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New Mass Properties Engineers' Aerospace Ballasting Challenge Facilitated by the SAWE Community

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Abstract
The discipline of Mass Properties Engineering tends to find the engineers; not typically vice versa. In this case, two engineers quickly found their new responsibilities deep in many aspects of mass properties engineering and required to meet technical challenges in a fast paced environment. As part of NASA's Constellation Program, a series of flight tests will be conducted to evaluate components of the new spacecraft launch vehicles. One of these tests is the Pad Abort 1 (PA-1) flight test which will test the Launch Abort System (LAS), a system designed to provide escape for astronauts in the event of an emergency. The Flight Test Articles (FTA) used in this flight test are required to match mass properties corresponding to the operational vehicle, which has a continually evolving design. Additionally, since the structure and subsystems for the Orion Crew Module (CM) FTA are simplified versions of the final product, thousands of pounds of ballast are necessary to achieve the desired mass properties. These new mass properties engineers are responsible for many mass properties aspects in support of the flight test, including meeting the ballasting challenge for the CM Boilerplate FTA. SAWE expert and experienced mass properties engineers, both those that are directly on the team and many that supported via a variety of Society venues, significantly contributed to facilitating the success of addressing this particular mass properties ballasting challenge, in addition to many other challenges along the way. This paper discusses the details regarding the technical aspects of this particular mass properties challenge, as well as identifies recommendations for new mass properties engineers that were learned from the SAWE community along the way.

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Introduction

This paper discusses the details regarding the technical aspects of this particular mass properties challenge, as well as identifies general recommendations for new mass properties engineers that were learned from the SAWE community along the way. First, context for the NASA program is provided, which is followed by how the mass properties discipline found both Amanda and Brendan. Then more details are provided about the mass properties challenges surrounding the ballast system in the vehicle and finally the recommendations for new mass properties engineers are identified.

Background

As part of NASA's Constellation Program, a series of flight tests will be conducted to evaluate components of the new spacecraft launch vehicles. Although the future of the NASA's Constellation program and Orion crew exploration vehicle[1] are currently under deliberation in the U.S. Congress, the latest test was still conducted as part of NASA's ongoing mission to develop safer space vehicles for all human spaceflight applications.[2] Specifically, the Orion flight test discussed in this report is the Orion Pad Abort 1 (PA-1) flight test which tests the Launch Abort System (LAS) and is managed by the Orion Flight Test Office (FTO). The LAS is a system designed to provide escape for astronauts in the event of an emergency, which could be used on the launch pad or during the first stage of ascent to orbit.[3]

The LAS has heritage related to the Apollo abort system, but advances the concept to provide protection in a broader range of situations, as well as provides an abort capability that is not currently available for the Space Shuttle.[4] The LAS motor stack consists of three solid propellant motors that will perform the abort, attitude control and jettison functions. The abort motor will provide the thrust needed to pull the crew safely away from the Ares I stack in an emergency.[5] An attitude control motor composed of eight nozzles will orient the abort vehicle as it pulls away from the launch vehicle and a jettison motor will propel the launch abort system away from the crew vehicle during a normal launch or once a launch abort has occurred.[6] Figure 1 provides a trajectory overview for the PA-1 flight test scenario that shows the sequence of these three LAS motors.

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[1] National Aeronautics and Space Administration (NASA) "Constellation, Orion Crew Exploration Vehicle" FS–2008–07–031–GRC, http://www.nasa.gov/centers/johnson/pdf/402684main_M-2140_orion_fs_rev2.pdf.

[2] National Aeronautics and Space Administration (NASA) "Orion PA-1 2010" Fact Sheet Poster. http://www.nasa.gov/centers/johnson/pdf/436455main_PA1_poster_finalCMR.PDF.

[3] National Aeronautics and Space Administration (NASA) "Pad Abort 1: Ensuring Astronaut Safety" , FS-2010-03-004-JSC, http://www.nasa.gov/centers/johnson/pdf/436454main_FS-2010-03-004-JSC%20PA1.pdf.

[4] National Aeronautics and Space Administration (NASA) "Constellation Program: Astronaut Safety in a Launch Emergency, The Orion Launch Abort System" FS-2008-11-156-LaRC, http://www.nasa.gov/centers/johnson/pdf/317642main_FS-2008-11-156-LaRC-OrionLAS.pdf.

[5] Ibid.

[6] Ibid.

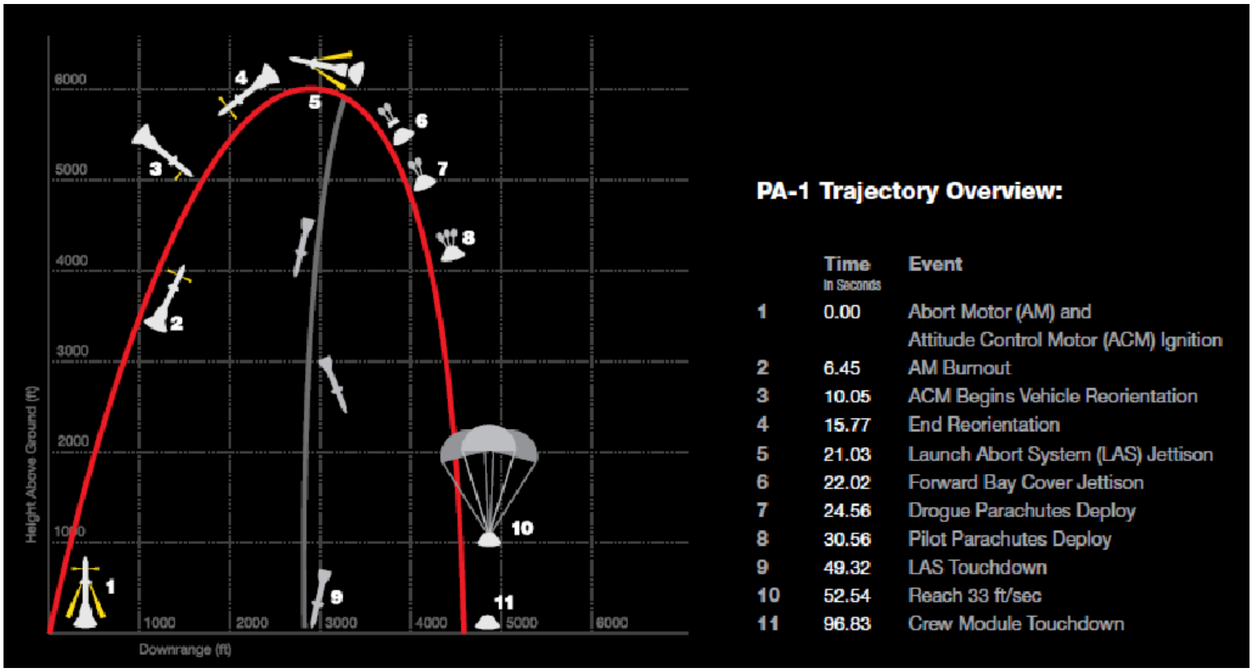

Figure 1: Trajectory overview of the LAS and CM for the Orion PA-1 flight test[7]

Although testing the LAS was the primary objective of the PA-1 Abort Flight Test (AFT), a Crew Module (CM) that represents the Orion capsule was necessary to conduct the test. The ballasting challenge for the CM FTA was identified up front for this project, however, Amanda and Brendan also encountered many other related mass properties challenges along the way. With the context and background on the overall project, now you can find out how Amanda and Brendan became mass properties engineers and how they overcame the ballasting challenge.

[7] NASA "Orion PA-1 2010" Fact Sheet Poster.

How Mass Properties Found Amanda

Everyone has their own story of how mass properties found them, if you are reading this, you certainly have your own, even if you are new to mass properties. This is Amanda's story.

One day the Design Team lead for the FTA project said to Amanda, a mechanical engineer and designer, "They need mass properties estimates for our flight hardware. Can you look into what they need?" She responded in less than a second with, "Yes, sure."

The first of many project customers had asked for mass properties estimates and since Amanda was willing to do work on whatever the team needed help with, the quick response to help with something new was no problem. After all how hard was that going to be, take a few minutes, give them what they need, and back to the other tasks on the design list? Right? Little did she know that quick and simple response would lead to working on mass properties on the same project for over four additional years and she would become responsible for the mass properties team.

Working by herself at first, Amanda knew she didn't have much time to waste and needed to leverage other available resources. A mass properties estimate sounded easy at first, just calculate the mass, center of gravity, and inertias. She explored resources available at work, surely there were other people on center that had received a similar task before and had an efficient means for responding to requests for deliverables. What she found was a few spreadsheets with lists of mass, center of gravity, and inertias for other projects but she was starting to realize mass properties was a little more involved than she thought and she was going to need more help.

Hoping that there would be resources out there similar to the American Society of Mechanical Engineers (ASME), American Institute of Aeronautics and Astronautics (AIAA), or the Project Management Institute (PMI), Amanda thankfully found the Society of Allied Weight Engineers (SAWE) online. She promptly became a member and started meeting the members of the local chapter. There were many members of the Hampton Roads Virginia local SAWE chapter that from then on were a valuable resource for advise, recommendations, and support.

Early on, Amanda was involved with requirements development, participating in technical reviews, providing mass properties estimates to a variety of project customers, supporting trade studies and design decisions with mass properties, and was quickly getting up to speed with what mass properties was all about. Additionally, Amanda quickly found herself being asked to take the lead of the mass properties working group (MPWG) for the Orion Flight Test Office (FTO) and therefore assumed even more responsibility. Now that she had a better understanding of mass properties along with more responsibility, she also knew there was more to learn and she needed more resources for support. Finding someone that was available and willing to try mass properties was not easy, but thankfully Amanda returned the favor and successfully helped mass properties find someone else too.

How Mass Properties Found Brendan

Brendan like Amanda joined the FTA team as a designer, but because of the restructuring of resources currently under way did not have any work to start on and was assigned to assist Amanda with her mass properties work sheet for the next month. At the time much of the mass properties estimations conducted were done so “by hand” within an Excel spreadsheet. Because of his interest in programming Brendan began to produce Excel macros for the estimations sheet to help speed up the process of mass properties estimations for the FTAs while assisting Amanda with her work.

Soon one month became two, two became three, and he was asked to help Amanda full time until a replacement could be found; the replacement was never found. Brendan’s new job was mass properties engineering and while unknown to him at that time, in hindsight it was an incredible opportunity. Through time that mass properties estimation spread sheet was developed more and more by Amanda, Brendan and Analytical Mechanics Associates Inc.(AMA) and became known as the Mass Properties Estimation Tool (MPET). As a contributing member to the development of MPET Brendan had to draw on many resources such as the SAWE Handbook and the AFT FTA MPWG to understand how mass properties were estimated and recorded. While it was certainly not the only influence the development of MPET was a driving force pressing him to learn as much as possible from the members of the MPWG and from SAWE mass properties members and documentation.

The Mass Properties Team

Thankfully Amanda and Brendan were not alone with their mass properties challenges. Due to the foresight of the Orion Flight Test Office (FTO), a Mass Properties Working Group (MPWG) was formed to support the program, among many other working groups to support different disciplines. Over the few years of the project, there were many participants in the MPWG and roles changed over time. At the time of the flight test launch, Figure 2 shows the organizations and people responsible for the mass properties of the different components of the flight test articles.

Overall this team coordinated exceptionally well together even though the working group was made up of members from a variety of disciplines, backgrounds, and experience levels. Primarily this was a good venue to discuss issues and coordinate with the project customers and within the mass properties team itself. The primary internal project customers included the Flight Dynamics Working Group, Structures Working Group, Aerosciences Working Group, the Loads and Dynamics team, as well as the Systems Engineering and Integration Team that ensured coordination across the entire project.

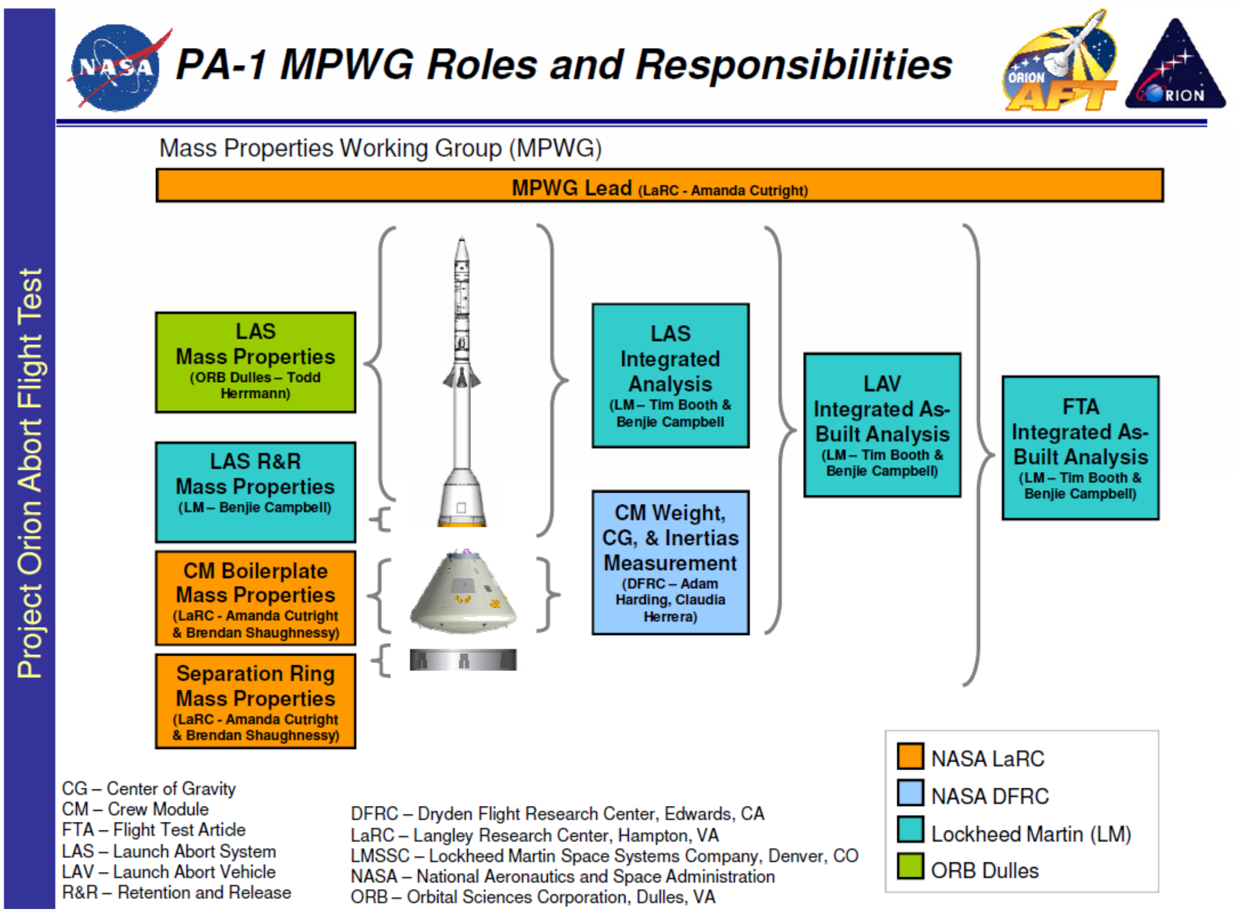

Figure 2: Orion Flight Test Office (FTO) Mass Properties Working Group (MPWG)

The experience on the mass properties side of this working group was a perfect combination of experienced and unproven mass properties engineers. Most of the members also had SAWE membership in common, which helped with communication both internal to the team and externally when necessary. SAWE provided a good avenue for the more experienced mass properties engineers to help mentor the members new to the discipline, even if the mentorship was across organizational lines. The long time SAWE members also had enough personal contacts within the society to be able to pick up the phone and contact other SAWE members for support in their areas of expertise. In the world of mass properties experience is invaluable, especially at foreseeing what could be an upcoming issue or concern before they become a major obstacle, particularly since much of the day to day activities is not taught in school or found in one text reference. On the other hand, the less experienced engineers brought innovation to the team by facilitating efficient processes for evaluating mass properties, which brought new methods and a change of pace of conducting mass properties evaluations. The team worked extremely well, with each member being a valuable contributor, and with SAWE as its cornerstone.

With the right team in place and with the right resources available, the task at hand was still ballasting the CM FTA, as well as meeting the other mass properties trials along the way.

The Ballasting Challenge

Since the PA-1 flight test of the LAS was conducted early in the design of the Orion Program, there was a need for a Flight Test Articles (FTA) for the Crew Module (CM) that represents the Orion vehicle. This FTA provides a CM structure that internally does not look like the Orion operational vehicle, but rather corresponds to Outer Mold Line (OML) and has mass properties to provide stable and controllable flight. Originally, the mass properties were desired to evolve as the Orion operational vehicle design evolved, which partially drove the desire to have a uniquely flexible ballasting situation. At one point in time it was necessary to "draw the line in the sand" for the development of the FTA CM and make it specific to PA-1 analysis, while the Orion operational vehicle continued to evolve.

The desire for a flexible ballasting configuration was a unique challenge for the mass properties team. Typically ballast is used to adjust mass properties a minimal amount[8], to achieve a more stable configuration for example, rather than as a design intent to use a larger percentage of vehicle mass approximately 25% of the vehicle. The ballast design was intended to be flexible and adjustable over time, anticipating that that the vehicle mass properties targets may need to evolve over time. Additionally, the ballast was at the mercy of all of the other subsystems within the CM, as their design and therefore mass properties progressed to become higher fidelity, the ballast system configuration was able to be adjusted to modify the end result mass properties of the vehicle. The mass properties team would often lovingly refer to the phrase "the ballast saves the day" when ballast was able to accommodate an unanticipated aspect of another system that required evolution to meet the requirements.

The requirements for the mass properties for this FTA were unique in order to constrain the ballast design and allow it to achieve the overall purpose. Although there was a desired nominal mass properties center of gravity (CG) point to aim for, there was also an envelope of minimum and maximum values that forced the ballast design to be flexible. Again, this was primarily in anticipation of changes on the operational Orion vehicle and for stability and controllability of the flight test articles. In order to meet these requirements, the structure and subsystems were evaluated to determine their current best estimates, then the ballast system was designed to allow mass properties requirements to be satisfied. The final ballast design allowed for 78 possible mounting locations in different areas of the vehicle, with most of the ballast primarily being towards the heatshield of the CM. The intent is that not all of these would be filled and that the only ballast blocks installed would be those necessary to meet the mass and desired center of gravity for the vehicle.

[8] Ian O. MacConochie. "Ballast – A Necessary Evil Few Want to Talk About", SAWE Paper 2331

Figure 3 shows an outline of the CM with location of ballast mounting locations, as well as an isometric and top view of the potential ballast block installation views. Figure 4 shows the same views but with ballast blocks only for all 78 possible installation locations.

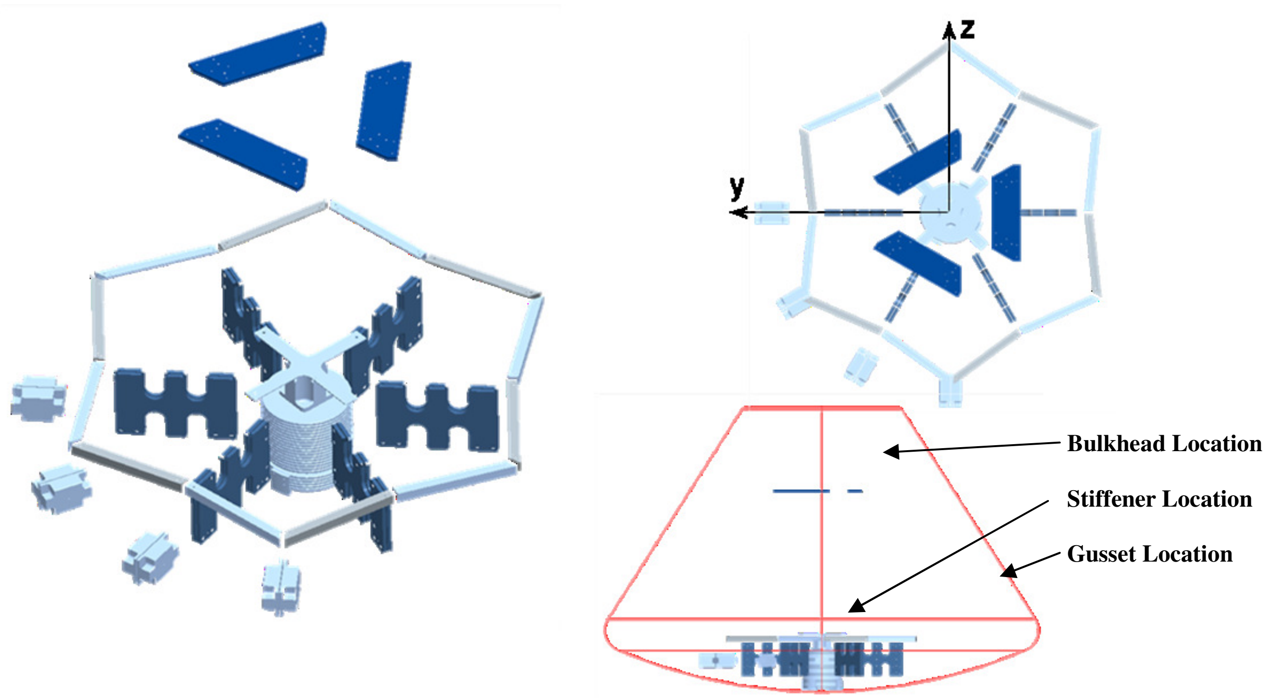

Figure 3: Ballast mounting locations[9]

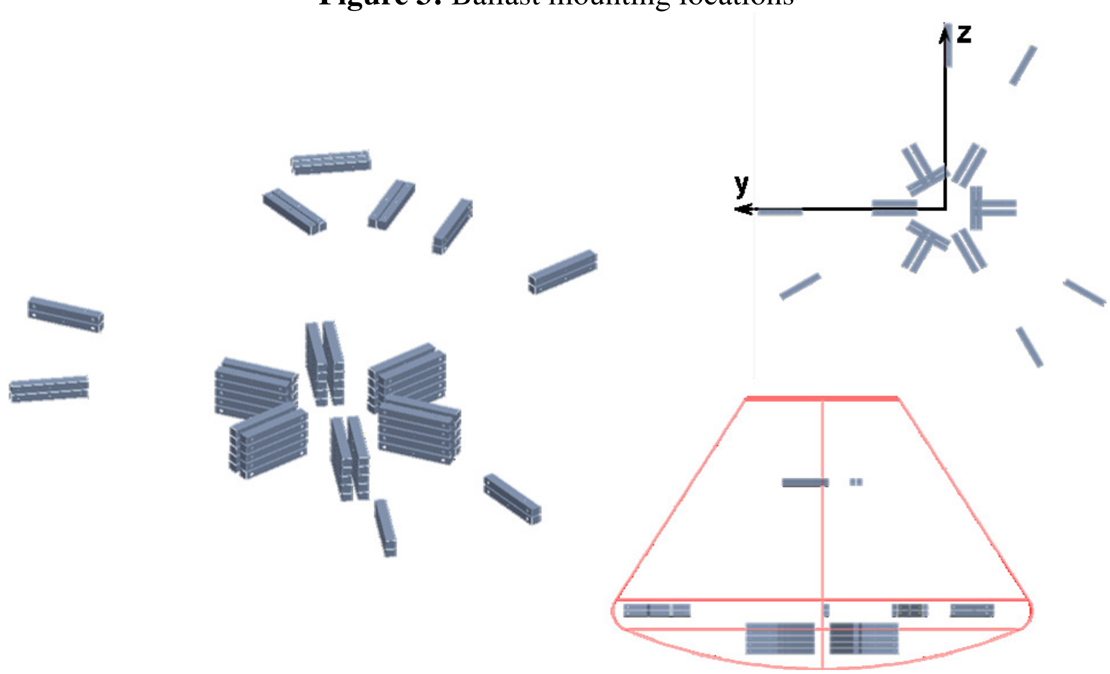

Figure 4: Ballast mounting blocks in all 78 possible installation locations[10]

[9] "1246831-1.asm" Pro/ENGINEER® Model. Maintained in the NASA Langley Research Center (LaRC) Windchill PDMLink® database. Accessed 13 February 2008.

Early on in the design of the CM boilerplate, the challenge of the adjustable ballast configuration while meeting mass and center of gravity requirements drove the need for a tool to help identify the desired configuration without relying on trial and error. Before the ballast design was even created, this tool was developed and used to help drive the design. Analytical Mechanics Associates Inc. (AMA) created the Ballast Solver (BSolv) Tool based on the projects needs. The tool allows for the user to input current mass properties, desired end result mass properties, potential ballast locations, additional subsystems, and priorities for meeting mass properties. The priorities are a choice of any component of mass properties including mass, CG, or inertias, and even a specific property within those categories, for example the x CG may be more desirable to meet than say the y CG. The tool has a wide range of options regarding the potential ballast locations as well, including options for specific points or stacking configurations. The user is then allowed to choose from a few different solvers, both linear and non-linear depending on the situation, and the end result is a ballast solution. This tool was used iteratively throughout the entire project, in early design phase as well as to determine the final installation configuration for the ballast.

While Bsolv was used to find a ballast solution that met mass properties requirements, another tool, the Mass Properties Evaluation Tool (MPET) was created over time to assist in the estimations of Flight Test Articles (FTAs). Throughout the following sections these FTAs will simply be referred to as "the vehicle" to simplify the wording.

This tool began as a simple Excel spreadsheet that was used to incorporate mass properties data extracted from Pro/Engineer Computer Aided Design (CAD) software and items that were part of the design but had not yet or where not going to be modeled. It was also used to apply weight growth allowances (WGA) to all items. Early on some of the line items in the Excel database represented entire assemblies in order to save time in producing the mass properties of the vehicle which was done "by hand" in Excel. As time progressed it was determined that it would be necessary to automate some of the calculations in the Excel database to help reduce human errors in creating the mass properties equations. Also, the level of detail within the CAD software far exceeded that of the Excel database. It was hoped that software could be developed that would help generate the Excel line items automatically from the Pro/Engineer data saving time and increasing estimation fidelity. This desired functionality spurred the creation of:

1) A standalone software capable of taking exported mass properties data from Pro/Engineer and populating an Excel spreadsheet with a model tree with matching mass properties information.
2) A large set of Visual Basic for Applications (VBA) functions was created within the Excel database for generating mass properties equations and performing other functionalities.

This software became known as the Mass Properties Evaluation Tool (MPET) and increased in functionality over time as it became apparent that more than weight growth allowance would need to be applied to the mass properties data.

[10] "1246831-1.asm" Pro/ENGINEER® Model. Maintained in the NASA Langley Research Center (LaRC) Windchill PDMLink® database. Accessed 13 February 2008.

One of the first major additions to MPET was the handling of mass actuals. It was decided that MPET would allow mass estimations to be completely overridden with mass actuals while preserving the original estimations in the sheet. What seemed to be a simple addition to the calculation of mass properties ended up being an involved and multi-organizational system. Before the mass actuals system expanded across the project a system for recording the actuals was implemented at NASA Langley Research Center (LaRC). The system was implemented within the Quality Assurance (QA) department as it was best suited for the task. Prior to being assembled on the vehicle the parts were weighed by the QA department, pictures taken of them and other pertinent information recorded in a log book. This log book became the source of mass actuals data used by MPET which was periodically updated with new information. The actuals "system" was expanded to other organizations where hardware was being produced and integrated such as Lockheed Martin Space Systems Corporation and NASA Dryden Flight Research Center (DFRC). The integration into other organizations, through no fault of their own, proved to be more difficult than anticipated. This difficulty was a good example to the new mass properties engineers in the MPWG of the challenges involved in multi-organizational activities. In the end the Mass Properties Working Group (MPWG) pulled through and smoothed out the mass actuals "system" enabling mass actuals of more than 90% of all parts within the vehicle to be incorporated into estimations prior to any full vehicle testing.

The incorporation and application of mass actuals into the estimations generated by MPET is one of many features that were incorporated overtime as Amanda and Brendan expanded their knowledge of mass properties. By the end of the project the MPWG, SAWE and other mass properties engineers provided the resources and knowledge for Amanda and Brendan understand and implement numerous mass properties concepts in their work. MPET reflects a small amount of these abilities and can now among many other abilities:

- Calculate moments of inertia and products of inertia
- Check to ensure inertias are physically possible
- Check for bad densities in estimations derived from CAD software
- Compare two similar or different assemblies mass properties and structure
- Classify items with user determined meta-data such as "fastener"
- Produce data for buoyancy calculations
- Compare previous estimations to current values
- Calculate partially assembled vehicle mass properties
- Invert mass properties data showing the mass properties of not yet assembled items

The tools used along the way helped provide an efficient means for evaluation of all mass properties and gave confidence to the final ballast configuration determination. Prior to the flight test, many technical reviews were conducted and the mass properties were vetted through many groups to verify the mass properties and ballast configuration.

The final result was that the ballast was successfully installed in the CM boilerplate by the operations team and Figure 5 shows pictures of some of the installed ballast blocks inside the vehicle.

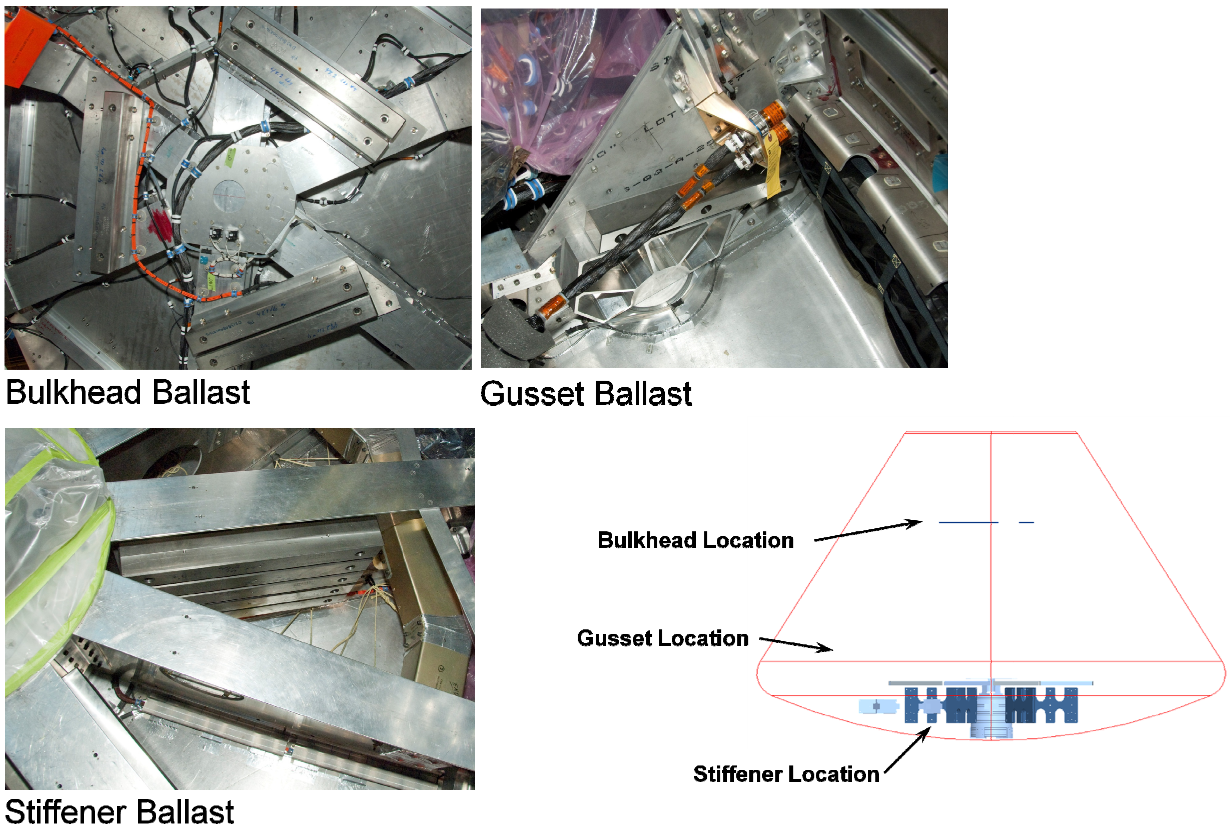

Figure 5: Examples of installed ballast blocks inside the PA-1 CM FTA

Recommendations

These recommendations are based on Amanda and Brendan's experiences throughout the PA-1 project. Keep in mind that each situation is unique and others may choose to agree or disagree with some of these recommendations, especially depending on the context, constraints, and resources available. We learned this information along our journey and hope they help you on yours, while we understand you may still learn some of your lessons the hard way. We hope that if you are reading this as a new mass properties engineer these recommendations will help you as an overview and also point you in the direction of some other SAWE papers with additional details on some of the topics. If you are a new mass properties engineer, welcome to the world of mass properties! If you are a veteran mass properties engineer, thank you for leading the way!

1) Software

Mass properties calculation software reduces the amount of work necessary for mass properties estimations and helps to keep your data organized, but one should understand as fully as possible the limitations and the methods used by their mass properties software. Whether you are working with OEM software or with software your company or organization has created you should track down any information available on how the software works and how it makes its calculations.

Does it adjust mass by densities or volumes?
Does it replace estimations with actuals?
Does it ratio your inertias?
Are the products of inertia in positive or negative integral formats?
Can it or how does it allow you to use weight growth allowances?

There may be many details built into the software that could affect your mass properties calculations; understanding what these caveats are is important for you to make good estimations. New mass properties engineers should be given the task of verifying the output of the software with hand calculations. This helps the new engineer hone or develop their ability to correctly calculate mass properties and can be used to verify proper operation of the software.

Even popular OEM software may miscalculate mass properties under certain conditions as the authors of this paper discovered. The software was Pro/ENGINEER® and when certain units were used the moments of inertias were not calculated correctly. This was found when it was discovered the software was providing negative moments of inertias (MOIs), these inertias are somewhat analogous to mass and should never be negative. A support call was opened regarding this issue and Parametric Technologies Corporation (PTC) released a new date code of the software that fixed the identified issue.[11] Assuming your software does everything correctly is risky business, don't assume, verify!

[11] Technical Support Call 6781384 Logged on Parametric Technologies Corporation (PTC) support system on 12 December 2008. Software Performance Report (SPR) 1671495 created on 06 January 2009 and Wildfire 3.0 Datecode M200 was released on 12 March 2009 to resolve the issue.

After you understand your software and have verified its calculations, hopefully under several different conditions, you still cannot assume the software will produce the correct results, only the correct calculations; as the old adage says "garbage in is garbage out". Whether they be based on shape codes or CAD models the unit items or parts that populate your software's data contain the fundamental basis to your estimations. It is important to understand that no matter how accurate your software is the mass properties used for these parts ultimately play a major role in the accuracy of your vehicle estimations.

2) Deliverables

At some point your estimations will need to be presented or provided to different groups. It is important that you know your "customer" (internal group, external group or individual) that will be receiving your data and what they need the data for.

Being ready – Mass properties data is used by many different disciplines and is needed at many stages of a vehicles development / production. Your customers will want previous estimations and current estimations and as a mass properties engineer you will need to keep your vehicles estimations up to date, organized and previous estimations readily available. Your customers may need data for transportation, simulations, analysis, requirement verification and more. Rushing to produce your estimations for what has been requested is never a good idea if it can be avoided. Good estimations usually take time to get through the details and as such good record keeping can help you stay on top of any requests for your data and ensure the data is accurate.

Get you and your work reviewed – If at all possible have a competent individual that understands mass properties thoroughly review your work. The source of good mass properties estimations are in the details and it's the details that usually go overlooked. Your estimations will be used by many disciplines; reviews help you ensure a good product. Mass properties is a field often looked at as easy and uncomplicated, having your work reviewed also aids in deflecting excessive scrutiny when mistakes persist despite the reviews. In such a case, hopefully, your reviews may help you show those that view your job as simplistic that it might not be as easy as they think. You should not only review your work, but also how your work is created.[12] This adds robustness to your work and discipline, especially when you do not have a mass properties department.

Presentation of Data – As in any discipline the presentation of your work should be done in a fashion that matches the audience. Generally speaking when presenting mass properties data one should remember to include references such as units, whether your inertias are in positive or negative integral format, the CG coordinate frame, what coordinate frame your inertias are about, the configuration of your vehicle, the fidelity of the data etc. Also remember to list all and any relevant assumptions about your data. Many times your audience will be unfamiliar with the caveats and assumptions within your estimations and assume that what you present is "as good as gold". The way your data is presented will vary slightly depending on what type of industry you are a part of, but remember to make sure it clearly coveys your mass properties data.[13]

[12] Glen Mathews. "Considerations for Performing Weight Reviews and Audits", SAWE Paper 3314.
[13] Daniel K. Jones. "A Weight Status Report for All Audiences", SAWE Paper 2348.

Content of Data - It has been the experience of the authors that many times the customer requesting the data is innocently ignorant of what is needed and does not ask for the correct data. If you choose to you may provided any and all information as it is requested, but this will likely result in extra work for you or worse taking the blame for a problem that could have been avoided. Understanding what the data is needed for goes a long way in helping to provide the correct and up to date data they truly need and saves you time in answering multiple requests for data until the right information has been provided. Your data should always be provided with a list of assumptions and or caveats. It is in your best interest that the deliverable contains these assumptions etc. so that your customer can correctly apply the data within and at the very least if it is used incorrectly leaves a record showing that you attempted to confine the use of the data to within acceptable bounds. Finally mass properties data, even estimations, are subject to a certain amount of uncertainty. Like your assumptions and caveats, uncertainties should be provided for your data because, *"It is insufficient merely to report the mass properties as a discrete entity"*[14].

3) Configuration Management

Accurate estimations are only possible if you know for certain what is on your vehicle. You might know what the final stage and perhaps a few stages in between are supposed to look like, but knowing what is on your vehicle any given day takes a lot of time and work; resources of which you probably don't have any extra. You will most likely have to work with another group to perform good configuration management of your vehicle. If your vehicle is large enough that you will not be able to do it on your own you will have to work with a group already involved in the vehicles assembly process. It is the experience of the authors that unless you have a team dedicated to configuration management no one on your project, not fabrication, not design, not quality assurance or anyone else will come forth with the time to do it; at least properly. You will most likely have to "fight" to convince your management that this is something you need and work with more than one group to accomplish it. Following are a few questions designed to help you determine how important configuration management of your vehicle will be and what you might need to point out to show why you need it.

- Will you be conducting mass properties tests after the vehicle is fabricated or even before?
- Will you need to present mass properties of the current state of your vehicle so that management can make a decision as to whether or not alterations to the vehicle are possible?
- Does any other discipline need mass properties throughout the vehicles fabrication to complete their assessments?
- Are ballpark estimations of your vehicle during its fabrication unacceptable? In other words is it NOT acceptable to base your estimations on what the vehicle <u>should</u> contain at a given stage?

Answering yes to any of the questions above will require you to have good configuration management of your vehicle during its fabrication in order for you to produce good mass properties estimations. At the bare minimum it is suggested that you help implement, if it does not already exist, a process wherein all items added or removed to your vehicle are logged and

[14] Zimmerman, Nakai. "Are you sure? Uncertainty in Mass Properties Engineering", SAWE Paper 3360.

their weights along with the date recorded. This does not make your job much easier but at the least it will provide you with the information you need to determine what is on the vehicle. If this is all that becomes available to you be sure to regularly keep an "ons file" updated that shows all of the items currently on your vehicle. You will likely be met with resistance by those assembling your vehicle as this process will take time away from their work, but rest assured that you will not be able to make good estimations without some form of this process. If your organization already uses RFID chips, bar codes or other part tracking systems see if those can be used to help those assembling the vehicle log what is going on or off the vehicle. It is unlikely that each individual part, especially fasteners, will be tracked by these systems, but any part that does should help reduce the amount of time those assembling your vehicle spend on your tracking process while at the same time provide you with the minimal data you need.

At best your configuration management process will be run by a team dedicated to the task. They will keep track of what is on the vehicle and other information such as, why changes were made, who made them, when they were made, what major systems are installed, the percent of the vehicle that is currently assembled, if the assembly process is behind schedule and what parts should be on, etc. At any given point in time your configuration management group should be able to tell you what is on or not on the vehicle and furthermore be able to provide it in a media or format that you can use with your software to quickly provide mass properties estimations.

4) Estimation Quality

The quality of your estimations can be compared to a neo-impressionist painting that from a distance seems to be smoothly drawn but upon close inspection is reviled to be the product of many many dots of paint. These dots of paint are analogous to the fundamental items that make up your estimations. If the dots are very small, i.e. you have accounted for every item in every subsystem down to the smallest detail; the "image" of your estimations will be clear and precise. One must understand what their mass properties estimations will be used for, in some cases they might only be required to select an appropriate transportation vehicle or lifting mechanism, in others they might be required for the efficient controlling of aeronautic or space vehicles. The required clarity of your estimation "image" that fundamentally resides in the size of those dots, that level of detail of your vehicles design, is what determines how much scrutiny and to what level of detail you will have to place on your estimations. The following section focuses on a level of detail for your estimations most new mass properties engineers do not realize is required to produce good estimations.

Due diligence is a legal term that is defined as follows, *"the care that a prudent person might be expected to exercise in the examination and evaluation of risks affecting a business transaction"* [15]. This term applies well to all the work you will perform as a mass properties engineer and might be reworded to say "*the care that a prudent mass properties engineer should exercise in the examination and evaluation of items affecting the mass properties of their vehicle(s) and the risks poor estimates pose to the success of the project"*. You must be prudent and detailed in your mass properties estimations while understanding the risks involved if you fail to achieve the estimation detail needed for your vehicle. Good mass properties estimations are based in detailed assessments and a thorough understanding of what makes up those estimations; as the saying

[15] Merriam-Webster's Dictionary of Law, © 1996 Merriam-Webster, Inc.

goes "the devil is in the details". It is quite common for engineers when calculating mass properties to ignore or "guesstimate" the contribution of "small items" such as fasteners, welds, paint etc. to the overall mass properties; these items <u>cannot</u> be ignored! It is up to the mass properties engineer and the process of due diligence to ensure that those "small items" are accounted for and that their impact on the overall mass properties of their vehicle is understood. Those small clips, rivets, wire ties, paint, grease and so on individually account for very little but together or and in large quantities these seemingly insignificant parts can account for a percentage of your vehicle well beyond the error range of any mass properties measuring equipment. Even when all of these items do not compromise a significant percent of the overall mass properties, failing to account for them can leave you at a loss when it comes time to verify mass properties testing performed on your vehicle; this is especially true in the case of your vehicle mass.

Item Estimations – Equally important as accounting for all of the items on your vehicle is producing accurate mass properties estimations of those individual items. In the past these estimations were predominately produced from drawings or and "shape codes" whereas today most of these initial estimations are generated from Computer Aided Design (CAD) software. In the absence of CAD software the mass properties engineer is directly involved in determining the fidelity of the estimations by determining what geometric shapes best represent the item to be estimated. Estimating the mass properties of a bolt as a single cylinder is not entirely accurate but may suffice depending on the required level of accuracy. In general, the authors would not recommend over simplifying the shapes of items to speed the estimation processes as this will likely result in poor vehicle estimations. If your vehicle is assembled predominately with those bolts whose mass properties estimations were represented by a simple cylindrical shape, your vehicles estimations will suffer because of it. While the error in mass properties for the individual item was slight, the contribution of many such items will result in lower fidelity estimation of the vehicle and worse still will most likely go unnoticed. Making good estimations of the fundamental items is really in your best interest and once completed is not too often changed.

If these fundamental item estimations are exported from CAD software a clear understanding of the designs fidelity is required before one can use those estimations with confidence. The accuracy of the estimation most likely, but not always, does not lie in the accuracy of the CAD software but in the detail of the design and the appropriate application of material densities. There is a tendency to believe any number that is produced with a computer, say it with me know, "my computer is not intelligent", *"Use the computer but don't trust it."*[16]. The computer is a very advanced calculator that can perform logic as it is instructed! The fidelity of your models and the reliability of your mass properties data based on those models starts with the users, the designers of those items and with your proper use of that data. Get to know to what level of fidelity your designers produce their parts and remember that it may vary depending on the type and its application.

After you have created or extracted your estimations of the fundamental items that make up your vehicle keep in mind that this data will need to be updated throughout the development of the

[16] Richard Boynton. "How to Waste Money While Trying to Save Money or Downsizing Mass Properties and Then Failing the Flight Test", SAWE Paper 2262.

vehicle. These updates are most obvious when they are the result of design changes. In such a case you will either obtain new mass properties data from the CAD system or you will have to recalculate this data from an updated drawing. For the latter case it is suggested that when making the first round of calculations you use a process that will lend itself to updates. Whether it is on a piece of paper, in a spreadsheet or saved in some other format breaking apart those calculations in a clear and logical fashion will help you make updates to those items efficiently. Regardless of how your estimations are made when they are changed, you should keep a log of the change that contains at a minimum, what the change is, when it was made and why it was made.

Not all updates will be the results of design changes. Changing the mass of your item will require the inertias of that item to be updated such as in the case of overriding estimations with actuals. It is not likely but certainly not out of the question for all of your items large and small to have their inertias measured with testing equipment. In such a case you will have inertia actuals to update your item inertia estimations. In the experience of the authors, it is likely that you will not have inertia actuals for individual items and will need to recalculate those inertia estimations based on mass actuals. A full recalculation can be performed or, as was the case for the authors, you may, if acceptable, scale your inertia estimations based on the new mass.

It is quite often a slow and meticulous process when creating the initial mass properties estimations in your vehicles database, especially if you do not pull data from CAD software. If you keep your estimations organized, detailed (as much as is required) and created in a fashion that lends itself to updates, you will save yourself a tremendous amount of time and frustration in the future. Prepare for the long haul by taking the time to make a good foundation.

5) Testing & Verification

The first thing to know about conducting mass properties testing is that your test results can be inaccurate. Test results are not magical values that automatically supersede your estimations. If a high degree of accuracy is desired great care must be taken in the selection of equipment, the test setup and the procedure. The following sections point out important facets of mass properties testing that a new mass properties engineer should be particularly aware of. When you need to get into the details of making mass properties measurements you'll likely have some questions like: *"What measurement accuracy is required?"* or *"What measurement equipment is available?"*[17] The SAWE has a great deal of information on testing and is an excellent source for determining how to conduct your mass properties tests. Talk to SAWE members and read papers on testing such as the one listed in the footnote.

[17] Kurt H. Wiener. "The Role of Mass Properties Measurement in the Space Mission", SAWE Paper 3354

Equipment –

- Make sure your equipment is CALIBRATED! In the case of load cells it is suggested that if it is within your resources at least a 10 point, or more if the cell has a large range, calibration curve be used.

- Make sure you understand what it is that your equipment is measuring. This might sound obvious but it is a common mistake to use values from weight scales as mass. While the English units for mass and weight are often interchanged a mass properties engineer must keep clear in one's mind that mass is not weight! Mass is the amount of material an object is made up of, weight is the gravitational force that acts on a particular amount of mass within its local gravity field. In the English unit system a small items weight does not differ in value much from that of the mass, but these small differences will add up. Also some load cells are calibrated to return a value equal to the mass of the item for a particular field (some region of the world) so again know what your equipment is measuring.

- Select your equipment appropriately for the size of the item you are looking to test. To continue the example of mass, you do not want to use a load cell capable of measuring thousands of pounds on an item that weighs only a few pounds. A good rule of thumb is that the estimated weight of the item should fall in a 20% to 80% range of the capacity of the load cell.

- As is with most testing equipment mass properties testing equipment is sensitive. Treat your equipment well, do not abuse it. Your equipment will also likely be sensitive to prolonged test setups. Understand what kind of errors can be induced if you leave your testing equipment in a test setup for long periods of time. Warning! For some instruments a long period may be as short as a few hours.

- If you create your own equipment, such as test fixtures, keep in mind that it should facilitate the testing of your item with the minimal impact to test values. As such keep in mind some of the following effects: temperature, rigidity, vibrations, stability (especially for dynamic equipment), electromagnetic influences as well as the percent of influence test fixtures have in readings.

- Defects aside your equipment will do what it has been designed to do; however, this doesn't mean that the values will be useable. Read the manual! Anyone operating the equipment needs to understand it thoroughly. If after reading the manual you have some questions call the equipment supplier. Most manufactures, especially of mass properties equipment, are more than happy to help you understand how to properly use their equipment.

Test Setup

- Your test setup will contain a test fixture of some kind. Large test fixtures "inline" with instrumentation will increase the uncertainty in your mass properties measurements. In general you should keep the size of the test fixture "inline" with measurements to a minimal while satisfying safety requirements and ensuring a rigid setup.

- Control the environment around your setup even if it means searching for a new location for the test. Air movement from natural or mechanical sources can adversely affect your measurements. Avoid areas where the temperature changes significantly or is at an extreme. Ensure that local electromagnetic influences (such as high power lines) are not interfering with the collection of your data.

- Ensure that any moving parts on your setup move freely in both loaded and unloaded configurations.

- Ensure there are no additional tare items on your vehicle other than your testing equipment. If tare items cannot be removed then estimations of those items must be done and subtracted from the tested values. Tools, supplies, another tests equipment, fuel (if testing for dry mass properties) and current test equipment that is resting on the vehicle such as load cell wires, are all examples of items that can negatively affect your test results. Ensuring these items are clear of the vehicle goes in hand with good configuration management, however, even with configuration management your vehicle should be checked for these types of items before testing begins.

- Prior to testing photograph your vehicles configuration in detail. Video tape and take pictures of the test while it is underway. Determine prior to the test those areas of interest for photographs and video such as load cell connection points and locations of cabling.

- Safety, safety, safety! There is never an excuse for not ensuring the safety of those conducting your mass properties tests! Work closely with your safety team and as early on as possible. Designing a test setup, constructing it and then not being able to use it because it is unsafe is as ill planned as trying to ensure good mass properties only after your vehicle has been built. Involve your safety team early on in a reasonable fashion; usually you will only need one individual to have a feel of what your setup will be like as you devise your plan. As your plans become more complete take them to your safety team for approval.

Test Procedure

- Your test procedure should allocate enough time for several test measurements. The quantity of measurements will depend on what mass properties data is being measured and what your test setup is like. It is suggested that at a bare minimum three measurements are made of any mass properties value. This provides you with a minimum number that can indicate (not with certainty) if there is a trend in your readings or if a reading contained an abnormality.

- When using load cells ensure that adequate time has been allocated for the cells to warm up; 30min at the minimum. If possible exercise the load cells to within a minimum of 25% of their capacity prior to zeroing the cells then take your first measurement.

- Try to keep the number of individuals required for the testing to a minimum especially when the conditions are hazardous.

- Record a time-line of testing events as they happen and if possible link them to the values recored by your equipment. It should not be very hard to acquire testing equipment that records the time and test readings "on the fly". If you are using this type of testing equipment do not rely on it completely. An individual should be chosen to record test events and the time at which they occurred so that this information can be compared to that of any automated system.

- Ensure that your procedure contains all the steps necessary to obtain reliable data and at the same time allows some flexibility to pause the testing or to repeat sections for various reasons. This flexibility should NOT be haphazard but have a location within the procedure for test pauses etc. It is very important that your test operations closely follow your procedures so that upon review of the test it is clear what transpired. As mentioned above an individual should be assigned to record events so that if it is required to pause the test, for example, for photographs, a record of those events has been kept.

- Another example of planned flexibility in your procedure, and also a good idea to ensure valuable data from testing, is to pause after measurements and calculate rough values for your mass properties values. In order to do this you will need to have software ready to take raw data readings, apply as many adjustments as necessary and output mass properties values. These will doubtfully be accurate final values, but if done carefully will help you identify possible problems in your setup before you have completed your testing. You will most likely be on a short time table and may have to take what you can get, however, that chance to discover setup issues is well worth the prep time required for this type of data checking.

6) All About Teamwork

"Anything truly great will take more than you to complete." The source of this quote is unknown to the authors, but the point is an obvious one that is often forgotten. The greatest of mankind's achievements have never been the result of one individual's accomplishments. From skyscrapers to aircraft carriers to spacecraft to the pyramids in Egypt, the most impressive human creations have been the labor of teams of people. The dynamic of teamwork has been studied and written about far more extensively than what could be hoped to be included in this document. It is hoped that you will gain from this section some appreciation for the value of working with others and how in general mass properties groups successfully interact internally and externally to their discipline.

Your project large or small is composed of multiple individuals working together and providing their unique skills and views to create something that they could not do alone; at all or at least in a reasonable time frame. As a mass properties engineer you will have to work with many different disciplines, some of which will need data from you and some of which will provide you with the data you need. Depending on your organizations history with mass properties you may meet with resistance from different disciplines even despite the necessity of which some may depend on your data. The "gray beards" of mass properties that the authors have met have talked about, fighting for mass properties, convincing management[18], wrestling with designers and getting Ops to cooperate. It is important that if you are in a situation where your mass properties group has not been properly integrated into your organization that you work patiently but determinedly with other disciplines. You may have to explain why mass properties is important over and over and why it's not as simple as most perceive it to be. This has been called the mass properties version of the movie "Ground Hog Day"[19], living the same day over and over. If you find yourself in such as situation you have friends in the SAWE community! Lots of them! They have gone through it many times before and have the experience to help you.

Each individual within your group contributes their skills and knowledge to the success of your work. It is of great advantage to you and your group to hold regular meetings that can keep all of the members up to speed on current work and provide a medium to "hash out" current issues. The Mass Properties Working Group (MPWG) was an invaluable asset to the PA-1 mass properties team that facilitated many discussions on testing, processes and estimations among many other topics. It was essentially a little SAWE actively involved in the project with individuals with varying backgrounds and organizations. Each individual shared his/her experiences and expertise with the group and the project and all involved benefited from it. The MPWG also pooled their collective connections to other experts across the mass properties field and in other disciplines and often included such individuals in discussions. Again this benefited the group and its individuals significantly. Hopefully, you are not alone in your struggle, but if you are it is all the more reason to reach out to the SAWE community and to those in your organization; to ensure mass properties is properly represented and that it ultimately benefits your project. Don't go it alone! A tremendous resource is awaiting you in the mass properties community!

[18] Brett L. Anderson. "Mass Properties and Management", SAWE Paper 3306.
[19] Correspondence with Bill Boze, Northrop Grumman Newport News (NGNN).

7) Use the SAWE Resources

SAWE is going to be your best resource, take advantage of the opportunities!

1) If you are reading this then you have made the first step – finding SAWE
2) Read the SAWE handbook! Enough said, this is a great resource
3) Understand the SAWE Recommended Practices and use them to help you
4) Get involved in the society especially local chapters. Attend conferences to meet people face to face. Even before meeting them face to face do not hesitate to call and ask questions
5) Read the SAWE papers! They contain a lot of great information on a variety of topics.
6) Find who in your company or organization has experience in mass properties. Every organization is different, some have MP departments others have engineers that were responsible for mass properties on a project.
7) Get others involved – do not go this alone – even having one other person working with you also responsible for mass properties goes a long way.
8) Take training and classes the society offers. These classes will save you from trying to figure out everything yourself by "reinventing the wheel". They also provide the opportunity to contact people directly if you need help and or have questions.

8) The Mass properties team is awesome!

Consider yourself lucky to be one of the few to discover the world of mass properties. Some have compared mass properties engineers to systems engineering, in the sense that the discipline interfaces with almost all the disciplines across the board and is involved in the integrated effort of the team. In our particular situation, the primary customers we interfaced with to provide mass properties estimates were flight dynamics, aerosciences, loads analysis, and design analysis teams. In order to do our job, we had to interface and coordinate with:

- The structural and subsystem design teams to get detailed information about the designs
- Quality assurance team to obtain actuals
- Testing team to conduct mass properties testing
- Safety engineers to make sure the tests were conducted safely
- Systems engineering and verification team to verify requirements
- Operations team for coordinating installation of ballast
- Logistics team for coordinating mass properties of hardware shipment configurations
- Management

In summary, mass properties is involved in many aspects of the project from start to finish and throughout the disciplines. For us, it was a pleasant surprise to have the opportunity to be an integral part of the project team for all phases of development including requirements development, design, fabrication, testing, and project execution.

Go Pad Abort 1 (PA-1)!

On May 6, 2010, PA-1 successfully launched at White Sands New Mexico!

The Launch Abort Vehicle (LAV) consisting of the LAS and CM boilerplate is shown at initial take off of the launch pad in Figure 6. As planned in the trajectory overview, Figure 7 shows the LAS jettison from the CM.

Figure 6: LAV for PA-1 leaving the launch pad[20]

Figure 7: Jettison of LAS from CM[21]

[20] Photos Courtesy of the U.S. Army White Sands Missile Range, from "Orion Crew Exploration Vehicle" on Facebook 6 May 2010.
[21] Ibid.

Figure 8: CM after Forward Bay Cover (FBC) jettison and LAS burn out[22]

Figure 9: CM just prior to landing[23]

Although to date the post flight analysis has not been completed, the preliminary assessment of the successful flight test showed video of the CM in free fall at what appears to be the correct hang angle, which of course is influenced by the correct selection of ballast configuration installation. All around, the mass properties team was successful with technical deliverables and

[22] Ibid.
[23] Ibid.

teamwork! Amanda and Brendan, along with the help of the MPWG, PA-1 team, and SAWE overcame the ballasting challenge and many other trials along the way. We also believe it is safe to say that Amanda and Brendan are no longer “New Mass Properties Engineers” and trust you agree with us. We believe our mentor agrees too, since on numerous occasions he mentioned that we “passed the test,” especially on May 6, 2010!

We trust that our recommendations and advice will help another fellow mass properties engineer, even if only in a small way. We wish you well and the same success on your projects! Thank you SAWE Community!

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- The entire Pad Abort 1 (PA-1) team!

Biographies

Amanda Cutright has a Bachelor's of Science degree in Mechanical Engineering from Virginia Tech and a Masters in Engineering Management degree from Old Dominion University. She started working at NASA Langley Research Center (LaRC) in 1999 as part of a student program while she was a freshman in college and now works full time at NASA LaRC. She served as the Mass Properties Working Group (MPWG) Lead for the Orion Flight Test Office (FTO) that conducted the Pad Abort 1 (PA-1) flight test.

Brendan Shaughnessy has a B.S. Degree in Mechanical Engineering from the University of Missouri – Rolla. He is currently working at Analytical Services and Materials (AS&M) in Hampton Virginia and is tasked to the Constellation Abort Flight Test Flight Test Articles project at NASA Langley Research Center. He has been a SAWE member for just over one year and this is his first SAWE paper.

He would like to say to all reading this paper "wiki wiki, wabi sabi!"