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# CONCEPT OF OPERATIONS VISUALIZATION FOR ARES I PRODUCTION

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## ABSTRACT

Establishing Computer Aided Design models of the Ares I production facility, tooling and vehicle components and integrating them into manufacturing visualizations/simulations allows Boeing and NASA to collaborate real time early in the design/development cycle. This collaboration identifies cost effective and lean solutions that can be easily shared with Ares stakeholders (e.g., other NASA Centers and potential science users). These Ares I production visualizations and analyses by their nature serve as early manufacturing improvement precursors for other Constellation elements to be built at the Michoud Assembly Facility such as Ares V and the Altair Lander. Key to this Boeing and Marshall Space Flight Center collaboration has been the use of advanced virtual manufacturing tools to understand the existing "Shuttle era" infrastructure and trade potential modifications to support Ares I production. These approaches are then used to determine an optimal manufacturing configuration in terms of labor efficiency, safety and facility enhancements. These same models and tools can be used in an interactive simulation of Ares I and V flight to the Space Station or moon to educate the human space constituency (e.g., government, academia, media and the public) in order to increase national and international understanding of Constellation goals and benefits.

## 1.0. Introduction

The National Space and Aeronautics Administration (NASA) Ares I launch vehicle program will develop and produce the first new human launch system for the United States in the last 40 years as part of its larger Moon/Mars Constellation Program. It is designed to safely transport up to 6 crew for rendezvous with the International Space Station (ISS) or transport up to 4 crew for rendezvous with the Altair Lander to support human lunar missions.

The Boeing Company was selected in 2007 to manufacture both the Ares I Upper Stage (US) and Instrument Unit (IU) to NASA's design. While similar to the Apollo Saturn 2nd and 3rd stages in function, the design of this liquid Oxygen/Hydrogen Upper Stage requires the use of the latest manufacturing and integration processes in order to meet NASA budget and schedule targets. Boeing is working with the NASA Marshall Space Flight Center (MSFC) to develop a cost effective and lean Ares I US/IU production process at MSFC's Michoud Assembly Facility (MAF) outside of New Orleans, Louisiana. One of the largest manufacturing plants in the world with 43 acres (174,000 $m^2$) under one roof, this facility was originally used to produce Saturn V components in the 1960s as shown in Figure 1.

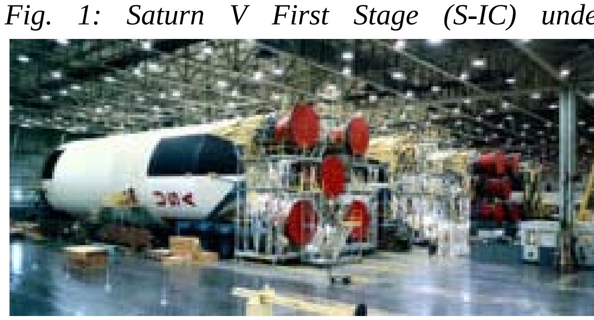


*Fig. 1: Saturn V First Stage (S-IC) under construction at MAF in 1968.*

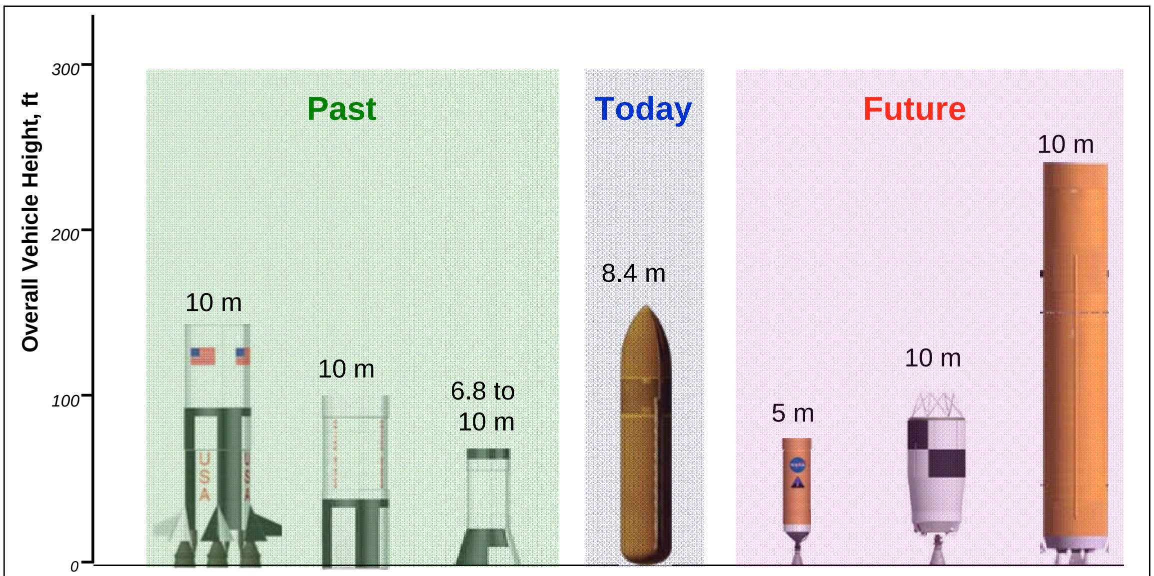
Updated in the mid 1970s to manufacture Shuttle External Tanks, MAF is now transitioning to Ares I production with Shuttle retirement in 2010 followed by initiation of Ares V production in ~2013.

Our experience on large development projects ranging from commercial aircraft to spacecraft shows that ~75% of the product life cycle cost is established during early hardware/production design (prior to Critical Design Review). We have found that tools that help the designers (engineers and management) and users (ground and flight crew) visualize potential Concept of Operations (CONOPS) can significantly reduce cost early in the life cycle. It also reduces schedule risk and help spread understanding, support and ownership across government, academia, media and public constituencies.

## 2.0 The Need for CONOP Visualization using Virtual Manufacturing in support of Ares

Currently NASA Marshall Space Flight Center (MSFC) is converting MAF into a 3rd generation liquid oxygen/hydrogen rocket stage factory capable of producing from 2 to 6 Ares I Upper Stages a year to support International Space Station (ISS) missions and up to 2 Ares V vehicles a year for lunar missions. This must be done while minimizing disruption to External Tank operations as well as working around Saturn V era monuments and building constraints. Figure 2 details the range of vehicle type and size to be considered while optimizing MAF for next 20+ years of Constellation missions. In addition this conversion must be done within a Constellation Program schedule and budget that also accommodates coordinated development of the Orion crew capsule and Altair lunar lander.

Through MSFC's Ares I Upper Stage Production (USP) and Instrument Unit Avionics (IUA) contracts, Boeing is tasked to evaluate MSFC's Upper Stage design for producibility. These producibility efforts are obviously most effective the earlier they are implemented in the life cycle. Boeing's experience on programs like 737, F-18, Chinook, Space Shuttle and International Space Station had shown that incorporating virtual manufacturing techniques minimizes production problems caused by design, planning tooling, safety, capacity and build processes before they impact the factory floor. This experience,




| | Saturn V (S-IC) | Saturn V (S-II) | Saturn V (S-IVB) | Shuttle ET | Ares I US | Ares V EDS | Ares V Core |
|---|---|---|---|---|---|---|---|
| **Height (ft)** | 138 | 82 | 58 | 153 | 84 | 74 | 215.6 |
| **Dry Mass (lb)** | 298,104 | 86,086 | 25,750 | 65,980 | 38,600 | 50,144 | 296,952 |
| **Total Mass (lb)** | 5.04M | 1.16M | .262M | 1.65M | .156M | .517M | 3.165 M |

*Fig. 2: Comparison of MAF manufactured hydrogen/oxygen launch vehicle stages.*

combined with MSFC's early adoption of similar tools to map and evaluate MAF for Ares, has led to use of a best in class virtual manufacturing approach to analyze the NASA Design Team's Upper Stage design concurrently and collaboratively.

Our Ares team is using Dassault Systemes DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) as a producibility tool during NASA's design cycles. DELMIA allows 3D hardware (ground and flight) models generated in a variety of Computer Aided Design (CAD) systems to be combined to efficiently model, experiment and analyze facility layout, tooling and traffic flow. Specifically, application of DELMIA can provide the benefits in the following areas (range of cycle time savings expected):

- Assembly Simulation (30% - 45%)
    - Validates design/assembly integrity prior to commitment
    - Validates operation sequences & tooling concepts
    - Identifies assembly anomalies
    - Drives & validates design release schedule
    - Enables optimization of assembly processes
    - Reduces downstream production planning (assembly)
    - Creates consistent virtual/simulation based work instructions
    - Captures best assembly practices
- Human Factors/Ergonomics (45% - 55%)
    - Identifies hazardous operations (hardware/ personnel)
    - Validates serviceability/operations
    - Ensures accessibility during assembly/test/ operation/maintenance
    - Highlights potential tooling/ground support equipment requirements
- Factory Definition and Analysis (50% - 75%)
    - Validates floor space & factory operations
    - Validates operation sequences & large scale tooling concepts
    - Highlights capital investment requirements
    - Identifies assembly anomalies
    - Drives & validates design release schedule

## 3.0 Virtual Manufacturing Applications to Ares I Production at MAF

Upon USP contract start in September 2007, NASA and Boeing quickly joined together to evaluate the proposed Ares I Upper Stage production flow for efficiency at MAF. An in-depth, joint analysis was able to reduce total production flow time over 100 man-days to 312.5 man-days (starting with the production of the Orion 4 Ares I Upper Stage). Understanding the production CONOPS by building a DELMIA virtual manufacturing simulation validated this efficiency. Figure 3 shows samples of this analysis. This early collaboration also enhanced NASA and Boeing team building and design knowledge transition.

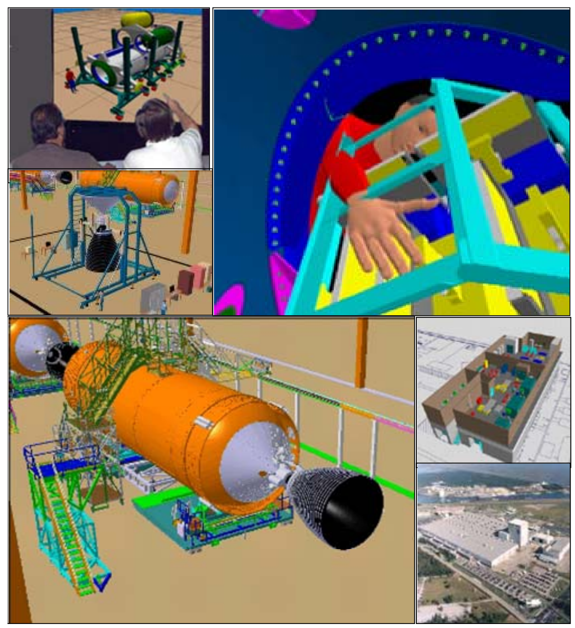



*Fig. 3: Early use of DELMIA based virtual manufacturing simulation of MAF Ares I production validated a 25% reduction in assembly man-days prior to Preliminary Design Review.*

Significant production changes simulated and verified included going to vertical weld of the cryogen tanks (from horizontal welding) and moving Upper Stage final assembly to a different building. This new flow meets nominal Ares I annual flight rates (2/year) with one shift and provides facility capacity margin that can support maximum Ares I annual flight rates (6/year) with just 2 shifts. This DELMIA visualization also assisted in more effective coordination with the External Tank Transition Team to better understand where and when this assembly area was needed to be available for Ares I.

In addition to be being used for leaning Ares I factory operations, this visualization can be effectively applied to solving quick turn-around issues as well. During Ares I Preliminary Design Review (PDR) in July 2008, a possible operational issue was identified in allowing technician access to remove the Ares I Thrust Vector Control (TVC) Actuator Locks. This access is required 48 hours before launch to enable TVC function for flight. NASA and Boeing coupled existing 3D CAD models to a late pad access CONOP and used DELIMIA to develop an ergonomic technician accessibility simulation. As shown in Figure 4, it was discovered that the Roll Control System (RoCS) plumbing obstructed the Ares I Upper Stage Interstage Access Panel and interfered with a related Work Access Platform.

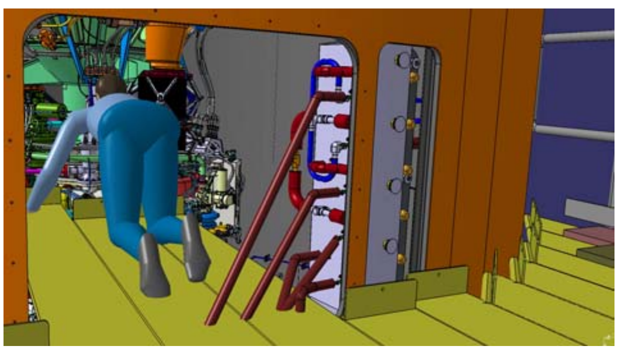


*Fig. 4: Launch Pad technician access obstructed to J-2X engine in Ares I Interstage.*

Once inside the Interstage, the technician (a DELIMA "ergo man") uses a specially designed Work Access Platform to access the actuator locks. As shown in Figure 5, the technician can safely and comfortably unlock the "left" TVC Actuator Lock.

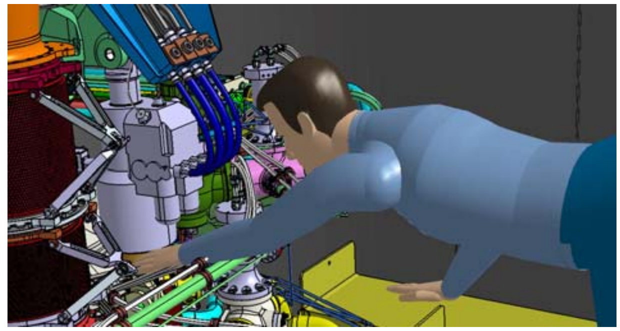


*Fig. 5: Technician easily accesses J-2X TVC "left" Actuator Lock.*

As shown in Figure 6 however, the technician has to reach in a strained manner using the as designed Work Access Platform to access and then unlock the "right" TVC Actuator Lock.

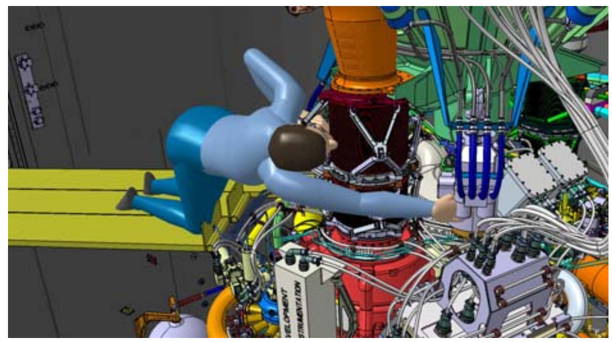


*Fig 6: Technician strains to accesses J-2X TVC "right" Actuator Lock.*

This visualization was built in less in 8 hours and allowed the NASA and Boeing team to identify a previously unknown obstruction (RoCS plumbing) and identify a need for the Interstage Work Access Platform to include a wrap around feature to enable access to the "right" TVC Actuator Lock. This CONOP visualization by its nature minimizes stovepipes between different work groups, promotes collaboration and radically reduces cycle time to determine a preferred solution. As in this case, by laying out all the CAD models and applying an ergonomic simulation, the NASA and Boeing team not only found a quick solution, it identified another previously unknown issue. Identifying both of these issues at PDR, where the cost to change the design still relatively low, is very much preferred to the alternative of costly design changes at Critical Design Review or procurement of contingency tooling solutions during initial launch pad operations.

4.0 The Need for CONOP Visualization to communicate the mission of Ares I, Ares V, and Constellation to different constituencies

The benefit of Ares vehicle CONOP visualization of is not limited to the design or manufacturing phase. In order to maintain national and international political and public good will as well as sustain funding for a space exploration enterprise that will take decades to implement, it is imperative that the mission (or CONOP) for Ares vehicles and Constellation be communicated simply and effectively. The range of element types, the scale of time for development, the complexity of integration both on the ground and in space, and the number of changing interfaces presents a challenge to "visualizing" the architecture and describing the benefits to the implementers (industry), owners (public) and financiers (government).

In order to get the same benefits virtual manufacturing simulation provides during the production process, MSFC and Boeing worked together to develop an Interactive Concept of Operations (ICON) that visualizes the entire Constellation architecture from Low Earth Orbit (LEO), International Space Station (ISS), the moon and Mars.

6.0 ICON Applications to Ares I and V missions

ICON can run on most laptop computers and is designed to allow the user to interact with any Constellation element during any mission phase from launch to landing. As shown in Figure 7, ICON provides a simple navigation screen where a user can choose a Constellation destination (ISS, Moon or Mars), a set of hardware (like Ares I or V), and then interact with that mission from beginning to end.

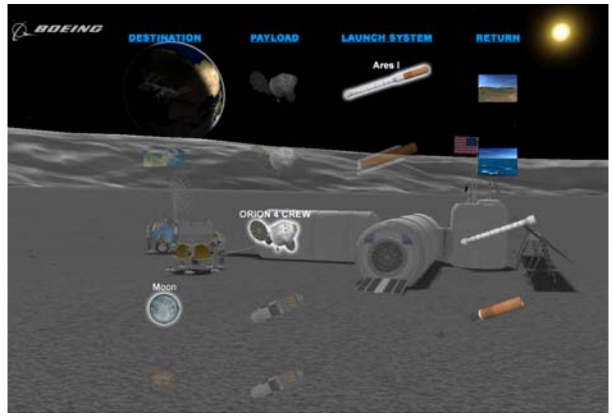


*Fig 7: ICON navigation page allows users to build a specific Constellation mission based on destination and return objectives.*

These missions are physics based combining timelines, locations, designs, and mission dependent events. We used ICON to integrate NASA and Boeing engineering data into a visualization engine using the same graphics capabilities as video games. ICON accommodates 2-dimensional data, 3-dimensional data and time elements into an interactive, 4-dimensional Constellation CONOPS simulation. Any 2D data (such as trajectory, or ephemeris data, operations schemas, slides, spreadsheets, movies, documents, or web-based data) or any 3D data (such as CAD models, contour maps, terrain maps, etc.) can be imported into ICON and used as a basis of the simulation or used in conjunction with the simulation during presentation.

Once this data is merged into ICON the user can then decide how to monitor the mission, whether from inside the crew cabin or outside the vehicle, if and when to abort a flight, or stop the simulation and bring in unique, supporting user generated content (like a DELMIA simulation). Figure 8 shows the results of a user selected launch abort. At abort initiation, ICON fires the Launch Abort System, and calculates the ballistic trajectory and then activates the crew recovery system. Also visible in this view are user controls that allow the simulation to pause, reverse or advance, change camera views, and add mission instrumentation as needed.


*Fig 8: ICON allows the user to interact and make decisions to evaluate system response (e.g., simulate a pad abort scenario).*

Figure 9 shows a different user selected view: destructive reentry of the Ares I Upper Stage after successfully completing its mission of orbiting Orion safely (shown in inset).

*Fig 9: Reentry of Ares I Upper Stage over the North Atlantic.*

NASA and Boeing are currently using ICON to communicate the Ares mission to employees at MSFC and MAF, to industry at conferences and symposia, to potential Ares V science users, students across the country, and the general public at museums like the US Space and Rocket Center in Huntsville, Alabama. Other optional Constellation missions are continuously being added to ICON including a Low Earth Orbit Propellant Depot and L2 Space Telescope delivery by Ares V. With the latest addition of a Media Toolkit to ICON, a user can real-time capture simulation stills at any point in the mission or make unique movies focusing on a particular mission phase.

## 7.0 Conclusion

CONOP visualizations can provide timely insight into potential system problems or allow evaluation of alternate approaches for Ares and Constellation elements. Together NASA and Boeing have used a variety of tools and techniques to enhance design producibility and more effectively operate the Ares systems. We have found that collaborative nature of these visualization and simulation tools significantly reduce design cycle time and encourage a diversity of involvement across different Constellation flight elements as well as different Constellation manufacturing and operation facilities.

Not only do these visualization tools identify changes earlier in the life cycle where the cost to change is less, they promote greater direct interaction by a larger pool of owners and constituents into the Constellation vision and mission. This expanded support will be critical to sustaining Constellation financially and technically over the next 20+ years.