MULTI-STAGE ROCKETS

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MULTISTAGE ROCKETS

Most modern, high performance rockets, particularly those used in space applications, are multistage rockets. The Saturn V moon rocket is a perfect example of a multistage vehicle; this rocket uses three distinct stages in order to send its payload of astronauts and equipment toward the moon.

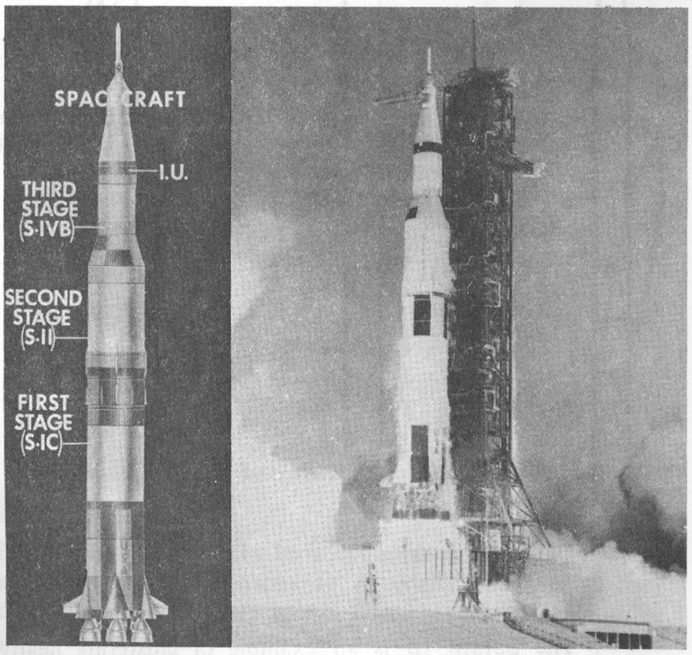


Figure 1. Saturn V Launch Vehicle *Photo Credit NASA*

The Saturn 1C first stage lifts the rocket to 200,000 feet with 7-1/2 million pounds thrust. The first stage then separates and the S-II second stage ignites to accelerate the rocket to 15,300 mph and lift it to 100 miles altitude. At that point the third stage takes over to complete earth orbital injection (17,500 mph), and later to accelerate the rocket to the 25,000 mph velocity necessary to escape the pull of earth's gravity.

WHY MULTISTAGE?

Why do rocket designers complicate their task with several engine sizes, many separate fuel tanks and complicated separation mechanisms, instead of simply designing one huge rocket, containing all the fuel, that will do the whole job at once?

There are two fundamental reasons for staging, the *first* being to improve performance by eliminating dead weight; near the end of powered flight the huge, nearly empty fuel tanks are merely dead weight, and are dropped off to reduce weight later in the flight. The small remaining amount of propellant is retained in the second and third stage tanks. This reduces the mass the upper stages must carry. The *second* reason is that the immense thrust required to lift the fully loaded rocket off the pad is far too much for the nearly empty rocket later in flight; the acceleration would be too severe for both men and instruments. Consequently engines with lower thrust are generally used on each succeeding stage, and the spent engines are dropped off along with their empty fuel tanks.

The reasons for staging are:

1. **To improve performance by eliminating dead weight during powered flight.**
2. **To maintain acceleration within reasonable limits by reducing thrust in mid-flight.**

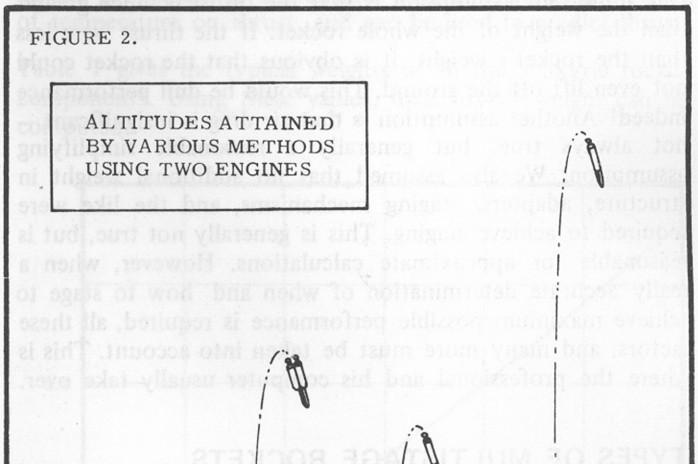
An example will illustrate the advantages of staging, and also a very important principle to remember about staging. Let us assume we have a payload we wish to launch as high in the air as we can, and by chance we have two identical rocket engines. Maximum altitude of the payload would certainly be a good measure of the rocket's "performance." What combination of engines and firing sequence will lift the payload the highest?

Brief consideration gives us four ways to use the two engines:

1. Launch the payload on one engine, and when it fell to earth launch it again on the second engine.
2. Launch the payload with both engines at once, lifting the payload with twice the thrust.
3. Launch a payload engine combination with one engine, and when the combination reaches its **peak altitude,** fire the second engine to shoot the payload further aloft.
4. Launch a payload engine combination with one engine, and as soon as it is spent **("burnout")** fire the second engine to give the payload additional velocity aloft.

FIGURE 2.

ALTITUDES ATTAINED BY VARIOUS METHODS USING TWO ENGINES



The results of launching our payload these four ways, with the two engines, assuming typical weights and thrust, would turn out more or less as illustrated in Figure 2.

Obviously the first method is not the way to achieve maximum altitude. Firing both engines at once, as in the second method does not double the performance (altitude); the gain however is significant. This two engine (clustered) rocket is actually just a single stage rocket; no dead weight was eliminated from the rocket during the flight.

Firing the second stage after the first stage has boosted the rocket to its peak altitude (as in the third method), gave disappointing performance. Weight was saved, but at the wrong time, and the net effect was merely to raise the altitude at which a one-engine, single stage rocket (the second stage) was launched. We also risked another hazard: if the second stage were to fire a little late, it may well fire **downwards.** This could be dangerous, and hardly contributes to the altitude performance of the rocket.

On the other hand, firing the second stage at first stage burnout (as in the fourth method) further accelerates the payload adding velocity, and dramatically increases the rocket's performance. This is the method used to gain performance when staging a rocket. Performance is greatly improved because the altitude an object can reach is proportional to the square of its vertical velocity and this method increases velocity. In other words, if Object A has a vertical velocity twice that of Object B, A will fly four times as high as B.

It should be clear that if we design our staging to add **velocities,** we will gain more than a proportionate increase in resultant altitude. The important principle to remember about staging, then, is:

Design so the second stage adds velocity to the payload, by firing the second stage at first stage burnout.

The examples and principles stated above are based on some reasonable assumptions that have not yet been mentioned. One important assumption is that the thrust is much greater than the weight of the whole rocket. If the thrust were less than the rocket's weight, it is obvious that the rocket could not even lift off the ground. This would be dull performance indeed! Another assumption is that air drag is insignificant – not always true, but generally a reasonable simplifying assumption. We also assumed that no additional weight in structure, adapters, staging mechanisms, and the like were required to achieve staging. This is generally not true, but is reasonable for approximate calculations. However, when a really accurate determination of when and how to stage to achieve maximum possible performance is required, all these factors, and many more must be taken into account. This is where the professional and his computer usually take over.

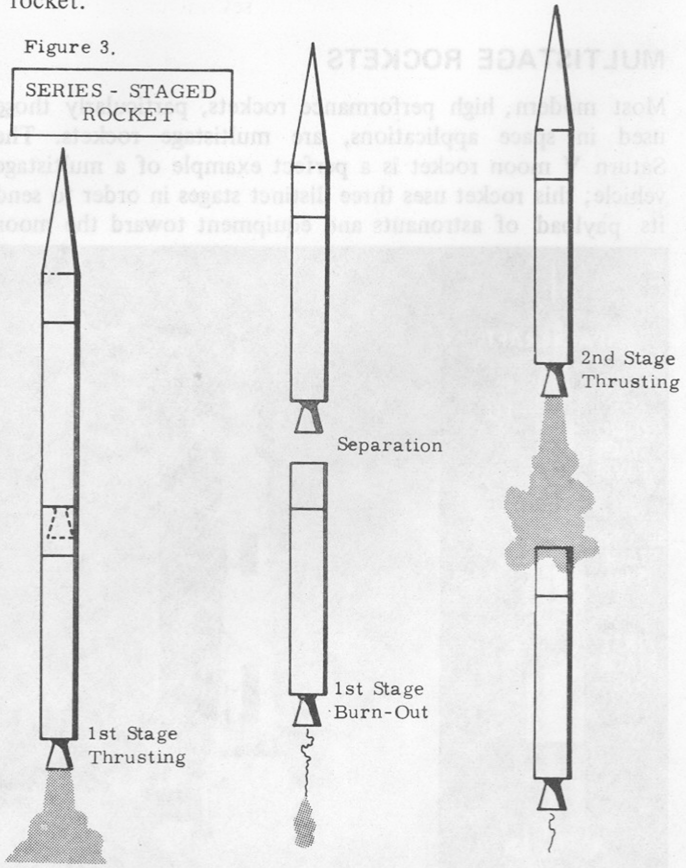
TYPES OF MULTISTAGE ROCKETS

There are two fundamental types of rocket staging: **series** staging and **parallel** staging. In a series-staged rocket, the second stage fires **after** the first stage is finished. In parallel staging both stages fire simultaneously at launch, but the first stage (booster) drops off in mid-flight when spent, while the second stage (sustainer) continues on. All multistage rockets fall into these two general categories.

SERIES STAGING

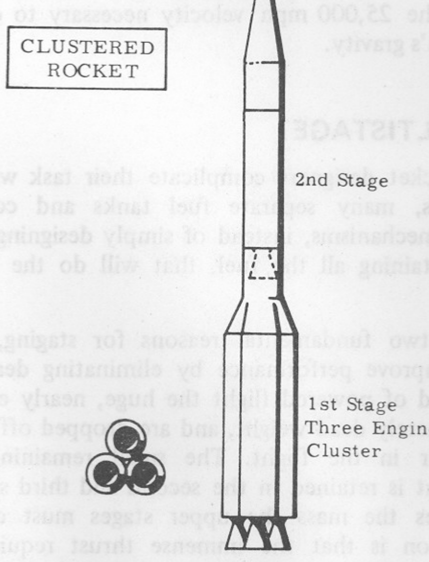
Series staging, sometimes referred to as vertical staging, is most common. Most space rockets, from Explorer I to Saturn V, have been series-staged, some with as many as five stages. A popular method for producing a large first stage has been to **cluster** several rockets together to provide greater combined thrust without actually having to build a larger rocket.

Figure 3.



The Saturn IB is an example of clustering nearly complete rockets; the Saturn IC and the Titan II are examples of engine clusters fed from a single set of propellant tanks. Valkyrie rockets may also be clustered to form high thrust first stages by strapping or attaching them together.

Figure 4.



PARALLEL STAGING

Several important missiles and space rockets are parallel-staged. For example, the Atlas is parallel-staged; it has two booster engines that are fired along with the central sustainer engine at launch. After a period of powered flight, the booster engines along with their pumps and structure are ejected, and the central sustainer engine carries on alone.

Another perfect example of parallel staging is the Titan IIIC. Two huge, solid propellant, strap-on rockets boost the central liquid rocket aloft, and then drop off when spent. The central Titan rocket continues firing for several minutes after separation.

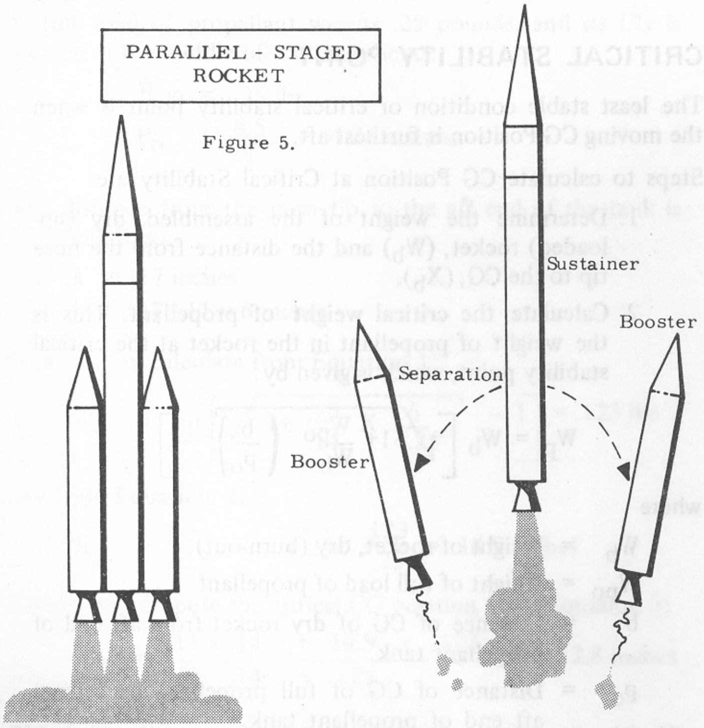
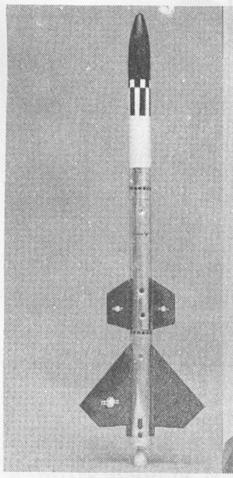


Figure 5.

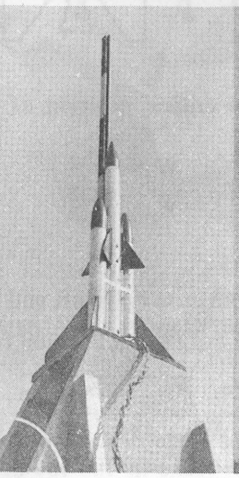
Parallel staging can also be accomplished with Valkyries by attaching strap-on boosters to a central sustainer so they detach themselves when spent. There are several spectacular ways to accomplish this which are described in the specific instructions.

PRINCIPLES OF MULTISTAGE DESIGN

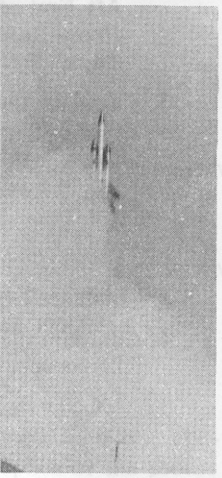
If you follow the Viking multi-stage kit instructions carefully you should have no difficulty getting terrific performance from your rockets. For those who are interested in the "why" of things and want to go beyond what can be arranged in a kit, there are many principles of multistage design which are fundamental to the basic understanding of staging. These you will find informative and interesting, perhaps, but not necessary in order to fly your Valkyrie.



Viking 2-Stage Constructed of Valkyrie Parts



An Experimental Clustered 1st Stage



Off in a Blur of Speed

STABILITY AT LIFT-OFF

All Valkyrie rockets are fin-stabilized, that is, they maintain their direction of flight just as an arrow does, by air flow past their tail fins as they move through the air. However, both are dependent upon speed through the air to exert enough force on the fins to provide a correcting force to maintain a stable flight direction. If the rocket flies too slowly, particularly just as it leaves the launching rod, it may not be stable, and might fly horizontally, or even back into the ground.

Anyone who launches a multistage rocket should be especially aware of this aspect of flight. The many combinations of rocket engines possible with staging make it easy to plan a rocket which is too heavy. If it is too heavy it may not gain enough flight speed leaving the launcher to be stable.

Rather than establish a minimum flight speed for stability, it is easier to establish a minimum acceleration at lift-off which will provide adequate flight speed leaving the launcher.

Acceleration at lift-off in terms of "g's" is just equal to the lift-off thrust divided by the loaded rocket weight minus one. That is:

$$\text{Acceleration in "g's"} = \frac{F}{w} - 1$$

where F = thrust

w = weight

The ratio $\frac{F}{w}$ is called the "thrust-to-weight radio."

It is advisable not to allow the acceleration to fall below 3 "g's" or in other words to allow the thrust-to-weight ratio to be less than 4-to-1.

Both thrust and weight must be evaluated, since both of these factors are variable. Thrust obviously depends upon the number of engines operating at the time, but thrust also depends heavily upon temperature – that is, **temperature of the propellant in the rocket.** Figure 7 shows the effect of temperature on thrust, and can be used to predict thrust.

Table 1 gives the typical weights of all the Valkyrie rocket components. Using these values, total lift-off weight can be computed.

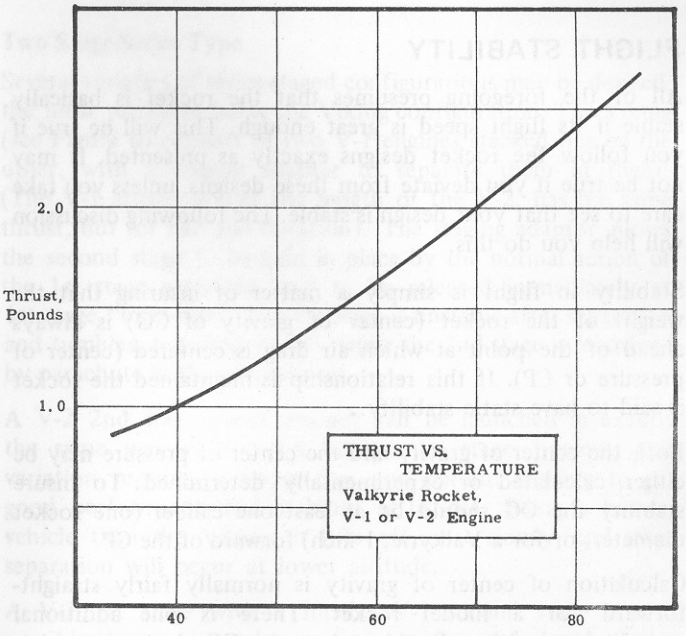


Figure 7

TABLE OF WEIGHTS

V-2 Engine with fins, dry	.085
V-2 Propellent load	.250
V-1 Engine with Fins, Dry	.063
V-1 Propellant Load	.125
Separator with Coupling	.020
Staging Plug (1st Stage)	.002
Staging Adaptor Tube (2nd Stage)	.008
Nose Cone, Balsa	.014
Nose Cone, Styrofoam	.010
Parachute Tube, Aluminum	.018
Parachute Tube, Paper, with Adaptor	.012
Parachute, Complete	.004

Example: We wish to launch a Viking Rocket. It is 60°F outside. Even when loading carefully it is likely that the loaded propellant will chill somewhat, say 10 degrees. If so it will be at 50°F in the rocket, and the thrust will be 1.28 pounds.

The total weight of all the components, i.e.:

2	V-1 Engines	@ .063 lbs.
2	V-1 Propellant Loads	@ .125 lbs.
2	Separators	@ .020 lbs.
1	Staging Plug	@ .002 lbs.
1	Adaptor Tube	@ .008 lbs.
1	Parachute Tube	@ .018 lbs.
1	Nose Cone	@ .014 lbs.
1	Parachute	@ .004 lbs.

is .462 pounds.

Consequently the thrust-to-weight ratio at lift-off is 2.77. This is less than the recommended 4:1 value. The rocket may not be completely stable at lift-off, and we should consider alternatives.

To achieve a 4:1 ratio, the thrust must be 1.85 lbs. From Figure 7 a propellant temperature of 67°F is required to provide this much thrust.

We could:

1. Wait for a warmer day.
2. Take the propellant from indoors immediately before loading, and load carefully to keep propellant warm.

Principle to remember:

Make sure that the thrust-to-weight ratio of your rocket at lift-off is greater than 4:1.

FLIGHT STABILITY

All of the foregoing presumes that the rocket is basically stable if its flight speed is great enough. This will be true if you follow the rocket designs exactly as presented. It may not be true if you deviate from these designs, unless you take care to see that your design is stable. The following discussion will help you do this.

Stability in flight is simply a matter of insuring that the weight of the rocket (center of gravity of CG) is always ahead of the point at which air drag is centered (center of pressure or CP). If this relationship is maintained the rocket is said to have static stability..

Both the center of gravity and the center of pressure may be either calculated or experimentally determined. To insure stability the CG should be at least one caliber (one rocket diameter, or for a Valkyrie, 1 inch) forward of the CP.

Calculation of center of gravity is normally fairly straightforward for a model rocket. There is one additional complication with a liquid rocket; the CG changes position as propellant is consumed. As propellant begins to flow out, the CG moves aft; when it is nearly exhausted and propellant weight becomes insignificant the CG moves forward again. For stability we should be concerned with the moment when the CG is furthest aft and the rocket is least stable. This generally occurs when the rocket is somewhere between full and half full of propellant.

CRITICAL STABILITY POINT

The least stable condition or critical stability point is when the moving CG Position is furthest aft.

Steps to calculate CG Position at Critical Stability are:

1. Determine the weight of the assembled, dry (unloaded) rocket, (W_b) and the distance from the nose tip to the CG, (X_b).
2. Calculate the **critical weight** of propellant. This is the weight of propellant in the rocket at the critical stability point, which is given by:

$$W_p = W_b \left[\sqrt{1 + \frac{W_{po}}{W_b} \left(\frac{b}{p_o} \right)} - 1 \right]$$

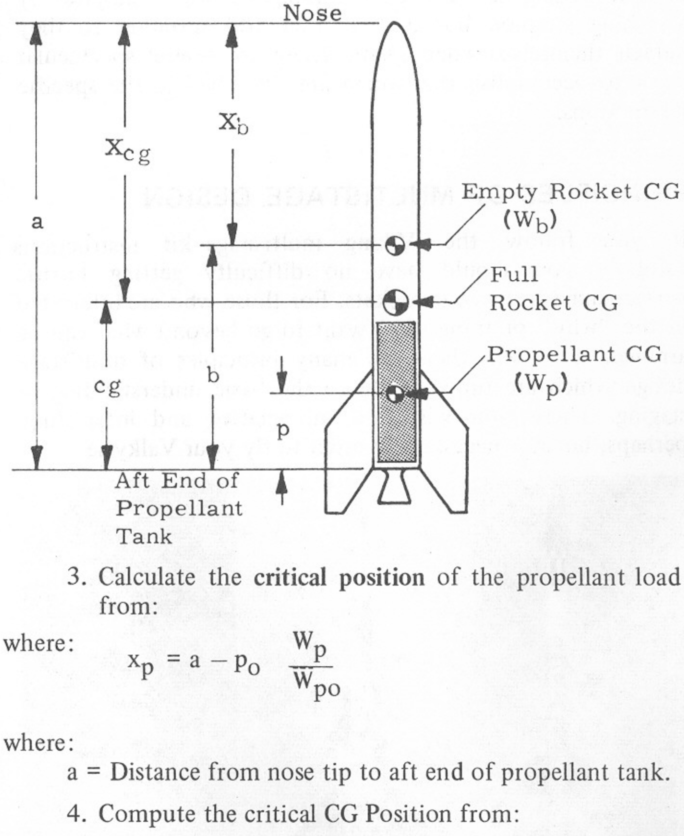
where

W_b = Weight of rocket, dry (burn-out)

W_{po} = Weight of full load of propellant

b = Distance of CG of dry rocket from aft end of propellant tank.

p_o = Distance of CG of full propellant load from aft end of propellant tank.



3. Calculate the **critical position** of the propellant load from:

where: $$x_p = a - p_o \frac{W_p}{W_{po}}$$

where:

a = Distance from nose tip to aft end of propellant tank.

4. Compute the critical CG Position from:

$$X_{cg} = \frac{X_b \; W_b \; + \; X_p \; W_p}{W_b \; + \; W_p}$$

which is the maximum distance from the nose tip to the CG which occurs during flight. This is the position of the CG when the rocket is least stable.

Example: Your single stage V-2 rocket weighs .14 pounds dry, and you determine by balancing it across a knife-edge that its CG is located exactly 11 inches from the nose tip. Thus:

$$W_b = .14 \text{ lbs.}$$
$$X_b = 11.0 \text{ inches}$$

A full load of propellant weighs .25 pounds, and its CG is located in the middle of the tank, hence:

$$W_{po} = .25 \text{ lbs.}$$
$$P_o = \frac{8.5}{2} = 4.25 \text{ inches}$$

The distance from the nose tip to the aft end of the tank is 17.0 inches, so:

$$a = 17 \text{ inches}$$
$$b = 17 - 11 = 6 \text{ inches}$$

Now we can calculate from Equation 1:

$$W_p = .14 \left[\sqrt{1 + \frac{.25}{.14} \text{ X } \frac{6}{4.25}} - 1 \right] = .123 \text{ lbs.}$$

and from Equation 2:

$$X_p = 17 - 4.25 \frac{.123}{.25} = 14.9 \text{ inches}$$

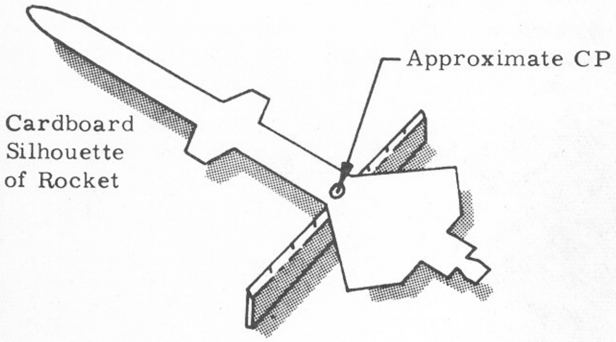
Finally we compute the critical CG position from Equation 3:

$$X_{CG} = \frac{11 \text{ x } .14 + 14.9 \text{ x } .123}{.14 + .123} = 12.8 \text{ inches}$$

This is the CG position which should be compared with CP in order to determine stability. The CG should be ahead of the CP for the rocket to be stable.

CENTER OF PRESSURE LOCATION

The center of pressure of your rocket is the point at which air drag is centered as it flies at small angles of attack. There are several methods of arriving at this, the best one being described in an easy-to-follow pamphlet available from NASA Goddard Space Flight Center, entitled "Calculating the Center of Pressure of a Rocket". Another less accurate but conservative method is to cut out an exact replica of the profile of the complete rocket from cardboard, and balance this cardboard silhouette on a knife-edge to find its center. This will be the approximate position of the CP.



DETERMINING APPROXIMATE CP BY THE CUT-OUT METHOD

CALCULATING STABILITY

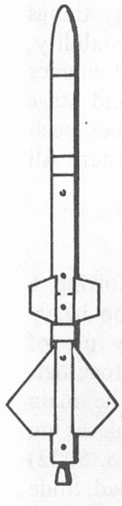
Having determined the critical CG point and the CP, all that is required is to compare their positions. For static stability the CG should be forward of the CP, or:

X_{cg} should be less than X_{cp}, measured from the nose tip.

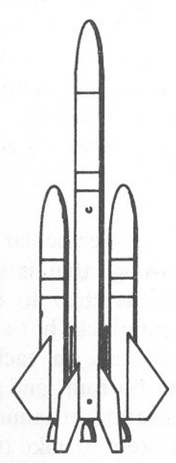
Note that we have determined stability at the worst possible moment when the CG is farthest aft. The rest of the flight should be considerably more stable than this. Also if you have used the cut-out method for finding CP the rocket will generally be more stable than indicated, as the actual CP is usually further aft than the point determined by the cut-out method.

STAGING METHODS

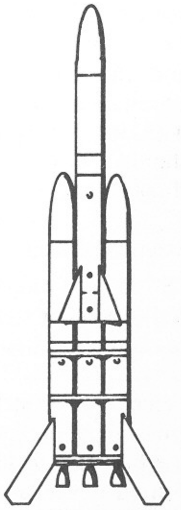
There are a number of methods possible to the imaginative modeler for accomplishing series staging or parallel staging with Valkyrie Rocket components. Methods range from straightforward to very difficult; the straightforward staged rockets may be avilable in kit form such as the Viking two stage rocket; the more challenging possibilities should be tackled only after some experience is gained in the design as well as launching of multistage configurations.



Series
Two-Stage
(Viking)



Strap-on
Boosters
Using Fin Rail
to Attach Them.



A Clustered
1st Stage with
V-1 2nd Stage.

Two Stage Series Type

Several varieties of series-staged configurations may be devised, the most workable being the Viking configuration. The Viking (see Figure 6) consists of two V-1 engines stacked one on the other, with a staging adapter to separate them in flight. (The V-1 engine is half the length of the V-2, has the same thrust, but for half the duration). The staging adaptor allows the second stage to be held in place by the normal action of the 1st stage separator, and to be released immediately at 1st stage "burn-out". The 1st stage is unstable after separation and tumbles, breaking its fall, while the 2nd stage is recovered by parachute in the normal way.

A V-2 2nd stage (large engine) can be launched in exactly the same way with a V-1 booster 1st stage, however this variation requires a warm day and careful loading to get good performance and stability at lift-off. Being a heavier vehicle than the Viking, it lifts off more slowly, and stage separation will occur at lower altitude.

A V-2 1st stage with a smaller V-1 second stage is also possible, however it takes some ingenuity to design 1st stage fins that are stable during boost but become unstable after separation. Another way to slow the fall of the 1st stage is to pack a small streamer in the adapter, but there is little room for one. The simplest solution is merely to launch over soft ground, and hope that the 1st stage separator is not damaged when it lands.

A V-2 stage on a V-2 booster is not recommended because the total lift-off weight is just too much for stability at lift-off.

Three-Stage Series Type

With the same precautions observed for thrust-to-weight ratio at lift-off, and flight stability, a three stage rocket made up of V-1 engines may be launched. It is spectacular, but it requires agile on-lookers to avoid all the falling stages without also losing them. Appropriate fin designs along with a staging adapter and plug for each stage are all that are required.

Clustered Boosters

A three engine clustered 1st stage may be constructed from three V-1 engines by taping them firmly together. Either a V-1 or V-2 second stage may be launched with this mammoth 6 pound thrust booster. Before attempting such a booster the modeler should recognize that this is a very complicated vehicle to launch, and like full scale space shots many things can go wrong. Large trailing fins are required for stability, and the booster must be launched electrically (all engines simultaneously). The central engine carries the second stage with its staging adapter, while the outer two engines each should carry a parachute for recovery of the booster. All three should have pierced timer discs for zero delay.

Strap-On Booster Rockets

"Strap-on" engines offer a spectacular way of lofting a Valkyrie-2 or vertical two-stage that is otherwise too heavy to launch. These may be attached to a rocket by use of fin rail, (No. 5021) which interlocks but slides freely together. Cement a 2 inch piece of rail on each side of the main (sustainer) rocket near the bottom, and matching pieces on the boosters. Add a short section of launch guide (No. 5022) behind the rails on the boosters to take the thrust load. Slide the boosters onto the sustainer from behind, and launch electrically all at the same time. Be sure that the whole rocket is stable, and that each strap-on has some means of safe recovery.

ASSEMBLY PROCEDURES

When assembling a multistage Valkyrie Rocket there are a few general rules to keep in mind to insure successful launches. These are:

Launching Guides on All Stages

For safety, be sure that both the 1st and 2nd stages are guided by the launcher. This insures that, should the second stage be released by accident after loading, it will fly vertically.

Test the 2nd Stage Recovery System

Verify by actual test that the 2nd stage parachute will release and deploy in the proper time.

Test for Immediate Release of 2nd Stage at 1st Stage Burn-out.

For best performance and for safety, stage separation must occur the instant the 1st stage propellant is exhausted. Verify by actual test.

Keep Rocket and Propellant Warm When Loading

Performance is drastically reduced, and stability at lift-off may be affected if propellant is allowed to chill itself too much when loaded. Be patient, load slowly, and vent only as necessary.

Be Sure Your Rocket is Stable in Flight

If you use our designs and follow directions carefully, you should have a stable rocket. However, if you make any changes, or design your own, you must also be certain that your new design is stable. See the appropriate sections and references for guidance on how to do this.

Rail Launcher

To launch the heavier multistage rockets you can improve their performance and enhance your launch complex by building a rail launcher. This can easily be done by using Fin Rail (No. 5021). Three 1-foot pieces of rail, carefully chamfered at the ends and glued end-to-end to a rod, stick, or rigid structure make an excellent launching rail. A mating piece of rail glued to the rocket will interlock but slide freely, providing rigid guidance to your rocket, and realistic appearance to your launch complex.

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