MEMORANDUM
RM-2300-RC
DECEMBER 1958

THE ROCKET PERFORMANCE COMPUTER

E. H. Sharkey

The RAND Corporation
SANTA MONICA · CALIFORNIA

NOTE

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The Rocket Performance Computer in the pocket of the back cover of this publication is designed as an aid for rapidly calculating approximate solutions. It is not intended for precise calculations. The following instructions and examples supplement the information on the back of the computer. An elementary description of basic rocket principles is included in the explanation.

The computer calculates single-stage rocket performance. Multi-stage performance is determined by computing the performance of each stage separately, and properly combining the separate solutions.

A single-stage rocket is made up of three parts, as shown in Fig. 1.

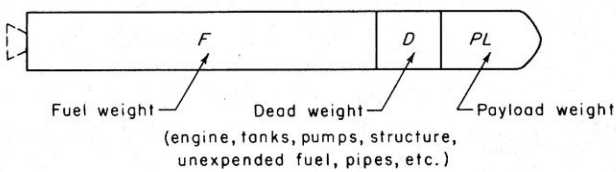

FIG. 1

The commonly used terms are those given in Fig. 2.

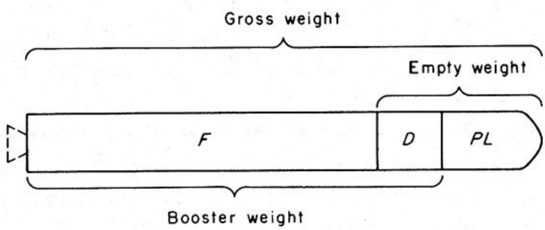

FIG. 2

The factors used in the calculation of single-stage rocket performance include the following:

$V_{BO} + V_{LOSS}$ ...... This is the sum of (1) the desired *burnout velocity* and (2) the *velocity lost* because of air friction, and because the rocket has to overcome the retarding effect of the force of gravity. (Since some potential performance has to be expended to take care of V_{LOSS}, the value $V_{BO} + V_{LOSS}$ is always used in rocket calculations rather than just V_{BO}.) This total velocity is in feet per second (fps).

I_{sp} .... This is the *specific impulse* of the fuel (propellant) used, in seconds. Usual values are in the 200–300 sec range; for a given fuel, I_{sp} is less at sea level than at high altitude.

%-fuel .... 100 × the ratio of fuel weight to gross weight.

The relationships between these three factors are best shown by an example worked out on the computer.

Suppose that it is desired to find the %-fuel weight required in a single-stage rocket that will have a burnout velocity of 15,000 fps, using a fuel (LOX/RP1) having an effective I_{sp} of 250 sec. V_{LOSS} is estimated to be 3500 fps (see the table of approximate V_{LOSS} values on the reverse side of the computer).

The large black (I_{sp}) arrow is first set to 250 (sec). The large red (V) arrow is then set to 18.5 (18,500 fps) on the outer velocity scale ($V_{BO} + V_{LOSS} = 15{,}000 + 3500$ fps). Under the radial portion of the red cursor can now be read, on the scale marked "FUEL," a %-fuel value of 90%. (See Fig. 3.) The rocket will have the %-weight

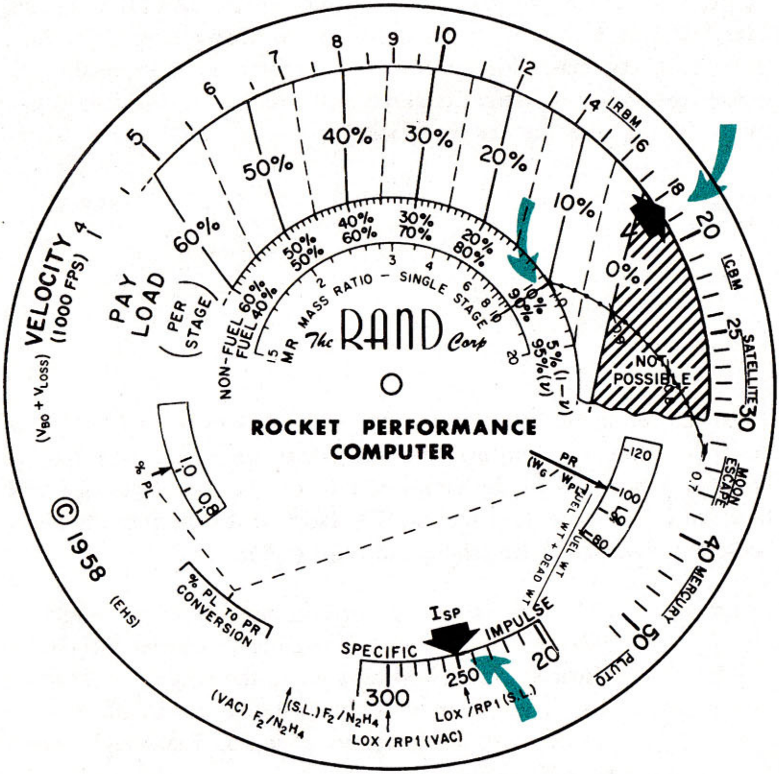
ROCKET PERFORMANCE COMPUTER
The RAND Corp
VELOCITY (1000 FPS)
(V_BO + V_LOSS)
PAY LOAD (PER STAGE)
MR MASS RATIO — SINGLE STAGE
NON-FUEL
FUEL
NOT POSSIBLE
IRBM
ICBM
SATELLITE
MOON ESCAPE
MERCURY
PLUTO
% PL
% PL TO PR CONVERSION
PR (W_G / W_PL)
FUEL WT + DEAD WT
FUEL WT
I_SP
SPECIFIC IMPULSE
(VAC) F2/N2H4
(S.L.) F2/N2H4
LOX/RP1 (VAC)
LOX/RP1 (S.L.)
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FIG. 3

configuration shown in Fig. 4. (It will be noted that on two other scales under the radial red cursor can be read the values 10% "NON-FUEL," or empty, weight and an "MR—MASS RATIO" of 10. Mass ratio is the ratio of gross weight to empty weight. %-fuel, %-nonfuel, and mass ratio are simply different ways of expressing the percentage of fuel by weight required in the rocket. In this description, the %-fuel value is the one used most.)

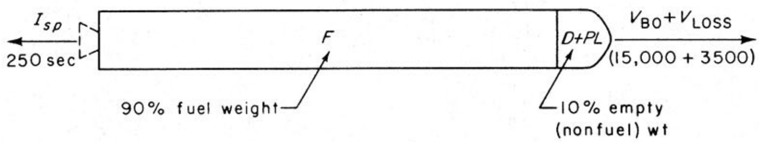

FIG. 4

So far, we know how much of the rocket has to be fuel, and how much is empty (or nonfuel) weight. What we would now like to know is how much of the empty weight can be useful payload and how much has to be dead weight. The factor that determines this is a booster design parameter called load ratio (*LR*):

LR . . . . . . *Load ratio* is the ratio of fuel weight to fuel weight plus dead weight, or fuel weight to booster weight. Usual values of load ratio are in the range of 0.90 to 0.95 (i.e., from 9 lb of fuel per pound of dead weight to 19 lb of fuel per pound of dead weight, or from $^{9}/_{10}$ to $^{19}/_{20}$).

Suppose that the booster of this rocket has an *LR* of 0.90. Holding the computer at the settings previously made, now read, under the "0.9" point on the curved red cursor, a "PAYLOAD (PER STAGE)" value of just zero per cent (i.e., all the empty weight is dead weight). (See Fig. 5.)

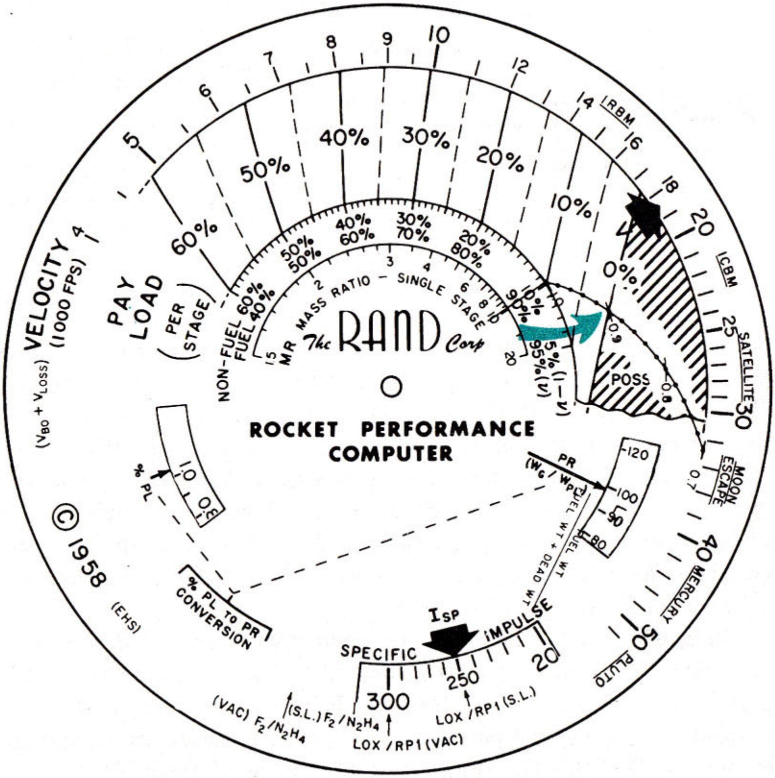
VELOCITY
(1000 FPS)
(V_{BO} + V_{LOSS})
PAY LOAD
(PER STAGE)
NON-FUEL
FUEL
MR MASS RATIO — SINGLE STAGE
The RAND Corp
ROCKET PERFORMANCE
COMPUTER
IRBM
ICBM
SATELLITE
MOON ESCAPE
MERCURY
PLUTO
POSS
% PL
% PL TO PR CONVERSION
PR (W_G / W_P)
FUEL WT + DEAD WT
FUEL WT
I_{SP}
SPECIFIC IMPULSE
(VAC) F_2/N_2H_4
(S.L.) F_2/N_2H_4
LOX / RP1 (VAC)
LOX / RP1 (S.L.)
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FIG. 5

The %-weight configuration of the rocket, for $LR = 0.90$, is shown in Fig. 6.

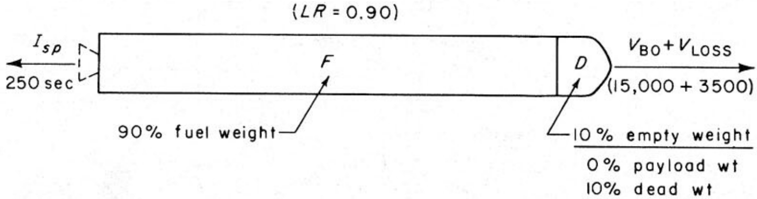


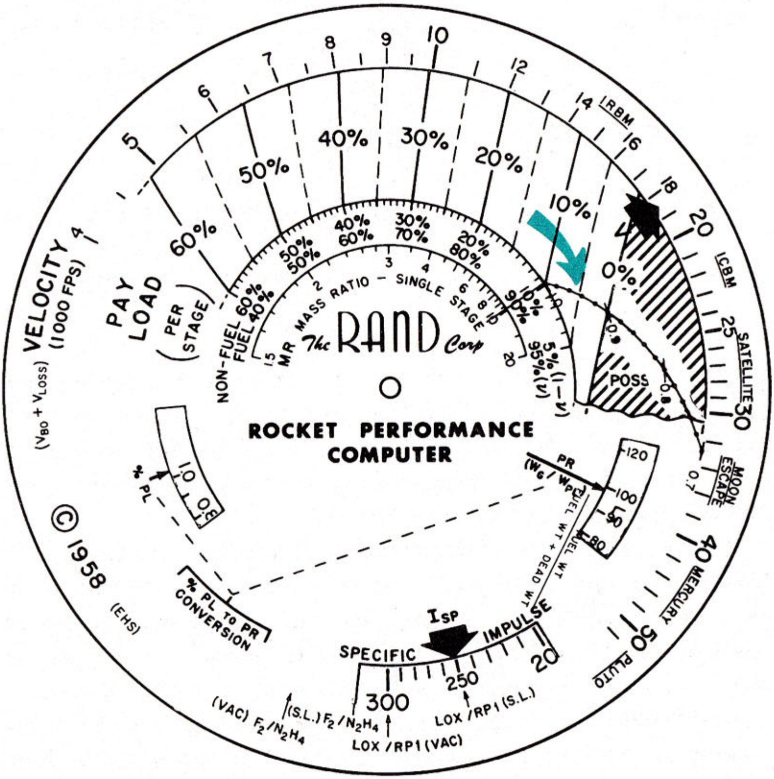
FIG. 6

Any value of LR lower than 0.90 would put the rocket in the "not possible" class. If, for example, an attempt is made to read off the "PAYLOAD (PER STAGE)" value, under the $LR = 0.85$ mark on the curved red cursor, it will be seen that the reading falls in the "NOT POSSIBLE" hatched area. This means that (with the necessary allowance for V_{LOSS}), this rocket could not be brought up to 15,000 fps, even with zero payload. For the fuel used, and the velocity required, the rocket simply has too much dead weight—a pound of dead weight for every 5.7 lb of fuel.

Obviously, a value of LR higher than 0.90 is needed if any payload is to be carried. Suppose that $LR = 0.95$; then what is the payload that can be carried? Holding the previous settings of I_{sp} and V, read now, under the point on the curved red cursor corresponding to 0.95, a "PAYLOAD (PER STAGE)" value of about 5.5%. (See Fig. 7.)

The %-weight configuration of the rocket, for $LR = 0.95$, is shown in Fig. 8 on page 8.

So, for values of $I_{sp} = 250$ sec, $V_{\text{BO}} + V_{\text{LOSS}} = 15{,}000 + 3500$ fps, and $LR = 0.95$, a 5.5-lb payload can be carried for every 100 lb of gross weight.


VELOCITY
(1000 FPS)
(V_{BO} + V_{LOSS})
PAY LOAD
(PER STAGE)
NON-FUEL
FUEL
MR MASS RATIO – SINGLE STAGE
The RAND Corp
ROCKET PERFORMANCE
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PLUTO
POSS
% PL
% PL TO PR CONVERSION
PR
(W_G / W_{PL})
FUEL WT + DEAD WT
FUEL WT
I_{SP}
SPECIFIC IMPULSE
(VAC) F_2/N_2H_4
(S.L.) F_2/N_2H_4
LOX /RP1 (VAC)
LOX /RP1 (S.L.)
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FIG. 7

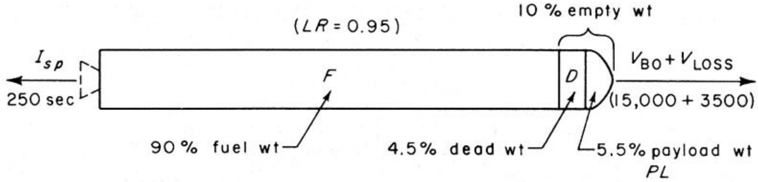


FIG. 8

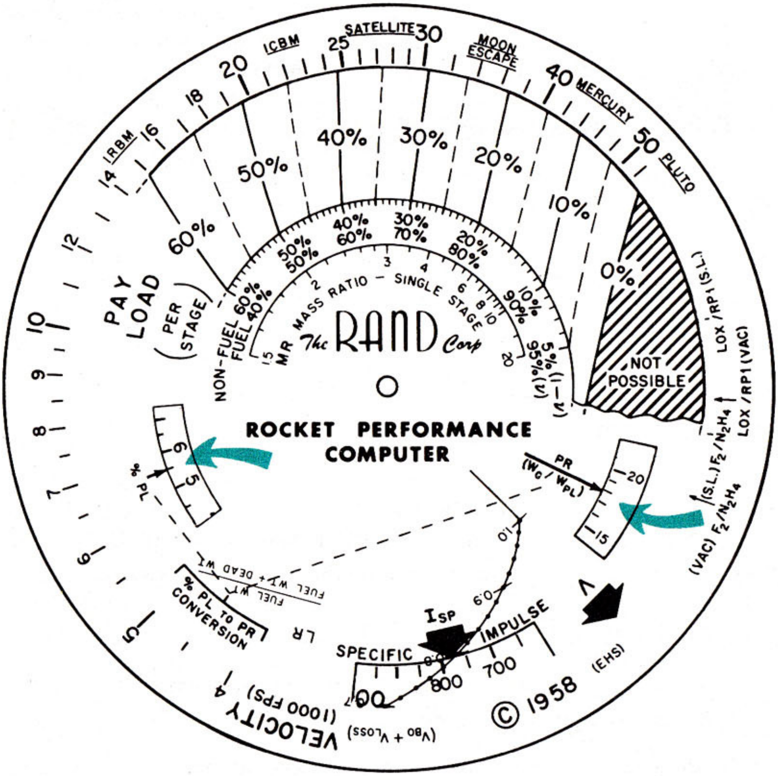
Another performance factor often used is the payload ratio (*PR*):

PR ...... *Payload ratio* is the ratio of gross weight to payload weight, and is equal to 100/%-payload.

The two small windows on the face of the computer (see Fig. 9) permit the payload ratio to be quickly determined, once the %-payload has been obtained by the methods just discussed. (The readings in these two small windows during the previous determination of %-payload are meaningless and should be ignored.)

To illustrate the use of these two small windows, suppose that it is desired to find the payload ratio corresponding to the previously determined value of 5.5% payload. Ignoring any previous settings or readings of I_{sp} or velocity, re-set the middle disc of the computer so that a value of 5.5 appears in the small window opposite the arrow marked "%PL." In the other small window to the right, read the corresponding value of payload ratio of about 18 opposite the arrow marked "*PR* (W_G/W_{PL})." (See Fig. 9.) This number means that for each pound of payload carried, 18 lb of gross weight are required.

A rocket having a burnout velocity of 15,000 fps can be calculated to have a range of about 1500 n mi if it is fired on a maximum-range trajectory. If it were desired to use this rocket to deliver a payload of


ROCKET PERFORMANCE
COMPUTER
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PAY LOAD (PER STAGE)
IRBM
ICBM
SATELLITE
MOON ESCAPE
MERCURY
PLUTO
NOT POSSIBLE
MR MASS RATIO - SINGLE STAGE
NON-FUEL
FUEL
% PL TO PR CONVERSION
PR (W_0 / W_{PL})
% PL
SPECIFIC IMPULSE
I_{SP}
LOX /RP1 (S.L.)
LOX /RP1 (VAC)
(S.L.) F_2 /N_2H_4
(VAC) F_2 /N_2H_4
F_2 /N_2H_4
VELOCITY (1000 FPS)
(V_{BO} + V_{LOSS})
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FIG. 9

1000 lb, the actual weights of this hypothetical IRBM could be easily calculated, as shown below:

Gross wt	Payload wt × *PR*, or 1000 lb × 18 =	18,000 lb
Fuel wt	Gross wt × %-fuel, or 18,000 lb × 90% =	16,200 lb
Empty wt	Gross wt × %-nonfuel, or 18,000 lb × 10% =	1,800 lb
Payload wt		1,000 lb
Dead wt (empty wt − payload wt)		800 lb

The actual weight configuration of this IRBM is shown in Fig. 10.

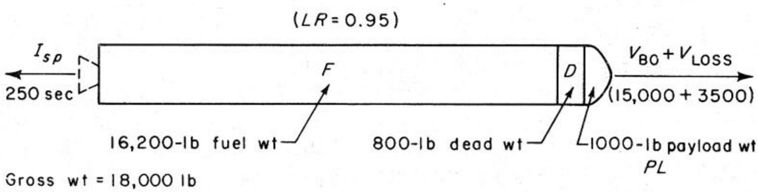

FIG. 10

As the computer is used on various problems, it will be evident that the %-payload increases, and the payload ratio decreases, as

1. the I_{sp} of the fuel is increased;
2. the value of *LR* increases;
3. the required value of burnout velocity is decreased;
4. the value of V_{LOSS} is decreased.

To show some of the possible improvements along these lines, suppose we compute the performance improvement over the previous example if the only change is to a fuel, such as *fluorine/hydrazine* (F_2/N_2H_4), having an effective I_{sp} of 325 sec. If the two large arrows are now re-set to values of 325 sec I_{sp}, and 18,500 fps velocity, and an *LR* value of 0.95 is used, the following values will be read on the computer:

Given		*Computer Answers*		
I_{sp}	325 sec	%-fuel		83%
$V_{BO} + V_{LOSS}$ ...	15,000 + 3500 fps	%-nonfuel		17%
LR	0.95	%-payload	13%	
		%-dead wt	4%	
		PR		7.7

The %-weight configuration of this improved-fuel rocket is shown in Fig. 11.

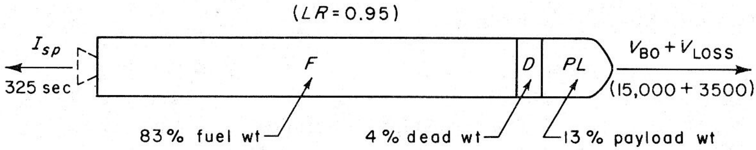

FIG. 11

The improvement in performance from simply going to the better fuel is a very marked one. The %-payload increased from 5.5% to 13%, and the payload ratio decreased from 18 to 7.7. Whereas to send a 1000-lb payload 1500 miles with the old fuel required a rocket with a gross weight of 18,000 lb, the rocket gross weight needed with the new fuel has decreased to 7700 lb (1000 lb × 7.7).

On the other hand, if the original rocket gross weight of 18,000 lb is retained, the payload that can be carried is increased from 1000 lb to 2350 lb (18,000 × 13%).

The actual weight configuration of this improved-performance 18,000-lb rocket is shown in Fig. 12 on page 12.

The beneficial effect of an increase in the value of *LR* has already been demonstrated in the original IRBM example.

Assuming that it was possible to reduce the value of V_{LOSS} from the old value of 3500 fps to 2500 fps, how much improvement in pay-

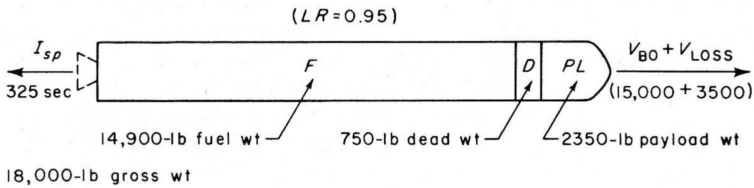

FIG. 12

load would be obtained, if this were the only change? The computer solution shows the following:

Given		*Computer Answers*		
I_{sp}	250 sec	%-fuel		88.5%
$V_{BO} + V_{LOSS}$ ...	15,000 + 2500 fps	%-nonfuel		11.5%
LR	0.95	%-payload	7.0%	
		%-dead wt ...	4.5%	
		PR		14.2

For a 1000-lb payload, the necessary gross weight is now 14,200 lb as compared with 18,000 lb using the higher value of V_{LOSS}. For an 18,000-lb gross weight, the payload is now 1260 lb as compared with 1000 lb previously. It is obvious that this same solution would apply if V_{LOSS} had been held at 3500 fps and V_{BO} had been reduced from 15,000 fps to 14,000 fps.

From these simple examples, it can be seen that the %-payload possible in a single-stage rocket is fairly sensitive to small changes in I_{sp}, *LR*, and velocity, and that the payload simply disappears below certain levels of parameters.

It will be recalled that our original IRBM example resulted in just zero payload, when parameters of $I_{sp} = 250$ sec, $V_{BO} + V_{LOSS} = 15{,}000 + 3500$ fps, and $LR = 0.90$ were used. Suppose now that we reduce the V_{BO} requirement on this rocket from 15,000 fps to 7000 fps. The computer will show the following:

Given		*Computer Answers*		
I_{sp}	250 sec	%-fuel		73%
$V_{BO} + V_{LOSS}$	7000 + 3500 fps	%-nonfuel		27%
LR	0.90	%-payload	19%	
		%-dead wt	8%	

The %-weight configuration of this rocket is shown in Fig. 13.

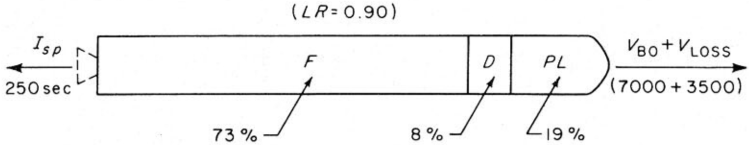

FIG. 13

For this reduced value of V_{BO}, the rocket is able to carry the relatively large payload of 19%, but the rocket could be calculated to have a disappointing maximum range of only 200–300 miles.

However, the 19%-payload we have in this rocket can be, if we choose, *a complete second-stage rocket* whose job is to boost *its* payload and *its* dead weight from a running start of 7000 fps up to an IRBM final velocity of 15,000 fps. The now useless dead weight of the first-stage booster is separated and discarded prior to firing up the second-stage rocket.

About the only difference between this second-stage rocket and the single-stage rockets considered previously is (and this must be kept in mind) that the V_{BO} value used in the solution for the second stage is *not* the actual burnout velocity of the second stage (15,000 fps); instead, it is the *increase* in actual velocity contributed by the second-stage rocket. In this case, the second-stage V_{BO} is 15,000 − 7000 = 8000 fps. (In a single-stage or first-stage rocket, V_{BO} is similarly the *increase* in velocity, from zero to V_{BO}.)

Because this second-stage rocket operates high up in the atmosphere, we get a better value of I_{sp} of about 300 sec for the same LOX/RP1 fuel. In addition, since the rocket will be on a flatter trajectory, and practically drag free, the V_{LOSS} value will be down to about 2000 fps.

The computer will show the performance of the second stage as given below and shown in Fig. 14 (*the computer solution procedure is exactly the same as before*):

Given		*Computer Answers**		
I_{sp}	300 sec	%-fuel		64.5%
$V_{BO} + V_{LOSS}$	8000 + 2000 fps	%-nonfuel		35.5%
LR	0.90	%-payload ...	29.0%	
		% dead wt...	6.5%	

*The percentages are percentages of second-stage gross weight.

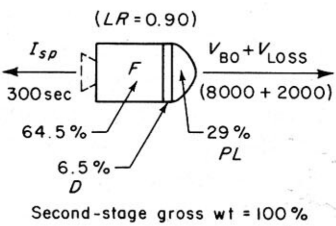

FIG. 14

Since the actual payload carried by the second stage is 29% of the second-stage gross weight, and since this second-stage gross weight is itself 19% of the gross (takeoff) weight of the entire rocket, the payload weight is 29% of 19%, or 5.5% of the gross (takeoff) weight. (In other words, the over-all %-payload of a two-stage rocket is found by multiplying the two values of "PAYLOAD (PER STAGE)" read off the computer.)

The %-weight breakdown, *in terms of gross takeoff weight,* is shown in Fig. 15.

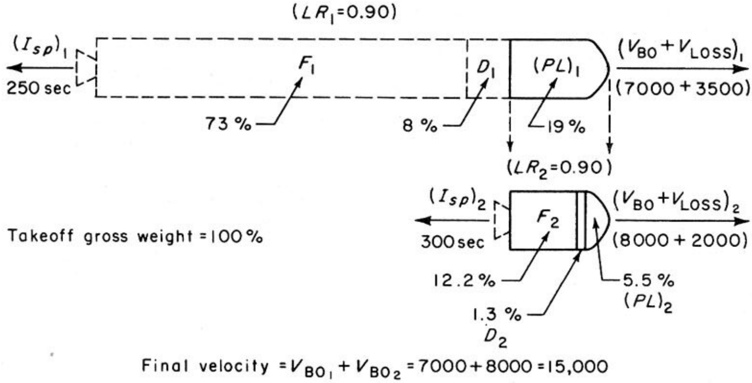

FIG. 15

When we first tried a one-stage IRBM with some moderate parameters, the payload that could be carried turned out to be just zero. Using about the same parameters, the two-stage IRBM is able to carry a 5.5% payload. While some of the improvement came from the better values of I_{sp} and V_{LOSS}, most of the performance improvement resulted from being able to dump most of the dead weight at about the middle point of the rocket-boost interval.

Using the two small windows again, the over-all *PR* value, corresponding to 5.5% over-all %-payload, turns out to be about 18.

It will be recalled that we obtained a 5.5% payload previously in a single-stage LOX/RP1 IRBM example, but that an *LR* of 0.95 was required. By going to two stages, we get the same payload without requiring the design sophistication necessary for the higher *LR* value.

The actual weights of the various portions of the two-stage IRBM delivering a 1000-lb payload are shown in Fig. 16.

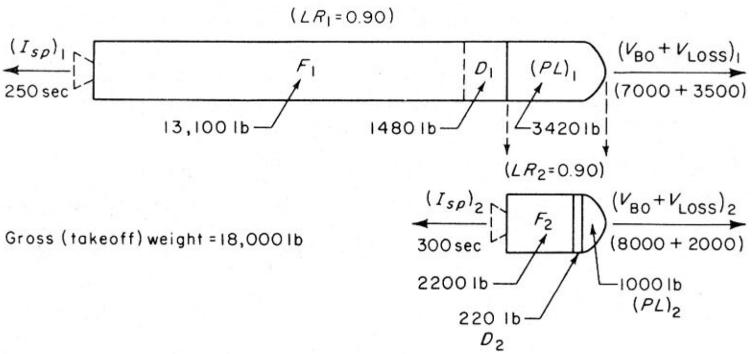

FIG. 16

The above two-stage example was worked out in a fairly detailed manner to show what can be done by using the computer. In many cases, however, the main interest will lie in the values of %-payload and *PR*. These values can be obtained by

1. reading off the %-payload for the first stage;
2. reading off the %-payload for the second stage;
3. multiplying these two values to get over-all %-payload;
4. using the small windows to get over-all *PR*.

The solution for a three- or four-stage rocket is obtained in a manner similar to that used for the two-stage rocket: the over-all %-payload is the product of the "%-PAYLOAD (PER STAGE)" values obtained for each stage.

It should be noted that none of the above examples represent real rockets. They were chosen primarily to emphasize the basic interrelationships involved. To simplify the discussion, it has also been tacitly assumed that such parameters as V_{LOSS} and LR remain constant regardless of the physical size of rocket, which is not exactly true. It has also been assumed that it is possible to change any single parameter without affecting other parameters, which again is not quite true. However, if the true values of the parameters are known for any particular real rocket, the computer (within the limitations of its accuracy) will provide the correct answers.

Additional problems involving two-stage ICBM's (final velocity of 24,000 fps) are given below and on page 18. As in the previous examples, slight deviations from the indicated answers, because of the limited accuracy of the computer, should not be a cause for concern.

ICBM (LOX/RP1)

First Stage

Given		*Computer Answer*	
I_{sp}	250 sec	%-payload	5%
$V_{\text{BO}} + V_{\text{LOSS}}$	12,000 + 3500		
LR	0.90		

Second Stage

Given		*Computer Answer*	
I_{sp}	300 sec	%-payload	15%
$V_{\text{BO}} + V_{\text{LOSS}}$	12,000 + 2000		
LR	0.90		

Over-all %-payload (15% × 5%)	0.75%
Over-all *PR*	133/1

ICBM (F_2/N_2H_4)

First Stage

Given		*Computer Answer*	
I_{sp}	325 sec	%-payload	15%
$V_{BO} + V_{LOSS}$	12,000 + 3500		
LR	0.90		

Second Stage

Given		*Computer Answer*	
I_{sp}	375 sec	%-payload	24%
$V_{BO} + V_{LOSS}$	12,000 + 2000		
LR	0.90		

Over-all %-payload (24% × 15%) 3.6%

Over-all *PR* 28/1