Store Separation Lessons Learned (*Mistakes Made*)

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ABSTRACT

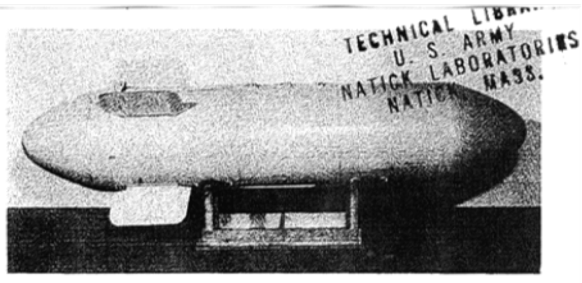
Store Separation is a complex process that every new aircraft/weapon combination has to follow before the store is first released from the aircraft. There are numerous things that can go wrong with serious consequences to the aircraft and pilot. This paper will describe many store separation programs where mistakes were made, but in a positive sense. One always makes mistakes. The greatest mistake one can make is to try to hide/cover-up the mistake, and not learn any lessons in the process.

1.0 INTRODUCTION

1.1 M-4A High Speed Delivery Container

My first involvement in store separation was as an intern at the Naval Air Development Center (NADC) in 1965. I was tasked to predict the trajectory of the M-4A high speed delivery container. The container was designed to deliver a payload at 500 feet and 500 KTS to Marines on the ground in Vietnam. I had no idea of what the tasks involved. There were no wind tunnel data, no six-degree-of-freedom (SDOF) code, no dynamic derivatives, ejector forces or estimates for the aerodynamic carriage loads.

I thought all I had to do was solve F = ma in short time steps (0.05). I used handbook methods to estimate the freestream aerodynamics of an Ogive shape with fins, assumed that the carriage loads would be +/- 1 for the aerodynamic coefficients at the release point (CN, CY, CA, CLL, CLM, CLN) and wrote a program in Fortran to compute the trajectories. To check if the program was working properly, I checked the computed results for several time steps. In those days there were no hand calculators, and slide rules were only good to 3 significant figures.



The Marine Corps' M-4A high speed aerial delivery container is being tested for use in supply of dispersed forces anticipated in nuclear and missile warfare. The container is made from aluminum and weighs 104 pounds.

Figure 1: M-4A High Speed Delivery Container.

To get more accurate results I had to use a Friden electronic calculator. Unfortunately, the program results did not match the calculated results after the first time step. There was obviously a problem with the code. I was assigned a GS-11 (senior engineer) to help me (GS-4, engineering aid) solve the problem. He couldn't find the error in the code. I took a machine language class. In machine language I would have to designate a location for every number used, and then the calculation that would be involved with each of the objects in memory. After having spent days doing the same process on the Friden calculator, this task was fairly easy. I found the error in the FORTRAN code, and finally got the code to run.

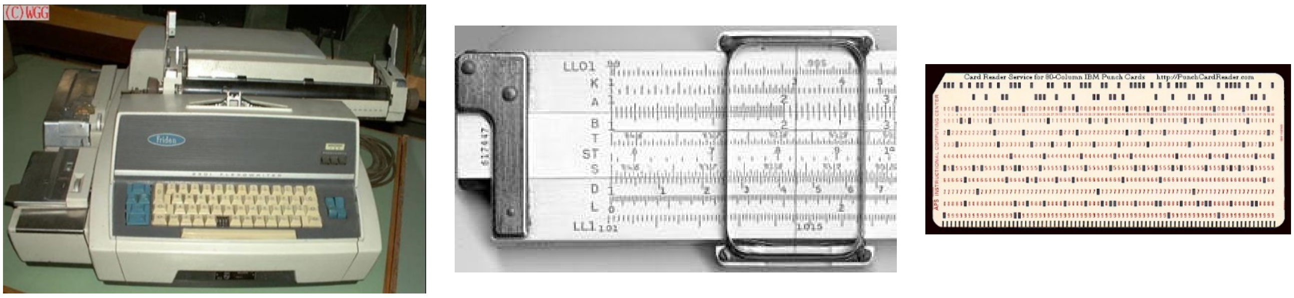


Figure 2: Store Separation Tools in 1964.

That was not the end of my problems. I now had to actually calculate a trajectory, using initial conditions (ejector forces, store loads at carriage) which I had no idea of how to estimate. Using +/- 1 for the aerodynamic coefficients (CLM and CLN) at carriage didn't work too well, since that made the store tumble.

As this was a success driven program, my boss's boss (GS-13 – the most powerful man I had met till that time) was not interested in failure. Since I did not know what the initial conditions were, I found that using 0 for the pitching and yawing moments, and no CG offset for the ejectors, gave a benign trajectory. Everyone was pleased.

I went back to school before the flight test occurred. At the first flight, the container tumbled (CG offset or large negative CLM?), the parachute never opened, and the container crashed a short distance away from the base commander and other assembled dignitaries.

Additional mistakes were made in the following 50 years.

2.0 BACKGROUND

2.1 Woodward I

My next involvement in store separation was while working at Grumman (Now Northrup-Grumman) using the Woodward I code [1]. This code was unique at that time since it did analysis and design at supersonic speeds. I was tasked to modify the code to allow it to calculate the loads on a store. The first step was to change the maximum number of panels for lifting surfaces from 100 to 400 [3].

2.2 Woodward II

Several years later NASA released an improved version of the code, [2]. This code replaced the vortex panels with doublets, still using sources for body surfaces. Frank Woodward called this the triplet option. This code lacked the design option present in the Woodward I code. My job was to put the design option into Woodward II [3].

When I presented my work the first question from the audience was "I hope you don't mind, but I would like to pose my question to Frank Woodward" (I had corresponded with, but never met before the meeting).

2.3 PAN AIR

Boeing, using NASA funding, developed the PAN AIR code. This code replaced the use of sources and vortices with doublet panels. It also allowed the use of a maximum of 1000 panels for the aircraft and store [4]. At that time, the code took over 24 hours to complete a single calculation on the supercomputer of the time (CDC 6600). Since the code used in iterative matrix inversion, no other programs could be run simultaneously.

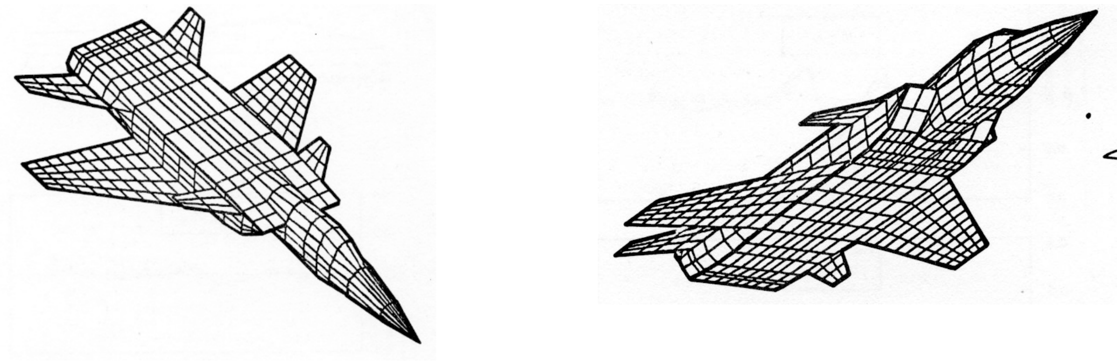


Figure 3: PAN AIR Panelling for the Advanced Weapons Carriage and Separation (AWCAS).

3.0 MISTAKES MADE AND LESSONS LEARNED

3.1 F-18C/BQM-126A

The BQM-126A, shown in Figure 4, was a powered UAV designed to be carried on the F-18C/D aircraft. CTS testing was performed in the DTRC 7x10 tunnel to determine safe separation.

Figure 4: BQM-126A.

The wind tunnel test only did CTS trajectories. No grid testing was done. No off-line trajectory simulations were performed prior to flight testing.

The CTS simulation indicated that the store would move aft and safely clear the aircraft. The wind tunnel CTS trajectories simulated three different levels of trust for the engine, with no change in trajectories. In the first flight, the store flew forward and almost hit the F-18C aircraft.

As can be seen in Figure 5, PAN AIR was able to accurately predict the F-18C aircraft flowfield. Using the predicted flowfield and the IFM technique [5] it was possible to develop a grid. Trajectory simulations were performed that predicted the BQM would pitch up as it flew forward [6] from its carriage position.

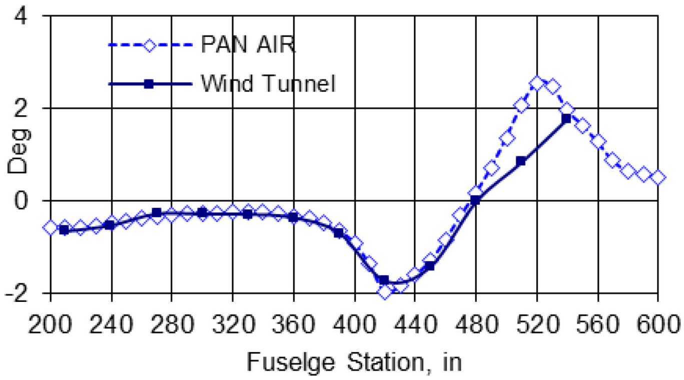
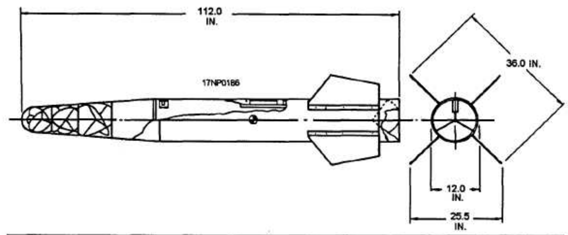


Figure 5: F-18C Aircraft Flowfield.

It was not possible to safely release the BQM-126 from the F-18C aircraft. The program was subsequently cancelled.

3.2 TDU-34A/A

The improved TDU-34/A/A tow target had an extended tail section. This target hit the reeling mechanism during the first flight test. After extensive wind tunnel testing and trajectory simulations, the only way the predicted trajectory would match flight test was by changing the CG location. The flight test was repeated, and it confirmed that the CG during the first flight [7] was in the wrong location.



ALTITUDE	35,000 FEET
WEIGHT	75 POUNDS
MAXIMUM TOWING VELOCITY	0.9 MACH
TOW AIRCRAFT	A-4, 1-6, F-4
AUGMENTATION	RADAR REFLECTIONS

Figure 6: TDU-33A/A Tow Target.

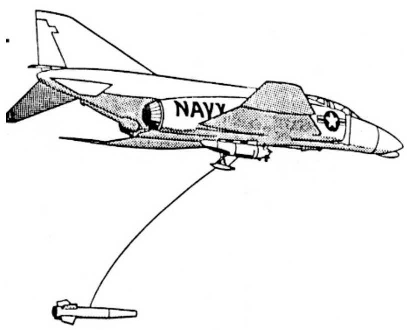


Figure 7: Tow Target and Reeling Mechanism.

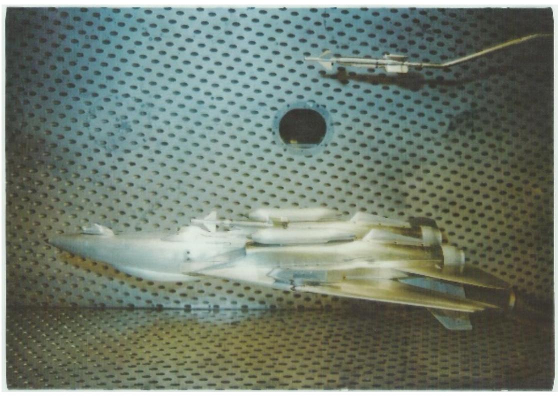


Figure 8: F-14/GBU-24 Wind Tunnel Test.

3.3 F-14/GB

The approach used for the GBU-24 store differed from most other aircraft/store programs. In this case the flight test results were used to determine how the wind tunnel data should be used [8].

The GBU-24 store has two characteristics that make predicting flight test trajectories challenging. The wing of the store opens during the first 0.15 sec. of the trajectory. Furthermore, the GBU-24 canards are free floating during the initial part of the trajectory. The floating canards could not be represented in the wind tunnel. The flight test configuration is shown in in Figure 9.

Figure 9: F-14/GBU-24 Flight Test.

Grid data were therefore taken for both the wings open, closed and intermediate configurations, with the canards on and off. Flight test data for the F-15 and F-18 aircraft failed to match predictions based on wind tunnel data for either fixed canards (at zero deflection angle), or for the store with the canards removed. To predict flight test trajectories, particularly for the GBU-24 configuration released from the F-14 forward station, flight test results were used to correct the wind tunnel data.

Flight tests for the GBU-24 from the F-14 aircraft forward station were conducted in early 1996. During the first release, trajectory predictions using the canards off freestream and grid data gave the best match to the flight test results for everything but the pitch rate. Since canard on wind tunnel data indicated a sharp nose down pitch rate, while the canard off data indicated a slight nose-up pitch, it was postulated that the reason for the disagreement in pitch results might be attributable to the aircraft flowfield effect on the undeflected canard.

If a fixed canard for this case carried a negative lift, the canard would have to deflect nose up to neutralize this effect. Once the store is released, the canard would take some time to return to its neutral position, which would initially cause the GBU-24 to pitch nose-up. When an increment of 2.2 in C_m was applied to the canards off grid data, an excellent match with the flight test results was obtained [8].

By using a C_m offset coefficients good agreement with flight test data was obtained for the entire flight envelope, up to M = 1.20. Flight test videos showed the canard was deflected nose up in carriage. Both the trajectory results, and the flight videos, indicated that the response of floating canards is opposite to that indicated by wind tunnel data for fixed canards.

3.4 F-18/ITALD

The Improved Tactical Air Launched Decoy (TALD) was sold to the Navy because it was "Just like a TALD'". However, the ITALD included a jet engine for thrust and a different tail, Figure 10. The first several flights were unsuccessful.

Figure 10: TALD and ITALD.

Trajectory simulations were done using PAN AIR predicted carriage loads. Simulations indicated that the probable cause of the flight test failures was a large flowfield induced yawing moment, causing the store to roll past 180 degrees (at which point the autopilot failed). The contractor disagreed with this assessment, claiming a more robust autopilot was required. The contractor redesigned the autopilot, and the next high speed flight again failed in roll.

Afterwards, a 6% F-18C/ITALD wind tunnel test was performed. This demonstrated that there was a large aircraft induced yawing and rolling moment, which caused roll divergence, and could account for the previous flight test failures.

The contractor again redesigned the autopilot to enable it to withstand the wind tunnel predicted aircraft induced yawing moments. The next flight test resulted in another failure (the autopilot was unable to correct for roll angles > 135 degrees). Flight test telemetry results showed that the autopilot was functioning properly. It was determined that the 40% freestream data supplied by the contractor were wrong [9].

The contractor returned to the wind tunnel and did a 40% ITALD test. The original ITALD data were estimated by adding increments to the TALD data for tail and engine, Figure 11. The ITALD as originally designed was incapable of separating without departing in roll. Based on the new freestream data the autopilot was redesigned.

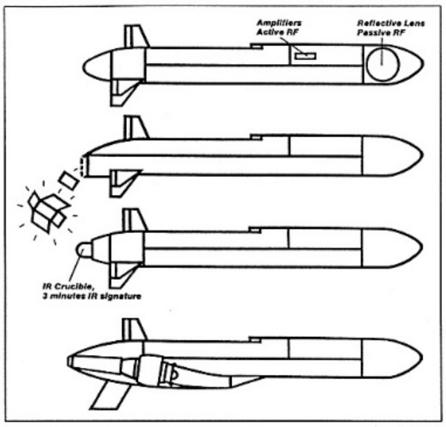


Figure 11: Incremental Build-up of ITALD Freestream Data.

The redesigned autopilot was successfully flown throughout the entire operational flight envelope.

The second law of famous contractor lies [10] states "We don't need a wind tunnel test - It's the same as a MK-XX/GBU-XX/AGM-XX /AIM-XX (pick any one)".

3.5 F-18C/JSOW

The program started in 1988 as the Advanced Interdiction Weapon System (AIWS) [11]. It was designed to fit into the A-12 weapons bay. This restricted the tail size, reducing stability, Figure 12. When the A-12 Program was cancelled, compatibility with F-18C/D became one of the selection criteria, Figure 13.

Figure 12: JSOW (AGM-158) Configuration.

Figure 13: F-18C Carrying 4 JSOW Weapons.

Multiple series of wind tunnel tests (CALSPAN, TI, and DTRC) were used to determine store separation characteristics. Program became joint and renamed JSOW. Original flight test plan was to drop 24 weapons at Mach numbers 0.6, 0.7, 0.8, 0.85, 0.9, 0.95 and 0.95 in a dive. Of the three different aircraft configuration; only one was determined critical.

Wind tunnel test data showed excellent match with flight test. Store separation recommended reducing the flight test matrix by 50%, from 24 to 12. Only four flight test points were removed.

The JSOW program manager [12] later stated "The engineers and I had several conversations for the need to believe SDoF predictions and reduce the flight test matrix" … "If I were to develop another weapon like JSOW I would stress the test community to complete the full test envelope with 8 to 10 test articles".

The store separation wind tunnel testing, the trajectory simulations, flight testing and program management were done at three locations and by four organizations.

3.6 F-18E/F

A comparison of the clean (no pylons) F/A-18C and F/A-18E aircraft flow fields was initiated to determine differences which might affect store separation. A PAN AIR model was developed and validated using wind tunnel pressure data measured on the wing. The preliminary analysis indicated that the F/A-18E increased inlet area, which produced an increased aircraft area ratio, had a significant impact on the aircraft flow field, and might have a detrimental effect on store separation. Prior to the wind tunnel tests at AEDC, flow field angularity predictions were made utilizing the PAN AIR model previously developed. Comparisons between test data and analytical predictions correlated very well for both the F/A-18C and F/A-18E aircraft [13].

However, warnings that the F-18E flowfield might have adverse consequences were dismissed by management as CFD predictions and not proven prior to wind tunnel testing.

After extensive weapons separation wind tunnel testing in the AEDC 16T transonic wind tunnel, with data analysis in the form of trajectories and miss distance calculations, it was determined that the aircraft configuration had a major store separation problem, Figure 14, with the red area indicating the store would hit the aircraft or adjacent store [14].

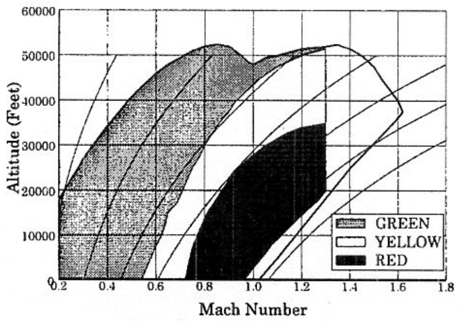


Figure 14: Projected MK-84 Release Envelope.

A trajectory improvement study was undertaken to improve the release and jettison operational envelopes. Several modifications were investigated, including pylon toe, pylon doors (spoilers deploying from the pylons during store release), change in release sequence and PACER bomb rack.

The final solution chosen was a change in pylon toe and release sequence. The change in pylon toe, Figure 15, had the effect of reducing the aircraft induced yawing moment at carriage, since for stable stores there would be a corresponding increase in the freestream restoring moment. It also increased the total drag.

Figure 15: F-18E/F Pylon Toe.

3.7 Mach Sweep Technique

Large discrepancies were seen in two different wind tunnel tests for the JSOW store grid data in proximity to the F-18C/D aircraft. The more conservative test data (higher yawing moment), from the CALSPAN 7x10 ft. wind tunnel, Figure 16, were used to predict the flight test trajectories.

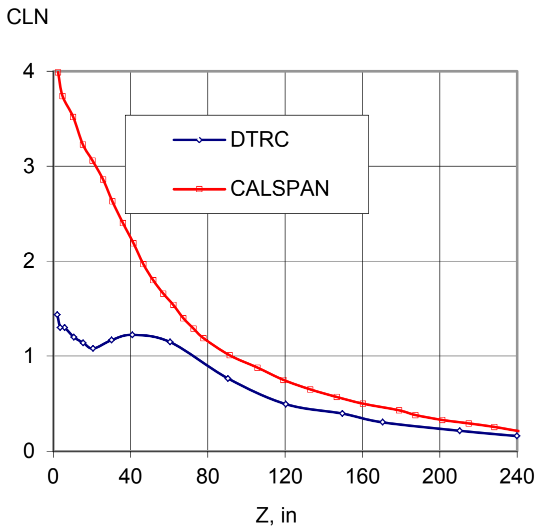


Figure 16: JSOW (AGM-158) CLN at M = 0.95.

At that time there was no way to explain the large differences in test results. It took me more than ten years to realize that testing at predetermined Mach numbers was inappropriate. Figure 17 indicates the change in CLN (yawing moment) with small changes in Mach number and store location (parent Pylon and Canted Vertical Ejection Rack (CVER). Note that the CVER store location is closer to the aircraft.

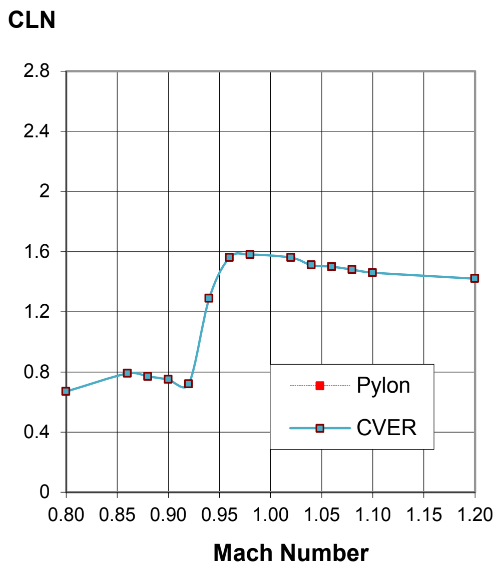


Figure 17: GBU-38 CLN Change with Mach Number.

It is important to note that the wind tunnel attempts to represent the actual aircraft flight condition. The nominal wind tunnel Mach number relative to free flight can obviously change depending on the tunnel size, blockage, flow angularity, etc. Since it's impossible to guarantee that the flight test will be conducted at a specific Mach number, particularly in a dive, the store separation engineer attempts to simulate the worst case condition.

Clearly the effective Mach number at the DTRC facility was different than that at CLASPAN, even though the set point Mach number was 0.95 in both.

This led to the development of the Mach Sweep technique [15]. Instead of conducting the wind tunnel test at predetermined Mach numbers, i.e. M =0.85, 0.90, 0.95, 1.05 and 1.20 to cover the transonic aircraft release envelope, the store is positioned at the aircraft carriage position, and the Mach number is increased.

This is done for each aircraft/weapon integration (i.e. pylon station, adjacent stores, aircraft attitude). The subsequent CTS and grid testing is then conducted at the critical Mach number for each configuration, usually one transonic and one supersonic.

Wind tunnel tests have been conducted on aircraft configurations for over a hundred years. Transonic tests have usually been at pre-set test Mach numbers. How is it that the Mach Sweep effect has not been previously observed for aircraft testing?

Some idea of the Mach Sweep effect may be deduced from CFD solutions [15]. As the Mach number is increased the shock wave forms at a lower transonic Mach number, and then progresses aft until it reaches the end of the wing. When the shock from an adjacent store hits another store there has to be a significant impact on the moments. Figure 18 demonstrates this this effect for two different target pods, while Figure 19 for a store at the CVER store location (Mach Sweep moments were previously shown in Figure 17).

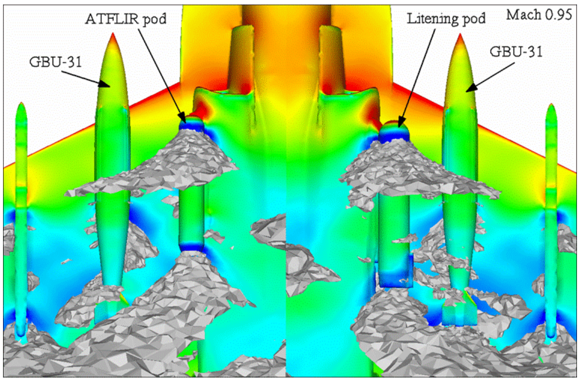


Figure 18: GBU-31 Parent Pylon at M = 0.95.

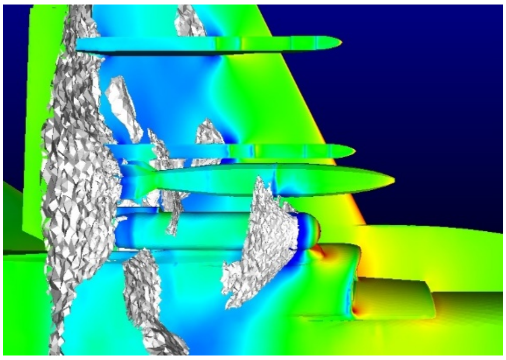


Figure 19: GBU-38 next to Litening Pod.

For the aircraft as a whole, this effect could be much less significant.

3.8 Store Separation CFD Challenges

There have been substantial improvements in store separation analysis over the past 50 years. One major improvement has been the capability to use CFD in aircraft/weapon integration. The F-8C/JDAM ACFD Challenge II first provided [16] validation of the process with flight test data. A complete description of this effort is available [17].

The last store separation CFD Challenge was for the GBU-38 store separating form the B-1B Bomb bay. The GBU-38 arrangement in the bomb bay is shown in Figure 20. The stores released were at the edges of the bay. A solution at carriage is shown in Figure 21.

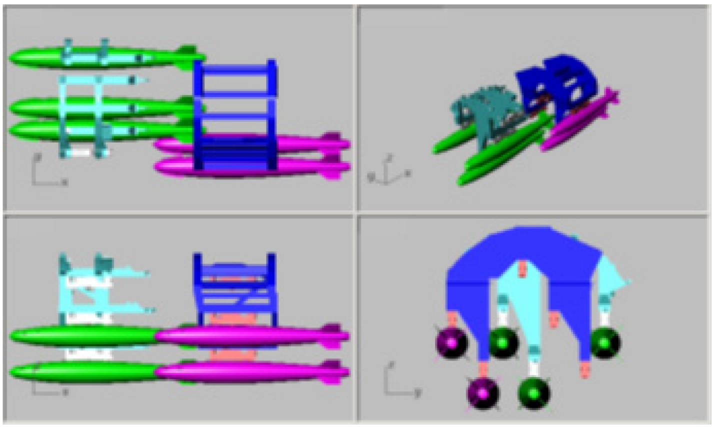


Figure 20: GBU-38 arrangements in B-1 Aft Bay.

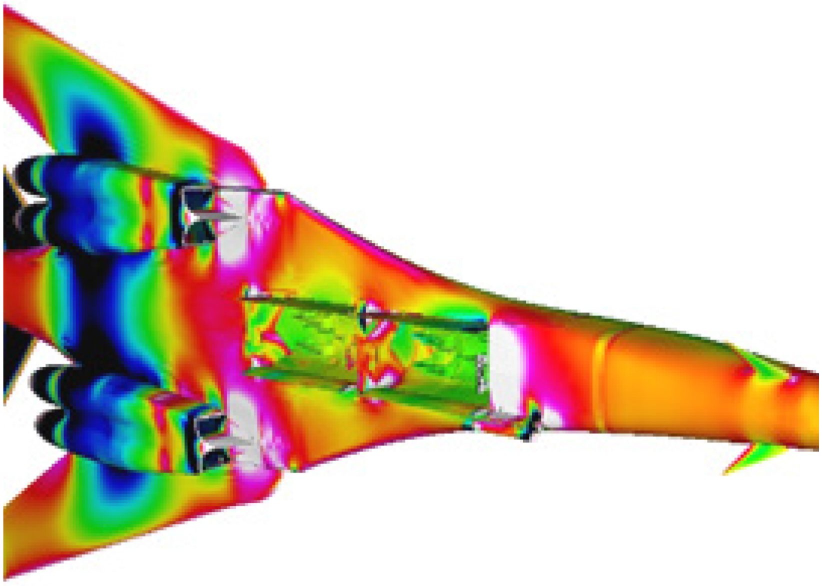


Figure 21: CFD Solution for B-1B/GBU-38.

This was a blind challenge; the participants were provided with the geometry and flight conditions, but not flight test results prior to submitting their solutions. Initially, all the participants got the wrong answer. The ejector forces provided were incorrect [18]. Flight test telemetry test data were then used to correct the ejector forces. When the correct ejector forces were used, all the solutions matched the flight test data. Quasi steady trajectory simulations worked as well as time accurate [19].

The importance of modifying trajectory simulations to account for rack vibration effect seen in telemetry data had been previously described [20].

3.9 JSF Program

Lockheed validated the SPLITFLOW code for store separation in ACFD Challenge I [21] and ACFD Challenge II [22]. SPLITFLOW was later coupled with a design code to examine fuel tank shape effects [23]. As may be seen in Figure 22 considerable improvements in aircraft flowfields can be achieved by changing store geometry.

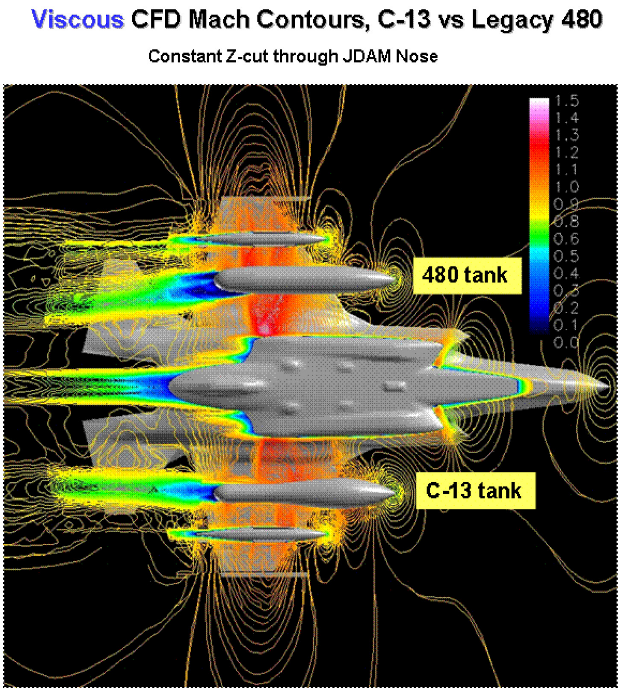


Figure 22: Flowfield Effects of Store Shapes.

This considerably improved the store trajectories, Figure 23.

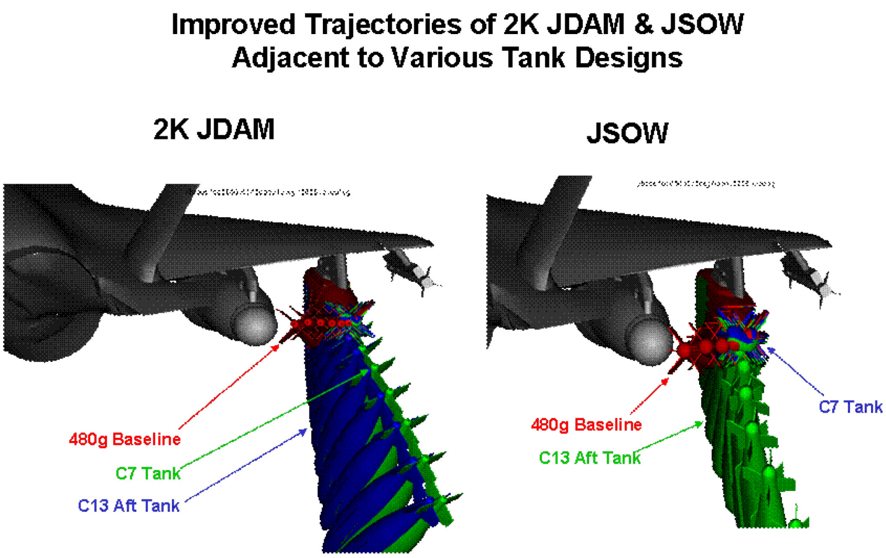


Figure 23: Wind Tunnel Validation of JSF Tank Re-design.

Another benefit of the tank re-design was a reduction in total configuration drag. Proper aircraft/weapon integration improves performance as well as store separation.

Examples of improvements in current store separation capabilities are shown below. Figure 24 is a view of the store separating from the JSF bomb bay.

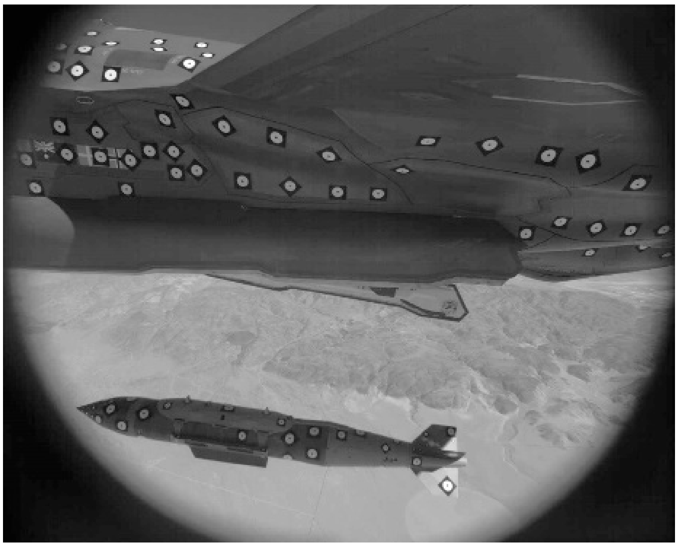


Figure 24: JSF Photogrammetrics.

The targets seen in Figure 24 on the store and aircraft are used to determine the store attitudes and displacements. The JSF program has shown how combining ejector force effects, wind tunnel freestream and grid data, store geometric changes (like floating canards, wind and tail deployment, autopilot), and photogrammetrics, telemetry and CFD can update and improve the trajectory simulations [24]. The result of this process is shown in Figure 25.

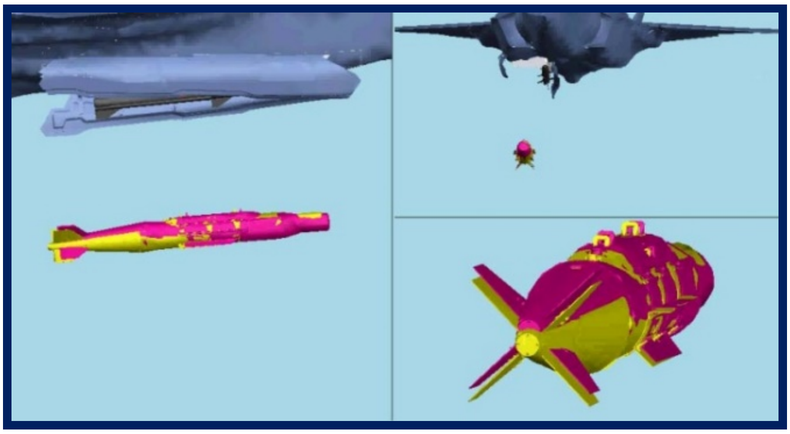


Figure 25: JSF Pre/Post Flight Test Trajectory Simulations.

This is similar to the process described previously [25, 26]. However, that procedure was hands on, sometimes required changes in the trajectory simulation program, and used to take days, weeks (or months) before the mistakes could be corrected.

4.0 CONCLUSION

Store Separation is a complex process. The likelihood of an engineer reading a SDoF user manual and then correctly calculating a trajectory is similar to someone reading an aircraft manual and successfully landing the airplane. Mistakes will be made. That is how the process can be improved. Documenting mistakes will make further improvements possible.

Success has hundreds of parents, one admitted mistake may lead to thousands of successes.

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