ANALYTICAL STUDY OF RECOIL SYSTEMS AND THEIR DESIGN

by

J. P. Sirpal

Institute of Armament Studies, Kirkee

ABSTRACT

A critical study of the various design parameters usually employed in the design of a recoil system has been made for some of the typical existing designs and it has been found that the order of magnitudes of some of these parameters are fairly different from those theoretically suggested. An explanation of this difference is also offered.

A few additional parameters that are necessary for a preliminary design have also been studied. Based on this some considerations regarding a new design have been suggested.

Introduction

A theoretical analysis of the recoil systems of QF 25 pr QF 3·7″ How, QF 6 pr 7 cwt A/TK and BL 5·5″ Gun/How has been done to assess the design loads and their variation for buffer, recuperator and control systems, retard valve force, factors of stability during firing and runout etc. with a view to generalising where possible such parameters that govern the design of a conventional type of a recoil system.

Since a gun which is stable at zero elevation, is stable for all positive angles of elevation, the analysis in each case was done for zero elevation of the gun when firing the highest charge. The total retarding force during recoil (Trunnion pull) is composed of frictional, recuperator and buffer forces and the method of analysis, therefore, was the estimation of each of these forces for various distances of recoil.

The frictional force was assessed by assuming a high co-efficient of friction (0·2) between the recoiling mass and the cradle as is likely to occur during actual service conditions. The gland friction, however, was estimated by actually pulling back the guns by a lever arrangement. The total frictional force was assumed to remain constant throughout the length of recoil and run out.

Forces during recoil

The variation of the recuperator force over the distance of recoil was calculated by knowing the initial air pressure and the actual dimensions of the hydropneumatic cylinders or the spring and its constants. In the case of hydropneumatic recuperators, the compression was assumed *adiabatic* with $\gamma = 1{\cdot}22$. The variation of recuperator and frictional force $(S+F)$ was therefore known as a function of distance of recoil (X).

The buffer force (B) which arises due to the flow of oil across the ports in the buffer cylinder can be shown to be equal to $\frac{\rho \Omega^3 V_r^2}{2gk^2\omega^2}$ where V_r is the actual velocity of reoil, Ω the cross sectional area of the buffer cylinder on the high pressure side, w the port area, k the discharge coefficient and ρ the specific weight of the buffer oil. It therefore follows that for the evaluation of B, variation of w and V_r with distance of recoil should be known. The first was obtained from the drawings and the latter was calculated from the relation :

$$V^2{}_r = V^2{}_f - \frac{2g}{w_r} \int (B + S + F)\, dx.$$

where V_f represents the velocity of free horizontal recoil at any instant and w_r the weight of the recoiling masses. This relation is not quite true during the period of gas action because gas thrust is a function of time whereas the retarding force is a function of displacement. However, the above relation in actual practice gives results which are very close to the actual ones because the retarding force is very small in comparison to gas thrust and therefore, the actual distance of recoil upto the end of gas action can be regarded as the same as in the case of free recoil.

By putting $V^2{}_r = y$ and differentiating, the above equation can be rewritten as :

$$\frac{dy}{dx} + \frac{\rho \Omega^3}{W_r k^2} \cdot \frac{y}{\omega^2} = \frac{d}{dx}(V_f)^2 - \frac{2g}{W_r}(S+F)$$

the solution of which is :

$$y e^{\int_0^{X_1} \frac{\beta}{\omega^2} dt} = \int_0^{X_1} 2V_f \frac{d}{dx}(V_f)\, e^{\int_0^{\omega_1} \frac{\beta}{\omega^2} dt} \cdot du \; - \delta \int_0^{X_1} (S+F)\, e^{\int_0^{\omega_1} \frac{\beta}{\omega^2} dt} du$$

upto the end of gas action when distance recoiled is X_1 *i.e.*

$$O < X < X_1$$

and

$$Y e^{\int_{X_1}^{X} \frac{\beta}{\omega^2} dt} = -\delta \int_{X_1}^{X} (S+F)\, e^{\int_{\omega_1}^{\omega} \frac{\beta}{w^2} dt} du + (Y)_{X_1}$$

for $X \geqslant X_1$

β and δ being constants and equal to $\frac{\rho \Omega^3}{W_r k^2}$ and $\frac{2g}{W_r}$ respectively.

The solution for velocity of retarded recoil was done by numerical integration and the buffer force calculated therefrom.

The evaluation of $\frac{d}{dx}(V_f)$ was done by first calculating various points on the $V_f - X$ curve and then approximating the curve so obtained by straight lines over small intervals of X. The various points on the $V_f - X$ curve were calculated with the help of the following equations—

$$V = f(x) \qquad (1)$$

$$V_r = \left(\frac{w + c/2}{W_r + c/2}\right) v \qquad (2)$$

$$X = \left(\frac{w + c/2}{W_r + m + c}\right) x \qquad (3)$$

$$(V_r)_{max} = \left(\frac{w + Kc}{W_r + c/2}\right) v_{max} \qquad (4)$$

and $$X_1 = \left(\frac{w + c/2}{W_r + w + c}\right) l + \frac{v_{max}\,\tau_4}{W}\left[w + \left(\frac{2K}{3} + \frac{1}{6}\right) c\right] \qquad (5)$$

in usual notation.

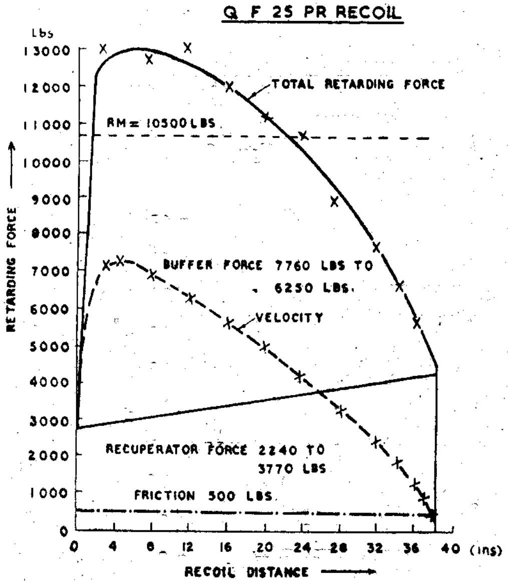

FIG 1

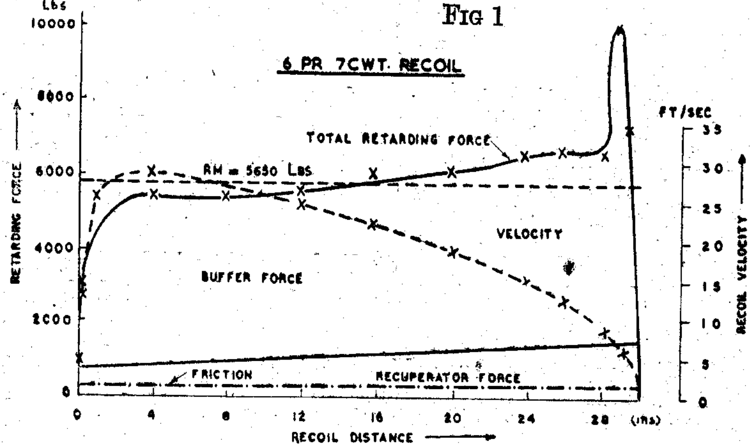

FIG. 2

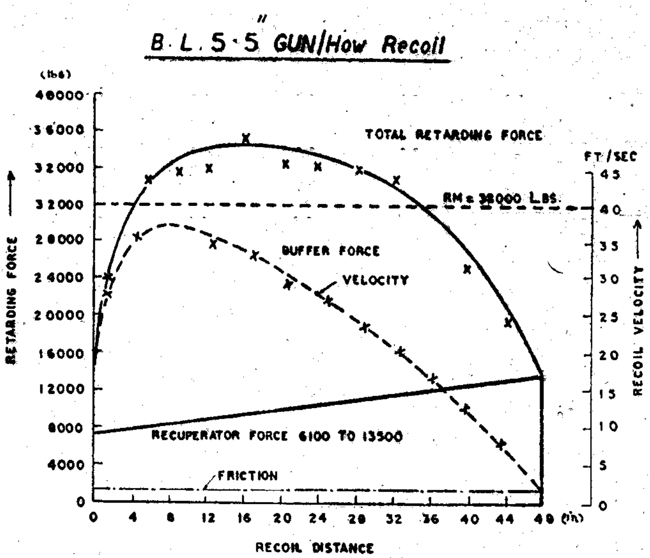

FIG. 3

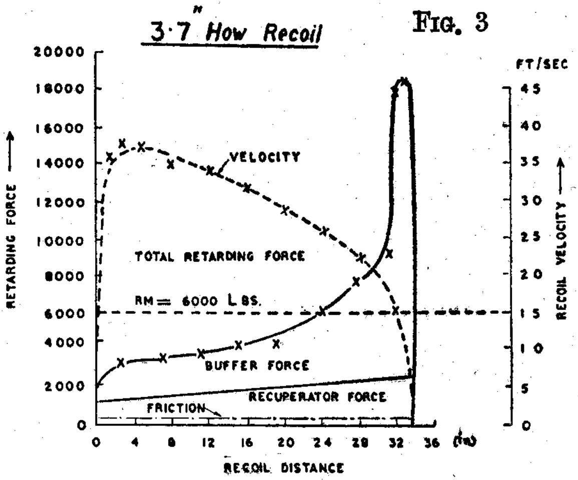

FIG. 4.

The first equation gives the relation between the velocity of the projectile (v) and its travel (x) within the barrel, and was solved by the Heydenreich method taking PLP as peak pressures for the solution. The other equations can be derived from the conservation of momentum equation and are well understood[1].

A mean value of the coefficient of discharge (k) which was assumed to remain constant throughout recoil and run out was taken as under[2]—

(*a*) For taper rods as in control systems or in buffer system of QF 6 pr 7 cwt and round holes as in retard valves ..	0·800
(*b*) For 3·7" How and 25 pr Buffer ports	0·746
(*c*) For B.L. 5·5" Gun/How Buffer Ports	0·685

Other dimensions of the component parts were taken from the relevant drawings for these calculations.

Curves in (Figs 1 to 4) on pages 217 and 218 show variation of buffer, recuperator, total retarding force and velocity of recoil with distance of recoil. From these other parameters as given in table I have been calculated.

Forces during run out

The analysis of the forces during run out was done for zero elevation of the equipment with runout adjusting valve fully closed and taking the same value of frictional force as before.

Three stage runout was assumed :

(*i*) Acceleration stage—during which partial vacuum created by the withdrawal of the buffer piston rod from the cylinder during recoil is taken up—the buffer being inoperative during this stage.

(*ii*) Intermediate stage—from the instant partial vacuum is taken up to the instant the control rod becomes operative.

(*iii*) Deceleration stage—during which the gun is brought to rest.

During the first stage the velocity of runout V_{ro} increases under the action of the recuperator force S against the frictional force F and the retard valve force which is given by the expression $\frac{\rho V^2_{ro} \Omega^3_r}{2 g k^2 \omega r^2}$ where ω_r is the area of oil flow in the retard valve and therefore the equation of motion is :

$$\frac{W_r}{g} \cdot \frac{d}{dt}(V_{r_o}) = S - F - \frac{\rho V^2_{r_o} \Omega^3_r}{2gk^2\omega^2_r} = S - F - K_1 V^2_{r_o}$$

where K_1 is a constant and S can be expressed in terms of the distance of runout 's'. With the usual compression ratio of about 2·5, it is sufficiently accurate to take S as falling off linearly with 's' during a stage and, therefore, putting $S - F$ equal to $a - bs$ where a and b are known, the solution to the above equation can be written as :

$$V^2_{ro} = \left(\frac{a}{K_1} + \frac{W_r b}{2gK_1^2}\right)\left(1 - e^{-\frac{2g}{W_r} K_1 s}\right) - \frac{bs}{K_1}$$

knowing that $V_{r_o} = 0$ when $s = 0$.

During the next stage, the buffer is also effective and retards the motion with a force $\frac{\rho V^2_r \Omega^3}{2gk^2\omega^2} = K_2 V^2_{ro}$ where K_2 is a function of ω, which varies with 's'. The equation of motion of the piece during this stage can therefore be put as :

$$\frac{d}{ds}(V^2_{ro}) = a_1 - b_1 s - A V^2_{ro}$$

and if A is assumed to remain constant for a small step interval of 's' the solution of this becomes :

$$V^2_{ro} = B - Cs + Ke^{-As}$$

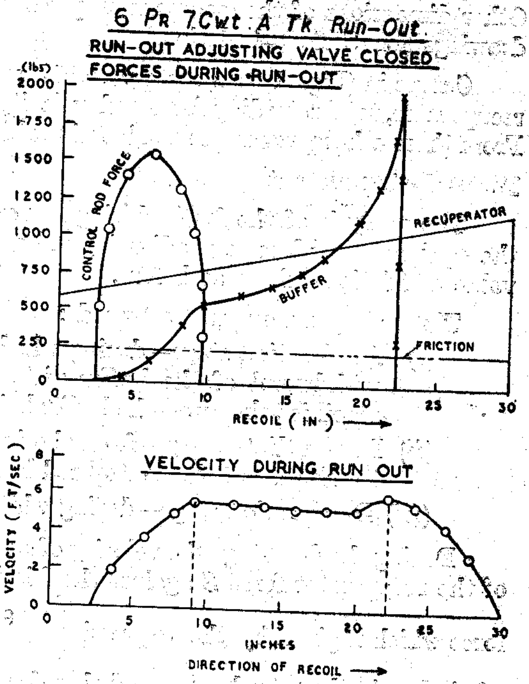
6 PR 7Cwt A Tk Run-Out
RUN-OUT ADJUSTING VALVE CLOSED
FORCES DURING RUN-OUT
(lbs)
2000
1750
1500
1200
1000
750
500
250
0
CONTROL ROD FORCE
RECUPERATOR
BUFFER
FRICTION
0
5
10
15
20
25
30
RECOIL (IN) →
VELOCITY DURING RUN OUT
VELOCITY (FT/SEC)
8
6
4
2
0
0
5
10
15
20
25
30
INCHES
DIRECTION OF RECOIL →

FIG. 5

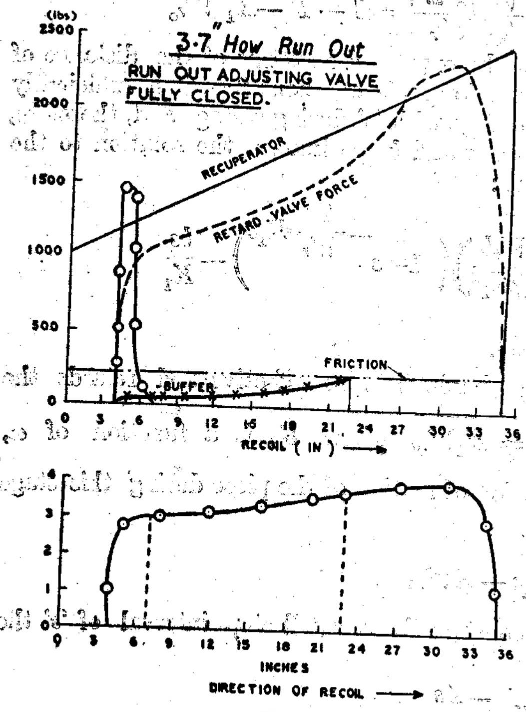
(lbs)
2500
3·7" How Run Out
RUN OUT ADJUSTING VALVE
FULLY CLOSED.
2000
1500
1000
500
0
RECUPERATOR
RETARD VALVE FORCE
FRICTION
BUFFER
0
3
6
9
12
15
18
21
24
27
30
33
36
RECOIL (IN) →
4
3
2
1
0
0
3
6
9
12
15
18
21
24
27
30
33
36
INCHES
DIRECTION OF RECOIL →

FIG. 6

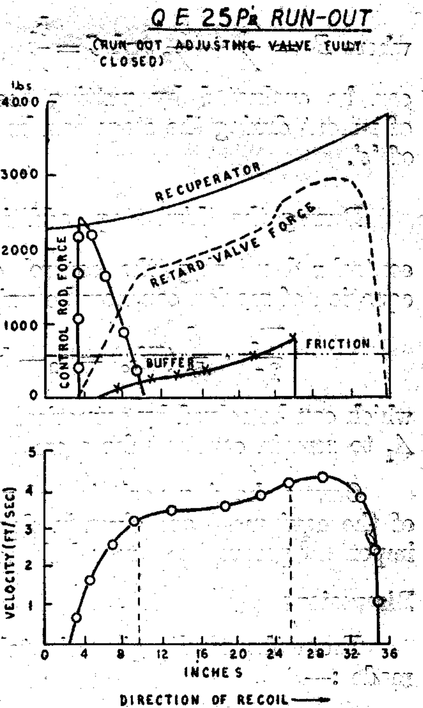
Q F 25 Pr RUN-OUT
(RUN-OUT ADJUSTING VALVE FULLY CLOSED)
lbs
4000
3000
2000
1000
0
RECUPERATOR
RETARD VALVE FORCE
CONTROL ROD FORCE
BUFFER
FRICTION
VELOCITY (FT/SEC)
5
4
3
2
1
0
4
8
12
16
20
24
28
32
36
INCHES
DIRECTION OF RECOIL

FIG. 7

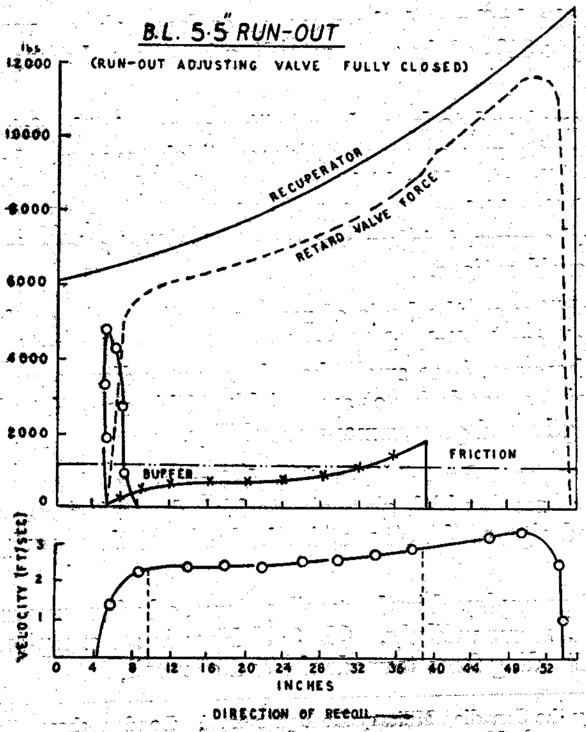
B.L. 5·5" RUN-OUT
(RUN-OUT ADJUSTING VALVE FULLY CLOSED)
lbs
12000
10000
8000
6000
4000
2000
0
RECUPERATOR
RETARD VALVE FORCE
BUFFER
FRICTION
VELOCITY (FT/SEC)
3
2
1
0
4
8
12
16
20
24
28
32
36
40
44
48
52
INCHES
DIRECTION OF RECOIL

FIG. 8

where $B = \frac{a_1}{A} + \frac{b_1}{A^2}$ and $C = \frac{b_1}{A}$ and K the constant of integration which can be evaluated by putting the initial conditions. Hence the velocity of runout during the stage can be computed by taking small step intervals of 's'.

During the third stage additional force equal to $\frac{\Omega^3_c\, V^2_{ro}}{2gk^2\omega^2_c}$ due to the control rod entering the control cylinder is brought into effect and the equation of motion can now be written as :

$$\frac{W_r}{2g} \cdot \frac{d}{ds}(V^2_{r_o}) = a_2 - b_2 s - A_1 V^2{}_{o}$$

which can be solved by numerical analysis as in the case above by assuming A_1 to remain constant for a small step of s.

Curves showing variation of various forces during the complete runout of the equipment are given in figs 5 to 8. on pages 220 and 221. Some important parameters are tabulated in table I.

Discussions

From the results given in table I, the following observations may be made :—

(1) The frictional force in any equipment is of the order of 4% of the mean retarding force and the buffer and the recuperator force almost vary from 79% to 62% and 17% to 34% of the mean retarding force over the length of recoil.

(2) Factors of safety employed to keep the recoiling masses in the firing position when gun is given its maximum elevation are high (approx. 1·6 against 1·2 which is generally stated[1]) which suggests that during service conditions coefficient of friction higher than 0·2 are likely to occur. In the spring type of recuperator, however, it is low because of other limitations imposed by spring design considerations.

(3) The factors of stability on the basis of mean retarding force at the beginning and end of recoil are in light field equipments lower than unity. The overturning impulse, however, is so small that the angular displacement of the wheels about the point of spade is not appreciable. This gives the advantage of shorter trail lengths and greater manoeuvrability.

(4) The total retarding force for 3·7″ How* and 6 pr 7 cwt increases suddenly towards the end of recoil which gives rise to high dynamic stresses. This strongly suggests a redesign of the oil port in the buffer of these equipments.

(5) For the usual sealings employed in the recoil systems, a buffer pressure higher than 4000 lbs/sq. in. seems unlikely. QF 3·7″ How is an exception because of the very high retarding force towards the end of recoil.

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*Artillery Vol II compiled by the Canadian Military Headquarters in London shows the max. T. P. for Q. F. 3·7″ How as nearly 11 tons.

(6) Upto the instant of end of gas action, the actual variation of the port area with distance of recoil is different from the one theoretically calculated which gives a constant factor of stability (Ref. fig 9). This is largely due to the difficulty of accommodating the relatively large increases in the port area with in small angular displacement of the valve assembly during this interval.

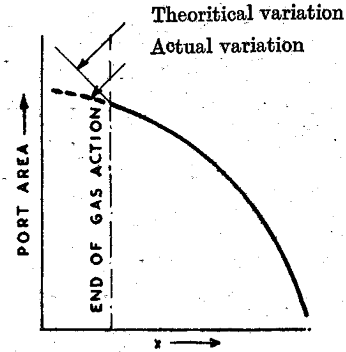

FIG 9: Variation of port area.

(7) The nominal length of run out with runout adjusting valve fully closed is almost 90% of the total length of recoil.

(8) The retard valve force during stage II of the runout is nearly 80% of the mean recuperator force during this stage. This indicates that if the velocity of runout is to be maintained, uniform during this stage, the rest of 20% must be contributed by the buffer.

(9) The control rod force may be as high as 0·3 *Rm* and brought into effect in the beginning of the third stage of runout when the stabilizing moment is more. The magnitude of this force should, however, decrease as the stabilizing moment decreases due to the motion of the recoiling masses towards the firing position.

(10) The factor of stability during the third stage of runout in the case of light field equipments is lower than unity when runout adjusting valve is fully closed. It is however greater than unity when the valve is sufficiently open to allow full runout.

Design Considerations

From the results of the above analysis, it follows that for a preliminary design of a new recoil system, the various forces and their variation, factors of stability, and other design parameters could be taken as follows :

(1) The frictional force could be neglected and the buffer and the recuperator forces during recoil could be made to vary from 82% to 65% and 18% to 35% of the mean retarding force over the length of recoil.

(2) The minimum recuperator force may be 1·6 times the minimum required to keep the gun in the firing position when it is given its maximum elevation. The factor may be kept lower for spring recuperators.

(3) The factor of stability during the recoil of the gun may be kept slightly lower than unity as a compromise between stability of the equipment on firing and weight and manoeuvrability in the case of light field equipments.

(4) The diameter of the buffer cylinder could be designed on the basis of a maximum pressure of 4000 lbs/sq. in. in case the usual sealings are used.

(5) The nominal length of runout with the adjustment valve fully closed may be taken as 90% its nominal recoil length *i.e.*, the runout adjusting valve may be so designed as to control the last 10% of the runout.

(6) A preliminary design of a retard valve could be made on the assumption that it provides almost 80% of the mean recuperator force during the second stage of runout. This, however, shall have to be modified after the first trials to ensure that the runout is neither, too violent nor, too sluggish.

(7) The control rod force could be made to vary from 0·3 Rm at the beginning of stage III to almost 0·2 Rm at the end of the stage. The factor of stability at any instant must, however, be higher, than unity.

Fig. 10 on page 225 shows the variation of various forces and some of the factors enumerated above.

Acknowledegments

The author is thankful to Prof C.H. Smith for the kind encouragement and helfpful suggestions during the course of this investigation. The author is also thankful to CSD (W) for supplying the gun data and to Mr A.M. Subramanian for his help in the computation work.

References

Military College of Science publication GM/9/45—*Recoil.*

Min. of Supply, Armament Design Data Sheet. DH/7.

Canadian Military Headquarters in London, Artillery Volume II.

4 Sirpal, J. P.,—Analytical study of recoil systems during recoil—*IAS research memorandum.*

5 Sirpal, J. P.,—Analytical study of recoil system during runout—*IAS Research Memorandum.*

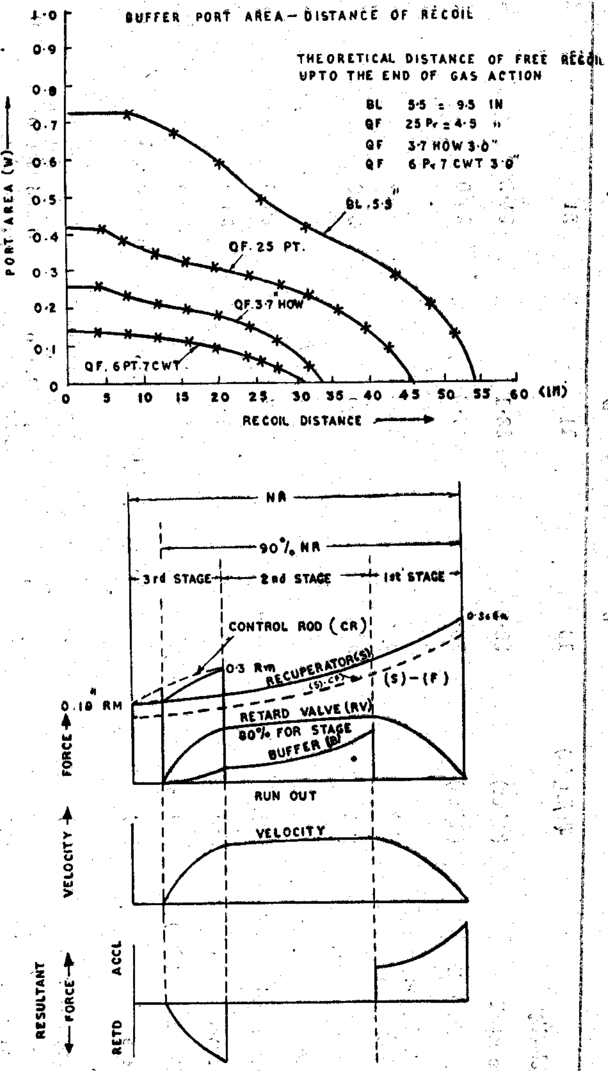
BUFFER PORT AREA — DISTANCE OF RECOIL
THEORETICAL DISTANCE OF FREE RECOIL UPTO THE END OF GAS ACTION
BL 5·5 = 9·5 IN
QF 25 Pr = 4·5 "
QF 3·7 HOW 3·0"
QF 6 Pr 7 CWT 3·0"
PORT AREA (W)
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
BL. 5·5"
QF. 25 PT.
QF. 3·7" HOW
QF. 6 PT. 7 CWT
0
5
10
15
20
25
30
35
40
45
50
55
60 (IN)
RECOIL DISTANCE
NR
90% NR
3rd STAGE
2nd STAGE
1st STAGE
CONTROL ROD (CR)
0·3 Rm
RECUPERATOR(S)
(S)-(F)
(S)-(F)
0·3×Rm
0.10" RM
RETARD VALVE (RV)
80% FOR STAGE
BUFFER (B)
FORCE
RUN OUT
VELOCITY
VELOCITY
RESULTANT FORCE
ACCL
RETD

FIG. 10

TABLE I

Analytical Study of Recoil Systems

Serial No.	Equipment		QF 25 Pr How	QF 3·7″ How	QF 6 Pr 7 cwt	BL 5·5″ Gun/How
a	*b*		*c*	*d*	*e*	*f*
1	P.L.P.	(T/Sq in)	16	11	21	17
2	Maximum Velocity					
	(*i*) Free recoil	(ft/sec)	39·5	38·1	31·2	41·5
	(*ii*) Retard recoil	(ft/sec)	35·8	37·6	30·0	37·0
3	Distance recoiled upto end of					
	(*i*) Shot ejection	(in)	1·41	1·08	0·63	2·84
	(*ii*) Gas action	(in)	4·50	3·00	3·02	9·50
4	Distance of recoil					
	(*i*) Theoretical	(in)	37·5	33·7	30·0	48·0
	(*ii*) Normal	(in)	36·0	35·0	30·0	54·0
5	Mean Retarding Force (Rm)	(lb)	10,500	5,400	5,650	32,000
6	Frictional Force	(lb)	0·047 Rm	0·0366 Rm	0·0398 Rm	0·036 Rm
7	Variation of					
	(*i*) Recuperator force	(lb)	0·213 Rm to 0·359 Rm	0·168 Rm to 0·400 Rm	0·106 Rm to 0·212 Rm	0·190 Rm to 0·396 Rm
	(*ii*) Buffer force	(lb)	0·740Rm to 0·594 Rm	0·796 Rm to 0·563 Rm	0·855 Rm to 0·748 Rm	0·773 Rm to 0·568 Rm
8	Ratio of the actual initial recuperator force to the minimum necessary to keep the recoiling masses up when given the maximum elevation ($\mu = 0\cdot2$)		1·60	1·61	1·30	1·40

TABLE I—*contd.*

a	*b*	*c*	*d*	*e*	*f*
9	Factor of stability on the basis of mean retarding force at				
	(*i*) beginning of recoil	0·856	0·85	1·41 (with shield)	1·33
	(*ii*) end of recoil	0·715	0·725	1·24	1·16
10	Maximum buffer pressure (lb/sq in)	2,900	7,900	3,850	3,150
11	Distance of runout with runout valve fully closed	92·5% NR	88·5% NR	90·5% NR	90·8% NR
12	Maximum velocity of runout (ft/sec)	4·30	3·85	6·32	3·00
13	Decrease of velocity during 2nd stage of runout	18·6 %	23·4%	7·3%	25·0%
14	Retard value force during 2nd stage runout	72·1% S	84·5% S	..	81·5% S
15	Maximum control rod force (lb)	0·22 Rm	0·24 Rm	0·28 Rm	0·16 Rm
16	Maximum retarding force during stage III	0·05 Rm	0·22 Rm	0·19 Rm	0·05 Rm
17	Factor of stability				
	(*i*) Minimum during stage II	1·05	3·28	1·15	2·97
	(*ii*) When maximum retarding force acts	0·85	0·40	0·74	1·28
	(*iii*) When runout adjusting valve sufficiently open to allow complete runout	1·12	1·18	1·02	2·90

NR=Normal Recoil; Rm—mean retarding force during recoil:,
S =mean recuperator force during stage II of runout.