The Problem with the Space Shuttle and the Space Program

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Fairfax, VA
1992, 2000, 2003

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Postscript – February 2003

It is time to fix the space program.

The Columbia tragedy has again plunged NASA into a period of uncertainty, investigations and recovery. National leaders are calling to learn from past experiences, particularly, the Challenger investigations. My extensive investigation of the Challenger accident revealed a very serious error in the design of the Space Shuttle and other space hardware. This Report describes how, when, and why the mistake happened; and how one major design mistake by a few engineers has needlessly undermined the whole space program.

The mistake may sound far-fetched. One engineer sent me an e-mail asking, "*Is this Report a joke*?" The major error is real. This Report is written so as to make the design blunder crystal clear to the student, teacher, professor, politician, lawyer, artist, scientist, engineer, reporter and others. Actually, the lengthy Report can be summarized in one plain paragraph:

If you release a bag of potatoes suddenly on a weight-scale in a supermarket from zero height, you will see the dial overshoot the weight of the potatoes, oscillate and then settle down on the actual weight. The momentary overshoot is called the "dynamic overshoot." Generally, the faster you release a force, the greater is the overshoot. The faster a rocket engine reaches its maximum thrust, the greater the dynamic overshoot and its adverse effects. The most important advances in the Shuttle program were the SSME (Space Shuttle Main Engine) and the SRB (Solid Rocket Booster). The SSMEs and SRBs packed more power that is released faster than anything we had before, and faster than any rocket engine used by the former Soviets or others. By neglecting the "dynamic overshoot" in Shuttle design in the 1970s, we shot ourselves in the foot. Ironically, everyone overlooked the dynamic overshoot effect in the design of his or her space hardware. Nonetheless, the former Soviets continued to launch 90 space missions annually in the 1970s and 80s primarily because their engines lumber to full thrust (hence, smaller dynamic overshoot), while we were reduced from 90 missions to a handful launches annually over the same period, primarily because our superior rockets jump to full thrust nearly instantly (hence, greater dynamic overshoot). In the meantime, great effort and resources were expended to pin down the "mysterious loads" that have been striking our space hardware with destructive effects. Have you ever read about the Shuttle "mysterious forces" in a newspaper or a magazine? The mysterious forces are caused by the dynamic overshoot that you will read about extensively in this Report. Our superior rockets of the 1970s became the invisible adversary of our space program.

In this Report, I will discuss the scientific, technical, historical, psychological, philosophical and political elements of the dynamic overshoot problem. The reader will see that the issue is more a psychological problem than a complex engineering problem, which exposes a flawed thinking process on the part of otherwise generally competent 20th century rocket engineers.

1. Introduction

You are about to plunge into a technical controversy that surrounds a massive engineering error, which has plagued the Space Shuttle, satellites, space probes and observatories. A serious error in the initial 1972 design of the Space Shuttle has undermined the effective operation and performance of the system. A first-order effect, known as the "dynamic overshoot," was completely overlooked by the aerospace engineers since the beginning of the space program. The mistake went unnoticed even after the extensive Challenger Accident Investigations. The "dynamic overshoot" design error is described at length in this Report. The nature and the magnitude of the error are easy to perceive and there is plenty of supporting evidence. You will see why rockets built during the early stages of the space program had the bad habit of exploding on the launch pad and why every launch vehicle that was built experienced failures or outright explosions during development. You will see why many missions to Mars, Venus, Jupiter and elsewhere have either experienced serious malfunctions or were lost altogether. The same mistake explains why the Shuttle has averaged less than 5 problematic missions per year, instead of the originally planned 60 flawless annual flights. This Report describes how, when, and why the mistake happened.

The consequential "dynamic overshoot" mistake was made in the design of almost all space vehicles and missions and almost all parts of the Shuttle and other hardware. This one error has undermined the whole space enterprise.

I am an aerospace mechanical-structural-dynamics engineer. I began my aerospace career with COMSAT Labs in 1969. In the 1970s, I discovered that my co-workers had the proclivity to repeatedly make a specific serious design error, which is the same "dynamic overshoot" subject of this Report. Specifically, I eliminated the random explosion of spacecraft fuel tanks during tests in 1970, and I recorded the mistake and the fixes in technical memos (see Fig. 64). I left my aerospace job in 1978 because the Space Shuttle, which was supposed to begin flights in that year, ran into serious problems. The Shuttle did not begin flights until 1981. Subsequent events would show that the initial delay was also caused by the same "dynamic overshoot" error, though no one noticed.

When the Report of the Rogers Commission on the Challenger Accident became available in June 1986, I examined it and discovered that the omission of the dynamic overshoot was rampant in Space Shuttle design. The engineers who design the Shuttle also design our military systems. I did not know how the Administration of President Ronald Reagan would handle a massive mistake in the design of sensitive systems. I therefore decided to keep the "dynamic overshoot" mistake confidential. In 1986, I shared the error only with NASA and military engineers in meetings behind closed doors. At the time, NASA decided to preclude me from participating in the recovery effort after Challenger to eradicate the massive mistake.

In 1989, I discovered that NASA, and others, were still making the same "dynamic overshoot" mistake in the Space Shuttle. I started another campaign to eliminate the mistake from the Shuttle and other systems. By now, the collective aerospace, engineering, academia and media communities stood firmly against my assertions. The doubters made it necessary to write this lengthy Report and to use many evidential examples to dispel any doubt in anyone's mind about the nature and the enormity of the "dynamic overshoot" blunder.

The extensive evidence in this Report was shared with the White House, the Congress, the DOD and, even, the courts, and some people recognized the major design error in the early 1990s. After Challenger, the Space Shuttle continued to experience difficulties and failures, e.g., the fuel leaks that literally grounded the Shuttle fleet in the early 1990s. The fuel leaks had nothing to do with the O-ring seals that were blamed for the Challenger tragedy. You will see that even the fuel leaks were caused by the same transient "dynamic overshoot" effect.

Many readers remember that the Challenger tragedy was officially blamed on faulty design of the O-ring seals in the solid rocket boosters. Since 1986, I held firmly to the opinion that the O-ring seal design was not the primary cause of the Challenger tragedy, nor was it the cause of the many failures that the Shuttle and its payloads experienced since first flight. My opinion is based on extensive hands on experience in the design and test of aerospace pressure vessels, O-ring seals, joint rotations and similar issues. Furthermore, film footage, wreckage and metallurgical evidence reveal that the O-ring seals failed in flight, 8-seconds after liftoff, and, hence, could not be the cause of the Challenger accident. My Report on the joint design and O-ring seals in the boosters was well received in engineering circles in 1986. That Report will be added to this web page later.

By the time you reach the end of this paper, you will discover that the dynamic overshoot problem is conceptually simple. The problem involves two numbers. The crux of the controversy that raged between NASA and me for six years centered on whether one compares the two numbers or adds them. Actually, the controversy goes back to the 1960s – then it was between the engineering faculty at my *alma mater* the George Washington University (GWU) and me. The thrust of a rocket engine or booster reaches maximum value rapidly. Because the thrust rises rapidly to maximum value, the effect on structures magnifies by a factor known as the "dynamic overshoot." The "thrust" and the "dynamic overshoot" hit the Space Shuttle hard at lift-off. The central controversy here is whether the engineers should add the maximum thrust force and the dynamic overshoot force to obtain the maximum-total force acting on the Shuttle, or should the engineers simply compare the two numbers and select the greater of the two values for design. What the engineers have been doing since, and including, Dr. Wernher von Braun has been to compare the thrust and the dynamic overshoot and then select the greater of the two values for design. The consequences of this practice have been devastating, not only to the Space Shuttle, but to the whole space program.

In great detail, with clear evidence and with simple examples, this Report describes a "huge" mistake in space design. The "huge" mistake is rooted in words that all of us learned when children: *"To every action, there is an equal and opposite reaction."* Think about it. In a 10-hours flight at constant engine setting, is the "reaction" in the airframe equal to the "action" for 36,000 seconds? How about in the first second, when the engines ramp up to full power? What if the engines ramp up gradually to full power? What if the engines ramp up suddenly to full power? What did Sir Isaac Newton say about it? Did Newton say anything about "gradual" or "sudden" actions – and their reactions? The Shuttle boosters burn for 2 minutes on a given flight. The boosters reach full thrust in 600 milliseconds. Is the reaction equal to the action for 120,000 milliseconds, or for only 119,400 milliseconds? What happens in the first 600 milliseconds? That is when the first-order "dynamic overshoot" effect strikes with full force.

The "dynamic overshoot blunder" is one mistake that produces a thousand problems in a system like the Space Shuttle. This Report shows that instead of fixing the one mistake, the engineers fell into the trap of fixing the thousand problems one at a time. The one mistake: (1) complicated the assembly, operation, maintenance, and management of the Shuttle, (2) delayed Shuttle flights, (3) drastically reduced the number of Shuttle flights, (4) increased the weight of the system, (5) reduced its payload capacity, (6) dramatically increased the cost of Shuttle launches, and (7) exposed the astronauts to tragic accidents.

I have dealt with this one major engineering mistake several times in 5 decades – yes, since the 1950s. I have seen the same mistake made many times by many engineers in space and other systems. I submit recommendations at the end of this Report to deal with the "dynamic overshoot mistake" in the Space Shuttle, *Space Shuttle-II,* the space program and in education.

2. *"I am not A Rocket Scientist. Will I get it?"*

You might say, "*I am not a rocket scientist, will I get it?* The answer is *YES*. The simple example below clarifies the issues that we will discuss in this Report to technical and non-technical readers. The reader should look not only to the nature and the magnitude of the massive error, but also to the thinking of the rocket scientists and engineers involved in the mechanical-structural-dynamic design of the Space Shuttle and the other space systems.

A woman who weighs 100 pounds steps suddenly on an old bathroom scale, *from zero height*. The dial overshoots, oscillates, and settles down to show her 100-lb weight. What is the maximum possible overshoot? The answer is 100-lb, exactly the weight of this woman. Even though it happens quickly, the weight-scale actually experiences the excess force, a total of 200-lb. If the bathroom scale has a little damping, then the first overshoot is less than 100-lb. Our young lady will be concerned if the dial settles on 110-lb. This means that she gained 10-lb. But, she will not panic if she glimpsed the first dynamic overshoot of, say, 190-lb. The lady will not think that she has gained 90-lb. Her weight is the applied force of 100-lb, but the scale in fact experiences 190-lb, due to the "transient dynamic overshoot."

Let us design a bathroom scale for this lady. Let us use a safety factor of 1.5, or a safety margin of 50%. If the maximum dynamic overshoot is 90-lb, then the bathroom scale must be designed to withstand 190-lb, and not only the 100-lb weight. To see what the aerospace experts have been doing, I have selected four Groups of engineers to design the bathroom scale. Look at what the four Groups do:

Table–1 Four Groups of Engineers Design an Old Bathroom Scale

Force Component	Group 1	Group 2	Group 3	Group 4
Applied force (the weight)	100 lb	100 lb	100 lb	100 lb
Dynamic Overshoot (or factor)	0 lb	10 lb	90 lb	90 lb
Maximum Force on the Scale	100 lb	110 lb	100 lb	**190 lb**
Safety Margin (50%)	50 lb	55 lb	50 lb	95 lb
Design Load	150 lb	165 lb	150 lb	285 lb
Actual Safety Margin	(-21%)	(-13%)	(-21%)	+50%

- Group #1 follows Newton's Third Law of Motion, "*To every action, there is an equal and opposite reaction*." The lady weighs 100-lb, the scale *reacts* with equal force of 100-lb. This Group designs the bathroom scale to withstand the applied force (100-lb) plus the safety margin of 50-lb, or to a total design load of 150-lb. This product is inadequate. It has negative safety margins and it will fail in operation. This Group does not know anything about the dynamic overshoot.

- Rather than take the dynamics of the scale into account, Group #2 incorrectly considers the dynamics of the lady's weight. The overshoot on the scale may go up to 170, 190, or 200-lb, but this Group is more interested in what happens to the lady's weight. The engineers keep track of how the lady's weight fluctuates; say 90 to 110-lb. To be safe, they select a dynamic factor of 10-lb and add this value to the applied load. This Group designs the bathroom scale to withstand a force of 110-lb plus 55-lb for the safety margin, or a total of 165-lb. This product also has negative safety margin, and it will fail. This Group is confused about the dynamic overshoot effect.

- Group #3 knows about the dynamic overshoot effect. They can calculate the effect correctly and, even, measure it correctly. Yet, these engineers end up with inadequate design. Their reasoning goes like this: The applied load (the lady's weight) is 100-lb. The dynamic overshoot is 90-lb. Since the dynamic overshoot (90-lb) is less than the applied load (100-lb), they reason that designing the weight-scale to the greater of the two values is sufficient. Notice how this Group ends up with the same inadequate design as Group #1. Group #3 badly mishandles the "start-up transient dynamic overshoot effect."

- Group #4 calculates the correct dynamic overshoot (90-lb) and adds the effect to the applied load (100-lb). These engineers design the weight-scale to the correct load (190-lb). They then add the 50% safety margin (95-lb) and correctly design the scale to withstand the maximum force of 285-lb. This is the right way to do it. This Group does not exist among the aerospace-structural-dynamics engineers.

The weight-scales designed by Groups #1, #2, and #3 have negative safety margins. The scales will fail, and will require repairs and re-design. Groups #1, #2, and #3 designed the Space Shuttle, other space systems, e.g., the Hubble Space Telescope, aircraft, and, even, nuclear power facilities.

The above examples sound vulgar, but the examples describe what has happened in the design of the Space Shuttle, other launch vehicles and many satellites and space probes.

I have tried to eliminate the "dynamic overshoot mistake" from the space program since the 1960s. The fact that the mistake is still widespread in the 1990s indicates deep-rooted confusion in the minds of the experts.

There is an important analogy that will help to reveal the stealthy nature of the "dynamic overshoot mistake" in space systems. *The pressure in a rocket combustion chamber is analogous to the weight of the lady in the above old bathroom weight-scale example.* Let me be specific.

> *When a lady steps suddenly on a weight-scale, from zero height and with zero momentum, the dial overshoots. Suppose the overshoot is 100%. Then the dial shows twice the weight of the lady on the first dynamic overshoot. The weight of the lady, itself, does not double – I repeat, the weight of the lady does not double, but the effect on the weight-scale is double the weight of the lady.*
>
> *In a rocket engine or motor, the combustion of propellants builds up pressure (and temperature) inside a combustion chamber and the combustion products flow out of nozzles, designed to maximize the thrust. Because the nozzles are open, the pressure build-up does not overshoot – just like the weight of the lady does not overshoot. But the effect of the sudden pressure build-up on the parts of the rocket "overshoot."*

The analogy is then like this: The "weight of the lady" is analogous to the "pressure in a rocket," and the "parts of the weight-scale" are analogous to the "parts of the rocket." The weight of the lady does not overshoot, nor the pressure in a rocket. The "weight of the lady" and "the pressure build-up in a rocket" may fluctuate with time, but neither will overshoot. But, if the weight is applied suddenly on a weight-scale and the pressure builds up suddenly inside a rocket, then the parts of the scale and the parts of the rocket will experience the "dynamic overshoot." Why is this silly distinction important?

It has been the habit since the beginning of the space program to derive the design forces from pressure build-up measurements. But, the pressure does not overshoot. The pressure fluctuates about 1-3%. However, the forces in the parts of rockets overshoot about 70-100%. The first order effect has been neglected by everyone in the space program, including, Dr. Wernher von Braun. For example, the near-doubling overshoot is completely missing from all sketches of thrust build-up by von Braun. Why would von Braun preclude the devastating effect from his diagrams if he knew about it? Why would the Shuttle engineers preclude the destructive dynamic overshoot effect, or completely mishandle it in Space Shuttle design, if they understood the effect? Why would engineering, physics and aerospace faculty and experts angrily dismiss my assertions if they recognized the importance of the effect? The reader should look for the subtle nuances underlying the "dynamic overshoot blunder" to see why the strength of important parts of the Space Shuttle was doubled after the system was completely built and after the Shuttle entered into service. All of this, and more, are discussed at length in this Report.

3. The Space Shuttle

A typical Space Shuttle vehicle consists of the Orbiter, External Tank (ET) and two Solid Rocket Boosters (SRBs), Fig. 1. The structures that make up the Shuttle and hold it together must withstand the forces of lift-off, ascent, orbital maneuvers, re-entry, and landing. The most critical design forces are the lift-off loads from the Space Shuttle Main Engines (SSMEs), which are mounted on the Orbiter, and from the SRBs. The critical lift-off forces consist of the 100% steady-state thrust developed by the engines and the boosters plus the dynamic force components, which depend on how rapidly the thrust builds up in the first place. The dynamic force component, which is referred to as the "dynamic overshoot," is always a fraction of the steady-state force. Sometimes, the dynamic overshoot can reach the 100% steady-state force value itself. In that case, the force acting on the parts of the system is literally doubled. Space systems are rather fragile. You can imagine the severe damage that can happen when delicate space hardware is designed to withstand only the static force plus safety margins, without adding the dynamic overshoot force to the maximum thrust. The Shuttle thrust values that you have seen in engineering textbooks, journals, magazines, newspapers and, even in the Shuttle specifications, are strictly and simply the 100% steady state, or static, forces.

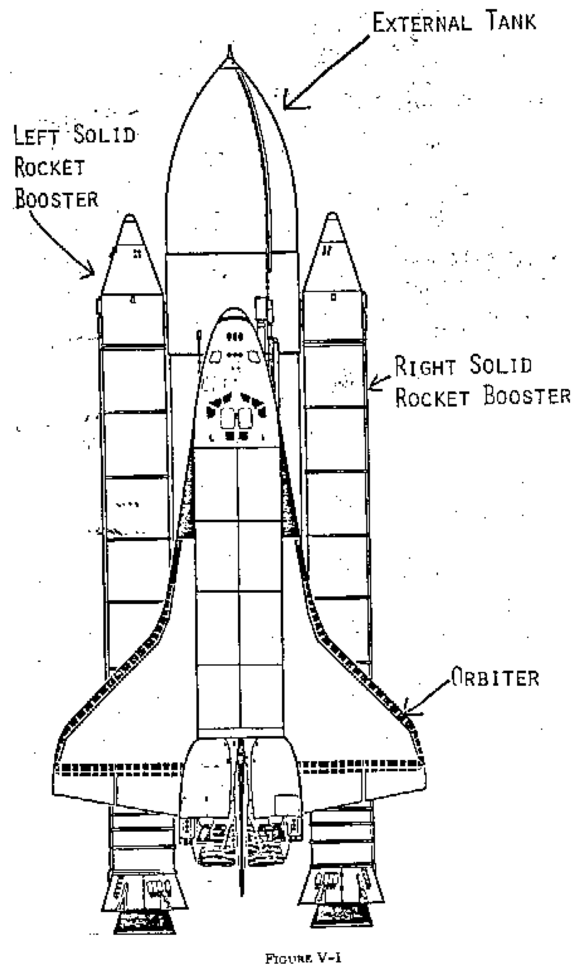


Fig. 1 The Space Shuttle

Rockets reach maximum thrust rapidly. For example, the SRBs reach maximum thrust in 600 milliseconds. This behavior approximates the familiar *unit-step-input* function, which is shown in Fig. 2. The *sudden thrust* causes the force to *overshoot* and it subjects the parts of the Space Shuttle to greater loads than the applied loads. Unless the *greater loads* are considered, the safety and reliability of the system will be threatened.

The response of a system to the unit-step-input is well developed. The effect on structures can reach *twice* the maximum input value. The near doubling of the input is the result of the "*dynamic overshoot*" phenomenon. The actual dynamic overshoot factors for the Space Shuttle are in the range of 70-100%. However, the Shuttle engineers used unreasonably small factors, e.g., 1-10%, which are grossly inadequate. In other instances, the Shuttle engineers knew that the start-up transient dynamic overshoot was 70 to 100% of the applied force, but the engineers failed to add the two forces. The consequences were ruinous to the Shuttle and to the space program.

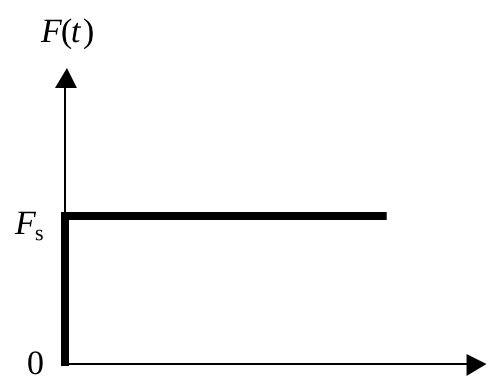


Fig. 2 Unit-Step-Input, or Sudden Forces Require Transient Analysis

4. *What Causes Dynamic Overshoot*?

Whether on the launch pad or in flight, a *sudden* change in thrust magnifies the effect of the applied forces before the final steady state is reached. A transient period always exists after engine start-up. In the case of undamped systems, the load effect is *doubled*. The phenomenon is commonly known in electrical circuits. When a switch is turned on, surge, or transient, current can trip circuit breakers, blow fuses or damage appliances.

Modern jet and rocket engines and motors have packed more power in smaller volume, which is released in shorter times. Starting powerful rocket engines is like turning on an electrical switch. Throttle-up of the Space Shuttle SSMEs and ignition of the SRBs approximates this behavior.

The effect of a suddenly applied force is stated clearly in some textbooks. In Shigley's *Mechanical Engineering Design*[1], we find: "*when the load is applied suddenly but without initial velocity … <u>the stress is twice</u> as large as that caused by a gradually applied load,*" (Emphasis added). For example, the stress, σ (sigma), in a beam of area *A* on which a weight, *W*, is suddenly released from zero height is given as[1]:

$$\sigma = 2\frac{W}{A} \qquad (1)$$

The term *W/A* is, by definition, equal to the stress, σ, which gives Eq. (1) the strange form:

$$\sigma = 2\sigma$$

or, in terms of the force, *F* (i.e., the weight W), the equally strange form:

$$F = 2F$$

Or, the unacceptable conclusion,

$$1 = 2!$$

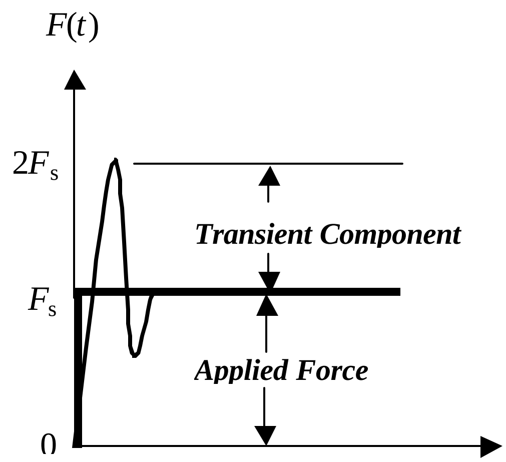


Fig. 3 Effect of Sudden Forces

To avoid any mix-up, let F_s be the suddenly applied steady-state force (the weight) on the beam and $F(t)$ be the total force experienced by the beam. Then,

$$F(t) = 2F_s \qquad (2)$$

The *doubled* force effect consists of two components as shown in Fig. 3. The force components are: (1) The applied force, or steady-state force, F_s, and (2) a transient-force-component, F_t. In other words, the total force, F(t), is:

$$F(t) = F_s + F_t \qquad (3)$$

The force doubling effect can be formally derived from the response of a system to a unit-step-input. The solution is standard and it can be found in vibration or control textbooks,[2-6] or,

$$x(t) = \frac{F_s}{k}(1 - \cos\omega_n t) \qquad (4)$$

The Greek *w* (omega) is the frequency of vibration. When the value of $\cos\omega_n t$ is equal to –1, we find that,

$$x(t) = 2\frac{F_s}{k} \qquad (5)$$

Extending the above result one step further by relating Hooke's Law, or $F = kx$, where k is the spring constant for the structure under consideration, to the time behavior of the system, or $F(t) = k\,x(t)$, we obtain,

$$F(t) = 2F_s \qquad (6)$$

This is what Shigley's textbook says in plain language in Eq. (1) above. Although Eq. (1) was given for stress, the *doubling* effect applies in tension, compression, shear, bending moment, and to related deflections. If the maximum thrust of a rocket is 1 million-lb, then the rocket, its payload and the launch pad may experience up to 2 million-lb, or *twice* the applied load. It is incorrect to design the rocket to the maximum applied thrust plus a safety factor as has been done with the Space Shuttle.

Strangely, the *doubling* effect is not mentioned at all in aerospace design textbooks and handbooks, and the consequential effect is almost never mentioned in physics textbooks or peer-reviewed scientific and technical papers. This may explain why the destructive effect was neglected in the design of the Space Shuttle and other systems. The oversight may also explain many failures of rockets, spacecraft and space probes since the beginning of the space program in the 1950s.

Damping is present in all real systems, and it can reduce the peak dynamic overshoot. Accurate peak dynamic overshoot with damping can be calculated using the following standard solution, (*Ibid*):

$$F(t) = F_s\,(1 + e^{-\pi\zeta\sqrt{1-\zeta^2}}) \qquad (7)$$

where, ζ is the damping ratio for the structural element, subsystem, or system being evaluated. The dynamic overshoot is the second term of the expression in the parenthesis.

The time to reach the peak dynamic overshoot can be calculated from the following expression,

$$t_{1\text{stOvershoot}} = \frac{\pi}{\omega_n\sqrt{1-\zeta^2}} \qquad (8)$$

The system response to a unit-step-input depends on the damping ratio, ζ, and the natural frequency, ω_n, of the structure under consideration. The overall time response, or the transient solution, to a suddenly applied force, takes the following form (see Refs. 2-6):

$$F(t) = \frac{F_s}{k}\left[1 - \frac{e^{-\zeta\omega_n t}}{\sqrt{1-\zeta^2}}\sin(\omega_n\sqrt{1-\zeta^2} + \cos^{-1}\zeta)\right] \qquad (9)$$

I have plotted the standard responses for different values of ζ (0.01, 0.1, 0.2 and 0.5) in Fig. 4. When a force, F_s, is applied suddenly in a system with a damping ratio of 0.01, then the effect of the force is nearly *doubled* to $2F_s$. There should be no doubt in anyone's mind that when the damping ratio is in the order of 0.01, as in the Shuttle's SRBs,[7] then the effect of the start-up force is nearly *doubled*.

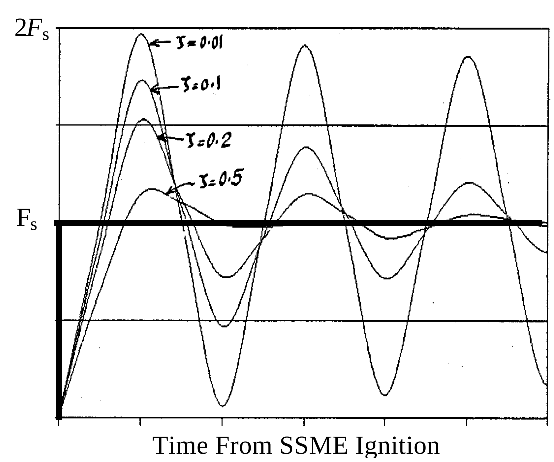


Fig. 4 System Response to a *Unit-Step-Input*

Damping ratios for aerospace and Shuttle-like structures range between 0.01 and 0.10. Typical overshoot factors for such systems can be found from Eq. (7), see **Table-2**. Look carefully at Eq. (7). There are two terms in the parenthesis. The first term, or one, is the 100% applied steady-state force. The second term is the *transient* force component. You can calculate the *transient* component separately, as shown in **Table-2**. But if you do, you must add the *transient* fraction to the 1 (one) term. One must not say that because the 100% applied force is greater than the 73% overshoot (0.10 damping ratio), then it is safe to design to only the 100% applied force. This may sound trite, but the practice has been widespread, especially, in the design of space systems, including the Space Shuttle.

Table-2 Dynamic Overshoot for Shuttle Damping Ratios

Damping Ratio	Dynamic Overshoot
0.01	96.9%
0.10	72.9%

For the SRBs, the overshoot (97%) is almost equal to the applied thrust itself. Using small dynamic factors, 1–10%, as has been done in Space Shuttle design had a devastating effect on the system.

The aerospace community vehemently rejected my assertions that the devastating *dynamic overshoot* was completely overlooked in the design of the Space Shuttle. The widespread confused attitude made it necessary to expand my research of the effect. I examined textbooks that are used to teach the design of aircraft, spacecraft and propulsion and I discovered alarming results. Consider the following engineering textbooks: "*Rocket Propulsion Elements,*"[8] "*Principles of Spaceflight Propulsion,*"[9] "*Aerospace Propulsion,*"[10] "*Mechanics and Thermodynamics of Propulsion,*"[11] "*Spacecraft Systems Engineering,*"[12] and "*Design of Geosynchronous Spacecraft.*"[13] These books do not even give, or explain, the standard methods available to calculate the first-order *dynamic overshoot* effect. These books and other engineering textbooks give extensive treatise on minor effects of the order of 5, 3 and 1%. But the consequential 70-100% *dynamic overshoot* effect is simply not discussed. This is nothing less than *collective amnesia*, for the authors of the textbooks, some of whom I know, are well versed in the straightforward transient analysis given above.

That the devastating *dynamic overshoot* occurs in rocketry is emphatically shown in the extensive database of *model rockets*. Since millions of model rockets have been sold, public safety demanded great scrutiny, random sample testing, certification and re-certification, which helped to identify the dynamic overshoot peak accurately.

Figure 5 shows how the effect of *thrust* in rocket motors is *doubled* at start-up. The curve, from the *Handbook of Model* Rocketry,[14] is the result of *two million tests* of model rockets, which used well-developed test techniques and equipment. One might ask, how can the model rocket engineers accurately identify the overshoot while the real rocket engineers fail to do so? The answer may be found in the relatively short burn-time of model rockets.

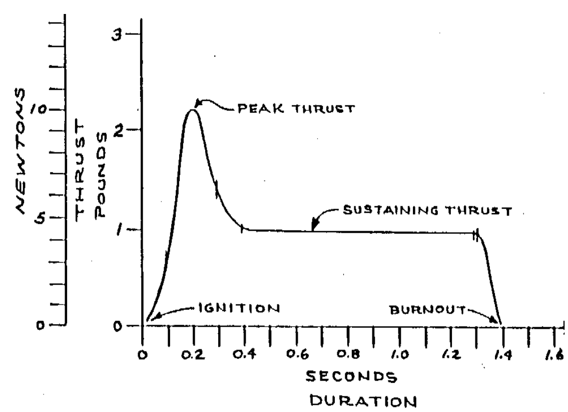


Fig. 5 Some two million tests of model rockets clearly show *dynamic overshoot*

Most model rockets burn for only one or two seconds. The total impulse (thrust × time, or the area under the thrust curve in Fig. 5) of a model rocket can vary by as much as 10% to 20% due to the dynamic overshoot peak. The total impulse of a Shuttle engine or booster, which burns for more than two minutes, is hardly affected by the dynamic overshoot peak. This may, in part, explain why this important overshoot peak has been less conspicuous in real rocketry than in model rocketry.

Engineering is applied science. The science is physics. Ironically, the physicists insist to this day that the dynamic overshoot in model rockets is due to the *shape* of the propellant charge in the toy rockets! These scientists refuse to see the glaring fact that solid rocket propellants ignite to full thrust in a fraction of a second, whether the charge is flat, dimpled or cored. It is the rapidity of thrust build-up that causes the overshoot, and not the shape of the propellant charge.

Unless accurate transient analysis and tests are specifically done to determine the magnitude of the dynamic overshoot for rocket engines and motors, the steady-state thrust must be nearly *doubled* for safe and reliable structural design. In the case of aircraft engines, the magnitude of the dynamic overshoot is not as severe as in rocket motors. Nonetheless, aircraft engines produce overshoot effects, which must also be accurately determined. Almost all of the aircraft technical literature that I examined gives only the *Rated Power Level* (RPL) thrust values. The RPL thrust designates the 100% applied thrust. The *dynamic overshoot* of aircraft engines is generally not mentioned or listed in aircraft design textbooks.[15,16] For example, only the RPL thrust for the American, European and Russian commercial transport aircraft can be found in books.[16] Using only the RPL values in design results in early fatigue, unexpected damage and accidents. Also, public safety demands that pilots be familiar with the *dynamic overshoot* concept and its devastating effects. For example, sudden throttle-up or throttle-down, or sudden correction of aircraft control surfaces can magnify the effect of forces. Generally, the pilots I spoke with about the dynamic overshoot phenomenon are not aware of the destructive effect.

It is incorrect to design space, or other, systems to the applied force plus a small factor for dynamics. The design load ***must*** include the applied force ***plus*** the correct dynamic overshoot force component. As you will see next, the consequential *overshoot* component was initially completely neglected in Space Shuttle design.

5. The Space Shuttle Designed to Static Loads Only

The lift-off loads are the most critical in Space Shuttle design. The *dynamic overshoot* factors are the second most critical because these are of the same order of magnitude as the applied lift-off loads. But, somehow, NASA and the Contractors failed to add the correct lift-off dynamic overshoot component to the static force component. You saw above that the lift-off *dynamic overshoot* could be of the order of 70-100%. The popular statistical method among the aerospace engineers, referred to as the 3-sigma (3σ) method, was used in Shuttle design. The 3-sigma method produces inadequate "*liftoff load parameters*," for example, 3% in Ref. 17, page 11. With such low factors for dynamics, it can be said that the Space Shuttle was designed to withstand only the applied, or steady state, or static loads.

The dynamic overshoot error is rooted in the history of the Space Shuttle. In 1972, Rockwell International, the Prime Contractor for the Shuttle, told a Congressional Committee outright that the Space Shuttle would be designed to static (i.e., steady-state), and not dynamic, forces:[18]

> "*So we have to do a loads and weights iteration on the static loads without the dynamics involved and then just put a factor in for what we think the dynamics are going to be.*" (Emphasis added).

The casual remark "*just put a factor in for what we think the dynamics are going to be*" betrays complete unawareness of the impending 70-100% mistake and its imminent devastating consequences. In 1973, Rockwell added dynamic factors in the range of 1-3%. A dynamic factor of 10% was used for the highest axial forces,[19] for which the dynamic overshoot is greater than 95%!

The primary tool used to design the Space Shuttle was the NASTRAN (NAsa STRuctural ANalysis) general-purpose finite-element computer program. Before the Shuttle Program, I was particularly active in the checkout of NASTRAN and I used the program extensively in aerospace design, e.g., Ref. 20. *Dynamic overshoot*, which is the largest load factor after the primary loads, was not mentioned in the massive computer program. Several Space Shuttle configurations were analyzed using NASTRAN in 1971, e.g., references 21-25. These, and other, studies dealt with a variety of *dynamic* conditions, but the start-up transient cases were not included in any of these studies. Ironically, NASTRAN is a powerful design tool for complex systems. The problem was not in the computer program, but in the manner that the aerospace engineers handled, or mishandled, the loading conditions.

Specifically, the designer does not tell NASTRAN that one SSME ramps up to 375,000-lb in a fraction of a second, and then hope that the program finds the maximum load, including the dynamic overshoot. Instead, he or she calculates the dynamic overshoot separately, adds it to the maximum thrust and gives the result to NASTRAN to do the analysis. This sounds simplistic, but it is important. For example, the dynamic overshoot for the SSMEs is about 73%. What should be the design load per SSME? Just take the thrust and add it to the 73% overshoot component. That's it.

Thrust per SSME at lift-off	375,000 lb
Dynamic Overshoot (73%)	273,750 lb
Design Load (1-SSME)	648,750 lb

What should be the design load for the three SSMEs? Use the same procedure. See Eq. (7). That's it.

Thrust (3-SSMEs) at lift-off	1,125,000 lb
Dynamic Overshoot (73%)	820,000 lb
Design Load (3-SSMEs)	1,945,000 lb

The reader should not worry about precision here. There is no need to find answers to nine significant figures. For our purposes, one can just say that the 1.1 million pounds (MP) start-up thrust from the 3-SSMEs strike the Shuttle with about 1.9 MP force at lift-off. You will see next that the SSME engine specifications were greatly underestimated in 1972.

5.1 Initial SSME Lift-off Specifications

What was the SSME lift-off *design load* in the initial 1972 Space Shuttle specifications?

The basic performance and design requirements for the Space Shuttle are given in the voluminous JSC 07700 Program Definition & Requirements documentation, which specifies detailed Management, Technical and Resource Requirements for the Shuttle. The maximum thrust for each SSME was initially specified as follows,[26]

Table-3 The Initial SSME Specification

Parameter	Sea Level	Vacuum
Thrust ($\times 10^3$ lb)	375 + 6	470 + 6

The JSC SSME lift-off thrust specifications and the correct lift-off loads are shown in Table-4. Notice how I add the correct dynamic overshoot of about 800,000 lb, whereas the JSC specification includes only a dynamic factor of only 18,000 lb:

Table-4 Comparison of JSC's SSME Specifications and Correct Lift-off Load

Description	JSC Spec.	Correct Load
Steady-State Thrust	1,125,000 lb	1,125,000 lb
Dynamic Factor	18,000 lb	810,000 lb
Design Load	1,143,000 lb	1,935,000 lb

Thoughtful readers, rocket scientists or not, can already see that the Shuttle was grossly underdesigned from the beginning. Adding only 18,000 lb to the SSME liftoff thrust, instead of the correct 810,000 lb, was a significant design error. The JSC dynamic factor is a mere 1.6%!

Incredibly, NASA and Rockwell measured the correct *dynamic overshoot* in 1982, ten years after the JSC 07700 specification document, and after the Space Shuttle began to fly. The engineers expected to measure the 1.1 million pounds force, as specified in the JSC document. Instead, the engineers measured 1.9 million pounds force striking the Shuttle at liftoff. Do you see where the excess 800,000-lb came from? The excess force was the dynamic overshoot, as clearly shown in Table-4. The measured 73% *dynamic overshoot* caused considerable confusion among the engineers, as I will show with the actual Space Shuttle test data in Section 7. In essence, the engineers treated the unexpected *dynamic overshoot* as a mysterious force.

In thousands of graphic illustrations of the SSME's *dynamics* (in books, specifications and peer-reviewed journals), the correct *dynamic overshoot* is simply missing. The SSME's thrust is represented graphically as in Fig. 6, without the overshoot dotted lines. The engines throttle up to the 100% RPL (Rated Power Level), throttle down to another level, throttle up again to 104% level, and so on. *No dynamic overshoot* whatever. The same is true for the other Space Shuttle thrusters, and many other modern systems. I have added the *overshoot* with the dotted lines in Fig. 6.

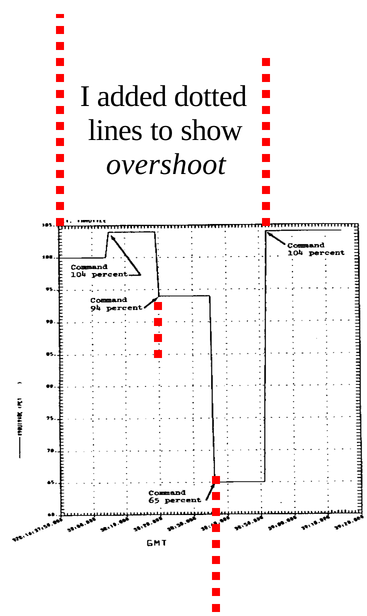


Fig. 6 SSME's Throttle-up and Throttle-down Commands do not Show Overshoot

A Rockwell Shuttle load's expert described the Shuttle "*Loads and Dynamics*" in a technical paper[27] presented to the International Council of Aeronautical Sciences Congress in 1982. The senior expert states that the dynamics of lift-off was included in the analysis. The expert writes,

> *"The principal variables that must be considered in the analytical simulation of lift-off are: 1. Structural dynamic mathematical model."*

The first item mentioned by the Rockwell expert under the titles, "*SSME thrust characteristics*," and "*SRB thrust characteristics*," was "*Build-up rate*." Build-up rate refers specifically to the *transient* conditions. The transient conditions must include the dynamic overshoot. But, there is no dynamic overshoot for the SSMEs, SRBs or any other force source. The graphic illustration of the Rockwell expert, "*Lift-Off Sequence*," is shown in Fig. 7. As you can see in the figure, the SSME thrust goes up to only the RPL condition, or the 100% force level. This is obviously wrong. I have added the approximate dynamic overshoot for the SSME's and SRB's with dotted lines in Fig. 7.

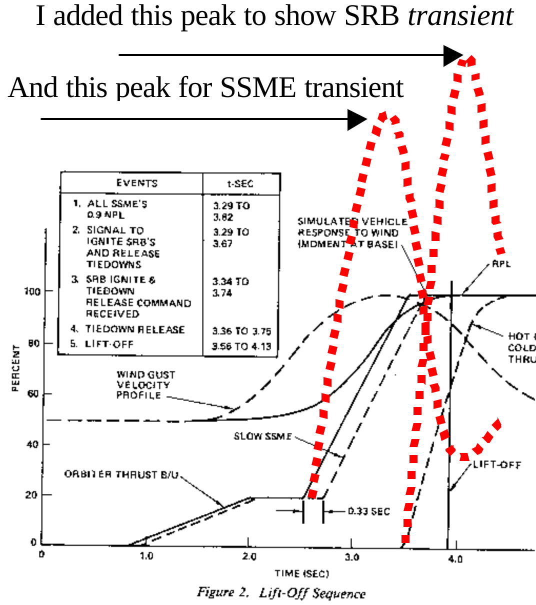


Fig. 7 1982 Rockwell Loads do not show dynamic overshoot at all

The correct dynamic overshoot factor of more than 70% was missing in the 1972 JSC specification (Fig. 6 and Tables-3 and -4), and it was missing ten years later, in 1982, in the Rockwell dynamic loads illustration (Fig. 7). The wrong practice continued.

During and after the extensive investigations of the Space Challenger accident in 1986, the SSME's lift-off thrust was mentioned often, and it was illustrated in many reports, but no one ever mentioned the dynamic overshoot that results from the rapid thrust build-up. No one told the Presidential Commission in plain language that the dynamic factor for the SSMEs was initially specified at 1.6% and that the liftoff dynamic factor was actually measured to be 73%, four years before the investigation. That was not a cover-up. Apparently, the aerospace experts failed, singly and collectively, to realize that the destructive overshoot effect actually happens in the Space Shuttle. Fig. 8 (Commission records, p. 84,058) gives the thrust (in pounds) for the three Challenger engines. As in the other illustrations of research, test, and operation, there is not even a hint of the enormous 73% dynamic overshoot.

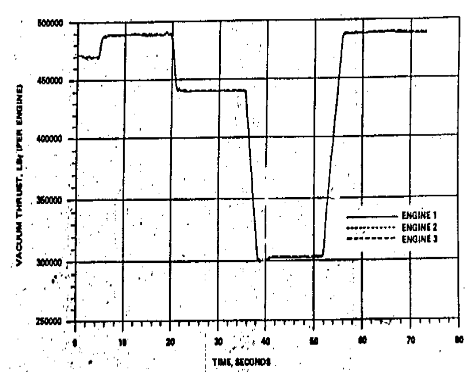


Fig. 8 Thrust-time profile for Challenger SSMEs do not show any dynamic overshoot

5.2 Initial SRB Lift-off Specifications

The initial SRB's specification was not better than the SSME's. A booster ramps up to full thrust faster than the SSMEs. The axial stiffness of the boosters is greater than the lateral stiffness associated with the SSME's loads. The damping ratio for the boosters' is around 0.01, compared with about 0.10 damping ratio for the SSMEs' lateral effect. Whereas the dynamic overshoot for the SSMEs is about 73%, the overshoot for the boosters is 96.9% (see Table-2). In plain language, the effect of the sudden SRB thrust is nearly *doubled*. What should be the design load per booster?

The nominal steady state thrust for each booster is 2.7 million lb. The transient dynamic overshoot force component for the boosters is 96.9%, or a maximum force factor of 1.969. Either one finds the transient component (96.9%) separately and adds it to the 2.7 million lb, or multiply the 2.7 million lb by 1.969 to get the design load per booster. Let us use the first method:

Steady-state Thrust at lift-off	2,700,000 lb
Transient Component (96.9%)	2,616,300 lb
Total Design Load per SRB at lift-off	5,316,300 lb

That's it. Each booster strikes the Orbiter, the External Tank, the Launch Pad, and its own parts with 5.3 million lb at lift-off. The maximum overshoot force for the two boosters at lift-off is more than 10 million lb. The *total design load* per SRB should have been around 5.3 million lb, and not only 3 MP.

What was the *total design load* per SRB in the initial JSC 1972 Shuttle specifications?

The JSC 07700 documents[26] specified and illustrated the nominal "thrust profile," thrust "limits" and "*ignition transient*" for each Solid Rocket Booster. The load specification for the SRBs is reproduced in Table-5 from Ref. 26, Appendix 10:

Table-5 The Initial JSC 07700 SRB Specification

Parameter	Sea Level	Vacuum
Thrust($\times 10^6$ lb)	2.9554	3.2464

At sea level, the thrust of each booster was specified to rise from zero to only 3 million pounds. Yet, with the *correct* overshoot, each booster strikes with more than 5 million lb force.

The JSC 07700 document illustrated the nominal SRB "*thrust profile*" graphically, which is reproduced in Fig. 9. The thrust build-up does not include the nearly *doubled dynamic overshoot* force effect! The design thrust climbs only to about 3 million lb, and not to the correct transient value of more than 5 million lb per booster, or more than 10 million lb for the two boosters.

Was the *transient* condition completely omitted in the JSC design documents? No. It was not done right.

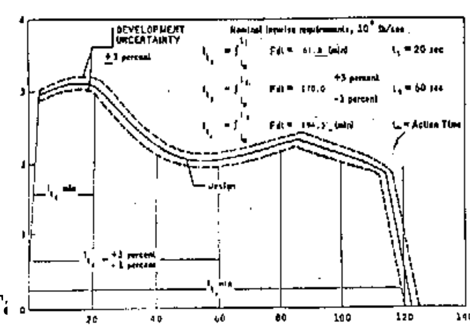


Fig. 9 JSC 07700 Illustration of SRB Thrust Build-up. No *Overshoot*

The thrust values during the *ignition transient* were tabulated in JSC 07700 (Vol. 10, Appendix 10.12) with ostensibly great accuracy, see **Table-6**. The steady-state thrust per SRB is about 2.7 million lb. The JSC transient specifications increase the steady-state value to a maximum of 2,955,403.0 lb. Considering that the correct *overshoot* goes above 5 MP per booster, the JSC 1972 specification was grossly inadequate. One cannot clearly see the enormity of the missing overshoot effect by merely looking at the JSC *transient* data in Table-6. The great accuracy of the data, eight significant figures, is intimidating. How can such precise values be wrong? Usually, engineers fuss over the decimal point, the right-most number. Here, I am criticizing the left-most number. I have plotted the JSC *transient* loads in Fig. 10. The correct *transient* force component is completely missing. I added the red-dotted line to show the actual peak *transient* SRB force at lift-off. The enormity of the error is apparent in the Figure.

Can you tell what's going on here? Was the 1972 JSC *transient force* incorrectly calculated? Is the maximum force in Table-6 the maximum SRB lift-off <u>*transient* force</u>, with the *dynamic overshoot*? Or, is it only the <u>*transient* force component</u>? Should we add the JSC 2.955 million lb (call it, 3 MP) to the nominal steady-state thrust (2.7 MP), and say that the maximum SRB force is 5.7 MP? This value is closer to our calculated maximum value (5.3 MP) in the previous page. But, the 5 MP value does not appear anywhere in the history of the Shuttle. There is another possibility. Is the JSC *transient* force the difference between their transient maximum (3 MP) and the steady-state value (2.7 MP). In other words, is their overshoot factor about 300,000 lb; i.e., (3-2.7 MP)? Is their dynamic overshoot for the SRB lift-off loads only 10%? This is not semantics. It is not safe. <u>The disparity is a mind-boggling 100% mistake.</u>

Table-6 JSC's SRB *Transient Data*

Time	Thrust (lbf)
.000	0.0
.197	1541085.8
.295	2531237.3
.394	2686710.8
.591	2929595.5
.788	2926813.0
.985	2927832.0
1.969	2955403.0

The yield safety margin and the ultimate safety margin for the Space Shuttle are 25% and 40%, respectively. With 70-100% overshoot errors; the Space Shuttle has always flown with negative safety margins and with drastic consequences.

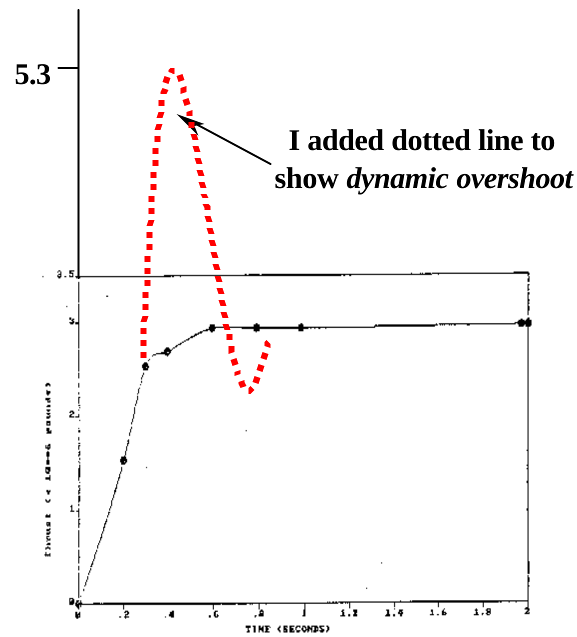


Fig. 10 The JSC *Ignition Transient* Thrust values (From Table-6)

The practice of neglecting the *dynamic overshoot* in SRB design persisted over the years. It began with the 1972 NASA specifications and continued to this day (1992). Fig. 11a is a 1981 NASA graph which shows the *"SRB <u>thrust</u> difference between two motors*"[17] in the first second after *ignition*. The engineers were concerned, and rightfully so, about the differences in thrust between the left and the right boosters. The difference that the engineers were studying is orders of magnitude smaller than the dynamic overshoot, but the overshoot is missing. I added the *dynamic overshoot* with dotted lines in Fig. 11.

The Shuttle experts use complicated statistical methods to calculate the *dynamic* design factors, or the dynamic overshoot. One method is referred to as the 3-sigma approach. The method produces tiny, and absolutely wrong, dynamic factors, but it has been the vogue in aerospace design. Fig. 11b, a NASA <u>1990</u> SRB thrust specification (Ref. 28), shows the small 3-sigma envelops. The 1990 specification still completely overlooks the significant startup *dynamic overshoot* force component, which I added with the dotted line. The original maximum thrust traces in Fig. 11 rise to only about 3 million lb, and no one noticed the massive error.

I said that the *transient* error is widespread. The manufacturer of the Solid Rocket Motors (SRM), Morton Thiokol, also completely overlooked the dynamic overshoot in their analysis and tests. The SRM thrust was found by tests to be approximately 2.7 million lb[29]. The Thiokol test results are reproduced in Fig. 12a. The maximum thrust is reached in less than ½ second. Here, you see that none of the tests showed the *dynamic overshoot*, which was so clearly detected in two million tests of model rockets, see Fig. 5.

The Thiokol thrust-time traces for two-minutes-flight-burn is reproduced in Fig. 12b. The dynamic overshoot is completely missing.

The engineers have been sanguine for many years because their tests do not show the sizable dynamic overshoot that I describe in this Report. What the engineers did not notice was that their test methods were incorrect, as will be shown later.

I added the dotted lines to show the correct *dynamic overshoot*

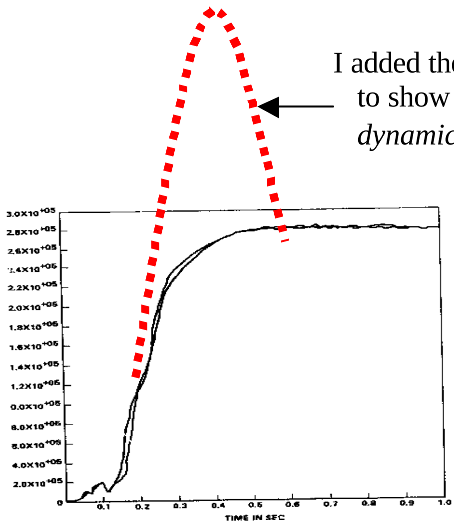


Fig. 11a 1981 NASA Illustration of SRB Thrust for 2 boosters. No *Overshoot.*

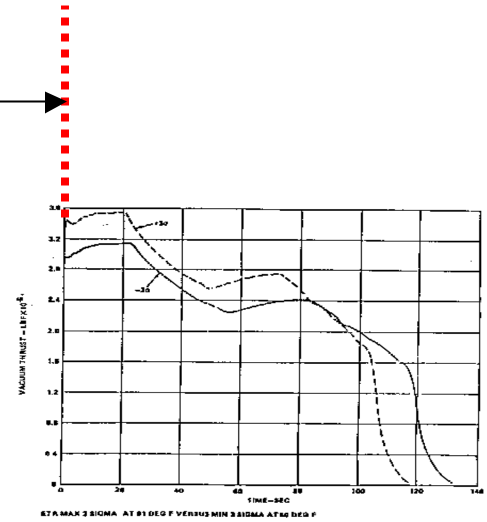


Fig. 11b 1990 SRB Thrust Specification. Also No *Overshoot.*

I added the dotted lines to show the correct *dynamic overshoot*

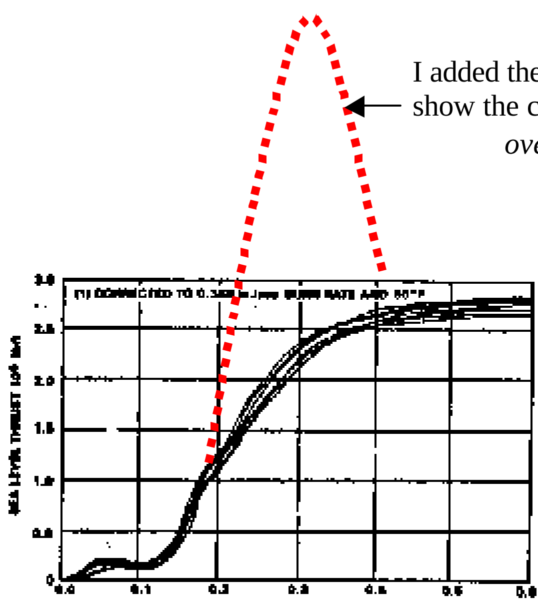


Figure 16. Composite of 26 SRM Thrust-Time Traces During Ignition

Fig. 12a *Transient Thrust Tests* of 26 Motors by Thiokol. *No Overshoot.*

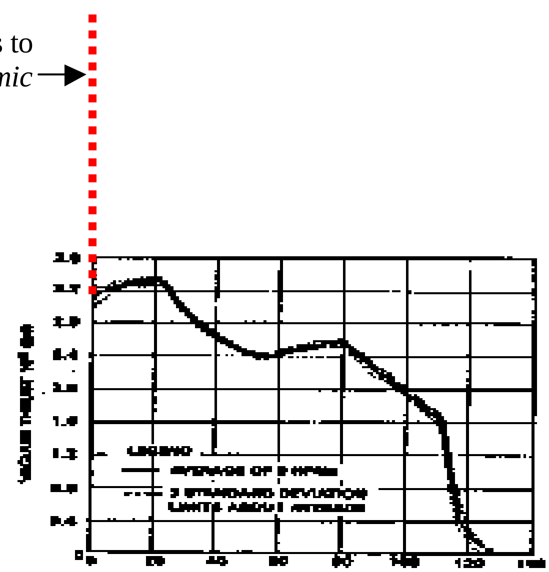


Figure 17. Thrust-Time Trace Reproducibility Experience

Fig 12b Thrust-Time Traces for SRMs by Morton Thiokol do not show *Dynamic Overshoot*

5.3 How was the Dynamic Overshoot Overlooked?

How could such a large force component as the *dynamic overshoot* be completely ignored by the rocket engineers in the design of such an important system as the Space Shuttle, and for three decades? There are several reasons for the oversight. Some of the reasons are psychological and philosophical in nature.

In Fig. 6, I showed the *overshoot* as quick spikes. This may explain why the ephemeral effect was not observed for many years. Unless the proper instruments are used, the spikes can be overlooked. The spikes I added in Fig. 6 are real, and one can see the real spikes in the Shuttle records. For example, sensitive acceleration measurements at the boosters' joints during liftoff captured the *overshoot* spikes, Fig. 13 (Ref. 30, Vol. II, L-121). If the acceleration, *a*, rises rapidly to a greater value during the transient period, then, according to Newton's $F=ma$, the force, *F*, will also rise to greater values. That's it. Fig. 13 was included in the Commission Report. The overshoot spikes were not discussed. The ephemeral punches that were recorded for, and hit, the Space Shuttle on every launch were always neglected.

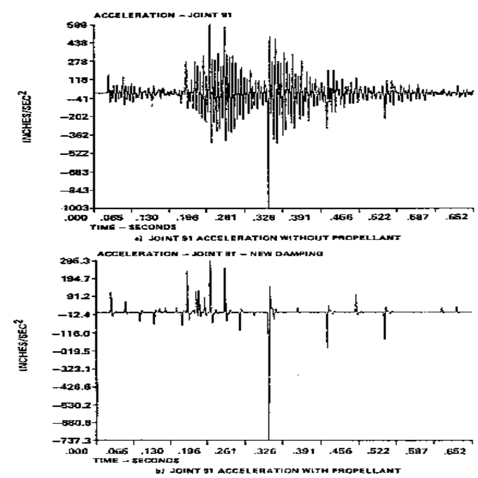


Fig. 13 Dynamic Overshoot Spikes clearly visible at SRB Ignition

The *spikes* are easy to explain. Perhaps, the engineers did not notice the ephemeral events.

But, how do we explain the thrust traces where the *dynamic overshoot* should be as plain as day, as in Figs. 11 or 12? Here, I insisted that there was sizable *overshoot* at lift-off. Experts from the aerospace community, academia, and even the media fervently dismissed my assertions. The issue became litigious between me, on the one hand, and NASA, the Contractors, and the professional organizations. It took more than five years to settle the issue.

Look carefully at Fig. 12a. The original title says, "*Composite of 26 SRM <u>Thrust-Time</u> Traces During Ignition*" (Emphasis added). Fig. 12b also gives <u>*Thrust*</u> values. The ordinates in the Figures give the thrust in million of pounds. Thrust is force. Pounds refer to forces. Also, the ordinates in the NASA figures 11a and 11b give <u>thrust</u> values. I was under the impression that the engineers were measuring *thrust or force* and that by some mysterious stratagem the *overshoot* simply disappeared. The way out of the predicament was preposterous.

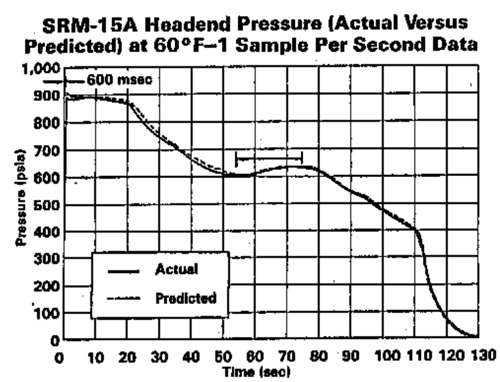


Fig. 14 SRM Actual and Predicted <u>*Pressure*</u>: Figure <u>Correctly excludes</u> *Dynamic* Overshoot.

Now, look at the NASA Fig. 14, which is similar to Figs. 11b and 12b. Fig. 14 shows <u>pressure</u> values in psi (pounds per square inch) for a Shuttle booster. Notice that in the caption, I say, "Figure <u>correctly excludes</u> dynamic overshoot!" It turned out that the traces in Figs. 11 and 12 (and countless similar figures by NASA and the Contractors) were measurements of <u>*pressure* and *not force*</u>. Does this make any difference? You bet it does. <u>*Pressure does not overshoot*</u> (see my paper, "*Transients in Pressure-Activated Systems*").

The issue here is not frivolous. The subject was hotly disputed for years. Claims and counterclaims were circulated in the halls of the White House, the Congress and, even, the Federal Courts during the period 1989 to 1992. Let me explain.

Philosophically, a CAUSE produces an EFFECT. In transient analysis, there is INPUT and OUTPUT. The INPUT is the CAUSE. The OUTPUT is the EFFECT. Let me add another relevant pair here, which comes from the important laws of science that we use to design the Space Shuttle and other systems, i.e., Newton's

Laws of Motion. Aerospace engineers are particularly indoctrinated in Newton's Laws, e.g., the Third Law, "*to every action there is always opposed an equal reaction*." We now have three pairs of words that are familiar to everyone: CAUSE and EFFECT, INPUT and OUTPUT, and ACTION and REACTION. The reader should think of these familiar terms and carefully interrelate them. For example, ACTION is a CAUSE, or the INPUT in a transient analysis. REACTION is an EFFECT, or the OUTPUT in a transient analysis.

Another functional pair is useful to explain how the transient analysis has been confused and mishandled in the design of the Space Shuttle. The pair relates to the transient analysis itself. The INPUT in transient analysis is usually called the "FORCING FUNCTION." The OUTPUT is called the "TRANSIENT RESPONSE." We now have the following four pairs:

CAUSE → EFFECT

ACTION → REACTION

INPUT → OUTPUT

FORCING FUNCTION → TRANSIENT RESPONSE

The arrows show the logical flow of events. One does not calculate the REACTION to obtain the ACTION. Logically, one begins with the ACTION and derives the REACTION. One enters the INPUT, say into a computer, to obtain the Result, or OUTPUT. If the INPUT and OUTPUT are equal, then there is no need for any analysis. Suppose you do transient analyses 10, 100, or 1,000 times and discover that the FORCING FUNCTION looks exactly like the TRANSIENT RESPONSE, then why do any transient analysis? Why do any analysis if the INPUT and the OUTPUT are identical?

Suppose we wanted to do transient analysis for the example of the 100-lb lady stepping suddenly on a weight-scale. Suppose the damping ratio for the weight-scale is similar to the Space Shuttle in bending mode at liftoff, i.e., 0.10. Then the dynamic overshoot is 73%, and the dial will rise to 173-lb on first overshoot. The parts of the weight-scale actually experience the magnified force, though momentarily. The transient analysis must follow specific steps and must produce specific answers. For example:

Step 1: Measure the weight of the lady. This is the Action, Input, Cause or Forcing Function.

Step 2: Calculate the dynamic overshoot. Use the equations in Section 4.

Step 3: Add the weight and the dynamic overshoot to obtain the maximum load on the parts of the weight-scale. This is the Output, Effect, or maximum Transient Response.

Engineering is a precise art within tolerances. The transient analysis must produce specific numbers, and not hunches or intuitions. Numerically,

Weight	= 100-lb
Dynamic overshoot	= 73-lb
Maximum Load	= 173-lb

What if the lady released her weight suddenly on the bathroom scale on one foot? Is the dynamic overshoot, or the maximum load, smaller or greater than in the above case? You will see later why I ask this question.

Do you remember the four hypothetical aerospace engineering Groups mentioned in Section 2? I said that Groups #1, #2 and #3 designed the Space Shuttle and other space hardware. I also said that Group #1 was not familiar with the correct transient analysis, Group #2 was confused about the analysis and Group #3 mishandled the transient effects.

Let us review what Group #1 has been doing in the design of the Space Shuttle and other space hardware.

The thrust from the three SSMEs rises rapidly before liftoff from zero to about 1.1 million pounds (MP). The sudden thrust causes a dynamic overshoot of 73%, or 800,000 lb. The maximum load on the Shuttle parts is approximately 1.9 MP (1.1 + 0.8). Group #1 uses Newton's Third Law, just as they learned in the engineering curricula. Notice that Sir Isaac Newton did not specify how the ACTION is applied. Newton's Third Law does not say whether the ACTION is applied suddenly or gradually! Every ACTION has an equal REACTION, wrote Newton. Group #1 were told that the SSMEs produce 1.1 MP. This is the ACTION. Newton, and the professors, told them that the REACTION is *always* equal to the ACTION. Those engineers proceeded confidently, though mistakenly, to design the Shuttle's parts to the applied force. They used the ACTION (1.1 MP) or CAUSE (1.1 MP) to calculate the stress, bending moments, deflections, etc. To those engineers, the CAUSE, EFFECT, ACTION, REACTION, INPUT, OUTPUT, FORCING FUNCTION and TRANSIENT RESPONSE have equal value, 1.1 MP. Those same engineers were puzzled when they actually measured a total force of 1.9 MP generated by the three SSMEs at liftoff, which included the dynamic overshoot. Where did the extra, or excess, 800,000 lbs come from? The Space Shuttle engineers actually asked the question. The seemingly mysterious, non-Newtonian, excess force baffled them. You will see the details of this case in **Section 7**. Group #1 did not do any transient analysis.

Groups #2 and #3 did transient analysis, but the engineers mishandled the analysis. How did this happen? How does one explain the missing *overshoot* in Figs. 11 and 12, where the force traces move up ever so slowly, millisecond by millisecond? How could the engineers measure the SRB thrust or force build-up and not capture the dynamic overshoot? Because those engineers were measuring pressure and converting the pressure readouts to force, they did not realize that there is a dynamic overshoot. A hint of the reasonable explanation came from two sources. A senior congressional scientist assured me that NASA used the most advanced pressure transducers in their measurements, and that the instruments did not show the type of overshoot that I was talking about. The Director of the Johnson Space Center later wrote me to say that their very accurate pressure measurements registered only 2% overshoot, compared with my claimed 70-100% magnification. The mystery was finally solved. Do you see it? Apparently, the Shuttle experts were not measuring force or thrust. They were measuring pressure. They then simply converted the pressure values to force values using the elementary relationship, **force = pressure x area**. It never occurred to the aerospace engineers in Groups #2 and #3 that the pressure fluctuates, but does not overshoot, whereas the force actually overshoots. They treated the small pressure fluctuations as the dynamic overshoot and completely overlooked the substantial dynamic overshoot force. That is why those experts fought the *dynamic overshoot* issue vehemently and confidently for many years.

Let me introduce a new twist to the above trite example of a lady stepping suddenly onto an old bathroom scale. Let us say that the area of the lady's feet is 20-in^2 (square inches). The area of one foot is 10-in^2. Do you see where we are going? If the lady is released suddenly on the scale on one foot or on both feet, the dial overshoots and eventually settles down to show the weight. I will now ask you (the reader) to do the necessary transient analysis to determine the maximum load on the weight-scale, beginning with pressure readouts. You don't need a calculator to do the analysis, but you must concentrate on the steps required to do the analysis.

There are many parts in the weight-scale, but let us concentrate on two important parts: (1) the platform on which you stand to obtain your weight, and (2) the internal spring (that works like a fish scale) which is calibrated to show your weight on a dial.

Let us place pressure transducers beneath the lady's feet to measure the pressure applied by the lady's feet on the platform. Let us also add another dial to the weight-scale that shows the pressure on the platform!

The lady is released suddenly on the platform, on one foot or two feet. Now, you will see the pressure readout on the pressure dial and the weight readout on the normal weight dial. Think carefully about it. The pressure dial gives the pressure on the platform, and the weight dial gives the force in the internal calibrated spring. We must make clear distinction between these two parts (platform and internal spring) and their associated readouts (the pressure on the platform and the force in the calibrated spring).

If the 100-lb lady is released onto the platform of the weight-scale on both feet, you will see a maximum pressure of 5 psi (pounds per square inch). Since the area of the lady's feet is 20 in^2, then the weight of the lady is 100-lb (5 psi x 20 in^2 = 100-lb). If the lady is released on the platform on one foot, you will see a maximum pressure of 10 psi. Since the area of one foot is 10 in^2, then the weight of the lady is still 100-lb (10 psi x 10 in^2 = 100-lb). Suppose the lady can hold her weight on a toe, with an area of about 1 in^2. Then the maximum pressure is 100 psi, and the weight is 100-lb (100 psi x 1 in^2 = 100-lb). This exercise allows us to establish the specific steps that we must undertake to do the correct transient analyses. First, let us organize the preceding calculations:

	Weight on 2 feet	Weight on 1 foot	Weight on 1 toe
Pressure	5 psi	10 psi	100 psi
Weight	5 x 20 = 100-lb	10 x 10 = 100-lb	100 x 1 = 100-lb
Dynamic Overshoot	73-lb	73-lb	73-lb
Maximum Load	173-lb	173-lb	173-lb

The pressure acts on the platform. It does not matter how the pressure is applied, on a toe, one foot or two feet. What is important in transient cases is that the pressure be applied suddenly. The dynamic overshoot occurs in the internal calibrated weight spring. The dynamic overshoot calculations must be consistent, the INPUT or the FORCING FUNCTION must be in force units and the OUTPUT or the maximum TRANSIENT RESPONSE will be in force units. The FORCING FUNCTION cannot be entered in pressure units! Think about it. A careful review of the initial and subsequent Space Shuttle specifications shows that the Shuttle engineers call the pressure readouts the "FORCING FUNCTION." This is wrong. Before we review the specific steps required to do the transient analysis when our INPUT is given in pressure values, let us make important comparisons between the simple old bathroom scale example and the Space Shuttle.

The pressure dial in the weight-scale example shows the pressure on the platform rise from zero to a maximum value without overshoot. The pressure on the platform may fluctuate, but it does not overshoot. The pressure in the Space Shuttle engines also rises from zero to a maximum value without overshoot. The pressure in the engines fluctuates, but it does not overshoot. The pressure in both cases transmits forces into the parts of the weight-scale and the Space Shuttle respectively. In the case of the weight-scale, the sudden force transmitted to the internal calibrated spring causes dynamic overshoot in the spring itself. This is why you see the weight overshoot on the dials of the weight-scale, a supermarket vegetable scale, a postal scale or a simple slinky. In the case of the Space Shuttle, say before liftoff, the sudden forces from the engines are transmitted through many springs, e.g., the body of the Orbiter, the struts and bipod that connect the Orbiter to the ET, the structure of the ET itself, the struts that connect the ET to the SRBs, the steel cases of the SRBs, the holddown posts and the Mobile Launch Platform. The sudden forces transmitted through these parts (springs) actually cause dynamic overshoots. The parts of the Space Shuttle listed here act like the internal spring in the weight-scale example. The parts of the Space Shuttle are real springs. When the Shuttle engineers measure the pressure in the SSMEs, and convert the pressure values to force values, they do not see any dynamic overshoot. The engineers only see a maximum force of about 1.1 MP. But, when the engineers measure the forces in the internal springs, say the holddown posts, they discover that the force generated by the SSMEs is about 1.9 MP! This is the maximum load, including the dynamic overshoot effect. But, no one recognizes the source of the sizable anomaly.

Let us develop the specific steps that must be taken to do correct transient analysis when the INPUT is given in pressure units (refer to the above Table):

Step 1: Measure the pressure (psi or Newtons per meter square) on the Platform.

Step 2: Convert the pressure readouts (psi or N/m^2) to force values (pounds or Newtons). The maximum value is the weight itself. This is the INPUT, ACTION, or FORCING FUNCTION for the correct transient analysis.

Step 3: Calculate the dynamic overshoot in the internal spring. Use the equations in Section 4.

Step 4: Add the weight (the maximum force in Step 2) and the dynamic overshoot (from Step 3) to obtain the maximum load on the internal spring of the weight-scale. This is the OUTPUT, EFFECT, or maximum TRANSIENT RESPONSE.

It is my hope that the above elaborate treatment will clearly demonstrate how the consequential dynamic overshoot error was made repeatedly throughout the Space Shuttle program and throughout the space program. When pressure is applied rapidly, the pressure rises to a maximum value, and a plot of the pressure versus time shows that the pressure then turns to the right on the plot. Look at Figs. 11 and 12 by NASA and a Shuttle Contractor. Here, the load rises to a maximum value and turns to the right. The initial Shuttle specifications, JSC 07700 document, show the same thing. The pressure, or the load, rises to a maximum value and turns to the right, e.g., Figs. 9 and 10. Sometimes, a small bump is shown near the maximum value. The small bumps represent pressure fluctuations and not the correct force dynamic overshoot. You will see examples of the pressure fluctuation bumps later in this Report.

Also, when you compare the curves of the pressure readouts, for the Shuttle engines or motors, and the force values, you will notice that the two curves are nearly identical! For example, look at the initial 1972 JSC 07700-specification for the SRB's thrust (Fig. 9) and the actual pressure measurement for an SRB (Fig. 14). The pressure curve and the thrust curve are identical. How can this be? Do you see my point? The engineers have been doing the above Step 1 (measuring the pressure) and Step 2 (converting the pressure values to force values), but without any attempt to do Step 3 (calculate the dynamic overshoot) and Step 4 (calculating the maximum load on the Shuttle parts).

If you examine the Space Shuttle technical literature, you will discover that the pressure-time curves, such as Fig. 14, are sometimes referred to as the FORCING FUNCTION for transient analysis. How can this be? This is like mixing apples and oranges. The pressure-time values are given in pressure units, e.g., psi (pounds per square inch), but the TRANSIENT RESPONSE is usually obtained in force units, e.g., pounds. The INPUT cannot be in pressure units while the OUTPUT is in force units.

Perhaps, the most alarming result of my research is that the pressure-time curve is also called the transient "FORCING FUNCTION" in the design of other modern systems. For example, in the design of nuclear power reactors, the pressure-time curves and the corresponding force-time curves are always nearly identical. Here, the engineers and the nuclear physicists measure the pressure, convert the non-overshooting pressure readouts to forces, and completely overlook the dynamic overshoot. This is evident in all the scientific papers published in international conferences, specifically held to deal with the stealthy transient issue. The dynamic overshoot mistake is widespread.

Consider this. The model, or toy, rocket engineers measured the *forces* generated by the small rockets and recorded a 100% *dynamic overshoot*. The model rocket engineers could not use pressure transducers in the measurements. Model rockets are tiny, and there is no room inside the tiny rockets to put pressure transducers. So, these engineers used a simple spring system, such as a fish scale. You can use a 2-pounds fish scale to do the 2 million measurements you see in Fig. 5. For a damping ratio like that of the Shuttle SRBs, a 1-lb weight will amplify the effect in the fish scale to about 2-lb! But, if you use a postal scale and carefully measure the *transient pressure* and then convert the pressure measurements to equivalent force or thrust, you will not get the dynamic overshoot values. And so, the *dynamic overshoot* was overlooked in real rocketry primarily because the engineers relied on pressure measurements, which do not overshoot, and, confidently but mistakenly, converted the pressure data to thrust, or force, values.

All the other Shuttle loads are based on the steady state, or static, or sans-dynamic-overshoot loading conditions. For example, all loads and deflection values that were used by the Challenger investigators were solely based on the steady-state values. There were no meaningful questions about the detrimental "dynamic overshoot" effects during the Challenger investigations.

You will see later in this Report how other modes of thinking contributed to the complete neglect of the sizable dynamic overshoot in the space program.

6. "Dynamic Overshoot" and *"The $64,000 Question"*

The sizable dynamic overshoot mistake is rooted in history, and the mistake is widespread. The error has picked up so much inertia and momentum that it has been extremely difficult, and nearly impossible, to eliminate the mistake from the space program and from other critical systems. Here is an historic glimpse.

The expression, *"The 64,000 Dollar Question"* is commonly used to express uncertainty over a puzzling issue. I have heard people say *"the 32 thousand dollar question,"* *"the 64 million dollar question,"* etc. Why not the "$10,000 Question," the "$100,000 Question," or the one million? *"Dynamic Overshoot"* and the "$64,000 Question" are related. This Section elaborates on the bizarre 2:1 mistake in aerospace design, a massive mistake that made its way into Space Shuttle design, with serious consequences.

In the 1960s, the expressions "32 dollar question" and "64 dollar question" (no thousands or millions) were widely used around schools of engineering. Where did the "$64,000 question" originate? It could have originated with Sir Isaac Newton and Gottfried Wilhelm von Leibniz. Exactly 300 hundred years before the Challenger Accident, in 1686, Leibniz infuriated his contemporary scientists with a paper entitled, "*A Brief Demonstration of a Memorable Error by Descartes*." Leibniz no less than identified the commonly overlooked, but massive, dynamic overshoot error. He wrote, "*force" is rather to be estimated from the quantity of the <u>effect</u> which it can produce*,"[31] (original emphasis) To modern scientists and engineers, this amounts to asking the question, should force be calculated using $F=ma$, or $F=2ma$!

The gravitational acceleration at sea level is about 32 ft/sec^2. Double this value, and you get 64 ft/sec^2. The 32 ft/sec^2 is referred to as the 1g, or one acceleration condition. The 64 ft/sec^2 is 2g. Astronauts and pilots feel several g's when making sharp maneuvers. A few g's can render a person unconscious. There are many g's: 1g, 2g, 3g, 4g etc. Why were the 1g and 2gs so important to the engineers? Why were the $32,000 Question and $64,000 Question codified? The 1g and 2gs, or 32 and 64 numbers, have a special meaning in engineering, particularly, to the aerospace-structural-dynamics engineers. I am one of them.

Consider again the old bathroom weight-scale of Section 2. The lady's weight is 100-lb. The lady steps suddenly on the scale producing the *dynamic overshoot* that she can clearly see on the dial. (Note: You do not see the *dynamic overshoot* in modern electronic weight-scales, but the effect is there. In the short period before you see your *digital* weight, the electronic scale is waiting for the overshoot to damp out). If the damping ratio, ζ, of the spring inside the weight-scale is similar to the damping ratio of the Shuttle boosters, or about 0.01, then the lady will glimpse 196.9-lb, or 197-lb, on the dial on the first oscillation.

The four Groups of engineers in Section 2 had to decide whether to design the weight-scale to withstand the lady's weight, 100-lb, or the lady's weight *plus* the *dynamic transient*, 196.9-lb or 197-lb. Precision becomes irrelevant here. Should the four Groups design the old bathroom scale to 100-lb or 200-lb? Should they design the scale to 1g or 2g's; i.e., use 32 or 64? Actually, the engineers in Section 2 had no problem whatever. They could design the weight-scale to withstand 10 g's, or 1,000-lb. All it takes is a little more steel, aluminum, or plastic.

To the aerospace engineers, the above situation presented a dilemma. Aerospace structures must be very light. Turn the bathroom scale upside down, and you have a rocket. Now, it is the pressure inside the chamber of the rocket, and not the pressure of the lady's feet on the scale, that matters. Throughout the space program, we have struggled to achieve lightweight design, actually the lightest-weight possible.

Suppose the pressure in a rocket chamber produces 1 million-lb thrust. Should the engineers design the rocket, its payload and the launch pad to withstand 1 million-lb or 2 million-lb? Should the engineers design the system to 1g or 2g's? The 2g's design is heavier than the 1g-design. You can see the likely source of the "$64,000 Question." Somehow, the entertainers jumped on the issue that was raised by the rocket scientists; and the "$64,000 question" expression became widely used in television programs.

Newton and Leibniz did not resolve the riddle. The reader may wonder if I am emphatically stating that Newton's Laws of Motion, especially the Third Law, are wrong. The answer is yes and no. Newton did not design launch vehicles, satellites or power reactors. In the design of modern systems, the overshoot must be considered. Newton needed his popular Third Law to use with his equally popular Second Law, i.e., F = ma, to corroborate his Universal Law of Gravitation. To Newton, the Moon is in free fall eternally and the apple is in free fall on its way to the surface of the Earth. *Had Newton released an apple tied to the end of a slinky from tree height, he would have noticed the dynamic overshoot in the slinky.*

Again, engineering is applied physics. The physicists use Newton's Third Law with the apple, and it works. They dictate the laws of science for the engineers. Both groups do not realize that the structures (springs) of the Space Shuttle are akin to the slinky, and not the apple! Both groups wrongly think that because the pressure (in engines, motors, boilers, etc.) does not overshoot, then the forces in the springs (e.g., the Space Shuttle structures) do not overshoot. The physicists have dismissed my assertions with the silly argument that the apple does not double in size when released suddenly! The aerospace structural engineers, and the physicists, must recognize that when we design the structures of the Space Shuttle, we are designing the slinky, and not the apple. Do you see the mix-up? The engineers and the physicists must examine the glaring "dynamic overshoot" measurements, made by the Shuttle engineers themselves, in the next Sections

In the 1960s and 70s, there were two schools of thought on the $64,000 Question: (1) The First Group felt that rockets should be designed to the *applied* thrust – or, 1g. The Group argued that Newton was on their side: $F = ma$, a = 1g. This is the "$32,000 Question" Group. (2) The Second Group argued that rockets should be designed to the maximum load *experienced* by the parts of the rocket. Sometimes, the maximum force is twice the applied force. I was probably the only student and engineer in the 1960s and 70s who advocated, and used, the correct start-up transient analyses.

Group #1 above designed rockets to withstand 1g forces. The engineers did not calculate the dynamic overshoot, which is straightforward. They grossly underestimated the dynamics; built and tested the rockets. The rockets exploded on or near the launch pad. The twisted pieces were collected and examined. The culprit pieces were identified and strengthened. The rockets were re-built. A second test, explosion, rebuild, test, explode, etc. And we made it to the Moon. No one realized the 1g, 2g's issue then.

The Space Shuttle Program began in 1972. I spent considerable effort studying the vehicle. By 1978, my responsibilities included directing the processing of satellites for Shuttle launches. It was a time of great anticipation. There were going to be some 60 Shuttle flights per year. We had a long list of domestic and international satellites waiting in line for the Shuttle. Then, the bad news came. The Shuttle was in trouble. NASA circulated new specifications for satellites to be launched on the Shuttle. The new specifications betrayed serious problems. By 1978, it became obvious to the insiders that it was going to take a few years to fix massive problems encountered by NASA. The Shuttle finally flew in 1981. But it was not the machine that we had anxiously anticipated throughout the 1970s. I quit my good aerospace job, as others did, in 1978 because of Shuttle-uncertainties. I would have had zero launches to oversee in four years.

To the best of my recollection, there were hardly any $64 advocates in the 60s and 70s. Everyone was a $32 advocate. F=ma. That's it. Despite the numerous failures that resulted from the designs of the $32 Group, everyone continued to make the same 2:1 mistake, placing blind trust in the so-called 3σ method and Newton's Action-Reaction law. The mechanical engineering and physics faculty at GWU dismissed my assertions in the 1960s. You will see later how I first identified and corrected the dynamic overshoot mistake in actual space hardware in 1970. Yet, despite repeated attempts to eradicate the mistake from the design of satellites and other space systems, the error continued unchecked.

The Space Shuttle Challenger Accident made it possible for me to collect massive evidence to support my contention that the dynamic overshoot oversight is widespread in science and engineering. In particular, I found instances when the Space Shuttle engineers actually measured the large dynamic overshoot effect in 1982. Rather than recognize the dynamic overshoot force for what it is, the surplus force, which they called, "EXCESS UPWARD FORCE," puzzled them. This is described next.

7. Measurement of the "Dynamic Overshoot" in the Shuttle

The *dynamic overshoot mistake* has been a quarrelsome issue. NASA and the Shuttle Contractors took my assertions that they made the unbelievable 2:1 (or, 100%) error to be flimsy, baseless and slanderous. They mounted massive counterattacks. Their first line of defense was that *there is absolutely nothing in the massive Space Shuttle technical record* to prove that the system was subjected to excessive forces of the order of 70% to 100%. Their assertions backfired. The *record* is strewn with evidence. In this Section, you will see that NASA and Rockwell actually measured the massive dynamic overshoot and that their experts were literally bewildered by the excessive *dynamic overshoot* force component, which they labeled "EXCESS UPWARD FORCE," or *surplus upward force*!

In 1986, I told a large team of NASA and Shuttle Contractor's experts about the *dynamic overshoot* error behind closed doors at the Kennedy Space Center. The engineers were astonished by the enormity of the design error, and some of them promised to search for data that might support my assertions. By early 1987, I had not heard from the engineers. NASA submitted more than 100,000 pages of technical reports to the Rogers Commission for the Challenger investigations, and the Commission filed the massive record[32] in the National Archives in Washington, DC. I doggedly searched the massive record looking for clues that might support my assertions. Eventually, I discovered that the correct *dynamic overshoot* was measured and recorded by NASA and Rockwell. The *overshoot* for the SSME's start-up thrust turned out to be about 73%, the value derived from my analysis in Section 2, and not the 1% or 3% that were used by NASA and Rockwell. There was no cover-up, nor dishonesty. The test results were there for everyone to see. It just happens that the *dynamic overshoot* has the nasty habit of disguising itself. You have to look carefully to see it and, perhaps, you have to believe that it is there to find it.

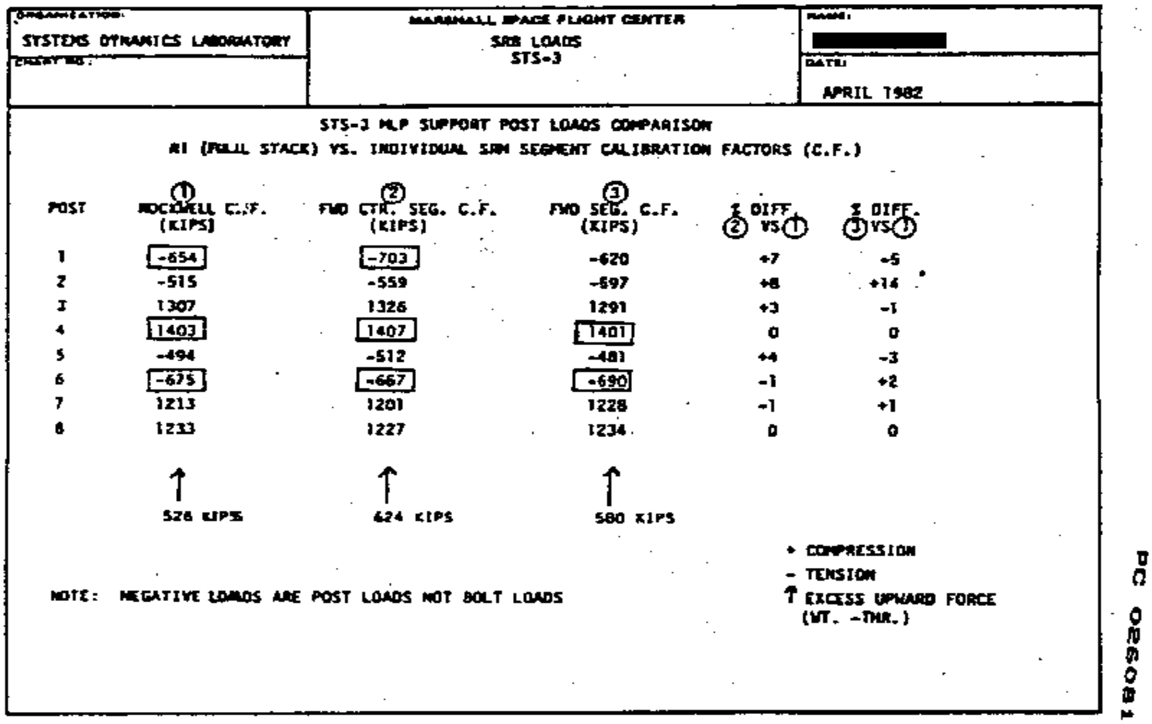
One of the irrefutable measurements of the 73% *dynamic overshoot* for the SSMEs is shown in Fig. 15, or page 26,081 of the Commission record (Ref. 32). Study it carefully. The Systems Dynamics Laboratory at the Marshall Space Flight Center (MSFC) actually measured and reported the massive dynamic overshoot in 1982, 10 years after the Shuttle program started, under the title, "SRB LOADS, STS-3." <u>Do you see the engineers' remark in the lower right corner</u>? "<u>**-EXCESS UPWARD FORCE**</u>." This is the notorious *dynamic overshoot force component*. Measured, but, apparently, not understood by anyone.

Notice first that the engineers use three calibration methods to confirm the results. Why three calibration methods? Either something is terribly wrong with the measuring instruments or something is terribly wrong with the results. The engineers mark the three calibration methods as follows: (1) Rockwell C.F., (2) FWD CTR. SEG. C.F., and (3) FWD SEG. C.F. The abbreviation "C.F." is clearly marked in the subtitle line as "CALIBRATION FACTORS." Using different calibration methods indicates that the engineers were skeptical of their own measurements.

Secondly, in the lower right corner of the Test Sheet, you see the comment: "*(WT.-THR.)*." And under the three primary columns, there are three up-arrows (-) and numbers given in KIPS, or, thousands of pounds force. What do the remarks mean?

The test engineers were expecting to measure about 1.1 million lb force from the 3 SSMEs at lift-off. But when the *measured* forces were added, the experts discovered that the instruments recorded 1.9 million lb, where did the *EXCESS* 800,000 lb come from? Using *three* calibration methods betrays that the engineers hoped to find that the *EXCESS* force was the result of calibration errors. Calibration was not a problem; the three methods were in general agreement. The 1.1 million lb engines produced 1.9 million lb! How can that be? Of course, the problem was completely hidden from view when the engineers measured the lift-off forces using *pressure* measurements. *Pressure does not overshoot, forces do*. Now, they were measuring forces, and forces overshoot. The engineers were not happy with the results.

Some officers involved in the Space Shuttle Program asked me how to derive the dynamic overshoot from the STS-3 measurement in Fig. 15. The calculations are given in detail next.



ORGANIZATION: SYSTEMS DYNAMICS LABORATORY
CHARGE NO.:
MARSHALL SPACE FLIGHT CENTER
SRB LOADS
STS-3
NAME: [redacted]
DATE: APRIL 1982

STS-3 MLP SUPPORT POST LOADS COMPARISON
R1 (FULL STACK) VS. INDIVIDUAL SRM SEGMENT CALIBRATION FACTORS (C.F.)

POST	① ROCKWELL C.F. (KIPS)	② FWD CTR. SEG. C.F. (KIPS)	③ FWD SEG. C.F. (KIPS)	% DIFF. ② VS ①	% DIFF. ③ VS ①
1	-654	-703	-620	+7	-5
2	-515	-559	-597	+8	+14
3	1307	1326	1291	+3	-1
4	1403	1407	1401	0	0
5	-494	-512	-481	+4	-3
6	-675	-667	-690	-1	+2
7	1213	1201	1228	-1	+1
8	1233	1227	1234	0	0
	↑ 526 KIPS	↑ 624 KIPS	↑ 580 KIPS		

+ COMPRESSION
- TENSION
↑ EXCESS UPWARD FORCE (WT. - THR.)

NOTE: NEGATIVE LOADS ARE POST LOADS NOT BOLT LOADS

Fig. 15 *Dynamic Overshoot* Measured in April 1982. Effect was described by Test Engineers as "-EXCESS UPWARD FORCE"!

First, let us take the "↑EXCESS UPWARD FORCE" values directly from Fig. 15. Note that "KIPS" in the NASA test sheet means thousands of pounds; e.g., 624 KIPS means 624,000 lb.

Table-7 "Excess Upward Force" Measured from STS-3 Lift-off

Description	Method 1 Rockwell C.F.	Method 2 SRB C.F.	Method 3 SRB C.F.
Excess Force	526,000 lb	624,000 lb	580,000 lb

The thrust from the SSMEs acts upwards. The weight of the Orbiter, which is attached to the External Tank, acts downwards. That is why the engineers subtracted the weight of the Orbiter from the Excess Upward Force, or "(WT. – THR.)" in Fig. 15. Subtracting the weight of the Orbiter made the problem seem less severe than it was, but it was severe nonetheless. We can find the *peak transient force* from the STS-3 lift-of measurement as follows:

1. Add the "Orbiter weight" to the "Excess Upward Force" to obtain the "Total Excess Upward Force."
2. Add the "Total Excess Upward Force" to the SSME "Steady-State Thrust."

That's it. The above steps are shown in Table-8. The "Peak Transient Force" measured for the STS-3 lift-off in 1982 is shown in the last row of Table-8. This force includes the *dynamic overshoot*.

Table-8 SSME's Peak Transient Forces at Lift-off

Description	Method 1	Method 2	Method 3
"↑Excess Upward Force"	526,000 lb	624,000 lb	580,000 lb
(Add) Orbiter Weight	200,000 lb	200,000 lb	200,000 lb
Total Excess Upward Force	726,000 lb	824,000 lb	780,000 lb
(Add) SSME steady-state thrust	1,125,000 lb	1,125,000 lb	1,125,000 lb
Peak Transient Force	1,851,000 lb	1,949,000 lb	1,905,000 lb

It is evident from actual measurements that the Shuttle *experiences* approximately 1.9 million lb force during the SSME's start-up transient; and not only the steady state thrust of 1.125 million lb, or 1.143 million lb (or the JSC 1.6% dynamic overshoot factor). It is clear that the Shuttle engineers were completely unaware that the *excess upward force* was simply the *dynamic overshoot*.

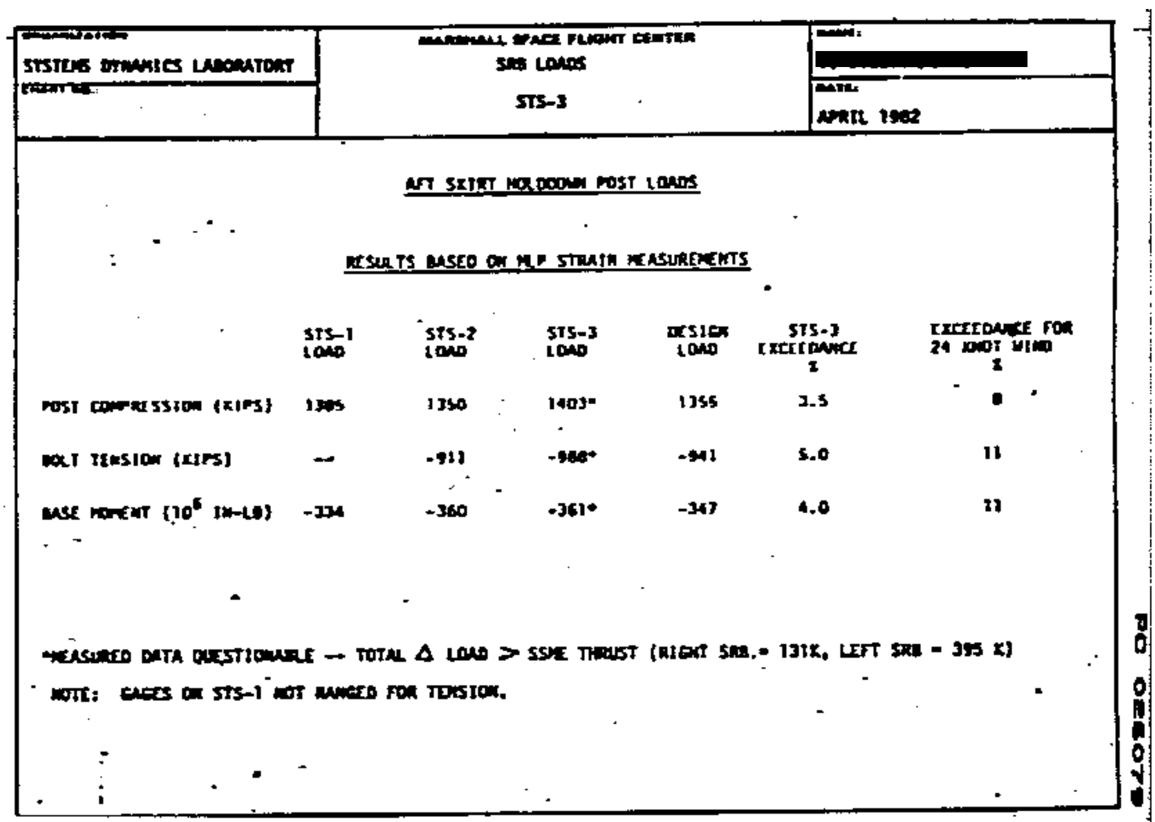
In 1972, the JSC documents specified a *dynamic factor* of only 1.6% for the SSME's lift-off thrust (see Table-2). We can calculate the actual *dynamic overshoot* factor directly from the correct and indisputable STS-3 measurement. This is shown in Table-9:

Table-9 Measured SSME's *Dynamic Overshoot*

Description	Method 1	Method 2	Method 3
Dynamic Overshoot	1,851,000 / 1,125,000	1,949,000 / 1,125,000	1,905,000 / 1,125,000
Overshoot Factor	1.65	1.73	1.69
Overshoot %	65%	73%	69%

The *dynamic overshoot* for the Space Shuttle Main Engines is 73% and not the initially specified, and grossly underestimated, 1.6%. Did I inflate the "excess upward force" by adding the weight of the Orbiter, or 200,000 lb? No. Here, the engineers were estimating the excess thrust, as indicated by their comment "WT.-THR." In essence, they subtracted the weight of the Orbiter from the measured thrust.

The STS-3 Test Sheets contain other evidence, from which the *correct dynamic overshoot* can be derived directly. Consider Fig. 16, another page from the STS-3 Test Report (Page 26,079 in the Presidential Commission Records). Here, we do not need to add or subtract the weight of the Orbiter.



SYSTEMS DYNAMICS LABORATORY

MARSHALL SPACE FLIGHT CENTER
SRB LOADS
STS-3

[redacted]

APRIL 1982

AFT SKIRT HOLDDOWN POST LOADS

RESULTS BASED ON MLP STRAIN MEASUREMENTS

	STS-1 LOAD	STS-2 LOAD	STS-3 LOAD	DESIGN LOAD	STS-3 EXCEEDANCE %	EXCEEDANCE FOR 24 KNOT WIND %
POST COMPRESSION (KIPS)	1305	1350	1403*	1355	3.5	8
BOLT TENSION (KIPS)	--	-911	-980*	-941	5.0	11
BASE MOMENT (10^6 IN-LB)	-334	-360	-361*	-347	4.0	11

*MEASURED DATA QUESTIONABLE -- TOTAL Δ LOAD > SSME THRUST (RIGHT SRB = 131K, LEFT SRB = 395 K)

NOTE: GAGES ON STS-1 NOT RANGED FOR TENSION.

Fig. 16 The STS-3 1982 Measurement of the Correct *Dynamic Overshoot* Considered "QUESTIONABLE" by Test Engineers

Note the comment at the bottom of the Test Sheet in Fig. 16:

MEASURED DATA QUESTIONABLE – TOTAL Δ LOAD > SSME THRUST (RIGHT SRB. = 131K, LEFT SRB = 395K) (MY EMPHASIS)

The load measured on one SRB using strain gages is 395,000 lb (the **395K** in Fig. 16). Because of the symmetry of the Shuttle, the other SRB experiences the same excess load. The steps to obtain the total transient force from the SSME's data at lift-off are straightforward. This time, we do not need to add the weight of the Orbiter. This time, the test result gives the "EXCESS UPWARD FORCE" directly:

Table-10 SSME's Peak Transient Force Derived from SRB's Data

Excess Force on one SRB	395,000 lb
Excess Force on 2 SRBs	790,000 lb
SSME steady-state thrust	1,125,000 lb
Peak Transient Force	**1,915,000 lb**

Again, that's it. The *transient force component* is about 800,000 lb, and not only 18,000 lb, as was initially specified for the Shuttle in JSC 07700. Also, the total force striking the Shuttle structures from the SSME's start-up thrust is about 1.9 million lb, and not only 1.1 million lb.

There are many places in the extensive database of the Space Shuttle where one can derive the correct dynamic overshoot effect from actual measurements. The engineers who conducted the tests, or analyzed the data, did not understand the transient effect. Notice how the experts called their results "QUESTIONABLE," and the destructive *dynamic overshoot* force remained hidden.

Experts from NASA, the Contractors, the professional organizations, academia, including the School of Engineering and Applied Science of my *alma mater* accused me of outright fabrication. For years, they insisted that I manipulated the numbers to "make them look bad." That is childish. The record is clear. The collective aerospace community has simply failed to recognize the enormous mistake, even after the error was accurately measured. The calculations above are straightforward.

If our 100-lb lady, in previous examples, steps suddenly on a weight-scale from zero height and glimpses the first overshoot reading of 170-lb, then it is questionable that her weight (a force) suddenly increased by 70-lb. It is not questionable, however, that the weight-scale experiences the total transient effect (another force) of 170-lb. The lady can think that the weight-scale experienced the brunt of 170-lb, or she may think that the scale experienced her weight (100-lb) plus the overshoot (70-lb), or, again, the same total of 170-lb. The analogy here is straightforward. If a mechanical defect in the weight-scale causes the dial to get stuck on the first dynamic overshoot, then the lady may become confused. She looks in the mirror and sees her 100-lb figure, she looks down at the dial and sees 170-lb for her weight. She does not know about the dynamic overshoot. And so, she concludes that the reading on the dial is "QUESTIONABLE." The Shuttle engineers look at the SSMEs and expect 1.1 million pounds. They look at the dial and see 1.9 million pounds. They do not know about the dynamic overshoot. And so, they conclude that their measurement is "QUESTIONABLE."

8. Confusion Over the *Dynamic Overshoot* Measurements

The *dynamic overshoot* force caused considerable confusion throughout the Space Shuttle program. Initially, the engineers designed the Shuttle to only the 100% steady-state load plus safety margins. They added small values for what they thought the *dynamics* would be in the system. Over the years, the experts measured the pressure in the SSMEs and the SRBs. They converted the *pressure* measurements into *force* values. They did not realize that the *pressure* does not overshoot, and they failed to specifically measure the *overshoot* forces. The *overshoot* forces exceeded the safety margins and caused considerable damage from mission to mission. When, by accident, the engineers noticed the dynamic overshoot force in their measurements, they became confused. They tried to reconcile their correct measurements with the incorrect calculations. The difference between the measured and the calculated values was so huge, which added to the confusion and which makes it easy to unravel the conflict and expose the mix-up.

The Shuttle experts think that the two boosters produce 5.4 million lb at lift-off (2.7 MP per SRB). The transient overshoot is 5.2 MP (96.9%). The engineers do not realize that the peak *transient* effect of the two boosters is 10.6 MP. They also think that the three SSMEs produce only the maximum steady-state thrust, or 1.1 MP, at lift-off. They do not realize that the peak *overshoot* of the SSME's is 1.9 MP. When they measure the SSME's *transient* lift-off load to be 1.9 MP, their test result looks absurd to them. They declare their measurement "QUESTIONABLE." How did this come about?

Consider our Eq. (7), which gives the total *transient* force directly,

$$F(t) = F_s(1 + e^{-pz\sqrt{1-z^2}}) \qquad (7)$$

Let us get rid of the parenthesis, or,

$$F(t) = F_s + F_s e^{-pz\sqrt{1-z^2}}$$

There are two terms in the transient solution. The first term on the right side is the steady-state value (this is the static or RPL value). The second term in the transient solution is the *transient* force component – or the dynamic overshoot. The exponential term is always less than 1.0. In other words, the *transient* force component is always less than the steady-state load.

Let us now substitute the 1982 STS-3 test results in the *transient force* equation. We need two numbers, and we have two numbers, namely, (1) the SSME's steady-state thrust of 1,125,000 pounds, and (2) the measured transient force component of 800,000 pounds. The maximum force $F(t)$ acting on the Shuttle is simply the sum of the two forces. Using either of the above expressions, we get:

$F(t)$ = 1,125,000 lb (1 + 0.73) ≈ 1,946,000 lb, or

$F(t)$ = 1,125,000 lb + 821,000 lb ≈ 1,946,000 lb

The NASA and Rockwell engineers truly *think* that I am confused about these transient forces. I *know* that they are confused about the transient forces. You, the reader, might think that the matter is trite and dull and that it is not worth the attention. After all, we are talking about adding two numbers. Who cannot add two numbers? There are hidden brain twisters here.

Some engineers simply do not know about the transient effect or how to calculate it. They think that the maximum force is the applied force or the maximum steady-state force. When the Shuttle engines are ignited, the engineers expect to measure about 1.1 million pounds. When they measure "excess upward force" of 800,000 lb, the mysterious force puzzles them. There is more to the confusion. It is not that the Shuttle engineers have never heard about transient forces. They know that there are transient effects, and they specifically mention "transient forces" and "dynamic forces" throughout their technical write-ups. Then, what happened?

Apparently, the Shuttle engineers feel that the steady-state force and the *transient force* are two separate things. To them, the 1.1 MP is the steady-state design load. They think that the 100% steady-state load is actually the maximum load. They know that there is a "transient" force component, but they think that the transient force happens independently of the maximum steady-state load. They do not add the two forces, instead, they compare the two numbers. Since the "transient" force is always a fraction of the steady-state force, the engineers use the latter (because it is the greater) for design purposes. What is incomprehensible here is that when the same engineers who calculated the dynamic, or transient, force see the measured 800,000 lb dynamic force, they fail to make the connection between the two values.

Let me describe the confusion in the Shuttle engineers' own words. First, the total maximum lift-off force is composed of two components, (1) the static force, and (2) the dynamics force. Let us take approximate values for the start-up thrust of the SSMEs and the SRBs. Remember that the dynamic overshoot factor for the SSME's is 73% (or, the dynamic force component is almost 80% of the static component). Also, the dynamic overshoot factor for the SRB's is 97% (or, the dynamic component is almost equal to the static component). The approximate values are tabulated below.

Description	Static Force	Dynamic Force	Max Force
SSMEs	1.1 MP	0.8 MP	1.9 MP
SRBs	5.4 MP	5.2 MP	10.6 MP

In Reference 17, "*Systems Analysis Approach to Deriving Design Criteria (Loads) for Space Shuttle and Its Payloads*," several NASA dynamics loads experts wrote in 1981:

> *"In general, since liftoff loads are approximately 80 percent due to dynamics, it was decided to use time-consistent loads,"* (p. 10).

Do you see the confusion? The engineers seem to know that the liftoff dynamics factor is 80% of the maximum steady-state thrust. The "*time-consistent loads,*" which are based on pressure measurements, go up to only the maximum steady-state force (see Figs. 11a and 12a). In effect, the engineers are saying that since the dynamic loads are only 80% of the 100% static loads, then they were justified to use the 100% static force for Shuttle design. You will see more evidence in Section 8.4 that the Shuttle engineers do not add the two forces, but rather compare the static and the dynamic overshoot force components!

Another stark example can be seen from the way that a large team of engineers handled the static and the dynamic components. In Volume II of the Report of the Presidential Commission, the Team writes:

> *"The dynamics of the problem do not yield results that differ from a quasi-static analysis using dynamic loads,"* (p. L-110).

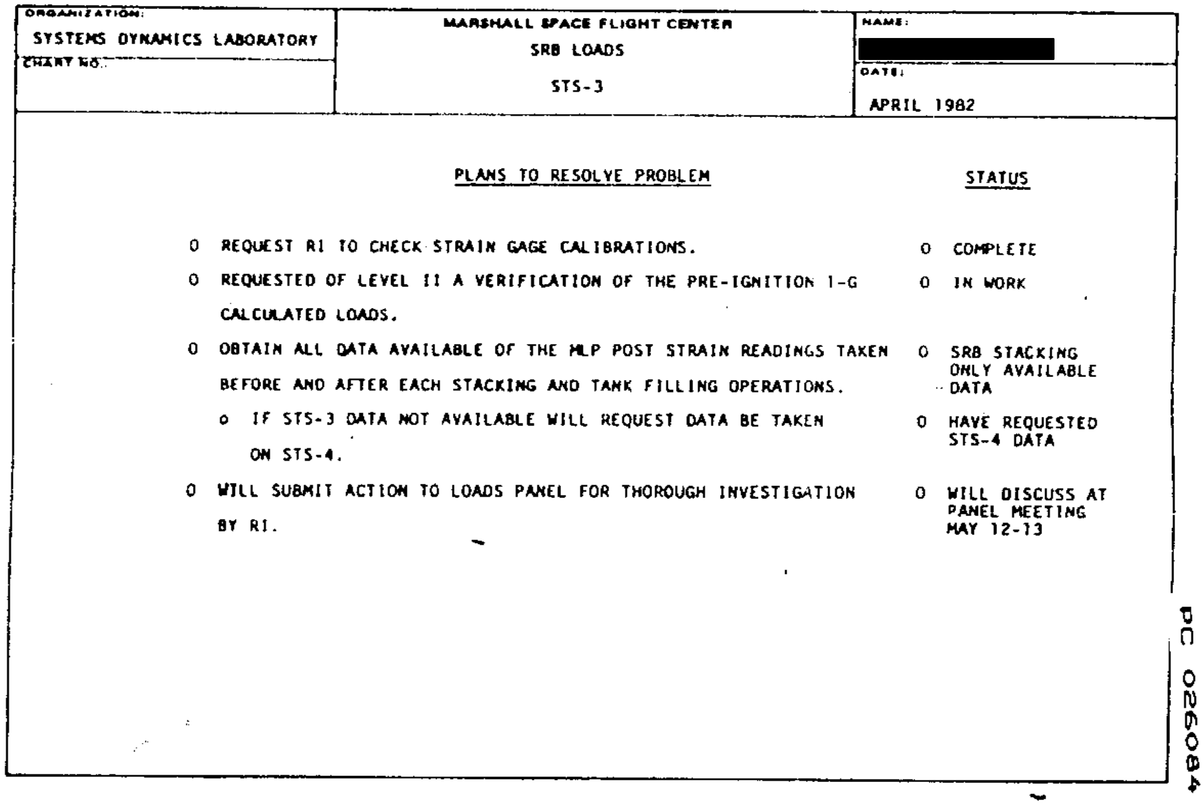
The static force for 2-SRBs is 5.4 MP and the dynamic force is 5.2MP. Again, the engineers do not add the two forces (5.4 and 5.2 MP), as they must, but rather they compare the static and the dynamic effects.

The non-technical reader will see the confusion as follows. Consider a 110-lb lady. She steps on a weight-scale. Some mechanical defect in the scale sticks the dial on the first dynamic overshoot. She sees 190-lb for her weight on the dial. She calibrates the scale and tries the process again. The lady looks in the mirror and sees her 110-lb shape (think of the above 1.1 MP thrust); she looks down on the scale and sees the 190-lb weight (think of the above 1.9 MP thrust). She decides that the extra 80-lb is simply some "excess downward force." As the lady goes about her chores, the "excess downward force" nags her. How can she have the figure of a 110-lb person when her weight is 190-lb?

The "excess upward force," of 800,000-lb, nagged the Shuttle engineers. The oddity required explanation. They might: (1) go to the NASA upper technical hierarchies requesting verification of the calculated loads, (2) go the Contractor to check the calibration of the instruments, (3) return to all previous tests to substantiate the odd measurement, or (4) ask for outright thorough investigation of the whole situation. The Shuttle engineers did all of the above. Their quandary over the *dynamic overshoot* measurements is obvious from their actions in the STS-3 Test Report, as you will see next.

8.1 Is SSME's Thrust 1g? The Engineers Ask the "$64,000 Question"

The predicament of the engineers who examined the STS-3 lift-off loads in 1982 is obvious from the comments in their Test Report. Fig. 17 is a reproduction of a Test Sheet entitled "*PLANS TO RESOLVE PROBLEM*." The problem is the excess 800,000 lb transient thrust measured for the SSME's during lift-off.



ORGANIZATION: SYSTEMS DYNAMICS LABORATORY
CHART NO.:
MARSHALL SPACE FLIGHT CENTER
SRB LOADS
STS-3
NAME: [redacted]
DATE: APRIL 1982

PLANS TO RESOLVE PROBLEM	STATUS
O REQUEST RI TO CHECK STRAIN GAGE CALIBRATIONS.	O COMPLETE
O REQUESTED OF LEVEL II A VERIFICATION OF THE PRE-IGNITION 1-G CALCULATED LOADS.	O IN WORK
O OBTAIN ALL DATA AVAILABLE OF THE MLP POST STRAIN READINGS TAKEN BEFORE AND AFTER EACH STACKING AND TANK FILLING OPERATIONS.	O SRB STACKING ONLY AVAILABLE DATA
o IF STS-3 DATA NOT AVAILABLE WILL REQUEST DATA BE TAKEN ON STS-4.	O HAVE REQUESTED STS-4 DATA
O WILL SUBMIT ACTION TO LOADS PANEL FOR THOROUGH INVESTIGATION BY RI.	O WILL DISCUSS AT PANEL MEETING MAY 12-13

PC 026084

Fig. 17 "PLANS TO RESOLVE PROBLEM" Betrays Complete Unawareness of the *Dynamic Overshoot* Force Component

The engineers expected to measure a little more than 1 million lb, but their instruments read a little less than 2 MP. Anyone familiar with the *dynamic overshoot* effect would recognize the general agreement between the analysis, which predicts 1.9 MP force and the test results, which also gave 1.9 MP. The comments of the engineers show complete unawareness of the *transient* effect. Let us review their comments in Fig. 17:

1. "REQUEST RI TO CHECK STRAIN GAGE CALIBRATIONS": Repeatedly, the test engineers refer to calibration as the potential culprit responsible for the "EXCESS UPWARD FORCE." Calibration errors are generally small. The magnitude of the error, 73%, could not be explained by calibration errors. The engineers ask *RI* (Rockwell International) to check the instruments' calibration. There is some hope here that the excess forces may disappear after calibration. This is wishful thinking.

2. "REQUESTED OF LEVEL II A VERIFICATION OF THE PRE-IGNITION 1-G CALCULATED LOADS": The "Level II" is the highest technical management Office at NASA. The engineers want *verification* of the 1g calculated loads for the SSMEs. This is the $64,000 Question that I described in Section 6. Is the thrust from the three SSMEs at lift-off the specified 1.1 MP, or is it the measured 1.9 MP? "Pre-ignition" refers to thrust before SRB ignition. In plain language, the engineers are telling the upper management, "you told us the engines produce 1.1 million pounds thrust, and we are measuring 1.9 MP thrust!" This demonstrates no differentiation whatever between input and output.

3. <u>"OBTAIN ALL DATA AVAILABLE OF THE MLP POST STRAIN READINGS TAKEN BEFORE AND AFTER EACH STACKING AND TANK FILLING OPERATIONS."</u> All the NASA directors must think carefully about these comments. The measured excess upward force (800,000-lb) is nearly one-million-pounds. This is a massive force. Here, the engineers are wondering whether the massive force originated in booster *"stacking"* or liquid hydrogen and oxygen *"tank filling"* operations! It does not occur to the engineers that they canceled the effect of these operations when they "calibrated" the strain gages – Remember, they used 3 calibration methods. The engineers do not give any indication that they know that the "dynamic overshoot" is the mysterious massive force. The "excess upward force" puzzled them.

4. <u>"WILL SUBMIT ACTION TO LOADS PANEL FOR THOROUGH INVESTIGATION BY RI":</u> The Space Shuttle Program has many expert panels. There is a Loads Panel, to resolve crucial loads' issues. The test engineers decide that the measured excess force of 800,000 lb is severe, which, of course, it is. They ask for *thorough investigation* by a special panel of experts. I found nothing in the record to this late (1992) date, which indicates that the "excess upward force" issue was ever resolved by anyone from NASA or Rockwell. The reader will see later that a NASA Level II director wrote to tell me (in 1992) that the "dynamic overshoot" is controlled so as not to exceed 2%. The director was referring to the "pressure fluctuation," and not to the correct "force dynamic overshoot."

The STS-3 Test Report includes other comments that clearly show unawareness of the *dynamic overshoot* even after the *effect* was accurately measured. In those comments, the *wind loads* and other factors were found to be *negligible*, and were determined by the engineers not to be the source of the measured excess forces.

Another comment that is of particular interest appears in the Test Sheet shown in Fig. 16. The engineers write, "<u>GAGES ON STS-1 NOT RANGED FOR TENSION</u>."

In my meetings with the KSC experts in October 1986, I presented analysis that pointed to *dynamic overshoot* factors of the order of 70-100%, and not 1-10%. The Director of Shuttle Engineering at KSC asked if I could corroborate my estimates with actual Shuttle data. Many drawings, specifications and test data were brought into the meeting. All the data brought into the meeting were from the first Shuttle mission, STS-1. I was not able to find the exact *peak overshoot*. The above comment explains why we were not able to find the *overshoot* from the STS-1 data. Apparently, the instruments were not *ranged, or set,* to measure the actual *transient* peak force. The test traces went off the charts. I was responsible for *setting* charts to measure pressure, strain, temperature and other readouts in a satellite control center in 1970, and I knew why the maximum forces were missed in the STS-1 measurements.

Also, note the engineers' remark in Fig. 16: "TOTAL Δ LOAD > SSME THRUST." The symbol Δ (delta) usually refers to a difference. The measured "excess upward force of 800,000 lb" is not greater than the SSME thrust of 1.125 million lb. Apparently, the test engineers intended to say that the total load that they measured was greater than the SSME thrust; or 1.9 MP> 1.1 MP.

Confusion over the *transient overshoot* effect is situation dependent. If you take a 10-lb bag of potatoes to a checkout counter at a supermarket and the clerk charges you for 19-lb because that was the first *dynamic overshoot* that registered on his or her vegetable weight-scale, some of you will disagree, and some will be furious. You are willing to pay only for the steady-state weight of the potatoes. You are right. If the vegetable-weight-scale could speak, it could convince you, the clerk and the supermarket manager that *it* really felt the brunt of the 19-lb force! The weight-scale is also right. If everyone knows about the dynamic overshoot effect, then there will be no disagreement and no need for further action. The "*plans to resolve problem*" after the STS-3 tests indicate that the Shuttle engineers were not at all familiar with the correct transient effect or analysis in the 1980s.

I had several meetings with NASA over the lift-off loads' issue over the years. Some engineers and managers were furious at my assertions. They felt strongly that they could not make such an outrageous mistake. I was certain they did. People make mistakes, and I was not accusing anyone of anything else.

8.2 Is the Base Bending Moment 700 MIP?

Before boosters' ignition and lift-off, the SSME's thrust (1.1 million lb) ***and dynamic overshoot*** (800,000 lb) push the Shuttle assembly forward producing bending moment at the base of the assembly, Fig. 18, while the boosters are still tied to the launch platform by eight holddown posts, Fig. 19.

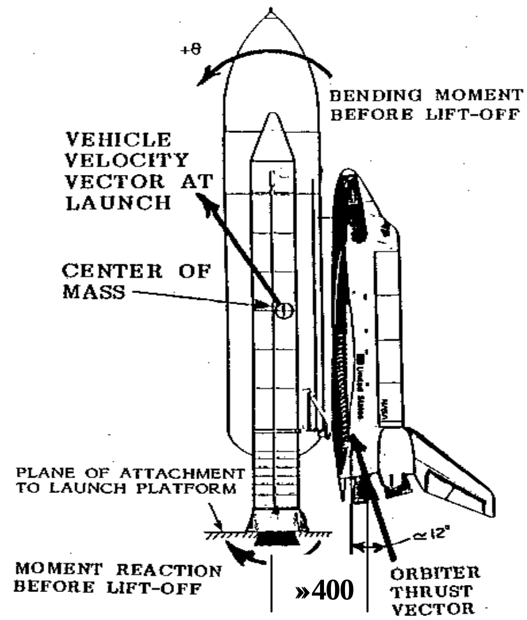


Fig. 18 Off-Center SSMEs Produce Base Bending Moment Before Liftoff

If the SSMEs are ignited and the Shuttle is held on the Launch Pad, the assembly oscillates in response to the *suddenly* applied force. The response was recorded during the Shuttle tests, Fig. 20. The oscillation is strictly the result of the *sudden* force. If you release a 10 lb bag of potatoes suddenly on a vegetable-scale, there will be oscillation and overshoot. If you release the 10 lb bag gradually on the scale, there will be no overshoot, nor oscillation. If the 1.1 MP thrust from the SSMEs is released in gentle steps, there will be no oscillation. The *sudden* rise of thrust is the cause of oscillation. *If there is oscillation, there is dynamic overshoot; if there is no oscillation, there is no dynamic overshoot.* The Shuttle oscillation was known and measured in the 1970s. The *dynamic overshoot* should have been anticipated from the beginning. Since it was not, the base bending moment caused considerable problems.

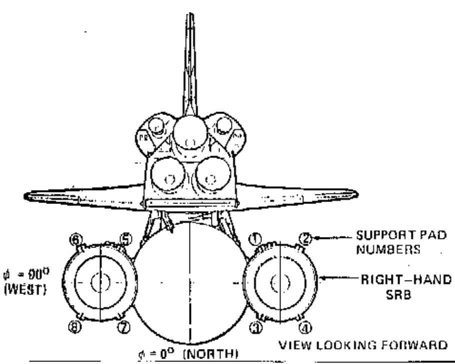


Fig. 19 Eight Holddown Posts tie the Shuttle to Pad Before Liftoff

A NASA compendium[33] on dynamics in space systems admitted that the Shuttle engineers encountered major problems in calculating and measuring the liftoff loads in the holddown posts. The Report says, "*Predicting and measuring this load* ***was a major problem***," (emphasis added). The overshoot excess forces caused enough damage to the posts to show "*the potential of not extruding*" on lift-off, *Ibid,* page 56. This is to say that the Shuttle was nearly welded to the Launch Pad during the lift-off process. NASA relied on the dangerous procedure of having the thrust of the SSMEs and SRBs pull "*the bolts out as a result of liftoff;*" *Ibid*. The grossly underestimated dynamic factors brought about the dangerous situation at lift-off.

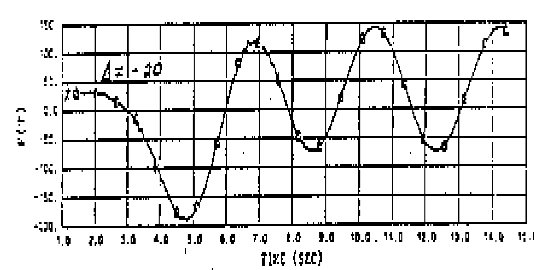


Fig. 20 Shuttle Oscillation on Launch Pad due to 100% SSME Sudden Thrust

The base bending moment is the torque produced by the off-center SSMEs' thrust, or **Torque = Force ´ Distance.** The *force* is the thrust from the main engines. The moment distance, or torque arm, is about 400 inches. The *force* and the *distance* have remained the same since the beginning of the Space Shuttle Program. The *approximate* value of the base moment should have been similar, though not identical, for all missions and tests.

Many parameters affect the value of the base moment from one Shuttle mission to another. These include the hot or cold start-ups (like you notice with your car in summer and winter), the payload weight in the Orbiter, the wind and wind direction, etc. Also, the line-of-action of the SSME's is canted from the vertical (see Fig. 18). But, all of the above factors combined do not *double* the value of the base bending moment from one Shuttle mission to another. So in this Section, I am specifically presenting *approximate*, but generally representative, values of the base bending moment using the relationship, torque = force x distance.

The SSME's RPL thrust is 1.1 million lb. The SSME's peak transient force is 1.9 million lb for a 73% dynamic overshoot. NASA and Rockwell used a dynamic factor of 1.6% for the SSME's thrust. Let us calculate the base bending moment for three conditions, **Table-11**:

Table-11 Vehicle Base Bending Moment

Description	No overshoot	10% Overshoot	73% Overshoot
Thrust for 3 SSMEs	1,125,000 lb	1,237,500 lb	1,950,000 lb
Subtract Orbiter Weight	200,000 lb	200,000 lb	200,000 lb
Resultant Force	925,000 lb	1,037,500 lb	1,750,000 lb
Bending Moment/2SRBs	370×10^6 in-lb	415×10^6 in-lb	700×10^6 in-lb

The total base-bending-moment is shared equally by the two boosters. The above results are summarized in **Table-12** for 1-SRB and 2-SRBs cases. For the correct dynamic overshoot of about 70%, the base bending moment for 2-SRBs is 700 x 10^6 in-lb (700 MIP), and for 1-SRB, it is 350 MIP.

Table-12 Base Bending Moment (10^6 in-lb)

Description	2-SRBs	1-SRB
SSME Steady State Thrust	370	185
10% Dynamic Overshoot	415	208
73% Dynamic Overshoot	**700**	**350**

The confusion over the base bending moment design values can be seen from the following partial list that I collected for values specified or reported by NASA and the Contractors over the years. The origin of the data for each case is referenced.

Table-13 The Checkered History of Base Bending Moment (MIP)

Source	**Year**	**Listed Value**	**1-SRB**
Steady-state Fatigue[34] (p. 4.19-8)	1979	170 (1-SRB)	170
Steady-state Fatigue[34] (p. 4.19-8)	1979	189 (1-SRB)	189
Steady-state Fatigue[34] (p. 4.19-18)	1979	187 (1-SRB)	187
Steady-state Fatigue[34] (p. 4.19-18)	1979	232 (1-SRB)	232
NASA Tech Paper[17] (p.20)	1981	200 (1-SRB)	200
Rockwell Measurement[27] (p. 380)	1982	580 (2-SRBs)	290
Rockwell Paper[26] (p. 311)	1982	310 (2-SRBs)	155
NASA Paper[17] (p. 13)	1981	320 (2-SRBs)	160
NASA Paper[33] (p. 58)	1985	320 (2-SRBs)	160
Challenger Commission[30] (Vol. I, p. 54)	1986	291 (2-SRBs)	146
NASA Specification[28] (p. 4.5-140)	**1990**	**355 (1-SRB)**	**355**
Rockwell Specification[35] (p. 1.3.2-120)	**1990**	**355 (1-SRB)**	**355**

You do not need to be a rocket scientist to see that with the exception of the 1990 specification values, the earlier estimates of the base bending moment were simply hodgepodge. What was the base bending moment? Was it 146, 155, 160, 170, 187, 189, 200, 232, 290 or 355 MIP? Were these values for one booster or for two boosters? Where did these chaotic values for the same parameter come? How did the Shuttle technical management allow such sloppiness in the first place? And, why weren't the messy values pointed out to the Rogers Commission during the investigation of the Challenger accident?

8.3 Compounding the Dynamic Overshoot Error

The *dynamic overshoot* factors (70-100%) for the Space Shuttle exceeded the safety margins (25, 40%). It was inevitable that the system was going to fail its first tests. That was what happened in 1978, see Sec. 10. The first Shuttle assembly was bolted at the base of the two SRBs to a launch pad. The off-center engines were brought up to full RPL (100%) throttle, Fig. 21, and the Shuttle Stack rocked back and forth, see Fig. 20. These tests last around 20 seconds. The tip deflection at the top of the External Tank is more than 20 inches and it is clearly visible in video footage. The unanticipated and unexpected *dynamic overshoot* struck with vengeance. How did this come about?

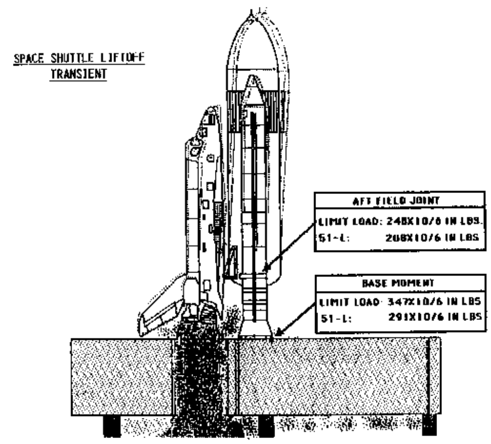


Fig. 21 SSME's Thrust Pushes Stack Forward While Boosters Tied to Platform

Before the Shuttle Program, there was a conspicuous general specification, which demanded that rockets be released from the Launch Pad when the thrust from the main engines reached 90% RPL level. Do you see the connection to the dynamic overshoot? Releasing the rocket from the Launch Pad before the thrust reached 100% level avoids the detrimental effects of the dynamic overshoot! The 90% throttle lift-off requirement was included in the Shuttle specifications. The Shuttle was designed to lift off when the SSME's thrust reached 90%, or before the first *dynamic overshoot* at the base!

When the Shuttle failed the initial tests in 1977-78, alternatives were considered to *alleviate* the unforeseen excess loads. The base bending moment was one of the important parameters. Remember that the base moment, or torque, is the result of the SSME's thrust before lift-off. Since the dynamic overshoot was not included, nor understood, in the thrust calculations, the transient effect was also missing, and misunderstood, in the base bending moment. In the late 1970s, NASA and Rockwell were trying to alleviate a problem that they did not understand.

A Rockwell International load's expert discussed the alternatives in a 1982 technical paper,[27] and the options considered are reproduced in the following list from reference 27:

1. *"Lift-off with a lower thrust level on the SSME's*
2. *Lift-off with one engine out*
3. *Tilt the vehicle on the launch pad*
4. *Devise a controlled release for the base restraints*
5. *<u>Introduce a time delay for SRB ignition and vehicle release</u>"*

These were drastic measures, and we knew in 1978 that the Shuttle Program was in great trouble. The reader should remember that the stealthy dynamic overshoot was the source of trouble, and it was the primary reason for evaluating the five drastic alternatives.

The Rockwell expert commented on the 5 alternatives as follows:

> *"A study of these options showed that most of them were either ineffective, unfeasible, or introduced undesired risks. <u>Option 5 proved to be both effective and easy to implement</u>."*

The decision to delay the Shuttle lift-off by 2.7 seconds compounded the problem. The decision would haunt the Shuttle and further confound the engineers. Delaying lift-off from the 90% RPL level exposed the Shuttle to the full brunt of the *dynamic overshoot*. It may sound unbelievable to the reader, but the engineers thought that the base bending moment would increase by only 10%. After all, they were only going from 90% throttle to 100% throttle. Isn't this a 10% difference? Everyone was happy with the decision and no one noticed that in going from 90% to 100% throttle, the bending moment **<u>doubled</u>**.

The advantage of the time-delay was widely described, and hailed, after the first Columbia mission. No one mentioned, or noticed, the *dynamic overshoot*. The Rockwell expert wrote in 1982:

> *"It is known that if the magnitude of the base-bending moment at the time of release could be reduced, the subsequent twang loads would also be reduced; thus, it was proposed that the time of lift-off be delayed past the time of peak moment until the vehicle has rebounded and the moment is in the trough. The delay chosen was 2.7 seconds. The effect of this time delay is to reduce the critical twang load in the forward attachment structure by 25 percent."* (Ibid – *my emphasis)*

Another Rockwell expert noted the benefit of lift-off time-delay in a 1982 report[36] as follows:

> *"Notice that if launch occurred as soon as possible following engine performance verification (90-percent thrust), the base bending moment is near the maximum level. But if we wait approximately 2.5 seconds, the cantilever bending torque is at a minimum. This is what is done in the launch of the Shuttle." (my emphasis)*

Several NASA experts had noted the benefits of delayed lift-off in 1981 as follows:[17]

> *"Due to the fact that the system is dynamic, the vehicle responds in a such a manner that some time delay in SRB ignition is used, then a minimum moment can be achieved." (my emphasis).*

The Shuttle engineers were satisfied with the lift-off time-delay because it reduced the base bending moment at lift-off from the 90% level to a trough value. But, no one noticed the basic fact that before the Shuttle reaches the new trough, it must first go through a new, unexpected and unaccounted for, peak! The initial 1972 mistake with the *dynamic overshoot* was *compounded*. You can begin to see how the hodgepodge base bending moment values in Table 13 came about. You can see what happened in Fig. 22.

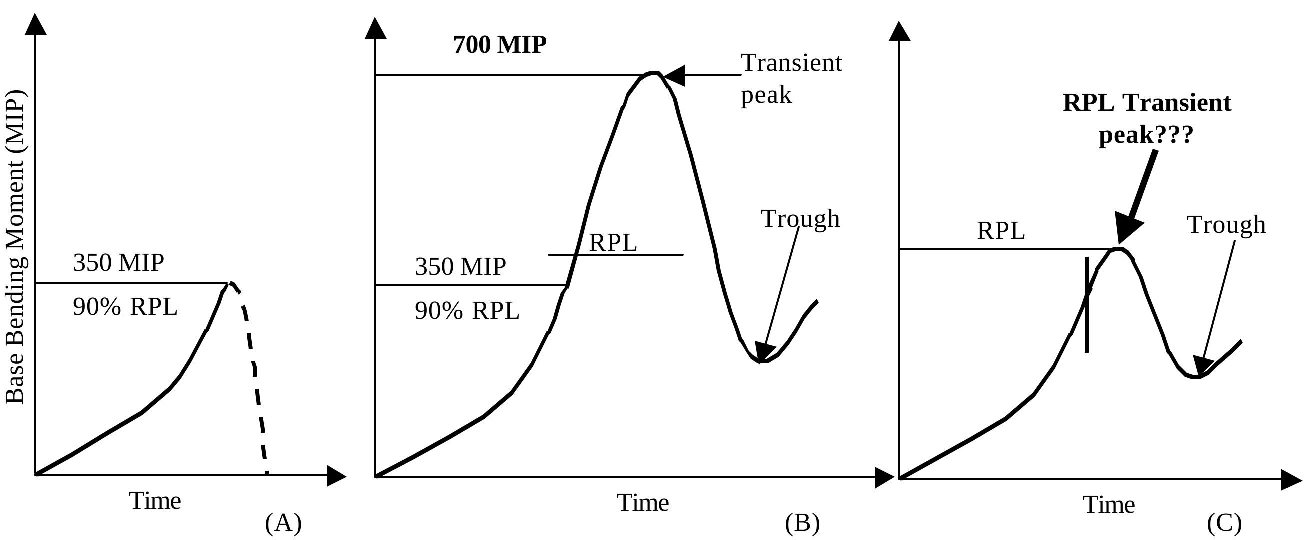


Fig. 22 Delayed Shuttle Lift-off Created Problems

Sketch (A) shows the initial plan, lift-off at 90% RPL.

Sketch (B) shows what happened with the time-delay. Before bouncing back into the trough, the Shuttle must first go through the dynamic overshoot peak.

Sketch (C) shows what the Shuttle engineers expected with the time-delay. They expected the base bending moment to rise to only the 100% RPL level and then fall back into the trough, which is absolutely wrong.

Notice the incredible happenstance. Completely by accident, the maximum bending moment for 2-SRBs in the early lift-off scheme (350 MIP) becomes the maximum bending moment for 1-SRB in the delayed lift-off plan (350 MIP)! Considering that the Shuttle engineers had missed the *dynamic overshoot* since the beginning of the Program, the event must have caused bewilderment. The hallways of engineering schools are filled with sad stories of students who failed to multiply, or divide, a number by 2 and failed the test. That was when the confusion got out of hand.

Unaware of the *dynamic overshoot effect*, some engineers did not even know how to illustrate the base bending moment graphically. As we will see next, some of them resorted to the situation shown in Sketch (C). Since the SSME's thrust went from 90% to 100%, these engineers reasoned that the base bending moment also goes up to the 100% level. *No dynamic overshoot*! That kind of illustration was a mess. For, how can a transient that does not exceed the steady-state value bounce back and oscillate?

Here, the engineers betrayed complete unawareness of how to correctly handle the *transient* forces. If the 100-lb lady steps ever so gently on the old bathroom scale so as not allow the dial to exceed her 100-lb weight, then there will be no oscillation and no overshoot. In order for the oscillation to exist, the effect of the sudden force must exceed the steady-state weight. In other words, the dynamic overshoot must exceed the lady's weight; else there will be no oscillation. Yet, the Shuttle engineers went ahead and included the *transient oscillatory* behavior in their graphs, even though their maximum base bending moment did not exceed the steady-state value. That was absolutely wrong.

8.4 Erroneous Transient Illustrations

The *base bending moment overshoot* happens leisurely. It is not a sudden spike that can be easily overlooked. It does not involve the mix-up of the overshooting forces and the non-overshooting pressures. Its frequency of oscillation is very low, about 0.25 Hz (Ref. 30, Vol. II, L-35). Its oscillation is visible to the naked eye. Its response time to the first overshoot is relatively long, about 2.01 seconds, from Eq. (9). It is measured directly with strain gages at the SRBs' holddown posts. Its maximum value is easy to calculate. Yet, this parameter has caused considerable difficulties for the Shuttle engineers.

What is the maximum base bending moment for the Shuttle? Or, what is the torque at the base of the boosters due to the SSME's thrust? The distance between the action center of the SSMEs and the center of the SRBs is about 400 inches. The damping ratio for the lateral mode of oscillation of the Shuttle is 0.10. For this ratio, the *dynamic overshoot* is 73%. The *dynamic overshoot* was actually measured by NASA to be 73%. We derived the dynamic overshoot directly from the STS-3 Test Report's Method 2 measurement column in Table-9. The 100% SSME's thrust is 1.125 million lb. The weight of the Orbiter is 200,000 lb. Estimating the maximum (or peak transient) base bending moment is straightforward:

Base Bending Moment = Force $\times$ Distance
$[(1,125,000 \times 1.73) - 200,000] \times 400 = 699 \times 10^6$ in-lb.

This is the maximum base bending moment (with the dynamic overshoot) for a full Shuttle Vehicle, with two SRBs. What is the maximum moment for one booster? **350 MIP**. That's it.

As I said in the previous Section, by happenstance, the base bending moment for the 90% SSME's throttle (350 MIP) turned out to be about half the value calculated above for two boosters (700 MIP). That coincidence added to the confusion.

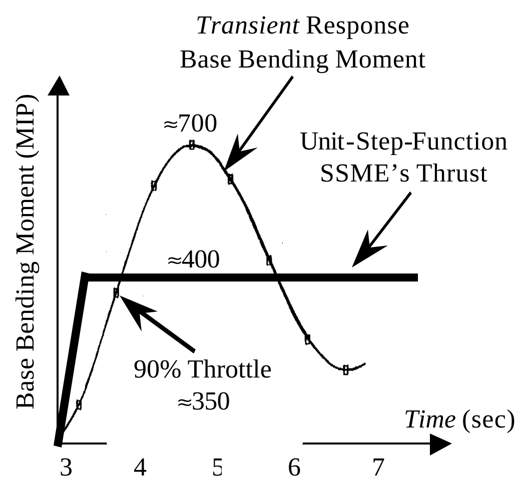


Fig. 23 Base Moment *Transient* Response for <u>2-SRBs</u>

How does the *transient* response for the base bending moment look like? One can use Equations 4, 7 or 9 in Section 4 to derive the response. A typical response is shown in Fig. 23. Notice that the *dynamic overshoot* <u>must</u> rise above the steady-state value in order for oscillation to occur. If the response peak does not rise above the steady-state value, then there is no *dynamic overshoot* and no oscillation.

The next question sounds tricky, but it is not. How do we illustrate the transient response for 1-(ONE) SRB? Do we just take the peak for 2-SRBs (700) and lower it to 350 MIP? Of course, not. If you do that, you have not grasped the *dynamic overshoot* concept. If you do that, then the *transient peak* falls below the steady-state value, which is marked "unit-step-function" in Fig. 23. And if the peak does not rise above the steady-state value, then you will not have *overshoot* or *oscillation*. The illustration in Fig. 24 is simply <u>wrong</u>. It is wrong for ONE SRB and it is wrong for 2-SRBs. It does not matter what values you use on the ordinate. If the *peak* is below the steady-state value, then the illustration is simply incorrect. Fig. 24 is crossed with X-mark to emphasize the point. One cannot argue that because reputable journals allow the wrong illustration, then it is correct. It is wrong, and the peer reviewers must make a note of the glaring fact.

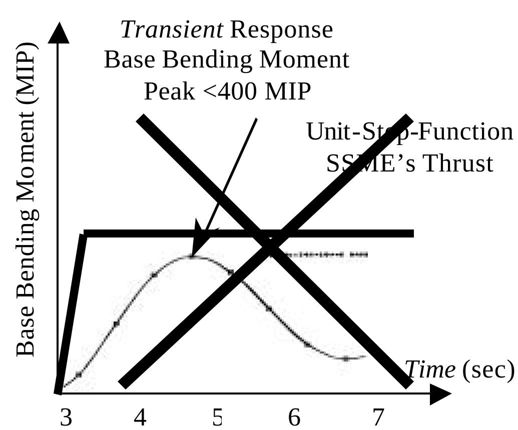


Fig. 24 *Transient* Response for Base Bending Moment

The easiest way to illustrate the transient response for <u>ONE</u> booster is to pick up a pencil and divide the values in Fig. 23 by 2. You get Fig. 25. This is it. The new Figure looks the same like Fig. 23, as it should. Of course, you can lower both the transient peak and the SSME's thrust to ½ their values. If you do this and stretch the figure vertically, you will get Fig. 25.

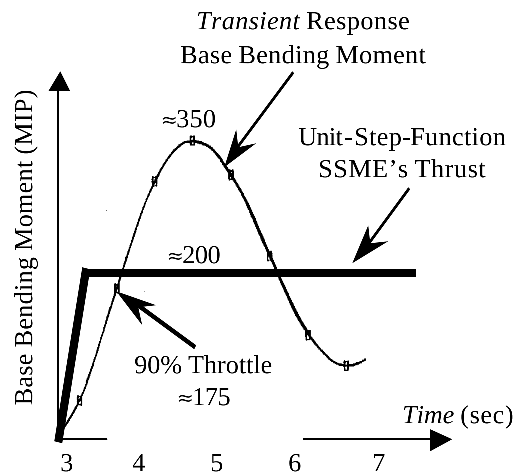


Fig. 25 Base Moment *Transient* Response for 1-<u>SRBs</u>

Let us now look at how the Shuttle engineers incorrectly portrayed the base bending moment *transient response* for more than twenty years.

In 1981, several NASA experts illustrated the base bending moment in a Loads Design Criteria Report.[17] That was four years after the lift-off time-delay was made, and after the Columbia FRF tests and first flight in 1981. The transient response derived by the NASA experts is shown in Fig. 26. A senior NASA dynamics expert also used the same *transient* response in a report entitled, "*Problems Experienced and Envisioned for Dynamical Physical Systems*,"[33] in 1985, (p. 58). That was long after the "excess upward force" was measured from the STS-3 lift-off data in 1982. *Liftoff dynamics* presented problems to the *dynamics* experts at NASA and the Shuttle Contractors.

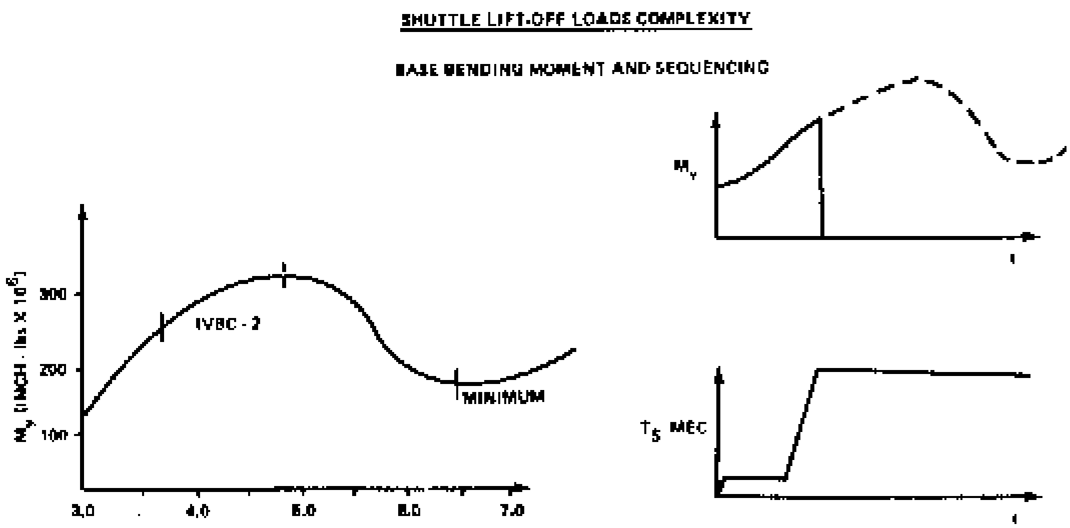


Fig. 26 <u>1981</u> Illustration of base bending moment *transient* solution by 5 NASA experts. Notice how *transient* peak does not reach the steady-state value!

The lower right curve shows the near unit-step-Input and the left curve shows the Output, or the transient response. The *transient* solution is nothing less than scandalous. Do you see why?

In Fig. 26, the peak moment does not even rise above the steady-state value! The 100% base moment is about 400 MIP, but this curve goes only to about 330 MIP. <u>There is no *dynamic overshoot.*</u> Or, is there? And what is its magnitude? I noted earlier that *if there is no overshoot, then there is no oscillation*. Oscillation happens because of the energy stored <u>*above*</u> the steady state, or applied, input. The engineers know that the Shuttle oscillates on the Launch Pad. Here, they seem to be trying to mesh erroneous calculations with observed behavior. The transient solution is certainly wrong for 2-boosters. Furiously, the Shuttle engineers countered that the diagram is for one booster. It is also wrong for ONE BOOSTER.

The NASA transient solution in Fig. 26 is terribly wrong. I have reproduced the NASA transient solution (shown on the left side in Fig. 26) in Fig. 27. Here are some observations:

1. The peak bending moment is *only* 330 MIP! The correct peak transient moment is about 700 MIP.
2. The peak transient moment is _smaller_ than the steady-state value. How can that be? How can a response that does not climb above, or even reach, the steady-state value spring back and oscillate?
3. The lift-off time-delay in 1977 was meant to achieve the smaller bending moment in the trough. The trough value of 170 MIP, which is marked "MINIMUM," is about the only correct thing in this curve. It is as if the engineers were only concerned with this value, to the exclusion of everything else.
4. The vertical markers at 3.8, 4.8 and 6.4 seconds correspond to (1) 90% SSME thrust (the abandoned lift-off condition), (2) the peak moment, and (3) minimum moment, respectively. The 90% SSME's throttle level had no useful meaning or use in the 1980s, but for some reason, this value seems to mean something to the Shuttle engineers, as it is always included in their graphic illustrations. It is included as a badge of honor, when it categorically proves the dynamic overshoot blunder.

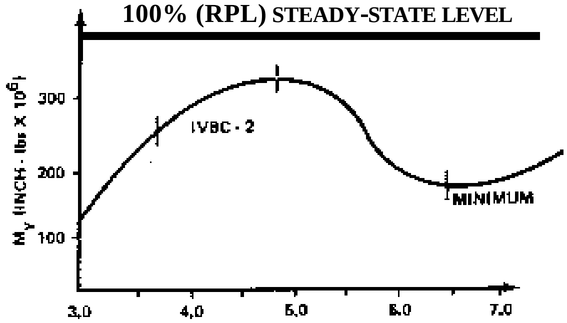


Fig. 27 NASA Transient Peak Falls Below Steady-State Static Value

When I presented my analysis of the base bending moment in 1990, the Shuttle engineers were furious. They claimed that their data and figures were for one booster. I knew that they _doubled_ the base bending moment, but my point was that they did not know why. I described the correct illustration of the base moment for one booster and for two boosters in Figs. 23, 34 and 25. The NASA transient solution is wrong for two boosters and it is wrong for one booster. If the NASA illustration is for 1-SRB, then the curve shows the following problems: (1) A peak of 320 MIP for 1-SRB instead of 350 MIP, a small difference, (2) A trough of 170 MIP for 1-SRB instead of half the value, or 85 MIP, a 100% error, (3) A steady-state moment of 280 MIP per booster, instead of a measured 175 MIP, a 60% error, and (4) Incorrect *dynamic overshoot* of less than 10%, which is much smaller than the measured 73% overshoot.

Claiming that the illustrations were for one booster revealed deep-seated confusion about the "dynamic overshoot" effect. Here is more. If the NASA curve is for 1-SRB, then the peak for 2-SRBs is 640 MIP (320 x 2) and the minimum is 340 MIP (170 x 2). Now, the transient oscillates about a value that is well above the steady-state value, which is impossible. The transient would now oscillate between 640 MIP and 340 MIP, or about the 560 MIP value! This is impossible because oscillation of the transient occurs about the steady-state value. In essence, the NASA transient solution (if it is for one booster) just barely undershoots the steady-state value to a minimum of 340 MIP; and then, with hardly any stored energy, it overshoots to 640 MIP. The original title of the NASA transient illustration is "_SHUTTLE LIFT-OFF LOADS COMPLEXITY_." Unfamiliarity with the correct start-up transient analysis led the engineers to think that the problem was more complex than it really is.

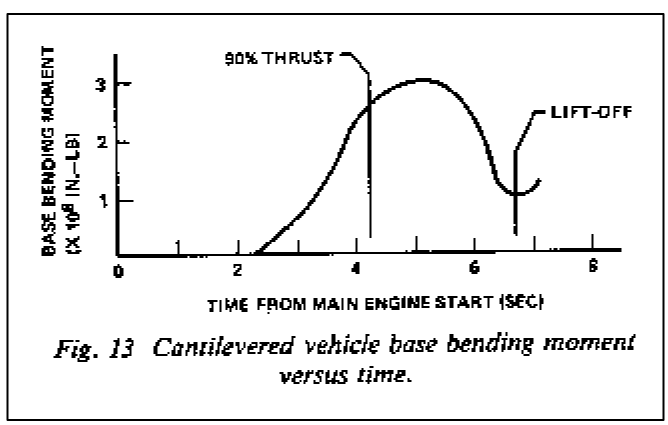


Fig. 28 _1982_ Base Bending Moment Illustration by a Rockwell Expert

Another illustration of the base bending moment response, Fig. 28, was given by another Rockwell expert in a 1982 technical paper.[36] The curve shows desperate attempts to reconcile the unexpected transient response with the specified 100% RPL value. The response is marked "_vehicle base bending moment_," or for 2-SRBs. The 90% SSME's thrust is also marked by this expert. Notice how the peak of the transient curve is about 10%

above the 90% level. The transient peak is merely the steady-state value, or the 100% RPL level, with no overshoot whatsoever. Some of the shortcomings of this illustration include, (1) A peak moment of 310 MIP, compared to the correct 700 MIP, a 120% error, (2) A trough of approximately 90 MIP (nearly the 1-SRB value), instead of 170 MIP, and (3) Instead of a 73% overshoot, the dynamic overshoot is nonexistent which is wrong.

In October 1986, engineers and officers at KSC agreed with me that the *transient* analysis of the Space Shuttle had been in a great mess. It was agreed that I would work with NASA to resolve the liftoff dynamics. Other NASA officers were furious with the arrangement, and the agreement was canceled. Apparently, the latter group headed by Admiral Richard Truly thought that they could handle the problem themselves, or that there was no problem.

Three years later, in October 1989, I had a Hearing at NASA to show that my work was used by the space agency. Two senior experts from the Marshall Space Flight Center were brought in as Technical Advisors. The experts were the authors of the 1981 and 1985 transient illustration in Fig. 26. They produced a new base bending moment *transient response*, which is shown in Fig. 29A. This time, I was furious. I declined to come back to the Hearing the next day and I decided to share the massive *dynamic overshoot* blunder directly with the engineering community at large. No one in attendance in the NASA Hearing noticed the deep-rooted confusion of the dynamics experts.

At first glance, the 1989 *transient* illustration, Fig. 29A, appeared better than previous illustrations. Here, you see a smooth rise to a peak. Did they get it? No. The 1989 illustration was as mediocre as the earlier presentations by NASA and the Shuttle contractors. Let me explain.

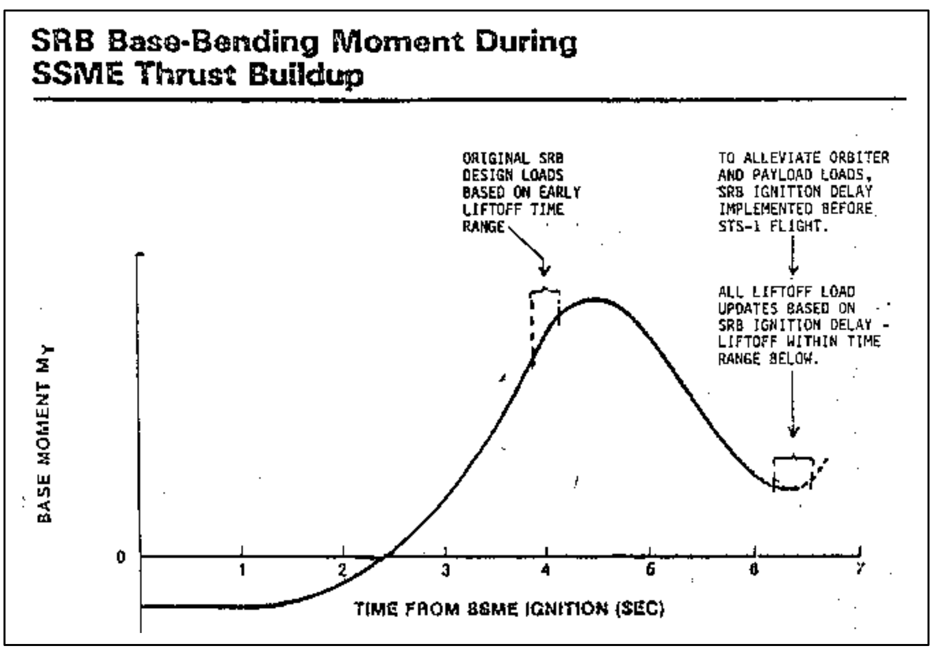


Fig. 29A <u>1989</u> NASA Base Bending Moment
Illustration Shows No *Dynamic Overshoot*!

The *Time*, in seconds, is clearly marked in the Figure. But, the experts did not *scale* the ordinate. The numerical values of the base bending moment are missing from their figure. Was that done purposely? The attending NASA experts and judge were impressed with the lift-off time-delay story. It seemed to them that I was the only idiot who did not see the virtue of the lift-off time-delay story. The story was told in ostentatious words in the Hearing, and you can see this in the three comments included in the NASA 1989 illustration. The three comments in the Figure are reproduced below:

1. "ORIGINAL SRB DESIGN LOADS BASED ON EARLY LIFTOFF TIME RELEASE."
2. "TO ALLEVIATE ORBITER AND PAYLOAD LOADS, SRB IGNITION DELAY IMPLEMENTED BEFORE STS-1 FLIGHT."
3. "ALL LIFTOFF LOAD UPDATES BASED ON SRB IGNITION DELAY LIFTOFF WITHIN TIME RANGE BELOW."

The NASA Figure 29A backfired. The Figure revealed *complete lack of familiarity with the dynamic overshoot concept or effect*. Do you see it? Try to figure it out before you read on.

Look particularly at the comment near their *transient* peak, or comment 1 above. This is the initial, obsolete, antiquated and irrelevant 90% SSMEs lift-off condition. Twelve years after the 90% throttle lift-off condition became obsolete, the NASA experts were still flaunting the irrelevant fact. The continued praise, which I heard in 1989, blinded the experts. They could no longer see their error.

You do not need to be a rocket scientist to reconstruct the confusion from Fig. 29A. Can you estimate how far is their transient peak from the 90% region in Fig. 29A? How about 10%?

The correct *transient peak* should be TWICE (or DOUBLE) the value at the 90% SSMEs throttle. You can use a plain ruler to see that the *correct transient peak* must rise to the NASA title in Fig. 29A. Try it. You will get the dotted line in Fig. 29B. These were the same engineers who measured a 73% dynamic overshoot for the SSMEs in 1982. The base bending moment does not happen in a vacuum. The base bending moment (or torque) is the result of the thrust from the SSMEs. If the SSMEs' thrust overshoots, then the bending moment overshoots. If the SSMEs' thrust went from 90% to 100%, then the effect of the thrust is nearly doubled. If the SSMEs' thrust went from 90% to 100%, then the base bending moment is doubled. It is that simple. The fact that NASA and Rockwell used the correct (doubled) base bending moment in the 1990 specifications, and even before, does not mean that the experts had a clear idea why the specification was doubled in the first place. As late as 1989, the NASA dynamics experts still had no idea of how to correctly illustrate the start-up transient behavior in the Space Shuttle.

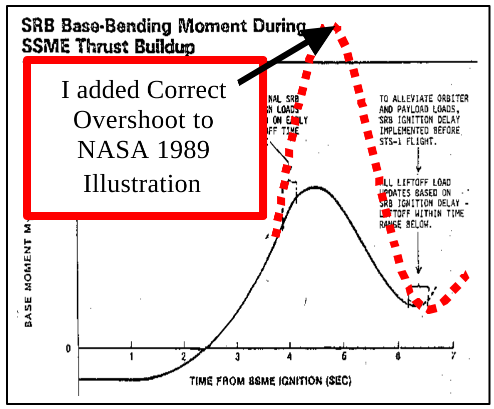


Fig. 29B 1989 NASA Base Bending Moment Illustration with the Correct Dynamic Overshoot

After the Challenger Accident investigations, the Presidential Commission described the base bending moment on page 54 of the Executive Summary as follows:[30]

> "*The resultant total bending moment experienced by STS 51-L was 291 ´ 10^6 inch-pounds, which is within the design allowable limit of 347 ´ 10^6 inch-pounds.*"

The sentence states plainly that the 347 MIP was the design allowable limit moment for the STS 51-L. The designation 51-L identifies the Challenger assembly. Challenger left the launch pad with two boosters. Here, the Challenger's two boosters experienced 291 MIP, i.e., resultant total bending moment.

But then, on page 1351 of Volume-V of the Commission Report,[30] I found the following entry:

> "*base moment: design value 347,000,000 in-lbs, 51-l right srb 291,000,000 in-lbs.*"

Now, the same values are allocated for one booster, the right booster. Do you see the mix-up? Is the 350 MIP value for one booster or for two boosters? The mix-up is common in the Shuttle records. That caused me concern in 1986, even though I was no longer working in the space program. The origin of the mix-up was in the complete unawareness by the Shuttle engineers of the *dynamic overshoot* concept and effects. I had encountered the same situation with my co-workers in the space program as far back as 1970, which I will describe later.

Where did the Commission design allowable limit of 347 MIP come from? Where did the *resultant total bending moment experienced by STS 51-L* (Challenger) of 291 MIP come from?

All the hodgepodge base bending moment values in Table-13 are traceable, including the values used by the Presidential Commission to investigate the Challenger accident. A Rockwell expert illustrated the base bending moment in Reference 27. His illustration is reproduced in Fig. 30. The curve was obtained from the first Shuttle Columbia's Flight Readiness Firing (FRF) tests. The expert marks the abandoned 90% lift-off condition in the Figure as, "NOMINAL TIE DOWN RELEASE." He describes the benefit of the lift-off time-delay with the words, "DELTA MOMENT AT RELEASE," i.e., the difference between the 90% point and the minimum trough point. While the benefit of delayed lift-off is clearly noted, nothing is said about the new destructive transient peak. The peak *dynamic overshoot* is about 580 MIP. This is for two boosters. What is the peak base bending moment for 1-SRB? The answer is 580/2 = 290 MIP. This is the most likely source for the Challenger's 291 MIP value that was referenced by the Presidential Commission. Where did the 347 MIP value come from? On the same Fig. 30, the 100% SSME's throttle level base moment is about 350 MIP. This is for 2-SRBs. The base bending moment values used by the Commission came from measurements like that shown in Fig. 30.

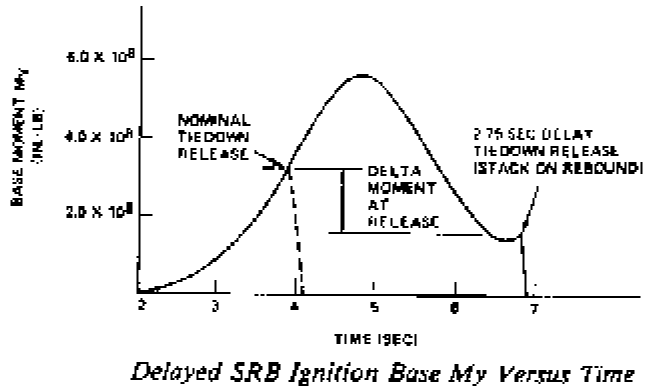


Fig. 30 SRB's Base Bending Moment Showing Benefits of Delayed Lift-off

When I examined the Shuttle Columbia records with the NASA engineers at KSC in October 1986, we discovered that the maximum bending moment was not correctly recorded in the early tests. Apparently, unaware of the *dynamic overshoot*, the engineers did not set the strain gages to capture the peak values. For example, see the last line in the STS-3 Test Report data sheet in Fig. 16, which states, "**GAGES ON STS-1 NOT RANGED FOR TENSION**." This indicates that the peak bending moment, 580 MIP, reported by Rockwell in Fig. 30 in 1982 was a guess.

Fig. 7 (without the overshoot curves that I added) and Fig. 30 appeared in the same 1982 Rockwell paper. Do you see the extent of the confusion over the dynamic overshoot phenomenon in these two figures? The expert shows a dynamic overshoot (albeit wrong) for the base bending moment in Fig. 30. NASA and Rockwell knew full well from measurements that the base bending moment overshoots. Where does the base bending moment come from? The answer is the SSME's thrust. Remember the elementary equation, torque = force x distance? We know for certain that the distance did not double. The only source for the base bending moment overshoot is the SSME's thrust overshoot. But, where is the overshoot in Rockwell's illustration of the SSME's start-up transient thrust in Fig. 7? It does not exist. We used measurements such as in Fig. 7 to design satellites. No wonder we lost satellites without ever knowing why. In essence, the experts show no inclination whatsoever to recognize that the overshoot in their (wrong) base bending moment curve is the result of the overshoot of the SSME's thrust. This explains why the recent 1990 SSME's thrust specification does not include any dynamic overshoot, while the base bending moment specification is doubled to account for the dynamic overshoot.

None of the illustrations discussed above, by experts from NASA and Rockwell, is correct. Even the measured base bending moment is wrong. The disparity among the illustrations of the *same* parameter is epidemic. It is difficult to explain how the same engineers working together for more than twenty years can misrepresent the *same* parameter so badly. For example, at 3-seconds after SSME ignition, one expert gives a base bending moment of 80 MIP (Fig. 30), another expert from the same Company gives the same moment to be 50 MIP (Fig. 28), and several of their peers at NASA give the same parameter to be 140 MIP (Fig. 27). The greatly dissimilar values for the same parameter appeared within one year in reputable publications. The reader can go back and forth between the base bending moment illustrations and find other variations; where there should have been only minor differences.

The illustrations discussed above show the general unfamiliarity of the Shuttle and aerospace engineers with the correct start-up transient responses and effects. The engineers had not anticipated, nor accurately calculated, the correct dynamic overshoot effects in advance for Shuttle design. It can only be surmised from the above that even though the design base bending moment load was doubled at some point in time, the correct reason for the need to double the load was not properly understood.

Do you remember the hodgepodge base bending moment values in Table-13? We want to explain the great differences among the values in Table 13. A simple scenario is helpful. Admittedly, the scenario is not complimentary. To use our 100-lb lady example, imagine that the lady is not familiar with transient analysis or dynamic overshoots. She steps suddenly on the old bathroom scale from zero height and she sees the first dynamic overshoot reading of, say, 200 lb (i.e., 100% overshoot). Unaware of the *dynamic overshoot* concept, she reasons that if she stood on one foot, the scale reads 100-lb, and if she stood on the other foot, the scale reads 100-lb. So maybe, she thinks, when she steps with two feet on the scale, the scale registers the 100-lb force for each foot, or a maximum 200-lb value. Suppose the weight of the lady gets out of hand and she reaches 175-lb. She finds this rather upsetting. To comfort herself, she sets the adjustment knob on the scale so that the dial reads –75 (minus 75) lb. Now, when she checks her weight, she sees the familiar, or desirable, 100-lb weight. In essence, the lady is putting *preload* in a spring. If she now steps suddenly on the scale, things will get very confusing. The overshoot reading will not be 200-lb, as she would have desired. The overshoot reading will not be 350-lb, which is the correct peak overshoot, if she did not *preload* the spring in the weight-scale. The peak overshoot she will see on the dial will be 275-lb. This value has nothing to do with her desired weight, 100-lb, or her actual new weight, 175-lb, or the correct maximum overshoot, 350-lb, or the desired maximum overshoot, 200-lb. Of course, with the exception of the *preloaded* spring, all the other parts in the old bathroom scale will be subjected to the full overshoot, or 350-lb. I use this example because after I discovered, in 1986, that the engineers preload the struts that connect the External Tank to the SRBs, the haphazard Shuttle loads finally made sense.

To explain the hodgepodge base bending moment values in Table 13, I have selected the approximate round figures below to describe the confusion that surrounded this important design parameter.

Description	Two SRBs	One SRB
100% SSME Throttle + Dynamic Overshoot	700 MIP	350 MIP
90% SSME Throttle (No Overshoot)	350 MIP	175 MIP

As I said before, it was by some incredible coincidence that the base moment for <u>two boosters</u> at 90% SSME throttle level (about 350 MIP) turned out to be equal to the base moment for <u>one booster</u> with 100% throttle and the correct dynamic overshoot (about 350 MIP). The congruence of the two values somehow gave the engineers a mechanism whereby the base bending moment specifications were shifted from a value for 2-SRBs to become the value for 1-SRB.

My point must be made abundantly clear. Let us say that in 1972, one of the engineering Groups mentioned in Sec. 2 is tasked with the design of a fancy bathroom scale for the 100-lb lady. They use the lady's weight for design, or 100-lb, or 50-lb per leg. After all, their textbooks tell them emphatically, "to every action, there is *always* an equal opposite reaction!" In 1978, the scale is ready. The engineers release the 100-lb lady on the scale from zero height, and the scale breaks down. The destructive dynamic overshoot effect strikes. Between 1978 and 1981, the engineers strengthen whatever broken pieces they notice. In 1982, the engineers conduct another test and release the 100-lb lady on the scale from zero height again. This time, they look at the dial. They see the maximum force of 200-lb that includes the dynamic overshoot. It doesn't make sense. It is around here that the Group decide that maybe they had meant their design to be 100-lb per leg (or 200-lb total weight for the lady), and not the initially wrong 100-lb for the total weight (or 50-lb per leg). Now substitute the values 200-lb, 100-lb, and 50-lb in the above Table and substitute the words 2-legs and 1-leg for 2-SRBs and 1-SRB, and you will see what happened. Some readers will say that this is highly unlikely. But, how else can we explain the chaotic base bending moment values in Table-13? The reader, and the Shuttle experts, should refer to Table-13.

We can finally trace the origins of the haphazard base bending moment values in Table 13.

1. In 1972, the Shuttle was designed to lift-off at 90% SSME throttle level. The base bending moment was correctly calculated for that condition to be 350 MIP for two boosters, or 175 MIP per booster. **You see where the 175 MIP bending moment per booster in Table 13 originated.**

2. After 1977, lift-off was delayed by 2.7 seconds and now the Shuttle was exposed to the full *dynamic overshoot* effect at liftoff. The FRF (Flight Readiness Firing) tests would have exposed the Shuttle to the full dynamic overshoot effect during the tests. Rather than calculate the base moment with the correct dynamic overshoot, the engineers calculated the base bending moment for the 100% SSME's throttle level. The base bending moment became, incorrectly, about 400 MIP for the vehicle with two boosters. **Now, you see where the 200 MIP per booster in Table 13 originated.**

3. In 1981, the base bending moment was measured from Columbia's FRF and first flight data. The maximum base bending moment was reported to be 580 MIP. By failing to range, or correctly set the strain gages, the engineers failed to capture the correct maximum base moment of 700 MIP. **Now you see where the 290 MIP values in Table 13 came from**.

4. The Shuttle engineers derive the *transient* response using elaborate computer programs. The analysis gives them a maximum base bending moment of only 330 MIP for a full Shuttle, or 165 MIP bending moment for one booster (for example, the Rockwell Fig. 28 and NASA Fig. 27). **Now, we see where the 165 MIP in Table -13 came from.**

5. All along, the engineers knew that greater forces than they anticipated were acting on the Shuttle, causing unexpected damage. They developed a stratagem, which they called "*load alleviation*"[17,33] to somehow get rid of the excess loads. For example, the External Tank is attached to the boosters with *struts*. Some struts showed damage. The engineers preloaded the struts in directions opposite to the applied forces, and the struts survived the tests and the launches. The preloading tactic, which is valid if the Shuttle engineers knew where the excess forces originated, explains the other haphazard base bending moment values in Table-13. The *preloading* tactic and the dissimilar values in Table-13 led me to discover that the loads' engineers were completely unaware of, and unacquainted with, the correct transient analysis, including the dynamic overshoot effect. Their friends in the media wrote sympathetically that the Shuttle engineers were trying hard to cope with *mysterious* forces.

6. After 1982, the Shuttle engineers realized the true magnitude of the "dynamic overshoot" effect, e.g., from the STS-3 lift-off data in 1982, but without understanding how the effect happens. If they did the simple analysis we did in Section 8.2, they would have discovered that the peak bending moment is 700 MIP for two boosters. The 350 MIP for a Shuttle vehicle, or for two boosters, becomes the specification for 1-SRB.

The above discussion is harsh, but it must be remembered that the base bending moment depends on the thrust from the SSMEs and the distance between the SSMEs and SRBs. These values have not changed since 1972 and, therefore, there should have been one, and only one, peak base bending moment value since 1972. The most important engineering lessons I learned in life came from my or others' mistakes. The first part of the lesson is to recognize that there is a mistake. The strange thing about the "dynamic overshoot mistake" is that the experts involved refuse to recognize that they made the mistake in the first place.

8.5 Flawed Transient Analysis

The reader may by now be shocked into disbelief and suspicion. You see the messy data for the base bending moment in Table 13. You see the faulty graphic illustrations of the same value by the NASA and Rockwell experts in the Figures of the last Section. You see the enormity of the error. You are justified to ask; can't the aerospace experts calculate the consequential *dynamic overshoot*? Did I receive my engineering education on Mars while the other experts learned their craft on an asteroid? You are justified to wonder. I wondered whether NASA and the Shuttle Contractors could not do correct transient analysis to get correct answers. I also wondered how the mechanical engineering faculty at my *alma mater* and other universities failed to detect the massive error, and the simple solution. Because the situation was embarrassing, I tried to work the problem privately with NASA, Rockwell and the rest of the aerospace community. Their conduct forced me to take the issue publicly.

This Section elaborates on how the transient analysis has been mishandled by the Shuttle engineers. Whether you are an electrical, mechanical, electronics, hydraulics, material, medical, chemical, civil, aerodynamics, aerospace, aeronautics, or whatever type of engineer, you must see how the transient analysis was mishandled. If your Company designs, constructs or operates systems that affect the safety of the public (airplanes, cars, trucks, trains, bridges, and even toys), you must see how the huge mistake can adversely impact those systems, and the public. Medical doctors, pilots, psychologists and other professionals will also find this Section useful.

The Shuttle experts can calculate the *transient* response and the *dynamic overshoot*. They have highly advanced computer programs to do that. Then, what went wrong?

The Shuttle engineers use a formidable technique to calculate the *transient* response. I disagreed with co-workers on using the method with start-up transients since 1970. The prevailing convoluted method used by the aerospace experts is best described in their own words:[17]

> "One method used extensively for approximating a 3-sigma response of a system under 3-sigma parameter variations is the A-factor approach. This approach determines a time-consistent, 3-sigma response run using a weighted variation on each parameter. The weight for each parameter variation is determined by first running each 3-sigma parameter variation individually producing a delta response. The delta responses are then RSS'd to obtain a 3-sigma RSS value. Using this 3-sigma RSS value of the deltas as a normalization factor, a weighting factor called an A-factor is obtained for each 3-sigma parameter variation. (Factor is always less than one.) Using these weighted parameters, a time (transient) response is run producing a peak value equal to the RSS value with time-consistent characteristics of other response parameters. This is a very effective approach if time-consistent loads are required." (My emphasis) (Vol. 1, pp. 17-18).

The reader should ask a statistician for the meaning of the paragraph. After all the circuitous maneuvers by the Shuttle experts, the NASA and Rockwell answers were likely to be more accurate than my answers. But they were off by 70% to 100%. Why? The problem was in the manner in which the experts handled, or more correctly mishandled, the start-up transient analysis. To see this, let us go back to the old bathroom scale example. Consider the following situation:

1. The weight of the lady is 100-lb. This is the applied force, or the steady state, load.
2. Let the scale be such that the first dynamic overshoot is a maximum, or 100%. This is to say that the *overshoot* component goes up to 100-lb. And, the maximum load on the scale is 200-lb.

There is a correct way and a wrong way to do the transient response for the above simple situation. These are shown in Fig. 31 as follows:

1. Sketch 1 is the Input. This is the lady's suddenly applied weight on the scale, a unit-step-function.

2. Sketch 2 shows how the dynamic transient, by itself and independent of the lady's weight, might behave. This method gives wrong numerical answers and meaningless graphical illustrations.

3. Sketch 3 shows the correct transient response.

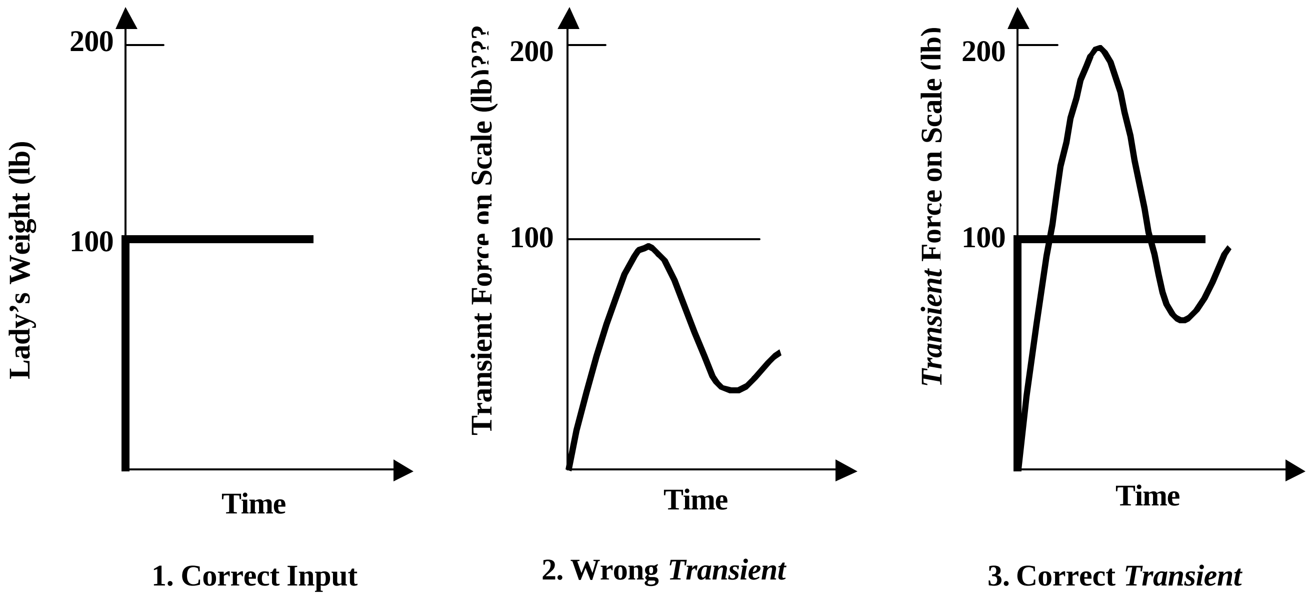


Fig. 31 The Wrong Way (Sketch 2) and the Correct Way (Sketch 3) to Represent A Transient Response

In Sketch 2, the maximum transient component can only reach the maximum applied force, e.g., the lady's weight, the thrust from the SSMEs, the thrust from the SRBs, etc. Do you see why this approach is wrong? This illustration does not give the true maximum load on the scale or in the Shuttle structures. The approach may serve as an intellectual exercise, but beyond that, the method is useless.

The complex method used by NASA to derive the transient response (given in the above quote) clearly states that the transient A-factor is always less than one. Actually, it is. What the Shuttle experts have been doing is astonishing. They have been deriving and illustrating the correct transient component by itself. To the Shuttle engineers, a system in a transient state consists of the static case, as shown in Sketch 1, and the dynamic case, as shown in Sketch 2. Do you see the mix-up?

Let us go back to the bending moment transient solution illustrated by the NASA experts in Figs. 26 and 27. I said that this response is a mediocre illustration of the Shuttle lift-off dynamics and I pointed out several mistakes in the figure. The peak in the NASA illustration is about 330 MIP. We know that the maximum steady-state base bending moment is about 370 MIP. How can the *peak transient response* be smaller than the steady-state value? How can the *maximum transient response* be smaller than the 100% RPL level? I added the horizontal line marked "100% (RPL) STEADY-STATE LEVEL" in Fig. 27. The similarity between the NASA illustration and Sketch 2 in Fig. 31 is obvious. Do you see the resemblance? Apparently, the dynamics experts from NASA and elsewhere have been misguided into believing that the *dynamic transient* load is something that happens independent of the static load.

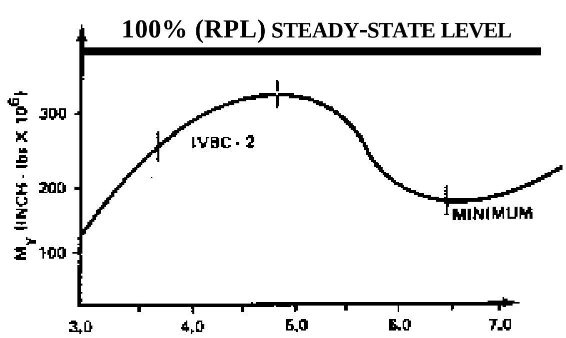


Fig. 27 NASA Transient Peak Falls Below Steady-State Static Value

The NASA author of Figs. 26 and 27 writes in his 1985 detailed Dynamics Report, under the heading "Liftoff Transient Loads,"[33] the following, *"The Space Shuttle and its payload experience a very large transient load at liftoff due to a large asymmetrical coupling (static and dynamic).*" When you "couple" the static load (Sketch 1, Fig. 31) and the dynamic component (Sketch 2, Fig. 31), you get the transient response shown in Sketch 3 in Fig. 31. What were the NASA experts doing coupling the static and dynamic loads to obtain the result in Sketch 2 of Fig. 31, or its equivalent in their Fig. 27? What were they thinking?

It is abundantly clear that the dynamics experts at NASA and elsewhere have been deluded into thinking that the second term in the transient equation, shown below, represents the transient response of a system. The second term is "always less than one." This is the A-factor they mention in their convoluted method in the above quote, where their "transient A-factor is always less than one. In short, they failed to add the two terms in the transient equations (in the parenthesis) to obtain the maximum transient peak.

$$F(t) = F_s\,(1 + e^{-pz\sqrt{1-z^2}}) \qquad (7)$$

We know that the maximum base bending moment is about 700 MIP. The maximum static base bending moment for the Shuttle is about 370 MIP. The NASA peak transient in Fig. 27 is about 330 MIP. Is it possible that the Shuttle experts just simply failed to add the two values? Let us add the two values:

Total Base Bending Moment = 370 MIP + 330 MIP = 700 MIP

It is indeed likely that the Shuttle, and other, experts calculate the correct transient force component, but they then simply fail to add the transient and static forces! Here is more emphatic evidence.

The dynamic overshoot blunder can be traced back to the beginnings of the Space Shuttle Program. The same NASA author of the mistaken transient illustrations of the 1980s co-authored another NASA Technical Report in 1973. The 1973 Report[37] dealt with Shuttle dynamics. Referring to their Fig. 32, the NASA experts write,

> *"The solid line is the bending moment due to bending dynamics divided by the total bending moment, illustrating that bending dynamic loads can be a high percentage of the total bending moment."*[37]

The underlined part of the 1973 sentence proves the central point of this Report. Think about it. Let's go further. The experts show that the ratio of the dynamic moment divided by the total moment approaches 1.0 (ONE) – see their Figure. Is this possible? Is it impossible?

This one Figure from the beginnings of the Space Shuttle Program (1973) tells it all. The Figure shows the roots of the dynamic overshoot blunder. This is a smoking gun. Do you see it? And remember, the engineers who authored Fig. 32 in 1973 designed Apollo, Gemini, Mercury, and then the Hubble and other space hardware.

Can the ratio of the "*bending dynamics divided by the total bending moment*" approach 1.0? Can the ratio of the overshoot on a weight-scale divided by the total force on the scale approach 1.0? The ratio the NASA experts wrote about in 1973 CAN NEVER BE GREATER THAN 0.50!

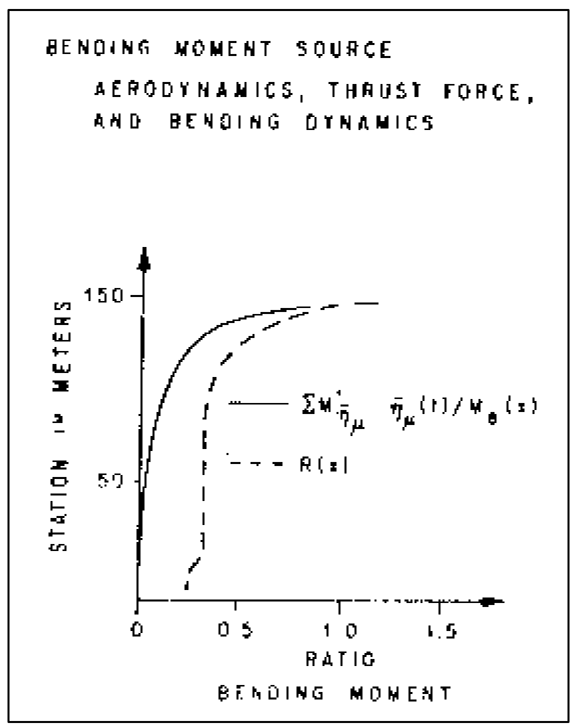


Fig. 32 Ratio of dynamic to total moment betrays lack of knowledge of correct transient effect since 1973

Let us use the base bending moment values shown above. The dynamic moment is 330 MIP. The total moment is 700 MIP. The ratio mentioned by the NASA experts is the 330/700, or 0.47. Now, let us look at the maximum possible ratio, use Fig. 31. The maximum dynamic force on the scale is 100-lb. The total force on the weight-scale is 200. The maximum ratio of the dynamic force to the total force, 100/200, is 0.5. The ratio mentioned by the NASA experts can never be greater than 0.50. This shows beyond any doubt that the NASA illustrations of the moment transient (such as Fig. 27) are simply the second component in the transient solution (Eq. 7), and not the correct total transient load. It is obvious that the experts have mishandled the dynamic overshoot force all along. The error was honest, but it is a blunder nonetheless. It is not clear whether the working aerospace engineers learned the erroneous method in their engineering classrooms or if they improvised the wrong method on their own. The authors mentioned in the above Paper are not to take all the blame. Several technical managers, chiefs, directors and administrators usually approve the NASA technical papers. And the papers are read (and used!) by thousands of scientists and engineers worldwide.

Do you see what happened with the transient analysis by the aerospace experts? Look at their quotation on Page 30. The engineers measured the liftoff loads to be "*approximately 80 percent due to dynamics.*" Their ratio of the dynamics load to the total load is 0.80 (approaching 1.0). The correct ratio must be 80/180, or 0.44 (never greater than 0.50). Do you see their *flowed reasoning*? There are other ways to describe the confusion. Perhaps, some readers may develop their own scenarios.

There are bona fide psychological case studies here. I discussed the straightforward transient analysis with experts from NASA, Rockwell, Thiokol, Lockheed, Martin Marietta, COMSAT, INTELSAT, my *alma mater* the George Washington University and other universities. Their mental resistance to seeing the problem is enormous. If they realized it (the dynamic overshoot problem), houses of cards would tumble. They seem to see that this is not just an isolated mistake. They are so used to making the massive mistake. The mistake is everywhere in their designs, publications, lectures and thinking. To merely think that they failed to add two numbers to get the correct answer sounds, to them, impossible. Suppose they admit it. Does that mean that they would have to redesign every system and subsystem, redraw every illustration, rewrite every technical paper, memo, note, report, book, lecture, etc. They have become so used to making the mistake that the inertia to do it right is colossal. Since the beginning of the space program in the 1950s, they have calculated the dynamic transient, not the dynamic overshoot. They call their calculated peak the dynamic transient peak. They do not call it dynamic overshoot. They know, possibly subconsciously, that if the peak is overshoot, then the peak must overshoot something. That means they must add the transient peak (dynamic) to something else (static). My assertions sounded to them outlandish, ridiculous and absurd.

When the 100-lb lady steps suddenly on the weight-scale, the dial overshoots, say, to 190-lb. The experts know that the overshoot itself is 90-lb. They can calculate the overshoot. They go through the trouble of illustrating the peak transient component rising to 90-lb in engineering curves. They examine their curves intently. They know that something is amiss, but they cannot find it. They get pretty upset when you tell them that the total load rises to 190-lb. They see the two numbers, 100-lb and 90-lb. You are telling them that they failed to add the two numbers. They do not like that. Some of them are so reckless as to call the 90-lb a mysterious force. It is excess, or surplus, force.

The dynamic overshoot is also a classroom problem. When I checked with a professor of mechanical engineering design at my alma mater in the 1990s, he was still unaware of the inconspicuous *doubling* equation (see Eq. 1, Section 4 – the first equation in this Report) in a textbook that the professor had used to teach mechanical design for three decades. And when I checked with the professor of dynamics, he said that the students are taught *transient* analysis; but that there were no specific instructions to take that knowledge and apply it to, say, the *applied forces*. When I discussed the problem at length with the distinguished Professor from MIT Eugene Covert, a Presidential Commissioner on the Challenger Accident, the professor endorsed my observations. Engineering students learn design in one part of the curricula and they then learn the *transient* analysis in another part. Somehow, the two interrelated subjects remain disjointed in the student's mind. The MIT Professor summed it up to me like this, "*You can lead a horse to the water, but you cannot make it drink*."

9. The Rampant *Dynamic Overshoot* Error

There is great accuracy and precision in space design. In satellites, we used safety margins of 15% and 25%. In the 1970s, we hoped to reduce those margins to only 5%, to further reduce the weight and increase the operational capacity of satellites. But, we were still losing satellites, during launches or after insertion into orbit. Because the Space Shuttle is a manned vehicle, safety margins of 25% and 40% are used. That still does not leave much room for error, especially large errors. In terrestrial systems, which do not fly, safety margins of 200%, 500% and even 1,000% are not unusual. Here, if you make a 100% mistake, it will not show up right away. If I design spacecraft components to 15% safety margin, then the margin is a very serious limit. I might stretch it here and there and have safety margins of 17%, 35% or 55%, depending on material properties, geometric limitations, etc. But, you will not find safety margins of only 5% or 3% for the 15% requirement. And you must not find negative safety margins at all.

The *dynamic overshoot* error in Shuttle design exceeded the safety margins. Negative safety margins were everywhere. Yet somehow, the agency administrators and managers, launch directors, astronauts, and assembly, maintenance and many other personnel managed to fly the system. Who made the mistake? None of these people did. Nor did the White House or the Congress make the mistake. A few engineers made the destructive dynamic overshoot mistake, and the mistake turned the world of hundreds of thousands, or millions, of other people upside down.

I have examined thousands of analyses and illustrations of transient effects in the Space Shuttle. But, I have not seen any expert include the correct overshoot peak in his or her calculations or illustrations. A few engineers made most of the erroneous transient analyses, but no one outside of the clique has been able to challenge the outrageous mistake. In some cases, the oversight is immediately noticeable, e.g., the thrust of the SSMEs and SRBs. You see the transient traces go only up to, or below, the 100% RPL level, and you immediately know that something is wrong. In other cases, you have to do a simple calculation to expose the error. In the last Section, we needed the bending moment equation, torque = force x distance, to uncover the missing dynamic overshoot. Every engineer knows the torque equation.

In this Section, I will give the reader examples of both kinds. In one case, we will need the area of a circle. Everybody knows the area of a circle (πr^2). In other cases, we will need the circumference of a circle ($2\pi r$), or the number of pins used to connect the Shuttle boosters' segments together (180 pins). My point is that sometimes you need to do a simple calculation to expose the transient mistake. Yet, no one, including the fussy peer reviewers of reputable professional journals, seems to be taking the effort to do the simple calculations to expose the blunder.

After repeated attempts to eradicate the *dynamic transient* error from Shuttle and space design in the 1980s, the error is still rampant. In early 1987, senior staff members on Senate Committees arranged a meeting for me with the major rocket manufacturers to tell them about the design loads' problem. One of the participants called me from California to say that he was on his way to the meeting. By the time the experts arrived in Washington, DC, the meeting was canceled. The experts from those companies did not get to hear about their dynamic overshoot mistake directly from me. I met independently with board members of some companies. Apparently, those executives did not grasp the nature or the extent of the transient problem. Five years later, papers published by engineers from the same companies clearly show that the engineers are still in the dark about the dynamic overshoot blunder.

The dynamic transient mistake is not transparent. By this I mean that the experts or non-experts can stare at a number and not realize whether the number is correct or grossly in error. Here are some examples. To check it out, all you need is a simple calculator.

9.1 The Static Axial Force

At start-up, the pressure inside the SRBs rises to a maximum in 300 milliseconds and the thrust surges to full power in 600 milliseconds. SRB's start-up is a controlled blast, and the *transient* effect in the SRBs is more prominent than the SSME's. The *overshoot* factor for the SRBs is about 97% (see Table-2), i.e., the transient peak is nearly *twice* the applied force. The sudden start-up nearly doubles the force effect.

The SRBs are made up of four segments, Fig. 33. The segments are tied at their ends with 180 pins around the circumference. The diameter of a booster is 146 inches.

The pressure in a booster rises suddenly to about 910 psi (pounds per square inch), Fig. 14. The pressure inside a booster produces radial, tangential and axial forces. The forces induce stress and deflection in the SRB case, joints, and other parts. The axial force acts along the axis of the booster tending to pull the boosters' segments apart.

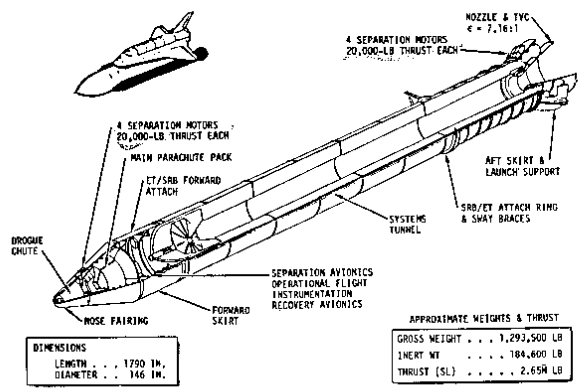


Fig. 33 Space Shuttle Solid Rocket Booster

The axial force in the boosters played a major role in the Challenger investigations. Do you remember the SRB's field joints, joint rotation and the O-ring seals? The Presidential Commission Report states:[30]

> "The Solid Rocket Motor field joint axial tension loads at lift off were within the design load limit (17.2×10^6 pounds). The highest load occurred at the forward field joint, 15.2×10^6 pounds. The mid-joint load was 13.9×10^6 pounds, while the aft joint showed 13.8×10^6 pounds load."

In the NASA 1990 Loads' Specification Books, the axial force is given to eight significant figures, or 15,344,717 lb. The SRB's maximum axial force given by the Challenger Commission (15.2 MP) and in the 1990 NASA specifications value (15.3 MP) (p. 4.6-88) are roughly equal.

Are these axial force values correct? Do the values include the *dynamic overshoot* effect? You really cannot tell by just looking at the numbers. We need to calculate the *maximum* axial force. *Force* and *pressure* are related as follows: **Force = Pressure × area.** The area of a circle is πr^2. Everyone knows the basic facts. The diameter of a booster is 146 inches. The pressure inside the boosters rises *suddenly* to 910 psi. This is all we need to calculate the axial force:

Pressure ≈ 910 psi
Area = $\pi r^2 = \pi(73)^2 = 16{,}742\ in^2$
Axial Force $= P \times A = (910\ psi)\ (16{,}742\ in^2) = 15{,}234{,}808$ lb

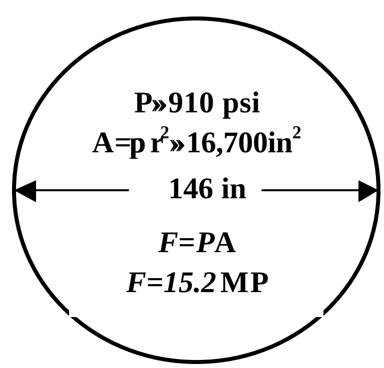


Fig. 34 Everything needed to calculate Axial Force in A Booster

That's it. Our result, 15.2 million lb, is not shabby. It agrees with the NASA and the Commission values. The calculation is shown inside the circle of a booster cross-section in Fig. 34.

But, we are not done yet. The 15.2 million lb is the applied, static, steady state, RPL, or sans-dynamic-overshoot force. What is the dynamic overshoot for the axial force? What is the maximum axial force in a booster during the transient ignition cycle?

The damping ratio for the boosters is about 0.01. I calculated the *overshoot* factor to be 96.9%, see Table-2. In rejecting my *dynamic overshoot* papers[38] submitted for publication, the peer-reviewers of the *Journal of Spacecraft and Rockets* said that the damping ratio is 0.015. OK, let us calculate the *overshoot* factor for their damping ratio. The *overshoot* factor for their

"0.015 ratio" is 95.4%. That issue settled, what is the *maximum* axial force in a booster? Let us calculate it for my factor and their factor:

Peak Axial Transient Force (0.010 damping ratio) $\approx 15.2 \times 10^6 \times 1.969 = 29.9$ million lb
Peak Axial Transient Force (0.015 damping ratio) $\approx 15.2 \times 10^6 \times 1.954 = 29.7$ million lb

The maximum transient axial force in the boosters at lift-off is about 30 MP. Whether the maximum force is 29.7 or 29.9 MP is not an issue here. The issue is whether the maximum axial force is 15 or 30 MP. The difference is big, and this issue is fundamental.

The "*design load limit*" used by the Commission of 17.2 MP is inadequate, Fig. 35A. If the maximum axial force is about 30 MP, then why is the design limit load only 17.2 MP? And, what is the 1990 NASA specification of 15.3 MP (or more precisely 15,344,717 lb) all about? This value contains the 3-sigma transient factor. Does it mean that this precise value is the maximum transient force component? Did the Shuttle engineers, again, calculate the correct transient component, but then failed to add it to the steady-state value? Is the true maximum axial force 30.5 million lb (or 15.2 + 15.3)? Again, failing to add the correct dynamic component to the static value is widespread and reprehensible.

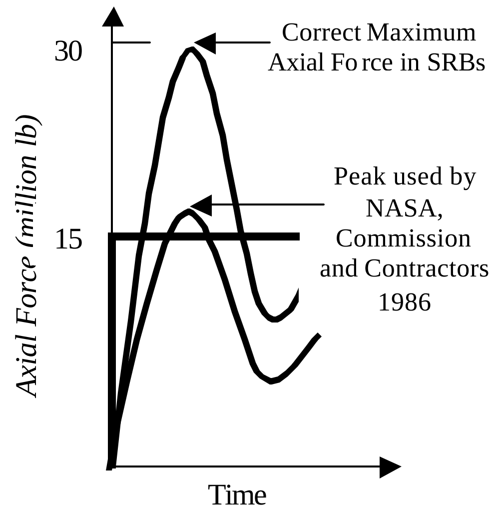


Fig. 35A Maximum Axial Force is 30, and NOT 17, million lb

Research engineers (NASA-Industry, NASA-Universities) continue to use greatly underestimated axial forces in their important work. The work is written and reviewed for accuracy by groups of engineers. Then peer-reviewers check and recheck every sentence and every calculation. Pre-prints are sent to space experts in the media to summarize the findings to the general public. The work is then published and the Journal distributed to thousands of discriminating engineers. The glaring 100% dynamic overshoot error is under everyone's nose, and no one sees it.

In response to my papers discussing the *dynamic overshoot* error in the Shuttle, the peer-reviewers wrote,[7] "*It is recommended that the paper not be published*," "*The subject manuscript is totally unacceptable*," and "*The author --- evolved numerous errors toward creating a non-existent, fictitious 'problem'*." The overshoot error is massive, real and it is not fictitious. Here are some more examples of the blunder.

NASA-Industry Engineering Group (1988)

Elaborate optimization procedures have been developed to find alternatives to redesign the Challenger's stricken SRB joint. In one study, "*Shuttle Solid Rocket Booster Field Joint Shape Optimization*"[39] in the *Journal of Spacecraft and Rockets,* NASA and industry engineers used the axial force of "36,406 lb/in" around the SRB circumference in their work. Can you tell if the axial force value includes the correct, or any, *dynamic overshoot*? Again, you really cannot answer the question by simply looking at the number. We must do a simple calculation to find out whether the *overshoot* is included or not. We need the circumference of a circle, $2\pi r$. We then find the axial force that the engineers used in their *optimization*. The answer should be nearly 30 million pounds. Is it?

Circumference = $2\pi r = 2\pi \times 73$ in = 458.7 in
Peak Axial Force = 36,406 lb/in $\times$ 458.7 in = 16.7 MP

The axial force (16.7 MP) used by this NASA/Industry team falls between the NASA 1990 specification value (15.3 MP) and the design limit load (17.2 MP). We know that this is the static force. It does not contain the transient force component. It does not include any transient effect. It does not include the correct dynamic overshoot factor. With the overshoot, the axial force is about 30 MP. If the engineers or the peer-reviewers made the simple sketch shown in Fig. 35B, they would have discovered with one look that the Peak Axial Force used in the above research is terribly wrong. The missing and enormous overshoot is not *"a non-existent, fictitious 'problem'*, as the AIAA reviewers said. Yet, the NASA/Industry paper received the blessing of the peer-reviewers, and was published. More importantly, the actual Shuttle SRBs continue to be grossly underdesigned after the Challenger accident.

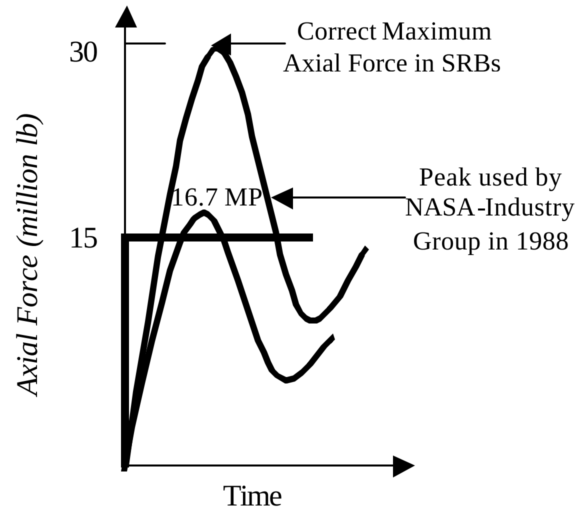


Fig. 35B Maximum Axial Force is 30, and NOT 16.7, million lb

NASA-University Engineering Group (1990)

The axial force appeared in another research by NASA-university experts and the results were published in the same *AIAA's Journal of Spacecraft and Rockets*, under the title "*Axisymmetric Shell Analysis of the Space Shuttle Solid Rocket Booster Filed Joint*."[40] Here, the NASA-University engineers describe the axial force as follows, *"This axial load corresponds to approximately 413,350 N (or, 92,220 lb) of axial force that is transferred by each pin*."[40]

Does this Group include the damaging overshoot in their work? Again, you cannot tell by looking at the numbers. Fortunately, we are saved the trouble of converting *Newtons* into *Pounds*. They give us the axial force in pounds, or 92,220 lb per pin. How many pins are there? These are the pins that hold the boosters' segments together. There are 180 pins in each joint. To find the axial force used by these engineers, we multiply the "force per pin" by the number of pins. That's all, or,

Peak Axial Force = 92,220 lb/pin × 180 pins
= 16.6 MP, or, 16,599,600 lb

These experts also use the applied force, or static force, or steady-state force, or without-dynamic-overshoot force. They do not include the near 100% overshoot in their important work! The Sketch in Fig. 35C should convince everyone that the above study is flawed. Why find out how far a joint deflects due to 17 MP, when the joint is hit with 30 MP? A joint designed to withstand the correct maximum force and with a smaller safety margin will be superior to a joint designed to the grossly low forces with greater, but imaginary, safety margins.

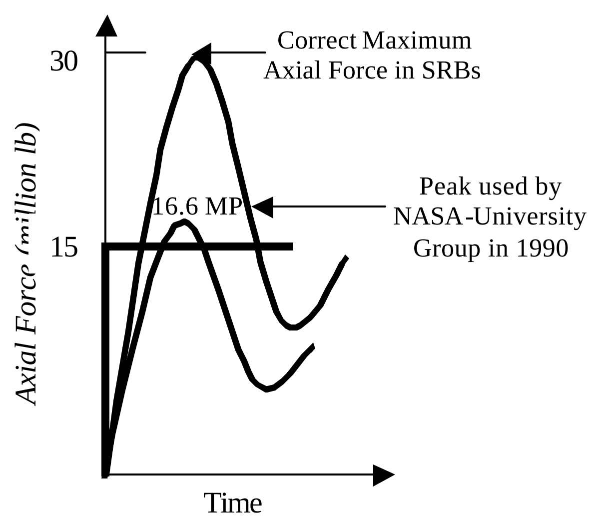


Fig. 35C Maximum Axial Force is 30, and NOT 16.6, million lb

The 15-17 MP design values are wrong and must be about 30 MP to account for the correct overshoot. It is obvious from contemporary technical journals that all SRB designs are grossly underestimated. This further confirms the deplorable unawareness by the spacecraft, rocket, and Shuttle engineering groups and faculty of the crucial dynamic overshoot effects.

I mentioned the mental resistance that engineers have with the dynamic overshoot concept. The two papers mentioned above were evaluated for publication around the same time as my dynamic overshoot papers. The peer-reviewers must have had nightmares thinking about my illustrations, e.g., Fig. 35. Do they reject all papers by experts from NASA, the Industry and the Universities? Do they recommend halting Shuttle flights until the serious matter is resolved? Did the peer-reviewers determine that because all papers did not include the overshoot effect, then the overshoot effect is a "*non-existent, fictitious, problem*? Someone from the Congress asked me if I invented the dynamic overshoot. I did not invent the dynamic overshoot effect. I am simply pointing out how to do it right.

Challenger Axial Force

Fig. 36 shows actual Challenger lift-off measurements, in particular, the "base bending moment" and the "axial force." I discussed the base bending moment at length in previous Sections. Here, I will discuss the axial force. I inverted the curves to be consistent with other figures. This does not affect the discussion.

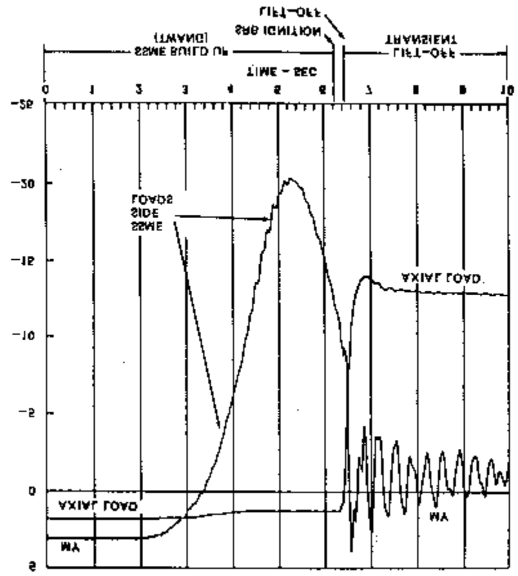


Fig. 36 Where is the Challenger Axial Force dynamic overshoot?

In August 1986, I arranged to meet Admiral Richard Truly, then Associate Administrator for Space Flight, to discuss the Space Shuttle loads' problems. Truly, who headed the Challenger Technical investigations, did not come to the meeting and, instead, he delegated another astronaut, Bonnie Dunbar, to meet me. Dr. Dunbar spoke about the crazy ideas that the agency was getting from people about the cause of the Challenger tragedy. There were files from pundits proposing that UFOs, Soviet laser beams or some other far out things struck the Challenger. Bonnie recognized the significance of what I was saying. She could not resolve the technical issues that I raised, and she then set up discussions for me with experts from the Johnson Space Center. Lengthy calls with the JSC experts were not productive. The "preloads" complicated the discussions. But face-to-face meetings with different engineering teams at the Kennedy Space Center in October 1986 were very productive. The Challenger lift-off measurement in Fig. 36 was a primary subject of discussion in those meetings.

In the figure, you see a prominent peak on the left. This is the base bending moment overshoot, which results from the SSME's thrust before lift-off. We discussed this at length before. To the right of this peak, you see a small peak. This is the <u>axial force</u> peak! The ordinate, on the left, is marked 5, 0, -5, -10, etc. These are millions of pounds. Do you see the maximum axial force peak with a tiny overshoot?

The SSME's overshoot lumbers up at an angle to a peak value. In comparison, the SRB start-up is an explosion. You see the vertical climb of the axial force trace. This behavior <u>must</u> lead to greater overshoot peak than that of the SSME's. Where is the axial force overshoot? Its overshoot must climb to 30 million lb. On top and to the right of the tiny peak you see the NASA original comment (inverted), "<u>LIFT-OFF TRANSIENT</u>". What did NASA do to avert the transient peak? Where is the 100% overshoot? No one could answer my questions at KSC. I added the approximate transient overshoot with a red dotted line in Fig. 37. If the peak I show is true, then that was a disaster. The engineers at KSC, especially, the Director of Shuttle Engineering, concurred with the assessment.

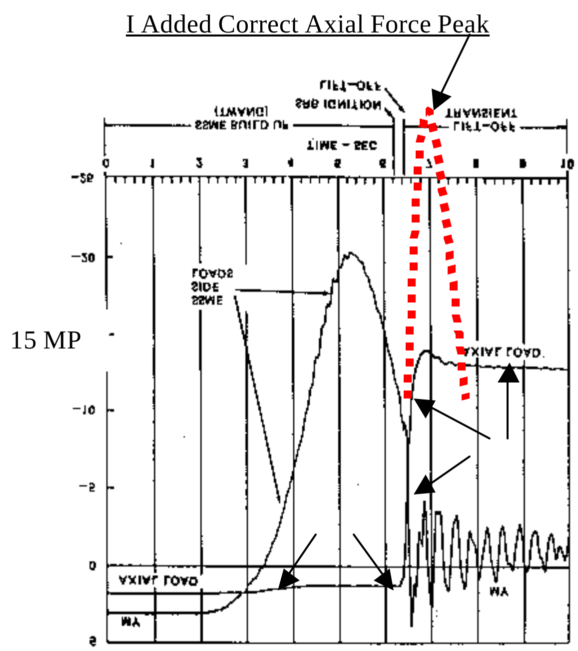


Fig. 37 Pressure -based Measurement of Axial Force does not show overshoot

Even though a large team of NASA engineers agreed with me about the enormity of the dynamic overshoot issue, Admiral Truly declined to meet me to discuss my findings. Of course, I knew there could be problems. Truly headed the technical investigations of the Challenger accident that blamed it on joint rotation, cold temperature and O-ring seals. I disagreed with these, as well as the sequence of events that happened to Challenger from lift-off to, and after, the explosion. My disagreement was purely based on facts. The enormous overshoot problem had to wait five years for a resolution.

The axial force hits like a sledgehammer. It strikes the External Tank, the Orbiter and its payloads, e.g., the Hubble Telescope, Galileo and other payloads. The overshoot was overlooked in the design these systems, with adverse consequences. Is the axial force's dynamic overshoot 10%, or is it nearly 100%?

The reader should by now be confident that the overshoot in the Shuttle is in the range of 70- 100%. Then, why didn't the enormous force show up in the Challenger's axial force, and other, measurements? The last question nagged me for years. The answer finally came in a NASA letter to me, in October 1992, (see Epilogue 2000). That was a letter from a Director of the Johnson Space Center, who insisted that I was wrong and that they were right because their pressure transducers record only 2% overshoot. The 2% overshoot is the miniature axial force transient peak you see in Fig. 36. Finally, I saw it. Finally, I saw the widespread and long-lived confusion. The confusion was betrayed in one word used in the JSC Director's letter, "*pressure.*" Pressure does not overshoot; pressure fluctuates, as I explained earlier.

Since 1986, I was told that the Shuttle engineers measure force directly. After all, they mark their curves of the axial force in lb-f (pounds force). I looked at their engineering curves, and I wondered, *"Well, where is the 97% overshoot?"* Apparently, NASA measured the pressure and then converted the pressure values (psi) to force values (lb-f). The experts used the calculated force values in their data sheets. They did not know that pressure fluctuates, but does not overshoot, and they did not capture the real dynamic overshoot force in measurements. And so, they were comfortable with their conclusion that there was no massive 100% overshoot, but only a tiny 2% overshoot (which is the tiny pressure fluctuation). They also did not know that force overshoots. When I told them that the SRB's overshoot is around 100%, they laughed. When they told me that the overshoot was 2%, I laughed. They called me specious, I got angry. I returned the favor, they got angry. Then, after six years of confrontation, they told me casually, in defense of their position, that their measurements were pressure measurements. They did not even realize what they were telling me. Like Sir Isaac Newton, they were concentrating on the apple, and not the slinky. The reader will see why I used simplistic examples, as a 100-lb lady stepping suddenly on an old bathroom scale (from zero height and with zero momentum). But, for some reason, the directors involved did not rush to tell the other engineers, even in their own organizations, about the embarrassing mistake. When you combine this sequence with what happened with the base bending moment confusion, you cannot help but conclude that this was a tragic comedy. It was a tragedy.

There is yet another reason why the dynamic overshoot did not show up in axial force measurements. The "axial force" build-up is 1,000 times faster than the "base bending moment" overshoot. In real life, it is a spike. Strain gages are used to measure the responses you see in Fig. 36. The response of strain gages is much slower than the speed of the axial force overshoot. That problem drove me up the walls in the early 1970s, when I tried to capture the elusive dynamic overshoot in tests. You can see a dynamic overshoot spike in a Challenger booster joint in Fig. 13. The spikes are real dynamic overshoot events.

Accident investigators, including aircraft crash investigators, will benefit from this, the previous, and the following Sections. Large errors can go undetected not only by a small number of experts, but by almost all of them. The dynamic overshoot error is nearly a 2:1 mistake. Errors of this magnitude must not go unnoticed in any crash investigation.

While I was trying to convince NASA and others of the devastating effects of the dynamic overshoot, particularly during ignition of the Solid Rocket Motors (SRM), the NASA management, under Admiral Richard Truly was pushing to develop a more powerful motor, the Advanced Solid Rocket Motor (ASRM). According to Truly, the ASRM will have greater thrust and, hence, more payload. The last point is obvious. But, the greater the thrust, the greater the dynamic overshoot! If the ASRM is designed like the SRM of the last twenty years, on the basis of the static and not the correct dynamic overshoot forces, it will surely run into the same, but greater, destructive dynamic overshoot forces. Time will tell.

9.2 The Static O-Ring Seals Joint-Rotation Parade

Joint-rotation in pressure vessels is a highly esoteric engineering subject. I had done extensive joint rotation and O-ring seal analyses and tests before. Before the Challenger accident, only a few aerospace engineers were familiar with the phenomenon. After the Challenger investigations, joint-rotation and O-rings seals became common terms. Every newspaper and magazine wrote about the subject. The NASA experts who understood the joint design, for example, George Hardy and Larry Mulloy, insisted that joint-rotation could not be the culprit in the Challenger accident, but to no avail. Joint-rotation was blamed for the accident. Hardy and Mulloy were expelled from the investigations.

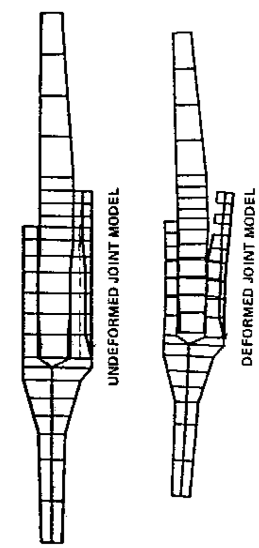


Fig. 38 Finite-element-models of deformed and undeformed joints

The NASA finite-element computer models of the deformed and undeformed joint are shown in Fig. 38. When the transient pressure build-up in the boosters reaches the joint in the left model, the joint deflects (opens) as shown on the right side of the figure. Detailed analysis of joint rotation and design is given in my other papers on the subject. Here, I will stay with the grossly inaccurate <u>transient</u> analysis of the joint by NASA and the Contractors. When you review the thousands of illustrations of the SRB joint-rotations and joint-deflections generated before, during and after the Challenger investigations, you will think that the scientists and engineers have never heard about something called dynamic overshoot. Not one single illustration includes the destructive dynamic overshoot effect.

For example, the Commission shows the primary and the secondary gap openings in the stricken Challenger booster in Fig. 39. No dynamic overshoot. Supposedly, the figure shows the <u>maximum</u> gap opening for the primary and secondary seals in the SRB field joints. I added the overshoot (dotted curves) for the gap opening of the two seals to show the true maximum transient deflections. The differences are enormous.

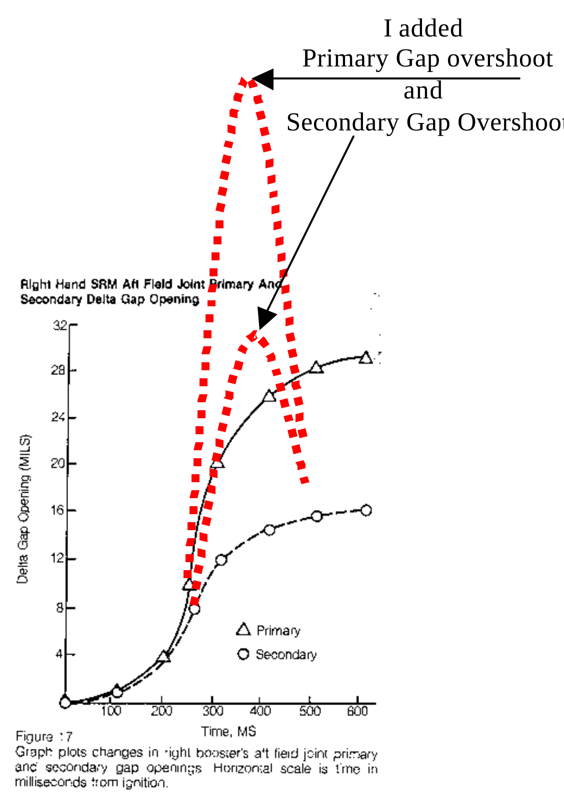


Fig. 39 Overshoot Missing in all Challenger Joint Deflections

This mistake by NASA and the Contractors is as glaring as the previous mistakes. My critics insisted that the problem is one of semantics. It is not. Imagine the 100-lb lady stepping suddenly on the old bathroom scale and that the dial overshoots to 190-lb. Suppose the area of the lady's feet is 20 in^2. When she steps on the scale, her feet apply 5-psi pressure on the scale's platform. Let us reformulate the problem like this. A lady steps suddenly on an old bathroom scale applying 5-psi pressure on the platform. Will there be a transient overshoot? What is the magnitude of the overshoot? Notice how the 100 lb force disappeared in the new problem. Just multiply the pressure (5-psi) by the area of the lady's feet (20 in^2), and you get the 100 lb. Now you proceed with the transient analysis to find the transient force component, in this case 90 lb. And do not forget to design the bathroom scale to withstand 190 lb plus safety margins, and not only to 100 lb (5 psi) plus safety margins.

One cannot use the pressure (5-psi) as the input in any meaningful transient analysis. The 100-lb lady could pull a trick on the Shuttle engineers. For example, she might suddenly release her weight on the scale on one foot. The area of one foot is 10 in^2, and the pressure transient function (if such exists) will be 10-psi. Is the transient unit-step-input 5-psi or 10-psi? It is neither. In both cases, the unit-step-input is 100 lb. One time, the transient force input is 5-psi x 20 in^2 (or, 100 lb); the other time, the transient force input is 10-psi x 10 in^2 (the same 100 lb). You will see next how the Shuttle experts carelessly used the pressure as the input transient function to analyze joint rotation, and they ended up with no overshoot whatsoever.

Fig. 39 shows no overshoot at all. What happened to the joint-rotation transient analysis? Was it treated like the base bending moment, the axial force and the thrust? And, how valuable (or worthless) were the many Challenger studies that did not take the correct transient effect into account?

Suppose a surge of electrical current trips the main circuit breaker in your house. You call an electrician who does not know anything about electrical surges, which is unlikely. The electrician examines all the circuits, fuses, wires and appliances in your house, makes extensive analysis of different things, and changes many things. You pay an exorbitantly high bill, and things work fine. If this happens repeatedly, you will go broke. Your knowledge of electrical surges, which are also known as transient overshoots or dynamic overshoots, can be very valuable. You reset the breaker yourself or, better yet, you protect your systems with surge arresting devices. In my tours at the Kennedy Space Center in 1986, I searched for mechanical protection schemes in the Shuttle. They do not exist. The system and its parts are exposed to the sudden surges of mechanical forces, or the dynamic overshoot. Some readers may wonder whether the deflections overshoot like the forces we discussed earlier. Of course they do. Deflections are the direct result of forces. The forces amplify; the deflections amplify. It is that simple.

Hang a segment of a slinky from a ceiling. Attach a weight to the slinky and let go of the weight *suddenly*. You see the *deflection overshoot*. Use a postal weight-scale. Release a weight on the postal scale *suddenly*. Now you see the *force overshoot* and the *deflection overshoot* together. If you increase the weight, the deflection increases. If you release a refrigerator gently in the middle of your kitchen floor, the floor deflects. If the floor deflects by 30 mils (1 mil = 0.001”), you will not see the deflection, but it is there. If you release the refrigerator suddenly (from zero height), the deflection of the floor overshoots. If the dynamic overshoot of your kitchen floor is 100%, then the floor deflects by *double* the static case, or 60 mils. There is a *deflection overshoot* of 30 mils, but you still do not see the total deflection. The fact that you do not see the overshoot with your eyes or, even, sense it with instruments does not mean that the effect is nonexistent. If you do not pick up the *overshoot* with instruments, it means your instruments are sloppy or your work is. The joint-rotation and related issues are discussed in detail in my other technical papers on that subject. In this Section, we will stay with the *transient* mistake.

“*The displacement – dynamic – response virtually tracks the applied loads.*”

What does this mean? This was the conclusion of a large technical team, the SRM Team that assisted the Presidential Commission in the Challenger investigations. The Team consisted of many experts from two NASA Centers, the Marshall Space Flight Center and the Johnson Space Center, and several companies including, *“Morton Thiokol, Lockheed, Rockwell International Space Division, Rocketdyne, USBI and Teledyne Brown.”* The above title appears in the words of the experts as follows:[30]

> *“Findings – The dynamics of the problem do not yield results that differ from a quasi-static analysis using dynamic loads. The displacement response virtually tracks the applied load, with almost no time lag.” (Vol. II, L-110)*

Many complicated transient analyses appear in the same report by the SRM Team. The conclusion is always the same in Ref. 30, e.g.,

> *“No real difference was noted between the dynamic and static response when the dynamic load was applied quasi-statically.” (Vol. II, L-110)*

What does it mean to say that the static and the dynamic displacements of the failed joint, or anything else, are virtually identical? The SRM Team illustrated the virtual similarity they talk about in Fig. 40. On the left, you see what they call the pressure build-up function, or (incorrectly) the transient function, in units of pressure (psi). In the middle, you see the incredibly virtually identical deflection curve for the O-ring seals, shown in inches. If you superpose the two curves, you discover that these are indeed identical! That is impossible. On the right, you see the slight difference that is produced by damping, due to propellant. Propellant damping hardly affects the results.

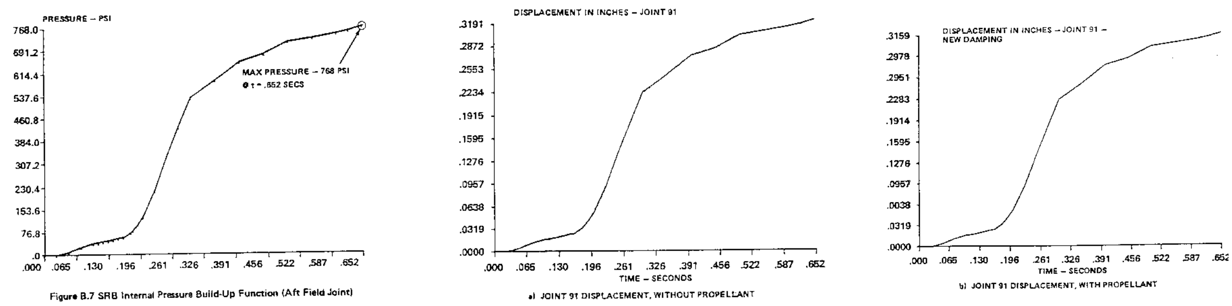


Fig. 40 Transient Analysis by NASA and Six Shuttle Contractors Reveals No Dynamic Overshoot Whatsoever for Joint Rotation!

It may not be obvious to every engineer that the deflection curves are terribly wrong. Granted, the curves were obtained using advanced computer programs, with which I am very familiar, but that does not make the curves right. Suppose I give the advanced computer the problem of suddenly releasing a weight at the end of a slinky. The computer tells me, the slinky does not oscillate. Do I believe the computer? Of course, not. The slinky oscillates. The computer tells me that the slinky does not overshoot. Do I believe the computer? Of course, not. The engineer cannot say that the computer program just simply does not know about the dynamic overshoot. It is the engineer who does not know about the correct transient overshoot. The situation shown in Fig. 40 is a terrible lapse on the part of a large team from two NASA Centers and several major aerospace contractors. Members of the SRM Team may argue that the engineering community at large agreed with their conclusion, and that the fussy peer-reviewers blessed the results. That does not get them off the hook. Nor does it get the rest of the engineering community, including the professors, the peer-reviewers and the pundits off the hook. They are all equally culpable. The solution in Fig. 40 is a terrible mistake, and it requires further verification.

The SRM Team used the computer programs NASTRAN, ANSYS and SPAR, which I had personally evaluated and used in the past. How did the sans-dynamic-overshoot illustrations in Fig. 40 come about? Apparently, the engineers themselves simplified the problem that they were trying to solve by eliminating the dynamic case. They literally deleted the dynamic transient problem. In their words:

> *"Simplification of the overall analysis was achieved by four special studies which allowed reducing the model and approach to a quasi-static or static analysis" (L-109).*

One hundred special studies will not make the overshoot in the old bathroom scale, the postal scale, the vegetable scale or the hanging slinky disappear. If I tell the computer there is no dynamic overshoot, the computer will oblige. The SRM Team told the computer programs not to worry about the transient effect, and the computer printouts obliged the engineers. The computers printed out Fig. 40, and the engineers believed it. I had many problems with this. It was not that the politicians swore by the computer printouts, but that the brilliant structural-dynamics engineers swore by the wrong illustrations.

The static analysis that the SRM Team did was not simple by any means. The analysis, which appears in Appendix B in Volume II of the Commission Report, is elaborate, intricate, complex and very difficult. I could not find any serious errors in the lengthy static analysis. Only, the dynamic overshoot effect, or the correct transient response, was missing or terribly misinterpreted and misrepresented. The enormity of the overshoot error rendered the otherwise excellent work of the SRM Team useless.

The pointer on a simple 2-lb postal scale deflects a total of 4 inches. Everyone can get a 1-lb weight and try the correct static deflection and the correct dynamic overshoot on the scale in their homes or offices. If you release the weight gradually, you will see something similar to sketch A in Fig. 41. If you release the weight suddenly, you get sketch B in Fig. 41. You can try a variety of tricks to induce Sketches C and D, but you will not be able to reproduce these responses.

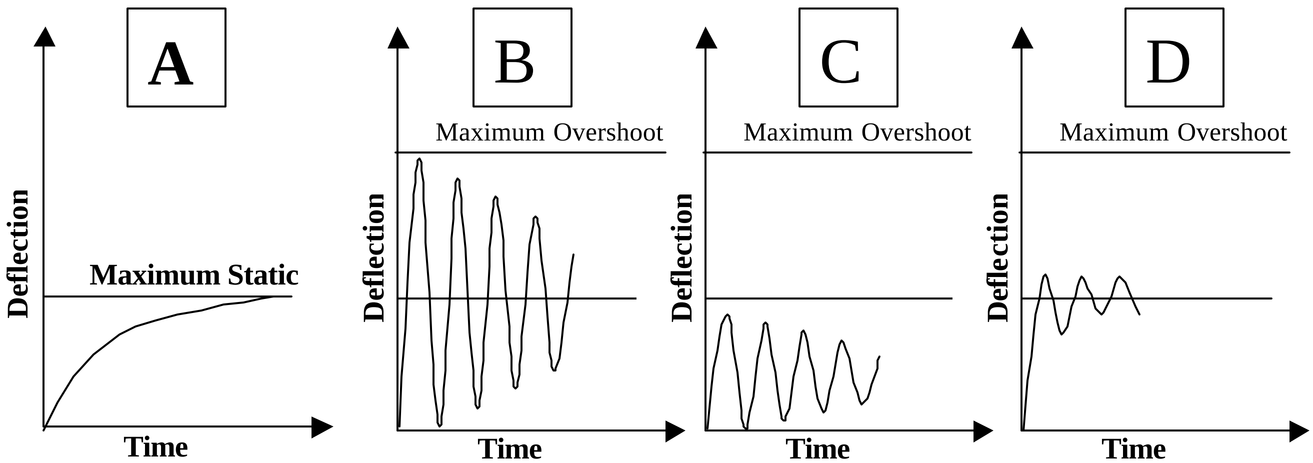


Fig. 41 (A) Correct Static Deflection, (B) Correct Transient, (C) Wrong Transient, and (D) Wrong Transient

The SRM Team, that developed the incorrect transient solution in Fig. 40, apparently consider the static, or what they call quasi-static; Sketch A in Fig. 41 to be a dynamic response. Look, try the 1-lb weight on the 2-lb postal scale again. Release the weight slowly and, either, envision Sketch A or draw it. The pointer will move only 2 inches. Release the weight suddenly; the pointer will deflect beyond 2 inches. This repetitious and boring exercise is specifically designed for the executives who do not have the time to examine the lengthy static-dynamic-transient analyses of their subordinates. If you correct the massive mistake by the befuddled few, you will benefit the many dedicated workers in your organization.

How can sketch A in Fig. 41 or the SRM Team's Fig. 40 be dynamic? If the ordinate in Sketch A were the speed of a car, then the Sketch is a dynamic situation. But the SRB's joint rotation, the postal scale deflection and the slinky deflection are not going anywhere. These are static situations. These are not dynamic situations. Sketch A, Fig. 41, has nothing to do with dynamic transient analysis or responses.

It remains for everyone to be convinced that the same behavior happens even if the deflections are not seen with the naked eye. We have done this in engineering over and over, and there is no need to present voluminous treatise on the straightforward matter. Sudden forces produce large overshoots. Sudden pressures do not overshoot. Sudden pressures produce sudden forces, which, in turn, produce transient overshoots. Sketches C and D in Fig. 41 are impossible, at least for the joint deflections cases. Let us look at the transient illustrations of the infamous Challenger joints by the same SRM Team.

Fig. 42 shows four illustrations of the Challenger joint deflections that were developed by the NASA/Industry technical Team. They specifically title each illustration as "Delta Gap Opening Transient." By now, everybody should recognize that these solutions are not transient solutions at all.

In Fig. 42-A, the engineers show a little ripple at the top of the deflection curve. This transient behavior has nothing to do with the actual sudden deflection of the joints due to the explosive pressure start-up in the SRBs. In particular, the ripples are the result of the external forces that are imposed by the struts that connect the External Tank to the SRBs, as the SRM Team notes,[30]

> *"The principal gap occurs during the first 600 milliseconds of SRM burn going to a peak between 36 and 45 mils. Only the aft field joint gap responds to any significant level to the dynamics. This response is mainly due to strut loads"* (Vol. II, L-114)

Essentially then, Fig. 42A does not show any transient effect, especially, the primary transient effect due to the sudden SRB's ignition cycle. If we subtract the struts' effect, the solution is a static solution.

Fig. 42-B shows the maximum and minimum delta gap openings for all the joints at any location. Again, the figure is the result of a purely static analysis. Fig. 42-C shows no overshoot whatsoever. It is purely a static solution. The discriminating reader would observe that the deflection in Fig. 42-C and the 1972 JSC 07700 SRB start-up transient in Fig. 10 are identical! The transient curve in Fig. 42-D starts at 6.6 seconds after SSME's ignition and goes through the SRB's ignition cycle, up to 8.2 seconds. There is only a slight ripple around the steady state, or static, value. This is also wrong.

Before the Team developed the sans-dynamic-overshoot joint deflection illustrations that you see here, they first developed the forces that caused the deflections. It was here that the experts presented the axial force figure that I reproduced in Fig. 36. The team describes Fig. 36 as,

> *"… a time response of two of these reconstructed loads of the aft field joint. Shown in this figure are the key lift-off events; the axial load and the pitch plane bending moment."* (Vol. II, L-112)

Do you remember how their axial force illustration showed no overshoot, or only a tiny overshoot bulge? I added the transient component in Fig. 37 to show the enormity of the error. Since the force that the SRM Team incorrectly developed with elaborate procedures did not overshoot, their deflections were not going to overshoot. The engineers recognize the importance of the axial force in the analysis of the joints. For example, they write:

> *"Since all field joints are designed to the highest axial load (forward field joint) and the gap opening is a function of this axial load in conjunction with the equivalent internal pressure and external loads, the forward field joint should experience the highest load and field joint seal gap opening."*

Have you noticed something missing in all the transient solutions by the Shuttle engineers? They never show the maximum steady state, or static or 100% RPL value in their figures. When the 100% RPL is clearly marked, you can then see how far the overshoot rises above the static value. You can then see if there is any overshoot at all. By failing to mark the steady-state value in every transient figure, one has no idea whether the transient

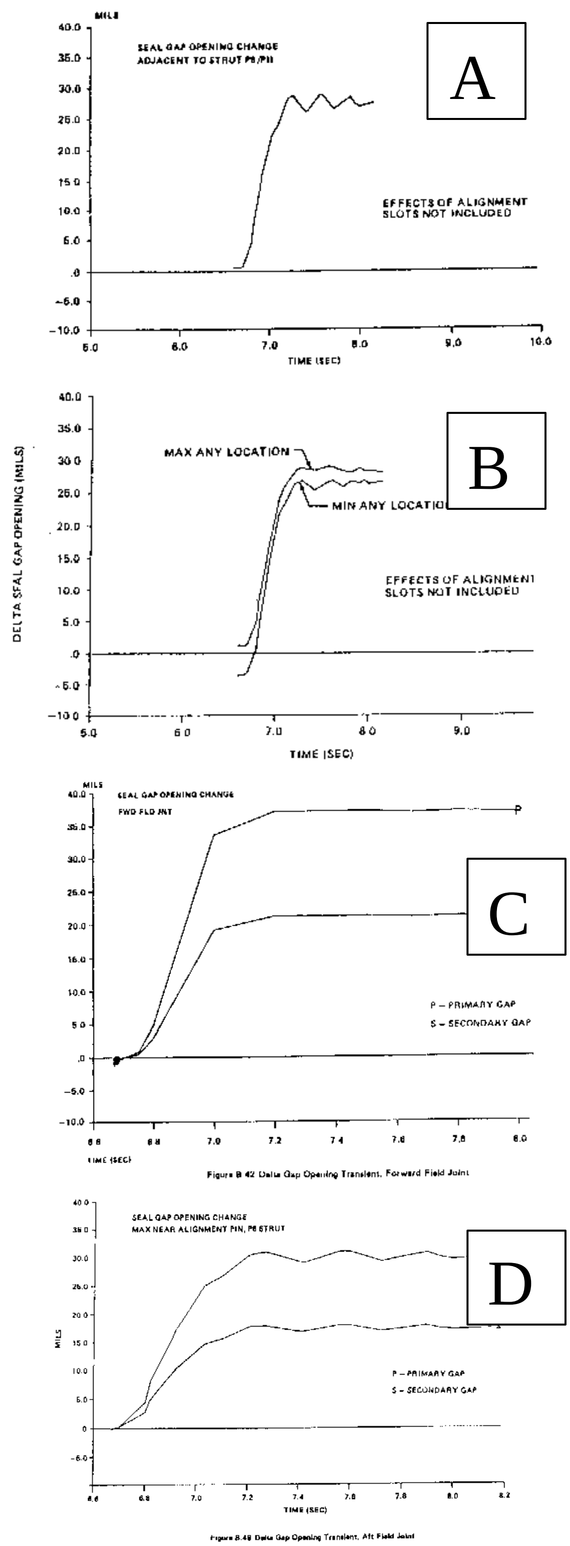


Fig. 42 Completely Incorrect Transient Solutions of Challenger Joints by NASA/Industry Team

analysis is correct or not. I added the dynamic overshoot peak to many curves. I could have also added lines to show the static or the RPL value. The reader is encouraged to mark the 100% RPL value on every figure and make his or her own comparison of the accuracy, or lack of it, of the engineering curves by the Shuttle experts. For example, the maximum steady state, or static, value is the middle line in my Fig. 41.

The maximum gap openings for the Challenger's failed field joint were developed by the SRM Team in other curves, e.g., Fig. 43. Again, even though the experts title their figures as transient representations, the maximum gap openings you see in their figure are only static values and do not contain the correct transient component. I added the overshoot for the forward primary joint gap (red) and the AFT primary joint gap (blue) in the figure. The maximum gaps (without the overshoot) were crucial in determining the probable cause of the Challenger accident. The correct maximum transient gap openings, thrust and other forces (with the overshoot) are far more crucial to determine the cause of the Challenger accident, and the many space accidents that preceded and followed Challenger.

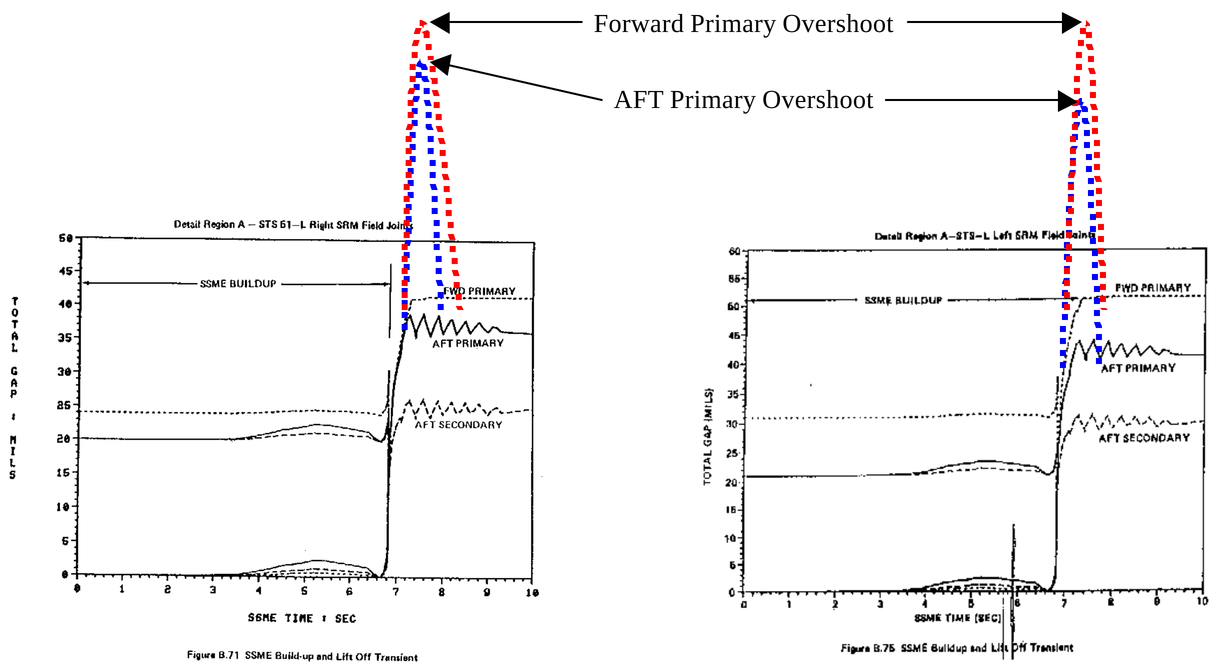


Fig. 43 Gap Openings Based on Loads in Fig. 37 Do Not Show the Enormous Dynamic Overshoot

Much attention was given to the SRB joints and the O-ring seals during the Challenger investigations by the investigators and the media. But no one noticed the 100% dynamic overshoot in the joint gap opening and the other parts of the Shuttle. This indicates that the data used to determine the probable cause of the Challenger accident were approximately 100% in error.

The SRM engineers know that the maximum transient response occurs around 600 milliseconds. They do not know that the transient responses of the thrust, axial force, deflection and other parameters overshoot to greater values than they ever thought. The Team concludes (Vol. II, L-114) that the maximum gap openings are somewhere between 36 and 45 mils (thousandths of an inch). They say that the accuracy of their results is ±10%. The 96.9% transient dynamic overshoot obliterates this confidence level.

There are forward, mid and aft joints on each booster. The gap openings of the forward joints are greater than the aft joint that failed on Challenger. The Team writes, "*The forward and midfield joints have 6 to 10 mils more opening of the primary seal gap at lift-off and max Q. All things being equal, these joints should leak first.*" (*Ibid*). My calculations show that the difference is greater than the estimate of this Team, even without the dynamic overshoot. Hardy and Mulloy, mentioned above, understood the joint design but were dismissed from the official investigations. Debates raged, in 1986, over whether the

Challenger stricken joint gap opened by 2, 5, or 10 mils more than Hardy, Mulloy and other skilled NASA engineers had predicted. The unanticipated, hidden and correct transient gap opening can be 40 or 50 mils more than anyone anticipated or expected. What would Hardy, Mulloy and the SRM Team think about the conclusion that a 5 mils gap opening caused the Challenger accident, when there was 50 mils, or greater, gap opening in all the joints unaccounted for in the flawed transient analyses? What do you, the reader, think of all of this?

The title of this subsection includes the word "parade." I could have easily included hundreds of engineering illustrations of joint rotations and thousands more curves of force, shear, and bending moment that simply do not include the correct dynamic overshoot, or any overshoot whatsoever.

The devastating 100% dynamic overshoot blunder left its mark on the Space Shuttle since 1977. Challenger was not the only accident. Long lists of damage and broken parts can be easily found in the extensive Shuttle records. The damage and accidents were often related to <u>mysterious</u> forces that came out of the blue to sabotage the excellent work of the Shuttle mechanical-structural-dynamics experts. All that these experts could do was to provide plausible excuses for the damage. While all engineering fields moved forward in quantum leaps (just look at the computer hardware and software you use today), the Shuttle structural experts have been busy repairing and redesigning and trying in vain to figure out the origin of the mysterious forces. The consequences of the dynamic overshoot in the Shuttle are discussed next.

10. Consequences of the *Dynamic Overshoot*

Have you ever had your car repaired for the same problem 3, 5, or 7 times? The mechanic explains the reasons for changing a part under the hood; you understand and pay the bill. Then another part, another bill, yet the problem persists. You go to a shop with ultra-modern equipment, they change other parts, more bills, but the problem lives on. Finally, you pull into a simple shop on a country road and a friendly fellow makes a simple adjustment, explains the reason for the adjustment, a small bill; to your unexpected delight, the problem is gone. The same scenario happens to people with the heating, electrical, water or other systems in their homes. The aerospace-structural-dynamics experts will shout that the analogy is not fair. It is. If you do not know the cause of a problem, you will run around in circles fixing the wrong things, while the causal problem lives on. The devastating dynamic overshoot 100% mistake lives on.

In the 1960s, space experts were the elite in engineering. The work of space structural engineers was intensely driven by the requirement for lightweight, or the lightest weight, products. NASA, with the industry, developed the NASTRAN finite-element program to model incredibly complex structures. That made it possible for us to optimize the weight of launch vehicles, space probes and satellites. Aircraft engineers used to visit us for counsel on how to apply our methods in the design of airplanes. Ten years later, the Boeing 747 was carrying the Shuttle Orbiter on its back, and that was the only way the orbiter could get off the ground. The aircraft engineers stopped visiting us; they must have felt that we were doing something terrible in space design. We were. Dynamic overshoot was tearing the Shuttle parts apart, and no one could figure out the root cause of the problems. Just like the above mechanics were guessing at your car and you believed them, the Shuttle engineers were guessing, redesigning, repairing and rebuilding the system, almost from scratch; and the owners of the Shuttle believed the engineers.

In the late 1970s, the Shuttle experts discovered that they made a massive design error. They noticed some of the damage that was caused by the transient forces and they redesigned some parts to withstand the excess forces. However, they could not identify the primary source of the excess loads. To them, the excess forces were of mysterious origin. Repeatedly, they would state in their technical reports that the transient effect was the source of the major problems, but no one recognized that the transient dynamic overshoot was the culprit. They thought that the SSME's thrust is about 1 million lb. They discovered that the strength of parts must be doubled to withstand about 2 million lb. They knew that the excess force happens at the lift-off transient. But, they did not know that the excess forces were the result of the transient dynamic overshoot.

If there was a massive design error in the Space Shuttle, then there should have been commensurate damage, failures and accidents. Where are the accidents, failures and damage? These were everywhere.

At least, a quarter million people should be interested in this Section. Serious damage to the Shuttle goes back to the very beginning. At one time, about 250,000 dedicated and skillful individuals worked to produce the Space Shuttle. One major mistake made by a handful of engineers might have ruined the superior work of the many brilliant workers who produced the incredible flying machine. It is important that many Shuttle workers, even if they have nothing to do with structural design, understand how the repeated damage in many areas can be directly related to the dynamic overshoot effect. The cases of damage and failure described in this Section are only a small sample from a large database.

Designing, building, testing, launching and operating a space system is not easy at all. Actually, all these tasks are extremely difficult. I oversimplified things in this Report to make the first-order dynamic overshoot mistake comprehensible to many readers. If a surgeon discovers that a certain incision can cripple or kill patients, is the surgeon obliged to tell about it to a few surgeons, or all of them, or everybody? I have compiled a long list of damage that can be related directly to the dynamic overshoot error. I will give a few examples next. Please study carefully the damage to the Shuttle, Hubble, space probes and satellites and see how the damage relates to the same dynamic overshoot effect.

10.1 Did the Tiles Fail at Half the Strength or Twice the Force?

The first publicized Shuttle problem was the failure of the thermal protection system (TPS), or the tiles, in the late 1970s. At the time, I did not know the true nature of the problem and I left my aerospace job. It took years to repair the tiles. After my investigation of the Challenger accident, it became abundantly clear to me that the dynamic overshoot mistake was the cause of the early Shuttle damage. Apparently, no one noticed the connection. Repairing, Redesigning, re-testing and reinstalling the tiles was time consuming, expensive and very elaborate. Eventually, the tiles worked successfully, and everyone forgot about it. How was the dynamic overshoot effect relevant to the publicized problem? Before I tell you what happened with the tiles and what the Shuttle experts said then, consider the following analogy. The simple analogy will lead directly to the dynamic overshoot in the Shuttle tiles.

Take two pieces of wood or plastic and bond them together with crazy glue. Tie one piece to a fish scale and pull slowly on the other piece until the bond breaks. Do the test 100 times, and write down the force at which the samples break. This is the reading on the fish scale. Let us say the glued pieces break at 10.5, 10.9, 11.5, 10.1, 12, 13.4-lb, etc. You decide it is safe to use 10-lb as the minimum breaking point, and you are right. You next build 1,000-glued pieces that are your final product. Most of your final products break in service. You go to the customer site and discover that the customer hangs 10-lb bags of potatoes on the bonded pieces. The potato bags are released suddenly on the hook, from zero height and with zero momentum. The bonded pieces break. Suppose you do not know anything about the dynamic overshoot effect. Then, you are puzzled. When you try product samples that can withstand 20-lb force, things go well. What is going on? How do you answer this question? Your alternatives are not many. You have two, and only two, answers to consider. Either the bonded pieces break at half strength or the applied force is, somehow, doubled. If you do not know about the dynamic overshoot, you cannot safely say that the load is doubled. Everyone will ask you, where did the "excess force" come from? If you cannot answer this question, then your only alternative is to say that, somehow, the glue has half the strength that you anticipated and verified with many tests. The example is silly, but it is really applicable here.

The loads on the tiles and the strength of the adhesive were determined early in the Shuttle program. Many tiles failed when subjected to the lift-off transient forces. The problem was summarized in 1980 by Maxime Faget, then Director of Engineering & Development at the Johnson Space Center, as follows:[41]

> *"Loads on most tiles are greatest during launch. These loads are produced by out-of-plane deflections of the skin … when the tiles were actually tested in place, a number of them failed at about 50% the load at which a failure would have been expected."*

It was abundantly clear in the minds of the Shuttle experts in the late 1970s that:

1. The tiles' problem is strictly a transient problem; the loads on the tiles are "*greatest during launch*."
2. The tiles failed at about 50% the anticipated applied load.

Do you see the correlation to my above example? We can ask the same question, "What was going on?" Did the tiles fail at ½ the strength that was painstakingly determined in the laboratory, or were the actual loads on the tiles doubled? It is reasonable to conjecture that the principal 2:1 problem with the tiles was directly related to the destructive 2:1 dynamic overshoot effect.

The forces on the Shuttle were always puzzling to the Shuttle engineers. Do you remember what some engineers wrote about "predicting and measuring" the forces in the holddown posts? "*Predicting and measuring this load was a major problem*," (See Section 8.2). In the case of the tiles, the other Shuttle experts spoke about the tiles' half strength and the mysterious doubled forces that were, in their words, "*very hard to calculate.*"[42] In the late 1970s, Dr. Aaron Cohen, then Orbiter Project Manager and subsequently Director of Research and Engineering at the Johnson Space Center, said,

> *"… so there we were with the tiles half the strength we originally thought and the actual loads involved very hard to calculate. (Ref. 42, p. 21, emphasis added).*

The initial strength of the tiles' bond was about 13-psi (pounds per square inch). You take this pressure and multiply it by the area of a given tile to get the resultant force on the tile. Remember, the pressure (13-psi) does not overshoot. When the tiles were tested on the Columbia Shuttle, the bonded tiles failed. It appeared to the engineers that the strength of the bond was now about 6.5-psi. Alternatively, they might have thought that the "actual loads involved" were 26-psi. This rendering of the problem is confusing. To set the story straight, we must use force, and not pressure, values in the discussion. For a one square inch tile segment, the force is 13 lb (13-psi x 1 in^2). During the transient start-up of the SSME's or SRB's, the sudden force of 13 lb (and not the pressure of 13-psi) overshoots to, say, 26 lb. This explains the tiles' problem. The 2:1 start-up transient mistake.

The failed tiles were described as "undensified" tiles. Elaborate and expensive procedures were developed and applied to densify the supposedly weak tiles. The tiles are made of ceramic, which is porous. The bonded sides of the tiles were impregnated with a material that hardens when it dries. This increased the contact surface area and the strength. That was a gruesome exercise, as Cohen said:

> *"It took a lot of energy, time and ingenuity from our contractor, Rockwell, from Johnson Space Center engineers, and other NASA centers throughout the country - such as Ames and Langley Research Centers." (Ibid)*

What did the densifying process accomplish? What do you think? In Cohen's words:

> *"This treatment increases the strength of the tile - at the surface where it bonds to the strain isolator pad - by a factor of two," (*Ibid*, emphasis added).*

By now the reader is familiar with such dynamic overshoot phrases as, "by a factor of two." There is also the oft-repeated term, "twice," which also appeared in tiles' description:

> *"Densified tiles have twice the strength of the undensified tiles, and all of them have been proof-tested," (*Ibid*).*

Just as the SSME's liftoff thrust was found by measurement to be nearly double the initial design value in 1982 (Section 7), we can conclude here:

- The Shuttle experts did not include the dynamic overshoot in the initial design of the tiles,
- The primary cause of the tiles' failure was the neglected near 100% dynamic overshoot,
- No one recognized the adverse dynamic overshoot during the tiles' repair period, 1978-1981. This is evident from the confusion over the dynamic overshoot measurement in 1982 (Sec. 7), and
- The overshoot effect went unnoticed even after the tiles were completely repaired, by doubling the strength of adhesion.

The 1970's Shuttle-on-paper gave us many dreams. We dreamed of a lightweight Orbiter and heavy payloads. We dreamed of 60 Shuttle missions every year. As the Shuttle evolved, it moved to a heavy vehicle with lighter payloads. The first step in the process began with the tiles. Densifying the tiles had a side penalty – it increased the weight of the Shuttle and reduced its payload capacity. In Cohen words,

> *"The new Orbiter,* Challenger*, already has all of its tiles densified. There's an overall weight penalty of about 1,800 to 2,000 pounds, but we think it's worth it." (Ibid).*

The dynamic overshoot in the lightweight tiles alone increased the Shuttle weight by some 2,000-lb. You can see where the trend was going. There was still the unanticipated and unrecognized overshoot effect in the heavy steel parts. More weight additions and more losses in payload capacity.

The tiles were strengthened to repair visually detected damage in a specific area, but the overall Shuttle structure was not modified for the *dynamic overshoot* effects. Since the nature of the problem was not recognized, protective measures, such as, slower ramping of thrust, which could have reduced the dynamic overshoot effects, were not even considered.

10.2 Number of Joint Pins Recklessly <u>Doubled</u>

For a few years, I was responsible for testing materials for use in spacecraft. I did elaborate testing of mundane and exotic aerospace materials. The strength of mundane materials, e.g., steel and aluminum alloys, was well represented by the suppliers. The exotic materials, such as, the ceramics and composites, were a different story. The engineers could spin stories around the exotic materials. The Shuttle tiles are exotic. The Shuttle engineers concluded (in the previous Section) that the tiles failed at ½ strength. The next example involves large steel pins. No engineer could say that the steel alloy failed at ½ strength. The next 2:1 dynamic overshoot consequence is glaring. The engineers notice damage, analyze it, repair it and move on without ever making notice of the destructive culprit, their 100% dynamic overshoot mistake.

Have you noticed the rivet patterns on the skin of an airplane, or the bolt patterns in steel plates on bridges, underpasses and other metal structures? The patterns are not for decoration, but are dictated by strict engineering design criteria. Edge-to-edge spacing between any two holes must be at least **1½** times the diameter of the holes. This is a strict safety design criterion. It is intended to ensure that enough material remains between the holes to avoid shear tear up in a joint. You can see the seriousness of the problem by imagining the holes to touch – then, there is no material left to hold together!

The SRB sections are connected together with 180 pins, and each pin is 1-inch in diameter. The Shuttle engineers were aware of the hole-spacing criterion. The diameter of a booster is 146 inches. Calculate the circumference and divide by 180 to get exactly 2.55 inches. Subtract the diameter of the hole (1-inch) to get 1.55 inches. This is the initial spacing for the holes in the SRB sections. It is just above the absolute required minimum. This is an optimum design for a static machine. But the Shuttle is a dynamic machine.

Unfortunately, because the dynamic overshoot effect was neglected in the initial design of the Shuttle, the holes' spacing was greatly reduced in some SRB sections. The otherwise excellent spacing of 1½ inch became a dangerously low ½ (0.5) inch. The Shuttle engineers <u>doubled</u> the number of pins to <u>double</u> the load carrying capacity of the SRB sections involved. How did this come about?

To the Shuttle engineers, the 3-SSMEs produce about 1.1 million pounds and each SRB produces 2.7 MP force at lift-off. But, we showed that with the correct dynamic overshoot, the peak transient lift-off forces are nearly doubled. The attachment between the SRB forward skirt and the External Tank carries the brunt of the forces from the engines and the boosters at lift-off. Was the dynamic overshoot effect taken into account in the initial design? No. The oversight necessitated doubling the number of pins in the area most affected by the dynamic overshoot.

As I walked into the Vehicle Assembly Building (VAB) at the Kennedy Space Center in October 1986, I was shocked to see a booster section that had extra one-inch holes added between the original holes in an angular sector of about 30^{o}. The new 1-inch holes were added in the 1½-inch spacing between the original holes. That left about ½ inches spacing, or ¼ (0.25) inch spacing on each side of the new holes. You can see the extra holes in a NASA artist sketch[30] of the recovered Challenger Forward Skirt Clevis Joint in Fig. 44. The SRB section with the extra holes was in plain view in the VAB. That SRB section was seen by thousands of engineers, scientists, investigators, politicians and reporters since the Challenger tragedy. The scene did not shock anyone. It shocked me. That was a clear fingerprint of the dynamic overshoot.

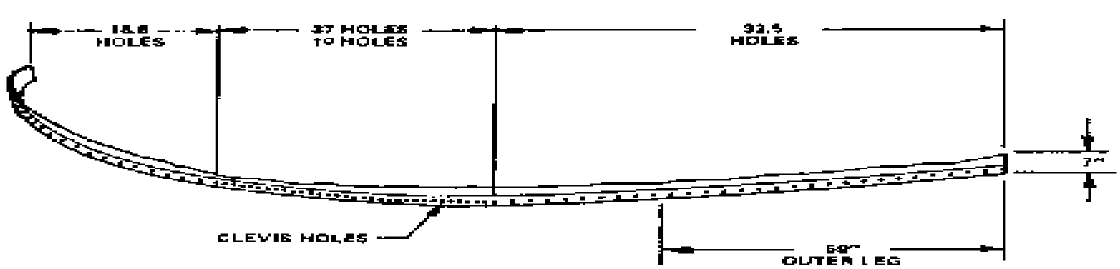
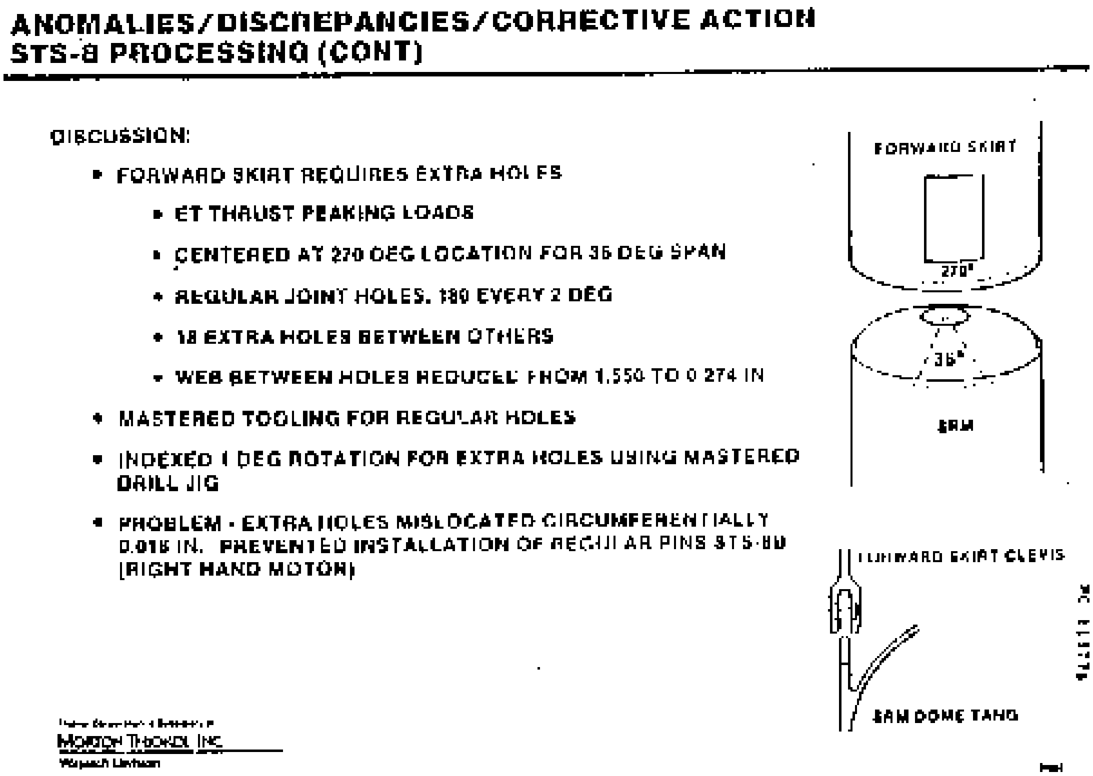


Fig. 44 NASA Sketch of Recovered Challenger Forward Skirt Clevis Joint Showing the Extra Holes

I asked my NASA escort at the Cape if all the SRB joints had the same hole-pattern at the same location, and he said yes. I insisted that he checks the record to find out if the hole-pattern was not an add-on feature, added only near the SRB-ET attachment. Next day, the NASA escort confirmed my suspicion. That was indeed a strong fingerprint of the overlooked 100% dynamic overshoot. Eventually, I found the reports of the add-on dangerous feature in the record of the Commission in the National Archives.[32]


ANOMALIES/DISCREPANCIES/CORRECTIVE ACTION
STS-8 PROCESSING (CONT)

DISCUSSION:

- FORWARD SKIRT REQUIRES EXTRA HOLES
  - ET THRUST PEAKING LOADS
  - CENTERED AT 270 DEG LOCATION FOR 36 DEG SPAN
  - REGULAR JOINT HOLES, 180 EVERY 2 DEG
  - 18 EXTRA HOLES BETWEEN OTHERS
  - WEB BETWEEN HOLES REDUCED FROM 1.550 TO 0.274 IN
- MASTERED TOOLING FOR REGULAR HOLES
- INDEXED 1 DEG ROTATION FOR EXTRA HOLES USING MASTERED DRILL JIG
- PROBLEM - EXTRA HOLES MISLOCATED CIRCUMFERENTIALLY 0.018 IN. PREVENTED INSTALLATION OF REGULAR PINS STS-8B (RIGHT HAND MOTOR)

Fig. 45 Dangerously Spaced Holes in Forward SRB Skirt Joint Around 270° Location (Source: Ref. 32, p. 113,776)

To counter what Morton Thiokol described as, "*thrust peaking loads,*" <u>in 1984</u>, it was decided that the "*forward skirt requires extra holes*."[43] Fig. 45 is a Morton Thiokol 1984 Report Sheet[44] that describes Anomalies, Discrepancies, and Corrective Action related to the added holes in the SRB section. The engineers' comments under the heading "Discussion" are reproduced below for clarity:

- Forward skirt requires extra holes
  - ET thrust peaking loads
  - Centered at 270 deg location for 36 deg span
  - Regular joint holes, 180 every 2 deg
  - 18 extra holes between others
  - Web between holes reduced from 1.550 to 0.274 in
- <u>Problem</u> – Extra holes mislocated circumferentially 0.018 in. <u>Prevented installation of regular pins</u>.

Do you see what was happening? Do you see the consequences of the neglected dynamic overshoot? Why did the Shuttle engineers double the number of pins in the SRB/ET attachment in 1984? Why weren't the pins doubled in 1972 during the initial design?

Let me show you how dangerous are the added holes. If the added pins were 1¼ in (one and one quarter inches in diameter) instead of 1-inch diameter, then there would have been no joint at all! Look at the

Thiokol engineering drawing in Fig. 46. If the new holes were 1¼–inch diameter, the holes touch and the width of the web between the holes would be zero. It is the width of the web between the holes that dictates the minimum spacing of "1½ times the diameter of the holes" or more.

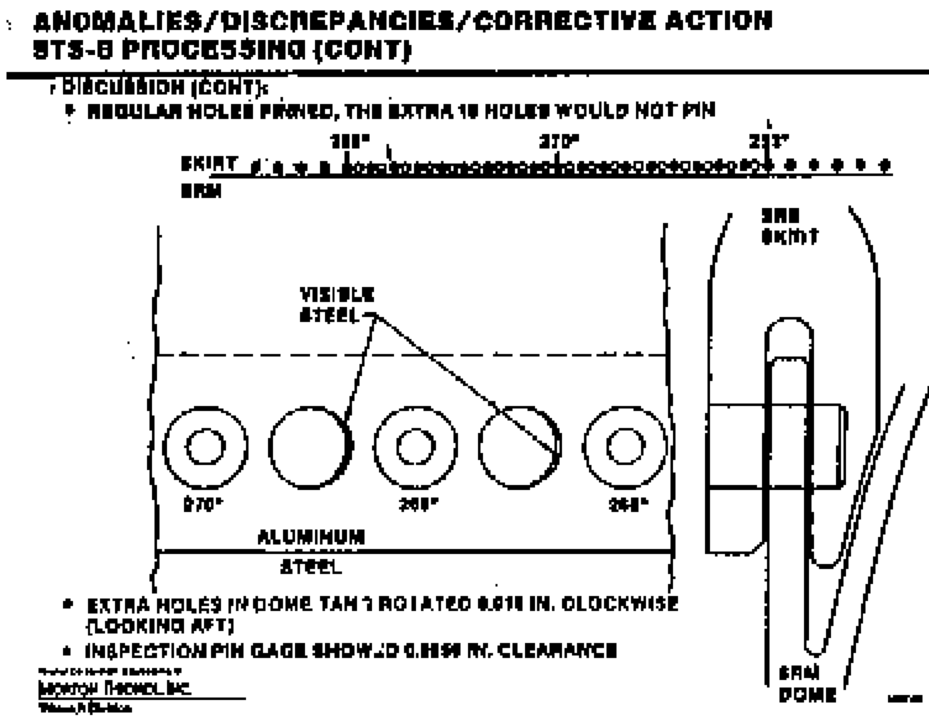


Fig. 46 Spacing between Original Holes Reduced from 1.550 inches to only 0.274 inches (Source: Ref. 32, p. 113,777)

By *doubling* the number of pins in the 36^o sector of the forward skirt, the load carrying capacity in that region was doubled. Again, a 2:1 error in the initial estimate of the loads was recognized by the Shuttle engineers, but the source of the excess loads, as being the dynamic overshoot effects, was not.

At the risk of being repetitive, let me point out the following facts about the added pins:

1. The Shuttle engineers know that the loads' problem is a transient problem, "*thrust peaking load*."
2. They discover that the loads are nearly twice of what they originally anticipated.
3. They do not know that the dynamic overshoot nearly doubles the applied forces.
4. They undertake a risky repair to alleviate the problem, doubling the number of pins.
5. They increase the weight of the Shuttle, decrease its payload capacity and introduce a new risk.
6. They run into more problems, e.g., "extra holes – prevented installation of regular pins.
7. You do not see any tendency on the part of the participating engineers to tell the other Shuttle engineers or all the aerospace community about the massive discrepancy that was encountered.

Failing to associate the doubling of the number of pins with the near doubling of forces due to the dynamic overshoot is further evidence of the Shuttle engineers' total lack of awareness of the correct start-up transient phenomenon in rockets.

In the next Section, you will see how a group of Shuttle engineers doubled outright (by multiplying by 2) the design thrust of the Booster Separation Motors, but did not disseminate the vital information of the massive change to the other Shuttle workers. This is another consequence of the dynamic overshoot mistake.

10.3 The BSM Design Thrust Doubled Outright

Finally, in the 1990 massive Shuttle Loads Books,[28] the Shuttle engineers made a small entry that gives a dynamic load factor of "two (2)," a 100% overshoot. The design load for the Booster Separation Motors (BSM) was doubled outright. The NASA entry demonstrates the importance of this Report and the value of the effort to wipe out a serious blunder that has haunted the space program from the beginning. The dynamic overshoot factor entry for the BSM, page 4.14-1 of the 1990 Loads Books, states:

> *"The loads were based upon a response to a step force input; and therefore, an amplification factor of two (2) on the thrust force was used as a load applied to the structure in a direction colinear with the motor orientation;"* (Ibid, p. 4.114-1).

This is the only entry I found of a correct peak transient effect in thousands of pages of specifications! The engineers who made the entry call the amplification factor the Dynamic Load Factor (or, DLF). The acronym DLF has never appeared before (1990) in the specifications of the Shuttle, Hubble, Apollo or Gemini. The engineer(s) who specified the recent BSM thrust load did not make any attempt to calculate the exact value of the overshoot. For example, we found the dynamic overshoot factor for the SRBs to be 96.9% or 95.4% (see Sec. 4). In the BSM case, the engineers simply multiply the steady-state thrust value by 2 (see the model rocket overshoot in Fig. 5).

Adding the large dynamic factor of 2.0 to the BSM specifications shows unequivocally the enormity of the design error. At the same time that the important change was made, the NASA Administrator Richard Truly and his assistants were expressing outrage over my dynamic overshoot studies. They expressed fierce opposition to my assertions about the missing correct dynamic overshoot effect in Shuttle design to the White House, the Congress, professional organizations, the contractors, the media and to me, in letters and meetings. At the writing of this paper (1991), staff members in the Office of the Vice President Dan Quayle are trying to figure out if there is dynamic overshoot in the Shuttle or not. There is either miscommunications or complete lack of communications within the space agency. It is as if the engineers who know about the overshoot effect can include it in their design, and those engineers who do not know about it can skip it.

Specifications are normally updated over time. When we asked NASA for the previous BSM specification, the Agency said that the old documents are usually shredded after revision. Furthermore, we were told that the latest (1990) specification should be taken as if it appeared in the original (1972) documents. While the 1990 BSM specification sentence clearly gives a DLF of 2, the record (probably inadvertently left in the same 1990 Loads Book) shows that the earlier DLF values were grossly in error. Here is how.

There are eight booster separation motors (BSMs) on each SRB, Fig. 47. In early drawings, the thrust of each BSM was given to be 20,000 lb. This could simply be a rounded value for graphic illustration.

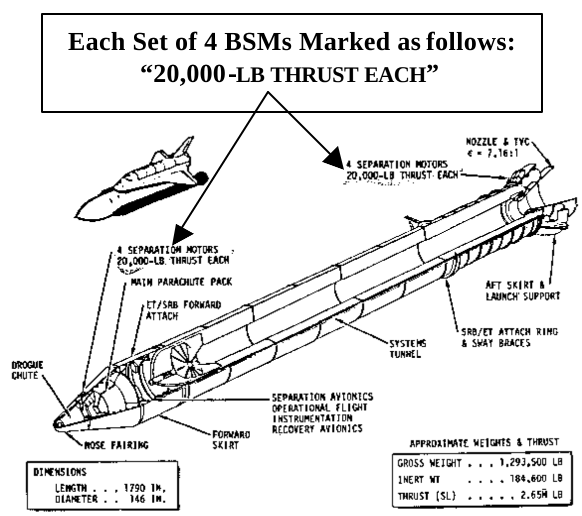


Fig. 47 Initial BSM Thrust Values

Let us review the evolution of the dynamic overshoot in the BSMs over the years. First, had the DLF of 2.0 been included in the initial Shuttle design, then the motors would have been robust and there would have been no structural damage in operation. But the separation motors experienced considerable damage over the years.

The steady-state thrust for each BSM is 22,300 lb (Ref. 28, Sec. 4.14). Initially, the BSM design thrust was specified to be 23,750 lb, or a dynamic factor (now called DLF) of only 6.5%, which is in the same mistaken ballpark of values used for the SSMEs, SRBs, etc. The initial and mistaken BSM thrust profile, with the smaller DLF, appeared in the same 1990 Loads Books, see Fig. 48. The dynamic overshoot, or the DLF, is only 6.5%. It is as if a typist had forgotten to remove the telltale curves from the specification books. This lapse made it possible to reconstruct how the DLF was increased from 6.5% to 100%.

Notice how the thrust is given in pounds on the left ordinate. The corresponding pressure values appear on the right side. This confirms my earlier observation that the Shuttle engineers measure the pressure and convert the non-overshooting pressure values to thrust values without deriving the correct transient response, with the correct dynamic overshoot.

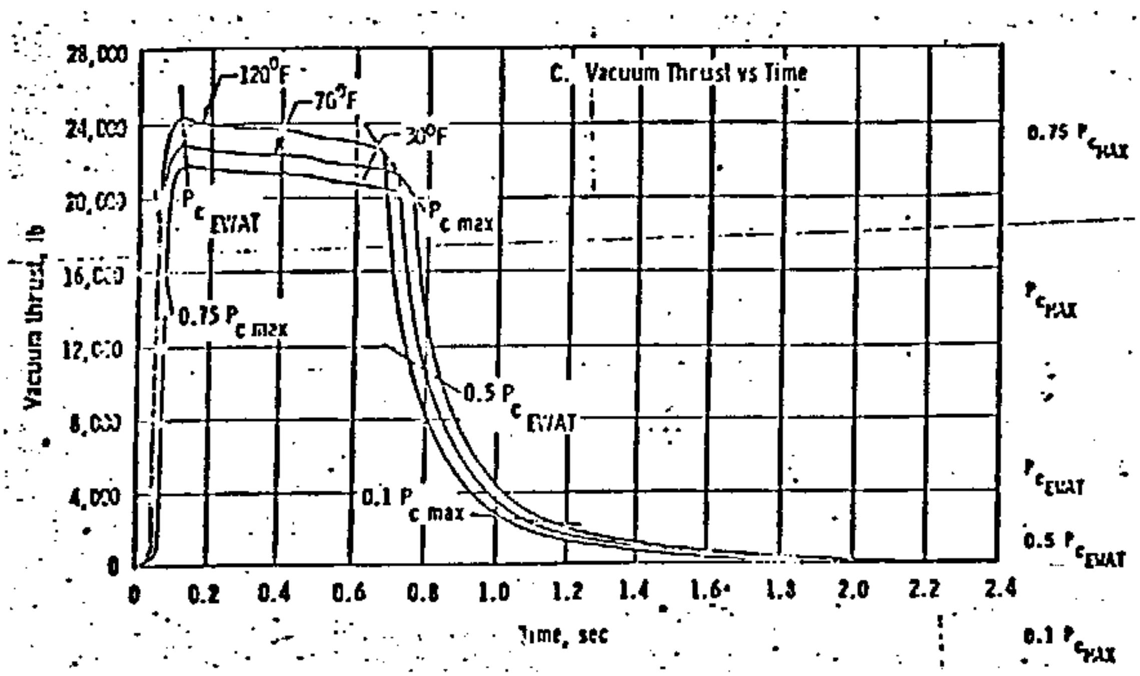


Fig. 48 BSM Thrust Profile Showing a Peak of only 24,000 lb. A DLF of only 6.5%

It is relevant to note here that the shape of the BSM thrust profiles in Fig. 48 is similar, even identical, to the thrust profiles found in engineering textbooks on propulsion systems, e.g., Ref. 8, "*Rocket Propulsion Elements*," pp. 267, 273 and 318. The same thrust shapes are also found in Wernher von Braun's and others' books. All of the above thrust profiles show only less than 10% load amplification during the start-up transient period. And none of the books explain how the small dynamic factors were derived in the first place. It can be said that the correct dynamic overshoot factors were neglected in the design of all space systems, including the Space Shuttle, which resulted in completely inadequate designs since the beginning of the space program. Do you remember the exploding rockets of the 1960s, 50s and 40s?

During the second year of Shuttle flights, 1982, considerable damage to the BSM structures was reported on every flight. The engineers wrote that the BSMs were *"not designed for: "reentry dynamic pressure," "water impact," "wave action," "* and *"drogue suspension line snag,"* (Ref. 32. p. 26100). Apparently, the engineers suspected splashdown to be the cause of *"bending, yielding, fracture and break damage"* that was observed in the BSM parts. Changes to counter splashdown effects, the wrong problem, were made. The damage continued. That led to an increase in the dynamic factor from 6.5% to 30%, as some engineers suspected that their initial estimate of the transient overshoot, or 6.5%, was wrong.

Apparently, the convoluted statistical 3-sigma method (see quote, p. 46) was then used to increase the BSM design loads. The 3-sigma factor produced a greater design load, which is shown in Fig. 49. Notice, in particular, that the design peak load is marked, "$+3\sigma$ = 29K," or 29,000 lb. This is another telltale sign of the changing DLF for the separation motors. The illustration is another confused Shuttle transient response. Here, the dynamic factor becomes 30% (i.e., 29,000/22,300), instead of the initial 6.5%. The 1990 specification curve in Fig. 49 indicates that, at some point, the engineers believed the peak load to be this 29,000-lb value. Again, the general shape of the transient overshoot response is wrong – see my earlier transient overshoot illustrations or the model rocket response in Fig. 5.

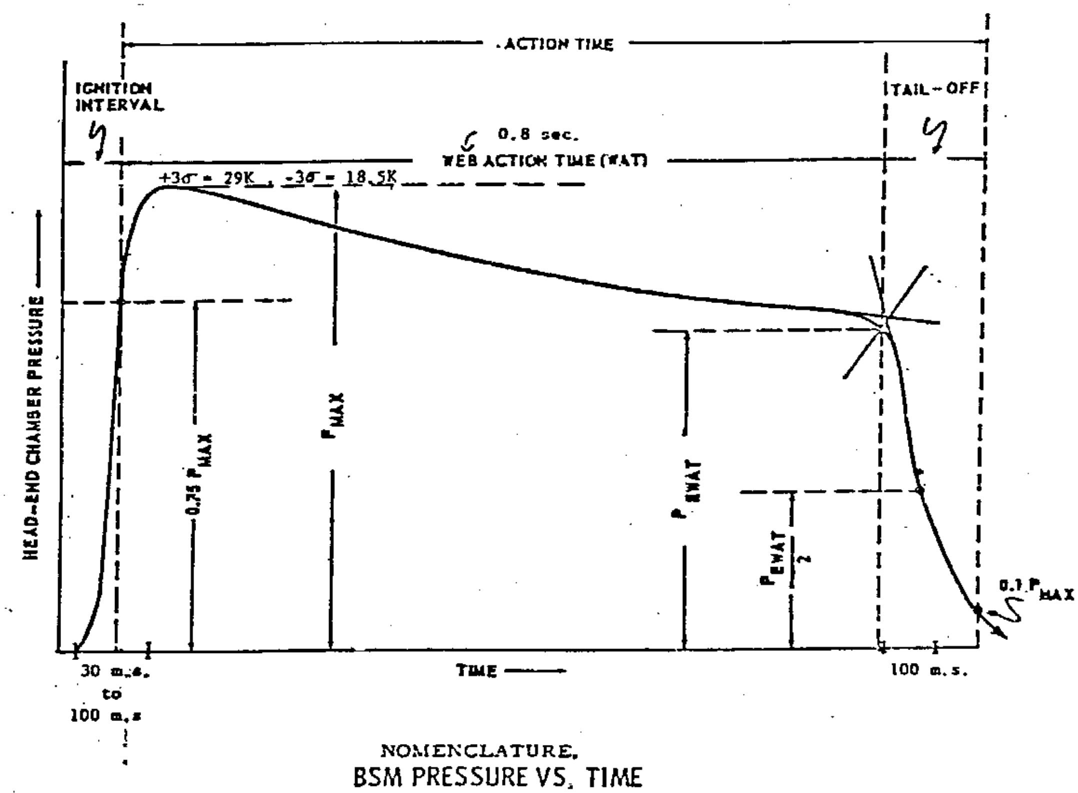


Fig. 49 NASA 1990 BSM 3s Overshoot Peak of only 29,000 lb. **<u>A DLF of 30%</u>**

I emphasized repeatedly how the Shuttle engineers, and others, measure the pressure (which does not overshoot) and convert the non-overshooting pressure values to force values. The force-overshoot is then missed altogether. I also said the experts use the pressure-time curves as the FORCING FUNCTION in transient analysis, which is wrong. For, again, how can the FORCING FUNCTION be in pounds-per-square-inch and the TRANSIENT RESPONSE in pounds? This is mixing apples and oranges. The NASA 1990 Fig. 49 shows it all. With the exception of the peak force marked "+3σ = 29K," everything in Fig. 49 is in pressure units! The confusion over the dynamic overshoot concept is abundantly clear here.

After the dynamic factor was increased from 6.5% to 30%, the situation improved. Major damage was averted, but yielding of some parts continued. The continued damage and the relentless push to explain the damaging dynamic overshoot effect might explain the recent increase of the BSM thrust dynamic overshoot factor from 30% to 100%.

Let me summarize the evolution of BSM transient loads from whatever revealing signs that were left in the 1990 specification book:[28]

1. Initially, a grossly inadequate dynamic factor of 6.5% was used in BSM design.
2. Graphic illustration of the transient response (Fig. 48) was wrong, even though the illustration followed the practice used in engineering textbooks.
3. Extensive structural damage, which could easily be explained to be the result of the "excess forces" during the ignition transient, was mistakenly attributed to splashdown into the ocean.

4. The dynamic factor was increased from 6.5% to 30%. The situation improved, but damage continued.
5. The new graphic illustration of the transient response (Fig. 49) is also wrong. Here, the transient response is given in pressure units, which should be the Input, not the Output, in transient analysis.
6. The dynamic factor, now called the dynamic load factor or DLF, was increased from 30% to 100%.
7. The exact DLF was not calculated using applicable transient analysis. Instead, the engineers use the simple doubling factor I mentioned repeatedly in this Report.
8. The correct transient behavior continues to be primarily misunderstood by the Shuttle engineers, as many parameters in the same 1990 Loads Books continue to be specified to the grossly inadequate steady-state or static force values plus the incorrect 3-sigma factors.
9. The mixture of correct and incorrect dynamic overshoot factors in the 1990 specifications indicates that NASA and the Shuttle Contractors continue to handle the important transient effect carelessly.
10. The same mixture in Item 9 indicates that the Shuttle is a highly non-optimized system. Doubling the load carrying capacity of some parts and leaving other parts uncorrected can easily and unknowingly lead to dangerous situations.

I have added the approximate correct dynamic overshoot effect for the Booster Separation Motors to the NASA 1990 illustrations (Figs. 48 and 49) in Figs. 50 and 51, with the provision that the ordinate in Fig. 51 be specifically marked with thrust, and not pressure, values.

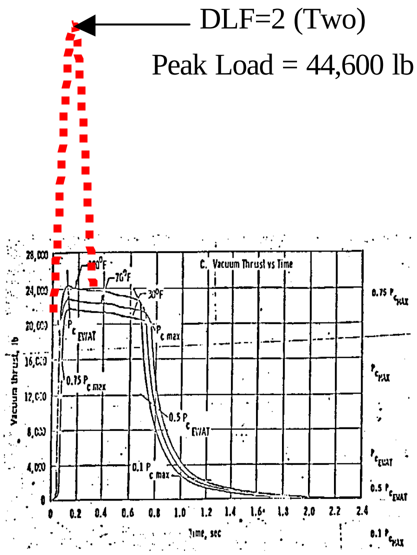


Fig. 50 Correct DLF Effect Added to BSM Thrust

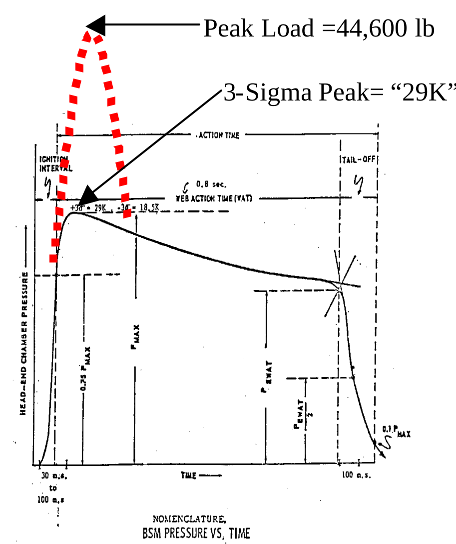


Fig. 51 Correct DLF Effect Added to BSM Thrust

I must say that it was never my intent that a dynamic load factor (or, DLF) of 2, or a dynamic overshoot component of 100%, be indiscriminately added to all the loads and deflections in the Space Shuttle. The correct DLF values must be calculated to find the minimum overshoot. Also, there are many methods that good engineers can come up with to reduce the maximum overshoot in any system. Neither of these important steps was taken in the case of the 1990 BSM specification, where the design loads were doubled outright.

Doubling the BSM transient dynamic load in 1990 and pretending that the doubling was done in 1972 embarrassed me greatly in some important quarters. This Section exposes the sham and, more importantly, it demonstrates that the Shuttle engineers continue the doubling exercise, piecemeal, without realizing that the problem is systemic in the whole Space Shuttle.

10.4 Widespread Damage Due to Dynamic Overshoot

Every area of engineering has progressed in leaps and bounds in the last thirty years. When the Space Shuttle Program began in 1972, audio and video equipment were crude, microprocessors and personal computers were not yet dreams in the minds of young visionaries, rapid digital communication was struggling to prove its viability, CDs did not exist, color graphics was unknown, laser copiers, printers and fax machines were primitive or non-existent and a multitude of home appliances were not invented. Just look under the hood, or on the dashboard, of your car to see progress. Stare at your computer monitor and you see progress. One area of engineering that remains antiquated and out-of-date is that of aerospace structural design. The primary affliction of aerospace structural design has been the devastating dynamic overshoot mistake. Even the civil engineers include the correct transient loads in their textbooks and in their design of skyscrapers, bridges, domes and other structures. Epidemic severe structural damage has been commonplace in the Space Shuttle and other space systems. Unfortunately, the satellites and space probes are usually lost in space, and the aerospace structural experts cannot be blamed outright for those losses. The Shuttle comes back and clear assessment of the damage and culpability for the damage can be made. In this Section, I will limit myself to another glaring case, but there are others on record.

The Shuttle was initially designed without dynamic overshoot. The system failed its first tests. No one knew what was the problem. The Shuttle began to fly and was declared operational. We are now in the early 1980s. The Shuttle engineers believed that the SSMEs struck with some 1 million lb force at lift-off, they did not know that the SSME's transient peak is about 2 MP. The engineers also believed that the SRBs struck with at most 6 MP at liftoff, when the peak dynamic overshoot was more than 11 MP. They thought the axial force in the SRBs was 15 MP, when the force was 30 MP at liftoff. The result of the mistake was widespread structural damage. The engineers saw the damage. They did not know that the dynamic overshoot was the culprit. Something else must be causing the damage, they thought.

The boosters are made of heavy steel. Every time the boosters were recovered from the ocean, the engineers noticed a long list of serious structural damage. Well, if they designed the boosters correctly, which they believed was the case and they were wrong but they did not know it, then what caused the serious structural damage to the heavy steel parts? Splashdown. The engineers blamed the damage on splashdown into the ocean. How credible are the splashdown stories?

In the early 1980s, NASA and the Industry conducted extensive "*scale model tests, finite element dynamic response analyses and full scale segments tests*"[45] to evaluate the "*splashdown*" effects. From the extensive and very expensive and time-consuming studies, the engineers discovered that the "*observed damage*" *could not have been caused by splashdown*."[45] They presented the conclusion in May 1983 to an AIAA Conference. SRB models and instrumented SRB hardware were jettisoned into the sea and evaluated for splashdown damage. The engineers concluded in 1983:

> *"The magnitudes of predicted stresses, however, were generally not sufficient to cause the observed damage," (*Ibid*, p. 475).*

The engineers concluded that splashdown could not cause the observed damage, but they were unable to find out what was causing the damage. So, they redesigned and repaired the damaged parts. And when damage recurred, the engineers were unable to free themselves from the splashdown alibi. Do you see their dilemma? Splashdown cannot cause the damage. Damage occurs. They do not know about the dynamic overshoot forces. They cannot find any other credible source of excess forces. And so, they resort to splashdown again. And everyone believed it. The sequence of events for the splashdown damage story is best illustrated from their study itself.

Let us move through five Shuttle missions, STS-1, STS-2, STS-3, STS-4, and STS-5. Some of the damage to the boosters was described as follows:[46]

> *"Significant internal stiffener ring damage was evident in both aft skirts" on STS-1 and STS-2."*

> *"The "new" reinforcement gussets and clips were added on the STS-3 flight set of SRB's," but, "Cracked inner and outer flanges were observed in localized peak load areas."*
>
> *"Subsequently, more gussets and clips were added," but, "Local cracks, however, were still experienced."*

Serious structural damage to heavy steel parts was observed, corrected, observed again, corrected again, etc. While the structural engineers were trying to figure out what was going on, the electronic engineers were waiting with advanced computer chips, others were waiting with superior digital hardware, and software writers were waiting with excellent routines to try out their superior products in space. Everyone waited while the structural-dynamics engineers went around in circles, and the Shuttle weight increased.

In preparation for the next Shuttle mission, STS-6, the engineers made an all out effort to avert the persistent damage, whether caused by splashdown or mysterious agents. In their own words:

> *"The STS-6 configuration includes a full complement of structural reinforcements plus foam located on the mid-ring bottom side between the inner and outer flanges."*

The subsequent severe and widespread damage to the STS-6 hardware must have been demoralizing to the Shuttle structural engineers. Page 36,827 of the Presidential Commission record (shown in Fig. 52) might explain why the structural engineers and everyone else were probably dispirited:

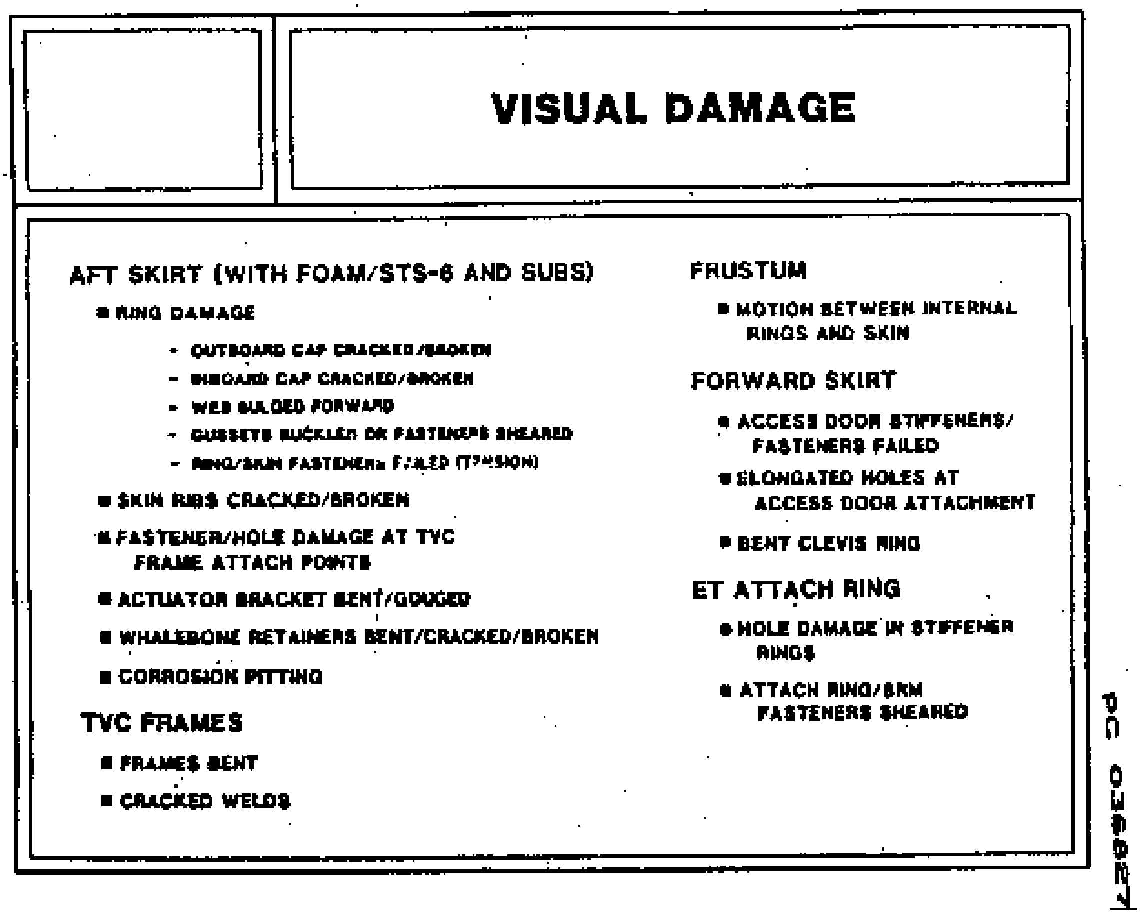


Fig. 52 After Extensive Structural Reinforcements to the STS-6 SRB Hardware, Severe and Widespread Damage Persisted

The boosters showed damage all over, in the aft-, mid-, and forward sections. There were *"cracked, broken, bulged, sheared, gouged, bent, elongated"* parts. Other parts failed in tension, i.e., the parts broke apart completely. It does not take rocket genius to see that something was amiss. That something was the dynamic overshoot in action. Notice that the damage sheet gives only a "visual damage" list. You can imagine the unseen internal damage to the boosters.

Subsequent to the demoralizing STS-6 damage experience, the fickle splashdown solution and the inordinate analyses and further tests of splashdown were described in detail in the 1985 NASA Technical Paper[33] on *"dynamical problems*." This was two years after earlier extensive studies had dismissed splashdown altogether. A NASA schematic of the splashdown is shown in Fig. 53.

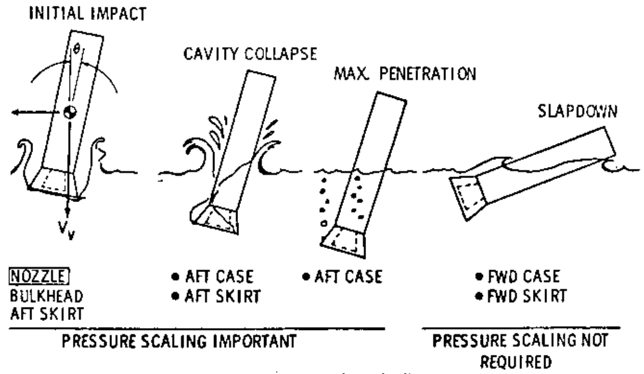


Figure 69. SRB water impact significant loading events.

Fig. 53 Booster splashdown

The NASA dynamics expert was aware that the boosters' splashdown problem specifically required dynamic "*transient response*" analysis, when he writes:

> *"The SRB is recoverable and <u>reusable for twenty flights</u> at a cost savings to Shuttle operations. Several problems have occurred in the recovery system and the water impact associated with recovery. These problem areas were (1) chute hangup and failure, (2) water collapse loads on SRB shell, (3) skirt and support rings <u>transient response</u> to impact, and (4) flow reversal during impact,"* (p. 66).

One of the meetings that I held with the NASA engineers at the KSC in October 1986 was to evaluate the splashdown loads. We reviewed several analyses and splashdown data, and we arrived at two conclusions in that meeting:

1. The transient dynamic overshoot loads were neglected in the splashdown analysis, and
2. The splashdown loads, with the correct dynamic overshoot, were not as severe as the transient dynamic loads of lift-off.

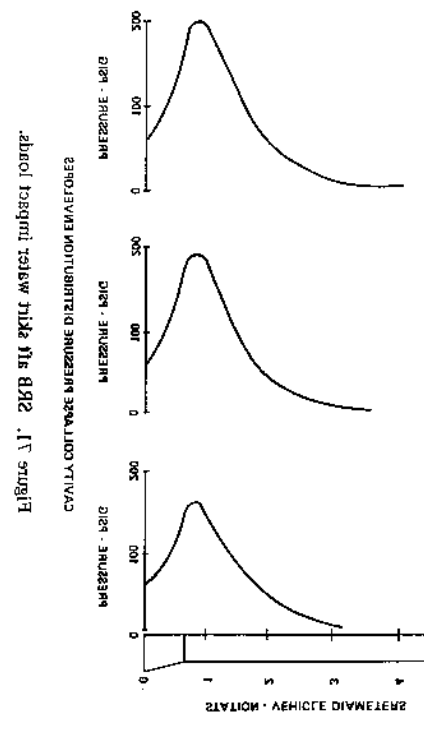


Fig. 54 Splashdown Analyses Show No dynamic Overshoot

You can see another sample of the wrong transient responses in Fig. 54, where the NASA expert omits the correct dynamic overshoot in splashdown loads. I inverted the curves to keep the figure consistent with the other figures. Notice that the ordinates give the non-overshooting pressure values! This means that there was no differentiation between the Input and the Output in the transient analysis. Also, notice that the maximum splashdown pressure is less than 200 psi, which is much smaller than the start-up lift-off pressure in the boosters, of nearly 1,000 psi. The reader can add his or her own estimate of the correct maximum dynamic overshoot to the NASA 1985 curves in Fig. 54.

The wishful "splashdown" pretext did not stop after STS-6, or even after the Challenger accident. The Space Shuttle structural engineers continue to feign that splashdown is at the root of their problems. This attitude had gained them sympathy and attention. Everyone wants to know what will the Shuttle structural-dynamics engineers do next to counter the mysterious forces that were arising from the depths of the ocean.

In the previous quote from the NASA dynamics expert, it was stated that the boosters were "*recoverable and reusable for twenty flights*." Actually, when you add the safety factor, the boosters were anticipated to be good for eighty (80) flights. The NASA-Industry SRM Team, whose work on the SRB's joint rotation (with no dynamic overshoot) was discussed in Sec. 9.2, confirmed the 20-reuses of the SRB segments in their final report on the Challenger accident:[30]

> *"A review of structural strength, fatigue, and fracture mechanics analyses was completed. These analyses were used to determine the required mission life of the motor case and demonstrate that the case could meet the fatigue and crack growth requirements of four times the cycles and growth expected in 20 uses,"* (Vol. II, L-82).

The SRM Team then confidently concludes that the booster's segments are actually good for 80 "uses":

> *"Using fracture mechanics analysis, an initial flaw of 0.05 inch deep and 0.100 inch long is allowed to grow through 80 (20 uses with a safety factor of 4) "uses in order to determine if it reaches critical dimensions before 80 uses."*

The NASA-Industry Team of engineers wishfully concluded:

> *"After 275 uses, by analysis the assumed initial flaw reached the calculated depth --,"*

Considerable redesign of the boosters took place between the time of the Challenger accident, in 1986, and 1991. It is reasonable to expect the boosters segments to be "useful" for hundreds, or even thousands, of flights. The opposite happened. The following is a fair review of the number of reuses that the boosters should be good for:

1. During 1972-1977, the boosters were designed for 20 uses.

2. During 1977-1981 (before the first Shuttle flight), the boosters were strengthened in many areas. One would expect that the useful life of the boosters' segments increased. It didn't.

3. During the period of 1981-1986 (from the first flight to Challenger), the boosters were strengthened repeatedly after many instances of "visible damage." Again, one would have expected the useful life of the boosters to increase further. It didn't.

4. During 1986-1991 (Challenger to Atlantis 1991 flights), the boosters were strengthened again. One would expect the useful life of the boosters to increase again. It didn't. Worse yet, the useful life of the boosters' segments was drastically reduced.

Based on the above confident statements of the SRM Team and the numerous cases of increased strength, the boosters' segments should be useful for hundreds or thousands of flights. The O-ring seals, which act like the washers in a kitchen faucet, could not have affected the useful life of the boosters before or after Challenger. The O-ring seals could not have caused the widespread structural damage of every section of the STS-6 boosters (see Fig. 52). Having said all of this, what would you think is a fair estimate for the number of reuses of a Shuttle booster's segment? On paper, the number went down to 5 reuses! In real life, some of the booster's segments were completely damaged after only 1 (one) mission!

Look at what happened to the Atlantis 1991 boosters. In January 1992, the Washington Post reported:[47]

> *"After launches of Atlantis in April and November (1991), NASA found that the forward section of one booster had buckled irreparably and that the forward part of another booster had cracked open halfway around and three of its four main segments had buckled,"* Emphasis added.

Booster segments that have *"buckled irreparably"* or *"cracked open halfway around"* after only one flight cannot be reused at all. The report went on to say that the NASA engineers consider splashdown to be the primary cause of the Atlantis SRB damage (p. A7). Do you see the terrible trend, since the 1970s? Repeated strengthening of the boosters repeatedly reduced the useful life of the boosters, increased the weight of the Shuttle, reduced its payload, delayed flights, and endangered the crew. Commonsense should lead us to identify the "dynamic overshoot" mistake. How can the strengthening of anything reduce the useful life of the thing? For twenty years, the boosters have been strengthened for the wrong reason – splashdown. In the meantime, the real problem – the massive dynamic overshoot forces, have been unknowingly chased up and down the boosters' lengths.

Interestingly, Robert Goddard used to retrieve his primitive rockets, which splashed down on the ground, to reuse them. Also, the author of the book "*Soviet Rocketry: Past, Present, and Future,*"[48] describes the Russians' experience with splashdown. The Russians' rockets splash down on the tundra. The author of Ref. 48 writes that going back to the 1930s, the Russians equipped their rockets with parachutes "*for controlled descent, recovery, and reuse,*" emphasis added. Perhaps, as long as the space reporters are appeased with the easy splashdown explanation, the structural engineers will continue to believe it and use it. The "dynamic overshoot" may no longer be an engineering mistake. It has become a mental condition from which the aerospace-structural-dynamics engineers cannot extricate themselves.

In this Section, I confined myself to limited instances of SRB damage. The list of damage to the Orbiter, External Tank, the SSMEs and the other Shuttle parts, in tests and in operation, is too long to include here. Thousands of problems with the Shuttle have been caused by ONE mistake, yet thousands of experts have failed, and refused, to see it. I had followed the development of the Space Shuttle Main Engines (SSME) closely in the 1970s. The Shuttle engines were a breakthrough unequal anywhere in the world. But, very serious failures happened during SSME development, and many of those failures can be directly traced to the greatly misunderstood dynamic overshoot effect. Yet, the Shuttle engineers never realized that the "dynamic overshoot" was at the root of their problems. How could they? Their primary measurement was the "pressure" and the "pressure rise" in the engines and in the boosters. As everyone must now know, pressure in rocket engines and motors does not overshoot – but the sudden thrust strikes all parts of the Shuttle with nearly double the initially expected forces. The Shuttle engineers furiously respond that the Space Shuttle never experienced "failures and damage." The record, in their words, shows otherwise. The neglected "dynamic overshoot" struck *all parts of the Shuttle*. Even the Mobile Launch Platform (MLP), which is left behind at the Cape, experienced serious damage, which could not be blamed on splashdown, as discussed next.

10.5 Massive Cracks in the Launch Platform (MLP)

The Mobile Launch Platform (MLP) is a massive steel structure. The two SRBs are bolted directly to the MLP at eight holddown posts, or four posts per booster. The External Tank is then attached to the two SRBs and finally the Orbiter is attached to the ET. The Shuttle assembly is driven on the MLP very slowly from the Vehicle Assembly Building to the Launch Pad. The MLP must withstand the lift-off forces. During the first six seconds after SSME's ignition, the Shuttle assembly sways forward and springs back (see the base bending moment illustrations in Sec. 8.4). The forces generated by the SSME's thrust propagate from the holddown posts, through the MLP steel structure and finally to the ground. We saw how the Shuttle engineers sincerely thought that the SSME's lift-off force is about 1.1 million pounds (Sec. 5.1 and 7). We also saw that they were surprised to measure a dynamic overshoot force component of 800,000 lb, which they called in 1982, "excess upward force." The load on the MLP was nearly double what the engineers initially and wishfully thought. What do you suppose happened to the MLP's steel structure during lift-off?

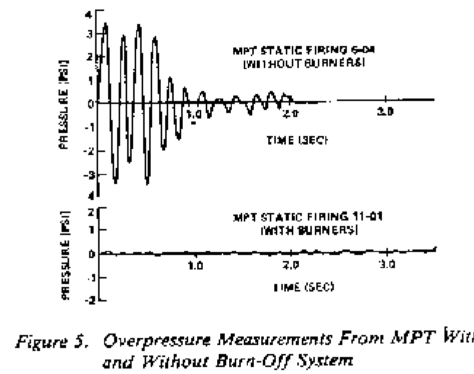


Fig. 55 Overpressure Problem Solved with Burn-Off System

The senior structural-dynamics-loads experts from NASA and Rockwell wrote extensively about the serious lift-off mishaps that were unexpected before 1981. A NASA expert[33] and a Rockwell expert[27] describe several steps that were taken to alleviate the unexpected lift-off damage. One major problem was the pressure and overpressure bouncing back at the MLP and the Shuttle assembly from the plumes of the SSMEs and SRBs at liftoff. Several measures were taken to solve the "unexpected" overpressure problems. Everyone has *seen* the solutions.

The sparks you see on television before SSME's ignition burn hydrogen "pockets" in the vicinity of the engines, thus eliminating one source of overpressure. The water "injection" deluge you see before lift-off is another correction measure. Initially, the three SSMEs were to ignite together, but then the ignition was scattered by 120 milliseconds. The Rockwell expert writes, "*Dedicated pressure instrumentation was added to the simulated aft fuselage and base heat shield*," to evaluate the overpressure lift-off problems. You can see the overpressure measurements before and after the addition of the spark system in Fig. 55.[27] The expert writes that the above "*measures had a dramatic effect in eliminating the overpressure wave*," (*Ibid*). The second curve in Fig. 55 shows that the problem was nicely eliminated. And so, after the first Shuttle mission, STS-1, there was no overpressure problem. But, how about the destructive effects of the neglected dynamic overshoot?

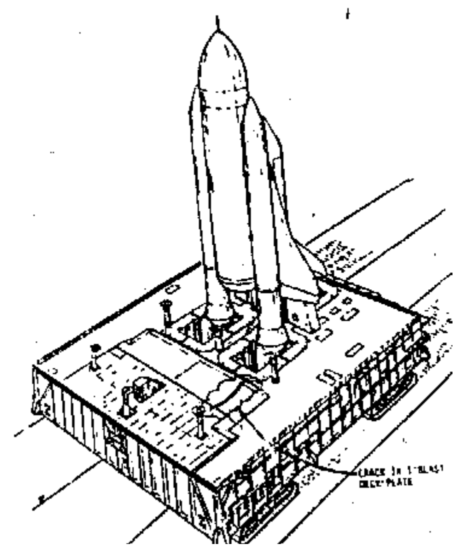


Fig. 56 Long Cracks in MLP in early 1980s

In my meetings with the engineers at the KSC in October 1986, we talked about the serious damage to the MLP earlier in the program. When I examined the Commission record in the National Archives, I found the MLP damage. Page 60,445 of the PC record shows a very long crack in the 1-inch thick steel plate, Fig. 56. The original arrow points to the long crack in the thick steel plate. The cracks were reported in 1982, after the overpressure problems were solved in 1981, but before the Shuttle engineers accidentally measured the dynamic overshoot "excess upward force" of some 800,000 lb in 1982. What do you suppose caused the massive cracks in the MLP?

A closer look at the long crack in the Mobile Launch Platform is shown in Fig. 57. The crack is 20 feet long in a 1-inch thick steel plate. Obviously the strength of the steel could not have been half (½) of what was anticipated. What do you suppose caused the long crack and the other cracks that are not shown in this Report?

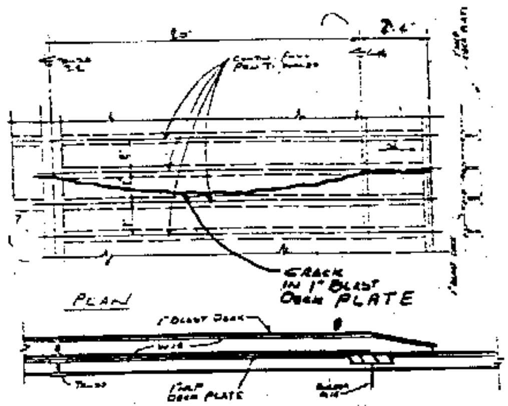


Fig. 57 20-foot long crack in 1-inch blast deck steel plate

The answer, of course, is the neglected dynamic overshoot, the excess 800,000 lb that the engineers were surprised to measure in 1982 (see Sec. 7). Splashdown into the ocean cannot be blamed for MLP damage. The Launch Pad is left behind at the Cape. The overpressure cannot be blamed for the MLP damage. The problem was solved in 1981, Fig. 55.

A clear picture of the dynamic overshoot mistake should be developing in the mind of the reader. Have you noticed the units of measurement in Rockwell's Fig. 55? Here, pressure units are used[27]. NASA also uses the pressure to solve the overpressure transient problem[33]. But, pressure does not overshoot. The Shuttle engineers are accustomed to look at the non-overshooting pressure readouts and make decisions accordingly. The maximum overpressure recorded, 5-psi by NASA (p. 49) and 3.5-psi by Rockwell (p. 379), are rather insignificant to the massive Mobile Launch Platform steel. Even after you add the correct dynamic overshoot to the overpressure data, the resulting loads are insignificant. The important thing to note here is that the same erroneous method was also used, no dynamic overshoot whatsoever, while the overshoots were everywhere.

The Shuttle is basically a pressure-based design. It is a static-based design. It is not a dynamic machine. It is dynamic only where the engineers accidentally measured and noted the dynamic overshoot effect and made corrections. The Booster Separation Motors are dynamic, but only because the engineers doubled the sudden thrust (Sec. 10.3). The thermal tiles became dynamic, but only after the bonding strength was doubled (Sec. 10.1). The holddown posts are dynamic, but only after the engineers noted that the SSME's thrust effect is nearly doubled (Sec. 8.2). And so on.

Sometimes, the Shuttle engineers thought that they turned a static-design into a dynamic-design, but they really did not. This was the case with the struts that connect the SRBs to the External Tank, Fig. 58. Like everything else, the struts were initially designed for static loads only. When the dynamic overshoot hit the struts, the parts failed. Now the engineers devised plans to alleviate the unexpected, and mysterious, dynamic loads in the struts. They preloaded the struts. If a strut experienced too much tension, they preloaded it in compression. If the strut experienced too much compression, they used tension. That was fine for the struts. But, do you see why that solution was not fine for the Space Shuttle and the MLP?

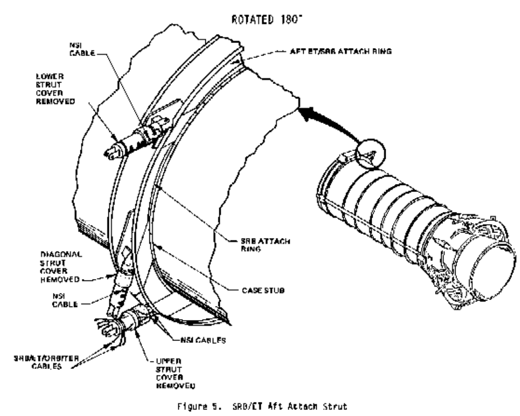


Fig. 58 SRB/ET Attach Struts

It is true that the maximum lift-off loads in a given strut were reduced by the preloading scheme. It is true that the preloaded struts were able to absorb the magnified overshoot loads. What about the rest of the Shuttle structure? If you preload a part of the slinky I mentioned before, in tension or compression, the preloaded part of the slinky can be relieved of some, or all, of the dynamic overshoot. But the ceiling and the rest of the slinky will experience the full brunt of the dynamic overshoot when you release a load suddenly at the end of the slinky. In essence, an originally statically designed part of the Shuttle (the struts) was made dynamic by the preloading scheme, but the dynamic overshoot went right through that part to strike the rest of the Shuttle and the MLP with the "excess overshoot force," and with adverse consequences.

10.6 Hubble Troubles and Dynamic Overshoot

Almost everyone was skeptical about the dynamic overshoot mistake. It seemed unlikely that the space experts could make such a silly mistake. The layman can see a 93% mistake a mile away. You negotiate the price of a car down to $18,000. When you go to pick up your car, the dealer tells you that he or she made a mistake. The price is $34,740. That's a 93% "overshoot" error. You don't need education to see the travesty. Yet, errors of this magnitude happened in the design of the Hubble Space Telescope.

After the Hearing I had at NASA headquarters in October 1989, I became convinced that the Shuttle engineers did not recognize the importance of my input about the transient effects in 1986. More importantly, it became clear that all aerospace engineers and faculty were oblivious to the destructive overshoot effects. I next discovered that the Hubble Space Telescope (HST), like the Shuttle, was designed to only the static loads; <u>no dynamic overshoot</u>. The launching of Hubble was nearing. I contacted NASA, the White House, the Congress, the Hubble Office and others. The launch was delayed while my assertions of 70% to 100% transient mistakes were investigated.

You do not need to be a rocket scientist to see the 2:1 mistake in the design of the Hubble Telescope. I will give here one example. The Primary and the Secondary mirrors in the HST are critical components for data gathering. The HST went through the normal development cycles of Preliminary, Intermediate, and Critical Design Reviews, Fig. 59. Notice how the load "<u>design value</u>" for the Secondary mirror was initially specified to be 6.7 g's in the 1970s. After the first Shuttle mission in 1981, the design load for the Secondary mirror was changed from 6.7 g's to 12.9 g's! The Secondary mirror design load was nearly <u>doubled</u>. Do you see it? The dynamic overshoot hit again. The arrow I added in Fig. 59 shows how the design load went from 6.7 g's to 12.9 g's; a 93% load increase. A 93% design blunder.

TABLE 31. DESIGN VALUES AND ANALYSIS CYCLE VALUES

COMPONENT	DIR.	MAXIMUM ACCELERATION (G's) LIFTOFF LOADS			
		DESIGN VALUE	P.L.C.	I.L.C.	C.D.R.
PRIMARY MIRROR	X	3.7	3.1	3.5	4.5
	Y	2.4	1.1	1.2	0.9
	Z	3.7	2.6	2.0	3.2
SECONDARY MIRROR	X	3.8	3.1	3.4	4.5
	Y	3.5	2.3	2.6	2.3
	Z	6.7	5.0	3.3	12.9

P.L.C. = PRELIMINARY LOAD CYCLE, USED 5.4 SHUTTLE DATA
I.L.C. = INTERMEDIATE LOAD CYCLE, USED 5.7 SHUTTLE DATA
C.D.R. = CRITICAL DESIGN REVIEW LOAD CYCLE, USED 5.8 SHUTTLE DATA

Fig. 59 Hubble Space Telescope Loads <u>DOUBLED</u> on Scondary mirror, but <u>NOT</u> on Primary mirror

My concerns over the Hubble design were discussed with everyone, but me. The Telescope was launched and it was almost lost. The repairs were very costly and dangerous. Let me show you how the Hubble-Shuttle engineers mishandled the enigmatic dynamic overshoot in the HST. This is a unique example, and it should become a case study of the dynamic overshoot blunder in the entire space program.

Consider the 93% change in the Secondary mirror load. Suppose the Hubble Telescope was placed on a truck and the truck was driven onto a wall so as to expose the Secondary mirror to nearly <u>twice</u> the design load. What would happen to the loads in all the other parts of the Telescope? The answer does not require any dynamic analysis. If the Secondary mirror were struck with <u>twice</u> the initially calculated design loads, then the Primary mirror, the sensitive solar panels, gyroscopes and other components in the Hubble would also be subjected to greater loads than the initially calculated design loads. Remember, all of these subsystems had to be fixed in orbit after deployment.

The following scenario is derived from the NASA technical Report, "*System Analysis Approach to Deriving Design Criteria (Loads) for Space Shuttle and Its Payloads*,"[17] which was written by several NASA experts and dated December 1981, i.e., after the first Shuttle mission. The first Shuttle mission is important because it allowed actual measurement, and not only calculations, of the surge forces. The NASA Report describes how teams of engineers, from the Johnson Space Center, the Marshall Space Flight Center, Rockwell International and elsewhere, developed the Hubble loads. The same confusion described in the next sequence happened before in the Shuttle design loads; see previous Sections.

1. The engineers know that the lift-off environment is critical for the Telescope design. They write:

   "*The Space Telescope is a very complex dynamic system designed to survive launch*," and "*the design loads are generally <u>launch derived</u>*," (*Ibid*, p. 77).

2. Unaware of the "dynamic overshoot" effect, the engineers incorrectly specify the Hubble in the 1970s to the static or steady state loads – just as was done with the Shuttle itself (see Section 5).

3. After the numerous experiences with the failures of their designs during 1977-1981, and after they managed to launch the first Shuttle in 1981, the engineers become aware that lift-off was the most critical event for Telescope design. They highlight this in one line that states,

   "*Liftoff is currently* (1981) *the primary design driver for most ST* (Space Telescope) *structure*," (*Ibid*, p. 83).

4. The engineers also become aware that the base bending moment at lift-off, which they designate M_y, is producing greater "transient responses" than anticipated. For a complete discussion of the base bending moment, see Sec. 8. Do you remember how the base bending moment for two boosters became the bending moment for one booster? The engineers write:

   "*The observed response was almost completely due to the launch release forces, <u>M_y</u> forcing function <u>being the primary driver</u>*," (*Ibid*).

5. The engineers show lack of familiarity with the start-up transient analysis. They believe that the loads rise up to only the 100% value. They know that transient responses oscillate. They do not know that the loads overshoot. They do not know that if there is no overshoot, there is no oscillation. They mix up the conflicting facts to produce the mediocre graph in Fig. 27. I added the 100% steady-state value to their Figure. By failing to identify the overshoot, the engineers attribute the problems to post-liftoff twang, or vibrations, than the pre-liftoff 100% overshoot.

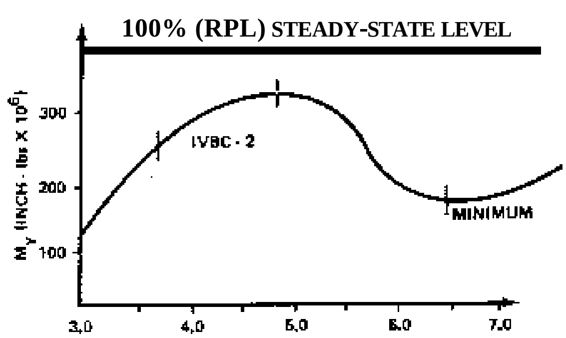


Fig. 27 NASA Transient Peak Falls Below Steady-State Static Value

6. The engineers note that the base bending moment M_y in their Fig. 27 is the "<u>primary driver</u>" for Hubble. As you see, the primary driver does not overshoot the 100% steady-state level, yet the curve in their illustration oscillates, which is impossible. So, when they discover that the Hubble Secondary Mirror

experiences nearly twice (or, 1.93) the initially calculated design loads, the engineers are puzzled. Do you see why? How could the load in the Hubble Secondary Mirror double, when their transient peak did not exceed the 100% level? How could the force in the Secondary Mirror overshoot when their TRANSIENT RESPONSE itself did not overshoot? Please, study this item carefully.

7. It does not occur to those engineers that the loads on the Primary mirror might also be nearly doubled, if only because that mirror is directly attached to the Secondary mirror. Instead, they search for ways to bring the insubordinate loads on the Secondary mirror to the seemingly obedient steady-state loads on the Primary mirror. They want to get rid of the insensible dynamic overshoot. They want to get rid of the overshoot, without even knowing that it exists! But first, they check to see if the Hubble Space Telescope caused its own woes!

8. The Shuttle-Hubble engineers write,

> "*Several avenues were explored as explanation of these changes* (i.e., the doubling of the forces on the Secondary mirror). *The first investigation centered on the change in the ST model by rerunning the loads, changing only the ST model. No change in trends was observed, thus removing the ST model as the reason for the increased loads,*" (*Ibid*).

9. Put the Telescope on the back of a truck, drive the truck into a wall, and measure the load on the Secondary mirror. Next, drive the truck at faster speed, strike the same wall and measure the load on the same mirror. The maximum load on the mirror is nearly doubled (193%). In the above quote, the engineers are wondering if the Telescope (and not the truck, or the Shuttle) caused the magnified loads. So, they rerun the Telescope computer models to remove the Telescope from being the cause of its own excess loads. Around that time, I visited a former colleague, Dr. Burton Edelson, then Associate Administrator for Science, at NASA headquarters. Burt was in charge of the Hubble and other major science payloads. There were many engineers, many graphs and many computer printouts all over the large office. The fuss was about the loads in the Hubble. I was a visitor, not a participant. Incredible coincidence as I write this Report ten years later.

10. So, if the Telescope did not cause its own "excess" loads, what did? The engineers write,

> "*A small glitch was found in the SRB forcing function, namely, the internal pressure versus time.*"

The sentence reveals the engineers' predicament with the correct transient analysis: The FORCING FUNCTION is the INPUT in a transient analysis. Unable to differentiate the INPUT from the OUTPUT, the situation of the Hubble-Shuttle engineers was hopeless. They treated the internal pressure as the INPUT and the OUTPUT! (See Sec. 5.3). I said repeatedly before that pressure does not overshoot. The engineers were looking at the non-overshooting pressure curves (INPUT) and wondering why the overshooting-forces (OUTPUT) in the Secondary mirror showed excess load. This one sentence by the Hubble-Shuttle engineers exposes the root of the confusion by everyone.

Do you remember Sir Isaac Newton and the apple? Newton gazes intently at the free falling apple, and he gives us the science laws to design the Shuttle and the Hubble. I said hook the apple to the end of a slinky. If you release the apple gradually, you get Newton's Action-Reaction law. If you release the apple suddenly, the slinky overshoots. Now, the weight of the apple is the unit-step-input in the transient analysis. The Hubble is not the counterpart of the apple. The Shuttle is not the counterpart apple. The structures of the Hubble and the Shuttle are parts of the slinky. Do you now see the confusion of the Hubble-Shuttle engineers? They suspect that a "glitch" in the internal pressure (or the apple) caused the near doubling of the force in the Secondary Mirror (or the slinky).

11. How did the Hubble-Shuttle engineers resolve the "*small glitch*" in their forcing function? How did they resolve the nearly doubled force in the HST Secondary mirror? You would not believe it:

> "*Smoothing out this glitch reduced the Z loads*," (p. 84).

Do you see the absurdity of their solution? They smoothed out the "INPUT" to the transient analysis! What does this mean? This is like saying that by smoothing out something in the apple, the dynamic overshoot in the slinky disappears! Suppose there is a warm in the apple. You core the worm out. Does this action on the INPUT cancel the dynamic overshoot in the slinky? It is really simple.

To get a better insight into the tricky situation, the reader can use the example of the 100-lb lady stepping suddenly on a weight-scale and causing a 93-lb overshoot. The "FORCING FUNCTION" is the pressure that the lady's feet apply on the platform of the weight-scale. The "pressure" is the INPUT. The transient OUTPUT is the total overshoot 193-lb force in the internal spring, and as appears on the dial of the weight-scale. The analogy is like this: The Hubble-Shuttle engineers stare intently at the 100-lb lady as she steps suddenly on the scale. They do not see the lady's 100-lb shape turn into a 193-lb shape. They recognize that the scale parts actually experience 193-pounds force. To eliminate the load amplification in the scale, they decide to smooth out something in the lady!

Is this lengthy and utterly trivial discussion necessary? Yes. You see, my concerns before the launch of the Hubble were dismissed, in my absence, with the argument that when a 100-lb lady steps suddenly on an old bathroom scale, the lady's weight does not double. Just read my lengthy and utterly trivial discussion above and make up your mind. The Hubble-Shuttle engineers' confusion over the INPUT and the OUTPUT in transient analysis has been made abundantly clear.

12. Finally, the Hubble-Shuttle engineers rationalize the irritating situation with the doubled load on the Secondary mirror as follows,

> "*This large load sensitivity to a small transient in SRB pressure was not intuitively realistic. It seems that rather the analytical procedure* (described above) *could be the cause of the problem by generating an unrealistic forcing function that tuned with the modes.*"

I beg the reader to review the last sentence carefully and repeatedly. This is a transparent intellectual alibi. I am not going to bother the reader with the elaborate normal modes analysis of the Hubble Space Telescope. How can the large transient load in the Secondary mirror not be intuitively realistic? The load overshoot in the old bathroom scale, in the slinky, and in the Secondary mirror should be intuitively realistic to everyone. The engineers decided that their analytical procedure (which we now know was completely wrong – e.g., a warm in the apple) produced the absurd large loads. Could they discard correct answers because the dynamic overshoot did not make sense to them? The reader should review the above sequence (1 through 12) again to clearly see the complete confusion over the dynamic overshoot effect. The confusion should be seen from the words of the Hubble-Shuttle engineers, and not from my words. I almost want to apologize to the Hubble-Shuttle scientists and engineers for being so harsh.

There should be no doubt in anyone's mind that:

1. The Hubble-Shuttle engineers did not know at all how to do correct start-up transient analysis.
2. The devastating dynamic overshoot effect was not considered in the design of the mirrors, structures and instruments on HST.
3. Numerous failures that happened in the Hubble after launch can be directly traced to the neglected dynamic overshoot effect.

Some pundits asked me, *"Why didn't the Hubble shatter irreparably during launch?"* The answer is given in the same NASA Report. The engineers write,

> "*External loads during the early design phase were to be of a max/min variety instead of time consistent. Also, it was decided to use an uncertainty factor on the external loads to cover changes in the Shuttle system forcing function and the Space Telescope dynamic model. This factor varies from 1.4 to 2.8 depending on the load station or hardware. Additional conservatism was introduced into the loads through the use of max/min loads instead of time-consistent loads.*"

Rather than derive and use the correct dynamic overshoot factors of 70-100%, the engineers guessed factors of 40-180% (i.e., their 1.4 to 2.8 factors). In doing so, they did not realize that the 40% factors were inadequate and the 180% factors were overkill. Many parts of the Hubble were saved not because of prudent design, but because of thoughtlessly added margins, or *"uncertainty factors."*

The same sequence described above happened with the other parts on the Hubble and with the other major science payloads. HST, Galileo, Magellan and the GRO observatories ran into serious and numerous problems after launch, and the missions were almost lost. Some satellites and space probes were completely lost. This Section reveals the deep-rooted and deep-seated confusion in the whole space community over the destructive "dynamic overshoot" effects.

During my meetings with the NASA managers at the Cape in October 1986, I met rational and sober people working in the space program. Bob Sieck, Director of Operations, had the formidable task of putting together thousands of parts that in the end make up the awesome scene of a Space Shuttle poised for lift-off on the Launch Pad. He often had the unpleasant task of explaining the goofs of others in the aerospace community. Subsequent to the initial release of this Report in January 1992, Sieck gave a sober account of the dynamic overshoot mistakes in a News Conference in March 1992. He described how the infamous fuel leaks that plagued the Shuttle in the early 1990s were transient-related. Tim Furniss, space correspondent from England, mentioned some of the dynamic overshoot mistakes in *Flight International* magazine. An excerpt from his article is given in Fig. 60.

The hydrogen leaks that grounded the Shuttle fleet, even after the extensive Challenger investigations, were caused by the same 100% dynamic overshoot described at length in this Report. I had tried so politely to eliminate the menace of the "dynamic overshoot" from the space program since the 1960s. By the time of the Hubble, I became fierce about it. It is so ironic that while Admiral Richard Truly and others were fiercely dismissing my "dynamic overshoot" assertions, the same blunder would ground the whole Shuttle fleet and, in my opinion, almost ruin the Hubble Space Telescope.

Is there a systemic problem in the Space Shuttle? Is there a systemic problem in the space program? Is the problem political, financial, operational, managerial or technical? The massive dynamic overshoot design error exceeds the built-in safety margins in space hardware. The dynamic overshoot error is the primary, and maybe the only, systemic problem in the space program. The aerospace-mechanical-structural-dynamics engineers must stand up and act to save the space program from the quagmire, into which they have driven it in the first place.

BY 1990, Ali AbuTaha made the dynamic-overshoot error known in the USA and abroad in lectures, courses and official documents. NASA and others began to take notice. Bob Sieck, Shuttle launch director, commenting on an earlier scrubbed launch at the STS45/*Atlantis* post-launch press conference on 24 March, 1992, said: "We scrubbed because of...transient leaks" during loading of the ET. "This was a transient-leak condition due to the thermal environment of the plate changing temperature during the first few minutes of the loading procedure," he added.

Analysing previous liquid-oxygen-tank loading, Sieck commented:"We expected to see the transients again, and we did." Loading of liquid hydrogen, using a different procedure where there is a longer cold-soak, resulted in "no leakage".

He was asked whether the "thermal transient" had occurred before. "When you really look at the data with a magnifying glass," he replied, the thermal transient "...had been there before on a number of missions".

Sieck says that the loading of the STS 45 ET had included loading the hydrogen "...in a slow fill...but we got the transient on the oxygen". Sieck was asked how much the thermal transient was. "The amplitude of the spike...was probably 100% more" than recognised before and he agreed that it had an effect on the "wear and tear" of parts.

This example of the dynamic overshoot is mirrored in sudden changes in temperature, pressure and voltage in aircraft, industrial and nuclear reactors — and the electrical industry.

Asked why fuses were being changed on the Hubble Space Telescope, a NASA spokesman explains that the agency had discovered that the original 3A fuses were inadequate and were replaced with 5A fuses.

When pressed, he says that, when the circuits were turned on, the current went up to 5A because of transient conditions before settling down at 3A — a 70% overshoot on the Hubble.

The Hubble launch was delayed for two weeks specifically while AbuTaha's claims were being analysed up to vice-presidential level, but NASA made the launch on the assumption that dynamic overshoot was understood.

Fig. 60 NASA Sober Account of Overshoot in Space Shuttle
***Flight International*, Jan. 1996**

10.7 A Challenger-like Failure Happened Before?

Yes.

The Presidential Commission (PC) investigating the Challenger accident generated more than 140,000 pages of write-ups. The massive record was eventually filed in the National Archives in Washington, DC. Did the investigators read those reports to connect the dots? No. Did the Shuttle engineers read and comprehend their own reports? No. Did the reporters who covered the investigation read the reports? No. It was in the massive record that I discovered the STS-3 Test Sheets which emphatically revealed that the dynamic overshoot for the SSME's was measured in 1982 to be 73% (Sec. 7), and not the wrong 1.6% used by NASA and Rockwell in 1972 (Sec. 5.1). The same Test Report revealed that the Shuttle engineers do not know how to do correct start-up transient analysis. There were other reports in the massive PC record that pointed to the neglected dynamic overshoot effect as the most likely cause of the Challenger accident and previous failures of the Shuttle and other space systems. There was a particular report in the PC record that described a 1983 failure in a solid rocket booster segment that was incredibly similar to the Challenger's booster failure. No one noted the relevant failure in the Challenger investigation or mention it in the media. The failure is described next.

The Shuttle boosters were initially designed for twenty (20) uses and, according to the engineers, the boosters' segments should have been <u>safe</u> after 80 uses. We noted before that the SRB segments failed "irreparably" after only one (1) mission, even after the Challenger accident. Does this not indicate that the wrong problem was fixed?

The boosters are normally recovered from the ocean, and the segments are tested for structural integrity before the next mission. Do you remember the *"widespread damage"* to the STS-6 booster (Sec. 10.4)? There were *"<u>cracked</u>, <u>broken</u>, <u>bulged</u>, <u>sheared</u>, <u>gouged</u>, <u>bent</u>, and <u>elongated</u>"* parts on that mission. All the segments of the booster, *"the Aft-, Mid-, and Forward-Sections,"* experienced damage. And all the damage occurred after the Shuttle engineers went all out with modifications to counter the cursed splashdown effects, even after their extensive analysis and tests told them that splashdown could not be the cause of damage. Look at what else happened to the same STS-6 booster segments.

During a 1983 test of one of the STS-6 booster's AFT segments (the same like the aft segment that failed on Challenger), a sudden failure occurred near the 330^o circumferential region while under internal *"<u>pressure rise</u>."* The test was conducted at Morton Thiokol facilities in Utah. The similarities of this failure to the failure of the Challenger booster's AFT segment are uncanny. The Utah accident caused considerable damage to the test building.

The following quotes give brief relevant description of the Utah accident from a 1983-84 investigation report[49], which I found in the National Archives:

> *On 10 October 1983, as part of normal refurbishment processing, a hydro-test of the aft segment assembly --- from STS-6B was conducted.* (Ref. 22, p. 11051)
>
> *The purpose of hydroproof testing is to verify that case segments are structurally sound for refurbishment and reuse -- Hydroproof pressure requirements are 1,055 (+30, -0) psi*
>
> *All seemed normal until the internal <u>pressure rise</u> passed through 690 psi. At that time a loud boom and fire occurred almost simultaneously;*" (Ibid, p. 11011).
>
> *The investigation team found that the <u>aft stiffener segment</u> --- had <u>burst at about the 330 deg position;</u>* Ibid, p. 11012)
>
> *The case under hydrotest <u>failed due to a crack</u> which occurred during the flight splashdown and the hydrotest proved the inadequacy of the case;"* Ibid, p. 11014)

Do you believe what you are reading? Do you believe that the above failure happened before Challenger?

Let us first get acquainted with the geometry and the parts involved in the Utah and the Challenger accidents. Fig. 58 (reproduced here again) shows the ET/SRB attach struts. The struts pass the SSME's thrust load plus the neglected dynamic overshoot load into the side of the boosters and down to the MLP. Fig. 61 shows the burned out area in the Challenger Right SRB Aft Center Segment. A crack in the Challenger SRB segment is clearly visible. The location of the burned out area in the Challenger RSRB stretched circumferentially from 291° to 320°, as shown in a NASA Sketch, Fig. 62. The SRB's Aft segments experience the brunt of the dynamic overshoot effects. The Aft segments were the culprits in the Challenger accident. I should point out that the Forward segments also experience the overshoot effects in the same general circumferential area. This is the area where the number of pins was doubled at the field joints (see Sec. 10.2). Doubling the number of the pins had nothing whatsoever to do with the O-ring seals and cold temperature. It had everything to do with the completely neglected, but consequential, dynamic overshoot loads.

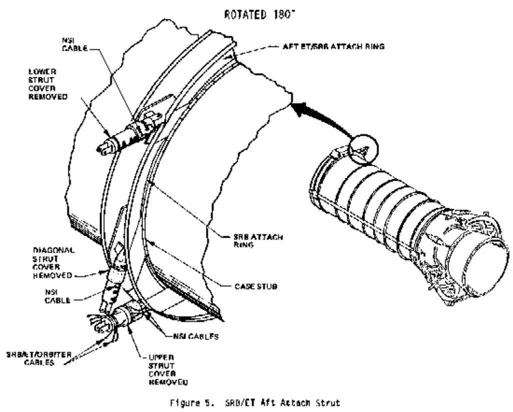


Fig. 58 SRB/ET Attach Struts

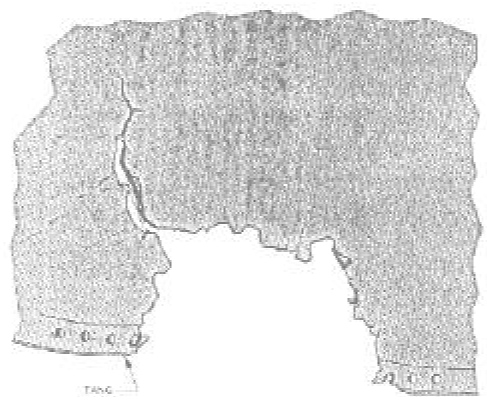


Fig. 61 Crack in Challenger Right Booster Aft Center Segment

One flight, and only one flight, the STS-6, rendered the booster aft segment useless. A crack in the failed booster segment was apparent to the investigators. The investigators blamed the failure on <u>flight splashdown.</u> STS-6 was the mission that the engineers made the all out effort to eliminate the mysterious "<u>splashdown</u>" damage. The repairs did not work because splashdown was not the problem. The booster segments that failed on Challenger and in the Utah test were hit hard by the dynamic overshoot. The engineers, and subsequently the investigators of the Utah accident, did not notice the missing and detrimental dynamic overshoot loads.

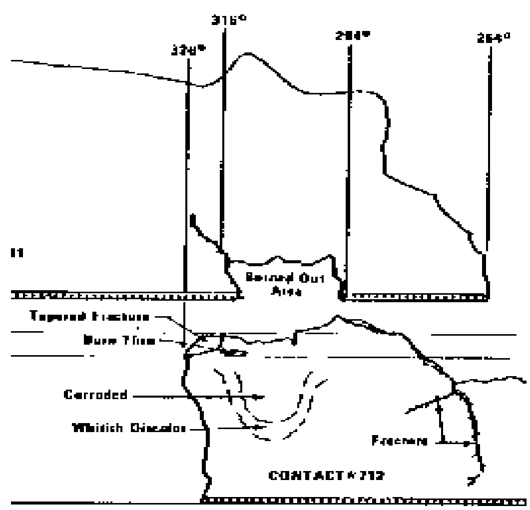


Fig. 62 Burned Out Area on RSRB Extends from 296° to 320°

Was the Utah test accident relevant to the Challenger accident? If I drive my car over a pothole and one of the tires explodes, then it is very likely that there is a connection between the pothole and the explosion. If I drive again over the same pothole and another (or the same) tire explodes, then there must be a connection between the pothole and explosions. The investigators of the Utah accident did not notice the relevance of the dynamic overshoot load to the accident. Nor was the Utah accident correlated to the Challenger accident later, even though the two failures compare in many ways. The correlation is straightforward and must be mentioned. The same segment, which was used once before in both cases, fails at the same moment of maximum start-up transient dynamic overshoot force in the same circumferential location causing similar damage. This is more than a mere coincidence. Table-14 gives a relevant comparison.

Table-14 Uncanny Comparison of the Utah Failure and the Challenger Failure

Utah Test Accident (October 10, 1983)	Challenger Accident (January 28, 1986)
Failure occurred in Right "aft stiffener segment"	Failure occurred in Right "aft stiffener segment"
Segment used once before	Segment used once before
Failure occurred during "pressure rise"	Failure occurred during "pressure rise"
Failure occurred during maximum transient loads	Failure occurred during maximum transient loads
Location of failure was "at the 330 deg position"	Same location of failure "291° to 320°"
Crack in the wall of the SRB case at 330°	Crack in the wall of the SRB case at 320°
Crack in location of maximum dynamic overshoot	Crack in location of maximum dynamic overshoot
Fire occurred immediately	Fire occurred immediately. Fire required filtering to overcome the glare of the bright day and the plumes (my other Challenger write-ups)
Joint rotation was not an issue at all	Joint rotation was the primary issue
Dynamic overshoot was not noted or reported	Dynamic overshoot was not noted or reported at all

It does not take a rocket scientist to see the similarities between the Utah Test failure and the Challenger failure. The Challenger right SRB Aft segment was driven over the same pothole that the STS-6 Aft segment treaded before. Police detectives would be publicly castigated if they ignored so many specific similarities in two cases. I have investigated many industrial and space failures since the 1950s, and I am amazed that the above specific similarities were not noted by anyone in the Challenger investigations. But then the Clerk in charge of the Challenger Records in the National Archives in Washington, DC, told me that I was the only engineer to visit the Archives and to examine the technical record. Perhaps, no one noticed the above similarities because no one read the massive record.

The Challenger failed booster segment required mechanical "rounding" to make it fit to the next segment. The mechanical force applied in the rounding process exceeded the pressure limit. The "out of round" shape of the Challenger booster segment was consistent with the excessive dynamic overshoot loads. The "out of round" condition was also consistent with the direction of the crack reported in the Utah test failure and the Challenger accident, Fig. 61. The "out of round" condition caused assembly problems over the years. Every mechanical-structural-dynamics engineer should know from elementary engineering courses that permanent plastic deformation does not occur if a part is correctly designed within the elastic limit. The Shuttle boosters were, supposedly, designed within the elastic limit and with safety margins, on top of that. The boosters' segments should have never experienced the "out of round" conditions. These are basic engineering facts. The "out of round" condition was not limited to the Challenger and the Utah test segments. There were "out of round" deformations in exactly the same 120°-300° axis direction on previous Shuttle missions, including, STS 51-B, STS 51-C, STS-51G, STS 61B, and STS 61-C (*Ibid*, p. 223). Excessive deflections are the result of excessive loads. Yet, the excessive loads were never suspected in the Utah, or the Challenger, investigations. I have delineated in this Report in plain words and with definite evidence the source of the mysterious and deadly forces.

11. Dynamic Overshoot, the Space Program and Me

Neglecting the destructive dynamic overshoot effect in design is the most likely cause of explosions, failures, lost missions, lost capital and above all, lost lives in the space program. The antagonism over the devastating mistake did not start between NASA and me only after my investigations of the Challenger accident in 1986. It goes back to 1970 and before, before the Space Shuttle Program began. The conflict involved co-workers and engineering faculty. The dynamic overshoot mistake was epidemic in the entire space program and the engineering curricula in the 1960s. I joined the aerospace-structural-dynamics design team in 1970 primarily because I detected and corrected the same mistake numerous times. In this Section, I will describe how my effort to wipeout the "dynamic overshoot" blunder from space design and engineering curricula began in the 1950s and lasted for five decades.

I worked temporarily as a mathematician with COMSAT Laboratories in 1969. I did mathematical and statistical analyses of digital transmission methods for satellite systems. In comparison, the transient mathematics you see on pages 8 and 9 of this Report was like child play. In the summer of 1969, the manager of the Digital Transmission Group, Dr. L. Golding, told me that mathematicians at Princeton University obtained different answers to a set of equations than I did. He asked me to go to Princeton to find out what was wrong with my work and to correct my analysis. I was given the Grand Princeton Tour: The walkway, the building, the hallway and the office where Dr. Albert Einstein walked and worked. I was impressed. The Princeton experts used a different method than I did. We spent hours examining both methods. In the end, we discovered that my solution was correct, and theirs was wrong. It was exhilarating. The story spread to the upper management at COMSAT. I was asked to work full-time with the Company and I accepted. Why did I leave the exotic mathematics to the mundane aerospace-structural design? The answer was the same dynamic overshoot blunder described at length in this Report.

In late 1969, COMSAT Labs was consolidated into a new facility outside of Washington, DC. Unlike the downtown offices, the new building has a large Environmental Testing Lab (ETL) area. In January 1970, I noticed a large crowd gathered around a very thick window at the end of the ETL. I joined the commotion. A test of a spacecraft fuel tank was about to begin. The experts were speculating whether the tank would explode or not. I watched. Pressure was applied remotely to the tank. A few moments of silence, then the tank exploded violently.

As had happened before in failures of space systems, the gathered experts speculated that (1) the material was defective, (2) the tank was damaged in transport, (3) the pressure setting was wrong, or (4) it was simply a random bad luck case.

I had experience with pressure testing in the family's factory in Jordan in the 1950s. I suspected that the dynamic overshoot struck the fuel tank.

Look at Fig. 63-A. The pressure was applied rapidly from zero to, say, 100 units. The material strength limit was, say, 25% greater than the maximum stress generated by the 100 pressure units. The pressure was less than the material strength. Why did the fuel tank explode? Thoughtful readers should by now know the answer. Just look at Fig. 63-B. The nemesis of the aerospace engineers, the same dynamic overshoot, was the likely cause of the explosion(s).

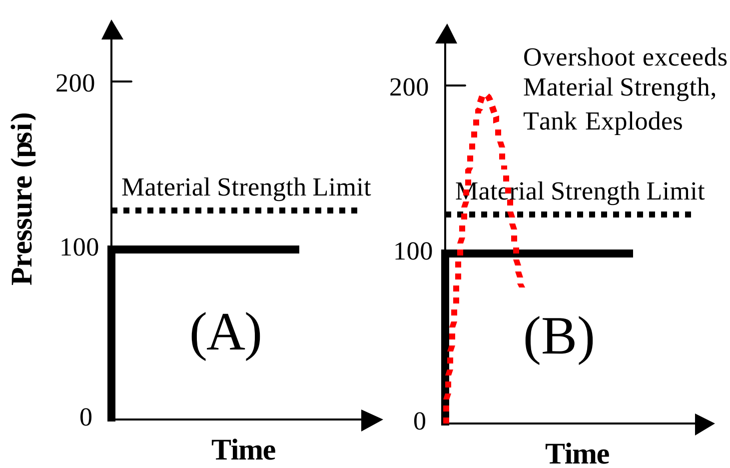


Fig. 63 Spacecraft Fuel Tanks exploded randomly in 1970. Notice <u>Peak Dynamic Overshoot</u> in B

I spoke with the manager of Spacecraft Dynamics, then James R. Owens, and explained how the start-up transient effect could explain the explosion that we witnessed, see Fig. 63-B. Owens asked if I would help to solve the problem. I was sent on loan from the Digital Transmission Group to the Spacecraft Group.

I began a series of tests and technical write-ups, e.g., Refs. 50 and 51, delineating important parameters in pressure vessel design. I included the start-up transient effect in the tests. I instituted my first dynamic overshoot test in the space program in early 1970. That eliminated fuel tank explosions altogether. I described the successful test steps in plain words in a COMSAT Inter-Office Technical Memo, TCLS/1222, dated July 22, 1970. In Section 10, I wrote:[51]

> **“***The pressure in the vessel is gradually increased to not more than one half of the test pressure. Thereafter, the test pressure is increased in steps of approximately one tenth of the test pressure until the required test pressure is reached.”*

My 1970 words are illustrated in Fig. 64, which shows the pressure steps that I used in the tests. The maximum possible transient response for each step is shown in Fig. 64-B. The peaks are the transient peaks. Notice that I did not eliminate the overshoot in this case. I simply kept the dynamic overshoot from exceeding the material strength.

The most dramatic result of the test procedure was that I would test the same fuel tank several times a day, and the next day, and so on; and the tank would not explode. The scientists and the engineers stopped gathering around for “the show.” Again, the managers were impressed with what I did, but now I was recruited to join the Spacecraft Structures Group.

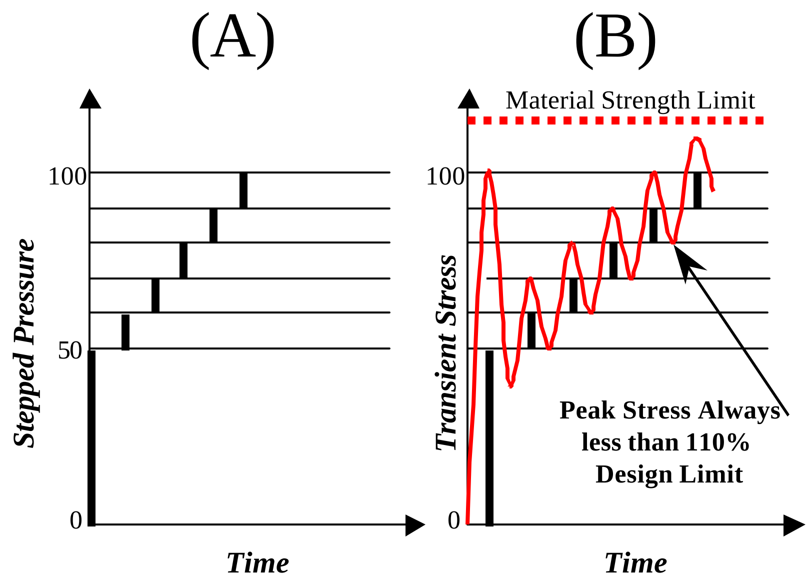


Fig. 64 Stepped Pressure Application Eliminated Explosions. Notice Peak Dynamic Overshoot

With the limited equipment in the new laboratory facilities, I could not measure the exact dynamic overshoot in 1970. That was why I used the conservative 100% overshoot factor that you see in Fig. 64.

I wanted to return to my mathematics job when the Apollo 13 accident happened on April 13, 1970. Oxygen Tank No. 2 blew up, almost killing the crew. My solution to the transient problem and the elimination of random explosions impressed the folks in the Spacecraft Labs. The relevance of my work to the Apollo accident was apparent to the managers. What happened to Apollo 13?

The official investigations blamed electric switches in a heater circuit inside the Oxygen Tank. Consider the chronology of events that happened to Apollo 13. James A. Lovell had finished the now familiar TV broadcast showing life in weightlessness at 55 hours 46 minutes into the mission. Next came the following events at the shown times. CapCom is the Capsule Communicator in the Control Center:[52]

55:52:58	CapCom: “*13, we’ve got one more item for you, when you get a chance. We’d like you to stir up your cryo tanks …*”
55:53:36	Oxygen tank No. 2 pressure begins rise lasting for 24 seconds.
55:54:00	Oxygen tank No. 2 pressure rise ends at a pressure of 953.8 psia.

The Oxygen tanks were sitting idle on Apollo 13. "Stirring up" the tanks sent the pressure rapidly to nearly 1,000-psi. This was followed by *"a sharp bang and vibration."* In Lovell's words:[52]

> "*Jack Swigert saw a warning light that accompanied the bang, and said, "Houston, we've had a problem here."*(Ibid, p. 249).

Did the dynamic overshoot play part in Apollo 13 explosion? CapCom asked the astronauts to *stir up* the tanks. The pressure rose rapidly. This is a transient situation. The situation is shown in Fig. 65. I am also showing in the Figure the possible dynamic overshoot in the Apollo Oxygen Tanks. Was the dynamic overshoot included in the design of the Apollo oxygen tanks? I doubt it. The same engineers, who neglected the dynamic overshoot effect in all Space Shuttle elements, designed the Apollo vehicle!

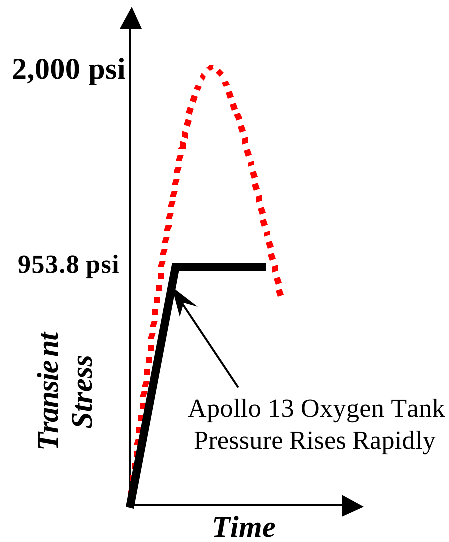


Fig. 65 Was Dynamic Overshoot included in Apollo 13 Tanks?

While NASA was trying to bring the Apollo 13 astronauts back safely in April 1970, I was asked to check out the stress analysis of all the parts of our upcoming launch, the INTELSAT III, F-8 satellite, the last satellite in that series. The launch was scheduled for early July 1970. The Contractor, TRW, had provided a large number of microfilms giving the stress analysis of every part on the satellite. I spent days and nights with the microfilms checking every calculation in the massive record. There is a solid rocket motor in the satellite, which is used to place the satellite in its operational orbit. Because I did not have the necessary clearance then, I was not allowed to examine the stresses in the apogee motor. Someone else did.

INT-III satellites provided the first global satellite network in July 1969, which allowed the whole world to see the first steps on the Moon, *live*. The first INT-II satellite was lost during apogee motor firing, and the next three launches were successful. Five INT-III satellites were successfully placed in orbit, but two satellites were lost during launch. Success was random, and so were the failures.

The green light was given for the launch of the F-8 satellite in early July 1970. For my efforts then, I was nominated to be a member of the Satellite Launch Team at the COMSAT Spacecraft Technical Control Center. I monitored pressure, temperature and other readouts on that satellite. NASA launched the satellite on a Long Tank Delta rocket, and handed operations of the satellite to us. For two days, all went well. On the third day, we prepared for apogee motor firing. Normally, the apogee motor fires for 33 seconds. There was silence in the control room when the motor ignited. All seemed well for 11 seconds. Then all data, and the satellite, disappeared. The frantic search for the satellite well into the night was in vain. Another satellite lost. Did the dynamic overshoot strike again?

Is this dynamic overshoot the cause of all space failures? Not really. Many unforeseen problems surfaced in launch vehicles and payloads in the 1960s and 70s. Many problems had nothing to do with the dynamic overshoot. NASA, COMSAT, DOD, the industry and academia brilliantly solved almost all of the other problems. But somehow, the start-up transient problem continued to stymie the engineers. I really thought that I would make a big difference in this area. The reader should note the similarity in the cases discussed above, and the previous cases involving the Space Shuttle. The pressure rises rapidly to a maximum value. The scientists and the engineers measure the pressure. The pressure does not overshoot. The experts think there is no overshoot. But, the forces in the system overshoot.

Operationally, the apogee motors in the satellites are similar to the Shuttle boosters, booster separation motors (Sec. 10.3) and the toy rockets (Sec. 4). You saw how the dynamic overshoot for the model rockets is nearly 2.0 (100% overshoot). You saw how NASA used a dynamic overshoot factor of 2.0 (i.e., a 100% overshoot) for the BSMs in 1990. How about the satellites' apogee motors? Was the dynamic overshoot included in the design of the apogee motors?

Typical pressure-time and thrust-time traces for one apogee motor are shown in Fig. 66-A.[53] Here, you see the ***pressure*** traces on the left, and the ***force*** traces on the right. The start-up transient Input (or Action, Cause, or Forcing Function) in the left traces and the transient Output (or Reaction, Effect or Transient Response) in the right traces are identical. How can that be? Where is the dynamic overshoot? It does not exist. The same Contractors who manufacture the Shuttle SRBs also manufacture the apogee motors. In Fig. 66-A, you see the same mistaken trend that I described repeatedly in this Report. My co-workers and the other engineers simply convert pressure readouts to force values, incorrectly showing 0 (zero) start-up dynamic overshoot.

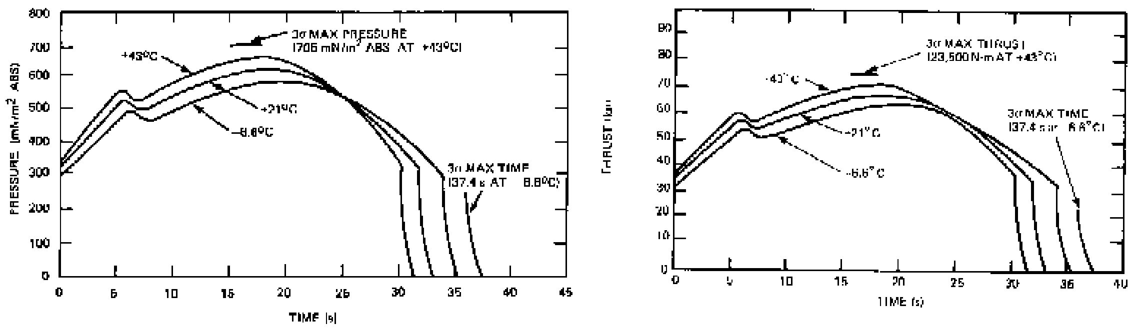


Figure 56. *Chamber Pressure vs Time*

Figure 55. *Vacuum Thrust vs Time*

Fig. 66A Thrust Curves for INT-IV Apogee Motors (on right) show no Dynamic Overshoot. Notice in particular how pressure and force curves are identical.

The start-up dynamic overshoot is short lived. It happens suddenly, and then disappears. How should the correct Transient Response for the apogee motor look like? I show the start-up dynamic overshoot for this apogee motor in Fig. 66-B (red dashed line).

Notice how the burn pattern for the apogee motor is arranged such that the peak occurs midway through the burn. The dynamic overshoot is slightly greater than the peak pressure (or thrust) at the midway-burn-point. The middle peak barely corrected for the dynamic overshoot effect, but the engineers could not bring themselves to add the start-up dynamic overshoot effect outright. You see their "3σ MAX" dynamics for the non-overshooting pressure and the overshooting force in their figures!

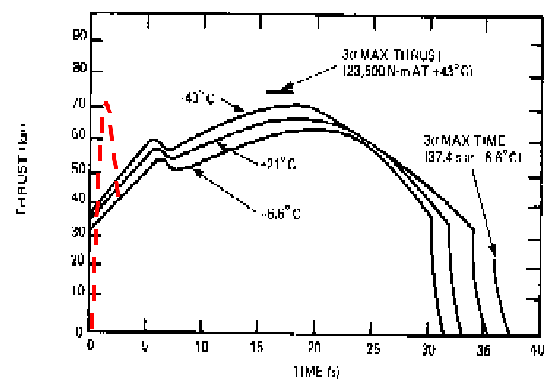


Fig. 66B INT-IV Apogee Motor Thrust. *Overshoot Added*

In the short period of six months, January to July 1970, I ran into the dynamic overshoot blunder in the space program at least three times: This apogee motor, the Apollo oxygen tank explosion, and the satellite fuel tank test explosion.

To a mathematician, the random explosions of rockets in the 1950s and 60s did not make sense. When the mathematics is done correctly, things work smoothly. Just look at quantum mechanics. Even though the phenomena involved are not clearly understood, the correct mathematics has led to phenomenal successes. In 1970, I really thought that I had identified the root cause of the random explosions and failures that haunted the space program from the beginning. I finally left my favorite mathematics work and joined the Spacecraft Structures Group. My primary responsibilities included material testing and the stress and structural analysis of all spacecraft and earth station equipment, as well as supporting dynamic analyses and design. In the next years, there were too many projects to do. Interspersed in these, I would find the dynamic overshoot mistake, correct it, report it and move on.

The Communications Satellite Act of 1962 created COMSAT. President John F. Kennedy appointed Dr. Joseph V. Charyk to become the first president of COMSAT in 1963. I first met Dr. Charyk in the Technical Control Center after 2 a.m. on the night that we lost the INT-III F-8 satellite in July 1970. Everyone in the Control Room was upset about losing the satellite. Charyk's presence had a calming effect on all of us then. In 1974, I had a long conversation with Dr. Charyk and David Nye, then Vice President of Personnel, in my office at the Labs. The theme of the conversation was how the large mistakes were doing more damage in our work than the small mistakes. Of course, the 70-100% start-up transient dynamic overshoot mistake was on my list. Work in spacecraft design was slowing down, as it was going to take three years before the Space Shuttle was ready to launch satellites. Dr. Charyk asked if I would spend a couple of years in the earth station segment to see if I could find other "big" mistakes. He asked Nye to make the transfer arrangement to COMSAT headquarters. There were big design mistakes in the earth stations from Maine to Hawaii and abroad, which I detected, analyzed and corrected. You can be sure that the start-up dynamic overshoot was often missing in the specifications and design of those systems as well! And everyone around the world made the same mistake.

In 1977, I returned to work in the space segment and I began to prepare for the upcoming Space Shuttle launches. That was when serious problems hit the Shuttle hard, e.g., the tiles problem in Sec. 10.1. NASA and the contractors struggled to solve the mysterious problems that hit the Shuttle unexpectedly. I left my good aerospace job in 1978 primarily because of the Shuttle problems. Afterwards, I managed other hi-tech systems and did advanced research.

The dynamic overshoot mistake is bizarre. The start-up transient dynamic overshoot is the simplest dynamics problem encountered in the design of launch vehicles, satellites and other payloads. Yet, the mistake is widespread.

During liftoff and powered flight, a launch vehicle and a satellite are subjected to complex dynamic conditions, including, sinusoidal, random, shock and acoustic vibrations at low and high frequencies. The satellite and its rocket are subjected to varying shocks at liftoff, MECO (Main Engine Cut-off), SECO (Secondary Engine Cut-off), wind conditions, and pyrotechnic separations. There are also the POGO, CHUGGING and other complex dynamic conditions that accompany rocket staging. Almost all of these events amplify the 1g loads on the satellite and the launch vehicle. The loads amplifications are painstakingly estimated analytically, with computer analysis and experimentally. NASA and ESA (European Space Agency) provided us with the load amplification factors for the launch vehicles, e.g., Delta, Atlas-Centaur and Ariane. The load amplification factors ranged from 1.5g - 2.0g at liftoff to 8g, 10g, 12g and greater values for staging, such as, MECO and SECO. The load magnification factors were given independently for the axial and lateral directions. In addition to the magnification factors, there were also the frequency bands in which the load amplifications applied. I developed stiffness models of the whole satellite and calculated the fundamental frequency for every component on the satellite. Many design parameters were driven by the requirement for minimum natural frequency, than by the strength of material. "Dynamics" is very complex and highly advanced.

The reader would note that I have not said anything about the complex dynamic conditions mentioned in the previous paragraph or the load amplification factors associated with the above dynamic conditions. That was done purposely. What the experts, particularly the dynamics experts, failed to recognize so far is that the start-up transient dynamic overshoot problem is not even a dynamics problem. It is a static problem. I almost want to call it: The start-up transient static (and not dynamic) overshoot blunder!

When a load placed on a surface, just touching the surface, is suddenly released, say on a table or a structure, the load and deflection in the table or structure are magnified. When the problem is solved statically, as I have shown with Shigley's equation in Section 4, the load and deflection are found to be double the values than if the load were gradually applied. Shigley solved the problem for a load released from a height, h. He then set the height to equal zero, $h = 0$. The result is Eq. (1), Section 4, Page 8 of this Report. There are elegant mathematical steps to derive Shigley's doubling equation directly from the basic laws of physics, but the physicists have not bothered with it yet.

When I would demonstrate Shigley's equation in the silly form F = 2F, or 1 = 2, the professors would call it a prank. They actually considered that to mean that I did not understand the trivial Law, *"To every action, there is an equal and opposite reaction!"* I ended up with high grades in complicated engineering subjects, e.g., aerodynamics, thermodynamics, elasticity, electronics, etc. But, I was failed in the elementary courses of mechanics and introductory physics. I was not able to impress on the faculty basic flaws in some laws of science and engineering in the 1960s.

If a design mistake exceeds the safety margins, the system fails. When a design error exceeds the safety margins, the mistake is *huge*. The dynamic overshoot in the satellite fuel tank (Fig. 63-B) exceeded the built-in safety margins. The tank exploded. The cause of the explosion was the neglected dynamic overshoot load. That's what the numbers showed. The fuel tank did not explode because of material defects (hunch), transport damage (hunch), wrong pressure setting (hunch), or bad luck (intellectual alibi). I eliminated the random failures of the fuel tanks by eliminating the root problem. No savvy in science, engineering, management, operation, maintenance, finance, politics, psychology, sociology or philosophy could have eliminated the random explosions. Fix the root problem, and the problem disappears.

Somehow, my career in the space program was accentuated by finding the "big" mistake. The dynamic overshoot was but one blunder I uncovered. I included several "big" mistakes in my short engineering course, *"Anatomy of Failure Mechanisms in Modern Systems,"* which I gave on campus and at public, private and military centers at home and abroad. How do you catch the "big" mistake? The failure of the satellite fuel tank was easy. The tank exploded. That was a clear sign of a huge design mistake. Suppose the tank did not explode? Many experts would have considered the test a success. But, how can you tell if there is a huge design mistake in a space system, especially, when the system does not explode outright? Just look at the operational history of the system. If the operation, maintenance and management teams are overwhelmed with nonstop technical difficulties, then it is very likely that there is a "big" design mistake. In Section 10, I included only some of the problems encountered with the Space Shuttle over the years. These were big problems. There was a "big" mistake in the design of the Space Shuttle.

Solving the start-up dynamic overshoot mistake in space systems was the main reason I remained in the United States and became a U.S. citizen. In the 1970s, I reported the dynamic overshoot blunder and other problems in space systems through the chain-of-command. Did the managers forward my findings to NASA, DOD and others? Subsequent events would show that that was not done.

On the morning of January 28, 1986, the Challenger exploded, killing the seven astronauts on board.

What happened?

The Report of the Presidential Commission became available in June 1986 and I examined it carefully. The Commission blamed the tragedy on the rubber O-ring seals in a booster joint (see Fig. 38). I could calculate the joint rotation of the stricken booster, and I did. At liftoff, joint rotation is insignificant. The rubber O-ring seals could not be the cause of the tragedy. I also discovered from film footage, wreckage and metallurgical evidence that the O-ring seals failed in flight: Eight seconds after liftoff. These are described at length in my other write-ups. If the O-ring seals did not cause the Challenger accident, then, what did?

Many disciplines are used in aerospace design, and I am not an expert in many of those subjects. Forces, stresses, strains and deflections of aerospace structures are my primary area of expertise. As to the start-up transient forces in space systems, I was probably the only space expert in this subject in the 1970s. I was shocked to discover that the destructive dynamic overshoot loads were badly mishandled – and even completely missing in the design of the Shuttle and from the Challenger investigations. There was no dynamic overshoot included in the thrust of the engines, the boosters or other thrusters. There was no dynamic overshoot included in the axial or shear forces or stresses. No dynamic overshoot was considered for the notorious joint rotations and O-ring seals. There was no dynamic overshoot in any system that experienced sudden start-up. It was as if the scientists and engineers had never heard of the destructive dynamic overshoot effect. Do you remember what Rockwell told the Congress in 1972, long before the Challenger tragedy? From Page 12 of this Report:

> *"So we have to do a loads and weights iteration on the static loads without the dynamics involved and then just put a factor in for what we think the dynamics are going to be."*

The Space Shuttle ended up being a static machine, even though the dynamics engineers produced brilliant solutions to many complex dynamic conditions that the Shuttle encounters from liftoff.

The strength of the tiles on the Orbiters was doubled in the late 1970s (Sec. 10.1). The tiles were not strengthened because of any problems with the O-ring seals. The number of pins near the attachment of boosters to ET was doubled in 1984 (Sec. 10.2); and the strengthening was not dictated by problems with the O-ring seals. The base bending moment was doubled (Sections 8.2-8.5), but not because of the rubber O-ring seals. The booster separation motor's design thrust was doubled in the 1990 specification (Sec. 10.3), but not because of any problems with the O-ring seals. The O-ring seals' design did not cause the massive 20-foot long cracks in the Mobile Launch Platform (Sec. 10.5). The booster parts in the Sixth Shuttle mission (STS-6) that *"cracked, broke, bulged, sheared, gouged, bent, elongated or failed in tension,"* (Sec. 10.4) did not fail because of any problems with the O-ring seals. The uncanny failure during test of the same STS-6 booster segment in Utah in 1983 in almost identical manner to the Challenger booster failure (Sec. 10.7) was not related to the O-ring seals. The design load for the Secondary Mirror on the Hubble was not doubled (Sec. 10.6) because of the O-ring seals. The O-ring seals did not cause the effect of thrust build-up at liftoff to nearly double, as measured by the Shuttle engineers in 1982 (Sec. 7). And finally, I did not fabricate any of the numbers or evidence mentioned in this paragraph, as some experts later insinuated.

In June 1986, I did not have any of the evidence mentioned in the previous paragraph. Relying on the numbers published by the Rogers Commission, I determined that the liftoff loads, particularly the loads in the struts that connect the Orbiter to the External Tank to the boosters, were a mess. My initial contacts with engineers from NASA led me to attribute the great disparity in the Challenger loads to extraneous causes. I proposed that roll out and the sharp turn that the Challenger made to Pad 39B were the source of the inordinate forces. As late as September 1986, astronaut Bonnie Dunbar would assure me that the struts were not preloaded. Dr. Dunbar then arranged for me to speak with other NASA engineers. I discovered from discussions with experts from JSC and KSC that the struts were preloaded before liftoff! The forces published by the Commission for the struts did not represent the forces generated by the engines and the boosters at liftoff. That changed everything.

With or without preloads in the struts, something was terribly wrong with the liftoff loads for the Challenger. The "preloads" in the struts caused great confusion, to me and to the NASA engineers. We were as confused as the 100-lb lady I mentioned on Page 44, which is reproduced here:

> *"Suppose the weight of the lady gets out of hand and she reaches 175-lb. She finds this rather upsetting. To comfort herself, she sets the adjustment knob on the scale so that the dial reads –75 (minus 75) lb. Now, when she checks her weight, she sees the familiar, or desirable, 100-lb weight. In essence, the lady is putting preload in a spring. If she now steps suddenly on the scale, things will get very confusing. The overshoot reading will not be 200-lb, as she would have desired. The overshoot reading will not be 350-lb, which is the correct peak overshoot, if she did not preload the spring in the weight-scale. The peak overshoot she will see on the dial will be 275-lb. This value has nothing to do with her desired weight, 100-lb, or her actual new weight, 175-lb, or the correct maximum overshoot, 350-lb, or the desired overshoot, 200-lb. Of course, with the exception of the preloaded spring, all the other parts in the old bathroom scale will be subjected to the full overshoot, or 350-lb. I use this example because after I discovered, in 1986, that the engineers preload the struts that connect the External Tank to the SRBs, the haphazard loads in the struts finally made sense."* (see Page 44).

The preloads in the Shuttle struts camouflaged the massive dynamic overshoot mistake.

My rollout solution for the Challenger was upsetting to many engineers. I was charging them with making design mistakes of the order of 20-40%. I did not know that the struts were preloaded. When I subtracted the actual preloads from the messy loads in the struts, the dynamic overshoot blunder became crystal clear. Now, I was accusing the engineers of making huge design mistakes of the order of 70-100% in an important national asset, the Space Shuttle. Many were annoyed.

Some NASA officers took my work seriously in 1986, e.g., Burt Edelson, Michael Weeks, Horace Lamberth, Cecil Houston, Bill Goldsby and Bonnie Dunbar. After I identified the "dynamic overshoot" mistake in the Shuttle with specificity, I was asked to work with, or for, the space agency immediately to deal with the start-up transient dynamic overshoot problems in the Space Shuttle. It was ironic, I thought. Again, I was asked to work on the same enormous "dynamic overshoot" mistake that led me to change the plans of my life, to remain in the U.S. and to work in the space program in 1970.

Other NASA officers insisted that the dynamic overshoot problem was a figment of my imagination. Admiral Richard Truly, Bob Crippen, Bill Lenoir and others dismissed the start-up transient overshoot problem in the Shuttle in writing. The invitation to work with NASA in 1986 was canceled.

Between 1986-89, I thought that NASA overhauled the dynamic overshoot mistake in the entire Shuttle. It is true that the design load was doubled in some Shuttle parts before 1986 without input from me. But, the mistake is systemic. The excess forces strike everything. Doubling the strength of the Shuttle parts piecemeal did not address the root problem. Think about it. When the lower segments of the boosters were strengthened in the early 1980s, the "EXCESS UPWARD FORCE" did not disappear. The forces were unknowingly chased away to other parts of the Shuttle. When the tiles' strength was doubled in the late 1970s, the amplified forces were unwittingly steered away to the other parts. And so on.

There are well-developed optimization techniques that are used in design. The strength of a complex structure can be doubled without doubling the weight. By doubling the strength of different parts of the Space Shuttle piecemeal, the engineers fell into two traps; (1) The payload weight penalty was high, and (2) the safety of the system deteriorated – if only because the "excess forces" were concentrated into other unknown parts of the system.

In 1989, I was upset that NASA precluded me from participating in solving the serious problem that I had identified in Space Shuttle design in 1986. Did NASA correct the dynamic overshoot mistake in the Shuttle during the recovery period, 1986-89?

In a Hearing at NASA in October 1989, I was surprised to see the NASA illustration of the Shuttle base bending moment (see Fig. 29, Sec. 8.4, Erroneous Illustrations). The Shuttle engineers did not even know how to illustrate the "start-up dynamic overshoot" as late as 1989. What happened between 1986 and '89? Massive Space Shuttle Loads Specification Books were released in early 1990. Again, I examined thousands of pages and thousands of numbers and discovered that the engineers were still in the dark about this dynamic overshoot effect. The NASA administrators, directors, managers and engineers who recognized the nature and enormity of the dynamic overshoot blunder, as I explained it in 1986, were no longer with the space agency.

I sought support from my former co-workers and the faculty of engineering at my *alma mater*. My solutions of 1970 and advocacy in the 1960s to eliminate the dynamic overshoot problem from aerospace systems were lost on almost everyone. Despite glaring evidence, my former professors in the School of Engineering and Applied Science (SEAS) at the George Washington University (GWU) mocked the idea of the dynamic overshoot blunder in Space Shuttle design and, even, in their teaching methods. On seeing the evidence in this Report, their red faces told another story. It turned out that the University had a five million dollar grant from NASA, and they could not risk that grant by getting involved! Other universities with aerospace departments also declined to participate to eliminate the blunder from aerospace systems and curricula. As to my former co-workers, most of them, particularly the aerospace-structural-dynamics experts, declined to get involved in the controversial issue.

It would take volumes to describe my effort on the "dynamic overshoot" blunder between 1989 and '92. I spent more time in the library at my *alma mater* than in the classrooms in the 1960s. I returned to the massive library and began systematic examination of textbooks, periodicals, journals and proceedings.

What I found out was alarming. Not one textbook on aerospace structural design described or explained the destructive phenomenon. The same was true of textbooks on aircraft and spacecraft propulsion systems. I could not find any mention of the destructive "dynamic overshoot" effect in the lengthy write-ups of Robert Goddard or the writings of Wernher von Braun or other national or international space celebrities. The peer-reviewed journals completely neglected the subject. The most disturbing finding was that the "dynamic overshoot" blunder was pervasive in the design of nuclear reactors. Here, I discovered that physicists from all over the world actually met biannually to examine the "pressure start-up transient" problems in nuclear reactors. In hundreds of published papers, the pressure-time curves and force-time curves were similar. The physicists, like the Space Shuttle engineers, convert the pressure to force and think that they are doing transient analysis (please read Section 5.3 again)! To those scientists, the CAUSE, ACTION, INPUT and FORCING FUNCTION are similar to the EFFECT, REACTION, OUTPUT and TRANSIENT RESPONSE! I contacted the physicists. Now, I was trespassing on the holy grounds of physics. Everyone got upset. Ironically, an elegant mathematical proof of the start-up doubling effect comes from the laws of physics, but the effect is not even described in physics textbooks. Perhaps, on reading this Report, a young physicist will step forward with the elegant "physical" mathematical solution.

During 1989-'92, I took the dynamic overshoot mistake to almost every professional organization and government office that was involved in space and defense systems. Wright-Patterson Air Force Base requested a briefing and sent an officer to visit me. We spent a full day reviewing the dynamic overshoot mistake, as described in this Report, and advanced applications of the effect, which are not described in this Report. The Captain from Wright-Patterson was very impressed. Senior scientists from Edwards Air Force base invited me to prepare lectures on the effect. The outrageous mistake in Shuttle design and the evidence astounded congressional aides. Pilots and aircraft crash investigators were also astounded by the enormity, and simplicity, of the mistake. Hundreds attended my short engineering course, *"Anatomy of Failure Mechanisms."* The skeptics, who initially dismissed the notion of a massive engineering blunder in Space Shuttle design, became believers. In the 1950s and 60s, I suspected that the dynamic overshoot mistake was the primary cause of explosions of rockets. Now, I was certain that the dynamic overshoot effect was the primary cause of many failures in the space program.

The late Wilbur (Bill) L. Pritchard was the first director of Comsat Laboratories. He was a recognized national and international leader in space and defense communities and he had impeccable credentials in satellite technology, science and electronics. Mr. Pritchard conceived, formed and chaired the first Direct Broadcast Satellite (DBS) Company. He was familiar with my successes in mathematics and aerospace design, including the detection and correction of the transient problems in aerospace and complex antenna structures since 1969. There were several tiers of management between Pritchard and me at Comsat Labs, but he had given me specific technical tasks to do; and I know that he was pleased with the results. I discussed the "dynamic overshoot" blunder in Space Shuttle design at length with Bill.

I mention Mr. Pritchard in this Report on the "dynamic overshoot" blunder for a reason. He received many honors from many reputable organizations, including NASA. Many people, including our former colleagues, do not know that he was instrumental in wiping out the same destructive "dynamic overshoot" mistake from electrical, electronics, and communications systems. Bill began his career in 1943. He was adept in mathematics. During World War II, he recognized that many failures of electrical and communications systems were due to the start-up transient effect. Pritchard told me how he spent days in a hospital in Italy during the war working out the mathematics of the start-up transient problem. He later gave me 20-pages of handwritten mathematical analysis that he wrote on old Raytheon Manufacturing Company stationary. I recognized the analysis and the correct sketches of the doubling overshoot effect. Pritchard was surprised that the dynamic overshoot effect would occur in the structural elements of the Space Shuttle. The mathematics was straightforward, and he was very familiar with it. He was not a structural engineer; I was. He found the numerical evidence compelling. He described the implications of the mistake in Shuttle design as *"frightening."* Pritchard's opinion on the dynamic overshoot blunder was valuable.

Pritchard suggested that I publish a technical paper on the dynamic overshoot problem in the Space Shuttle to explain the effect to the rank and file in the aerospace communities. I wrote a technical paper, *"The Space Shuttle: A Fundamental Oversight,"* and I used the base bending moment as illustrative example (see Sections 8.2-8.5). Pritchard was a top arbiter in the publication of hundreds or thousands of technical papers, particularly in space systems. He edited my paper, and so did the Chairman of the Dynamics Committee of the American Institute of Aeronautics and Astronautics (AIAA). I incorporated the comments of these top experts and submitted the paper for publication in the AIAA *Journal of Spacecraft and Rockets*.

Past experience had taught me that the engineers would feel insulted by my thesis. In the paper, I tried to lessen the enormity of their mistake by using the minimum base bending moment value and by excluding the chaotic values listed in Table-13 of this Report. I did not mention other cases when the engineers doubled the design load in different parts of the Shuttle. It was like dealing with spoiled children.

What happened next was surreal.

Four anonymous peer-reviewers rejected publication of my paper and, in their comments; they insulted me outright, professionally and personally. I was upset and that led to litigation.

Several senior professionals wrote letters and affidavits and made many calls to try to get my paper published. In a letter dated April 3, 1991, Pritchard wrote to the Editor of the *Journal of Spacecraft and Rockets*:

> *"At this point, in view of the importance of the issue, and in recognition of Mr. Ali AbuTaha's respectable credentials as a member of the space fraternity, this paper should be published. If indeed he is right, and there is some reason for thinking that he might be, then the implications of refusing to publish it in the event of any further shuttle disaster are frightening, indeed."*

Subsequently, on August 1, 1991, Pritchard prepared a sworn affidavit, in which he wrote:

> *"I was much interested in his ideas and found them to be plausible and consistent with my knowledge of the physics involved,*
>
> *… much of the theoretical side of his case is based on the dynamic theory of vibrations which appears in many disciplines; and indeed the differential equations that form the basis of this theory had their origin in electrical engineering, thus the general ideas were familiar to me and Abutaha's case seemed plausible*
>
> *… I am anxious to have his work published and debated openly. I can see little reason for not publishing it, and many reasons for going ahead with it. Perhaps most important is to avoid the faint aroma of cover up that is drifting across the atmosphere."*

The full text of the above letter and Affidavit are included in Appendix A.

Pritchard's words show that the problem is not about the mathematics of transients. The problem is in the perception of what the analysis mean. I remember the moments of anxiety every time we started large electro-mechanical equipment in the family factory in Amman, Jordan in the 1950s. There was always fear that the equipment would fail at start-up. Once the equipment survived the start-up hurdle, all was well. This must be familiar to many old hands. Today and daily, we start up a multitude of electrical, electronics, and communications equipment, and we don't fear the start-up surge failures. Operating electronics and communications equipment, as Pritchard said, would have been a mess if the electrical, electronics and communications engineers continued to neglect the "dynamic overshoot" effect. I mention Bill Pritchard and his support of my work to honor him for his vital role in eliminating the start-up transient dynamic overshoot problems in electrical, electronics and communications systems.

The anonymous peer-reviewers wrote that they had doubled the base bending moment value before my paper. That was a fact! They then used that fact to dismiss the paper. The purpose of my paper was to show that the engineers did not realize the reason for doubling the base bending moment in the first place.

They had doubled the strength of the Shuttle tiles, doubled the number of pins in the SRB-ET attachment, doubled the number of stiffeners in the lower booster segments, and doubled and doubled the design loads over the years; piecemeal. The engineers did not realize why they were doubling the design loads. But the peer-reviewers and their supporters succeeded to dismiss my paper summarily.

I wanted a showdown with the anonymous peer-reviewers, at the White House, the Congress, the Federal Courts, or at NASA, or on-campus, on television or any other forum. The unidentified peer-reviewers disappeared and I was told to go to hell. It may still be instructive to have the showdown here.

I said that the Shuttle engineers shifted the base bending moment (torque) value on two boosters to one booster. I said that they doubled the torque without knowing why. You can see the details of my allegations in Sections 8.2 – 8.5. The evidence was in the "force" value that the engineers used, and not in the "torque" value! They doubled the torque, but not the force that produced the torque.

Suppose you use a wrench to apply 1-lb force at 1-inch distance. What is the torque?

1 LB X 1 IN = 1 IN-LB

Suppose you could measure the torque, but not the force. Suppose you measure a torque of 2 inch-pounds for an unknown force applied at a 1-inch distance. What is the force?

? LB X 1 IN = 2 IN-LB

The unknown force (? LB) is 2 lbs. The only way one can get 2 in-lb torque at 1-inch distance is if the force is 2-lbs. There is no other way. The peer-reviewers produced evidence that they used 2 in-lbs torque before my paper. But, what "force" value did the engineers use in the Shuttle specifications? What force value did the Shuttle engineers give to the Rogers Commission to investigate the Challenger tragedy? One pound (1-lb)! And no one recognized the blunder.

At some point, the Shuttle engineers measured the torque to be the doubled value, 2 in-lbs. Then in 1982, they measured the liftoff force on STS-3 (the third Shuttle mission). Why were they measuring the force in 1982 anyway? The liftoff force should have been known from the beginning. Not knowing about the dynamic overshoot, in their minds or on a scratch pad, things looked to them like this:

1 LB X 1 IN = 2 IN-LB???

It was here that the Shuttle engineers wrote their "*plans to resolve problem*," see Fig. 17. It was here that the engineers asked the highest technical level at NASA to verify that the calculated loads for the SSME's were 1-g; in plain language, the engineers asked, was the force from the SSME's 1-lb? It was here that the Shuttle engineers revealed their complete unfamiliarity with the physical dynamic overshoot effect. But, the blunder was more profound than I had shown with the 1982 Shuttle force measurement.

The NASA 1982 STS-3 test is the most important dynamic overshoot measurement in the history of the space program. Let me explain why that measurement (Fig. 15) is unique. Engineering is applied science. The science is physics. The tool is mathematics. Mathematics gives numbers. The numbers must be verified by tests. Here is a question:

What is the dynamic overshoot force for the Shuttle engines' start-up thrust that propagates through the Orbiter's aft compartment and fuselage through the struts (connecting the Orbiter to the External Tank) through the External Tank structure through the second set of struts (connecting the External Tank to the boosters) through the structure of the boosters' segments to the aft-skirt to the posts that hold the boosters to the Launch Platform? The question sounds intimidating. It is not.

We can use Eq. (7) to obtain the answer. The damping ratio for the Shuttle in bending mode was widely known since the early 1970s, or 0.10. All one needs is a simple calculator:

$$Dynamic\,Overshoot = e^{-p(0.1)\sqrt{1-(0.1)^2}} = 0.7315538$$

The dynamic overshoot at the hold-down posts is 73.15538%, or simply 73%. This mathematical answer must be verified by tests.

Measuring the dynamic overshoot is difficult and tricky. For example, the overshoot in a booster's joint was captured using accelerometers, Fig. 13. The overshoot is a spike. The frequency of vibration in which the spike occurred is about 250 Hz (cycles per second). This rate is too fast to capture with strain gages.

Several factors made it possible to accurately measure the dynamic overshoot in the Shuttle, though no one noticed. The frequency of oscillation of the Shuttle assembly about the hold-down posts is about 0.25 Hz (see first paragraph, Sec. 8.4), which is 1,000 times slower than the speed of the above spike (i.e., 250/0.25). The leisurely pace made it possible for the Shuttle engineers to measure the dynamic overshoot with strain gages. The Shuttle engineers did not derive the "dynamic overshoot" from their measurement in Fig. 15, on the contrary, the overshoot caused considerable confusion, see Sec. 7. I derived the dynamic overshoot directly from the STS-3 test data; see Table-9. The overshoot for the three calibration methods used by NASA and Rockwell was 65, 69 and 73%.

A remarkable good fortune made it possible to verify the calculated dynamic overshoot with a test. My calculated dynamic overshoot of 73% is in full agreement with the NASA and Rockwell measured overshoot of 73%. The engineers did not realize the implications of the measured 73% dynamic overshoot at the boosters' hold-down posts. They did not even recognize that what they called "EXCESS UPWARD FORCE" was nothing other than the start-up dynamic overshoot itself.

The thrust and the dynamic overshoot (together) from the SSME's propagate through the Shuttle structure at liftoff. There are thousands of structural elements in the Shuttle. All the structures between the main engines and the hold-down posts experience overshoot. Everything! Let us look at what happened at only several locations in the primary-structural-load-paths over the years. The following list gives partial sequential stations from the hold-down posts to the engines:

1. The strength of the hold-down posts was doubled to account for mysterious forces (early 1980s).
2. The boosters' aft-skirts were repeatedly strengthened (1980s).
3. The number of stiffeners in the boosters' aft-segments was doubled (early 1980s).
4. The boosters' lower struts were strengthened and preloaded for "mysterious loads," (1980s).
5. The number of pins in the boosters' forward strut-attachments was doubled (1984).
6. The bipod (Orbiter to ET attachment) was redesigned to eliminate problems (1986). Challenger flew with a newly designed bipod.
7. The Orbiters' fuselage and wings were rebuilt to counter premature cracks (1970s – present).
8. The adhesive strength of the tiles was doubled (1978).
9. The engines' compartment and components were repeatedly strengthened and rebuilt to counter premature cracks that grounded the Shuttle fleet (1970s – Present).
10. Pressure measurements in the engines did not show sizable dynamic overshoot (1970s – present). Then, where did the sizable forces in Items 1-9 above come from?

The short list exposes the enormity of the dynamic overshoot blunder. The mistake is scandalous.

All the corrections in Items 1-9 were made after the Space Shuttle was completely built. All the actions took place after 1978. None of the actions was anticipated in 1972. The scandal is that the Shuttle engineers think that they identified nine (9) different mistakes and that they developed nine (9) different solutions. The scandal is in the glaring fact that there is only ONE (1) mistake, a first order mistake.

Imagine a slinky with 10 coils. Hang the slinky from a ceiling. Hook a 1-lb apple on the tenth coil. Think of the ten coils to be the 10 Shuttle stations in the above list. Release the apple gradually with your hand. The coils will experience a maximum force of 1-lb. Now, release the apple suddenly. For a dynamic overshoot of 100%, the deflection and the force in the spring will double on first overshoot. The weight of the apple, in the tenth coil, will not double, just like the "pressure" in the Shuttle engines will "fluctuate," but will not double! Now, compare the slinky to the Shuttle. The 10-coils slinky was designed in 1972, without the dynamic overshoot effect. In 1978, the slinky was tested, the eighth coil broke, and its strength doubled (this is the doubling of the Shuttle tiles' strength in 1978). Then after 1981, the third coil showed serious damage, and its strength was doubled (this is the number of stiffeners in the boosters' aft segments). Then in 1984, the fifth coil showed damage, the strength of the coil was doubled (this is the reckless doubling of the number of pins in the boosters' forward attachment). Before the Challenger tragedy in 1986, the sixth coil showed damage and the coil was redesigned (the bipod on the Challenger was a new design). Rather than design the 10 coils correctly from the outset, or fix all the coils that experienced the same problem when the eighth coil broke in 1978, the coils were fixed one at a time.

Can you imagine what would happen if the slinky was made of 10,000 coils? There are tens of thousands of structural elements in the Shuttle and its payloads!

The "dynamic overshoot" blunder is a first order mistake. First order mistakes in the Shuttle (or in cars, bridges, buildings, airplanes, or refineries) kill people, damage the economy, impede progress and undermine education. The peer-reviewers mentioned above and the Shuttle engineers are not deterred. They will eventually solve the thousands of structural mistakes that they will find while operating the Shuttle. That was how they did it with Apollo, Gemini and Mercury. That was how von Braun did it since the 1940s. And no one realized that there is only ONE mistake.

The above elaborate discussion was made necessary, actually vital, by the narrow-minded and insulting responses I received from NASA, Rockwell, the American Institute of Aeronautics and Astronautics, the School of Engineering and Applied Science of GWU, and others. They really don't think that there is a massive systemic problem in the space program. I know there is.

In the last page of his Affidavit, Wilbur L. Pritchard wrote:

> *"I know for certain that Abutaha has devoted the past several years to winning this argument. It has become a matter of principle and virtually a crusade with him,"*

Others described my effort to wipe out the dynamic overshoot blunder as a crusade. Why a crusade? By the 1950s, everyone knew that electrical surges occur during the start-up transient period. I ran into the same effect early in life in mechanical systems. I likened the mechanical effect to the widely known electrical effect. Just like there are surge-currents and surge-voltages, I envisioned surge-forces acting in mechanical systems. The civil engineers included the "dynamic overshoot" effect in their designs and curricula. The aerospace experts didn't. The mission to wipe out the dynamic overshoot blunder in space systems began with me in the 1950s.

Among other products, my father's factory in Jordan produced high-pressure pipes and fittings since the 1950s. Military specifications are stringent. One contract to supply products to airports created havoc in the factory. There were many unexpected failures during tests. I remember my father struggling with the effect. The problem was identified to be the "sudden" application of pressure and external forces. The strength of parts was nearly <u>doubled</u>, and all proceeded flawlessly afterward. My father, my great mentor, invented a process that doubled the strength of products without affecting the overall weight. That was a great success, measured by the trouble-free operation of all products. The strength was doubled despite the accepted engineering practices. I knew then that something was wrong with the Action-Reaction Law. Although young at the time, I was the mathematician in the factory. I ranked first in mathematics in classes of nearly one hundred students all my years in school. We were not the only facility to fall into Newton's Action-Reaction trap and to <u>double</u> the strength of products in the 1950s. Here is a glaring example that everyone involved in rocketry should have recognized at the time.

The most beautiful machine I saw in the 1950s was the de Havilland Comet, the first jet-powered commercial airplane. I saw the elegant plane when I accompanied deliveries of our products to the airport. The Comet was breathtaking. Like all jet planes, it was a large reinforced pipe with closed ends, fittings and wings. But then, unexpectedly, two Comets fell from the sky killing everyone onboard. The investigations were elaborate. Aircraft were pressurized and depressurized to determine the cause of the disasters. The world learned many lessons from the tragedies of the elegant airplane. To me, the most notable news item did not come from de Havilland, the British investigators or from England; instead, it came from the Boeing Company in America! Boeing announced that it was going to nearly <u>double</u> the thickness of the skin on two new aircraft then, the Boeing 707 and the B-52. The action by Boeing validated our decision to nearly double the strength of pressure products in our factory before. The eventual record of the 707 and B-52, compared with all other aircraft, was further evidence to me that the Reaction is not always equal to the Action.

By the late 1950s, the space race was on. The Soviets announced their successes widely, but the failures were not reported. The American space program was open and, to me, eye-opening. Like the Comet and the pipes of our factory in Jordan, the rockets are also pipe-like structures. Anyone who remembers that period will recall the outrageous rate of failure of the early rockets. The headlines told the story: *"Freakish accident," "jinxed rocket," "the largest pad explosion," "qualified success," "humiliating disaster," "something went wrong and the rocket blew up," "the hazards of launch."* It became a cliché that every rocket must go through its *"baptism of fire,"* and every rocket did. The Soviets held most records in the early years. The race was grueling. It was not until the Gemini Program before the American space program shattered almost all records. It should not come as a surprise that I suspected the same "dynamic overshoot" destructive effect to be at the root of the early rocket problems. The rockets were always brand new, with no prior use and abuse. *"If a system fails, it is not designed correctly."*

I learned many important engineering lessons in our factory in Jordan, e.g., *if a system is designed correctly, it'll work fine, if a system fails, it is not designed correctly.* This, of course, after eliminating other causes of failure, such as, natural events, operator errors or maintenance mistakes. During 1962-64, I worked in the Engineering Division in the Ministry of Defense of Kuwait. In the O&M *Section* in a Brigade, I could see and classify in my mind the operation, maintenance and design problems in modern military systems. I developed a skeptical attitude towards the established engineering methods.

My attitude, rooted in experience, turned my engineering education into a nightmare. Before attending the George Washington University (GWU) in 1964, I had reservations about Newton's Action-Reaction, Inertia and Gravitation Laws and faulty engineering practices. The faculty in the School of Engineering and Applied Science (SEAS) and the School of Physics at GWU found my attitude shocking. I took the first space design course in mid 1960s. There were no space textbooks or encyclopedia. Everyone was learning on the run. I knew that sudden pressure produced mechanical-surge-forces. To me, the dynamic overshoot was the most important design parameter after the thrust. One either eliminates the overshoot, or includes it in design. The faculty did not see things my way. The safety factors, they argued, took care of the overshoot effects. I disagreed. The consequences were terrible; the faculty controlled the grades. I wanted the faculty to tell the space agency about the potential terrible mistake in rocket design. A note, still in my files, by a professor illustrates the dispute, *"This student is full of himself!"* At the time, the Accreditation Board placed the SEAS on probation. That was another reason for me to take my education from the classroom to the rich library. My point here is to show the reader the bizarre nature of the "dynamic overshoot" blunder. It is a belief system, a dogma. Recent incidents emphasize my point. Shigley's *Mechanical Engineering Design* textbook (Reference 1) is widely used to teach the design of mechanical systems, such as the Space Shuttle. There are several hundred equations in the book, to calculate forces, deflections and stresses. To me, the doubling equation (Eq. 1 in this Report) was (in the 1960s), and is (in the 1990s), probably the most important equation in the book! The equation is inconspicuous, almost hidden, in the textbook. In the 1990s, I was, and maybe the reader will be, shocked to discover that the GWU professor who used the textbook since the 1960s was completely unaware of the doubling equation. I asked another professor, who works on testing aircraft engines, to describe how they measure the dynamic overshoot in the engines. They don't, he said! The reader can see how generations of engineers have not been told about the most important effect in mechanical engineering design. In fairness to the mechanical engineering faculty at GWU, it would turn out that other mechanical-aerospace and physics faculty and experts have been in the dark about the mechanical-surge-forces all along, as has been shown in this Report. In the 60s and 90s, the University administration sided with the faculty, and the dynamic overshoot blunder lived on.

My late father and older brother eagerly awaited my return to Jordan after 1969 to resume my duties in the factory. There were projects, proposals and upgrades to do. That was when I ran into the "dynamic overshoot" blunder in quick succession with the fuel tank explosion, the Apollo 13 oxygen tank problem and the apogee motor failure, which I described at the beginning of this Section. Working in the space program was a privilege, making a difference was an honor. The many tests I did in the 1970s vindicated my assertions at GWU in the 1960s. By July 1970, I was making a difference in the space program beginning with the "dynamic overshoot" blunder, which was not part of the curricula at the University.

Executing a space project from inception to design, construction, test, and operation is magical. Tens of thousands of people work like ants in a colony towards one goal. Thousands of engineers struggle with thousands of problems to the same end, a successful mission. Not one engineer can cover the whole spectrum, and specialists and experts are the rule. Each engineer is specialized in one or, at most, several subjects. I was the de facto expert on the "mechanical start-up transient dynamic overshoot effect" at COMSAT. For nearly ten years, I would detect and correct the start-up transient problem in a variety of systems. As the reader can gather from this Report, there were no other mechanical "start-up transient dynamic overshoot" experts in the space program.

The closest I came to deal with the "dynamic overshoot" effect in the Space Shuttle, before my studies of the Challenger tragedy, was in 1977-78. COMSAT was a primary user of launch vehicles for a variety of satellites. My years of preparation for Space Shuttle launches were rewarded. My position was described as *"A structural analyst ideally with both static and vibration test experience."* My responsibilities, *"to manage the final assembly and pre-launch testing at the launch site."* The management emphasized in a kit to those of us who were going to be involved in Space Shuttle launches the following track record, *"COMSAT's engineers tend to know more of both the spacecraft and launch vehicle than any other group."* That was based on the turnover in personnel over the years. The most critical event in Shuttle launches was going to be the lateral, or sideways, vibration before liftoff, in which the satellite is weakest. This is when the base bending moment, discussed at length in this Report, is produced. The dynamic overshoot was uppermost in my mind, as my extensive experience taught me since the 1950s. COMSAT was a private company, but it was also a semi-governmental agency. My modus operandi was that if success of my projects depended on other entities, I wanted to know about their work. The mistakes of others could easily become my failures, and I never liked that. My record spoke for itself, and that gained me the respect of the upper management at COMSAT. With the reports of trouble with the Shuttle then, I could sense the "dynamic overshoot" effect at work. At the time, the strength of the tiles was <u>doubled</u>. I wanted to participate in, or at least observe, the structural tests of the Shuttle itself. That was not possible. I left my good aerospace job in 1978. It would take three years before the Shuttle flew. But, the "dynamic overshoot" mistake was only partially corrected then, as clearly demonstrated in this Report.

For four decades (1950s-80s), I dealt with the "dynamic overshoot" mistake routinely. My effort was not a crusade; it was part of the job. Solving the mistake was neither a discovery nor an invention. I knew all along that the mistake is enormous. The events of the '90s, particularly the appalling response of faculty, peer-reviewers, NASA management and others convinced me that the dynamic overshoot blunder is more than a mistake. That was when my mission to eradicate the mistake turned into a crusade. The mistake is a widespread disease in mechanical engineering, particularly aerospace systems. The mistake is rooted in Newton's Action-Reaction Law.

The skeptics argued: If a mistake as massive as the dynamic overshoot was made in the design of the Shuttle, then why didn't every Space Shuttle explode? Here are some reasons. During the period 1977-81, some parts were strengthened, e.g., doubling the adhesive strength of the tiles after the Shuttle was completely built. Then during the period 1981-86, the strength was doubled in other parts, e.g., the number of pins in the SRB-ET attachments in 1984. Other factors helped. We normally use minimum material properties in space systems, which add to the safety margins. Complex structures are more forgiving than computer models, another source of extra margins. Some materials exhibit greater strengths when the load is applied rapidly, and the transient loads are fast. This is another source of extra safety margins. We also use conservative measures in space design. These factors, which I tested and used while working in the space program, made the Space Shuttle more forgiving in real life than on paper. These factors explain why the Shuttle did not explode on every mission. The reader can use his or her imagination to think of what would have happened had all the huge (100%) structural corrections described in this Report were not made at all since 1978.

Neglecting the dynamic overshoot effects, then strengthening twisted parts and taking advantage of the inherent safety factors described above barely worked with the one-shot vehicles, such as, Atlas, Titan and Saturn in the Mercury, Gemini and Apollo. But, the Shuttle is a reusable vehicle. Neglecting the "dynamic overshoot" in Shuttle design struck the system in a different way.

The "dynamic overshoot" mistake made a mockery out of fatigue analysis. The "*safe life*" criterion for aircraft never worked. Airplanes continued to crash before the predicted safe-life-fatigue estimates. The "*fail safe"* criterion was then used, where airplanes are inspected periodically for structural cracks, at great cost. Still, unexpected crashes continued. The primary parameter to estimate the fatigue life of anything is the force acting on a system. Fatigue methods are well developed, but using the wrong force renders all fatigue estimates meaningless. How many times can the Solid Rocket Boosters of the Shuttle be reused safely? How many times can the Shuttle Orbiters be reused safely? Any answer to these questions that does not take the "dynamic overshoot" forces into account is meaningless. Alternatively, the premature failure of the Shuttle boosters and Orbiters is clear evidence that something is terribly wrong with the estimates of the forces used in fatigue analysis. Unless the dynamic overshoot mistake is completely and correctly handled in all Shuttle components, troubles will continue, success will be limited, resources will be wasted, and lives will be at risk.

Over a period of five decades, I have seen the "dynamic overshoot" mistake made by many people in many ways. Some of the modes are described in this Report, e.g., failing to add the transient force to the suddenly applied force, failing to recognize the existence of the start-up transient forces, failing to see that the pressure in rockets does not overshoot – but the forces overshoot, or indiscriminately using Newton's Action-Reaction Law in design. The ego of the faculty, scientists and engineers involved has clouded their better judgment, and the deadly mistake lives on.

After all the effort I put into it since the 1960s, I find it incomprehensible that the massive dynamic overshoot mistake has not been taken straight up to the NASA upper management, down to everyone at all centers, outward to all contractors, onward to all schools of engineering and, eventually, to all K-12 science teachers and the children. Perhaps, the crusade should begin with the Saturday morning cartoons or the education programs on *NASA Select TV*, where the children are bombarded with the messages that the ACTION is always equal to the REACTION and that the FORCE is equal to the PRESSURE times the AREA, etc. The children are not given a hint that the force effect can be magnified, though momentarily, if the ACTION or PRESSURE is applied SUDDENLY.

12. Conclusion and Recommendations

It is common knowledge that when an electrical switch is turned on, "surge current" flows in circuits. The surge current consists of the applied current plus a momentary transient component known as the "dynamic overshoot." The maximum start-up transient current can be double the applied current. Unless included in design, surge currents can trip circuit breakers, blow fuses or damage electronics and electrical devices. It has not been recognized before that a similar effect occurs in physical-mechanical systems, such as, rockets, including the Space Shuttle.

Conceptually, starting-up powerful rockets is similar to turning on electrical switches. "Surge forces" propagate through the structure of aerospace systems during start-up, and the maximum forces can be double the actually applied forces. This Report shows that the "physical-mechanical dynamic overshoot surge forces" were neglected in the design of the Space Shuttle and other systems. Since the dynamic overshoot forces exceed the safety margins in space systems, this one mistake has caused numerous failures, delays, accidents and tragedies since the beginning of the space program.

Repairs to counter the neglected destructive "dynamic overshoot" effects in the Space Shuttle began after the system was completely built in 1978. For example, doubling the adhesive strength of the Thermal Protection System, or tiles, delayed Shuttle flights from 1978 to 1981.

Unaware that start-up "surge forces" strike like "surge currents" and "surge voltages," the engineers continued to battle what they thought were mysterious forces after the Shuttle began to fly. From 1981 until the Challenger tragedy in 1986, many structural parts of the Shuttle failed and were strengthened or redesigned. Specific examples of the doubling corrections are described in this Report. ONE mistake by a few engineers led to drastic results. The mistake: (1) delayed Shuttle flights, (2) complicated the assembly, operation, maintenance, and management of the Shuttle, (3) drastically reduced the number of Shuttle flights, (4) increased the weight of the system, (5) reduced its payload capacity, (6) dramatically increased the cost of Shuttle launches, and (7) exposed the astronauts to tragic accidents.

Neglecting the "dynamic overshoot" effect in Shuttle design is a 100% mistake; or in plain words, a design blunder. "Doubling" the strength of Shuttle parts, which is well documented, is admitting the 100% mistake; the same design blunder in the previous sentence. These words have gotten me into a lot of trouble with scientists, engineers and faculty since the 1960s. I had identified and corrected the dynamic overshoot effect in industrial and space systems numerous times since the 1950s. Yet, the other experts and faculty vehemently rejected the overwhelming evidence. This attitude revealed deep-seated confusion over the "dynamic overshoot" effect in physical systems, which is explained in this Report.

The deep roots of the "dynamic overshoot" mistake are discussed in this Report. The discussion includes scientific, technical, educational, historical, philosophical, psychological and political elements of the design blunder. The Report shows (1) how some engineers are completely unaware of the "surge" effect in physical systems, (2) how some engineers miscalculated and mishandled the effect in Shuttle design, (3) how the engineers actually measured the correct "surge forces" in the Shuttle in 1982, but did not even realize the meaning of the correct measurement, (4) how Newton's Action-Reaction Law is at the root of the problem, (5) how scientists and engineers mistakenly and regularly equate the CAUSE and EFFECT, INPUT and OUTPUT, ACTION and REACTION, and FORCING FUNCTION and TRANSIENT RESPONSE in mechanical start-up transient situations, and (6) how relying nearly exclusively on pressure measurements (which do not show the "surge" effect), physicists and rocket engineers repeatedly fell into the tricky "dynamic overshoot" trap, with drastic results.

Doubling the strength of Shuttle parts (100% mistakes) is evident in the official records; yet, no one highlighted the actions to the Presidential Commission that investigated the Challenger Accident. No one alerted the Commission that the "dynamic overshoot surge effects" were missing in almost all the data used to determine the cause of the Challenger tragedy. Thus, inconsequential 1-3% mistakes in the design of O-ring seals received greater consideration in all circles than the deadly 70-100% mistakes in the estimates of the forces that propagated through the primary structures of the Challenger at liftoff.

Since the engineers who initially designed the Space Shuttle, without the dynamic overshoot effect, also designed Apollo, Gemini and Mercury, it is safe to suppose that the destructive effect was mishandled in the earlier systems. The author identified cases when the same mistake happened before. Moreover, the destructive "surge forces" were not even mentioned in writing by any space expert before, including Dr. von Braun. Instead, trial-and-error methods were used to identify some "mysterious forces" by studying twisted wreckage. The reader can see the potential explanation for the inordinate number of explosions that haunted the early rockets in the 1950s and early 60s.

"Doubling" the strength of Shuttle structures that failed outright, and not knowing why, led to a false sense of security. Everyone thought the problems were over and the Shuttle became operational. But, the dynamic overshoot forces (called "excess upward force" by the Shuttle engineers in 1982) cause accelerated fatigue and the surge forces consume the useful life of reusable structures faster than anticipated by analysis. The numerous fatigue failures in the Shuttle's operational history are clear signs that the physical-mechanical-surge-forces were mishandled in Shuttle design.

A thousand things can go wrong in every Space Shuttle mission. A thousand dedicated men and women search for problems to avert accidents and tragedies. But one mistake has by itself produced a thousand serious problems, hidden from view. This is the dynamic overshoot blunder.

This lengthy Report and the "dynamic overshoot blunder" can be brought into sharper focus to all readers, *liberal arts* or *science* major, as follows. We all learned Newton's Third Law when we were children:

"To every action there is always opposed an equal reaction."

We use these words to design rockets and other things. We teach these words to design the rockets and the other things. But, think carefully about it:

"Is the reaction equal to the action whether the action is applied gradually or suddenly?"

To be specific, in a 10-hour flight at constant engine setting, the Action-Reaction law is valid for 35,999 seconds! For one second (out of 36,000 seconds) at the beginning of the flight, the aircraft structures are struck with greater loads than generated by the steady thrust. If the surge forces are neglected in design and a vital part breaks in the aircraft at start-up, then tragedy follows. If the dynamic overshoot does not break something vital in the aircraft, the flight will be safe. This is not the end of it. The dynamic overshoot, if neglected, reduces the operational life of the aircraft or any reusable system, including the Space Shuttle. How many aircraft met its initial life expectancy? Some research aircraft lost their wing(s) on initial trials. How did this come about in the twentieth century?

In Section 6, *"Dynamic Overshoot" and "The $64,000 Question,"* I gave a cursory account of the history of the dynamic overshoot mistake. The aerospace engineers did not initially make the mistake. The physicists made the mistake in late 18th Century, long after Newton and Leibniz. There were no airplanes or space shuttles then. Maybe, the surge forces were not considered deadly in horse-pulled-carriages at the time. The surge forces have been deadly to aircraft riders and space astronauts in the 20th Century. In the case of the Shuttle boosters, the Action-Reaction law is valid for 119,400 milliseconds in flight, but for the first 600 milliseconds, the Action-Reaction law is not valid. The loudest hecklers to my mission to wipe out the dynamic overshoot blunder from the space program since the 1960s have been the physicists. *"Is the reaction equal to the action, when the action is applied suddenly?"* The physicists, before the engineers, must answer the question. They can begin by calculating the work (energy) at sudden start-ups and then derive the "dynamic overshoot surge force" accordingly! The dynamic overshoot mistake has all alone ruined our space program, impeded progress, damaged the economy, undermined education, increased unemployment, and killed innocent people in the twentieth century, and the mistake must be dealt with effectively.

Recommendations

The "dynamic overshoot blunder" is one mistake that produces a thousand problems in a system like the Space Shuttle. There are two ways to deal with the situation:

1. Fix the one mistake.
2. Find and fix the thousand problems, one at a time.

Unaware of the nature, enormity and consequences of the one mistake, the Space Shuttle engineers fell into the trap of fixing the thousand problems – one at a time. I have included serious problems and fixes in this Report, and there are more problems and fixes on file. Because the Shuttle is reusable, Method 2 created many problems. Rather than develop recommendations to the NASA management on how to correctly deal with the situation, the experts who peer reviewed my papers on the subject rudely dismissed my concerns. I have a few recommendations.

The reader must first be convinced that there have been a thousand major problems with the Shuttle and, more importantly, that the thousand faults are caused by one mistake. This Report does it. Doubling the strength of the tiles in 1978 did not fix the causal mistake. Doubling the stiffeners in the boosters' aft segments did not fix the causal mistake. Doubling the number of pins in the booster/ET attachment in 1984 did not fix the causal mistake. Doubling the design base bending moment after the Shuttle was completely built did not fix the causal mistake. Strengthening stiffener rings, gussets, clips, and other boosters' hardware did not fix the causal mistake. Searching for, finding and fixing, or redesigning for, cracks all over the system did not fix the causal mistake. On the contrary, the haphazard, yet necessary, corrections increased the weight of the Shuttle, reduced its payload capacity, complicated its operations, dramatically increased its costs and exposed the astronauts to tragic accidents.

Early in the space program, major mistakes attracted everyone's attention. When fuel slosh (which produced unpredicted damping) threatened to send satellites into flat spin in orbit in the early 1970s, everyone, including myself, heard about it, thought about it, helped to analyze it, simulate it, test it, write about it and the problem was eliminated. At the same time, I was doing tests of the "dynamic overshoot" effect in space systems. I thought about it, analyzed it, simulated it, tested it, wrote about it, distributed my write-ups; but no one picked up on the massive 100% mistake! It was worse in the 1960s when my views on the "dynamic overshoot" and other engineering blunders were ridiculed by the faculty at GWU. After I tried to eliminate the overshoot mistake from the Shuttle in the 1980s, there was only one entry of the dynamic overshoot in the massive Shuttle Loads' Books in 1990; that was doubling the design load for the booster separation motors (Sec. 10.3). The fact that the dynamic overshoot effect was still missing in other Shuttle parts in 1990 is further evidence that Step 2 above predominates, or, *"find and fix the thousand problems, one at a time!"* Just as we did early in the space program, the scientists, particularly the physicists, and engineers must think about, analyze, simulate, test and write about the "dynamic overshoot blunder" to completely eliminate it from the space program.

The space program was initially driven by the Cold War and the space race. There was no infrastructure when the call to go to the moon was made. Experience was limited and the experts were few. Yet, with boldness and resolve, NASA took us to the moon and far beyond. Then, because the Shuttle is reusable, the neglected liftoff physical-mechanical-dynamic-overshoot-surge-forces from the engines (SSME) and boosters (SRB) struck with vengeance. Decades after we made it to the moon, we can hardly make it to low earth orbit. Our children don't know how it feels to wait for a moon shot, to watch the magnificent launch, the figure-8 trajectory to and from the moon, the lunar dusty rocky terrain, the earth from the moon, liftoff from the moon, ascent and voyage home. Where did it all go? Some pundits blame it on the Presidents. Others blame it on the Congress. Some say that it is the result of different mind-sets. There are other speculations, and these are not supported by numerical evidence. I have shown in this Report that a major scientific mistake made in the 17th Century, and set in concrete by the physicists in the 18th Century, is to blame for the ills of the Space Shuttle and the space program. Unless the mistake is clearly understood and properly handled, extensive and expensive effort will be wasted.

There have been a thousand brilliant ideas and recommendations by thousands of brilliant men and women on thousands of vital issues over a period of five decades to implement and invigorate the space program. Nothing in this Report is intended to obviate or disparage those valuable efforts. The “dynamic overshoot blunder” is a stand-alone problem. It affects the whole space program. Yet, I have not seen the problem addressed by anyone associated with the space program since the 1950s. When some NASA officers asked me to work with the space agency on the dynamic overshoot mistake in 1986, I thought of many things that I would do to deal with the problem. Here is a short recommendations list:

Space Program

1. NASA must determine with particularity the reality of the dynamic overshoot effect in physical-mechanical systems, including the Space Shuttle. Just as it is universally accepted and understood that sudden electrical currents produce magnified “surge currents,” it must be unequivocally established that sudden physical forces produce magnified “surge forces.”

2. NASA must play a lead role in developing government-wide strategy for handling the “surge forces” in aeronautical and space systems, whenever and wherever the effect occurs. The “surge forces” effect must be included in the procurement documents of DOD, DOE, DOT, NIST, etc.

3. The contractors, academia and professional organizations must be notified of the results of, and/or be invited to participate in and contribute to, Steps 1 and 2. The technical personnel must be able to show that the hitherto high “risk” factor in space missions will be greatly reduced. The management and finance officers must see that the hitherto high “risk” factor in space missions will be greatly reduced. Eliminating the scourge of the 100% mistake from future space systems will lead to dynamic business plans, investment strategies, insurance and other policies that will greatly enhance our space program and the national economy.

4. NASA must lead an integrated effort to determine the tradeoffs between (a) eliminating the “surge forces” in aerospace systems and (b) designing aerospace structures to withstand the “surge forces.” The choices are limited: Either we keep a handful of engineers gainfully employed to find and fix the thousand problems created by the “dynamic overshoot blunder,” or we create dynamic business opportunities to many people. Dealing with the dynamic overshoot mistake effectively will lead to many profitable patentable ideas. The available alternatives must be considered and new methods must be developed. The practice of doubling the strength of structures after a system is completely built must be eliminated. The last method has been the first and primary technique used with the Space Shuttle, as has been clearly shown in this Report.

5. NASA should revive the studies and wonderful designs that were developed concurrently with the Space Shuttle in the 1970s to benefit the young engineers from the vast experience of the old hands. Many systems, including moon habitats, were mothballed primarily because the Space Shuttle failed to meet its stated objectives. And the dynamic overshoot effect must be considered in all designs.

6. The national leaders and the congressional committees must be told with specificity, and with no ambiguity, about the nature, magnitude and consequences of the dynamic overshoot mistake in space systems and how appropriations and authorizations to the above, and the following, tasks will lead to many national benefits.

Space Shuttle–I

Is the Space Shuttle an experimental or operational vehicle? It is neither. The "dynamic overshoot mistake" has turned the Shuttle into a platform for conjecture about some mysterious forces that seem to strike the system out of the blue, causing many failures. The number of failures has been demoralizing; and the failures zapped the spirits and confidence out of everyone involved in the space program. This Report shows that the mysterious forces are simply the neglected "physical-mechanical surge forces."

7. NASA must assign the responsibility for the "start-up transient" conditions to specific experts, e.g., either the structural engineers or the dynamics engineers. The experts must be able to identify the overshoot mistake immediately, without elaborate calculations or deliberation. This Recommendation is far more important than it sounds at first. Specific examples are powerful.

   The history of the Shuttle "base bending moment" was a mess, as the reader can see from Table-13 in this Report. The "base bending moment" was <u>doubled</u> according to the Shuttle engineers' own records in the early 1980s. Furiously, the Shuttle engineers responded (to my paper) in 1991 that they had doubled the base bending moment before that. Everyone knows the simple fact that the base bending moment is produced by the thrust from the shuttle main engines. One look at the engines' thrust specification tells it all. Why is the dynamic overshoot factor missing in the "main engines' thrust" in the 1990 specifications? How could the base bending moment "overshoot" if the causing "thrust" does not overshoot? It is very simple. There must be no indecisiveness about the effect.

   The engineers who measured the 73% dynamic overshoot in 1982 (Section 7) should have informed the highest technical Level II at NASA in plain words and without hesitation that the overshoot was neglected in the initial calculations, instead of asking Level II to verify if the initial calculations were right or wrong. Furthermore, the experts must be able to relate specific findings to other areas. The measurement of the dynamic overshoot by the Shuttle engineers in 1982 should have been related to the <u>doubling</u> of the adhesive strength of the Orbiters' tiles in 1978 and to the other similar corrections made over the years; and those corrections should have been related to weaknesses encountered with the Orbiters' fuselage, wings, aft-compartment, and other parts. Also, <u>doubling</u> the adhesive strength of the tiles in 1978 and the base bending moment, whenever that happened, should have led the engineers to anticipate the "dynamic overshoot" measurement in 1982.

8. The ultimate responsibility for the start-up transient conditions in the Space Shuttle must lie with NASA, and not with the contractors, subcontractors or other suppliers. After all, NASA generates the procurement and specification documents. The NASA experts must ensure that all contractors are familiar with the effect, and must learn from the contractors who might have developed better understanding of the effect.

9. The existing computer models of the Shuttle can be used without modifications to evaluate the "dynamic overshoot" effect in all parts. Using overshoot factors of 2.0 (or 100% overshoots) is unacceptable. Outright doubling of strength must not be used indiscriminately. The actual minimum overshoots must be calculated accurately. The real "stresses" and real "safety margins" for all parts must be generated from the existing finite-element computer models. The astronauts must know the real "structural" safety margins of their vehicle. Every astronaut must know everything there is to know about the "dynamic overshoot" effect, and there is much to know.

10. The life expectancy of the remaining Orbiters must be evaluated with the "surge forces," and the earlier fatigue estimates must be discarded. Where the "overshoot" effects were neglected, the fatigue life of the particular part(s) is meaningless. The original life expectancy must be revised by first determining the life-fraction that was consumed with the "excess forces," and by then estimating the remaining life-fraction for those parts. The analytical, computer and testing tools for these tasks are available and well developed. Unless rebuilt from scratch, the remaining Orbiters must be used sparingly.

Space Shuttle-II

It is time to procure a new vehicle – *Space Shuttle–II*. It is imperative to carry out Recommendations 1 through 10 expeditiously to return the "can do attitude" and instill confidence at every level in the space program. It is imperative that the aerospace-structural-dynamics-engineers deliver a structurally clean machine to the administrators, directors, astronauts and assembly, operation, maintenance and flight personnel. The original goals of the Space Transportation System (STS) will be a natural byproduct of doing it right the first time.

11. Procure 7 (seven) *Space Shuttle–II* Orbiters with Option on 5 (five) more Orbiters. Integrating *Recommendations 1 through 10* will produce a clean machine that will move swiftly from "experimental" to "operational" phases.

At the risk of being repetitive, but it is important to remind everyone:

a. The adhesive strength of the Thermal Protection System, or tiles, will not be doubled on *Space Shuttle–II* five years (yes, 5 years) after the issue of Contract, or because that was the way it was done with *Shuttle–I*. Instead, the actual maximum liftoff loads will be correctly calculated from the outset.

b. The number of pins in the booster to External Tank attachment will not be recklessly doubled on *Space Shuttle–II* twelve years (yes, 12 years) after Contract signing. Instead, the correct liftoff loads will be correctly calculated and proper designs instituted from the outset.

c. The number of stiffeners in the aft boosters' segments will not be doubled after *Space Shuttle–II* begins operation, as was done with *Space Shuttle–I*. I should point out that when the aft segment was strengthened to account for the mysterious forces, the "surge forces" were unknowingly chased to the next forward segment, the very segment that failed on Challenger and caused the tragedy! Galileo wrote about a similar effect four hundred years ago.

d. *Space Shuttle–II*, with integrated "surge forces," will be far more reliable than a Shuttle with a thousand "surge force" fixes.

There was debate among the engineers in the early 1970s over the use of "solid rocket motors" in manned vehicles. I opposed the use of the solid rocket motors then. My fears were based on (1) the ability of the manufacturers to produce crack-free propellants every time, and (2) the dynamic overshoot effect. One crack in the propellant can lead to instant explosion. I was wrong about Item (1). The record of NASA and the contractor(s) in this regard has been phenomenal. Even the violent explosion of the oxygen tank in the Challenger tragedy did not affect the propellant in either booster. The impressive record must be acknowledged. But, unlike liquid engines, the start-up of solid propellants is a controlled explosion, and the dynamic overshoot for the solid rocket motors was going to be near maximum. I was doing the "dynamic overshoot" tests then at COMSAT. My concern, reported through the chain-of-command, was not forwarded to NASA or others at the time, and the reader can see why from this Report. No one believed it. Neglecting the devastating dynamic overshoot effect has left a bad mark on our space program. People make mistakes. Engineers make mistakes. It is only when we learn from our mistakes that we can move forward with confidence. If we either eliminate the "surge forces" or include the "dynamic overshoot" effect in our designs, then *Space Shuttle–II* will be a success story unprecedented in the history of the space program. The effort must also include *education* at every level.

Education

12. I said before that engineering is applied science, and the science is physics. Eliminating the dynamic overshoot mistake must begin with physics, before engineering. What can the physicists do? The task is straightforward. Every physicist knows that work is equal to force x distance:

$$\mathbf{W = F \times d}$$

   a. Calculate the work (energy) done by a gradually applied force,

   b. Calculate the work (energy) done by a suddenly applied force.

   For the same distance, displacement, or deflection, **d**, the "work" calculated in Step 2 is double the value calculated in Step 1. The effect of the force on a structure in the second case is twice the effect of the force in the first case. It is this simple. It takes less than one-page in physics textbooks to describe the "surge force" effect, including the mathematics and diagrams. The philosophical arguments over the issue by Descartes, Leibniz and Newton can wait. The lives of innocent people cannot wait.

13. The sudden force doubling and magnification effect should be more prominent in mechanical and aerospace engineering textbooks – and education. There is inherent ambiguity in Newton's Action-Reaction Law, which must be clarified. The Space Shuttle engines produce 1,125,000-lb sudden thrust at liftoff. The force propagates throughout the Shuttle structure. At the last structural station in the Shuttle, i.e., the holddown posts, the dynamic overshoot imposes (by measurement) 1,900,000-lb force. What is the Action? What is the Reaction? What are the Action and the Reaction values at every structural station from the SSMEs to the holddown posts? Surely, the answers cannot be found by measuring the "pressure" in the engines, as has been done by the aerospace-structural-dynamics engineers and others to date.

14. K-12 students learn by heart the words: *"To every action, there is an equal and opposite reaction."* The students must be taught that for constant engine setting, the Action-Reaction law applies for 35,999 seconds in a 10-hr flight, but that for the first second, the law does not apply. Or, does it? (See Recommendation 13). Should children be taught such complexities? I learned about the "surge force" effect when I was a child, and it proved very useful in my engineering career since the 1950s.

15. *NASA Select TV* broadcasts educational programs that target the K-12 teachers and students. Sometimes, the Action-Reaction law is repeated daily to the children. The children are also taught that force is equal to "pressure x area," but nothing is ever said about whether the action, or pressure, is applied gradually or suddenly. In almost all rocket engines and motors to date, the start-up pressure build-up is rapid and sudden. The children are the backbone of tomorrow's space program. Will the children also fall into the "dynamic overshoot" trap because we selected not to teach them about the destructive effect of sudden pressure and action build-up, particularly, in rockets?

16. An accurate historical account of the "dynamic overshoot blunder" in twentieth Century science and engineering will be painful, but useful and necessary.

There are endless other tasks that must be done to eliminate the "dynamic overshoot" mistake from all modern systems.

Epilogue (2000)

The "dynamic overshoot" saga did not happen in vacuum. Many people, in and out of government, were involved. A synopsis of some of what happened between the years 1986-93 is given here.

The Space Shuttle is an incredible machine. And so are the satellites, the space probes and observatories and the related space and terrestrial systems. These are the crowning achievement of thousands of creative and diligent men and women working at NASA and at thousands of companies. It seems absurd that one mistake made by a few engineers could undermine the whole space enterprise. This Report should dispel any doubt in anyone's mind that the devastating dynamic overshoot effect has been at the root of many failures in space systems, including the Challenger accident. The true absurdity was in the controversy that surrounded my straightforward transient analysis. The magnitude of the dynamic overshoot mistake is embarrassing. This has made it difficult to even talk about the mistake with the other engineers, especially the engineers who make the mistake. Who wants to talk about making a 100% blunder?

Although I did not write publicly about the dynamic overshoot blunder until 1989, I had outlined the mistake in precise terms at the Kennedy Space Center in October 1986. William D. Blakely, a crash investigation attorney, and our NASA escort Bill Goldsby, attended the numerous meetings that I held with the engineers. There were lengthy technical discussions for three days. I presented the transient problem in concise terms, as can be seen from my notebook of those meetings.

I reproduce here 3 entries from my notebook, Fig. 67. I shared these notes with the Director of Shuttle Engineering at KSC, the MSFC manager at the Cape and other senior engineers. These 3 entries were all that NASA, or anyone else, needed to complete the transient analysis and to eliminate the devastating transient effects in the Space Shuttle:

1. (A), I specifically asked in writing: "*Are there instruments to measure transient response to step-input*?" That was a concise way to draw attention to the blunder.

2. Sketch (B) shows the struts' preload strategy that NASA developed to correct the damage in the struts. The preload worked nicely for the struts, but the dynamic overshoot went right through the struts and into the rest of the Shuttle structure unchecked. In Sketch (C), I showed exaggerated rendering of the dynamic overshoot.

3. Also, during inspections of the Shuttle hardware, I pointed out to Goldsby the doubled pins in the forward SRB/ET attachment, the doubled stiffeners in the SRB's aft segments, and other instances of dynamic overshoot evidence. All my observations were on record.

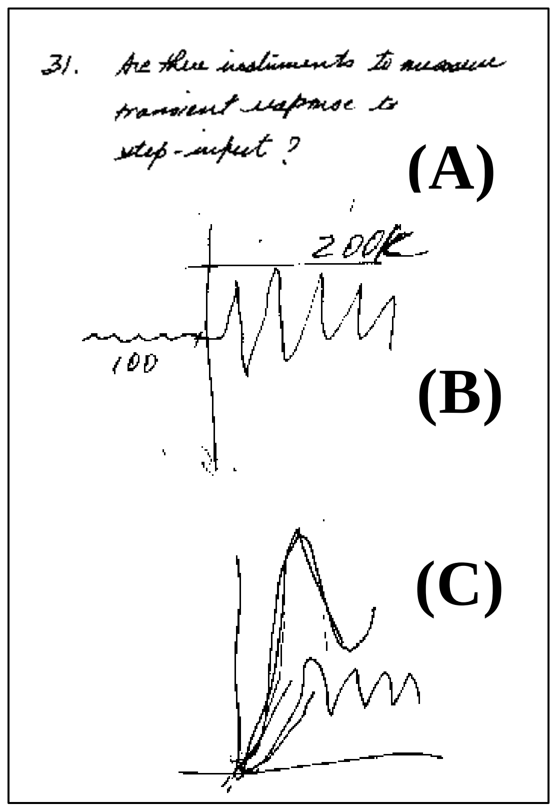


Fig. 67 Three Entries from KSC Oct. '86 Meetings: (A) "*Are there instruments to measure transient response to step-input?*" (B) Preloading Struts Philosophy Backfired, and (C) Dynamic Overshoot Illustration

After my three-days at the Cape, there was unanimous agreement by all the attending NASA officers and engineers that very serious work had to be done with the start-up transient analysis of the Space Shuttle.

I had made tentative arrangements with astronaut Bonnie Dunbar, delegated by Richard Truly to interface with me, that after my trip to the Cape, I would go to the Johnson Space Center and the Marshall Space

Flight Center to follow up on the excessive loads' issue. But, one incident that happened at the Cape changed all the plans. The incident interrupted the important steps that I accomplished with the KSC engineers and the NASA officials at headquarters in 1986.

In October 1986, some congressional offices wanted me to observe the roll-out of the Atlantis Shuttle Assembly to the Launch Pad and to report to them about my observations. That was the first roll-out of a Shuttle after the Challenger tragedy. Roll-out was going to take all night. As I always do before all-night work, I took a nap in the afternoon at the motel. Things were going great at KSC. Suddenly, everything changed. I was awaken by a visibly shaken William Blakely, who had apparently borrowed my rental car while I was asleep, went to the Cape by himself (without our NASA escort), drove up to the Launch Pad, and was caught by the security guards taking pictures with his cameras, which he had registered in the name of Goldsby upon our arrival at the Cape. That was an outright breach of security. I was furious with Blakely. Goldsby was furious with us. NASA was also furious. I had worked in, lectured at or visited sensitive centers at home and abroad before, and abiding by every center's security arrangement is paramount. I was in charge of our mission, and not Blakely, and I felt responsible for his foolish act. NASA calmed down and said that they would allow me to watch the roll-out. I was disgusted with what happened and decided to leave the Cape without watching the complete roll-out. I left the Cape soon after that. Any plans to visit JSC and MSFC were canceled. I felt that the dynamic overshoot design error was adequately presented and explained by me in the three-day meetings at KSC.

After the Blakely incident at the Cape, there were meetings to discuss my work at the White House and other high offices. Blakely, who blatantly violated the security rules at the Cape, was invited to those meetings, but I was not asked to attend! Blakely had investigated aircraft crashes, and it is possible that he understood the transient loads problem as I presented it to the KSC officers and engineers. In a letter to T. F. Davidson, Vice President of Technical Aerospace Group at Morton Thiokol, dated November 25, 1986, and copied to me, Blakely wrote:

> *"Early in October, we (Bill and me) travelled (sic) to the Cape to conduct an on-site investigation and to observe the roll-out to Launch Pad 39B. The evidence gleaned from Mr. AbuTaha's analysis of the documents supporting the Rogers Commission's finding, along with the information we obtained during our trip to the Cape and from our interviews with members of NASA's staff, may have a significant bearing on the U.S. Space Program and, as a result, should be of equal importance to Morton Thiokol - - - As all potential sources were exonerated, he found it reasonable to suspect the roll-out, and certainly some of the loads did originate during that phase. <u>Other loads, however, now appear to be more crucial to the analysis</u>." (Emphasis added)*

The "*<u>Other loads</u>*" that Blakely wrote about were the dynamic overshoot loads. I had met with teams that handle different aspects of processing of the Shuttle for launch operation at KSC. I asked many questions, and listened carefully. I kept the transient overshoot issue until the last meeting, which was headed by the top technical officer at KSC. Blakely was euphoric during, and after, that meeting. He could not believe the attention that the issue attracted from the attending engineers. Blue prints, measurement charts and textbooks were ordered to the meeting. The dynamic overshoot mistake was real. The Director of Shuttle Engineering told my escort at KSC, who sat on the other side of the conference room, "*take him,* (i.e., me)*, to Marshall and Johnson. He should speak with* (names)."

In December 1986, I was ready to tell the reporters about the massive and widespread 100% dynamic overshoot blunder in Shuttle design, although I preferred to let NASA tell the story. On the eve of my meeting with a large NASA team at headquarters in December 1986, Dr. Burton Edelson, then Science Associate Administrator, called me from his office at NASA after 7 p.m. Burt said that "Dick" (Richard Truly) had just walked by and that he (Truly) requested that we (primarily me) "*should not leave the wrong impression out there,*" and some other ambiguous messages. I took that to be a specific request from Richard Truly to withhold the dynamic overshoot story. The next day, I appeared like an idiot at NASA and on television, where I tried to make a story about excessive loads in the Shuttle struts; but without the destructive dynamic overshoot, the real story.

Senator Kerry to Fletcher and Truly: "*excessive pressure, strain, etc.*" (January 22, 1987)

The "dynamic overshoot" blunder almost blew up in everyone's face in January 1987. In a Senate Hearing on January 22, 1987, Senator John Kerry of Massachusetts asked Dr. Fletcher and Admiral Truly about my work and the Shuttle excessive loads. Visibly uneasy, Fletcher and Truly dodged and sidestepped the devastating excessive loads issue.

> Senator Kerry: "*for the record purposes – recent reports --- which have received a certain amount of circulation suggesting possibly other considerations may also have contributed to it (Challenger accident); such as, struts due to excessive pressure, strain, etc.*"

Al Rossiter, later Vice President with UPI, was at the Hearing and he later told me that he sat on the edge of his chair thinking that the whole "excess loads" issue that I had raised was about to blow up in NASA's face. The picture of millions of pounds-force mysteriously propagating through the structures of the Orbiter, ET, SRBs, the Launch Pad and the delicate Shuttle cargo at lift-off was frightening to Rossiter. He had asked his UPI reporter at the Cape, Bill Harwood, to find out what was going on in my visit to the Kennedy Space Center in October 1986. Harwood was in touch with the NASA engineers with whom I had shared the "dynamic overshoot" mistake behind closed doors. He was also in touch with Rossiter. I thought that Harwood had put the dynamic overshoot story together from the NASA engineers. But even if Harwood put the story together, it didn't matter. Rossiter wanted someone in the government to break the story first.

In the Senate Hearing, Dr. Fletcher responded to Senator Kerry's inquiry:

> Dr. Fletcher: "*I think I can say without equivocation that we do understand what caused the accident, it was the field joint. Having said that, though, we have interviewed and spent a considerable length of time with some of the folks that feel that there might have been a structural failure.*"

Truly echoed Fletcher's words saying, "*I would echo Dr. Fletcher's basic answer. In the broadest sense of the word, we are absolutely confident that the cause of the accident was what was indicated, and that is the failure in the field joint.*" Senator Kerry then asked if Truly would dismiss *my* assertions:

> Senator Kerry: "*And would you dismiss any of those other assertions, at this point in time*?"

> Admiral Truly: "*Well, I treat them seriously, as a matter of fact, we are dealing with one now that we met with the individual and we didn't dismiss it. We are going back and doing some analysis to explain to him what we think the – what the facts were in the matter. But … and we are communicating with that individual.*"

I was not at the Hearing, but I was watching it on television. Truly's response, "***I treat them seriously***" indicated that he was going to take charge of the *excessive* overshoot loads. As a colleague later said, hiding the dynamic overshoot blunder was like trying to hide an elephant in a back pocket. It could take years, but the problem will always reemerge. Senator Kerry wondered why were there "*conversations and dialogue with him* (i.e., me)" if Fletcher and Truly were so confident about the field joint failure.

> Senator Kerry: "*..why the continuing dialogue? Is that been put to rest, or is there still an issue whether or not there is some credibility to those assertions of that individual.*"

> Admiral Truly: "*You said an important word, credibility. I think, for us to be credible, we have to continue to treat seriously technical opinions and advice that we get and we do so.*"

Admiral Truly dodged the issue of the "credibility" of my assertions. He was not at the Cape only three months earlier to see the solemn faces of the KSC engineers on seeing how the massive dynamic overshoot effect was completely misconstrued, miscalculated and confused. Did Fletcher and Truly receive a full report of my presentations at the Cape in 1986? I don't know. Exactly five years later after the Senate Hearing (January 1992), the "credibility" of my assertions was finally established. By then, Truly was asked to leave his post as Administrator of NASA.

The Congress sometimes works in mysterious ways. UPI's Rossiter is sitting on the edge of his chair waiting for the "mysterious forces" issue to blow up, but the Senator's time to ask questions was up:

> Senator Kerry: "*Mr. Chairman, my time is up now and I will stop now* .."

This Report was not available to the U.S. Senate and Rossiter, or Harwood, in that Hearing. Can you imagine if an old bathroom scale was brought into the Hearing and a 100-lb person was asked to step suddenly on the scale and for everyone to see a dynamic overshoot of, say, 73% on the dial? Why was the dynamic overshoot factor for the SSME's only 1.6% and not the measured 73%? Why was the dynamic overshoot factor for the SRB's only 10% when the real overshoot is 97%?

Senate Staffers (1987)

To have my work mentioned in a Senate Hearing, even without using my name, implied that some people recognized the significance of the issues that I raised in the Challenger investigations. But the number of people who knew about the dynamic overshoot blunder in 1987 was very small. To me, the dynamic overshoot mistake was (in 1987), and is (in 2000), the biggest and most widespread and consequential technical mistake of the 20th Century. It spread like cancer beyond the space program to the design of aircraft, power plants and other vital systems. I considered it imperative that government officials support the disclosure of the blunder publicly. I was not going to disclose the subject publicly alone. I met and spoke with some members of the Rogers Commission and others in the Administration and the Congress. There were times when I almost succeeded in getting official support to get my work into print. Martin Kress, the senior staff member on the Senate Space and Science Committees at the time, had expressed interest in my work. After my meetings at KSC, Kress arranged for me to meet with the U.S. rocket boosters' manufacturers in Washington, D.C. There were many important meetings to discuss my work, but I was excluded from all those meetings. Yet, I thought that Blakely, Kress and the others who knew about the transient loads from me would carry the message forward. As you now know, no one grasped the nature or enormity of the mistake. Kress tried privately to get my work published. For example, consider the following excerpts from Jay Lowndes (then editor-in-chief of AIAA's Aerospace America) to his reporter at the Marshall Space Flight Center, Dave Dooling, on July 1, 1987:

> *"I had occasion today to speak with Marty (Kress) on something I'm doing for August and so I sounded him out for you. He says: "Abutaha definitely warrants consideration. When are you guys going to publish a story?"*

There is something peculiar about the dynamic overshoot error, as the reader might have gathered from this Report. It really sounds far-fetched. I was accused of fabricating it. My detractors, inside and outside of NASA, genuinely disbelieved my assertions. Martin Kress is a typical example. Later, Kress became a skeptic. And so, the most consequential mistake that had undermined the whole space program went unrecognized and unreported for years.

<u>The Roll-out Story (June -July 1986)</u>

Many space reporters who covered the Challenger tragedy would be delighted to tell you about the roll-out story. So, let me tell you briefly about the roll-out issue myself.

When I first examined Volume I of the Rogers Commission Report in June 1986, I noticed that something was terribly wrong with the estimates of loads. For example, there were more forces going through the struts, that connect the boosters to the External Tank, than was produced by the SSMEs and SRBs. Where did the excess forces come from? NASA told the Commission that the lift-off loads were accurately calculated and measured. Well, if the lift-off thrust was not the source of the excess forces, what was?

Taking the struts' loads in the Commission Report at face value, I thought of different sources for the excess forces. All Shuttle missions before Challenger were launched from Pad 39A, which was also used to launch the Apollo missions to the Moon. Challenger was the first Shuttle to be launched from Pad 39B. There is a gentle turn to Pad 39A, but a sharp 90^o turn to Pad 39B. The more weight you put on a truck making a sharp turn, the greater the bending moment that will be transmitted. The Mobile Launch Platform moves extremely slowly, but its payload is well over five million pounds. The bending moment due to the sharp turn could be calculated accurately. I found out that the sharp turn to Pad 39B could explain some of the excess forces in the struts and, therefore, could have contributed to the Challenger tragedy. But then, I discovered that the published lift-off loads were wrong, and the loads in the struts were not representative because the struts were preloaded. The lift-off loads were not accurately calculated, nor accurately measured. My conjecture about the roll-out effect was wrong. To Richard Truly and Bob Crippen at NASA, the lift-off loads problem was over. To me, it was back to step one, what was the source of the excess forces?

The voluminous Appendices of the Commission Report, which were released in August and September 1986, made it abundantly clear to me that the source of the mysterious loads was specifically the transient dynamic overshoot effect. And so, <u>before</u> I traveled to the Kennedy Space Center in early October 1986, the transient forces were central in my mind, see my written question in Fig. 67. Roll-out was no longer an issue. The media did not know that.

On average, NASA used about ten boosters every year. There are more boosters in our defense systems and, frankly, that caused me more concern than the Shuttle problem. Before I went to the Cape in early October 1986, I arranged with a longtime friend Dr. Andrew Meulenberg, Jr., a senior scientist with COMSAT, to meet with an Assistant to General James A. Abrahamson, who headed the Strategic Defense Initiative Organization (SDIO). Drew and I visited the Officer at his home in McLean, Virginia on the eve of my departure to the Cape. I explained how roll-out was not an issue and that there was an enormous-excess-forces issue in the Shuttle, and possibly in defense systems, that required resolution. Drew was going to join me to the Cape, but he could not, and so I asked Blakely to come along. At the time, I did not have the type of evidence and analysis that you see in this Paper.

As I said before, I withheld the consequential dynamic overshoot mistake from the media in 1986. When I finally wanted to tell the space reporters about the massive blunder, in 1990, they did not want to listen. Some space reporters relished the possibility that they understood the complex Shuttle loads issue and they dismissed my work in print under the banner of roll-out.

<u>The Challenger Course (January 1989)</u>

I really wanted to work with NASA on the Shuttle transient problems in 1986. I was rooting for Burt Edelson, who successfully directed numerous space programs, to become the next NASA Administrator. Burt was familiar with my work, and I hoped to be asked to fix the dynamic overshoot problem in the Shuttle from the tip of the External Tank to the foundation of the Mobile Launch Platform. Some NASA managers asked me to join the Agency then. At the time, it appeared that Admiral Truly did not want me to be part of the Shuttle Recovery Program, even though I had identified the most serious design problem in the Shuttle. Anyway, the Shuttle Recovery Program was placed in the hands of Richard Truly, J. R. Thompson, Bob Crippen, Bill Lenoir, Bonnie Dunbar and others. I stepped aside to allow them to fix the dynamic overshoot blunder and the other problems.

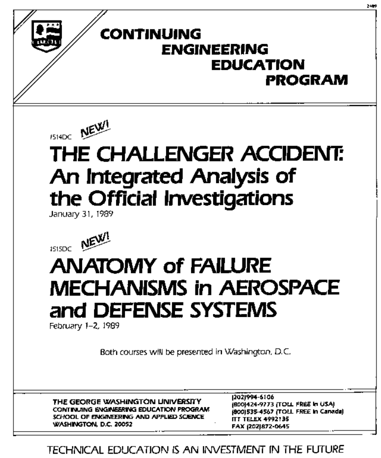

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Fig. 68 Challenger Course - Canceled Immediately

In early 1989, I prepared a short course on my Challenger accident work. The Course was given in the Continuing Engineering Education Program (CEEP) at the George Washington University on January 31, 1989. I was still waiting for NASA to publicly announce the dynamic overshoot mistake in the Shuttle and what the Agency did about it in the three years. Even though I did not yet make full public disclosure of the overshoot mistake, my Course was well received by engineers from NASA, the aerospace contractors and several Air Force bases.

The feedback from the attending engineers was phenomenal. The Course coordinator said that my Course received the highest ranking in the CEEP Program. The comments of the engineers showed that they understood the voluminous data that were presented in the course. A sample "critique" from one of the senior engineers in attendance read:

> *"Since there is no "cook book" method for failure analyses, the lecturer, in my opinion, very effectively demonstrated the need on the investigator's part (be it a committee or an individual) to be open-minded, objective, imaginative, keen minded and especially able to reconsider in terms of engineering/scientific multi-disciplinary basis all aspects, data, information, no matter how detail or apparently insignificant, before dismissing them as non-contributing to the evolution of the most plausible cause."*

Another engineer wrote:

> *"I found the entire course extremely interesting and potentially beneficial relative to my job responsibilities."*

The connection between the "dynamic overshoot" mistake by the Shuttle engineers and similar mistakes by my co-workers at COMSAT and INTELSAT in the 1970s did not escape the attention of the engineers, as one of them wrote:

> *"Instructor was very knowledgeable and had interesting/pertinent instances as analogies. Subject matter would greatly benefit co-workers."*

The primary thing missing in 1989 was to know, what did Admiral Truly and his Team do with the dynamic overshoot mistake in the two years since the Senate Hearing mentioned above? How did they fix the problem? Did they change the ramp-up of the SSME's? Did they change the burn pattern of the SRB's? Did they discover new ways to get around the vexing transient start-up conditions? And, what were the new solutions? At the time, I was still waiting for NASA to make the first public announcement of the dynamic overshoot blunder. I thought that Truly, or the Reagan and subsequently the Bush Administrations, would want to placate the enormity of the mistake with political words. Nothing was said about the dynamic overshoot.

I thought that my Course on the Challenger Investigations, which received highest ranking in more than one thousand courses, was there to stay. It was canceled immediately. Why? Here is one reason.

Royce E. Mitchell, Manager of Solid Rocket Motor Project Office at the Marshall Space Flight Center sent a letter to Dr. Stephen J. Trachtenberg, President of the George Washington University, dated Feb 28, 1989, and copied to J.W. Perkins, Director of CEEP at GWU, and to me. I had not met, or heard of, Mitchell before. Mitchell wrote to Trachtenberg:

> *"I was surprised to receive the enclosed course brochure and cover letter and find that your institution would sponsor the courses – "The Challenger Accident: An Integrated analysis of the Official Investigations" and, "Anatomy of Failure Mechanisms in Aerospace and Defense Systems" – by Ali F. Abutaha."*

Mitchell concluded his letter with the seemingly intimidating remark:

> *"I suggest that you seriously review your Continuing Education course screening process."*

What attracted my attention in Mitchell's letter was the last sentence in the middle paragraph (underlined below). Here is the whole paragraph:

> *"I have been exposed to a number of Mr. Abutaha's qualitative analyses regarding the Challenger accident, and I find them to be flawed and his conclusions unsupportable. There has been no physical evidence, math modeling nor fault tree logic which refutes the investigative findings of the Presidential Commission or the several astute oversight committees, the Congress, NASA or leading members of industry. Further, the implication in the Abutaha cover letter that "(his work) led to major modifications to the Space Shuttle" is unfounded."* (Emphasis added)

The last sentence led me to suspect that Mitchell and his co-workers at MSFC were trying to claim my transient analysis of 1986 to be their own. That made me angry. Let me explain. The dynamic overshoot blunder must be fixed in the Space Shuttle, satellites, probes and related systems, as well as many other modern engineering systems, including aircraft, nuclear power reactors, etc. The mistake was not only made by von Braun, Mitchell or Truly. The most eminent scientist in history, Sir Isaac Newton, made the same mistake, as I explained in this Report.

Again, "*To every action, there is an equal and opposite reaction*." This is Newton's Third Law of Motion. In engineering, we turn these simple words into complex notations and we do complicated mathematical analyses to design the shuttle and other things. But, I have shown the reader repeatedly and unequivocally that the reaction is not always equal to the action, particularly when we start up a rocket. Did you ever hear anyone say, "*To some actions, the opposite reaction is 1.73 times the action*, as in the case of the SSMEs? This value was actually measured by NASA. Did you ever hear anyone say, "*To some actions, there is an opposite reaction that is 1.97 times the action*, as in the case of the SRBs? Did you ever hear anyone say, "*To some actions, the opposite reaction is nearly double the action*, as Mitchell and his colleagues did with the BSM? I was content to let NASA fix the dynamic overshoot blunder in the Shuttle without my participation, but I was not about to let others claim my work to be their own. The dynamic overshoot blunder in not about a mistake made by mortals at Marshall or Johnson, it is about a mistake made by geniuses, such as the incomparable Newton. As you will see later, Mitchell & Co. did not fix the dynamic overshoot mistakes in the Shuttle nor did they grasp the nature and enormity of their mistake, but they succeeded in canceling my Courses. I had paid for all the effort to tell NASA and others about the blunder. To gain credit for uncovering the mistake and for delineating many aspects of the blunder, I eventually resorted to the Federal Courts. But, the dynamic overshoot was an enigma, even to the federal judges.

Challenger Course Canceled (1989)

The President of the George Washington University, Dr. Stephen Trachtenberg, formed a committee to look into the Mitchell letter. No one from the Committee spoke with me. I was told politely that the Challenger Course was not acceptable. The course was canceled.

Afterwards, I established again that the mechanical engineering faculty at my *alma mater* was still not well acquainted with the correct start-up dynamic overshoot analysis. The mechanical engineering design professor who used the Shigley *Mechanical Engineering Design* textbook since the 1960s was not even aware of the inconspicuous doubling equation in that textbook in the 1990s. The professor insisted that the doubling effect that I was speaking about had no basis whatever in engineering. When I showed him the nearly hidden Shigley doubling equation (Eq. 1 in Sec. 4), his face turned red. It now seems that my Course was canceled not only because of the Mitchell letter, but also because of the uninformed and biased recommendations that Dr. Trachtenberg might have received from the faculty.

NASA Closed-Doors Hearing (October 1989)

I arranged for a Hearing at NASA headquarters in October 1989. I asked the Agency to investigate my technical input concerning the "excess loads" issue that I shared with NASA at the Kennedy Space Center in October 1986. I was asked to choose between closed-doors or open hearing. Sharing the "dynamic overshoot" mistake behind closed doors and only with NASA in 1986 was my decision. It was primarily based on national security considerations. A 100% blunder is not the type of thing you throw out in the street. Truly and his Teams had three years to fix the problem, and this time I opted for an open hearing. This time, I wanted the world to hear about the dynamic overshoot blunder.

Two dynamics experts from the Marshall Space Flight Center, R. Ryan and T. Bullock, were brought into the hearing as NASA Technical Advisors. Ryan and Bullock presented the confused base bending moment curve that you see in Fig. 29A. I was not given a hard copy of their presentation at the hearing. I subsequently requested, and was given, a copy of the NASA presentation. Concealing the "*quantitative*" value of the base bending moment from the base bending moment Figure added to my mistrust of what the engineers were doing. As I described in Section 8.4, including the 90% SSME's thrust point in Fig. 29A exposed the engineers' complete unfamiliarity with the important transient overshoot subject. They had no idea where the peak dynamic overshoot should be relative to the 90% SSME's thrust. When I used the NASA 1989 base bending moment figure in a paper submitted for publication, one of the peer-reviewers (who seemed to be very familiar with the figure) wrote:

> *"The figure shows the large difference of the residual moment at release, thus lowering "twang" loads. The fact that this qualitative curve does not graphically nor quantitatively describe the intermediate moment is irrelevant - - the ordinate is not even scaled."*

"The ordinate is not even scaled," wrote the peer-reviewer dismissingly. The reader can see why I dealt with this matter in great detail in Section 8. The enormity of the error is shown in Fig. 29B, where I added the correct "dynamic overshoot." How can anyone, even in a qualitative curve, fail to notice and show a 100% (doubling) effect? The peer-reviewer remark highlights what I said earlier that the engineers were primarily concerned with reducing the base bending moment from the 90–100% level to the trough level, without ever realizing that the *"intermediate"* moment doubled in the process. The base bending moment was doubled 'in value' without realizing why.

After the hearing in October 1989 and despite the glaring evidence, the Shuttle engineers were as much in the dark about the dynamic overshoot mistake as they had been since 1972. The space agency refused to revisit the potential blunder issue again.

Greg Kitsock, a reporter with the Washington City Paper called me after the hearing to say that he was not allowed to attend the hearing. I also discovered that other people could not attend. Apparently, this time NASA selected to have the discussion behind closed-doors without telling me.

<u>Defense Science Magazine, "*If We Don't Tell It, Who Will?*" (March 1990)</u>

One reporter managed to attend the NASA closed-doors hearing, and that was Dr. Jay Lubkin of *Defense Science* magazine. Lubkin had written extensively about hi-tech defense systems for years and he had written about my Challenger related work since 1988. Jay was astounded by what he heard and saw at the NASA hearing, and he wrote a scathing article on the Shuttle dynamic overshoot blunder in the April 1990 issue of *Defense Science* magazine titled, *"Four Years Since Challenger, What Did NASA Know? When Did They Know It?"* Robert daCosta, Editor-in-Chief and Chairman of *Defense Science*, introduced the Lubkin April article in the March 1990 issue under the editorial title, "*If We Don't Tell It, Who Will?*" daCosta wrote:

> *"A fine engineer named Ali AbuTaha, through a detailed investigation of his own at great personal expense, did find out what really happened to the Challenger, and now teaches two short courses on the subject at George Washington's School of Continuing Engineering education program. It was pointed out by Dr. Feynman that NASA lied in order to get continued funding. Dr. Lubkin pointed out that they then spent three years and billions of dollars fixing an imaginary O-ring problem."*

Jay's writing is piercing, and NASA did not escape his sharp wit as he described in the April 1990 issue the proceedings in the NASA hearing that he, somehow, managed to attend:

> *"Ryan did not present a technical case, except to say that people like Hoot Gibson and John Young didn't understand the problem. Ryan spent an hour talking about the convoluted levels of decision making at NASA, and how it was impossible that NASA could have taken AbuTaha's findings and used them because the decision process at NASA was so involved that almost no changes can ever get through the system."*

Lubkin went on:

> *"The saber-toothed tiger can make a Big Mac out of the brontosaurus' tail long before the brontosaurus' brain gets the message that something is wrong. It turns out that NASA had the information of the cause of the Challenger disaster years before the Challenger tried to fly. <u>They still have not fixed the problem</u>."*

The Defense Science article used base bending moment figures from my papers, particularly, Fig. 29B, which showed no "dynamic overshoot" by the NASA engineers as late as 1989.

Royce Mitchell who wrote the intimidating letter to the George Washington University to cancel my Courses was possibly right. Jay Lubkin was also possibly right when he wrote, "*They still have not fixed the problem.*" What did NASA do with the dynamic overshoot mistake? Nothing. What corrections did they make? Apparently, none. Robert daCosta had written editorials on my work before. In the May 1988 issue, he introduced another Lubkin article in the editorial page, writing:

> *"We hope this article and the evidence it provides will lead our Congress to demand a reexamination of the Challenger incident."*

<u>Leippe to *Defense Science*</u>

Defense Science was widely read, and appreciated, in the military communities. Lubkin's articles on my work generated many letters-to-the-editor, both pro and con. David L. Leippe, a pilot with United Airlines in 1986, happened to be flying off the coast of Florida when the Challenger exploded. Leippe and the crew of the Boeing 727 saw the flight and the explosion from a unique angle. After landing, the crew recorded their observations independently, and Leippe volunteered to share those observations with the official investigators. Understandably, Leippe was upset that the investigators declined to speak with him or the other crew. I did. We discussed what the crew saw on that tragic day. In a letter to *Defense Science*, August 1988, Leippe wrote:

> *"I have been in touch with Mr. AbuTaha from time to time since Fall 1986. I am an airline pilot, ex-military pilot, graduate of the USAF Academy, and once involved with an organization named ASAP …with an interest in training civilian shuttle pilots.*
>
> *"My observations seem to support Ali's observations and calculations very well. My greatest concern is, like Ali, that everything get fixed. But it appears that the fixes and problems, and exact cause of death are being covered up "Watergate" style.*

David Leippe's career and my career took sharp turns in the late 1970s precisely because of the dynamic overshoot blunder. I mentioned how the Shuttle failures of 1978 led me to leave my aerospace job. For the young readers, and others who have forgotten, rich people had signed up, and some made down payments, for space trips on the Space Shuttle in the 1970s. Pilots like Leippe were training for the upcoming Shuttle *fleet*. There was no *fleet* by the end of the 70s, there were no Shuttle flights by the end of the 70s; there was *doubling* of the tiles adhesive strength and similar corrections to counter mysterious forces that were "*difficult to calculate,*" according to NASA and Rockwell. The dynamic overshoot error was beginning to take a greater toll on the whole space program. Before the Shuttle, the design blunder cost us time and money, after the Shuttle, the blunder cost us lives and the space program itself. Those who worked on the space program in the 1960s and 70s know that the space program in 2000 is not anywhere near what we anticipated, hoped, and worked for.

***Defense Science* Silenced**

Without sponsors, a trade magazine is dead. Not long after publishing feature articles and letters-to-the-editor on my Challenger investigations, a valuable military technology information publication, *Aerospace & Defense Science magazine*, was silenced. The reason was the coverage it gave to my Shuttle-related work.

Editors of European *Space* magazines wrote to tell me that they did not cover my shuttle-related work for fear that they would lose access to NASA and the support of advertisers, primarily, the Shuttle Contractors. Others gave their readers a one-sided story, for example, Donald E. Fink, Jr., the Editor-in-Chief of Aviation Week magazine, wrote me a letter, dated November 11, 1986, saying, **"***We can only relay to our readers what NASA's engineers determine as a result of their studies."* So, if Richard Truly and his engineers said that there is no dynamic overshoot, then there is no dynamic overshoot. And the readers of AW&ST and others, who were making the dynamic overshoot mistake before and after the Challenger tragedy, were left in the dark.

Of all the glossy defense, science, technology, aviation and space magazines, *Defense Science* distinguished itself by giving thorough analysis of contemporary issues by highly qualified military technical experts. Its *Editorial Advisory Board* included prominent defense and science people, including, Dr. Edward Teller, the father of the hydrogen bomb. The Chairman of *Defense Science*, Robert daCosta who lives in Florida, visited me at home to see the evidence first-hand. He told me how the magazine was in trouble primarily because of the coverage of my work. We contacted some prominent people in the Washington DC area, who had good relations with the companies involved. But the feedback that these people received from NASA and others was that my work was "rubbish." We could not generate any support to save the magazine. *Defense Science* was silenced and it stopped publication. The only meaningful voice in the American media that could have forced NASA to take the dynamic overshoot issue seriously was out of the way. And we would swim in the consequences of the dynamic overshoot blunder for two more years.

<u>Dynamic Overshoot Blunder Bottled Up</u>

Getting the dynamic overshoot blunder to the rank and file in aerospace engineering was frustrating. Here are some examples:

1. In 1987, I was invited to write on my Challenger work for *Aerospace America*, a publication of the American Institute of Aeronautics and Astronautics (AIAA). The article was canceled just before publication, and after the editors received a scathing letter from a prominent professor.

2. I was invited to talk to the AIAA Conference on Dynamics in 1987, but my "invited talk" was canceled just before I was to leave to California for the Conference.

3. The Chairman of the Dynamics Committee of a subsequent Conference, Dr. Keto Soosar, became greatly concerned with the *dynamic* overshoot issue in the Shuttle, and I received another invitation in 1990 to give a talk at the AIAA Dynamics Conference. Before I left to California, Keto called to tell me that the invitation was canceled. Some senior engineers from NASA and elsewhere had threatened to walk out on my talk, and have all the other engineers walk out. I did not attend the conference.

4. Peer reviewers from the AIAA's *Journal of Spacecraft and Rockets* insulted me personally and professionally in comments to my dynamic overshoot papers submitted for publication. They were 100% certain that I was 100% wrong, and that the transient overshoot error was a figment of my imagination. The peer reviewers were senior engineers, from NASA and shuttle contractors, who designed and operated the Shuttle. One reviewer began his comments as follows:

   > *"The subject report in its entirety reflects lack of understanding of the development of shuttle and SRB design loads criteria and the structural certification process. The report in its entirety is based on false assumptions and therefore has led to false conclusions on the author's part. The report could be very misleading to those who are not familiar with shuttle design loads, specifications, and certification and therefore it is recommended that this report not be accepted by the AIAA for publications."*

   Another reviewer wrote:

   > *"The subject manuscript is totally unacceptable. The author has misunderstood and miscalculated a large number of factors in the design and operation of the Space Shuttle and has thus evolved numerous errors toward creating a non-existent, fictitious "problem."*

   According to the above Shuttle engineers, I don't understand it and the "dynamic overshoot blunder" is "*a non-existent, fictitious problem."* The reader can see why I used the trivial examples of the old bathroom and vegetable weight scales and the slinky in this Report, and why this very lengthy Report. The "blunder" is not fictitious; it is real.

5. The publications of the American Society of Mechanical Engineers (ASME) were quick to reject my "dynamic overshoot" paper. Their counterparts in England, The Institution of Mechanical Engineers, were kinder (or maybe smarter). The Managing Editor for Proceedings, Judith Constantine, wrote me on March 30, 1992,

   > "*The Editor of the Journal of Aerospace Engineering (Part G, Proceedings) has reviewed your paper. <u>He thinks it is an excellent piece of work with far-reaching consequences</u>*."

The massive record just simply cannot be included in these pages. In short, the "dynamic overshoot blunder" was bottled up very tightly. The next two years would see the most embarrassing phase in post-Challenger operations with repeated fuel leaks, launch scrubs and damaged payloads – caused by the same controversial "dynamic overshoot blunder."

<u>The Congress (December 1991- January 1992)</u>

Not many people in the Congress knew about the dynamic overshoot blunder in 1986. Only officers and engineers, from NASA, DOD and other offices, who heard me speak about the dynamic overshoot, were aware of the details of the widespread and huge mistake. I wished then that the technical staff in the Congress were more receptive to hear me out. By the end of 1991, the evidence was overwhelming, and the Congress recognized the nature and the magnitude of the dynamic overshoot mistake in space and Shuttle design. This can be seen in a letter from the Chairman of the House Committee on Science, Space, and Technology, then, Chairman George E. Brown, Jr., who wrote me on December 13, 1991:

> *"… Our staff has carefully reviewed every submittal that you have made to this Committee over the past five years. When necessary, this review has included technical consultations with appropriate experts at NASA, the aerospace industry, and, when they were in being, with members of the technical staff of the Rogers Commission and the National Research Council committee assigned responsibility for overseeing the design and development of the Redesigned Solid Rocket Motor. As I am sure you will appreciate, <u>reconciling conflicting views</u> on <u>a highly technical subject</u> can be <u>a very complex task</u>."*

The reader can see from this Report how "a simple task" turned into *"a very complex task."* How do you reconcile *conflicting views on a highly technical subject?* For my part, it was easy. The Shuttle engines (SSMEs) produce "dynamic overshoot" or "surge forces" at start-up. The Shuttle engineers measured 73% (seventy three percent) dynamic overshoot in 1982, but the overshoot was not included in Shuttle design. That's it. That's all there is to it. Case closed. But the Congress must listen to the other experts. Look at what one of the AIAA peer-reviewers wrote in January 1991 (ten years after the dynamic overshoot measurement):

> *"Because Mr. AbuTaha's paper is based on an erroneous assumption at the onset, his rationale has no basis. His paper contains repetitious charges and manipulation of numbers in his atempt* (sic) *to prove that a fundamental oversight existed which he claims to have discovered,"*

A "very simple task" turned into *"a very complex task"* because the <u>few</u> engineers responsible for the "overshoot effect" were completely in the dark about the destructive effect. Literally, a few engineers ruined our space program. Chairman Brown concluded his December 1991 letter with a kind invitation:

> *"In the future, should you wish to share any new information with us, we will be pleased to give that information the same level of close scrutiny that we have given all of your previous submittals."*

The former Vice President Al Gore, Jr., then Senator and Chairman of the Senate Subcommittee on Science, Technology, and Space, also expressed interest in following-up on my "*transient-forces*" paper. Mr. Gore wrote me on January 24, 1992:

> *"I have yet to review the material you enclosed with your letter. Be assured that I will notify you of any action that the Subcommittee may take in the future with respect to your request."*

Other senators wrote to me expressing their interest in the "dynamic overshoot" issue then. But then the interest waned. Did the anti-dynamic-overshoot experts win again? I don't know. Unless the universities and professional organizations recognized the massive design mistake, I wanted the Congress to *legislate* that the destructive "dynamic overshoot" effect be included in the design of every airplane, launch vehicle, satellite and power facility. At the time, NASA had not yet publicly acknowledged the transient-dynamic-overshoot mistake in the Space Shuttle, which is described next.

<u>Finally, NASA admits 100% Transient Overshoots (March 24, 1992)</u>

The most embarrassing phase in the post-Challenger Shuttle operations were the fuel leaks during 1989-92. Mission after mission was delayed or scrubbed because of fuel leaks. There were embarrassing daily press conferences when Truly, Crippen and Lenoir tried in vain to explain the problem to the space reporters and to the American people. The Shuttle was not fixed.

I mentioned before how the infamous fuel leaks were caused by the same "transient dynamic overshoot" that you have read about in this Report. Can you imagine how Admiral Truly and his assistants felt when they were told that the fuel leaks were caused by the same dynamic overshoot blunder that they were quarreling about with me <u>at the same time</u>? This time, the revelation came from NASA itself. Just read what Shuttle Launch Director, Bob Sieck, said in a press conference on March 24, 1992 (see Fig. 60):

> ***"We scrubbed because of … transient leaks,"***
>
> ***"This was a <u>transient</u>-leak condition due to the thermal environment…"***
>
> ***"We expected to see the transients again, and we did."***
>
> ***"When you really look at the data with a magnifying glass," he replied, the thermal <u>transient</u> … "had been there before on a number of missions,"***
>
> ***"<u>The amplitude of the spike … was probably 100% more</u>."***

"*The amplitude of the* (transient) *spike … was probably 100% more*!" That was when the reporters with the funny hats in the old Black & White movies ran excitedly to the telephones in the hallway to call their editors with the news: "The overshoot in the Shuttle can be 100%!" Most of the reporters in the press conference knew about my work and about the controversy that raged between NASA and me over the years. None of the reporters wrote a word about the shocking revelations. Perhaps, none of the reporters thought it was shocking.

Everyone working on the Shuttle must be told that sometimes, "*the reaction can be greater than the action*." In the 1960s, we were taught: A rocket produces 1 million pounds thrust. Design it. We picked up our slide rules, did convoluted analysis, added safety factors and designed the rocket. The professors did not tell us about the dynamic overshoot. The consequences were terrible. The *NASA Select TV* would continue throughout the 1990s to teach young students, the future Shuttle engineers, the wrong lessons: "*To every <u>action</u>, there is an <u>equal</u> and opposite <u>reaction</u>*."

After the Sieck press conference in 1992, I thought that NASA would spearhead a campaign to wipe out the dynamic overshoot blunder, not only from the Space Shuttle or its payloads, but also from all other modern systems and from all science and engineering curricula. None of that happened.

After Bob Sieck's exposé of the transient dynamic overshoot blunder in plain language in March 1992, I was honored to receive a letter from President George H. W. Bush and to be selected a 1992 Presidential Trust Delegate from the State of Virginia by the President on June 19, 1992. I was also honored to receive a Certificate of Commendation from Vice President Dan Quayle on July 17, 1992. The Vice President's Office was active and effective in 1990-92 to get to the bottom of the dynamic overshoot controversy that raged between NASA and me. I was also honored to be endowed with a Republican Congressional Order of Liberty, to be selected a Distinguished Life Member in the Armed Forces Communications and Electronics Association, Member of the Year of the Challenger Society, and to receive numerous certificates and letters recognizing my effort. For example, John H. Darrah, Chief Scientist and Technical Advisor in the Department of the Air Force, wrote me on May 26, 1993:

> "*Air force Space Command appreciates the effort you have expended to make us aware of a potential problem area that might adversely impact our current and future launch vehicles.*"

<u>The Dynamic Overshoot Saga Turns Into A Nightmare (1993)</u>

I thought the dynamic overshoot saga was over in 1993, but the saga turned into a nightmare.

One official from NASA told me in 1992 that those who were involved in the dynamic overshoot controversy had either left the agency voluntarily or were fired. I hope the reader did not get the impression from this Report that my intent was to get people fired or punished. My intent has always been specific, loud and clear: Understand the problem and fix it. The enormous mistake kills innocent people. The dynamic overshoot blunder has more lives than a cat. It lives on.

For six years, I could not understand how the Shuttle engineers convinced the Presidential Commission that there were no excess forces at lift-off. How did the engineers persuade the White House that there is no dynamic overshoot in the Shuttle? How did they convince the Congress that the dynamic overshoot does not exist in the Shuttle? How did the engineers convince themselves that the destructive dynamic overshoot does not strike across the whole vehicle? Here is how.

I received a letter from Paul J. Weitz, Acting Director of the Johnson Space Center, dated October 13, 1992. Confidently, Weitz tried to explain to me how the dynamic overshoot "*near-doubling*" that I spoke about does not exist and how NASA "*intentionally*" controls the overshoot to less than "*2 percent!*"

> *"The dynamic overshoot "near-doubling" you state on page 2 of your proposal does not occur in Space Shuttle main engine startups. <u>Chamber pressure is intentionally controlled to prevent overshoot greater than 2 percent above rated thrust level during the approximate 5-second Space Shuttle main engine start transient."</u>* (my emphasis)

Do you believe this? Do you believe that the *"rated thrust level"* (this is the 100% RPL I mentioned at the end of Section 4 of this Report) is *controlled* to less than *"2 percent?"* Weitz does not realize what he is telling me here. Do you remember the 100-lb lady example? Weitz is saying that they control the weight of the lady between 98 lbs and 102 lbs (his *2 percent*). He does not realize that the *structural engineers*, like myself, are expected to design the old bathroom scale. The structural engineers are not expected to design the lady! The analogy is straightforward: The aerospace structural engineers are supposed to design the Shuttle structures that actually experience the brunt of the dynamic overshoot forces, and not the "input pressure," which fluctuates by Weitz' 2%, but does not overshoot!

Weitz says that they control the *"chamber pressure"* to *"prevent overshoot greater than 2 percent above rated thrust level."* Then, where did the 73% "excess upward force" that NASA itself measured in 1982 come from? No wonder the test engineers at Marshall were confused ten years before Weitz' letter when they measured a "dynamic overshoot" of 73% for the SSMEs' liftoff thrust (as I calculate), instead of a mere 2% overshoot (as Weitz claims), see Sec. 7. You can see why those engineers asked the "$64,000 Question" of the Shuttle upper management Level II in April 1982 – see Sec. 8.1. I said that I was unable to find the response of Level II to the engineers' question: Is the liftoff thrust 1.1 million pounds, that Level II initially calculated, or is the liftoff thrust 1.9 million pounds, as the engineers measured in 1982? Weitz' 1992 letter is the Level II answer. What no one seems to realize since the early days of rocketry is that the rapid pressure build-up in a *"pressure chamber"* finds a hole in the *"chamber"* – the nozzle, and the pressure fluctuates, but does not overshoot. The forces overshoot. I wrote to Weitz. He did not answer.

When NASA and its Shuttle contractors run into technical problems, they go to high-powered consulting firms and individuals for help. Three days before the Weitz letter, October 10, 1992, I received a fax from an expert, whose company helps NASA with failure analysis. This expert wrote me:

> "*I earned my doctorate in the System Dynamics and Controls division of the ME (*mechanical engineering) *at MIT* (Massachusetts Institute of Technology). *I believe that anyone with a background in system dynamics would quickly conclude after reading your material that you don't.*"

The above message betrays the psychological barrier that has undermined the ability of the experts to grasp the nature of their blunder. My *material*, evaluated by the above correspondent, was mathematically abstract technical in nature. He did not get it, so, he insulted me outright. Notice how the arrogant MIT graduate did not give me, or the reader, anything to evaluate. At the time, I did not use the silly examples of a 100-lb lady stepping suddenly on an old bathroom scale or a bag of potatoes released suddenly on a weight-scale in a supermarket. The silly examples are now handy. The MIT expert, like Weitz and others, thinks that he is designing the lady or the potatoes and not the bathroom or the supermarket weight-scales! I mentioned before a lengthy telecon over the dynamic overshoot blunder with the distinguished MIT professor, Eugene Covert, a member of the Rogers Commission that investigated the Challenger tragedy, and how Dr. Covert summarized the sad situation with the sentence, "*You can lead a horse to the water, but you cannot make it drink*." The above MIT expert could have been one of Dr. Covert's students. I think the MIT expert can calculate the dynamic overshoot for the SSME (73%) and for the SRB (96.9%). He did not get the simple message: Add the dynamic overshoot and the thrust to obtain the maximum design values. NASA uses the services of the expert and his company to evaluate failures in the Space Shuttle. This gives a special meaning to the expression, the blind leading the blind.

Not everyone was blind. A distinguished professor of mechanical engineering, former undersecretary for technology with DOD, former Corporate Director of R&D with a major aerospace company and other credentials had read the same *material* mentioned by the above MIT-graduate. This top national expert recognized how the Shuttle engineers, and others, have been confusing the overshooting forces and the non-overshooting pressures. He wrote me in July 1993:

> "*I had the opportunity of reading your papers concerning the correct way to handle transient loads in pressure-activated structures, and found them to be very enlightening. The errors you point out in calculating transient loads are indeed fundamental.*"

Another expert wrote:

> "*The problem seems to be far more serious than I had imagined. I hope the material gets into the hands of someone who can act on it.*"

Face-to-face discussions with the engineers were valuable. Admiral William D. Houser, a former COMSAT executive, arranged a meeting with other senior retired officers and some engineers who had worked on the *recertification* of the Shuttle boosters after the Challenger accident. It took a while in the meeting before the engineers began to realize the reality of the overshoot mistake and the enormity of the error in Shuttle design. One of the engineers wrote a letter, dated October 13, 1993, which he requested be copied to Admiral Houser and to me. In the letter, the engineer wrote:

> *"I have been trying to recollect all the ignition work I performed on the Shuttle SRMs during the flight recertification process – after the challenger accident. I do not remember the ignition overshoot being the most significant factor as far as the overall Shuttle structure."*

The reader can see how teams from NASA, the industry and universities continued to use the 100% RPL for SRB design well into 1990 – see Sec. 9.1. And rather than produce boosters good for hundreds, or thousand, missions, the boosters failed badly in one mission in 1991 – please refer to Section 10.4.

The dynamic overshoot saga was a brutal roller coaster ride. Every time I thought the message got through loud and clear, someone, "*who can act on it*," jumped in with a silly idea. On September 8, 1993, the Director of Space Shuttle Operations, Brewster H. Shaw, wrote me a letter claiming to have no knowledge about the *transient load design deficiencies* in the Space Shuttle. Shaw wrote:

> *"Nothing in our postflight assessment process indicates any problems with transient load design deficiencies, and we are confident that our development and flight verification activities have successfully demonstrated the capability to sustain the transient loads experienced by the systems."*

Did Shaw hear Sieck? Did Shaw speak with Weitz? Did Shaw read, and comprehend, my Report? Valuable payloads were damaged after the Challenger, the Shuttle was grounded because of the transient overshoot effects in the fuel leaks, pieces continued to fall off the Shuttle during ascent, the boosters experienced serious damage in one flight, but Shaw saw *"nothing"* in the record that indicated transient load design deficiencies. After all the progress that I achieved with the deadly blunder, Shaw's assertions were the penultimate regression. Shaw proves my summary of the "dynamic overshoot blunder" at the beginning of the above Recommendations Section. The tiles' strength doubled, the stiffeners in the aft boosters' segments doubled, the pins in the ET/SRB attachment doubled, the BSM design thrust doubled, and so on. NASA and the contractors related all the doubling corrections to the start-up transient effect. Do you see my point? The Shuttle experts will absolutely eventually *"find and fix the thousand problems caused by the one mistake* – the dynamic overshoot blunder – *one at a time*.

Hundreds of engineers attended my Continuing Engineering Education Course, *"Anatomy of Failure Mechanisms in Modern Systems,"* which was given on-campus and at public, private and military centers at home and abroad. Generally, the engineers knew about the transient analysis and structural design. But, just as I described in this lengthy Report, the engineers really did not know about the transient dynamic overshoot blunder. Three days of extensive presentations and analyses convinced the engineers of the reality and enormity of the dynamic overshoot blunder. I tried to guide the engineers beyond Thompson and von Braun to recognize a mistaken assertion that is taught at all levels, e.g., *"to every <u>action</u>, there is an <u>equal</u> and opposite <u>reaction</u>."* The words of the engineers tell the story:

> *"Thought provoking course."*

> *"This was very informative and will influence critical thinking for sure."*

NASA selected not to think *critically* about the dynamic overshoot blunder. In August 1993, NASA asked me firmly in writing to cease all contacts with the Agency. I did. Did that mean that the Shuttle engineers finally understood, and fixed, the dynamic overshoot mistake? No.

In 1986-87, I discussed my work at length with David Acheson, a member of the Rogers Commission on the Challenger Accident, in his Washington, D.C. office, and he attempted to convince NASA to take my assertions seriously. Mr. Acheson is an attorney, a former officer with COMSAT in the 1960s-70s, when I was testing the dynamic overshoot effect. NASA snubbed the distinguished Presidential Commissioner publicly. Here are some words from Mr. Acheson's last consolation letter to me, dated December 7, 1987:

> *"There is no way I know to compel agreement of someone who honestly disagrees with you. The important thing is not to take it personally as a slight on your honor or competence. No one has made any such implication or intends any."*

> *"I see no useful role for myself in such a thankless effort, much as I admire your thoroughness and dedication. Perhaps the time has come for you to take disagreement philosophically and turn the page on this chapter."*

When I read the words of my detractors, I can see that these experts "honestly" believe that the dynamic overshoot blunder is a figment of imagination. This Report shows the stark reality of the design blunder. No level of appropriation and authorization by the Congress will ever achieve safe, economical and effective space flight before all the aerospace scientists and engineers are compelled to honestly comprehend the nature and the magnitude of the dynamic overshoot mistake.

Do you remember Plato's allegory of the cave? One day, the engineers who "honestly" disagreed and quarreled with me over the major dynamic overshoot mistake will walk out of the cave into the brightness and they will panic from the enormity of their mistake. When that happens, the question will not be, "how do we fix the Space Shuttle?" Rather, the question should be, "how do we fix the space program?"

References

1. Shigley, J. E., "*Mechanical Engineering Design*," McGraw-Hill Book Company, Inc., New York, 1963, p. 69.

2. Thomson, W. T., "*Vibration Theory and Applications*," Prentice-Hall, Inc., New Jersey, 1965, Ch. 7 on Transient and Nonperiodic Vibration

3. D'Azzo, J. J., and Houpis, C. H., "*Feedback Control System Analysis and Synthesis*," McGraw-Hill Book Company, New York, 1966.

4. Hurty, W. C. and Rubinstein, M. F., "*Dynamics of Structures*," Prentice-Hall, Inc., New Jersey, 1964, Ch. 7 on damping.

5. Amrosius, E. E., Fellows, R. D., and Brickman, A. D., "*Mechanical Measurement and Instrumentation*," The Ronald Press Company, New York, 1966.

6. McDonald, A. C., and Lowe, H., "*Feedback and Control Systems*," Reston Publishing Company, Inc. A Prentice-Hall Co., 1981.

7. Peer reviewers correspondence, "*Journal of Spacecraft and Rockets*," AIAA, February 1991.

8. Sutton, G. P., "*Rocket Propulsion Elements*," John Wiley & Sons, New York, 1986.

9. Goodger, E. M., "*Principles of Spaceflight Propulsion*," Pergamon Press, Oxford, 1970.

10. Shepherd, D. G., "*Aerospace Propulsion*," American Elsevier Publishing Company, Inc., New York, 1972.

11. Hill, P. G., and Peterson, C. R., "*Mechanics and Thermodynamics of Propulsion*," Addison-Wesley Publishing Company, Inc., Reading, Mass., 1965.

12. Fortescue, P. W., and Stark, J.P.W., "*Spacecraft Systems Engineering*," John Wiley and Sons, Chichester, 1991.

13. Agrawal, B. N., "*Design of Geosynchronous Spacecraft*," Prentice-Hall, Inc., Englewood Cliffs, NJ, 1986.

14. Stine, G. H., "*Handbook of Model Rocketry*," Acro Publishing, Inc. New York, 1983, Ch. 5.

15. Sechler, E. E., and Dunn, L. G., "*Airplane Structural Analysis and Design*," Dover Publications, Inc., New York, 1963.

16. Taylor, M.J.H., "*Commercial Transport Aircraft*," Tri-Services Press Ltd., London, 1990.

17. Ryan, R. S., et al., "*Systems Analysis Approach to Deriving Design Criteria (Loads) for Shuttle and Its Payloads*," NASA TP 1949 and 1950, December 1981.

18. "*Space Shuttle – Skylab 1973*," Status Report for the Committee on Science and Astronautics, U.S. House of Representatives, 93rd Congress, Committee Print, 89-959 O, Washington, January 1973. Excerpt from, Status Review of CSM and Space Shuttle Programs, November 1972, North American Rockwell Corp., p. 414.

19. Space Shuttle Structural Loads Data Book, Rockwell International, SD73-SH-0040, Section 4.5 – Main Engine Ignition, June 1973.

20. AbuTaha, A. F., "*NASTRAN Structural Analysis of the RET Torus Antenna,*" COMSAT Labs, TM CL-34-73, December 1973.

21. Thornton, E. A., "*Application of NASTRAN to A Space Shuttle Dynamics Model;*" NASA TM X-2378, NASTRAN: User's Experiences, September 1971, pp. 421-437.

22. Gleseke, R. K., "*Modal Analysis of the Mated Shuttle Configuration,*" *Ibid*, pp. 221-236.

23. Giles, G. L. and Dutton, J. H., "*Application of NASTRAN to the Analysis of a Space Shuttle Orbiter Structure,*" *Ibid*, pp. 451-464.

24. Giles, G. L. and Blackburn, C. L., "*Procedure for Efficiently Generating, Checking, and Displaying NASTRAN Input and Output Data for Analysis of Aerospace Vehicle Structures,*" *Ibid,* pp. 679-696.

25. Grooms, H. R. and Yahata, S., "*Space Shuttle – The Need for Substructuring,*" *Ibid*, pp. 769-778.

26. NASA Level II Space Shuttle Program Definition and Requirements, JSC 07700, Vol. X.

27. Gatto, R.E., "*Effects of System Interactions on Space Shuttle Loads and Dynamics,*" International Council of Aeronautical Sciences Congress Proceedings, Seattle, WA, August 1982, pp. 376-383.

28. NASA Specifications, "*Space Shuttle Solid Rocket Booster Design Loads,*" Book 1, Prelaunch Through Separation, April 1990, released September 1990.

29. McDonald, A., "*Design Evolution of the Space Shuttle Solid Rocket Motors,*" 21st AIAA/SAE/ASME/ASEE Joint Propulsion conference, July 1985, pp. 496-507.

30. "Report of the Presidential Commission on the Space Shuttle Challenger Accident," Washington, June-September 1986, Volumes I-V.

31. Westfall, Richard S., "*The Construction of Modern Science, Mechanisms and Mechanics,*" Cambridge University Press, London, 1977.

32. Presidential Commission (PC) on the Challenger Accident, National Archives Records, Washington, D.C., 1986.

33. Ryan, R. S., "*Problems Experienced and Envisioned for Dynamical Physical Systems,*" NASA TP 2508, August 1985.

34. NASA Specifications, Space Shuttle Solid Rocket Booster Design Loads, June 1979.

35. Structural Design Loads Data Book – Volume 4 - Solid Rocket Booster Structural Loads, Rockwell International, STS 85-0169, December 1990.

36. Pearson, D. W., "*Space Shuttle Vehicle Lift-off Dynamics Occurring in A Transition from A Cantilever to A Free-Free Flight Phase,*" Guidance and Control Conference, San Diego, CA, August 1982, pp. 304-312.

37. Ryan, R. S., et al., "*Structural Control Interaction,*" NASA TM X-64732, January 1973.

38. AbuTaha, A. F., "*The Space Shuttle: A Fundamental Oversight,*" April 1990. Submitted to, and rejected by Journal of Spacecraft and Rockets, February 1991.

39. Barthelemy, J. M., Chang, K. J., and Rogers, J. L., "*Shuttle Solid Rocket Booster Field Joint Shape Optimization,*" Journal of Spacecraft and Rockets, March-April 1988, pp. 117-124/

40. Nemeth, M. P., and Anderson, M. S., "*Axisymmetric shell Analysis of the Space Shuttle Solid Rocket Booster Field Joint,*" Journal of Spacecraft and Rockets, Jan-Feb 1990, p. 87.

41. Faget, M. A., "*The Space Shuttle,*" Proceedings of the 27th AAS Annual Conference, Boston, MA, Oct. 20-23, p. 5887.

42. Macknight, N. "*Shuttle,*" Macknight International, Nottingham, 1984, p. 21.

43. Report to NASA by Morton Thiokol, Inc., "*Quick Look Report of the nonlinear Structural analysis Performed on the SRM Cracked Stiffener Stub Flanges*," TWR-14193, Jan 1984.

44. "*Anomalies/Discrepancies/Corrective Action*" for STS-8 Processing, Morton Thiokol, Inc. 1984, see Ref. 22. P. 113,776.

45. Kross, D. A., Kiefling, L. A., Murphy, N. C., and Rawls, E. A., "*Space Shuttle Solid Rocket Booster Initial Water Impact Loads and dynamics – Analysis, Tests, and Flight Experience*," AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, NV, May 2-4, 1983, pp. 473-478.

46. Orphan, V.J., and White, R.A., "*Real-Time X-Ray and Neutron Radiographic Inspection System for NASA Space Shuttle Solid Rocket Booster Refurbishment*," Presentation to NASA headquarters, February 12, 1985.

47. Sawyer, K., "*Booster Rocket Damage*," Washington Post, January 6, 1992, p. A7.

48. Stoiko, M., "*Soviet Rocketry: Past, Present, and Futures*," Holt, Reinehart and Winston, New York, 1970, p. 53.

49. "*Investigation Report Clearfield Incident, Building H-7* (10 October 1983), Morton Thiokol, Inc., TWR-14193, Jan 1984.

50. AbuTaha, A. F., "*Fuel Cell Design Specifications,*" COMSAT TCLS/1110, March 5, 1970.

51. AbuTaha, A. F., "*Cylindrical Pressure Vessel Design and Specifications,*" COMSAT TCLS/1222, July 22, 1970.

52. Cortright, E, M., Ed., "*Apollo Expeditions to the Moon,*" NASA SP-350, Washington, D.C., 1975, Chapter Thirteen.

53. Lardy, N. R., "*The INTELSAT IV Spacecraft, Apogee Motor*," COMSAT Technical Review, Volume 2, Number 2, Fall 1972, p. 366.

APPENDIX A

The late Wilbur L. Pritchard encountered the "dynamic overshoot" mistake numerous times in electrical and communications equipment during World War II, and he was instrumental in eliminating the mistake from those systems. Bill did lengthy mathematical analysis of the start-up transient effect in electrical circuits during the war, and he gave me a copy of his 1940's handwritten analysis. Pritchard understood the destructive "dynamic overshoot" effects. The Letter and Affidavit by Mr. Pritchard, mentioned in Section 11, "Dynamic Overshoot, the Space Program and Me," are given in this Appendix. Pritchard's words capture the dismissive attitude of the aerospace experts, who are responsible for the destructive "dynamic overshoot" effect in the Space Shuttle, and the controversy that surrounded this Report.

Pritchard wrote, *"the implications of refusing to publish it* (my paper on the dynamic overshoot submitted to the *Journal of Spacecraft and Rockets* in 1990) *in the event of any further shuttle disaster are frightening, indeed."* Here is the analogy that Pritchard had in mind. Imagine the Space Shuttle to be a large circuit board with many electrical and electronics devices and components, e.g., resistors, capacitors, inductors, amplifiers, rectifiers, tubes, power supplies, etc. etc. The board has two main power switches – Switch #1 (SSMEs) and Switch #2 (SRBs). Suppose the "transient currents," "surge currents," or "dynamic overshoot currents" were neglected in the initial design of the circuit board. That is, the components are rated to the "applied current" and not to the "applied current plus the dynamic overshoot surge current." What will happen when Switch #1 is turned and then, six seconds later, Switch #2 is turned on? Students, faculty and experts in electrical, electronics, communications and related fields know the answer. The neglected "surge currents" will fry up some components. The first component to fry on the Shuttle was the Thermal Protection System (TPS), or tiles, closest to Switch #1. The strength of that component was doubled (100% correction) in 1978 (Section 10.1). And in 1984, the dynamic overshoot in the last component on the circuit board (the holddown posts) was found by measurement to be 73% (Section 7).

The engineering students of electronics do not have a dogmatic law that states, *"To every voltage there is always opposed an equal voltage!"* These students learn matter of fact, without controversy or battle, that the output voltage of a rectifier is twice the input voltage. To recognize what has happened with the Space Shuttle, the reader need only be convinced that there are "surge forces" associated with the sudden start-ups of the SSMEs, SRBs and other thrusters. Hopefully, this Report establishes the reality of the physical-mechanical-dynamic-overshoot-surge-forces.

Pritchard wrote,

> *"The peer review that's needed must be done by the profession at large rather than by just a few, possibly biased, reviewers."*

The verdict on the "physical dynamic overshoot surge forces" in the Space Shuttle and other hardware should not be made *"by just a few, possibly biased, reviewers,"* but by the *"profession at large."* Accordingly, this Report has been written for everyone.

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WLP 550
April 3, 1991

Dr. Earl A. Thornton
Associate Editor
AIAA Journal of Spacecraft and Rockets
University of Virginia, Thornton Hall
Charlottesville, VA 22903-2442

Dear Earl:

Thanks for the lengthy and thoughtful phone discussion on the possible publication of Ali AbuTaha's paper. I have known Mr. AbuTaha for about 20 years and was associated with him professionally at Comsat Corporation, while I was Director of Comsat Laboratories. He is a competent engineer.

More recently, I have followed his efforts to get a hearing on his controversial ideas on the space shuttle design. I am not a specialist on structural design, and therefore not qualified to comment specifically, but I have observed in looking at the comments of others that the dispute seems often to be factual rather than theoretical and the comments seem to reflect an underlying hostility.

At this point, in view of the importance of the issue, and in recognition of Mr. Ali AbuTaha's respectable credentials as a member of the space fraternity, this paper should be published. If indeed he is right, and there is some reason for thinking that he might be, then the implications of refusing to publish it in the event of any further shuttle disaster are frightening, indeed. The Institute, through its journals, has an obligation to its members to air a dispute on so important an issue. I see no reason why the publication could not be accompanied by a disclaimer pointing out that it was being published despite the negative recommendations because of the importance and implications of Mr. AbuTaha's hypothesis and in recognition of his professional status. Once again, I think that your letter to the reviewers set exactly the

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Page 2 - Dr. Earl A. Thornton
Associate Editor
AIAA Journal of Spacecraft & Rockets

right tone, but I would expect that after their comments the situation will be still murky. It is best resolved by publication and open debate. The peer review that's needed must be done by the profession at large rather than by just a few, possibly biased, reviewers.

Cordially,

W.L. Pritchard
President

WLP/jg

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August 1, 1991

To whom it may concern:

My name is Wilbur L. Pritchard and I'm making the following statement under oath. I am a graduate electrical engineer. I've practiced my profession since 1943, and I am registered in the states of Maryland and Massachusetts. Currently, I am President of W.L. Pritchard & Co., a small consulting engineering located in Bethesda, and dedicated to telecommunications work, principally in satellite communications. I am a Member of the International Academy of Aeronautics and Astronautics, a Fellow of the Institute of Electrical and Electronic Engineers and a Fellow of the AIAA. I have been the recipient of a number of professional awards including the AIAA Communications Award and the American Astronautical Society's "Lloyd C. Berkner" award for Commercial Space. A resume of my professional career is attached to this statement, and it contains an extensive list of publications in the archival literature. A brochure describing the company is also enclosed for reference.

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I've known Ali Abutaha for about twenty four years and indeed was associated with him closely during the period from 1969 to 1978 when he worked at Communications Satellite Corporation. I myself was a Vice President of Communications Satellite Corporation and was the first Director of Comsat Laboratories, serving in that position between 1967 through 1973. I know Mr. Ali Abutaha to be a competent and dedicated mechanical engineer, well educated in his subject with many years of related experience.

Several years ago he approached me as a colleague and acquaintance of long standing to discuss his ideas on defects in the design of the shuttle and some hypotheses on the Challenger failure. I was much interested in his ideas and found them to be plausible and consistent with my knowledge of the physics involved. It's important to note that I had neither the means nor even the inclination to check on the numerical data and historical facts that formed part of Mr. Ali Abutaha's theory, nor am I a specialist in launch vehicle design. Nonetheless, much of the theoretical side of his case is based on the dynamic theory of vibrations which appears in many disciplines; and indeed the differential equations that form the basis of this theory had their origin in electrical engineering, thus the general ideas were familiar to me and Abutaha's case seemed plausible. I urged him to discuss his case with responsible people at NASA and to publish his results in the professional literature. It is in connection with his attempt to publish that my statement is particularly addressed. I know that Ali Abutaha has spent much time discussing his theory with members

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of the aerospace community, in particular people from NASA, but I do not have direct knowledge of the results of these discussions nor the rebuttals if any. I do know that he submitted, partly at my urging, a copy of his paper to the AIAA for publication in an appropriate journal and, as of the writing of this letter, this paper has not been published. Abutaha has shown me the comments that independent reviewers made of his paper, and the negative recommendations for its publication. On reading these reviews, I was disturbed. I have read many such reviews during my career, and these struck me as not being objective but rather, seeking by any reason, to justify a prior conclusion that the paper shouldn't be published. I spoke to Earl Thornton, assistant editor of the journal and he informed me that he too was disturbed by the reviewers comments, especially in view of Abutaha's rational responses and rejoinders to these comments, and that he had requested further comment from the reviewers. My own opinion was that the issue was so interesting and so important that the editor should publish the work and leave judgement to the entire community. Abutaha, as a qualified and responsible member of the aerospace engineering community, clearly has struck a discordant note, both politically and technically. As an engineer and member of that community, I am anxious to have his work published and debated openly. I can see little reason for not publishing it, and many reasons for going ahead with it. Perhaps most important is to avoid the faint aroma of cover up that is drifting across the atmosphere.

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If Abutaha's analysis is based on numbers and events that are in factual and historical error, then the people who can correct these errors should do so publicly after his paper has been aired. They should be delighted to see the work published and to have the chance publicly to attack it. The rumors of his work are already circulating and people who could attack it successfully should welcome the chance to put these rumors to rest. If there are theoretical disputes about his methods, then by all means they should be debated. In no way should his ideas be suppressed based on anonymous "peer" reviews which could be less than objective.

I know for certain that Abutaha has devoted the past several years to winning this argument. It has become a matter of principle and virtually a crusade with him, and I am afraid that he has paid a terrible price personally. He has incurred a substantial cost in time and money, and is probably a victim of hearsay allegations, and insinuations. At this point, the matter should /be dragged into the open and debated.

W. Pritchard
Wilbur L. Pritchard

Subscribed and sworn to before me this 1 day of August, 1991.

Sheldon E. Sacks
Notary Public

My commission expires: Sept. 1, 1991.

The Author

Mr. Ali F. AbuTaha has over 40 years of experience in the design, procurement, construction, test, operation and maintenance of spacecraft, satellite earth stations and other engineering systems. He is recognized for identifying and explaining the "physical transient surge force" effects in space hardware design, including the Space Shuttle. He has developed multi-disciplinary approach to the solution of technical problems. Mr. AbuTaha developed numerous key contributions in science and engineering, for example, he invented the self-motion mechanism and pulsing-thrust rocket propulsion, explained the cold fusion process, developed a gravitational theory, investigated the Challenger accident and developed the cosmic-life-line concept.

General Experience

- Contributed to numerous spacecraft and earth station R&D programs.
- Directed the installation, alignments and modifications of many earth stations.
- Generated procurement and contractual documentations for many programs.
- Participated in the negotiations for satellite systems, earth stations, integrated national security telecommunications networks and other programs.
- Developed interdisciplinary approach to dealing with modern systems.
- Directed the design, installation, test, commissioning, operation and maintenance of national television station, cable systems and closed-circuit-television educational systems.
- Developed Performance Characteristics documents for earth stations operating in different satellite systems.
- Developed training programs and trained personnel on many aspects of hi-tech systems.
- Developed and managed newly found corporate divisions.
- Developed and lectured the program, "Anatomy of Failure Mechanisms in Modern Systems."

Aerospace and related Experience

The following list demonstrates the diverse activities and contributions that Mr. AbuTaha made during the period of 1969-78, with Comsat Labs, Clarksburg, MD, Comsat Corporation Earth Station Division, Washington, DC and Comsat Space Segment Engineering Division, Palo Alto and El Segundo, CA:

- Carried out extensive mathematical, statistical and computer analyses of coding, sampling and synchronization of PCM/PSK/TDMA and other digital transmission methods.
- Identified the transient "dynamic overshoot" effect in the tests of spacecraft fuel tanks and he developed test procedures to eliminate random explosions.
- Developed technical specifications for the design of pressure vessels.
- Responsible for and conducted extensive tests for physical, mechanical, thermal and corrosion properties of high strength metals, alloys and composites for lightweight spacecraft design.
- Responsible for structural and stress analyses of spacecraft and earth station systems.
- Developed the sequenced mass properties of many satellites for all mission phases.
- Developed axial and lateral stiffness models of spacecraft for vibration modal analysis.
- Calculated natural frequencies of satellite components, subsystems and systems.
- Identified mechanical failure mechanisms in spacecraft and earth station facilities.
- Evaluated the effects of fatigue, corrosion, hydrogen embrittlement and high stresses on failures of spacecraft and antenna structures and components.
- Designed and operated a structural-test-stand for testing satellites and components.
- Designed and operated device to measure moment of inertia of satellites and components.
- Contributed to feasibility and configuration studies and launch vehicle selection and interfaces of MARISAT, AEROSAT, DOMSAT, LABSAT and other research satellite systems.
- A key team member on the NASA ATS-F COMSAT Millimeter Wave Transponder program.
- Played a key role in the evaluation, installation, check out and initial use of NASTRAN, SAAS, ANSYS and other finite-element general-purpose computer programs for structural, dynamic, thermal and modal analyses at Comsat Labs.

- Developed computer programs and subroutines for digital transmission techniques, alignments of numerous antennas, the design of shell-supported rings and bands, e.g., the attachment rings of spacecraft to launch vehicles, and for numerous applications.
- Conducted extensive structural analyses using NASTRAN and self-written programs for:
    - The semi-automated procedures for the structural design and alignment of the Unattended Earth Terminal (UET) Torus Antenna.
    - Lightweight transportable and mobile antenna structures.
    - Feasibility studies of 30-m multi-beam torus (MBT) antennas for different global locations and for operation with different satellite stations.
    - Axial and lateral stiffness models of international and domestic satellites.
    - Normal mode analyses of satellite solar panels in stowed and deployed configurations.
    - Feasibility studies of different satellite configurations.
- Contributed to the technical specifications, evaluations, negotiations and monitoring of many programs, including,
    - High speed momentum wheel
    - Magnetic bearing momentum wheel
    - Advanced materials structures
    - Nickel-Hydrogen fuel cells
    - Improved lightweight solar arrays
    - Silicon solar cell interconnect system
    - Seals for fuel cells systems
    - Deployable honeycomb solar panels
- Developed the Performance Characteristics documents for Standard A and B Earth Stations operating in INTELSAT IV, IVA, and V satellite systems 6 and 4 GHz bands.
- Generated the first draft of the Performance Characteristics of Standard C antennas to operate in the 14/11 GHz frequency bands.
- Contributed to the specifications and evaluation of test results of antennas worldwide.
- Reviewed and approved final documentations, drawings and manuals for many installations.
- Participated in wide-angle-pattern measurements of antennas using the NASA ATS-6 satellite.
- Contributed to the technical specifications, request for proposals, technical evaluations and negotiations of numerous programs, including,
    - INTELSAT TTC&M/IOT international network for INT V and future satellites.
    - SBS domestic RFT program.
    - SBS satellite system.
    - COMSAT 14/11 GHz antennas.
    - Comsat Lab's UET, MBTA, CMBTA and transportable antennas.
- As Project Engineer,
    - Responsible for the structural and dynamics analysis and generating alignment data, and was a key engineer for in-plant testing and installation of the Unattended Earth Terminal (UET) first Torus antenna in Clarksburg, MD.
    - Monitored field installation, alignments and acceptance tests of 30-meter Beam-Waveguide Wheel-and-Track antennas in Etam, West Virginia and Andover, Maine.
    - Directed the first and successful on-site modifications, in West Virginia, of a Standard-A antenna to operate in dual-polarization satellite systems, and met stringent axial ratio requirement while improving the RF performance.
    - Developed and implemented solutions to greatly improve the tracking performance of the Telemetry, Tracking & Command antennas in Maine, Hawaii and abroad.
    - Prepared and conducted Inspection Program of East Coast and Hawaii earth stations to determine time- and environmental-effects on performance, particularly, corrosion in sea water environments, and developed actions to correct deficiencies.
    - Modified a Hawaii antenna to enable remote testing of satellites in orbit.
    - Designed, developed procedures and directed installation, alignment and test of auxiliary drive subsystems for remote operations in normal and emergency situations.
    - Evaluated the effect of asymmetric snow build-up on antennas and its effect on dual polarization operation, and developed and implemented corrections.
    - Evaluated the effect of snow build-up on large radar dome structures.
    - Monitored the in-plant tests and on-site installation, alignments and tests of the first East Coast SBS experimental antenna in Poughkeepsie, New York.

  - o Developed the structural design, monitored in-plant tests, and directed the field installation and alignment of the very-high-surface-accuracy 35-60 GHz Multi-Beam experimental Torus antenna.
- Monitored the design, fabrication and tests of INT V and SBS satellites deployable appendages and mechanisms.
- Responsible for test procedures of satellite structures, mechanical and electro-mechanical subsystems for Space Shuttle launches.

After 1980, and as a key or senior consultant with Comsat General, Flour Technology, and other space and engineering companies, Mr. AbuTaha made numerous other professional contributions, including:

- Design, procurement, training and documentation for a national security telecommunications network using satellites and terrestrial transmission links, and video and encryption services.
- Conceptual studies of a remote-sites-network for enhanced telecommunications services using satellites, microwave, fiber optics and other transmission techniques in Saudi Arabia.
- Feasibility of an international satellite business system and evaluation of concept with public and private telecommunications organizations in Europe, Africa and the Middle East
- Development and processing of chemical and mechanical data in the manufacture of single- and multi-layered printed circuit boards to provide real-time decision-making and improve quality assurance and control.
- Developed animated color graphics manual for use in manufacturing printed circuit boards.
- Directed the design, installation, tests, commissioning and initial operation of the first Television Station in Mogadishu, Somalia.
- Trained personnel on the operation and maintenance of transmission, video, and studio room equipment and facilities in Mogadishu, Somalia.
- Directed the production of daily news and documentaries, and trained personnel on daily management of television station in Somalia.
- Directed the design of a close-circuit-television and video systems for a university educational program using high frequency microwave links.
- Directed marketing of communications, computers, television, video and technical services for public, private and military sectors in the Middle East and Africa.

Before attending the George Washington University in 1964, Mr. AbuTaha worked with the Engineering Division of the Department of Defense of Kuwait (1962-64). With the O&M Section in a Brigade, he coordinated the activities of electrical, mechanical and civil technicians in routine and emergency situations.

Since the 1950s, Mr. AbuTaha had extensive engineering experience in the family cement products factory in Amman, Jordan, where he first ran into the “dynamic overshoot” problem in pressure-activated-products. The problem revealed inherent limitation in Newton’s Action-Reaction Law, which AbuTaha would repeatedly encounter in engineering for the next four decades, including the design of space hardware and the Space Shuttle.

The following is a partial list of key research, inventions and discoveries made by Mr. AbuTaha:

Transient-Surge-Forces in Space Systems

Just as “surge” effects occur in electrical circuits, Mr. AbuTaha has shown that “surge” forces occur in physical systems. AbuTaha has encountered, tested and corrected the destructive effect in modern systems since the 1950s. He has shown that the destructive effect has been mishandled, and even completely neglected in space hardware design since the beginning of the space program.

Natural Motion, or Self-Motion (Patent Pending)

After many years of research and tests, Mr. AbuTaha produced self-motion of mechanical models, or lifeless bodies. He also developed the mathematical formulations that govern the motions and he linked the mathematics of Classical Mechanics, Quantum Mechanics and Electromagnetic Theory.

Pulsing Thrust – Advanced Rocket Propulsion

Mr. AbuTaha developed the pulsing-thrust technique that utilizes the transient start-up effect in rockets to greatly improve the performance of launch vehicles.

The Heat Mechanism in Cold Fusion

Mr. AbuTaha was the only scientist to include the correct energy-balance-sheet in Cold Fusion. He showed that the fracture energy, due to internal cracking of the electrodes, is the source of heat in Cold Fusion. Specifically, AbuTaha showed that the heat generated in Cold Fusion is always less than the heat required to melt and form the metal electrodes in the first place.

Challenger Accident Investigation

Mr. AbuTaha discovered, and published some of the, unique events in the last flight of the Space Shuttle Challenger, which were not identified in the other investigations.

Theory of Gravitation – A Unified Interaction

The theories of Gravitation by Newton, Einstein and others relate gravity to mass – which is dormant. Mr. AbuTaha derived the dependence of gravity on the active property of Temperature. He developed over fifty equations to test and verify the theory on many familiar classical and quantum effects.

Oscillations in Force Fields

Mr. AbuTaha has shown that the widely used “Simple Harmonic Motion” models, which are used to simplify the mathematical analysis, are inadequate to describe motions in force fields; and he identified the characteristics of oscillations in force fields.

Cosmic-Life-Line Concept

The average conditions of pressure, temperature and density at sea level on earth specify a thermodynamic state of equilibrium, which is conducive to the evolution and maintenance of life. Mr. AbuTaha developed the hypothesis that similar, but not identical, states of equilibrium can exist in extreme conditions, also conducive to the evolution and maintenance of life. On a p-v-T surface, the stated conditions form a line, the cosmic-life-line. The extreme conditions near undersea hydrothermal volcanic vents, where living creatures were subsequently found to thrive, represent a point on the cosmic-life-line.

Scientific Study of the Unidentified Flying Objects

Mr. AbuTaha made an extensive study of the UFO phenomenon, identified super-technological performances of the reported objects, and he attempted to analyze and reproduce the reported features. Instantaneous accelerations, sharp turns and other features were demonstrated by AbuTaha in his above “natural motion, or self-motion” invention.

Solar and ExtraSolar Life

Extending the cosmic-life-line concept and the scientific study of the UFO phenomenon, Mr. AbuTaha proposed that the harsh conditions on the Sun and the stars can be conducive to the evolution and maintenance of terrestrial-like carbon-based water-nourished life under a master-blue-print plan. In addition, he did extensive Judeo-Christian-Islamic theological studies to reconcile the scientific concept with the religious teachings.

Anatomy of Failure Mechanisms in Defense and Aerospace Systems

Mr. AbuTaha developed and lectured the short engineering Program, which deals with common design errors in modern systems, including space hardware. The Program is based on “huge” design mistakes that he had personally analyzed and corrected since the 1950s. The Program was greatly praised by attending scientists and engineers from public, private and military centers at home and abroad, e.g.,

“Thought provoking course.”
“I can’t believe how much I understood.”
“Excellent course for all ... engineering fields.”
“Outstanding ... very rewarding.”
“His presentation was fantastic.”
“Content was very good but time was too short.”
“Excellent – the use of other examples was outstanding.”
“This was very informative and will influence critical thinking for sure.”