

LTA 14

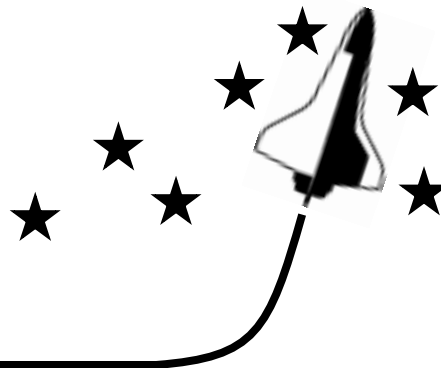
*NASA - AMATYC - NSF
Project Coalition*

Kennedy Space Center

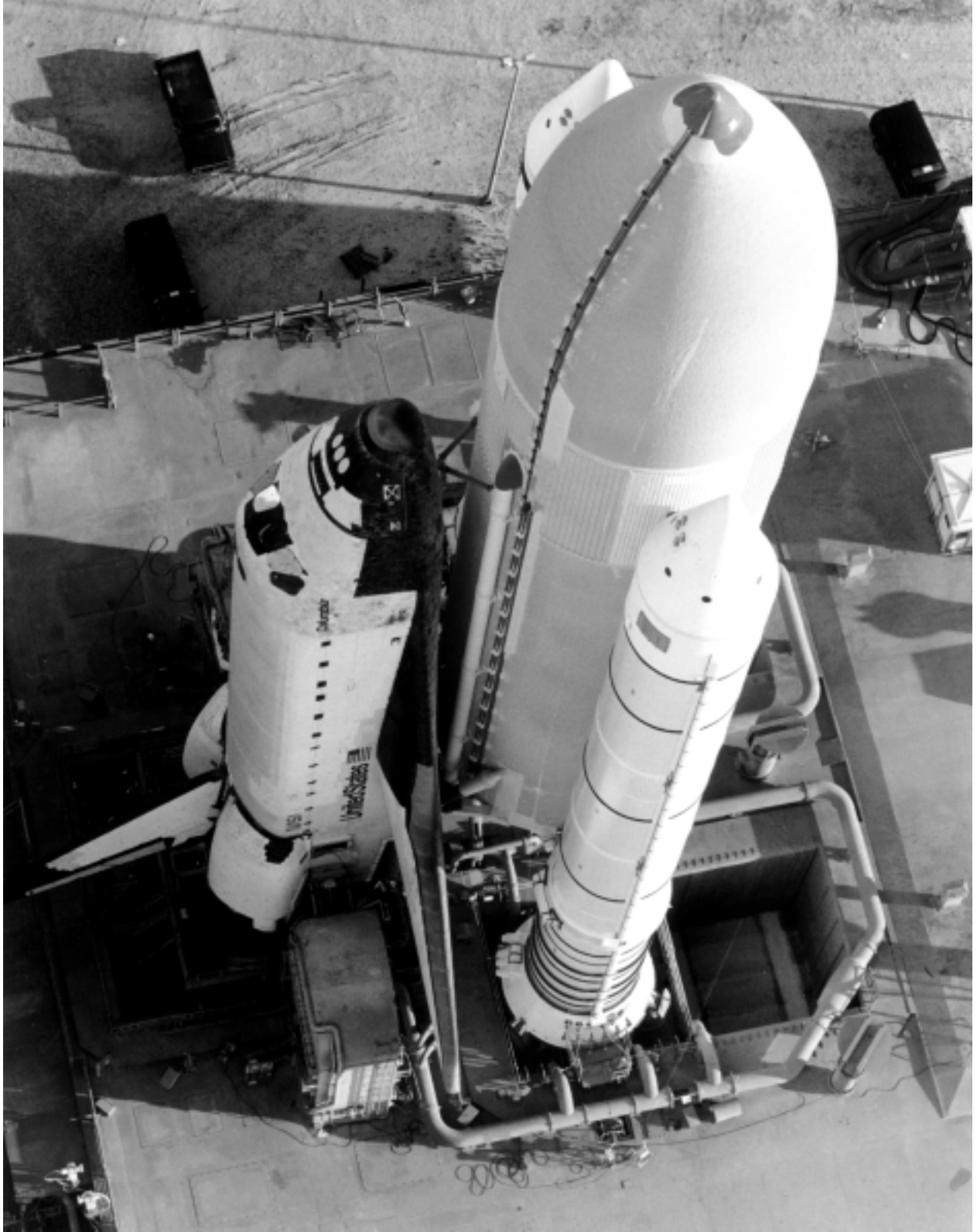
**Space Vehicle Hold Down and
Release Mechanism Design**

Mathematics for Engineering Technology

Mechanical



Capital Community College



The Space Shuttle COLUMBIA, its External Tank, and Solid Rocket Boosters are readied for launch as its moves from the Vertical Assembly Building to Launch Pad 39B.

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Space Vehicle Hold Down and Release Mechanism Design

Mathematics for Mechanical Engineering Technology

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Space Vehicle Hold Down and Release Mechanism Design

Background

Space vehicles are expensive to launch. The rockets, which are used to lift a vehicle into space, are only able to lift a certain maximum weight. Since both the vehicle's structure and payload contribute to the total weight, any decrease in structural weight would increase the payload weight that could be launched. As a result, it is important to design a vehicle and launch system so that the vehicle's structural weight is kept to a minimum. It is also important, where possible, to keep external forces on the vehicle to a minimum. External forces include the force of winds in the atmosphere and the jerking motion encountered when the bolts, which hold the rocket in place before launch, are blown loose. If the external forces can be reduced, then the vehicle's structure will not need to be as strong. This in turn will allow the structural weight to be reduced. In summary, to maximize the payload weight which is typically less than 10 percent of the total vehicle weight at liftoff, it is necessary to minimize the external forces encountered during launch and flight.

Just before liftoff, the rocket engines are ignited and they build up thrust to full power in about 4.5 seconds. During the buildup, the engines ignite at different times, so the thrust is uneven. If the vehicle were just resting on the launch pad, it would tilt and fall over while the engines were building up thrust. Therefore, the vehicle must be held down until all of the engines are balanced, working properly, and up to full power. When all the conditions are go, the vehicle is released.

Release Mechanisms

There are two general types of release mechanisms: soft and hard. A hard release is an instant release at full power. Typically, the hold down bolts of the restraining mechanism are secured by explosive nuts that are blown away to release the vehicle. A hold down bolt with an explosive nut is referred to as a pyrobolt. There is then a sudden jerk as the vehicle accelerates off the launch pad. This is analogous to what would happen at a tractor-pull contest if the cable attaching the tractor to the load suddenly broke. If the cable broke, the tractor would lurch ahead and the driver would be slammed against the back of the seat. Much more force is involved in launching a space vehicle. This sudden acceleration, or jerk, is hard on both payload and passengers. In order to mitigate the jerk, a controlled (soft) release mechanism, CRM, is added to the hard release structure. The diagram in Figure 1 on the next page shows the general components of a release mechanism and their relative positions. If a soft release mechanism is used in a launch, there would be little or no jerk. Then, it is possible that the structural weight of the vehicle could be reduced and its payload capacity increased.

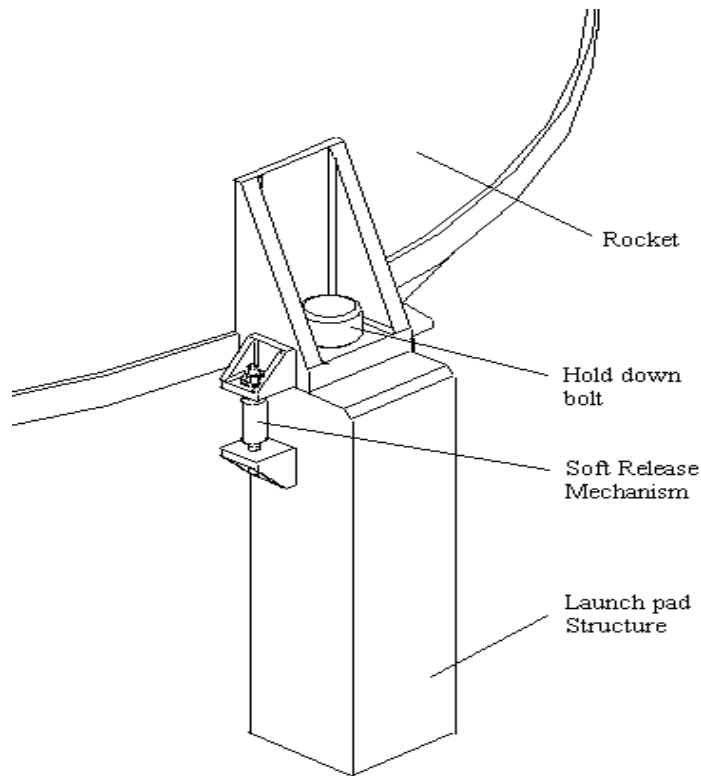


Figure 1: Controlled Release Mechanism

Jerk

In engineering applications, the concept of jerk is defined as the rate of change of acceleration. Jerk can be calculated by dividing the change in acceleration by the corresponding change in time.

Section I

Restraining Force vs. Displacement Graphs

The general property required of a soft or controlled release mechanism is that it should have a high initial restraining force which will gradually decrease to a small value when the rocket is completely released. The high initial restraining force serves to steady the rocket on the launchpad after the pyrobolts have been exploded. Then, as the restraining force of the controlled release mechanism (CRM) decreases, the rocket will begin to lift off the launchpad. With current requirements, the launch vehicle is under restraint only during its first few inches of liftoff and is then released. If the vehicle were restrained for too long, the rocket exhaust would severely burn the launchpad. Note that after the pyrobolts are blown away, the rocket remains attached to the launchpad by the controlled release mechanism until the rocket is a few inches above the pad. At that point the CRM has separated, and the vehicle is completely released from the launchpad.

The new Evolved Expendable Launch Vehicle (EELV) is now on NASA's drawing boards. NASA scientists are presently evaluating several release mechanisms. To maximize the payload, the EELV will use eight controlled release mechanisms (CRMs), not just a simple hard release system. Figure 2 shows a simplified diagram of the launch forces acting on each CRM. The divisions by 8 shown in the diagram assume that the launch forces are distributed equally to each of the eight CRMs.

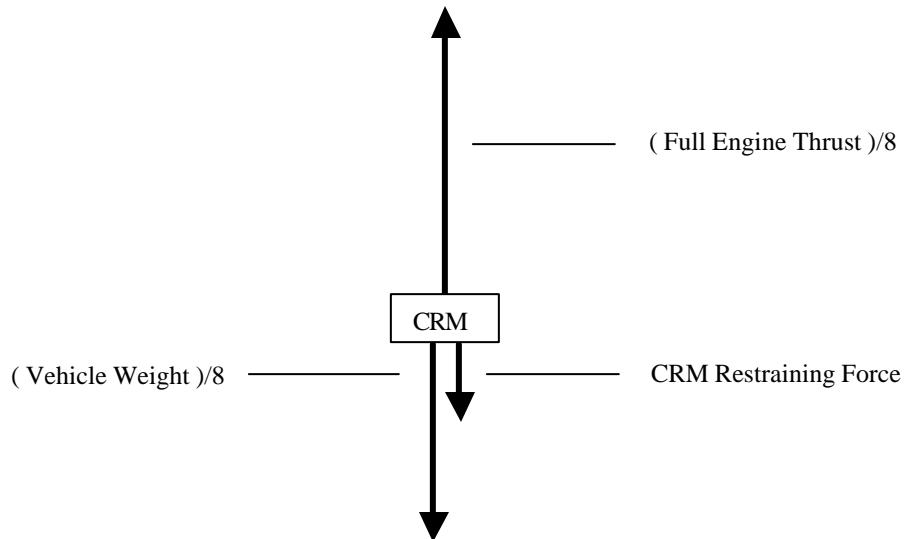


Figure 2: Launch Force Diagram

At the moment when the pyrobolts are blown away, the CRM restraining force together with one-eighth of the vehicle weight should equal one-eighth of the upward thrust of the rocket. In the next few seconds, the restraining forces of each CRM will diminish to zero, the **net** upward force will increase, and the vehicle will ascend.

Exercise

- 1) Sketch a possible graph which represents the restraining force, F , as a function of the displacement, d , that the launch vehicle is above the launchpad. Assume $d = 0$ when the pyrobolts are blown away. Refer to the properties and requirements of a CRM specified in this Section. Remember to label your axes appropriately. Your instructor may ask you to work on this exercise in groups. If so, compare your sketch with the sketches of several other groups. Critique the sketches of the other groups. Do you think the graphs of the other groups reasonably satisfy the conditions for a soft release mechanism? Why or why not? Explain.

Section II

Characteristics of a Restraining Force vs. Displacement Graph

The graphs of the force versus displacement functions in Figure 3 below represent the same three forces that are shown on the previous page in Figure 2. These graphs pertain to any one of the eight CRMs and assume that the forces are equally distributed to each CRM. Notice that at 0 displacement, one-eighth of the vehicle's weight added to the restraining force equals one-eighth of the full thrust. The graph of the Restraining Force vs. Displacement function is typical of a good soft release mechanism.

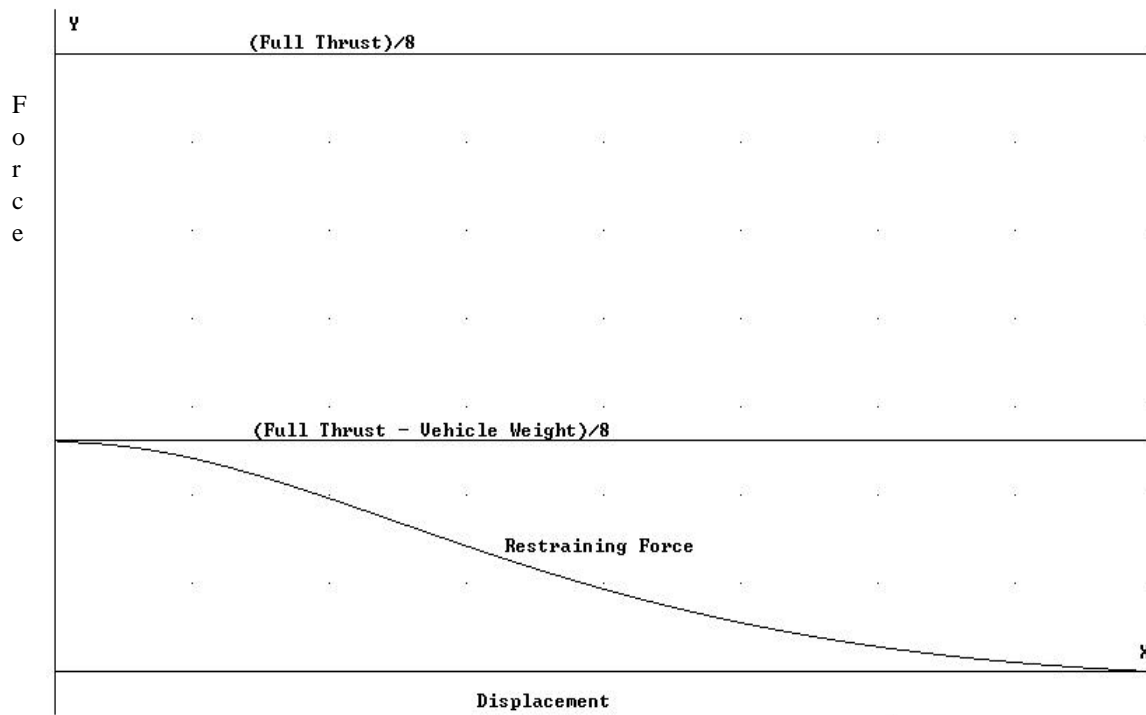


Figure 3: Launch Forces on Vehicle at Each Hold Down Point

Important characteristics of a good CRM restraining force vs. displacement graph:

- **Flat or nearly flat at the initial and final displacements:** This is significant because there will be little or no change in acceleration at these displacements. So, when the pyrobolts are blown away and the vehicle finally lifts clear, there will be a smooth transition. In general, sharp drops in the force curve are undesirable since these cause sudden jerks of the launch vehicle.
- **Decreasing restraining force:** According to Newton's Third Law, $F = ma$, the acceleration of the launch vehicle is directly proportional to the difference between the thrust of the rockets and the sum of the vehicle's weight and the combined restraining forces of the release mechanisms. The objective of the soft release mechanisms is to provide a smooth, yet swift, liftoff. If the force curve were to increase with displacement, then the acceleration of the vehicle would be impeded, slowing the launch of the vehicle and wasting energy. In fact, if the restraining force kept increasing

indefinitely the vehicle would never leave the launch pad. Hence, the CRM restraining force should decrease throughout the entire displacement interval.

- **Low restraining force at release:** Upon release, if the restraining force is nonzero, there will be a jerk.
- **No sharp corners:** Sharp corners in the restraining force curve would also cause jerk.
- **Energy absorption:** Another general property of the restraining force vs. displacement curve is that the area between the curve and the horizontal (displacement) axis represents the energy absorbed by the soft release mechanism during the launch. If too little energy is absorbed, the area under the force vs. displacement curve would be relatively small. If this were the case, the restraining force would diminish too rapidly and the vehicle would experience a jerk during launch. That is, if the energy absorbed by the restraining mechanism is insignificant compared to the energy generated by the thrust, it will not smooth out the motion very much.

On the other hand, the CRM must be designed so that it does not absorb too much energy. The CRM must absorb only enough energy to perform its function of smoothing out the motion. Any energy absorbed above this minimum requirement would take away energy needed to launch the payload. Also, any excess energy absorbed by the CRM would keep the rockets near the launchpad for a longer period of time, a result that could seriously damage the launch platform. In order to balance the need to keep jerk to a minimum against the need to get off the launchpad in a short time, NASA scientists require that the maximum displacement be approximately seven (7) inches when the vehicle is fully released.

Note: With respect to the following exercises, assume that an acceptable range for CRM energy absorption is 125,000 in-lb to 250,000 in-lb.

Exercises (2 - 6)

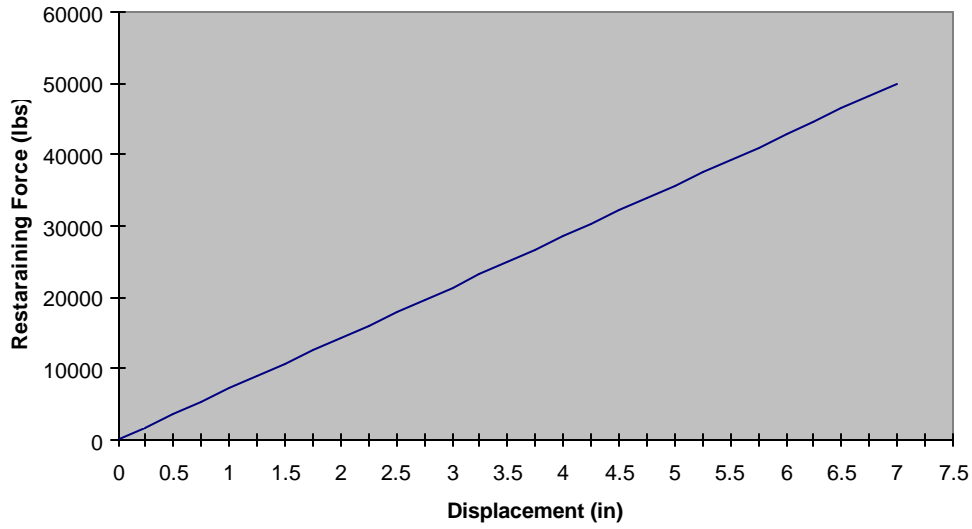
Each of the following graphs for Mechanisms A through E represents either a real or a hypothetical controlled release mechanism (CRM).

- a) List the characteristics for a good restraining force curve, as described in this Section, that each mechanism exhibits and the characteristics it lacks.
- b) For each graph, shade in the region between the curve and the horizontal axis. The area of this region represents the total energy absorbed by the mechanism before release. Approximate the energy absorbed for each mechanism. To do so, you will need to approximate the region with one or more non-overlapping geometric objects such as rectangles, triangles, or trapezoids. Show clearly on the graph how you have subdivided the region and estimated its area.

In all of the following graphs **assume** a total, constant launch vehicle thrust that is 400,000 lbs more than the vehicle's weight.

Note: Each graph represents the behavior of a particular CRM mechanism. Recall that there are eight (8) CRMs per launch vehicle.

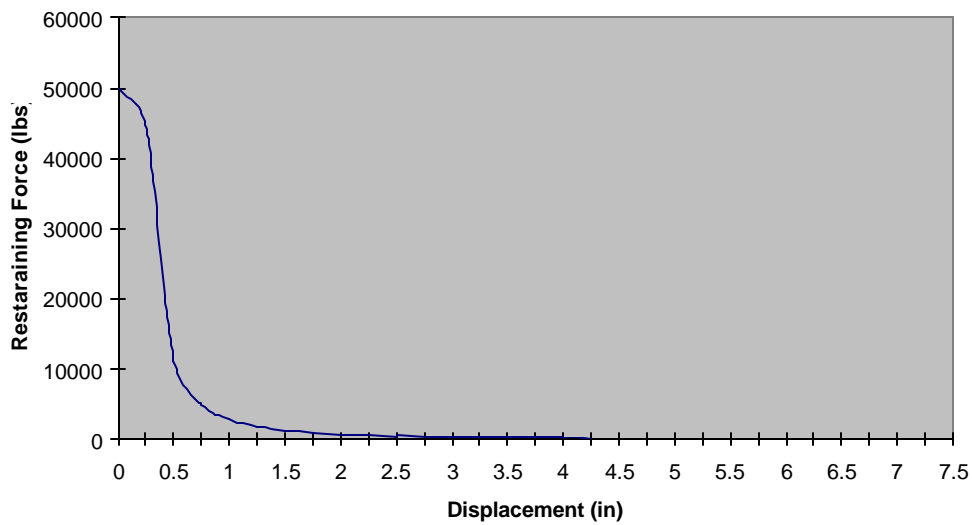
Mechanism A



2a)

2b)

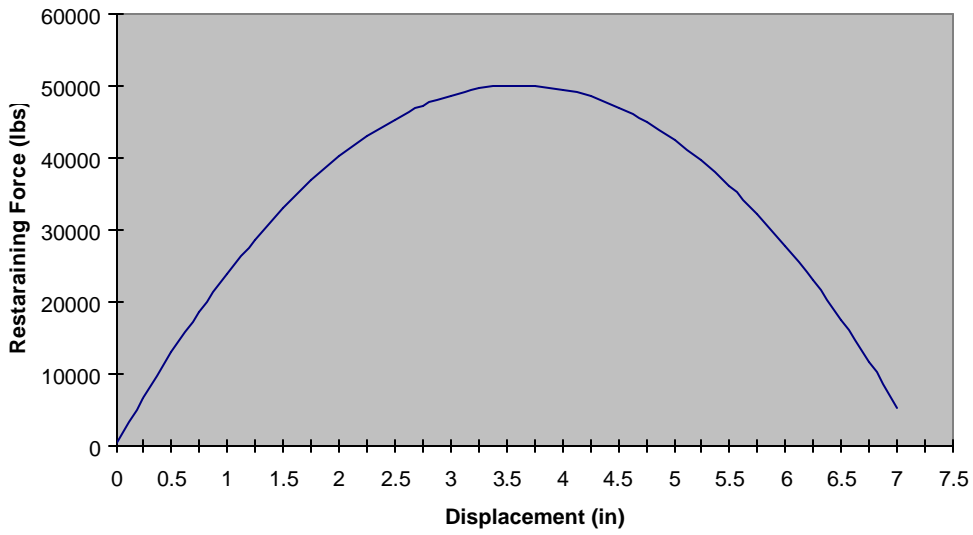
Mechanism B



3a)

3b)

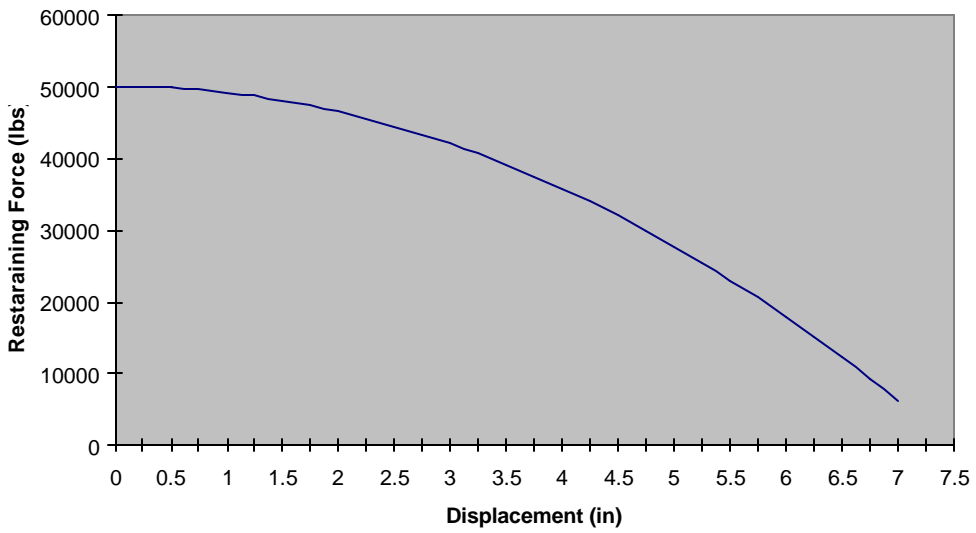
Mechanism C



4a)

4b)

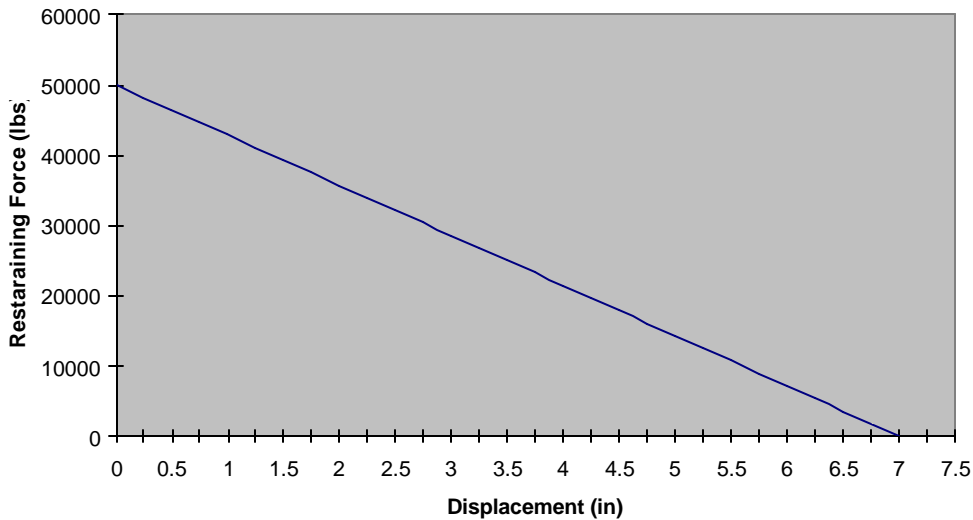
Mechanism D



5a)

5b)

Mechanism E



6a)

6b)

- 7) Rank the three best mechanisms, and justify your selection by referring to the list of characteristics for a good CRM.
- 8) Rank the mechanisms by energy absorbed.
- 9) Which mechanism would you choose as the best mechanism, and why?

Section III

Controlled Release Mechanisms for the Evolved Expendable Launch Vehicle (EELV)

The general requirements for any Controlled Release Mechanism designed for the EELV are:

- 13.5 kip (kilopounds) load capacity
- 7 inch stroke (maximum displacement at release)
- Tension in the mechanism should decrease as the displacement increases.

As you read about the following CRM mechanisms, try to imagine their restraining force vs. displacement graphs.

To meet the general requirement that the tension due to the CRM decreases as the displacement increases, two of the following mechanisms need to be pre-loaded before they are installed. **Pre-loading (pre-stressing)** a mechanism involves stretching it a certain amount before it is placed in service. Once the mechanism is stretched, it does not shrink back to its original length. Materials that can be continuously deformed into other shapes are said to have **plasticity**. To understand why a CRM may need to be pre-loaded, refer to the graph for Mechanism C in Section II. One of the disadvantages of this force vs. displacement curve is that the force increases for the first part of the curve. If we could start the curve at its maximum, then the remainder of the curve would be a reasonable force/displacement profile for a CRM. As you can tell from its graph, if Mechanism C were stretched by approximately 3.5 inches before attachment to the EELV, the force/displacement curve would then decrease for the remainder of the graph and become a valid force/displacement profile. Pre-loading is commonly used in engineering applications.

CRM Descriptions

The following drawings are not to scale. In each case, the flight side of the mechanism is attached to the rocket, and the ground side is attached to the launchpad and remains on the ground.

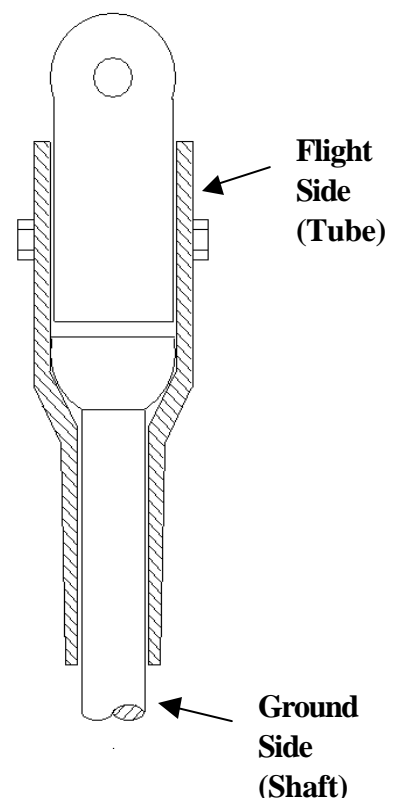
Mandrel Mechanism

Description:

The flight side is a tapered 300 Series stainless steel tube. The ground side is a hardened steel shaft with a hemispherical end. At liftoff the tube is pulled over the shaft. The tube then becomes plastically deformed. The wall thickness of the tube can be designed to “tune” the Force-Displacement diagram. Narrower walls provide less restraint, thicker walls provide more restraint. The taper (decreasing wall thickness) of the steel tube creates a restraining force that decreases with displacement (shaft movement).

Advantages:

- Can be modeled with relative accuracy
- Tolerant of machining errors
- Moderate manufacturing difficulty
- Predictable stroke length
- Tunable Force-Displacement curve means that the jerk can be made small upon release and allows the curve to be smooth during all phases of the liftoff. In particular, the curve can be made relatively flat just before release.



Disadvantages:

- Expensive to build
- Extensive testing required
- Pre-loading is required

Tensile Bar Mechanism

Description:

This mechanism consists of a single 300 Series stainless steel bar with a necked-down central section. There is a small groove near the flight connection. At liftoff, the bar stretches like salt water taffy. That is, once the initial stretching has begun, the rod stretches more easily as it gets longer.

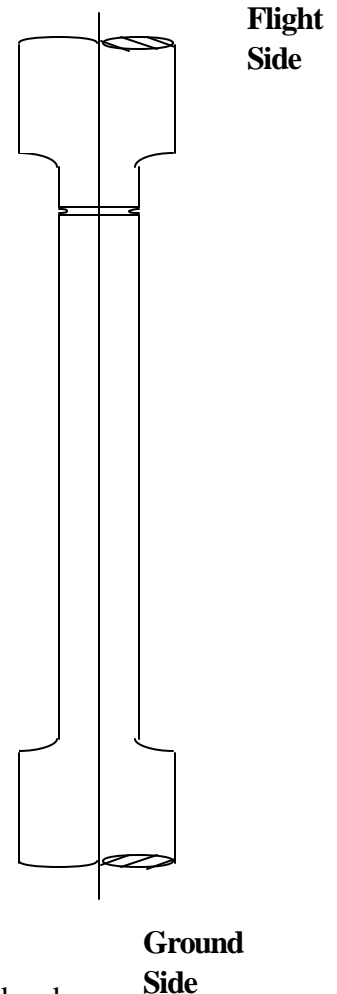
When the rod has stretched 50% more than its original length, it will reach the failure point and break. However, the high plasticity of 300 series steel allows the rod to stretch at least seven (7) inches before it breaks. This mechanism is designed to break at the groove when the launch vehicle has stretched the bolt to its failure point, thus releasing the vehicle.

Advantages:

- Very easy to machine
- No moving parts
- Inexpensive
- Very accurate force values
- Easy to model/predict force results

Disadvantages:

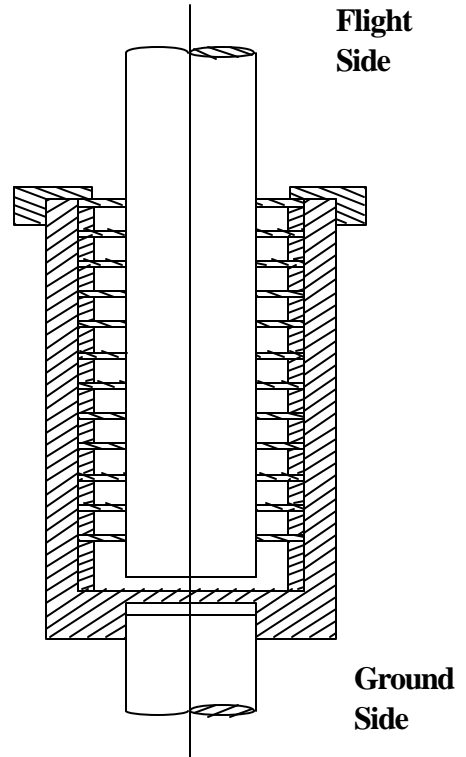
- Stroke length is not accurate since the point of failure is uncertain
- Force/displacement profile is not optimal since the shape of the profile for stainless steel is fixed due to the material's properties and may not allow for a flat or nearly flat curve just before release.
- Force/displacement profile is also not optimal since the breaking point of the bolt may occur at a large non-zero force for the stroke lengths considered.
- Device is longer than other concepts (about 15" vs. 9")
- Pre-loading is required



Friction Rod and Washers Mechanism

Description:

The flight side is a straight, hardened steel shaft. The ground side consists of a stack of flat circular washers and a washer retaining tube. The washers are shrink-fitted to the shaft. At liftoff the shaft is pulled through the washers. As the shaft clears each level of washers, the restraining force decreases.



Advantages:

- Repeatable use
- No pre-loading required
- Simple internal machining (straight hole)
- Tolerant of vertical motion

Disadvantages:

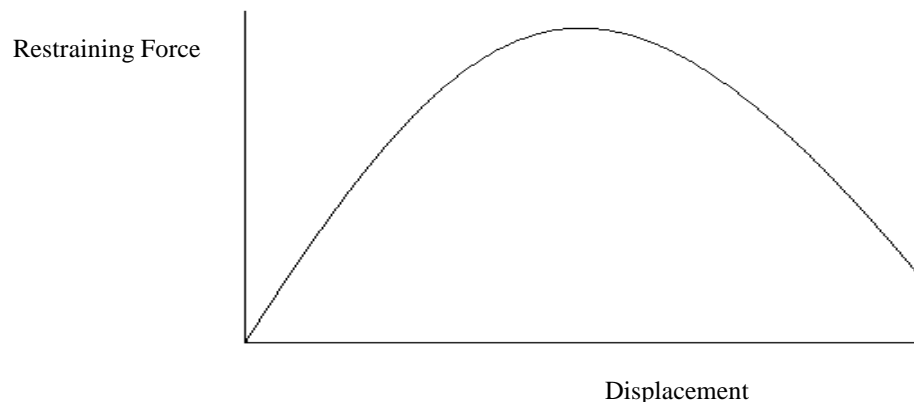
- High machining tolerance required
- Expensive
- Force will be difficult to predict accurately
- Requires extensive testing

Exercises (10-12)

Match each graph with one of the CRMs described in this Section. Explain each of your choices. In your explanations, quote a sentence or phrase from the mechanism descriptions that support your choice. Assume the graphs in Exercises 10-12 represent CRMs that have **not** been pre-loaded. For each mechanism that requires pre-loading, sketch a force vs. displacement graph for the mechanism **after** it has been pre-loaded.

10)

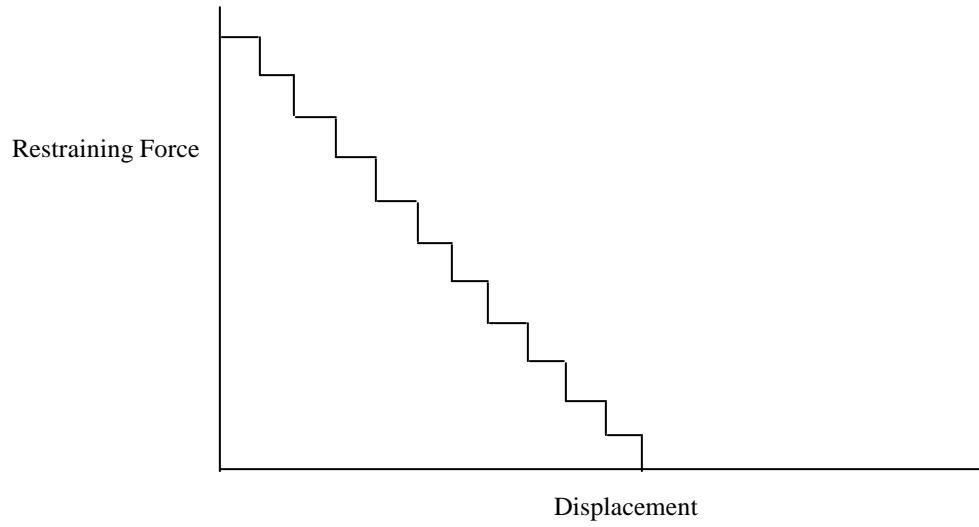
Graph 1



- a) Mechanism: _____
- b) Explanation:
- c) Force vs. displacement graph after preloading (if preloading applies):

11)

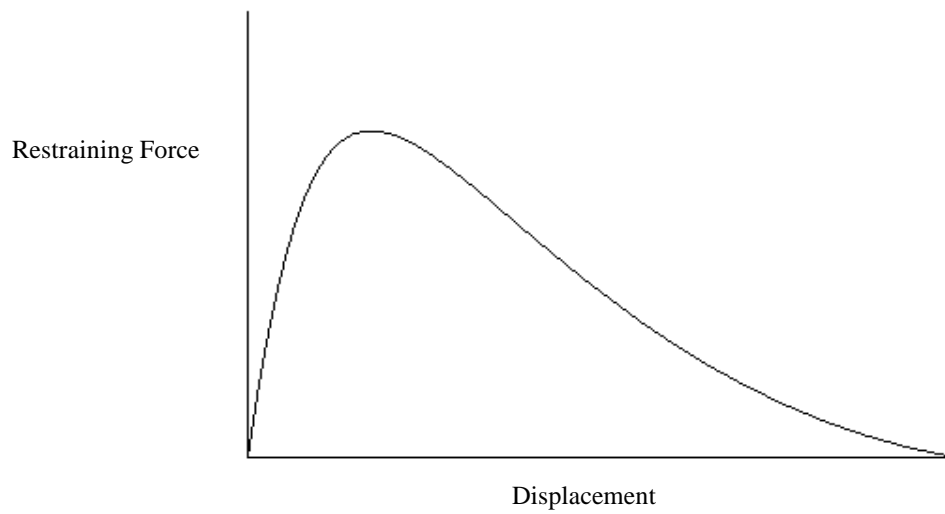
Graph 2



- a) Mechanism: _____
- b) Explanation:
- c) Force vs. displacement graph after preloading (if preloading applies):

12)

Graph 3



- a) Mechanism: _____
- b) Explanation:
- c) Force vs. displacement graph after preloading (if preloading applies):

Section IV

Data Analysis and Curve Fitting

NASA engineers are responsible for designing a CRM which will satisfy the requirements of the EELV. To determine how the CRM will perform, a CRM is constructed and then tested in a materials laboratory. Data on its force/displacement profile are collected. A polynomial curve is fit to the data to create a model of the CRM's behavior during launch.

Exercises

The following table contains data representing the force/displacement profile of a CRM. Use a polynomial fit (of degree 4 or greater) to model this data and answer the questions below.

Displacement (in)	0	0.5	1	1.5	2	2.5	3
Restraining Force (lbs.)	50,001	48,766	45,243	39,927	33,517	26,764	20,329

3.5	4	4.5	5	5.5	6	6.5	7
14,688	10,095	6,600	4,104	2,428	1,366	731	372

- 13) Determine your polynomial model.
- 14) If launch occurs when the CRM has been displaced 6.83 in, what is the restraining force at release?
- 15) If the CRM releases the launch vehicle when the restraining force is 1,044 lbs, what is the displacement of the CRM?
- 16) For the Tensile Bar CRM, the failure should occur at 50% elongation. If the tensile bar is 14" long, at what **displacement** will it break? Sometimes the bar does not break exactly at the 50% mark. What would be the restraining force if the bar broke at 47% elongation?

17) What would be the restraining force if the bar broke at 53% elongation? What are some limitations of your polynomial model?