(J.EQ.1) GO TO 16
30 CONTINUE
CALL SIMP(G,DELTA,N,ERR,SUM,LP)
H(J)=H(J-1)+2.*SUM
F(J)=SURT(ABS(I/(H(J)-KL*(BETA*BETA-BET-J*BETAO-2.*BSTAR*(BETA-
1 BETAO))*CO)))
59
GO TO 15
16 CO=1*BDOTC*BDOTO
F(J)=ABS(LL/BDOTC)
10 CONTINUE
CALL SIMP(F,DELTA,N,ERR,SUM,LP)
IF(LP.NE.0) GO TO 45
IF(ITR.EQ.1) GO TO 45
IF(ABS(SUM1-SUM).GT.100.*ERR*ABS(SUM)) GO TO 45
SUM=(15.*SUM-SUM1)/15.
GO TO 25
45 ITR=2
SUM1=SUM
DELTA=DELTA/2.
N=2*N-1
IF(N.GT.NMAX2) GO TO 17
GO TO 15
17 ALAN=1
20 T=ABS(SUM)
RETURN
END

```

10
SIBFTC BT5

07/30/68

PAGE 35

07/30/68

RIS - EEN SOURCE STATEMENT - IFN(S) -

```

FUNCTION BETAS(RHO)
COMMON DALLP
COMMON/MALAM/FLAG,Z
FLAG=0
Z=0.1*SIN(P/2.-RHO)
IF(Z.GT.1.) GOTO 1
Z1=Z
GOTO 2
1 FLAG=1.
Z1=1.
2 BETAS=ARSIN(Z1)-P/2.*RHO
RETURN
END
    
```

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07/30/58

10
510FTC UNIC

50
SIBFTC GEOM1

GEOM1 - EFN SOURCE STATEMENT - JFN151 -		07/30/68	PAGE 42
SUBROUTINE GEOM1(A,B,PPP,GAMMA,R1,R2,REE,R1E,R2E,PHI,OMEGA,OMEGA IE,Q,LD,LOE,RP,RPPE,BETA,RHO,EPS,EPSP,RHOD)			
DIMENSION BETAI(13),RHOI(13),EPSI(13)			
COMMON DAL,PA,PPES,BB,GE,BA,LA,IN,JA,IE,MU,SN			
COMON/MALAM/PLAG,7			
REAL R,L,LO,LA,IE,MU,LD,LOE			
RHOI(1)=ARCOS(PPES+SS-RORI/TRPES)			2
EPSI(1)=R1*ANGLE-ARCSIN(R1-R2+SS-RPES)/(12.*SORI)			5
EPSSI(1)=R1*PI-11.-2.*SN/RN1-ANGLE-ARCSIN(R1-R2+SS-RPES)/(12.*SORI)			
1) CALCULATION OF GEOMETRIC PARAMETERS			8
PI=3.1415927			
PHI=PI/BN1*(SV0.9)			11
RP=SQRT(AA+BB)			12
P=2.*ATAN(A/B)			13
SG=SIGN(GAMMA)			14
LD=2.*COS(GAMMA)-SQRT(R1-R1-R2+R2+SG*SG)			15
D=42*SS			
OMEGA=ARCSIN(Q/R1)			16
REE=42+PPP			
RPE=PP			
SS=5*5			
RPE=RPPE+2			
TRPLS=2.*RPE+5			
RPL=TRPP			
R1E=R1			
R2E=42+PPP			
LOE=LD			
OE=Q			
C OMEGA=OMEGA			
CALCULATION OF LEVER ANGULAR DISPLACEMENTS			
RHO(1)=RHO(REE)			
RHOI(1)=RHO			
RHOI(2)=RHO(1E)			
RHOI(4)=RHO(1R2E)			
RHOI(5)=P-RHOI(1)			
RHOI(6)=RHOI(5)			
RHOI(7)=P-RHOI(1)			
RHOI(8)=P-RHOI(2)			
RHOI(10)=P-RHOI(4)			
RHOI(11)=RHOI(1)			
RHOI(12)=RHOI(1)			
C CALCULATION OF BALANCE ANGULAR DISPLACEMENT			
BETAI(1)=BETAS(RHOI(1))			17
IF(PLAG.EQ.0.) GOTO 1			
N=1			
WRITE(5,105017,MN			21
BETAI(2)=BETAS(RHOI(2))			23
IF(PLAG.EQ.0.) GOTO 2			
N=2			
WRITE(5,105017,MN			27
BETAI(4)=BETAS(RHOI(4))			29
IF(PLAG.EQ.0.) GOTO 3			
N=3			
WRITE(5,105017,MN			33

.....

SAMPLE DATA DECK

.....

SDATA
SDAT ICOND=1,IGEOM=1,RE=1.685,A=1.286,B=1.3957,APP=0.0061,BN=15,SN=3,
GAMMA=50,
S=241,ORI=7.0635,JBT=0.1ERR=1.E-6,REL=5.E-3,RELW=1.E-6,
NO=23,NMAX=50,NMAX2=100,MMAX=20,A=921.9,IB=0.374,II=0.3268,IE=0.134,LI=13.63,
MU=0.3,A1=12,A2=15,A3=40,JA=8,AMPL=52,75,90,120,150,210,270,330,
NO=11,
R1=18,R2=2019,JWRITE=2,OSTAR=1.58
SDAT BSTAR=2,S=0.2378,IGEOM=1,URI=38
SDAT BSTAR=3.28

CLOCK GEOMETRY

	RPP	RE	RP	R1	R2	L	O	OMEGA
ACTUAL	0.0061200	0.1685000	0.1602011	0.1840000	0.2019000	0.0301047	0.1546644	57.2000656
EFFECTIVE	0.0061200	0.1746000	0.1603211	0.1840000	0.2080000	0.0301047	0.1546644	57.2000656

	GAMMA	SPAN	TEETH	S	P	A	B	D/R1	PHI
	49.99999952	3.00000000	15.00000000	0.24100000106.68911362	0.12860000	0.09570000	7.0634999	1.99999905	

PARAMETERS

	K	L	IL	IE	MU	UB1	A1	A2
	921.9000153	13.83000004	0.02680000	0.01340000	0.30000000	0.05243810	12.000000	16.000000

CONDITIONS

	ERR	REL	REL	NO	VMAX	MMAX2	IPARAM	ICOND	IGEOM	IMRITE	BSTAR	A3
	1.0E-05	5.0E-03	1.0E-06	11	50	20	1000	1	1	0	1.5000000E 00	-40.000000

EQUITY ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	505.489235	TOTAL SYSTEM ENERGY BALANCE	
ENERGY GAINS		TOTAL ENERGY	505.489235
FOR CATCHUP COL	16.536185	ENERGY GAINS	
FOR IMPULSE	5.104334	FOR INPUT	44.313670
REV CATCHUP COL	13.554356	REV INPUT	44.313670
REV IMPULSE	5.281453		
TOTAL GAINS	39.576327	TOTAL GAINS	88.627340
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	14.398245	FOR SIDE THRUST	14.398245
FOR UNLOCK COL	0.575143	FOR UNLOCK COL	0.575143
FOR UNLOCK FRICTION	3.328491	FOR UNLOCK FRICTION	3.328491
FOR L AND E LOSS	1.359085	FOR CATCHUP COL	7.301238
REV SIDE THRUST	14.398245	FOR L AND E LOSS	15.438723
REV UNLOCK COL	0.345845	REV SIDE THRUST	14.398245
REV UNLOCK FRICTION	3.328491	REV UNLOCK COL	0.345845
REV L AND E LOSS	1.845765	RE UNLOCK FRICTION	3.328491
		REV CATCHUP COL	6.299324
TOTAL LOSSES	39.576308	REV L AND E LOSS	23.213570
		TOTAL LOSSES	88.627316

POSITION	BETA	RHO	EPSILON	PERIOD	BDOT
0	60.00000000E 00	46.39104900E 00	92.00066400E-01		5.00000000E-39
1	51.82112900E 00	46.39104900E 00	92.00066400E-01	34.34429900E-04	-46.27515900E 02
2	22.68198700E 00	49.75136900E 00	88.78014600E-01	42.93354300E-04	-83.93067000E 02
3	-10.77955900E 00	55.10618200E 00	23.95837300E-01	37.85532500E-04	-89.01815900E 02
4	-33.24685900E 00	58.37596000E 00	10.1367000E-01	27.20252300E-04	-74.20252300E 02
5	-49.27700400E 00	60.29806400E 00	-27.99993300E-01	20.59933200E-04	-53.06852500E 02
6	-56.88039700E 00	62.29826400E 00	-27.97993300E-01	36.91392200E-04	03.00000000E-40
7	-51.82112300E 00	60.29826400E 00	-27.99993300E-01	26.91457200E-04	36.87383100E 02
8	-27.68198700E 00	56.93774500E 00	-24.77882400E-01	46.32515400E-04	81.76618900E 02
9	74.81981500E-01	52.11673600E 00	-78.56196500E-01	34.47536400E-04	95.20747100E 02
10	33.24685900E 00	48.31315300E 00	-92.1360200E-01	30.33152100E-04	77.02281100E 02
11	51.50704300E 00	46.39104900E 00	-14.79993300E 00	28.9584600E-04	46.87745500E 02
12	59.99999900E 00	46.39104900E 00	-14.79993300E 00	35.82270200E-04	03.00000000E-40

EQUIV ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	789.825378		TOTAL ENERGY	789.825378	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	27.526091		FOR INPUT	78.453238	
FOR IMPULSE	12.512527		REV INPUT	78.453238	
REV CATCHUP COL	22.517523				
REV IMPULSE	10.267024				
TOTAL GAINS	72.803197		TOTAL GAINS	156.906475	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	22.758975		FOR SIDE THRUST	22.758975	
FOR UNLOCK COL	1.568597		FOR UNLOCK COL	1.568597	
FOR UNLOCK FRICTION	5.992784		FOR UNLOCK FRICTION	5.992784	
FOR L AND E LOSS	6.150027		FOR CATCHUP COL	11.277114	
REV SIDE THRUST	22.758975		FOR L AND E LOSS	31.582230	
REV UNLOCK COL	1.568454		REV SIDE THRUST	22.758975	
REV UNLOCK FRICTION	5.992784		REV UNLOCK COL	1.568454	
REV L AND E LOSS	5.932575		REV UNLOCK FRICTION	5.992784	
			REV CATCHUP COL	10.064439	
			REV L AND E LOSS	43.762287	
TOTAL LOSSES	72.903166		TOTAL LOSSES	156.906435	

POSITION	BETA	RMD	EPSILON	PERIOD	BOOT
0	75.0000000E 00	46.39104900E 00	92.00066400E 01	52.41199600E 04	0.0000000E 39
1	51.82112900E 00	46.39104900E 00	92.00066400E 01	29.82618500E 04	-83.09754000E 02
2	22.68198700E 00	49.75136900E 00	88.78014500E 01	27.25897000E 04	-15.82325100E 03
3	-77.61421700E 01	56.61853500E 00	29.27483300E 01	23.46639500E 04	-11.34055500E 03
4	-33.24685900E 00	58.37596000E 00	13.13600000E 01	15.06390300E 04	-13.25915300E 03
5	-50.54377200E 00	60.29806400E 00	-27.99933300E 01	15.06390300E 04	-86.52641800E 02
6	-71.96893300E 00	62.29806400E 00	-27.99933300E 01	51.22829300E 04	00.0000000E 43
7	-51.82112300E 00	62.29806400E 00	-27.99933300E 01	48.68762100E 04	78.39731000E 02
8	-22.64198700E 00	56.93774500E 00	-24.77882400E 01	30.65088300E 04	15.66812200E 03
9	50.39535600E 01	52.51508800E 00	-74.76829100E 01	24.98441700E 04	11.39072500E 03
10	32.24685900E 00	48.31315300E 00	-90.13500200E 01	25.60927300E 04	15.43155800E 03
11	53.57601500E 00	46.39104900E 00	-14.79993300E 00	21.68325600E 04	81.35288500E 02
12	74.99999800E 00	46.39104900E 00	-14.79993300E 00	49.26021900E 04	00.0000000E 45

EQUIN ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	1137.348541	TOTAL SYSTEM ENERGY BALANCE	
ENERGY GAINS		TOTAL ENERGY	1137.348541
FUR CATCHUP COL	40.992700	ENERGY GAINS	
FOR IMPULSE	21.829942	FOR INPUT	120.525517
REV CATCHUP COL	33.536156	REV INPUT	120.525517
REV IMPULSE	17.225878		
TOTAL GAINS	113.512674	TOTAL GAINS	241.051335
ENERGY LOSSES		ENERGY LOSSES	
FUR SIDE THRUST	33.019990	FOR SIDE THRUST	33.019990
FOR UNLOCK COL	3.425041	FOR UNLOCK COL	3.405541
FUR UNLOCK FRICTION	9.052919	FOR UNLOCK FRICTION	9.052919
FOR L AND E LOSS	12.058460	FOR CATCHUP COL	16.265911
REV SIDE THRUST	33.019990	FOR L AND E LOSS	52.361201
REV UNLOCK COL	3.075396	REV SIDE THRUST	33.019990
REV UNLOCK FRICTION	9.052919	REV UNLOCK COL	3.075396
REV L AND E LOSS	10.427564	REV UNLOCK FRICTION	9.052919
		REV CATCHUP COL	16.753366
		REV L AND E LOSS	69.044294
TOTAL LOSSES	113.612676	TOTAL LOSSES	241.051323

POSITION	BETA	RHO	EPSILON	PERIOD	MDOT
0	90.0000000E-00	46.39104900E-00	92.07006400E-01	61.99406200E-04	0.0000000E-39
1	51.8211200E-00	46.39104900E-00	92.0006400E-01	23.45969900E-04	-11.29234100E-03
2	22.68198700E-00	49.75136900E-00	88.78016500E-01	21.50739700E-04	-13.20771100E-03
3	-63.22087100E-01	54.38360500E-00	31.87075900E-01	20.19902700E-04	-12.70531400E-03
4	-33.24685900E-00	58.37596000E-00	10.1365200E-01	12.08923700E-04	-12.88119900E-03
5	-51.09117200E-00	60.29806400E-00	-27.99933300E-01	19.98045200E-04	-11.60182500E-03
6	-87.03913300E-00	60.29806400E-00	-27.99933300E-01	54.33131400E-04	0.0000000E-43
7	-51.8211200E-00	60.29806400E-00	-27.99933300E-01	23.81252700E-04	1.96372700E-03
8	-22.68198700E-00	56.97774500E-00	-74.77882400E-01	19.78894500E-04	13.09150900E-03
9	38.96507300E-01	52.70270600E-00	-72.95735500E-01	21.82541300E-04	13.72657200E-03
10	33.24685900E-00	46.33131300E-00	-90.13672200E-01	17.46741900E-04	11.15891400E-03
11	54.50172800E-00	46.39104900E-00	-14.79993300E-00	58.57227100E-04	0.0000000E-40
12	89.99999800E-00	46.39104900E-00	-14.79993300E-00		

FUEL ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY			TOTAL ENERGY		
2021.952942			2021.952942		
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	74.596420		FOR INPUT	228.227663	
FOR IMPULSE	45.849975		REV INPUT	228.227663	
REV CATCHUP COL	61.721952				
REV IMPULSE	35.795331				
TOTAL GAINS			TOTAL GAINS		
217.943674			456.455326		
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	59.242928		FOR SIDE THRUST	59.242928	
FOR UNLOCK COL	7.365899		FOR UNLOCK COL	7.365899	
FOR UNLOCK FRICTION	17.142648		FOR UNLOCK FRICTION	17.142648	
FOR L AND E LOSS	27.821261		FOR CATCHUP COL	29.126584	
REV SIDE THRUST	59.242928		FOR L AND E LOSS	99.750744	
REV UNLOCK COL	6.942295		REV SIDE THRUST	59.242928	
REV UNLOCK FRICTION	17.142648		REV UNLOCK COL	6.942295	
REV L AND E LOSS	23.542081		REV UNLOCK FRICTION	17.142648	
			REV CATCHUP COL	26.805352	
TOTAL LOSSES			TOTAL LOSSES		
217.943682			456.455303		

POSITION	BETA	RHO	EPSTON	PERIOD	BDOT
0	12.0000000E-01	46.3910490E-00	92.0000000E-01	72.0619390E-04	0.0000000E-39
1	51.8211290E-00	46.3910490E-00	92.0000000E-01	16.7278970E-04	-16.6411350E-03
2	22.6819870E-00	49.7513690E-00	88.7801460E-01	15.3001430E-04	-17.9133380E-03
3	-50.1924440E-01	54.1726980E-00	34.2434940E-01	15.3583950E-04	-18.3877170E-03
4	-33.2468590E-00	58.3759600E-00	12.1360030E-01	87.4627790E-05	-17.8452170E-03
5	-51.5622340E-00	62.2980640E-00	-27.9993330E-01	70.3378840E-04	-17.3158210E-03
6	-11.7152930E-01	60.2980640E-00	-27.9993330E-01	70.3378840E-04	00.0000000E-43
7	-51.8211290E-00	60.2980640E-00	-27.9993330E-01	16.8301020E-04	16.4413870E-03
8	-27.6819870E-00	56.9377450E-00	-24.7788240E-01	16.8301020E-04	17.8474130E-03
9	28.7490000E-01	52.8737320E-00	-71.3151470E-01	14.1334210E-04	18.4013450E-03
10	33.2468590E-00	48.3131530E-00	-90.1360020E-01	16.8644710E-04	18.2259110E-03
11	55.3104520E-00	46.3910490E-00	-14.7999330E-00	12.6775470E-04	16.8644550E-03
12	12.0000000E-01	46.3910490E-00	-14.7999330E-00	69.4531640E-04	00.0000000E-43

EQUIV ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	3159.301514		TOTAL ENERGY	3159.301514	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	117.985352		FOR INPUT	367.239288	
FOR IMPULSE	76.925244		REV INPUT	367.239288	
REV CATCHUP COL	97.863983				
REV IMPULSE	59.767643				
TOTAL GAINS	352.542271		TOTAL GAINS	734.478577	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	93.067069		FOR SIDE THRUST	93.067069	
FOR UNLOCK COL	12.460716		FOR UNLOCK COL	12.460716	
FOR UNLOCK FRICTION	27.584096		FOR UNLOCK FRICTION	27.584096	
FOR L AND E LOSS	45.766190		FOR CATCHUP COL	45.766190	
REV SIDE THRUST	93.067069		FOR L AND E LOSS	163.549902	
REV UNLOCK COL	11.946543		REV SIDE THRUST	93.067069	
REV UNLOCK FRICTION	27.584096		REV UNLOCK COL	11.946543	
REV L AND E LOSS	39.989317		REV UNLOCK FRICTION	27.584096	
			REV CATCHUP COL	42.582738	
TOTAL LOSSES	352.542194		REV L AND E LOSS	217.070051	
			TOTAL LOSSES	734.478455	

POSITION	BEIA	RMO	EPSILON	PERIOD	BDOF
0	15.0000000E 01	46.39104900E 00	92.03066400E 01	78.62190330E 04	6.60000000E 39
1	51.82112900E 00	46.39104900E 00	92.03066400E 01	13.09225107E 04	-21.67129900E 03
2	22.68198700E 00	49.75136900E 00	88.78014500E 01	11.94729500E 04	-22.57826600E 03
3	-44.59817600E 01	54.07892600E 00	35.27229500E 01	11.94729500E 04	-23.05471300E 03
4	-33.24685900E 00	58.37596000E 00	10.13630300E 01	12.57643230E 04	-22.87759100E 03
5	-51.75546200E 00	60.29808400E 00	-27.99933300E 01	68.82447230E 05	-22.14531600E 03
6	-14.72493800E 01	60.29808400E 00	-27.99933300E 01	76.32717930E 04	0.00000000E 00
7	-51.82112300E 00	60.29808400E 00	-27.99933300E 01	77.27979300E 04	21.53945700E 03
8	-22.64198700E 00	56.93774500E 00	-24.77882400E 01	13.12820000E 04	22.54599600E 03
9	24.38019900E 01	52.94266300E 00	-70.61818200E 01	11.05664230E 04	25.36568200E 03
10	33.24685900E 00	48.31313300E 00	-92.13630300E 01	13.42036600E 04	22.91994500E 03
11	55.65130700E 00	46.39104900E 00	-14.79993300E 00	99.89141800E 05	21.84430300E 03
12	15.0000000E 01	46.39104900E 00	-14.79993300E 00	75.68223900E 04	0.00000000E 43

EQUIV ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	6192.231010		TOTAL ENERGY	5192.231010	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	233.943040		FOR INPUT	739.077934	
FOR IMPULSE	160.114822		REV INPUT	739.077934	
REV CATCHUP COL	194.535522				
REV IMPULSE	121.932122				
TOTAL GAINS	712.524361		TOTAL GAINS	1478.155869	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	183.518854		FOR SIDE THRUST	183.518854	
FOR UNLOCK COL	26.044229		FOR UNLOCK COL	26.044229	
FOR UNLOCK FRICTION	55.513659		FOR UNLOCK FRICTION	55.513659	
FOR L AND E LOSS	99.466151		FOR CATCHUP COL	90.309269	
REV SIDE THRUST	183.518854		FOR L AND E LOSS	334.341015	
REV UNLOCK COL	26.044229		REV SIDE THRUST	183.518854	
REV UNLOCK FRICTION	55.513659		REV UNLOCK COL	26.044229	
REV L AND E LOSS	83.581949		REV UNLOCK FRICTION	55.513659	
			REV CATCHUP COL	84.068247	
TOTAL LOSSES	712.524399		REV L AND E LOSS	439.961201	
			TOTAL LOSSES	1478.155823	

POSITION	BETA	RHO	EPSILON	PERIOD	BODY
0	21.0002000E-01	46.3910490E-00	92.0006400E-01	85.1648000E-04	0.0000000E-39
1	51.8211290E-00	46.3910490E-00	92.0006400E-01	91.7697620E-05	-31.3847560E-03
2	22.6819870E-00	49.7513690E-00	88.7801640E-01	83.5368050E-05	-31.6574880E-03
3	-39.9384430E-01	54.0024000E-00	36.1329500E-01	90.5235280E-05	-32.5791150E-03
4	-33.2468590E-00	58.3754620E-00	10.1360000E-01	48.4433140E-05	-32.5855450E-03
5	-51.9151220E-00	62.2986400E-00	-27.9993300E-01	83.0211430E-04	-32.5694980E-03
6	-20.7420320E-01	62.2986400E-00	-27.9993300E-01	84.2657120E-04	31.332785-03
7	-51.8211230E-00	60.2993640E-00	-27.9993300E-01	91.7805620E-05	31.8724890E-03
8	-27.6819870E-00	56.9377450E-00	-24.7789240E-01	77.4335410E-05	32.2913720E-03
9	20.7526290E-01	53.0024000E-00	-70.0141600E-01	96.3019070E-05	32.5763650E-03
10	33.2468590E-00	48.3131530E-00	-93.1362020E-01	70.3852520E-05	31.6167740E-03
11	55.9319410E-00	46.3910490E-00	-14.7999330E-00	82.5993390E-04	00.0000000E-40
12	21.0002000E-01	46.3910490E-00	-14.7999330E-00		

EQUIV ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	10236.136719		TOTAL ENERGY	10236.136719	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	388.853271		FOR INPUT	1235.962112	
FOR IMPULSE	271.313347		REV INPUT	1235.962112	
FOR CATCHUP COL	323.690918				
REV IMPULSE	209.592034				
TOTAL GAINS	1193.547623		TOTAL GAINS	2471.924225	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	304.375256		FOR SIDE THRUST	304.375256	
FOR UNLOCK COL	44.155579		FOR UNLOCK COL	44.155579	
FOR UNLOCK FRICTION	92.835649		FOR UNLOCK FRICTION	92.835649	
FOR L AND E LOSS	169.527324		FOR CATCHUP COL	169.527324	
FOR SIDE THRUST	304.375256		FOR L AND E LOSS	562.709221	
REV UNLOCK COL	43.336418		REV SIDE THRUST	304.375256	
REV UNLOCK FRICTION	92.835649		REV UNLOCK COL	43.336418	
REV L AND E LOSS	141.735456		REV UNLOCK FRICTION	92.835649	
			REV CATCHUP COL	139.777294	
			REV L AND E LOSS	727.679482	
TOTAL LOSSES	1193.547623		TOTAL LOSSES	2471.923523	

POSITION	BETA	AMD	EPSILON	PERIOD	BOOT
0	27.0000000E-01	46.3910490E-00	92.0306450E-01	88.70899600E-04	5.0000000E-39
1	51.8211290E-00	46.3910490E-00	92.0306450E-01	-40.9093350E-03	-40.9093350E-03
2	22.6419070E-00	49.7513690E-00	88.7801450E-01	70.8124270E-05	-41.1072850E-03
3	-38.0759130E-01	53.9717840E-00	36.4779090E-01	64.3862230E-05	-41.7002750E-03
4	-33.2468390E-00	58.3759600E-00	10.11360000E-01	70.5893740E-05	-47.2052790E-03
5	-51.9780590E-00	60.2980640E-00	-27.9993330E-01	37.4392630E-05	-41.8060050E-03
6	-26.7578390E-01	60.2980640E-00	-27.9993330E-01	86.6855690E-04	0.0000000E-40
7	-51.8211230E-00	60.2980640E-00	-27.9993330E-01	86.0061470E-04	40.9093370E-03
8	-22.6419070E-00	56.9377400E-00	-24.7786240E-01	70.7492040E-05	41.1581140E-03
9	19.33203620E-01	53.0263180E-00	-49.7771170E-01	59.7213180E-05	41.7157650E-03
10	33.2468390E-00	48.3131530E-00	-90.11360000E-01	75.0032310E-05	47.1575670E-03
11	56.0433280E-00	46.3910490E-00	-14.7999330E-00	54.4197250E-05	41.5697610E-03
12	26.9999990E-01	46.3910490E-00	-14.7999330E-00	86.3699410E-04	0.0000000E-40

INITIAL ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	15291.519287		TOTAL ENERGY	15291.019287	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	582.725098		FOR INPUT	1857.878036	
FOR IMPULSE	410.537538		REV INPUT	1857.878036	
REV CATCHUP COL	485.335205				
REV IMPULSE	317.262227				
TOTAL GAINS	1795.508067		TOTAL GAINS	3715.756973	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	455.532628		FOR SIDE THRUST	455.636238	
FOR UNLOCK COL	66.794765		FOR UNLOCK COL	66.794765	
FOR UNLOCK FRICTION	139.549028		FOR UNLOCK FRICTION	139.549028	
FOR L AND E LOSS	258.226765		FOR CATCHUP COL	224.360962	
REV SIDE THRUST	455.535238		FOR L AND E LOSS	848.650285	
REV UNLOCK COL	65.956128		REV SIDE THRUST	455.636238	
REV UNLOCK FRICTION	139.549028		REV UNLOCK COL	65.856108	
REV L AND E LOSS	214.359840		REV UNLOCK FRICTION	139.549028	
			REV CATCHUP COL	224.575142	
TOTAL LOSSES	1795.507986		REV L AND E LOSS	1110.218246	
			TOTAL LOSSES	3715.755798	

POSITION	BETA	AMQ	EPSILON	PERIOD	BOOT
0	33.00000000 01	46.39104900 00	92.03066400 -C1	90.93852200 -04	6.00030000 -39
1	51.82112000 00	46.39104900 00	92.03066400 -C1	57.64632200 -05	-50.35282300 03
2	22.68194700 00	49.75136900 00	88.78014500 -01	57.64632200 -05	-50.35282300 03
3	-37.16452800 -01	33.95646400 00	38.65050300 -05	52.62865800 -05	-51.52051800 03
4	-33.24685900 00	58.37596000 00	13.13500300 -01	57.81629300 -05	-51.78551600 03
5	-52.00927600 00	60.29808400 00	-27.99933300 -01	30.52421900 -05	-51.65975800 03
6	-32.77306400 01	60.29808400 00	-27.99933300 -01	89.00111900 -04	00.50600000 -40
7	-51.82112000 00	60.29808400 00	-27.99933300 -01	90.36843100 -04	50.39333700 03
8	-22.68194700 00	56.93774500 00	-24.77882400 -01	57.61615000 -05	50.62545700 03
9	19.57784900 -01	52.03825100 00	-69.65863400 -01	48.64647000 -05	51.39964600 03
10	33.24685900 00	48.31315100 00	-90.13050200 -01	61.39470300 -05	51.70533100 03
11	56.09932280 00	46.39104900 00	-14.79993300 00	44.38335400 -05	51.22574800 03
12	32.99999900 01	46.39104900 00	-14.79993300 00	86.74895500 -04	50.50000000 -40

CLOCK GEOMETRY

	RPP	RE	RP	R1	R2	L	Q	OMEGA
ACTUAL	0.0001200	0.1605000	0.1603011	0.1840000	0.2019000	0.0301047	0.1546544	57.2000656
EFFECTIVE	0.0001200	0.1740000	0.1603011	0.1840000	0.2080000	0.0301047	0.1546544	57.2000656

GAMMA SPAN FEETH S P A B D/R1 PH1
49.99999952 3.00000000 15.00000000 0.237800000106.60911362 0.12860000 0.09570000 7.06349999 41.99999905

PARAMETERS

K L IL IE MU UB1 A1 A2
21.00000153 13.83000004 0.03740000 0.02680000 0.01340000 0.0000000 0.05243811 12.000000 16.000000

COMPOSITIONS

FRA REL RELM NO VV48 MM48 MM482 IPARAM ICOND IGEOM IWKITE BSTAR A3
1.0E-04 5.0E-03 1.0E-04 11 50 20 1000 0 1 1 0 2.00000000E 00 -40.000000

EQUITY ESCAPEMENT ENERGY BALANCE				TOTAL SYSTEM ENERGY BALANCE			
TOTAL ENERGY	505.400235	TOTAL ENERGY	505.400235	ENERGY GAINS			
FOR CATCHUP COL	17.132082	FOR INPUT	49.451113	FOR INPUT	49.451113		
REV IMPULSE	7.769372	REV INPUT	49.451113				
REV CATCHUP COL	13.524210						
REV IMPULSE	5.911216						
TOTAL GAINS	44.317690	TOTAL GAINS	98.902226				
ENERGY LOSSES		ENERGY LOSSES					
FOR SIDE THRUST	14.221494	FOR SIDE THRUST	14.221494				
FOR UNLOCK COL	1.892350	FOR UNLOCK COL	1.892350				
FOR UNLOCK FRICTION	3.714375	FOR UNLOCK FRICTION	3.714375				
FOR L AND E LOSS	2.480935	FOR CATCHUP COL	8.257682				
REV SIDE THRUST	14.221494	FOR L AND E LOSS	20.126531				
REV UNLOCK COL	1.417418	REV SIDE THRUST	14.221494				
REV UNLOCK FRICTION	3.714375	REV UNLOCK COL	1.417418				
REV L AND S LOSS	2.555369	REV UNLOCK FRICTION	3.714375				
		REV CATCHUP COL	6.766523				
		REV L AND E LOSS	24.590313				
TOTAL LOSSES	44.317688	TOTAL LOSSES	98.902229				

POSITION	BETA	RHO	EPSILON	PERIOD	BOOT
0	60.00000000E 00	47.24089500E 00	92.03066400E-01	51.08103800E-04	6.70030000E-39
1	42.57733000E 00	47.24089500E 00	92.03066400E-01	51.08103800E-04	-64.08140000E 02
2	17.01136400E 00	50.40200700E 00	95.16626100E-01	33.21844900E-04	-86.01122900E 02
3	-13.68530400E 00	55.56861800E 00	33.62532800E-01	34.91639500E-04	-80.81974200E 02
4	-40.70283200E 00	59.24938000E 00	14.77186700E-01	35.49991100E-04	-62.40391900E 02
5	-55.92675600E 00	59.44821800E 00	-27.99933300E-01	22.94301800E-04	-34.36156400E 02
6	-56.13790700E 00	59.44821800E 00	-27.99933300E-01	22.68295700E-04	00.00000000E-40
7	-42.57732500E 00	59.44821800E 00	-27.99933300E-01	44.73302200E-04	57.70889400E 02
8	-17.01136300E 00	56.08710700E 00	-31.15494000E-01	34.80721200E-04	84.50346400E 02
9	10.46819700E 00	51.63292600E 00	-80.42748100E-01	31.23462200E-04	89.25034900E 02
10	40.70283200E 00	47.43973400E 00	-94.77186400E-01	37.43960300E-04	68.40924300E 02
11	55.42903600E 00	47.24089500E 00	-14.79993300E 00	27.79252400E-04	35.85099900E 02
12	59.99999900E 00	47.24089500E 00	-14.79993300E 00	25.36448300E-04	05.00030300E-40

EQUILY ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	789.825378	TOTAL SYSTEM ENERGY BALANCE	789.825378
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	28.195160	FOR INPUT	83.642816
FOR IMPULSE	15.017349	REV INPUT	83.642816
REV CATCHUP COL	22.197739		
REV IMPULSE	11.386765		
TOTAL GAINS	76.797015	TOTAL GAINS	167.285631
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	22.525129	FOR SIDE THRUST	22.525129
FOR UNLOCK COL	4.336527	FOR UNLOCK COL	4.336527
FOR UNLOCK FRICTION	6.282584	FOR UNLOCK FRICTION	6.282584
FOR L AND E LOSS	6.233616	FOR CATCHUP COL	12.824271
REV SIDE THRUST	22.525129	FOR L AND E LOSS	35.846146
REV UNLOCK COL	3.447288	REV SIDE THRUST	22.525129
REV UNLOCK FRICTION	6.282584	REV UNLOCK COL	3.447288
REV L AND E LOSS	5.664134	REV UNLOCK FRICTION	6.282584
		REV CATCHUP COL	10.751319
		REV L AND E LOSS	42.764894
TOTAL LOSSES	76.796958	TOTAL LOSSES	167.285568

POSITION	BETA	RHO	EPSILON	PERIOD	BODY
0	79.0000000E 00	47.24089500E 00	92.00086600E-01	62.98325300E-04	3.00000000E-39
1	42.5773300E 03	47.24089500E 00	92.00086600E-01	62.98325300E-04	-93.8331700E 02
2	17.0112640E 03	50.62200700E 00	95.15626100E-01	24.76398500E-04	-15.9585700E 03
3	-12.16558300E 03	55.32789700E 00	36.31683600E-01	26.25330100E-04	-11.12919900E 03
4	-40.70283200E 00	59.24938000E 00	14.77186700E-01	27.53859800E-04	-94.02808700E 02
5	-58.96280200E 03	59.44821800E 00	-27.99933300E-01	17.00233500E-04	-72.76100400E 02
6	-71.19348300E 03	59.44821800E 00	-27.99933300E-01	40.84176700E-04	05.0000000E-43
7	-42.57732600E 03	59.44821800E 00	-27.99933300E-01	58.78274500E-04	89.7657200E 02
9	-17.01106300E 00	56.08710700E 00	-31.15494000E-01	25.31916900E-04	10.64314300E 03
9	91.56086100E-01	51.84443800E 00	-78.43559800E-01	23.52972800E-04	11.29147700E 03
10	40.70283200E 03	47.43973400E 00	-94.77186900E-01	29.55333900E-04	97.94757700E 02
11	58.8596100E 03	47.24089500E 00	-14.79993300E 00	21.03992400E-04	72.57390100E 02
12	7.99999800E 00	47.24089500E 00	-14.79993300E 00	42.95153200E-04	05.0000000E-43

EQUILY ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	1137.348541	TOTAL SYSTEM ENERGY BALANCE	1137.348541
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	41.714478	FOR INPUT	129.736367
FOR IMPULSE	24.244118	REV INPUT	129.736367
REV CATCHUP COL	32.795990		
REV IMPULSE	18.175929		
TOTAL GAINS	116.735514	TOTAL GAINS	251.472734
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	32.730511	FOR SIDE THRUST	32.730511
FOR UNLOCK COL	6.557186	FOR UNLOCK COL	6.557186
FOR UNLOCK FRICTION	9.444317	FOR UNLOCK FRICTION	9.444317
FOR L AND E LOSS	12.425596	FOR CATCHUP COL	18.478497
REV SIDE THRUST	32.730511	FOR L AND E LOSS	55.241392
REV UNLOCK COL	5.956632	REV SIDE THRUST	32.730511
REV UNLOCK FRICTION	9.444317	REV UNLOCK COL	5.956632
REV L AND E LOSS	9.341446	REV UNLOCK FRICTION	9.444317
		REV CATCHUP COL	15.675616
		REV L AND E LOSS	65.113344
TOTAL LOSSES	116.735515	TOTAL LOSSES	251.472719

POSITION	BETA	ZMO	EPSILON	PERIOD	BODY
0	90.00000000E 00	47.24089530E 00	92.00056400E-01	70.05220100E-04	0.00000000E-39
1	42.57733000E 00	47.24089530E 00	92.00056400E-01	19.94546400E-04	-12.07428400E 03
2	17.01106400E 00	50.60200700E 00	95.16826100E-01	21.15628700E-04	-13.29512500E 03
3	-11.38614000E 00	55.20335100E 00	97.71940000E-01	22.69450700E-04	-13.51275500E 03
4	-40.70283200E 00	59.24938000E 00	14.77106700E-01	13.64832400E-04	-12.21525700E 03
5	-60.25355200E 00	59.44921800E 00	-27.99933300E-01	51.63616200E-04	-13.46405500E 03
6	-86.26606800E 00	59.44921800E 00	-27.99933300E-01	66.82333900E-04	05.00000000E-40
7	-42.57732400E 00	59.44921800E 00	-27.99933300E-01	20.22136400E-04	11.77629900E 03
8	-17.01105300E 00	59.44921800E 00	-31.15494000E-01	18.94492200E-04	12.21366900E 03
9	65.00947300E-01	51.95052500E 00	-77.42516500E-01	24.45657400E-04	14.63590900E 03
10	40.70283200E 00	47.43973400E 00	-94.77106700E-01	17.04137300E-04	12.55380100E 03
11	60.25355200E 00	47.24089530E 00	-14.74903300E 00	53.48299800E-04	10.42208300E 03
12	89.99999800E 00	47.24089530E 00	-14.74903300E 00		00.00000000E-40

EQUITY ESCAPEMENT ENERGY BALANCE		TOTAL SYSTEM ENERGY BALANCE	
TOTAL ENERGY	2321.952942	TOTAL ENERGY	2321.952942
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	76.100705	FOR INPUT	233.541796
FOR IMPULSE	47.276168	REV INPUT	233.541796
REV CATCHUP COL	59.966779		
REV IMPULSE	35.216127		
TOTAL GAINS	210.947357	TOTAL GAINS	467.083591
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	58.846489	FOR SIDE THRUST	58.846489
FOR UNLOCK COL	13.327957	FOR UNLOCK COL	13.327957
FOR UNLOCK FRICTION	17.541804	FOR UNLOCK FRICTION	17.541804
FOR LAND E LOSS	21.727164	FOR CATCHUP COL	32.997221
REV SIDE THRUST	59.946489	FOR LAND E LOSS	104.967592
REV UNLOCK COL	12.513750	REV SIDE THRUST	58.846489
REV UNLOCK FRICTION	17.541804	REV UNLOCK COL	12.513750
REV LAND E LOSS	18.721954	REV UNLOCK FRICTION	17.541804
		REV CATCHUP COL	28.508152
		REV LAND E LOSS	122.292263
TOTAL LOSSES	210.947405	TOTAL LOSSES	467.083514

POSITION	META	RHO	EPSILON	PERIOD	BOOT
0	12.0000000E-01	47.24089300E-00	92.00066400E-01	78.27963700E-04	0.0000000E-39
1	42.5773300E-00	47.24089300E-00	92.00066400E-01	14.48386700E-04	-17.13329100E-03
2	17.01106400E-00	50.60200700E-00	95.15626100E-01	15.34088400E-04	-17.93817000E-03
3	-10.84431300E-00	25.58647300E-00	39.06362200E-01	15.34088400E-04	-18.22123400E-03
4	-40.70283200E-00	59.24938200E-00	14.77185700E-01	15.86097200E-04	-17.45850300E-03
5	-61.3572100E-00	59.44821800E-00	-27.99933300E-01	98.7747000E-05	-16.19482800E-03
6	-11.63459200E-01	59.44821800E-00	-27.99933300E-01	64.27435700E-04	00.0000000E-40
7	-42.57732600E-00	59.44821800E-00	-27.99933300E-01	78.27963700E-04	16.95187500E-03
8	-17.01106200E-00	26.08710700E-00	-31.15494000E-01	14.55689200E-04	17.9345600E-03
9	75.88431100E-01	52.54993400E-00	-76.47136400E-01	13.78533200E-04	18.30654400E-03
10	40.70283200E-00	47.24973400E-00	-94.77186900E-01	16.27276900E-05	17.6337000E-03
11	61.73087500E-00	47.24089300E-00	-14.79993300E-00	12.42748200E-04	16.64845500E-03
12	12.0000000E-01	47.24089300E-00	-14.79993300E-00	65.75444800E-04	00.0000000E-40

EQUITY ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	3159.301514	TOTAL SYSTEM ENERGY BALANCE	3159.301514
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	120.646362	FOR INPUT	372.797016
FOR IMPULSE	77.342492	REV INPUT	372.797016
REV CATCHUP COL	94.798309		
REV IMPULSE	58.112612		
TOTAL GAINS	350.95775	TOTAL GAINS	745.594032
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	92.569426	FOR SIDE THRUST	92.569426
FOR UNLOCK COL	21.434662	FOR UNLOCK COL	21.904662
FOR UNLOCK FRICTION	28.001549	FOR UNLOCK FRICTION	28.001549
FOR L AND S LOSS	36.385241	FOR CATCHUP COL	51.767733
REV SIDE THRUST	92.569426	FOR L AND S LOSS	159.260342
REV UNLOCK COL	20.748776	REV SIDE THRUST	92.569426
REV UNLOCK FRICTION	28.001549	REV UNLOCK COL	20.748776
REV L AND S LOSS	30.736892	REV UNLOCK FRICTION	28.001549
		REV CATCHUP COL	44.635725
		REV L AND S LOSS	196.045552
TOTAL LOSSES	350.957806	TOTAL LOSSES	745.594225

POSITION	BETA	RHO	EPSILON	PERIOD	BODY
0	15.0000000E 01	-7.2408950E 00	92.0006400E -01	92.9846370E -04	0.0000000E -39
1	42.5773300E 00	47.2408950E 00	92.0006400E -01	-22.0079140E 03	-22.0079140E 03
2	17.0110640E 00	50.6020070E 00	95.1562510E -01	11.4158230E -04	-22.5617600E 03
3	-10.3133370E 00	25.0312430E 00	39.6577180E -01	12.0764670E -04	-22.9028230E 03
4	-40.7028320E 00	59.2493600E 00	14.7718670E -01	13.4293440E -04	-22.2878630E 03
5	-61.8153660E 00	59.4482180E 00	-27.9993300E -01	77.7304770E -05	-21.4897190E 03
6	-14.6444970E 01	59.4482180E 00	-27.9993300E -01	71.5447350E -04	0.0000000E -40
7	-42.5773260E 00	59.4482180E 00	-27.9993300E -01	81.2342550E -04	21.6942500E 03
8	-17.0110630E 00	56.0871070E 00	-31.1649420E -01	11.4374090E -04	22.5003960E 03
9	76.1797160E -01	52.0939090E 00	-76.0727300E -01	10.8601770E -04	22.9688790E 03
10	40.7028320E 00	-7.4339730E 00	-94.7718630E -01	14.5315630E -04	22.5962470E 03
11	62.3175290E 00	-7.2408950E 00	-14.7999330E 00	98.1076420E -05	21.3784220E 03
12	15.0000000E 01	47.2408950E 00	-14.7999330E 00	72.7698890E -04	00.0000000E -40

EQUIV. ESCAPEMENT ENERGY BALANCE		TOTAL SYSTEM ENERGY BALANCE	
TOTAL ENERGY	6192.231018	TOTAL ENERGY	6192.231018
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	239.593445	FOR INPUT	745.600384
FOR IMPULSE	157.894873	REV INPUT	745.600384
REV CATCHUP COL	188.280884		
REV IMPULSE	118.582401		
TOTAL GAINS	704.351593	TOTAL GAINS	1491.212769
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	182.836170	FOR SIDE THRUST	187.836170
FOR UNLOCK COL	44.775876	FOR UNLOCK COL	44.775876
FOR UNLOCK FRICTION	56.324026	FOR UNLOCK FRICTION	56.324026
FOR L AND E LOSS	75.727230	FOR CATCHUP COL	102.033134
REV SIDE THRUST	182.836170	FOR L AND E LOSS	341.526733
REV UNLOCK COL	43.292523	REV SIDE THRUST	187.836170
REV UNLOCK FRICTION	56.324026	REV UNLOCK COL	43.292523
REV L AND E LOSS	62.830069	REV UNLOCK FRICTION	56.004026
		REV CATCHUP COL	89.351158
TOTAL LOSSES	704.351570	REV L AND E LOSS	303.552564
		TOTAL LOSSES	1491.212562

POSITION	BETA	RMO	EPSILON	PERIOD	ROOT
0	21.00000000 01	47.24089500 00	92.03066400 01	88.20766200 04	0.00000000 -39
1	42.57733000 00	47.24089500 00	92.03066400 01	80.45016100 05	-31.54453100 03
2	17.01106400 00	50.60200700 00	95.15626100 01	80.45016100 05	-31.78453100 03
3	-10.03092800 00	54.98584400 00	40.18391400 01	84.98477600 05	-32.24118000 03
4	-40.70283200 00	58.24380000 00	14.77186700 01	95.49918800 05	-37.30273700 03
5	-62.19208000 00	59.44821800 00	-27.99933300 01	54.70428500 05	-31.59814900 03
6	-20.66375900 01	59.44821800 00	-27.99933300 01	79.65086800 04	03.00000000 -43
7	-42.57732600 00	59.44821800 00	-27.99933300 01	86.94980700 05	31.51619400 03
8	-17.01106300 00	56.08710700 00	-31.54453100 01	86.34742600 05	31.63336500 03
9	73.89020700 01	52.13116800 00	-75.68688200 01	76.48348000 05	32.28931200 03
10	40.73283200 00	47.43973400 00	-94.77116900 01	13.34149500 05	32.28267000 03
11	62.80382600 00	47.24089500 00	-14.79993300 00	69.22377400 05	31.46369700 03
12	21.00000000 01	47.24089500 00	-14.79993300 00	80.55270100 04	00.00000000 -40

EQUIV ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	10236.136719	TOTAL SYSTEM ENERGY BALANCE	
ENERGY GAINS		TOTAL ENERGY	10236.136719
FOR CATCHUP COL	398.614380	ENERGY GAINS	
FOR IMPULSE	265.941529	FOR INPUT	1244.127029
REV CATCHUP COL	313.288066	REV INPUT	1244.127029
REV IMPULSE	199.381893		
TOTAL GAINS	1176.925853	TOTAL GAINS	2488.254059
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	303.530716	FOR SIDE THRUST	303.530716
FOR UNLOCK COL	75.270826	FOR UNLOCK COL	75.270826
FOR UNLOCK FRICTION	93.448935	FOR UNLOCK FRICTION	93.448935
FOR L AND E LOSS	128.587137	FOR CATCHUP COL	169.251083
REV SIDE THRUST	303.530716	FOR L AND E LOSS	572.027191
REV UNLOCK COL	73.467876	REV SIDE THRUST	303.530716
REV UNLOCK FRICTION	93.448935	REV UNLOCK COL	73.467876
REV L AND E LOSS	125.520955	REV UNLOCK FRICTION	93.448935
		REV CATCHUP COL	146.809212
		REV L AND E LOSS	657.468658
TOTAL LOSSES	1176.926067	TOTAL LOSSES	2488.254123

POSITION	BETA	RMO	EPSILON	PERIOD	BDOF
0	27.0000000E 01	47.2438930E 00	92.0306640E -01		0.0000000E -39
1	42.5773300E 00	47.2438930E 00	92.0306640E -01	91.0518850E -04	-40.9623680E 03
2	17.0112640E 00	50.6020070E 00	93.1682610E -01	62.1489920E -05	-40.9930560E 03
3	-99.1645650E -01	54.9674040E 00	40.3938350E -01	65.6725720E -05	-41.5675370E 03
4	-40.7028320E 00	59.2493830E 00	14.7718670E -01	74.1073640E -05	-41.9821510E 03
5	-62.3401220E 00	59.4482180E 00	-27.9993330E -01	42.2701570E -05	-41.4370660E 03
6	-26.6828140E 01	59.4482180E 00	-27.9993330E -01	84.0813010E -04	03.0000000E -40
7	-42.5773300E 00	59.4482180E 00	-27.9993330E -01	90.1170440E -04	40.9925960E 03
8	-17.0112640E 00	56.0871070E 00	-31.1547430E -01	62.0761520E -05	41.8625590E 03
9	72.9647160E -01	52.1462330E 00	-75.5468530E -01	59.1121410E -05	41.6069020E 03
10	40.7028320E 00	47.4397340E 00	-99.7718590E -01	80.2685310E -05	41.9468780E 03
11	62.9971620E 00	47.2438930E 00	-14.7999330E 00	53.5438840E -05	41.2784960E 03
12	26.9999900E 01	47.2438930E 00	-14.7999330E 00	84.7967530E -04	03.0000000E -40

EQUILY ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	15291.519287		TOTAL ENERGY	15291.519287	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	597.719116		FOR INPUT	1858.353134	
FOR IMPULSE	400.572636		REV INPUT	1868.353134	
REV CATCHUP COL	469.763916				
REV IMPULSE	300.564465				
TOTAL GAINS	1768.620117		TOTAL GAINS	3736.706268	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	454.653091		FOR SIDE THRUST	454.653091	
FOR UNLOCK COL	113.389316		FOR UNLOCK COL	113.389316	
FOR UNLOCK FRICTION	140.335838		FOR UNLOCK FRICTION	140.335838	
FOR L AND E LOSS	194.828789		FOR CATCHUP COL	253.417572	
REV SIDE THRUST	454.653091		FOR L AND E LOSS	860.759582	
REV UNLOCK COL	111.314846		REV SIDE THRUST	454.653091	
REV UNLOCK FRICTION	140.335838		REV UNLOCK COL	111.314846	
REV L AND E LOSS	159.109571		REV UNLOCK FRICTION	140.335838	
			REV CATCHUP COL	225.066668	
			REV L AND E LOSS	987.840370	
TOTAL LOSSES	1768.620529		TOTAL LOSSES	3736.706451	

POSITION	BETA	MD	EPSILON	PERIOD	BDOT
0	33.0000000E-01	47.24019500E-00	92.00066800E-01	92.84847630E-04	1.0000000E-39
1	42.5773300E-00	47.24089500E-00	92.03056400E-01	92.84847630E-04	-50.32815400E-03
2	17.01106400E-00	50.60200700E-00	95.16626100E-01	50.72348630E-05	-50.19518200E-03
3	-98.58772900E-01	54.95810900E-00	40.49972100E-01	53.53856300E-05	-50.88940900E-03
4	-40.70283200E-00	59.24938000E-00	14.77186700E-01	60.54783500E-05	-51.60239200E-03
5	-62.61359200E-00	59.44921800E-00	-27.99933300E-01	34.46156300E-05	-51.15774300E-03
6	-32.73174000E-01	59.44821800E-00	-27.99933300E-01	86.07857500E-05	00.0000000E-40
7	-42.57732600E-00	59.44821800E-00	-27.99933300E-01	92.08438600E-04	50.44822800E-03
8	-17.01106300E-00	56.08710700E-00	-31.16494300E-01	50.61454300E-05	50.32109400E-03
9	72.69910800E-01	52.15382200E-00	-75.46730900E-01	48.19693200E-05	50.92433500E-03
10	40.75283200E-00	47.63973400E-00	-94.77186900E-01	65.58841800E-05	51.51899000E-03
11	63.09340000E-00	47.24089500E-00	-14.79993300E-00	43.67471800E-05	50.97333300E-03
12	32.99999900E-01	47.24089500E-00	-14.79993300E-00	87.46236900E-04	00.0000000E-40

AMPLITUDE	APPLIED TORQUE DYNE-CM	PERIOD SEC	BEAT RATE BEATS/SEC	BEAT RATE ERROR PERCENT (REL.)
62.03000 JOE 00	23.6111700E 01	40.17182330E-03	49.78614300E 00	-36.45537800E-02
74.03200 JOE 00	39.93650210E 01	40.05370700E-03	49.93295700E 00	-70.7349800E-03
90.03200 JOE 00	60.01469200E 01	40.01220800E-03	49.98474500E 00	32.90641300E-03
12.03200 JOE 01	11.15279800E 02	39.98924230E-03	50.01342800E 00	90.30917500E-03
15.03000 JOE 01	7.79974600E 02	39.98591000E-03	50.01636800E 00	96.19326100E-03
21.03000 JOE 01	35.6000000E 02	39.99174300E-03	50.01612300E 00	84.0940900E-03
27.03000 JOE 01	59.42264900E 02	39.99399430E-03	50.00375700E 00	70.95639130E-03
33.03000 JOE 01	89.23729000E 02	40.00104300E-03	49.99870300E 00	60.83530500E-03

CLOCK GEOMETRY

ACTUAL RPP RE RP R1 R2 L Q OMEGA
0.0061200 0.1685000 0.1603011 0.1040000 0.2019000 0.0301047 0.1546644 57.2000656

EFFECTIVE 0.0061200 0.1740000 0.1603011 0.1040000 0.2080000 0.0301047 0.1546644 57.2000656

GAMMA SPAN TEETH S P A B U/R1 PHI
59.99999992 3.00000000 15.00000000 0.23780000104.68911362 0.12860000 0.04370000 7.06349999 41.99999905

PARAMETERS

21.0000153 L IL IE MU U/R1 A1 A2
0.02680000 0.01340000 0.30000000 0.05243811 12.000000 16.000000

CONDITIONS

ERR REL RELM NO WMAX WMAX2 IPARAM ICOND IWRITE BSYN A3
1.0E-05 5.0E-03 1.0E-06 11 50 20 1000 0 1 0 3.20000000E 00 -40.000000

EVALUATION ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	505.408235		TOTAL ENERGY	505.408235	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	16.233402		FOR INPUT	47.070423	
FOR IMPULSE	7.296424		REV INPUT	47.070423	
REV CATCHUP COL	12.948036				
REV IMPULSE	5.221134				
TOTAL GAINS	42.579166		TOTAL GAINS	94.140846	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	13.565421		FOR SIDE THRUST	13.665421	
FOR UNLOCK COL	1.892350		FOR UNLOCK COL	1.892350	
FOR UNLOCK FRICTION	3.535556		FOR UNLOCK FRICTION	3.535556	
FOR L AND E LOSS	1.291626		FOR CATCHUP COL	8.004958	
REV SIDE THRUST	13.565421		FOR L AND E LOSS	18.768760	
REV UNLOCK COL	1.137898		REV SIDE THRUST	13.665421	
REV UNLOCK FRICTION	3.535556		REV UNLOCK COL	1.137898	
REV L AND E LOSS	2.655369		REV UNLOCK FRICTION	3.535556	
			REV CATCHUP COL	6.400923	
TOTAL LOSSES	42.579176		REV L AND E LOSS	23.536029	
			TOTAL LOSSES	94.140852	

POSITION	BETA	RHO	EPSILON	PERIOD	BOOT
0	60.00000000	00	47.24089500	00	92.03066400E-01
1	42.57732000	00	47.24089500	00	92.00066400E-01
2	17.01106400	00	50.60200700	00	95.16626100E-01
3	-13.82875500	00	55.59123600	00	33.37367500E-01
4	-40.70283200	00	59.24930000	00	14.77186700E-01
5	-57.36617500	00	59.44821800	00	-27.99933300E-01
6	-53.73528700	00	59.44821800	00	-27.99933300E-01
7	-42.57732600	00	56.08710700	00	-31.16494000E-01
8	-17.01106300	00	51.62596900	00	-83.49248000E-01
9	10.51189300	00	47.43973400	00	-94.77186900E-01
10	40.70283200	00	47.24089500	00	-14.79993300E-00
11	55.54542000	00	47.24089500	00	28.43190300E-00
12	59.99999900	00	47.24089500	00	25.32825800E-00

FUJIV ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	789.825378		TOTAL ENERGY	789.825378	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	27.143417		FOR INPUT	80.617341	
FOR IMPULSE	14.380539		REV INPUT	80.617341	
REV CATCHUP COL	21.467655				
REV IMPULSE	10.973980				
TOTAL GAINS	73.965590		TOTAL GAINS	161.234081	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	21.816526		FOR SIDE THRUST	21.816526	
FOR UNLOCK COL	4.035527		FOR UNLOCK COL	4.035527	
FOR UNLOCK FRICTION	6.055311		FOR UNLOCK FRICTION	6.055311	
FOR L AND E LOSS	5.410180		FOR CATCHUP COL	12.483695	
REV SIDE THRUST	21.816526		FOR L AND E LOSS	34.146243	
REV UNLOCK COL	3.091090		REV SIDE THRUST	21.816526	
REV UNLOCK FRICTION	6.055311		REV UNLOCK COL	3.091090	
REV L AND E LOSS	5.564104		REV UNLOCK FRICTION	6.055311	
			REV CATCHUP COL	10.310253	
			REV L AND E LOSS	41.422774	
TOTAL LOSSES	73.965573		TOTAL LOSSES	161.234055	

POSITION	BETA	RHO	EPSILON	PERIOD	BOOT
0	75.0000000E 00	47.24089500E 00	92.00066400E-01	63.55463500E-04	0.0000000E-39
1	42.57733000E 00	47.24089500E 00	92.00066400E-01	25.06530600E-04	-92.83648200E 02
2	17.01106400E 00	50.60200700E 00	95.16626100E-01	26.77357400E-04	-11.80838300E 03
3	-12.24448700E 00	55.24029800E 00	36.17757300E-01	28.28590300E-04	-13.89586700E 03
4	-40.70283200E 00	59.24938000E 00	14.77180700E-01	17.42282600E-04	-93.24540300E 02
5	-60.97121800E 00	59.44821800E 00	-27.99933300E-01	37.29241600E-04	-67.94467100E 02
6	-68.79034700E 00	59.44821800E 00	-27.99933300E-01	56.58098400E-04	05.0000000E-43
7	-42.57732000E 00	59.44821800E 00	-27.99933300E-01	26.11612700E-04	85.91278100E 02
8	-17.01106300E 00	56.08710700E 00	-31.16476000E-01	23.96755500E-04	13.40050600E 03
9	91.56922700E-01	51.84430200E 00	-78.43689100E-01	29.92769300E-04	11.12265400E 03
10	40.70283200E 00	47.43973400E 00	-94.77185900E-01	21.43215500E-04	96.90071700E 02
11	58.92001700E 00	47.24089500E 00	-14.79993300E 00	43.17518200E-04	71.69928800E 02
12	74.99999900E 00	47.24089500E 00	-14.79993300E 00		05.0000000E-43

EQUIV ESCAPEMENT ENERGY BALANCE		TOTAL SYSTEM ENERGY BALANCE	
TOTAL ENERGY	1137.348541	TOTAL ENERGY	1137.348541
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	49.470139	FOR INPUT	122.067507
FOR IMPULSE	23.254123	REV INPUT	122.067507
REV CATCHUP COL	31.883835		
REV IMPULSE	17.555223		
TOTAL GAINS	113.266619	TOTAL GAINS	244.135014
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	31.869386	FOR SIDE THRUST	31.869386
FOR UNLOCK COL	6.57186	FOR UNLOCK COL	6.57186
FOR UNLOCK FRICTION	9.158741	FOR UNLOCK FRICTION	9.168741
FOR L AND E LOSS	9.567972	FOR CATCHUP COL	18.055266
REV SIDE THRUST	31.869386	FOR L AND E LOSS	53.176286
REV UNLOCK COL	5.523766	REV SIDE THRUST	31.869386
REV UNLOCK FRICTION	9.169741	REV UNLOCK COL	5.523766
REV L AND E LOSS	9.341446	REV UNLOCK FRICTION	9.168741
		REV CATCHUP COL	15.160470
		REV L AND E LOSS	63.495977
TOTAL LOSSES	113.266619	TOTAL LOSSES	244.134798

POSITION	BETA	RHO	EPSILON	PERIOD	BODY
0	90.0000000E-03	47.24089500E-03	92.00064600E-01	70.58986300E-04	5.0000000E-39
1	42.5773300E-03	47.24089500E-03	92.00064600E-01	20.15637300E-04	-11.96106500E-03
2	17.01106400E-03	50.6020700E-03	95.16627100E-01	21.48810700E-04	-13.13950200E-03
3	-11.43431600E-03	55.21105300E-03	37.63212500E-01	23.14243200E-04	-13.29133800E-03
4	-40.70283200E-03	59.24938000E-03	14.7718700E-01	13.89968100E-04	-11.88839800E-03
5	-62.43770100E-03	59.44821800E-03	-27.99933300E-01	48.74386100E-04	-10.08771400E-03
6	-83.84256800E-03	59.44821800E-03	-27.99933300E-01	65.26759800E-04	0.0000000E-43
7	-42.57732600E-03	59.44821800E-03	-27.99933300E-01	20.65258900E-04	11.44748200E-03
8	-17.01106300E-03	56.04710700E-03	-31.15494300E-01	19.26546400E-04	17.98255400E-03
9	84.92632900E-01	51.95185700E-03	-77.41243600E-01	24.73117800E-04	13.46284200E-03
10	40.70283200E-03	47.43973400E-03	-94.77185900E-01	17.27855200E-04	12.78552200E-03
11	60.44637900E-03	47.24089500E-03	-14.70993300E-01	53.78948100E-04	16.32460700E-03
12	89.99999800E-03	47.24089500E-03	-14.79993300E-01		0.0000000E-43

EQUIV ESCAPEMENT ENERGY BALANCE		TOTAL SYSTEM ENERGY BALANCE	
TOTAL ENERGY	2021.952942	TOTAL ENERGY	2021.952942
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	74.548996	FOR INPUT	228.588223
FOR IMPULSE	46.190254	REV INPUT	228.588223
REV CATCHUP COL	58.532986		
REV IMPULSE	34.386567		
TOTAL GAINS	214.258812	TOTAL GAINS	457.176445
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	57.582341	FOR SIDE THRUST	57.680341
FOR UNLOCK COL	13.327957	FOR UNLOCK COL	13.327957
FOR UNLOCK FRICTION	17.169731	FOR UNLOCK FRICTION	17.169731
FOR L AND E LOSS	20.721175	FOR CATCHUP COL	32.44181
REV SIDE THRUST	57.582341	FOR L AND E LOSS	152.176115
REV UNLOCK COL	11.527555	REV SIDE THRUST	57.680341
REV UNLOCK FRICTION	17.169731	REV UNLOCK COL	11.827555
REV L AND E LOSS	18.701954	REV UNLOCK FRICTION	17.169731
		REV CATCHUP COL	27.645396
		REV L AND E LOSS	120.095246
TOTAL LOSSES	214.258776	TOTAL LOSSES	457.176384

POSITION	BETA	RHO	EPSILON	PERIOD	BOOT
0	12.0000000E 01	47.2408950E 00	92.0305640E-01	78.7397460E-04	0.0000000E-39
1	42.5773300E 00	47.2408950E 00	92.0305640E-01	14.6046730E-04	-17.0031440E 03
2	17.0110640E 00	50.6020070E 00	95.1662610E-01	15.5123430E-04	-17.7756850E 03
3	-10.6683000E 00	55.0883250E 00	39.0199690E-01	15.5123430E-04	-16.1129300E 03
4	-40.7528320E 00	59.2493800E 00	14.7718670E-01	17.0799450E-04	-17.1786330E 03
5	-63.6617670E 00	59.4482180E 00	-27.9993330E-01	99.9994620E-05	-15.8703340E 03
6	-11.3942930E 01	59.4482180E 00	-27.9993330E-01	62.1450070E-04	06.0000000E-47
7	-42.5773260E 00	59.4482180E 00	-27.9993330E-01	75.0425960E-04	16.6731710E 03
8	-17.0110630E 00	56.0871070E 00	-31.1649420E-01	16.7542670E-04	17.0854970E 03
9	78.7974600E-01	52.0513450E 00	-76.4577670E-01	13.9323120E-04	16.1285600E 03
10	40.7528320E 00	47.5397360E 00	-94.7718690E-01	18.3903890E-04	17.4987500E 03
11	61.7991460E 00	47.2408950E 00	-14.7999330E 00	12.5544900E-04	15.9843210E 03
12	12.0000000E 01	47.2408950E 00	-14.7999330E 00	66.0892440E-04	05.0000000E-43

EQUIV ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	3159.301514	TOTAL SYSTEM ENERGY BALANCE	3159.301514
ENERGY GAINS		ENERGY GAINS	
FOR CATCHUP COL	118.506567	FOR INPUT	366.559151
FOR IMPULSE	75.965338	REV INPUT	366.559151
REV CATCHUP COL	93.245392		
REV IMPULSE	57.227259		
TOTAL GAINS	345.344552	TOTAL GAINS	733.118301
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	91.098266	FOR SIDE THRUST	91.098266
FOR UNLOCK COL	21.904662	FOR UNLOCK COL	21.904662
FOR UNLOCK FRICTION	27.533010	FOR UNLOCK FRICTION	27.533010
FOR L AND E LOSS	35.291201	FOR CATCHUP COL	51.005602
REV SIDE THRUST	91.098266	FOR L AND E LOSS	155.742659
REV UNLOCK COL	20.349253	REV SIDE THRUST	91.098266
REV UNLOCK FRICTION	27.533010	REV UNLOCK COL	20.049253
REV L AND E LOSS	30.735892	REV UNLOCK FRICTION	27.533010
		REV CATCHUP COL	63.824865
TOTAL LOSSES	345.344548	REV L AND E LOSS	193.328669
		TOTAL LOSSES	733.118248

POSITION	BETA	ALPHA	EPSILON	PERIOD	BODY
0	15.00000000E 01	47.24089500E 00	92.00066400E-01	83.38023500E-04	0.00000000E-39
1	42.57733000E 00	47.24089500E 00	92.00066400E-01	83.38023500E-04	-21.6742000E 03
2	17.01106400E 00	52.60200700E 00	95.16826100E-01	11.49471100E-04	-22.3951000E 03
3	-12.32791500E 00	55.03363000E 00	39.6454300E-01	12.18177200E-04	-22.69854900E 03
4	-40.70283200E 00	59.24238000E 00	14.77186700E-01	13.55934500E-04	-22.2304800E 03
5	-64.16278500E 00	59.44821800E 00	-27.99933300E-01	78.46147600E-05	-21.19987100E 03
6	-14.40476800E 00	59.44821800E 00	-27.99933300E-01	69.86332900E-04	0.00000000E-43
7	-42.57732600E 00	59.44821800E 00	-27.99933300E-01	80.51939100E-04	21.63912500E 03
8	-17.01106300E 00	56.08710700E 00	-31.15494300E-01	11.55732700E-04	22.34976400E 03
9	76.111728300E-01	52.09492400E 00	-76.03745500E-01	10.95099500E-04	22.78924000E 03
10	40.70283200E 00	47.43973400E 00	-94.77186900E-01	14.63874800E-04	22.4506800E 03
11	62.35874400E 00	47.24089500E 00	-14.79993300E 00	98.90277300E-05	21.25229300E 03
12	15.00000000E 01	47.24089500E 00	-14.79993300E 00	73.08553500E-04	0.00000000E-43

EQUIV ESCAPEMENT ENERGY BALANCE			TOTAL SYSTEM ENERGY BALANCE		
TOTAL ENERGY	6192.231018		TOTAL ENERGY	6192.231018	
ENERGY GAINS			ENERGY GAINS		
FOR CATCHUP COL	236.749573		FOR INPUT	736.800148	
FOR IMPULSE	155.939180		REV INPUT	736.800148	
REV CATCHUP COL	186.090698				
REV IMPULSE	117.209275				
TOTAL GAINS	695.989021		TOTAL GAINS	1473.600266	
ENERGY LOSSES			ENERGY LOSSES		
FOR SIDE THRUST	180.754997		FOR SIDE THRUST	180.754997	
FOR UNLOCK COL	44.775876		FOR UNLOCK COL	44.775876	
FOR UNLOCK FRICTION	55.342572		FOR UNLOCK FRICTION	55.342572	
FOR L AND E LOSS	73.941894		FOR CATCHUP COL	100.932930	
REV SIDE THRUST	180.754997		FOR L AND E LOSS	336.566919	
REV UNLOCK COL	42.246367		REV SIDE THRUST	180.754997	
REV UNLOCK FRICTION	55.342572		REV UNLOCK COL	42.246367	
REV L AND E LOSS	62.830063		REV UNLOCK FRICTION	55.342572	
			REV CATCHUP COL	87.246357	
			REV L AND E LOSS	389.646751	
TOTAL LOSSES	595.989120		TOTAL LOSSES	1473.600311	

POSITION	BETA	RMJ	EPSILON	PERIOD	BDOT
0	21.0000000E 01	47.24089500E 00	92.0066400E 01	88.51314000E 04	5.0000000E 39
1	42.5773300E 00	47.24089500E 00	92.0066400E 01	80.86326700E 05	-31.59188100E 03
2	17.01106400E 00	50.60200700E 00	95.16626100E 01	80.86326700E 05	-31.61306500E 03
3	-10.03900100E 00	54.98714400E 00	42.15912300E 01	85.51289500E 05	-32.54263200E 03
4	-40.70283200E 00	59.24438000E 00	14.77186700E 01	96.11836300E 05	-32.06752500E 03
5	-64.56836500E 00	59.44821800E 00	-27.99933300E 01	55.05317500E 05	-31.34206100E 03
6	-20.42324100E 01	59.44821800E 00	-27.99933300E 01	78.47336400E 04	00.0000000E 00
7	-42.57732600E 00	59.44821800E 00	-27.99933300E 01	86.52788700E 04	31.28399300E 03
8	-17.21112600E 00	56.08710700E 00	-31.16494300E 01	80.94972000E 05	31.62065600E 03
9	78.86152400E 01	52.13163500E 00	-75.68236600E 01	76.93528500E 05	32.10715100E 03
10	40.70283200E 00	-7.43973400E 00	-94.77186900E 01	17.39673200E 06	32.16857200E 03
11	62.82699300E 00	47.24089500E 00	-14.79993300E 00	69.62255500E 05	31.32175200E 03
12	21.0000000E 01	47.24089500E 00	-14.79993300E 00	80.81615900E 04	00.0000000E 40

EVLIV ESCAPEMENT ENERGY BALANCE				TOTAL SYSTEM ENERGY BALANCE			
TOTAL ENERGY				10236.136719			
ENERGY GAINS				ENERGY GAINS			
FOR CATCHUP COL				396.966966			
FOR IMPULSE				263.159001			
REV CATCHUP COL				310.461528			
REV IMPULSE				107.579012			
TOTAL GAINS				1166.394498			
ENERGY LOSSES				TOTAL GAINS			
FOR SIDE THRUST				300.839550			
FOR UNLOCK COL				75.270826			
FOR UNLOCK FRICTION				92.596634			
FOR L AND E LOSS				126.219426			
REV SIDE THRUST				300.839550			
REV UNLOCK COL				72.115091			
REV UNLOCK FRICTION				92.596634			
REV L AND E LOSS				105.523955			
TOTAL LOSSES				1166.394589			
TOTAL LOSSES				TOTAL LOSSES			
				2465.505829			

POSITION	BETA	RND	EPSILON	PERIOD	BODY
0	27.00300000E-01	47.24089500E-00	92.03066400E-01	91.30161500E-04	0.00000000E-39
1	42.57733000E-00	47.24089500E-00	92.03066400E-01	62.45310200E-05	-40.60276300E-03
2	17.01106400E-00	50.60200700E-00	95.10626100E-01	62.45310200E-05	-40.81892000E-03
3	-99.21967000E-01	54.96829200E-00	40.38371400E-01	65.98093800E-05	-41.57201800E-03
4	-40.70283200E-00	59.24938300E-00	14.77185700E-01	74.46759200E-05	-41.75798400E-03
5	-64.72599600E-00	59.44821800E-00	-27.99933300E-01	42.47663300E-05	-41.19757300E-03
6	-26.44232600E-01	59.44821800E-00	-27.99933300E-01	83.17829100E-04	00.00000000E-40
7	-42.57732600E-00	59.44821800E-00	-27.99933300E-01	89.77650400E-04	40.77198200E-03
8	-17.01106300E-00	56.008716700E-00	-31.15494200E-01	62.41374100E-05	40.68406500E-03
9	72.95236300E-01	52.14643900E-00	-75.53891500E-01	59.38291300E-05	41.42391500E-03
10	40.70283200E-00	47.43073400E-00	-94.77186900E-01	80.60559400E-05	41.78209900E-03
11	63.01275200E-00	47.24089500E-00	-14.79993300E-00	53.78366500E-05	41.12694900E-03
12	26.99999900E-01	47.24089500E-00	-14.79993300E-00	85.01253200E-04	00.00000000E-40

ENVIV ESCAPEMENT ENERGY BALANCE			
TOTAL ENERGY	15291.019287	TOTAL SYSTEM ENERGY BALANCE	
ENERGY GAINS		TOTAL ENERGY	15291.019287
FOR CATCHUP COL	593.263062	ENERGY GAINS	
FOR IMPULSE	397.664146	FOR INPUT	1856.411102
REV CATCHUP COL	456.303781	REV INPUT	1856.411102
REV IMPULSE	298.331753		
TOTAL GAINS	1755.359726	TOTAL GAINS	3708.822205
ENERGY LOSSES		ENERGY LOSSES	
FOR SIDE THRUST	451.351917	FOR SIDE THRUST	451.351917
FOR UNLOCK COL	113.389516	FOR UNLOCK COL	113.389516
FOR UNLOCK FRICTION	139.288626	FOR UNLOCK FRICTION	139.288626
FOR L AND E LOSS	191.924387	FOR CATCHUP COL	251.641517
REV SIDE THRUST	451.351917	FOR L AND E LOSS	652.985971
REV UNLOCK COL	109.555425	REV SIDE THRUST	451.351917
REV UNLOCK FRICTION	139.288626	REV UNLOCK COL	109.555425
REV L AND E LOSS	159.109571	REV UNLOCK FRICTION	139.288626
		REV CATCHUP COL	218.312439
		REV L AND E LOSS	941.656219
TOTAL LOSSES	1755.359940	TOTAL LOSSES	3708.822235

POSITION	BETA	RHO	EPSILON	PERIOD	BOOT
0	33.00000000E 01	47.24089500E 00	92.00066400E-01	93.05653400E-04	5.00000000E-39
1	42.57733000E 00	47.24089500E 00	92.00066400E-01	50.89555300E-05	-50.16472900E 03
2	17.01106400E 00	56.62007000E 00	95.15626100E-01	50.89555300E-05	-50.01428800E 03
3	-98.62978500E-01	56.95478600E 00	40.49199800E-01	53.74326100E-05	-50.69557900E 03
4	-40.70283200E 00	59.24938000E 00	14.77186700E-01	60.78329300E-05	-51.38496700E 03
5	-64.80533000E 00	59.44421800E 00	-27.99933300E-01	54.59596700E-05	-50.92811900E 03
6	-32.46127700E 01	59.44421800E 00	-27.99933300E-01	86.14736200E-04	00.00000000E-00
7	-42.57733000E 00	59.44421800E 00	-27.99933300E-01	91.81693500E-04	50.19214000E 03
8	-17.01106400E 00	56.62007000E 00	-31.15494300E-01	50.82071200E-05	50.12521700E 03
9	72.49499700E-01	52.15388800E 00	-75.45665100E-01	48.37761300E-05	50.74035900E 03
10	-2.73283200E 00	47.43073400E 00	-94.77186900E-01	65.81531100E-05	51.54989700E 03
11	63.10382700E 00	47.24089500E 00	-14.79993300E 00	43.83442000E-05	50.81554300E 03
12	32.99999900E 01	47.24089500E 00	-14.79993300E 00	87.65248100E-04	00.00000000E-00

AMPLITUDE	APPLIED TORQUE, DYNE-CM	PERIOD SEC	BEAT RATE BEATS/SEC	BEAT RATE ERROR PERCENT(REL.)
60.0300000E 00	22.4747100E 01	40.13528700E-03	49.83146100E 00	-46.38941300E-02
75.0300000E 00	39.49180100E 01	39.95401700E-03	50.0575400E 00	-12.30388900E-03
90.0300000E 00	58.28294100E 01	39.90053500E-03	50.12464100E 00	12.17197300E-02
12.0300000E 01	10.91928400E 02	39.88542200E-03	50.14359500E 00	15.95790300E-02
15.0300000E 01	17.50191000E 02	39.89584300E-03	50.12928300E 00	13.04934800E-02
21.0300000E 01	35.17961500E 02	39.92328000E-03	50.0968400E 00	64.67780300E-03
27.0300000E 01	58.85961700E 02	39.94231600E-03	50.07195800E 00	16.48739600E-03
37.0300000E 01	88.54160800E 02	39.95599100E-03	50.05527100E 00	-17.24335300E-03

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This report presents a continuation of the first detailed mathematical analysis made on a detached-lever escapement timing device. The model studied was based on the T5E1 pin-lever escapement, designed primarily for ordnance applications. Although good quantitative results evolved from the original study, subsequent work suggested that the model was not capable of simulating certain characteristics of the detached-lever escapement. For example, this type escapement often had a torque sensitivity characteristic (frequency vs driving torque) that was concave upward. Further mathematical analysis has resulted in minor but apparently significant changes to the original model, indicating the feasibility of predicting the performance of an escapement more accurately. Also, this analysis—though probably incomplete—now indicates that certain basic characteristics of timers can be changed without changing the basic mechanism.		

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