Manufacturing Process Simulation of Large-scale Cryotanks

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Introduction

NASA's Space Launch Initiative (SLI) is an effort to research and develop the technologies needed to build a second-generation reusable launch vehicle. It is required that this new launch vehicle be 100 times safer and 10 times cheaper to operate than current launch vehicles. Part of the SLI includes the development of reusable composite and metallic cryotanks. The size of these reusable tanks is far greater than anything ever developed and exceeds the design limits of current manufacturing tools. Several design and manufacturing approaches have been formulated, but many factors must be weighed during the selection process. Among these factors are tooling reachability, cycle times, feasibility, and facility impacts.

The manufacturing process simulation capabilities available at NASA's Marshall Space Flight Center have played a key role in down selecting between the various manufacturing approaches. By creating 3-D manufacturing process simulations, the varying approaches can be analyzed in a virtual world before any hardware or infrastructure is built. This analysis can detect and eliminate costly flaws in the various manufacturing approaches. The simulations check for collisions between devices, verify that design limits on joints are not exceeded, and provide cycle times which aide in the development of an optimized process flow. In addition, new ideas and concerns are often raised after seeing the visual representation of a manufacturing process flow.

The output of the manufacturing process simulations allows for cost and safety comparisons to be performed between the various manufacturing approaches. This output helps determine which manufacturing process options reach the safety and cost goals of the SLI.

As part of the SLI, The Boeing Company was awarded a basic period contract to research and propose options for both a metallic and a composite cryotank. Boeing then entered into a task agreement with the Marshall Space Flight Center to provide manufacturing simulation support. This paper highlights the accomplishments of this task agreement, while also introducing the capabilities of simulation software.

Factory Layout and Process Flow Simulations

The size of the cryogenic tanks needed to accomplish the goals of SLI is on a colossal scale. Preliminary designs for both the composite and metallic tanks had the tank dimensions in the neighborhood of 30 ft. in diameter by 100 ft. in length. Not only is it a challenge to build a tank of this size, but throw in the need for adequate tooling and you have a truly daunting task. Simulations proved very valuable at looking at the interfaces between tooling and parts. As these tanks are being built, the tooling has to be assembled and disassembled without colliding with or damaging the tank in any way.

Early in the design process, design details for individual parts and workcells do not exist. However, a well laid out manufacturing process plan for the composite tank did exist. This written process was translated into a simulation to help give a visual representation of the factory floor as well as preliminary tooling footprint information. The baseline manufacturing process included the use of an autoclave, fiberplacement machine, and a Nondestructive Test (NDT) cell.

Figure 1 (below) is a view into this simulation. It gives an overall perspective of the preliminary factory floor layout. In the forefront is the NDT cell. In the middle of the factory floor the internal tool, on which the tank will be built, is stationed at the fiberplacement machine. The autoclave can be seen in the background. Figure 2 (below) gives a better perspective as to the colossal size of the tank and required tooling. In this figure, the internal tool is entering the autoclave. The two human figures in the foreground are 5' 9" tall.

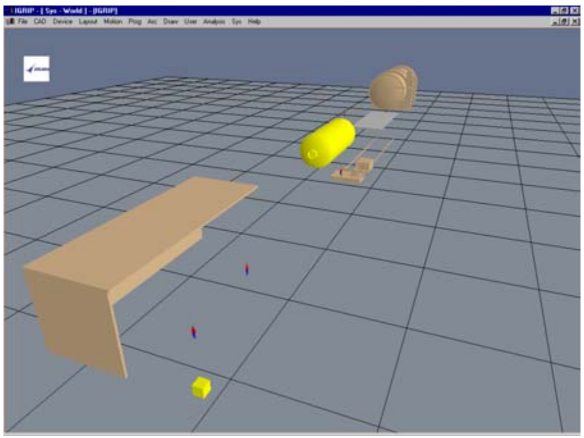


Figure 1 – The preliminary layout of the factory floor

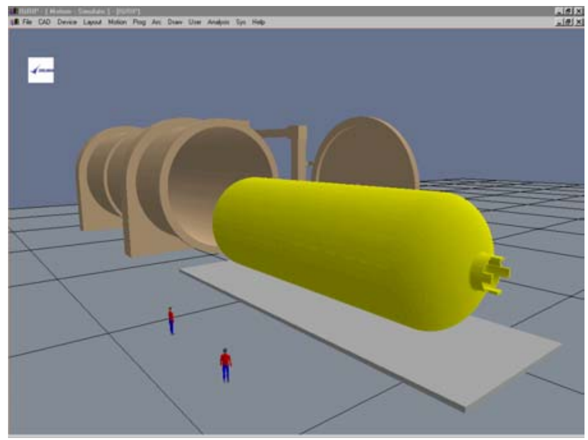


Figure 2 – Internal tool stationed at the autoclave

The Power of Simulations

Simulations are not mere pretty cartoons. While simulations do add life and action to the manufacturing processes, simulation software offers a wealth of output data. The software has the capability to check for collisions between parts, compare joint geometry values against design tolerances, calculate cycle times, and produce machine optimization charts among others. The MSFC simulation team utilized each of these capabilities to verify the design concepts proposed by the Boeing Composite Tank and Metallic Tank Teams.

Joint Tolerances

Figure 3 (right) shows the internal tool stationed in the Nondestructive Test cell. This simulation tested a preliminary inspection method. As the simulation runs, the software dynamically displays and compares the joint values of the inspection device against design tolerances. If a joint violation is detected, the errant joint will highlight in a different color. This is a powerful feature of simulation software. Without the use of simulation software, a post-production violation of design joint tolerances would be very costly to fix and retool. By testing the design upfront with simulation software, costly design flaws can be eliminated since the software verifies that the tooling design will work properly within the given production environment.

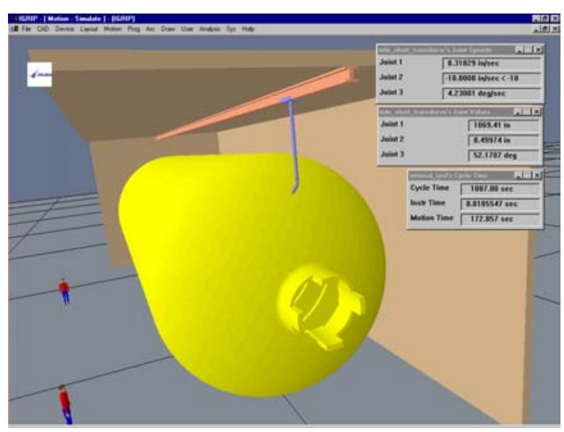
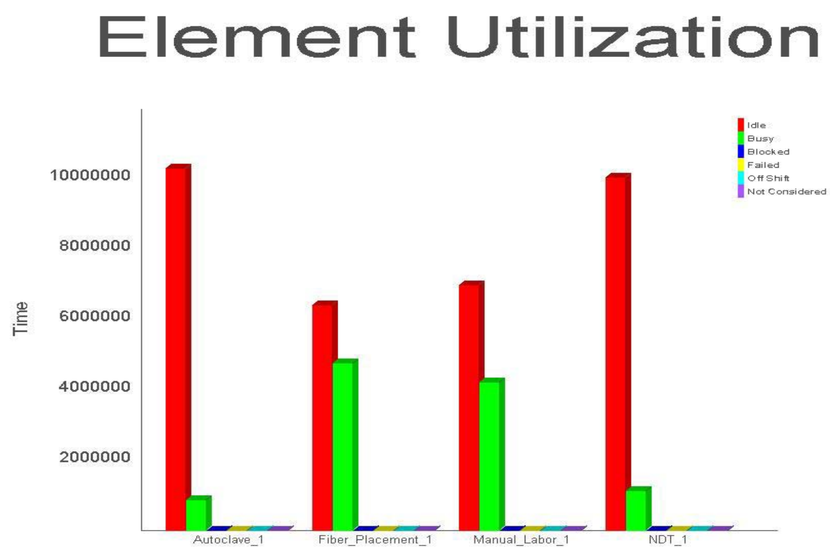


Figure 3 – Software output values for the NDE cell

Machine Optimization

Another powerful capability of simulation software is its ability to calculate machine usage. Busy and processing times for each machine in a factory simulation can be collected. Given this type of data, bottlenecks can be detected along with under usage of a machine. Figure 4 shows the actual output of the Element Utilization analyses for the preliminary process flow of the Composite Cryotank. As you can see, there is severe idle time for the autoclave and NDT cells. To better optimize machine usage, one possible scenario would be to build multiple tanks simultaneously (Figure 5).



Custom_Report_1

	Autoclave_1	Fiber_Placement_1	Manual_Labor_1	NDT_1
Avg. Utilization (%)	7.741936	42.580646	37.677419	10.064516
Idle Time (hr)	2860.000069	1780.000043	1932.000047	2788.000068
Busy - Processing Time (hr)	144.000003	960.000023	1168.000028	216.000005
Busy - Setup Time (hr)	96.000002	360.000009	-	96.000002

Figure 4 – Machine utilization chart for the preliminary composite tank process flow

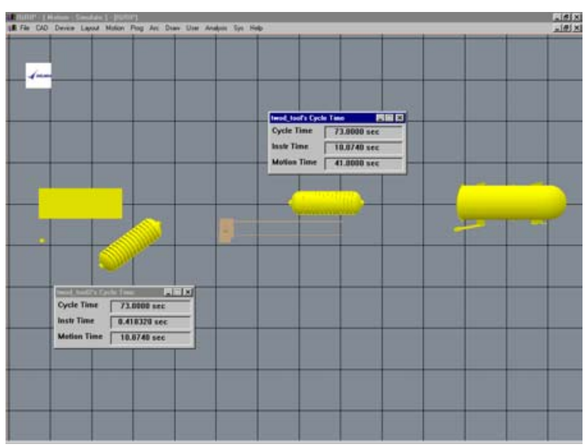


Figure 5 – Simulation showing multiple tanks being built simultaneously (Top view)

Assembly/Disassembly Simulations

One of the most useful features of simulation software is the ability to simulate assembly/disassembly sequences. These type simulations verify the following:

1) The feasibility of the assembly/disassembly sequence(s)
2) That parts do not collide with one another
3) That part clearances are not violated.

Assembly/disassembly simulations were utilized on both the metallic and composite cryotanks. To build the metallic tank, a sequence of welds must take place. The tank is built by first welding together barrel sections. Once welded together, these sections form the body of the tank. Additional formed pieces of metal are welded together to form the tank domes. Once the domes and body have been manufactured, they are then joined together to form the metallic tank. Using preliminary design sketches, a simulation was developed showing the assembly process in sequence.

Figure 6 is a view into the simulation showing the welding of the barrel panels. Notice the massive internal tooling and clamps used to hold the barrel sections in place while the welding is taking place. The human figure in the lower right-hand corner helps give perspective to the size of the tooling. Figure 7 shows the barrel section after the welding process has finished. The barrel section is now ready to have the domes attached. Figure 8 shows the welding of the dome panels.

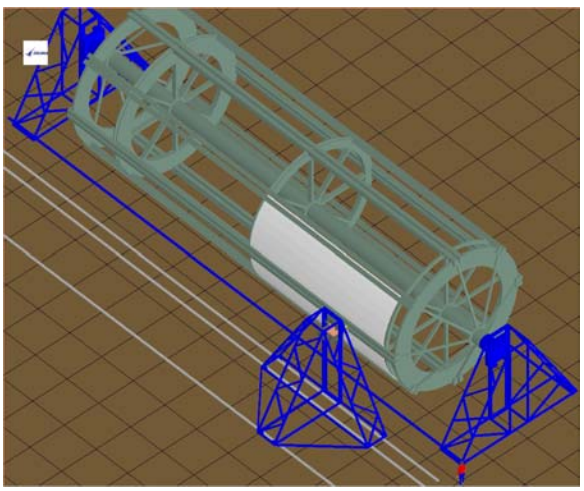


Figure 6 – Welding of the barrel panels

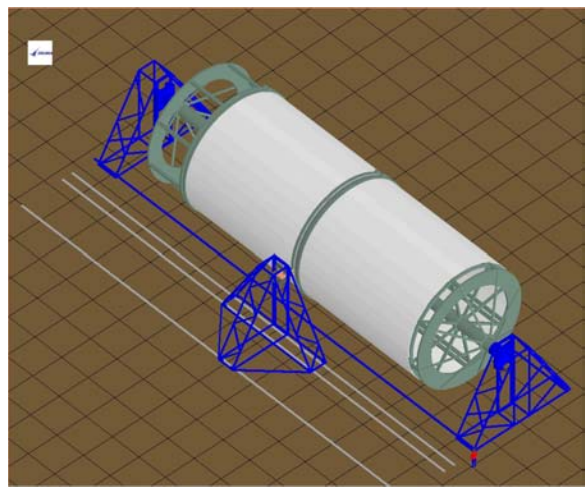


Figure 7 – A finished barrel section

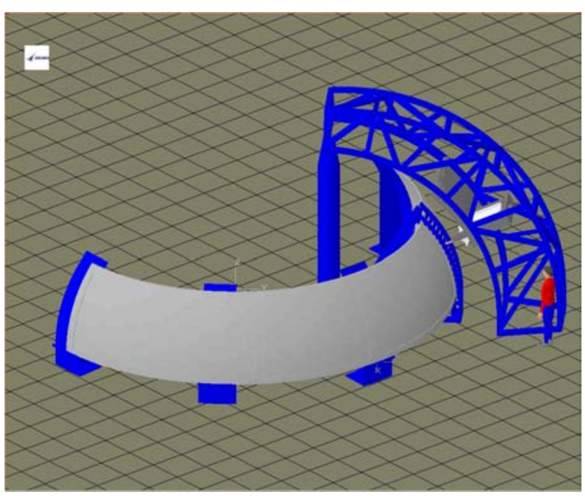


Figure 8 – Welding of the dome panels

The composite tank is built by using an internal tool. This internal tool allows for the manufacturing of a single piece tank. A great challenge for this manufacturing method is the removal of the internal tool once the tank has been cured. One leading candidate was a multi-piece, breakdown internal tool. Using this tooling approach, the internal tool must be broken down and removed via the port ends after the tank has been fabricated. Manufacturing simulations were used to verify this disassembly process. The internal tool was composed of 100s of different segments, along with both radial and longitudinal stiffeners. One important question was whether the individual segments could be removed without colliding with other segments, stiffeners, or port openings.

Figure 9 below shows the process of removing the internal tool's segments. A boom has entered through the porthole and has begun to lift the segment up and through the longitudinal stiffeners. Once this segment has cleared the stiffeners, it is brought to the centerline of the tank and removed via the porthole (Figure 10). The clearances on this design were very close, but the simulation did verify that the segments could be removed through the porthole without colliding with other segments or the porthole itself.

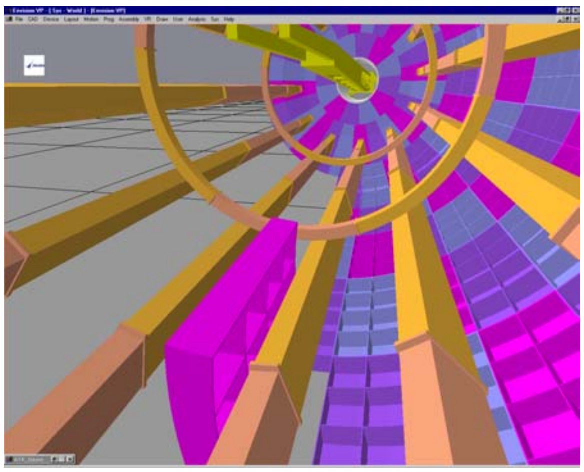


Figure 9 – Lifting the segment to the centerline

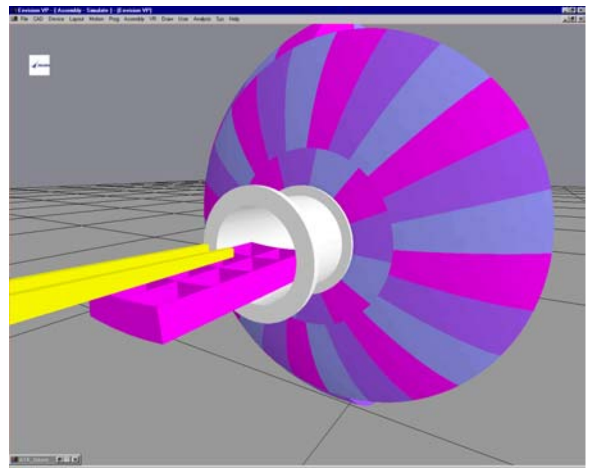


Figure 10 – Extraction of the segment via the boom

Conclusion

The goal of the basic period contract between The Boeing Company and NASA's Marshall Space Flight Center was to provide baseline simulations of the manufacturing process for both the metallic and composite cryotanks. High fidelity geometry did not exist at this early point in the design stage, however the groundwork has been laid. As more refined processes and higher fidelity models are provided, these baseline simulations can easily be updated to execute against the new geometry. Once the updated simulations are executed, the output values that were detailed in this paper can be fed back to design engineers. This feedback may or may not lead to further design and process modifications. The end product of this cyclic process will be highly defined simulations that thoroughly examine, analyze, and verify the manufacturing processes for the metallic and composite cryotanks. The cost and safety benefits gained by using simulation software cannot be ignored as NASA and industry strive toward the goal of developing this nation's next generation of space launch vehicles.