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# Cost-Benefit Analysis for the Advanced Near Net Shape Technology (ANNST) Method for Fabricating Stiffened Cylinders

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## **Abstract**

This cost-benefit analysis assesses the benefits of the Advanced Near Net Shape Technology (ANNST) manufacturing process for fabricating integrally stiffened cylinders. These preliminary, rough order-of-magnitude results report a 46 to 58 percent reduction in production costs and a 7-percent reduction in weight over the conventional metallic manufacturing technique used in this study for comparison. Production cost savings of 35 to 58 percent were reported over the composite manufacturing technique used in this study for comparison; however, the ANNST concept was heavier. In this study, the predicted return on investment of equipment required for the ANNST method was ten cryogenic tank barrels when compared with conventional metallic manufacturing. The ANNST method was compared with the conventional multi-piece metallic construction and composite processes for fabricating integrally stiffened cylinders. A case study compared these three alternatives for manufacturing a cylinder of specified geometry, with particular focus placed on production costs and process complexity, with cost analyses performed by the analogy and parametric methods. Furthermore, a scalability study was conducted for three tank diameters to assess the highest potential payoff of the ANNST process for manufacture of large-diameter cryogenic tanks. The analytical hierarchy process (AHP) was subsequently used with a group of selected subject matter experts to assess the value of the various benefits achieved by the ANNST method for potential stakeholders. The AHP study results revealed that decreased final cylinder mass and quality assurance were the most valued benefits of cylinder manufacturing methods, therefore emphasizing the relevance of the benefits achieved with the ANNST process for future projects.

## **Introduction**

As NASA prepares to send humans to Mars in the 2030s through the development of the Space Launch System (SLS) and other new capabilities, the continual need for reducing mass and cost of launch vehicle components without compromising performance is of utmost importance. Cryogenic fuel tanks represent a significant fraction of the empty weight of launch vehicles, consequently there is high operational payoff for weight reduction of this structure. The current state-of-the-art manufacturing method for cryogenic tank barrels is multi-piece, welded construction using machined, shaped panels. Machining integrally stiffened panels from thick plate results in a 90-percent scrap rate. Operations to shape panels to curvature and assemble tank structure by welding are costly due to high labor hour and inspection requirements. Furthermore, the welding creates sites of reduced material properties and their associated weld lands add mass to the cryogenic tank barrel. Reducing the weight of launch vehicle structures enables launch of larger payloads and reducing manufacturing costs lowers the payload price per pound to orbit.

The Advanced Near Net Shape Technology (ANNST) project, supported by NASA's Game Changing Development Program, is exploring an alternative method for manufacturing single-piece integrally stiffened cryogenic tank cylinders using the single-step, integrally

stiffened cylinder (ISC) process. During the ISC process a thick-walled metal tube is formed over a mandrel with grooves that have the shape of the desired stiffeners. Material flows along the mandrel to lengthen the cylinder and into the grooves to create the integral stiffeners. The ISC process eliminates all longitudinal welds needed to assemble a tank barrel segment and reduces scrap rate to 5 percent. The ISC process derives its origin from the automotive industry, where a similar process is used for mass production of small-diameter steel clutch housings. NASA researchers partnering with the European Space Agency and MT Aerospace, Augsburg, Germany, approached the fabricator of flow-forming equipment, Leifeld Metal Spinning, Ahlen, Germany, to develop the ISC process for fabricating cryogenic tank barrels. Initially, an aluminum clutch housing of 8 inches in diameter and 4 inches in length was produced using the automotive process and existing tooling to demonstrate compatibility with an aerospace grade aluminum alloy. Further process development demonstrated forming taller, more widely spaced stiffeners typical of those used for cryogenic tank applications. Initial process scale up was achieved with fabrication of a 17-inch diameter, 20-inch long integrally-stiffened cylinder used to manufacture a sounding rocket skin and which represents the largest cylinder fabricated using the ISC process.

The sounding rocket skin launched as part of the primary structure of the payload assembly from Wallops Flight Facility in October 2015. Through flight data compared with structural analysis and ground testing, the launch data provided flight heritage and validation for the technology. The cylinder was instrumented to monitor material strain to evaluate the cylinder's performance in flight as compared with preflight structural analysis and ground test results. Follow on research will investigate further scale up of the ISC process to determine the optimal application for launch vehicle structure. A cost-benefit analysis (CBA) of the ISC process was performed to support determining viable applications for the process and development of relevant business cases.

This CBA assesses the potential of the ISC process for replacing conventional metallic manufacturing processes and competing with composites for producing the next generation of launch vehicle cryogenic tanks. Quantifying and analyzing the benefits of using the ISC process to manufacture cryogenic tanks is challenging given the low technology readiness level of the process. Hein et al. (1976) state that "the primary difficulty encountered in quantifying the benefits of space technology is that the technology has never been deployed and thus cannot fully be assessed." However, the development of new capabilities for NASA's journey to Mars requires that state-of-the-art manufacturing techniques be challenged by technologies competitive both on development and production costs. Through analysis, research and development, discovery reveals ways to work within the affordability constraint of space mission design.

This study is a cursory look at the potential benefits of the ISC process as compared with the conventional metallic and composite manufacturing techniques.

## Method

### 1. Literature Review

A literature review was conducted to explore existing research regarding cryogenic tanks, composites, and integral and spun structures, as well as to gather information on the general practices of cost-benefit analyses. Previous cost-benefit analyses focusing on other emerging technologies were targeted in order to assess how to conduct the study with limited information on hardware heritage and materials verification of properties. A study by Metschan (2000) describes the cost modeling of transitioning airplane fuselage panels from long established multi-piece riveted structure to a unitized integrally stiffened configuration to reduce weight and decrease machining time. The paper's focus on optimizing the manufacturing process for a specific product was analogous to this study and provided insight into conducting cost benefit analyses with regards to manufacturing capabilities.

The Ares V Earth departure stage (Martin Marietta, 1987) and the Game Changing Development Program's composite cryogenic tank (Johnson, et al., 2013) studies provided insight on the predicted state-of-the-art manufacturing approaches for composites. These studies also provided benchmarks to evaluate how the ANNST manufacturing approach compares with manufacturing methods for composites. The literature review and other studies visited are documented in appendix A.

### 2. Cost and Schedule Estimation

Two approaches were used to produce cost and schedule estimates for the three manufacturing processes in the case study: cost estimating by analogy and parametric cost estimating. The analogy method utilizes the costs of similar projects and adjusts for the differences in order to produce an estimate for the project under consideration. This method is based on comparison and extrapolation to similar projects (*NASA Cost Estimating Handbook*, 2015). Data was gathered by contacting and interviewing subject matter experts (SMEs) and discussions with the ANNST researchers provided the basis of the adjustments. SMEs throughout NASA and industry were consulted. Many were involved in the construction of cryogenic tanks for a variety of launch vehicles, ranging from the space shuttle external tank to the Delta IV rocket. These conversations focused on gaining detailed information regarding process steps, rough cost estimates, and schedule of the manufacturing processes, as well as benefits and challenges associated with each process. The information was synthesized in flowchart form for the three manufacturing processes. Tables with breakdowns of the cost and schedule estimates were also produced.

Parametric cost modeling is based on regression analysis of historical data. Cost is estimated as a function of typical cost drivers, such as mass or heritage. The parametric estimate

produced for this CBA was done with the NASA Langley Research Center basis of estimate (BOE) tool developed by Bob Fairbairn of the Office of Strategic Analysis, Communication and Business Development. The BOE tool was selected over other parametric cost estimating tools—such as Project Cost Estimating Capability (more commonly known as PCEC), Price® Systems software or SEER® project estimation—because of the greater level of detail that it offers for manufacturing processes. Using the input of final cylinder mass, the tool enabled a detailed cost breakdown—including estimates for labor, materials, tooling, and capital investment—for each of the three manufacturing processes under consideration.

### 3. *Assumptions*

#### *a. Geometry*

The case study focused solely on fabricating the cylindrical portion of a cryogenic tank with the assumption that only the cylindrical portion would be fabricated using the ISC process. As a result, Y-ring adapters and associated fabrication and assembly steps were excluded. The stiffener geometry was limited to longitudinal stiffeners because it remains unknown whether isogrid or orthogrid stiffener patterns can be formed using the ISC process. Longitudinally stiffened cylinders, such as those found on the lightweight tank of the space shuttle (STS), are usually supported by ring structures, but these elements were also ignored, along with fasteners, to simplify the geometry.

#### *b. Materials*

For the two metallic methods, the material for the cylinders was specified to be aluminum (Al) 2219, an alloy commonly used in space-grade tanks. For the conventional metallic method, an Al 2219 plate is supplied in the T8 temper and the completed tank is in the T8 temper. The ANNST method will begin with an Al 2219 thick-walled tube in the as-fabricated (F) temper and the completed tank will be in the T6 temper. The difference in mechanical properties between the T8 and T6 tempers was not considered in estimates of cylinder mass.

For composites, a single-piece tank cylinder is assumed to be fabricated from carbon fiber, honeycomb core, and resin, a method similar to the Game Changing Development (GCD) Program's Composite Cryotank Technology Demonstration (CCTD) project (Johnson et al., 2013). The carbon fiber is assumed to be the IM7/977-2 fiber with toughened epoxy IM7/8552-1. The core material would be a 3.2-density aluminum honeycomb core, which could be either thermally bent or preformed over the curved surface.

#### *c. Assumptions for the parametric BOE tool*

The parametric cost estimate is based on the following assumptions:

- All cost estimates are in real-year dollars.
- The estimate is limited to the straight cylinder portion of the tank and does not include end caps or fluid management devices.



- Materials assumptions:
  - ANNST Method: 1/10<sup>th</sup> inch thick Aluminum, formed on tool. The manufacture of the tool is not considered here.
  - Conventional metallic method: 1/10<sup>th</sup> inch thick Aluminum. The cylinder is made by machining, brake forming and welding the Aluminum plate. Assumes 8 plates per 20-foot section, 10x1/4<sup>th</sup> circumference and 3 circumferential welds.
  - Composites: the cost of the tool is scaled up from calibrated data.
- No special interfaces (y-ring) are assumed at the ends of the cylinder. The cylinder is designed to fit a ring.
  - ANNST Method: no flange assumed, possibility of drilled holes.
  - Conventional metallic method: a flange is assumed, flange mass is included.
  - Composites: a composite buildup to accept a ring is assumed, as well as a perimeter buildup (doubling width) to interface with the ring. No drilled holes.
- All methods assume that the cylinders are built in two 20-foot sections, with either circumferential welds or composite joints.
- Two prototypes are assumed:
  - First prototype is fabricated at ground specifications levels for structural testing.
  - Second prototype is flight qualified but unmanned.
  - The single total cost for each task includes design (first prototype), fabrication (second prototype) and test.
  - Assembly level integration and test costs are assumed at higher specification levels.
- The autoclave size and cost are scaled from the interstage data.
- A 7000 lbs steel mandrel is assumed for the ANNST method. The mandrel is assumed to be formed from a thick cylinder, from which the channels are machined out. A full-scale mandrel is assumed.
- Buildup/weld lands are assumed at the end of the cylinders.
- Labor is calculated with standard industry rates.

#### 4. Phase I – Case Study of a 16-foot Cylinder

To best assess the impact of the manufacturing methods on production variables such as material cost, schedule, and manufacturing process complexity, a case study was initiated to provide consistent comparison among the three alternatives of the conventional metallic, composite, and ANNST methods. A cylinder of the dimensions listed in Table 1 was selected for its geometric similarity to other contemporary first stage launch vehicle cryogenic tanks. A diameter of 16 feet is a common dimension in the spectrum of launch vehicles, which range from 3.8 feet (Pegasus) to 27.5 feet (SLS). Furthermore, the 40-foot cylinder length was chosen because it fell in the mid-range of cryogenic stage lengths for 16-foot diameter vehicles, which range from 45 feet (Delta IV upper stage) to 134 feet (Delta IV first stage). Applications of this case study tank would be primarily used for cryogenic tanks on launch vehicles of the size of the

Atlas V, the Delta IV or the Ariane 5, whose first-stage diameters run on the order of 16 feet.

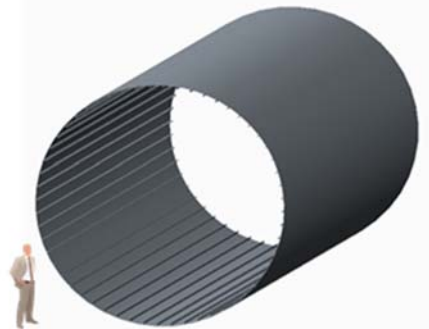
**Table 1: Case Study Cylinder Geometry**

Geometric Feature	Dimension
Tank barrel diameter*	16 feet
Tank barrel length*	40 feet
Wall thickness	0.1 inches
Longitudinal stiffeners	60 stiffeners, 10-inch spacing
Stiffener height	0.75 inches
Stiffener width	0.25 inches
Material specification	Aluminum 2219

\* Only the length and diameter of the case study cylinder will be considered for the fabrication of the composite tank because the stiffener's construction method is not analogous to that of metallic tanks.

### 5. Phase II – Scalability Study

Following the acquisition of cost and schedule estimates for the 16-foot-diameter tank cylinder through both the analogy and parametric approaches, it was necessary to understand how those parameters vary based on the tank size, particularly for the conventional metallic and ANNST methods. A scalability study was conducted to compare estimates for cylinder production of 8-foot and 27.5-foot diameters while retaining all other geometry, such as the 40-foot length, stiffener spacing and dimensions, etc. While a cylinder with an 8-foot diameter and 40-foot length is less plausible, the geometric parameters outside of tank diameter were maintained in order to judge scalability purely on diameter. This would allow analysis primarily into the impact of diameter on total weld length for a cylinder, and as a result how much mass and production and inspection time could be saved by using the ISC process. An illustration for scale perspective is given in figure 1.



**Figure 1: 16-foot integrally stiffened cylinder with scale.**

### 6. Phase III – Assessment of the value of the achieved benefits

Following the cost and schedule comparisons of the three manufacturing methods, the analytic hierarchy process (AHP) was used to assess the value of the benefits achieved by each

method. AHP was developed by T. Saaty in the 1970s to assist with the decision making process when both quantitative and qualitative criteria are under consideration. AHP models the decision problem through a hierarchical structure of the evaluation criteria, referred to herein as figures of merit (FOMs). The FOM definitions are shown in Table 2. Through use of pairwise comparisons, weights are allocated to the FOMs and the value of the benefits achieved by the various manufacturing methods is clearly and quantitatively articulated. Five FOMs were selected to model the decision problem: cylinder mass, scrap produced, production and assembly time, process complexity, and quality assurance (figure 2).

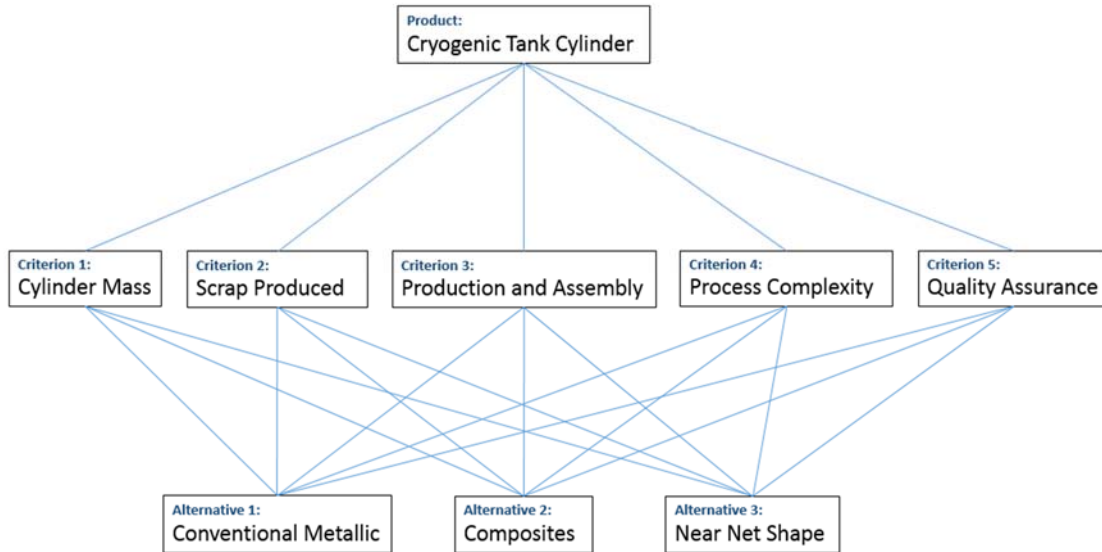
**Table 2: Figure of Merit Definitions**

Figure of Merit	FOM Definition
Cylinder mass	Considers the mass of the cylindrical portion of a cryogenic tank, fabricated using each of the three listed alternatives. The resulting mass is calculated assuming that all tanks are of the same strength and approximate dimensions. This will include additional mass that accompanies a particular technique of the same strength, such as the extra mass resulting from weld lands and bonded joints.
Scrap produced	Accounts for the scrap and wasted material associated with each of the alternatives and their associated manufacturing processes. This also takes into consideration the process associated with the disposal and recyclability of the scrap material.
Production and assembly time	Accounts for the time associated with each of the manufacturing steps in the various alternatives. This includes the time spent preparing materials, machining, and heat/chemically treating the parts. This does not include time spent on design or administrative tasks.
Process complexity	Considers the number of steps and special facilities/locations needed for the manufacturing of the cylinder. This includes the impact of schedule caused by relocating the parts to different facilities for steps that cannot be performed in-house.
Quality assurance	Accounts for the inspection process for each of the alternatives. This mostly focuses on the labor hours associated with the inspection, as well as the impact of schedule if a defect is found. This is measured by the defect rate of each of the manufacturing processes, as well as the total length of inspection-heavy features, such as welds, stiffeners, and bonded joints.

To gain some insight into how the various benefits of the ISC process are valued by different groups of stakeholders, the SMEs were contacted from three primary groups located across various NASA centers and industry: materials and structural researchers, systems engineers, and program managers. Each SME was sent an email containing two documents. The first document contained the project abstract, instructions for completing the task, and definitions of the FOMs. The second document was an MS Excel-based AHP tool, which allows comparing FOMs in pairs. When performing a pairwise comparison, the user first selects which of the two FOMs is most significant in terms of cylinder manufacturing. A linear 1 to 9 scoring scale is then used to assess this level of significance. To ensure that all users interpret the scale consistently, linguistic definitions were provided for each integer on the scale. A consistency ratio was displayed on the spreadsheet to provide feedback on the user's consistency in scoring. AHP theory recommends a consistency ratio under 0.1 to ensure that the results are coherent. The task took between 15 and 30 minutes to complete, and SMEs were asked to return spreadsheets once completed via email. For each response, the SME's name, group identification, weighted

prioritization of the FOMs, and consistency ratio were recorded. Eighteen of 25 SMEs contacted completed the AHP task.

The row geometric mean method was used to compute weights and aggregate weights among multiple SMEs, and all weights were normalized.



**Figure 2: Model of the ISC decision problem.**

## Analysis

### *Mass Estimates*

Mass estimates were made for the 16-foot diameter case study tank manufactured using the conventional and ANNST metallic methods and the composite method. Calculated mass of the metallic concepts indicated a 7-percent mass reduction for the ANNST over the conventional concept. The composite tank was assumed to be 50 percent lower mass than the lightest metallic concept.

The computation for the metallic methods is detailed in table 3 and shows masses of 3927 and 3646 pounds for the conventional and ANNST concepts, respectively. For the conventional and ANNST metallic tanks the difference in weight stems from the number of longitudinal and circumferential welds required to assemble the 40-foot-long tank barrel, which is related to the size and form of the material used for fabrication. Commercially available plate used in the conventional fabrication method are 13.5 feet long and 10 feet wide and it was assumed that the long dimension is parallel to the circumference. Consequently, four 10-foot-long cylindrical segments must be fabricated, stacked, and joined with three circumferential welds to assemble the tank barrel and each cylinder requires four machined plates to span the circumference, joined

**Table 3. Estimated Mass of the Metallic Tank Fabricated Using Conventional and ANNST Methods**

Conventional Manufacturing					
	Inches	Feet		Inches	Feet
Length of the tank (in, ft)	480.00	40.00			
Wall thickness (in, ft)	0.10	0.01	Plate dimensions are 10 ft by 13.5 ft by 2 inch		
Outer diameter of tank (in, ft)	192.00	16.00	Plate length (in, ft)	120.00	10.00
Inner diameter of tank (in, ft)	191.80	15.98	Plate width (in, ft)	162.00	13.50
Volume of tank skin (in <sup>3</sup> )	28,937.81		Plate thickness (in, ft)	2.00	0.17
Stiffener length (in, ft)	480.00	40.00	Cylinder circumference (in, ft)	603.19	50.27
Stiffener height (in, ft)	0.75	0.06	Number of stiffeners	60.00	60.32
Stiffener thickness (in, ft)	0.25	0.02	Number of vertical welds per barrel section	4.00	3.72
Number of stiffeners	60.00		Number of circumferential welds	3.00	3.00
Total volume of Stiffeners (in <sup>3</sup> )	5,400.00		Length of all vertical welds (in, ft)	1,920.00	160.00
Total weld land length (in, ft)	3,729.56	310.80	Length of all circumferential welds (in, ft)	1,809.56	150.80
Weld land thickness (in, ft)	0.22	0.02	Total length of welds (in, ft)	3,729.56	310.80
Weld land width (in, ft)	4.00	0.33	Total number of plates	16.00	
Weld land vol. overlap (in <sup>3</sup> )	28.16				
Vol. build-up at ends of cylinder (in <sup>3</sup> )	530.80				
Total number of welds	19.00				
Volume of welds (in <sup>3</sup> )	3,784.65				
Total volume (in <sup>3</sup> )	38,122.47		Amount of scrap material in <sup>3</sup>	583,957.53	
Starting volume needed (in <sup>3</sup> )	622,080.00		Percent scrap	93.87	
Weight (lbs)	3,926.61				
ANNST Manufacturing					
	Inches	Feet			
Same tank skin volume (in <sup>3</sup> )	28,937.81				
Same stiffener volume (in <sup>3</sup> )	5,400.00		Mass savings (lbs):	280.47	
Height of barrel section (in, ft)	240.00	20.00			
Number of barrel sections needed	2.00				
Length of one cir. weld (in, ft)	603.19	50.27			
Number of circumferential welds	1.00			percent	
Total length of welds (in, ft)	603.19	50.27	Material yield from ingot conversion	80	
Vol. build-up at ends of cylinder (in <sup>3</sup> )	530.80		Percent scrap	20	
Volume from weld lands (in <sup>3</sup> )	530.80				
Total volume (in <sup>3</sup> )	35,399.42				
Starting volume (80% yield) (in <sup>3</sup> )	44,249.27				
Weight (lbs)	3,646.14				
		Input			
		Computed			
		Output			

by four longitudinal welds. A total of 16 plates are needed for the completed tank. The starting material form for the ANNST method is cast ingot. Analysis of available commercial scale ingots indicated that the ISC process can produce integrally stiffened cylinders up to 20 feet long, requiring two cylinders be stacked and joined with one circumferential weld to assemble the tank barrel. A material yield of 80 percent was assumed after conversion of the cast ingot to a preform for the ISC process. Fabrication by the ANNST method reduces the total weld length by nearly 85 percent and results in a mass reduction of 7 percent.

For this study it was assumed that a composite tank of the case study scale would use a core stiffened sandwich structure for the tank barrel, similar to that evaluated in the CGD Program CCTD project. It was also assumed that single-piece, 16-foot diameter, 20-foot long composite cylinders can be fabricated. The completed tank would have no longitudinal joints but would have one circumferential joint. The majority of a composite cryogenic tank’s mass resides in building up the joints between the barrel and domes, where ply counts may reach upwards of 250 layers thick in comparison with the 10 to 17 plies used in acreage of the tank barrel. The CCTD study and SMEs estimate that a composite tank will be 30 percent lighter than current metallic tanks. Because this study evaluated only the barrel portion of the cryogenic tank, it was

assumed that a composite barrel would be 50 percent lighter than the metallic concepts. Applying a 50-percent mass reduction to the tank barrel resulted in a composite tank mass of 1809 pounds. However, it should be recognized that a more balanced comparison of mass savings among the three manufacturing methods would be accomplished by including the domes and joint features, such as Y-rings for the metallic tanks and extra plies in the composite tank joints.

*Definition of Processes*

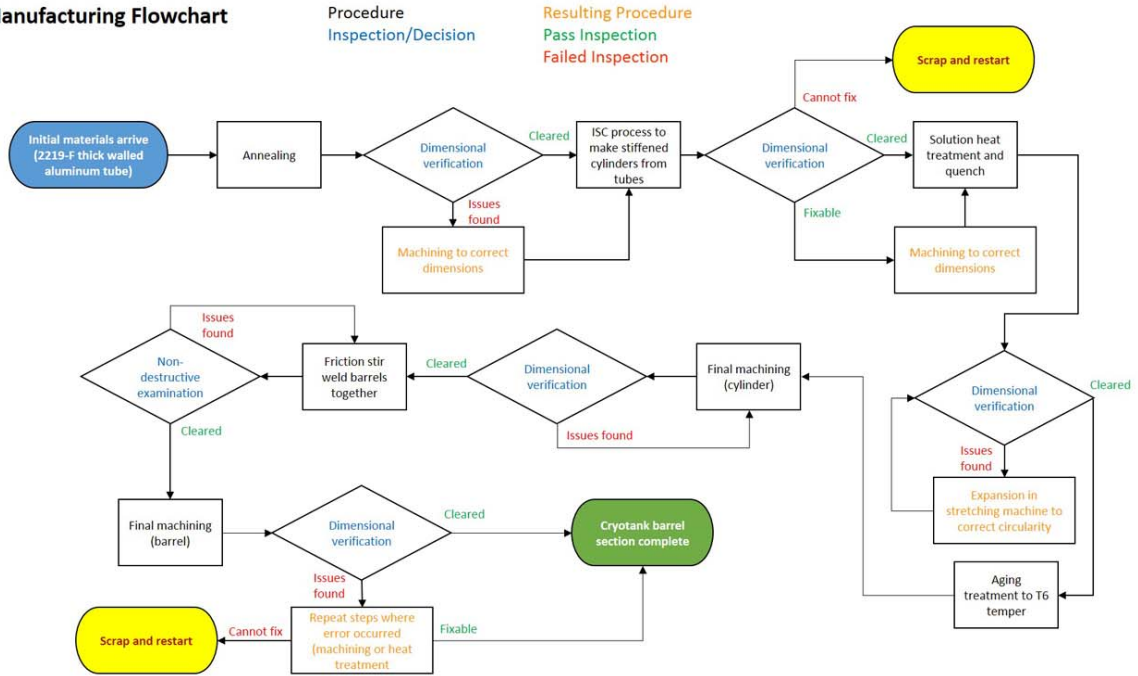
Process flowcharts and manufacturing timelines were developed for the conventional and ANNST metallic and composite manufacturing processes to provide guidance for cost estimating. Figure 3 lists the estimated materials and infrastructure requirements, and figures 4 to 6 are the flowcharts assembled for each of the three manufacturing processes. Each process flow is followed by its associated timeline table, wherein 1 day equals 8 hours (tables 4 to 6). These were compiled from conversations with various SMEs across NASA and industry, and include steps on material acquisition, fabrication method, inspection, and product acceptance. The flowcharts and timelines reflect the requirements for all materials and subassemblies for the complete cryogenic tank barrel section. As noted in figure 3, the only resource common to all three manufacturing methods is nondestructive examination (NDE) and for this study is associated with inspection of welds in the metallic tanks and layups and joints in the composite tank. NDE time will be lowest for the ANNST method owing to the fewer welds than in the conventional metallic method and acreage to be examined in the composite tank. Requirements for machining, welding, and heat treatment are common to the conventional and ANNST metallic processes but they differ in material and forming equipment requirements and in some cases the duration of operations. The flowcharts provide a high level description of the manufacturing steps, decision points and potential off ramps due to component failure. The manufacturing timelines parallel the flowcharts and reflect the time associated with each step.

<b>Requirements</b>		
ANNST	Conventional	Composite
Aluminum 2219 Thick Walled Tube	Aluminum 2219 Plates	Carbon Fiber Plies (Number of plies varies)
Spinning Equipment from Leifeld	Machining Equipment	Epoxy Resin
Circumferential Welding Equipment	Brake Forming Equipment	Robotic layup machine
Nondestructive Examination Equipment (White light scanning)	Furnaces and water tank for heat treatment and quenching	Bagging and preservation equipment needed for curing process
Furnaces and water tank for heat treatment and quenching	Vertical welding equipment	Autoclave for curing process
Machining Equipment	Circumferential welding equipment	Premade Aluminum honeycomb core
Weld Inspection Equipment	Weld inspection equipment	Film adhesive
	Nondestructive Examination Equipment.	Nondestructive Inspection equipment
		Software Necessary for layup process

**Key**  
 Black – Common to all three  
 Green – Unique to ANNST  
 Blue – Unique to conventional  
 Orange – Unique to composite  
 Pink – Common to metal methods

**Figure 3: SME estimated materials and infrastructure requirements.**

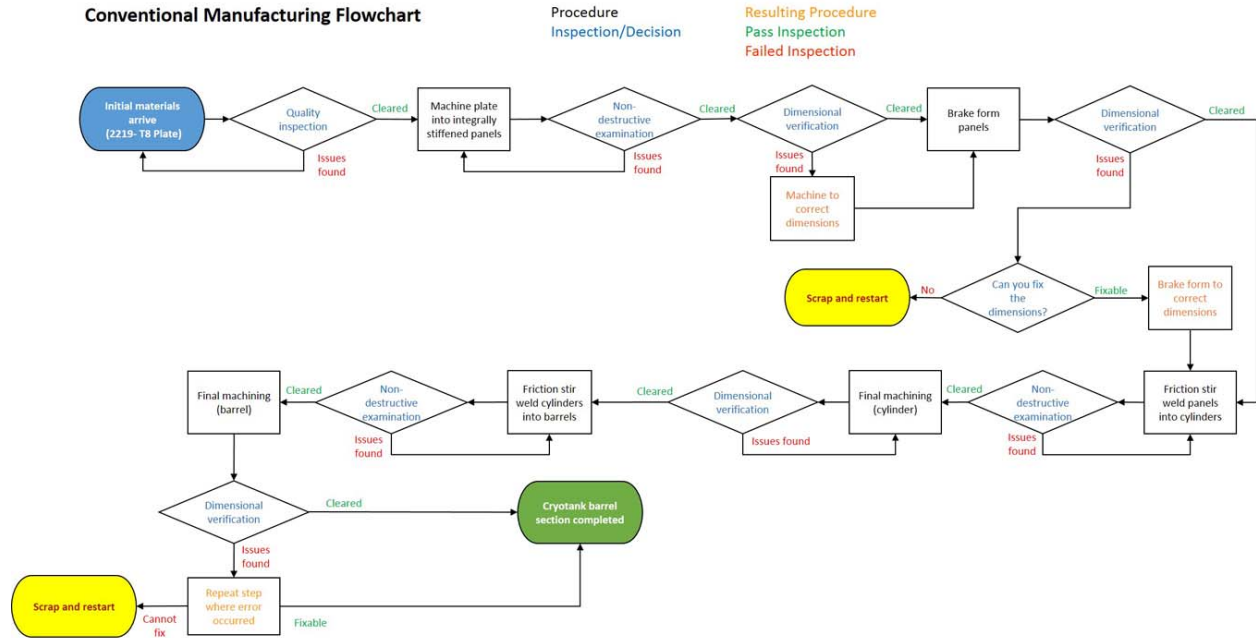
**ANNST Manufacturing Flowchart**



**Figure 4: Manufacturing flowchart for the case study cryogenic tank cylinder fabricated through the ANNST manufacturing method using the ISC process.**

**Table 4: ANNST Manufacturing Timeline**

ID	Task	Notes	Duration
1	Initial materials arrive	Two 2219-F Thick-walled aluminum tubes	Start
2	Annealing	Two tubes in one batch	3 days
3	Dimensional verification	Machine if needed; 1 day per tube	2 days
4	ISC Process to make stiffened cylinders from tubes	1 day per tube	2 days (2 days set up)
5	Dimensional verification	1 day per cylinder	2 day (5 days preparation)
6	Solution heat treatment and quench	Two cylinders in one batch	2 days (5 days preparation)
7	Dimensional verification	1 day per cylinder	2 days
8	Expansion over stretching machining	If needed; 1 day per cylinder	2 days
9	Aging treatment to T6 temper	Two cylinders in one batch	3 days
10	Final Machining (cylinder)	7 days per cylinder	14 days
11	Dimensional verification	1 day per cylinder	2 days (5 days preparation)
12	Friction stir weld cylinders together to form barrel	One circumferential weld	4 days
13	Nondestructive examination	FSW inspection; 3 days per weld	3 days (5 days preparation)
14	Final machining (barrel)	Per barrel	5 days
15	Dimensional verification	Per barrel	1 day (5 days preparation)
16	Cryotank barrel section complete		end
<b>Time (No setup time)</b>			<b>47 days</b>
<b>Total Time (Setup included)</b>			<b>74 days</b>

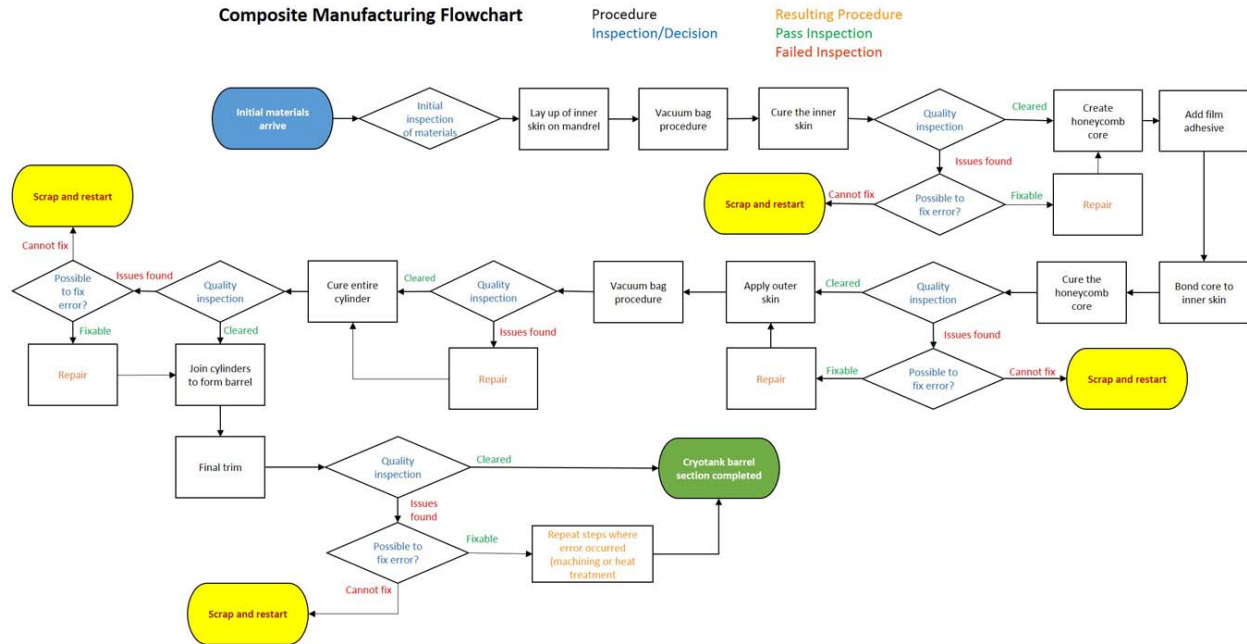


**Figure 5: Manufacturing flowchart for the case study cylinder fabricated through the conventional metallic manufacturing process.**

**Table 5: Conventional Metallic Manufacturing Timeline**

ID	Task	Notes	Duration
1	Initial materials arrive	2219-T8 Plate; Qty 16 plates	Start
2	Quality inspection	16 plates	1 day
3	Machine plate into integrally stiffened panels	16 panels	20 days (2 days set up)
4	Non destructive examination	Dye penetrant inspection; 1 hour per panel plus 5 days for set up	2 days (5 days preparation)
5	Dimensional verification	2 hours per panel plus 5 days set up	4 days (5 days preparation)
6	Brake form panels	16 panels	10 days (2 days set up)
7	Dimensional verification	2 hours per panel plus 5 days set up	4 days (5 days preparation)
8	Friction stir weld panels into cylinders	Four longitudinal welds per cylinder; four cylinders; 3 hours per weld	6 days
9	Non destructive examination of FSW	16 welds, 1 hour per weld; 5 days set up	2 days (5 days preparation)
10	Final machining (cylinder)	7 days per cylinder; four cylinders	28
11	Dimensional verification	1 day per cylinder; 4 cylinders	4 days (5 days preparation)
12	Friction stir weld cylinders together to form barrel	Three circumferential welds; 4 days per weld	12 days
13	Nondestructive examination	3 FSW; 3 days per weld	9 days
14	Final machining (barrel)	Per barrel	5 days
15	Dimensional verification	Per barrel	1 day (5 days preparation)
16	Cryotank barrel section complete		end
<b>Time (No setup time)</b>			<b>108 days</b>
<b>Total Time (Setup included)</b>			<b>147 days</b>





**Figure 6: Manufacturing flowchart for the case study cylinder fabricated through composite manufacturing method.**

**Table 6: Composite Manufacturing Timeline**

ID	Task	Notes	Duration
1	Initial materials arrive	Carbon fiber, epoxy resin, aluminum honeycomb core	Start
2	Inspection of materials	Enough materials for two cylinders	1 day
3	Layup of inner skin on mandrel	4 days per cylinder	8 days (4 days of preparation work)
4	Vacuum bag procedure	1 day per cylinder	2 days
5	Curing of the inner skin	Two cylinders cured in one batch	3 days (5 days of preparation work)
6	Quality inspection (includes NDE and dimensional verification)	1 day per cylinder	2 days (5 days setup)
7	Create honeycomb core	Enough for two cylinders	4 day
8	Add film adhesive	1 day per cylinder	2 days
9	Bond honeycomb core to inner skin	4 days per cylinder	8 days
10	Curing of honeycomb core	Two cylinders cured in one batch	3 days
11	Quality inspection	1 day per cylinder	2 days (5 days setup)
12	Apply outer skin	4 days per cylinder	8 days
13	Vacuum bag procedure	1 day per cylinder	2 days
14	Quality inspection	1 day per cylinder	2 days (5 days setup)
15	Curing of the entire cylinder	4 days per cylinder	8 days
16	Quality inspection	1 day per cylinder	2 days (5 days setup)
17	Join cylinders to form barrel	Circumferential bond (assume time similar to circumferential weld of metal barrels)	4 days (5 days of preparation work)
18	Final trim	Two cylinders completed	5 day
19	Quality inspection	2 days per cylinder	4 days (5 days of preparation work)
20	Cryotank barrel section complete		end
<b>Time (No setup time)</b>			<b>70 days</b>
<b>Total Time (Setup included)</b>			<b>104 days</b>

*Note: Diameter: 16 ft; length: 40 ft; ply layup dependent on design; aluminum honeycomb core; material specification: carbon fiber and epoxy resin, robotically laid.*

### *Capital Costs*

In order for the ISC process to become a more desirable manufacturing method than the conventional metallic and composite manufacturing methods, the capital investment required for the tooling and facilities must be justified by the benefits provided by the ANNST method. The infrastructure required for the conventional metallic method exists as this is an established commercial manufacturing process. Manufacturing facilities exist for composite tanks at launch vehicle scales; however, these tanks are developmental. The capital costs of establishing commercially certified composite manufacturing facilities was not evaluated in this study. No equipment or tooling currently exists for the ISC process at launch vehicle tank scales. From conversations with contacts in industry, it was estimated that the nonrecurring investment to build a large scale ISC process system would be on the order of \$6.5 to 8.7 million. For this study, capital equipment cost was excluded. Comparisons were based on the cost to manufacture a tank barrel using each method assuming that necessary facilities were available.

For the ANNST method, in addition to the capital investment in the ISC process equipment, the facilities for heat treatment and quenching must be evaluated to ensure that the infrastructure exists for post-forming processing of the resulting tank barrels. Because single-piece cylinders of this diameter are difficult to transport, captive manufacturing would be required in order to produce completed tanks at one location before shipment to rocket integration facilities. The Michoud Assembly Facility in New Orleans, Louisiana, the site for constructing the external tank of the space shuttle, provides an example of captive manufacturing, in which cryogenic tanks for liquid hydrogen and oxygen were assembled using conventional metallic construction. After construction at Michoud, the completed tanks were shipped by barge to NASA's Kennedy Space Center for integration onto the space shuttle. If implemented, the ISC process could utilize a similar captive manufacturing approach for production and shipment of single-piece tank barrels.

### *Analogy and SME Estimations*

A review of the materials requirements, processes, costs, and manufacturing timelines of the three manufacturing methodologies reveals that each has its own inherent benefits. The benefit of the conventional metallic method is that the facilities and associated nonrecurring engineering costs for cylinders of all diameters up to 27.5 feet have already been acquired and maintained; however, the high labor hours needed for machining and assembly by welding render this the highest cost option. While composites are still under development, the greatest benefit comes in anticipated mass savings, but there are associated higher costs of the composite material. Benefits of the ANNST method are realized by eliminating the longitudinal welds and machining time, which decreases the mass of the cylinder and reduces the production and inspection time associated with the welds. Furthermore, by flowing material into grooves on the mandrel rather than removal of material by machining to yield stiffeners, reduced scrap rate and machining time result in lower costs. Table 7 summarizes the total manufacturing time and cost for manufacture of the 16-foot diameter case study tank and shows that the ANNST process offers schedule and cost benefits over the conventional metallic and composite manufacturing

methods. The cost breakdown for the three methods, based on estimates from the SMEs, are summarized in table 8. The ANNST method reduces manufacturing time by 50 percent and 33 percent, and cost by 58 percent and 35 percent over conventional metallic and composite methods, respectively. Both the schedule and cost analyses are discussed in subsequent sections. For the 16-foot diameter case study tank, based on the reduced manufacturing cost compared with conventional metallic manufacturing and the estimated capital equipment cost for the ANNST method, the return on investment will be realized after fabrication of ten cryogenic tank barrels.

**Table 7: Results from Analogy Method and POC Estimates for Cost and Schedule for Case Study Cylinders Produced by the Three Manufacturing Processes**

	<b>Conventional Metallic</b>	<b>ANNST</b>	<b>Composite</b>
<b>Touch time, no set-up</b>	108 days	47 days	70 days
<b>Total time, includes set-up</b>	147 days	74 days	104 days
<b>Rough cost</b>	\$1.55 million	\$658,000	\$1.01 million

Process complexity looks at the number of steps necessary to each of the manufacturing methods as well as the movement of the product from different locations. Production time refers to the amount of work hours in manufacturing, shipping, and assembly that occurs in each of the processes. Quality assurance focuses on the steps necessary to ensure that the final product achieves the desired quality in order to be flight capable. This accounts for inspection and nondestructive examination steps that occur throughout each of the three manufacturing methods.

The complexity of a manufacturing process contributes to how likely the process will adhere to the schedule for fabrication. A benefit of the ANNST method is in reduced complexity as reflected in either fewer manufacturing steps or less complex operations when compared with the conventional metallic and composite manufacturing methods, as shown in the flowcharts and manufacturing timelines. The steps eliminated in the ANNST method for fabricating the cylinders needed for the complete barrel reduce the process complexity. Conventional metallic manufacturing requires machining, brake forming, and vertical friction stir welding to form one cylinder, as seen in figure 5 and table 5. The ANNST method simplified those steps down to the one manufacturing step and two heat treatment steps by using the ISC process (figure 4 and table 4). In addition, when compared with composite manufacturing (figure 6 and table 6), both the ANNST and conventional metallic methods have fewer overall fabrication steps and fewer inspection points. A larger number of manufacturing steps are needed for composite assembly because multiple fabrication steps are required for each sub-component, including the inner and outer skins and the core. The ANNST method also had lower requirements to move material or subassemblies during fabrication of the tank barrel. For example, plate material used in the conventional metallic method must be moved between machining, brake forming, dimensional inspection, welding, and NDE facilities in order to fabricate the cylinders needed for the tank

**Table 8: Cost Breakdown of the Conventional and ANNST Metallic and Composite Manufacturing Methods**

<b>Cost Breakdown</b>	<b>ANNST</b>	<b>Conventional</b>	<b>Composites</b>
Material costs per pound (US)	4	4	20 / 20 / 30 *
Final amount of material (lbs)	3,646	3,927	110 / 54 / 1,509 *
Final material cost (US)	14,585	15,706	2,397 / 1,088 / 45,272 *
Percent scrap (%)	20	88	
Amount of scrap material (lbs)	912	28,795	
Costs of scrap material (US)	3,646	115,181	
Number of labor hours for part	264	544	344
Number of workers on payroll	100	100	100
Average labor cost per hour (US)	20	20	20
Labor costs (US)	528,500	1,088,000	688,000
Likelihood of schedule delay; process complexity (%)	20	30	25
Additional hours for delay	53	163	86
Additional delay labor costs (US)	105,700	326,400	172,000
Time spent shipped (hrs)	40	30	40
Shipping cost per hour (US)	100	100	100
Shipping and handling Costs (US)	4,000	3,000	4,000
Likelihood of defect (%)	5	10	20
Additional materials cost for defect (US)	182	393	23,621
Additional labor hour costs for defect (US)	1,321	5,440	6,880
Final mass (lbs)	3,646	3,927	1,673
Flight mass cost per pound (US)	5,930	5,930	5,930
Payload weight limit (lbs)	28,440	28,440	28,440
Additional payload weight obtained (lbs)	280	0	2,253
Start-up costs (US)	8 M	0	0
Total amount of materials (lbs)	4,558	32,722	1,673
Total material costs (US)	18,231	130,877	118,104
Total costs (US)	<b>657,934</b>	<b>1,554,120</b>	<b>1,012,604</b>
Wasted costs (US)	110,850	447,413	202,501
Applied costs (US)	2,195,357	1,203,181	14,168,027
Percent cost of material (%)	2.77	8.42	11.66
Percent cost of labor (%)	80.33	70.01	67.94
Percent cost of delays (%)	16.07	21.00	16.99
Percent cost of shipping/handling (%)	0.61	0.19	0.40
Percent cost of defects (%)	0.23	1.30	3.01
		Input	
		Output	
		Not applicable	
		Total percentiles	
	*	Break out is "composite / resin / core"	

barrel. The commercial facilities currently established are not co-located, which increases the time associated with the moves. For ANNST the material moves between heat treatment, forming, and dimensional inspection facilities. The time associated with these moves can be streamlined by careful selection of locations for establishing the ISC process facilities.

A comparison of the metallic manufacturing timelines shows that the total time required to produce the cylinders needed to assemble the tank barrel is reduced by half for the ANNST method over the conventional method. This reduction stems from eliminating the machining time required in conventional processing to produce stiffened panels and the weld assembly needed to fabricate cylinders segments for the 40-foot-long tank barrel. In the ANNST method, pre-machining of the ISC process forming blank and post-forming heat treatment require fewer days, even when accounting for the need to produce the two flow formed cylinders required for the 40-foot-long tank barrel. These differences are reflected in the cost breakdown (table 8) primarily in the per-part labor hours and labor costs. Because welds are the primary source of defects in the metallic manufacturing methods, reduced costs for the ISC process are also reflected in the lower defect rate, and associated labor costs, needed for weld repairs. Finally, the ANNST method has lower cost for scrap material because the stiffeners are integrally formed rather than machined from thick plate as in the conventional method.

Cost savings of the ANNST method over composite fabrication come primarily from material cost and labor hours. The total time to produce the case study tank is more than 30 percent lower for the ANNST method. The labor associated with layup of the composite material results in 30 percent higher labor hours for initial assembly. The higher defect rate for composite manufacturing incurs labor and material costs that are 20 times higher than for ANNST.

NDE steps necessary to ensure the correct quality of flight hardware added additional time and steps to all three of the manufacturing processes. However, because the ANNST method has less overall length of welds compared with the conventional method, inspection time and associated labor costs are lower. Likewise, inspection will be higher for the composite method due to the greater amount of material to inspect because the entire acreage of the layups must be inspected.

### *Parametric Analysis Results*

Table 9 shows a breakdown of cost estimates derived from the parametric model. The ANNST method for fabricating the 16-foot diameter case study cylinder reduces the total cost by 46 and 58 percent over the conventional metallic and composite methods, respectively. Labor costs were lower for the ANNST method by 60 to 70 percent and material costs by 72 to 83 percent. Tooling costs for the ANNST method were higher than for the conventional metallic method due to the capital investment costs associated with ISC process equipment. Tooling costs were lower for ANNST compared with composite manufacturing.

Cost estimates from the analogy and SME estimates and the parametric analysis both showed that the ANNST method was the lowest cost option; however, the cost reduction over the other methods was different for the two analyses. The parametric analysis showed ANNST to have a greater cost benefit over the composite method and the analogy/SME analysis showed the greater benefit over the conventional metallic method. This is likely related to differences in the assumptions made and level of detail used in each analysis.

**Table 9: Results from the Parametric Method for Cost and Schedule Estimates for Case Study Cylinders of 8-, 16- and 27.5-foot Diameters Produced by the Three Manufacturing Processes**

8 foot diameter				ANNST Savings, %	
Cost in \$K Real Year	Conventional Metallic	ANNST	Composites	Over Conventional	Over Composites
<b>Cylinder Mass, lbs.</b>	<b>1,963</b>	<b>1,822</b>	<b>904</b>	<b>7.1</b>	<b>-101.5</b>
<b>Total Cost, \$K</b>	<b>2,083</b>	<b>1,368</b>	<b>3,461</b>	<b>34.3</b>	<b>60.5</b>
· Labor Cost	1,143	391	1,361	65.8	71.3
· Material Cost, ODC	501	85	301	83.0	71.7
· Tooling Cost	439	892	1,798	-103.2	50.4
Recurring Unit Cost, \$K	894	246	582	72.5	57.8
16 foot diameter				ANNST Savings, %	
Cost in \$K Real Year	Conventional Metallic	ANNST	Composites	Over Conventional	Over Composites
<b>Cylinder Mass, lbs.</b>	<b>3,927</b>	<b>3,646</b>	<b>1,809</b>	<b>7.1</b>	<b>-101.6</b>
<b>Total Cost, \$K</b>	<b>3,842</b>	<b>2,076</b>	<b>4,936</b>	<b>46.0</b>	<b>57.9</b>
· Labor Cost	2,208	651	1,645	70.5	60.5
· Material Cost, ODC	998	165	562	83.5	70.7
· Tooling Cost	636	1,261	2,729	-98.1	53.8
Recurring Unit Cost, \$K	1,761	433	877	75.4	50.6
27.5 foot diameter				ANNST Savings, %	
Cost in \$K Real Year	Conventional Metallic	ANNST	Composites	Over Conventional	Over Composites
<b>Cylinder Mass, lbs.</b>	<b>6,763</b>	<b>6,276</b>	<b>3,109</b>	<b>7.2</b>	<b>-101.9</b>
<b>Total Cost, \$K</b>	<b>6,350</b>	<b>3,008</b>	<b>6,868</b>	<b>52.6</b>	<b>56.2</b>
· Labor Cost	3,753	1,007	1,982	73.2	49.2
· Material Cost, ODC	1,713	278	933	83.8	70.2
· Tooling Cost	885	1,723	3,953	-94.8	56.4
Recurring Unit Cost, \$K	3,019	694	1,260	77.0	45.0

### *Scalability Study Results*

Results of mass calculations for 8-, 16-, and 27.5-foot diameter tanks manufactured using the ANNST and conventional methods, shown in table 10, illustrate that tank weight is directly proportional to diameter. The difference in weight between the two methods remains about 7 percent for all three tank diameters. This trend is also illustrated in figure 7(a) by the proportional relationship between tank diameter and both longitudinal weld length and mass. Cylinder length was held constant during this scalability study in order to isolate the effect of the number of longitudinal welds. A more thorough evaluation would have adjusted the length of each tank to reflect current commercial tanks of each size.

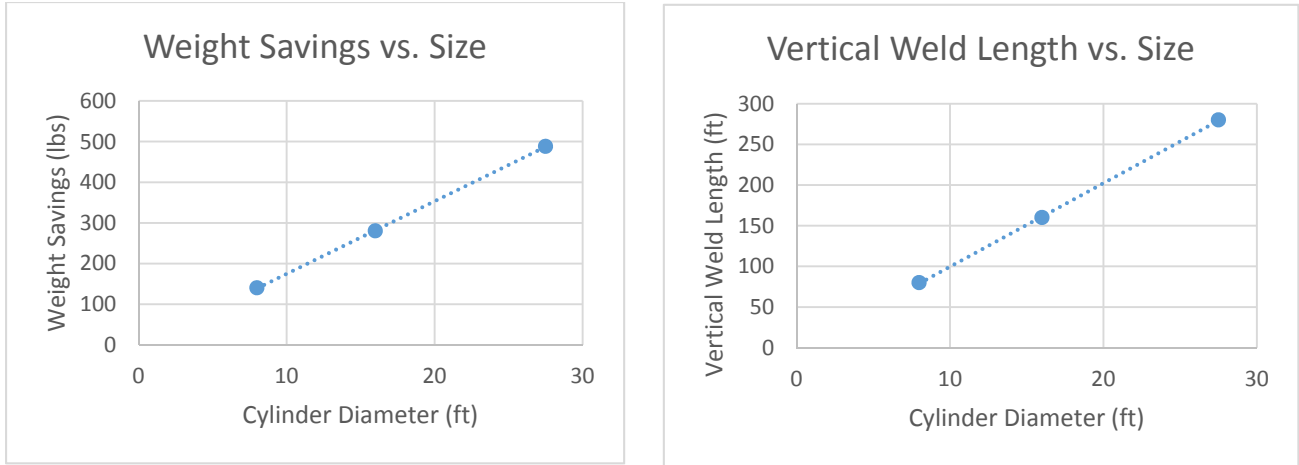
The parametric cost analysis results for 8-, 16-, and 27.5-foot diameter tanks shown in table 9 show an increasing cost benefit for the ANNST method as compared with the conventional metallic method, with the percent reduction in costs rising from 34 percent for the 8-foot tank to 53 percent for the 27.5-foot tank, largely due to labor costs. The larger diameter conventional metallic tanks require more welds and thus greater labor hours for welding and inspection. The total cost differential between the ANNST and composite tanks is comparable for all three tank diameters at 56-60 percent.

Figures 7(b) through 7(e) show cost curves for cylinders of the three diameters (8, 16 and 27.5 feet) produced with both the conventional metallic and ANNST methods. The cost curves shown depict total cost versus size, labor cost versus size, material acquisition cost versus size, and scrap metal savings versus size. The cost curves were produced from results of the parametric estimation tool. Material acquisition and scrap rate costs are fairly proportional with size and is likely due to considering only the tank barrel in this analysis. Including domes and joints might change this relationship due to the increased scrap associated with increased machining. Total and labor costs show a greater rate of cost increase for tanks in the range of 16 to 27.5 feet as compared with tanks below 16 feet in diameter.

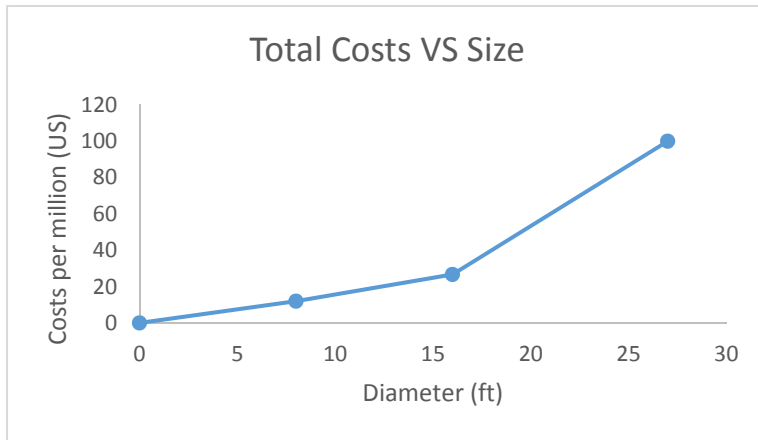
**Table 10. Mass calculations for 8-, 16-, and 27.5-foot cryogenic tank barrels manufactured using the conventional manufacturing and ANNST methods.**

Conventional Manufacturing						
	8 foot diameter		16 foot diameter		27.5 foot diameter	
	Inches	Feet	Inches	Feet	Inches	Feet
Length of the tank (in, ft)	480	40	480	40	480	40
Wall thickness (in, ft)	0.1	0.008	0.1	0.0083	0.1	0.0083
Outer diameter of tank (in, ft)	96	8	192	16	330	27.5
Inner diameter of tank (in, ft)	95.8	7.98	191.8	15.98	329.8	27.48
Volume of tank skin (in <sup>3</sup> )	14461		28937.81		49747.71	
Stiffener length (in, ft)	480	40	480	40	480	40
Stiffener height (in, ft)	0.75	0.0625	0.75	0.0625	0.75	0.0625
Stiffener thickness (in, ft)	0.25	0.0208	0.25	0.0208	0.25	0.0208
Number of stiffeners	30		60		104	
Total volume of stiffeners (in <sup>3</sup> )	2700		5400		9360	
Total weld land length (in, ft)	1864.78	1864.78	3729.56	310.80	6470.17	539.18
Weld land thickness (in, ft)	0.22	0.0183	0.22	0.0183	0.22	0.0183
Weld land width (in, ft)	4	0.3333	4	0.3333	4	0.3333
Weld land vol. overlap (in <sup>3</sup> )	14.08		28.16		42.24	
Vol. build-up at ends of cylinder (in <sup>3</sup> )	265.40		530.80		912.32	
Total number of welds	11		19		31	
Volume of welds (in <sup>3</sup> )	1626.92		3784.65		6563.83	
Total volume (in <sup>3</sup> )	19053.69		38122.47		65671.54	
Starting volume needed (in <sup>3</sup> )	311040		622080		1088640	
Weight (lbs)	1962.53		3926.61		6764.17	
Amount of scrap material in <sup>3</sup>	291986		583958		1022968	
Percent scrap	93.87		93.87		93.97	
Plate dimensions are 10 ft by 13.5 ft by 2 inch						
	Inches	Feet	Inches	Feet	Inches	Feet
Plate length (in, ft)	120	10	120	10	120	10
Plate width (in, ft)	162	13.5	162	13.5	162	13.5
Plate thickness (in, ft)	2	0.167	2	0.167	2	0.167
Cylinder circumference (in, ft)	301.59	25.13	603.19	50.27	1036.72	86.39
Number of stiffeners	30	30.16	60	60.32	104	103.67
Number of vertical welds per barrel section	2	1.86	4	3.72	7	6.40
Number of circumferential welds	3	3	3	3	3	3
Length of all vertical welds (in, ft)	960	80	1920	160	3360	280
Length of all circumferential welds (in, ft)	904.78	75.40	1809.56	150.80	3110.17	259.18
Total length of welds (in, ft)	1864.78	155.40	3729.56	310.80	6470.17	539.18
Total number of plates	8		16		28	
ANNST Manufacturing						
	8 foot diameter		16 foot diameter		27.5 foot diameter	
	Inches	Feet	Inches	Feet	Inches	Feet
Same tank skin volume (in <sup>3</sup> )	14461.37		28937.81		49747.71	
Same stiffener volume (in <sup>3</sup> )	2700		5400		9360	
Height of barrel section (in, ft)	240	20	240	20	240	20
Number of barrel sections needed	2		2		2	
Length of one circumferential weld (in, ft)	301.59	25.13	603.19	50.27	1036.72	86.39
Number of circumferential welds	1		1		1	
Total length of welds (in, ft)	301.59	25.13	603.19	50.27	1036.72	86.39
Vol. build-up at ends of cylinder (in <sup>3</sup> )	265.40		530.80		912.32	
Volume from weld lands (in <sup>3</sup> )	265.40		530.80		912.32	
Total volume (in <sup>3</sup> )	17692.17		35399.42		60932.34	
Starting volume (80% Yield) (in <sup>3</sup> )	22115.21		44249.27		76165.43	
Weight (lbs)	1822.29		3646.14		6276.03	
Percent scrap	20		20		20	
Mass savings of ANNST over Conventional (lbs)	140.24		280.47		488.14	
Mass savings of ANNST over Conventional (%)	7.15		7.14		7.22	





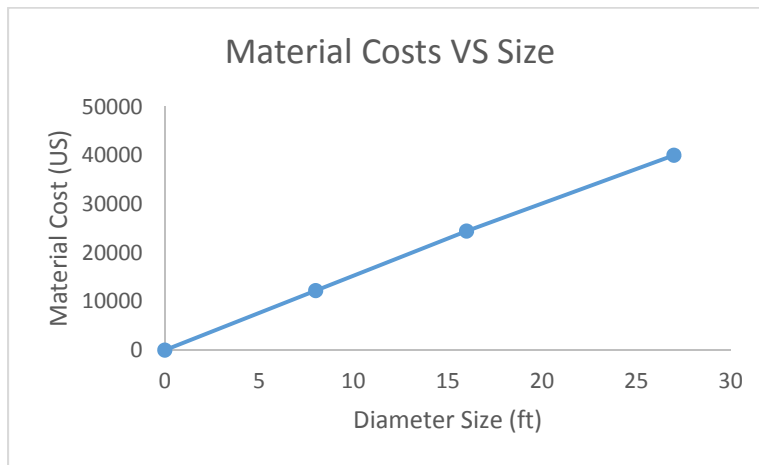
**Figure 7(a). Variation in mass and longitudinal weld length with cylinder diameter.**



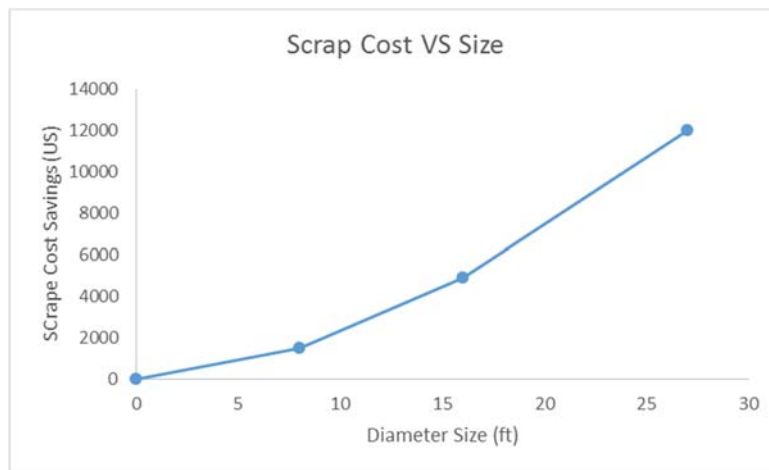
**Figure 7(b). Effect of tank barrel diameter on total cost vs. size.**



**Figure 7(c). Effect of tank barrel diameter on labor cost vs. size.**



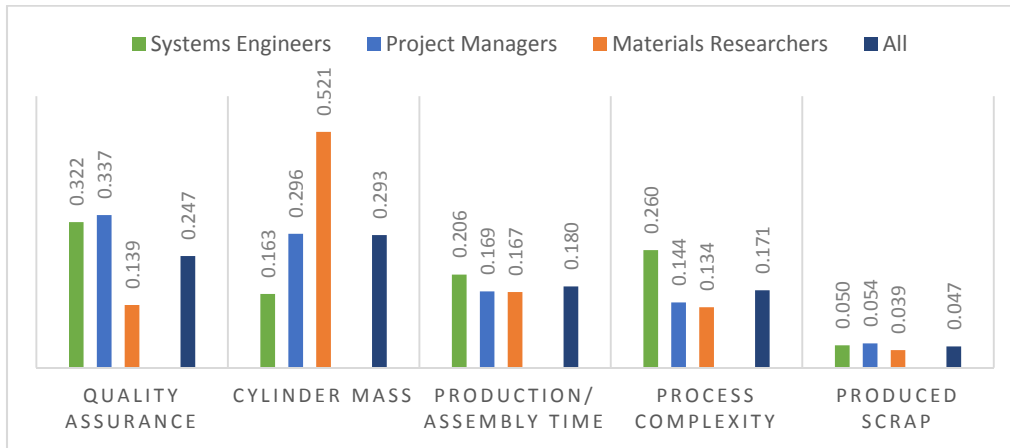
**Figure 7(d). Effect of tank barrel diameter on material acquisition cost vs. size.**



**Figure 7(e). Effect of tank barrel diameter on scrap cost vs. size.**

### *AHP Results*

Results were obtained from 18 SMEs from three different disciplines. Six SMEs were systems engineers, six were project managers and six were materials researchers. Each SME used the supplied AHP tool to perform pairwise comparisons of the figures of merit. The pairwise comparison values are stored in matrix form and are aggregated to form a priority vector. These priority vectors store the weights allocated for each FOM under consideration. The aggregation of the pairwise comparison values are typically performed with the eigenvalue method or the row geometric mean method. In this analysis, the row geometric mean method was used for its ease of implementation in an MS Excel environment. Individual priority vectors were subsequently combined with the row geometric mean method to obtain group priority vectors for each discipline. Figure 8 shows the weights obtained for each figure of merit. Weights are displayed for each discipline and also for the entire group of SMEs.



**Figure 8: Figures of merit prioritization.**

Trends are evident across the various disciplines: independently of the specific expertise of the SMEs, cylinder mass and quality assurance consistently scored high, production / assembly time and process complexity obtained midrange scores and produced scrap scored the lowest. Materials researchers consistently ranked cylinder mass high, with a score for this FOM greater than the combination of the four other FOMs under consideration for this group.

More variations were observed among individual weights for the group of project managers; however, both cylinder mass and quality assurance were consistently ranked high, with a final combined weight slightly greater for quality assurance. Systems engineers also ranked quality assurance high, which resulted in this attribute being ranked first for this group. The weights of process complexity and production and assembly time were also high for systems engineers, which is consistent with typical areas of emphasis for this discipline.

Table 11 shows the combined weights for all SMEs, providing some insight into the prioritization of the potential benefits associated with the various manufacturing methods. A breakout chart detailing individual and group weights for each FOM is available in appendix B.

**Table 11: Combined FOM Weights for All 18 SMEs**

Figure of Merit (FOM)	Normalized Prioritization
1 Cylinder Mass	0.312
2 Quality Assurance	0.263
3 Production and Assembly Time	0.192
4 Process Complexity	0.182
5 Scrap Produced	0.050

The results obtained with the AHP prioritization of benefits show that a 7-percent reduction in mass with the ANNST process over the conventional metallic manufacturing process has great value to all stakeholders. Composite tanks offer a greater benefit in terms of mass reduction for cylinders. This mass reduction benefit is however less significant when the entire tank structure is under consideration. In addition, quality assurance has obtained a high combined weight for this group of SMEs. The reduction in weld length for the ANNST process over the traditional metallic process and the reduced amount of acreage to inspect for the ANNST method over the composite method place the ANNST method as the leading manufacturing method in terms of time and labor involved for quality assurance tasks.

Production and assembly time, and process complexity obtained mid-range scores in the prioritized list of FOMs. The process flowcharts shown in figures 4 to 6 have shown that the ANNST method offers the benefit of a streamlined process, which reduces both production time and complexity. This benefit is valued by this group of SMEs, as reflected by the obtained combined weights.

Scrap produced is one of the most significant improvements of the ANNST method when compared to the traditional metallic manufacturing method, with a decrease in scrap rate from 90 to 5 percent. The AHP study however shows that scrap rate is not a highly valued figure of merit for this group of SMEs. This observation can be made across the three disciplines that were interviewed. The relative low cost of materials when compared to other costs involved with the fabrication of space-rated components might provide some rationale for the low weight allocated to this FOM.

## **Conclusion**

Cost-benefit analysis of the ANNST method for manufacturing single-piece integrally stiffened cryogenic tank cylinders showed a cost savings of about 50 percent over conventional multi-piece metallic and composite manufacturing methods used for comparison in this study. Mass calculations showed a 7-percent reduction for the ANNST method over the conventional metallic method. Cost savings were attributed to reduced labor hours for the ANNST method, largely associated with eliminating welds and reducing machining and inspection time. Mass reduction was due to eliminating welds and associated weld lands. For the 16-foot diameter case study tank, the return on investment in ANNST equipment would be realized after fabrication of ten cryogenic tank barrels, based on comparison with conventional metallic manufacturing.

The Integrally Stiffened Cylinder (ISC) flow forming process used in the ANNST method produces single-piece cylindrical structures with integrally formed stiffeners in one manufacturing step. Conventional metallic and composite fabrication are multi-piece manufacturing methods. The ISC process eliminates all longitudinal welds and reduces machining requirements by over 80 percent. Overall manufacturing time is reduced by half compared with conventional metallic manufacturing.

Results from both the analogy and parametric cost analyses concluded that the ANNST method was the lowest cost manufacturing option; however, the cost reduction over other methods was different for the two analyses. The parametric analysis showed ANNST to have a greater cost benefit over the composite method and the analogy/SME analysis showed the greater benefit over the conventional metallic method. This is likely related to differences in the assumptions made and level of detail used in each analysis. All results pertain to the cylindrical section of the tank and exclude domes and joint features. The assessment results would differ if these elements were to be included.

AHP analysis showed overall prioritization of cylinder mass and quality assurance over production time, process complexity, and scrap rate. Materials researchers consistently rated cylinder mass the highest priority while systems engineers placed higher priority on quality assurance, production time and process complexity. These priorities reinforce that the mass and cost reduction benefits afforded by the ANNST process have high value for stakeholders producing launch vehicle structural components.

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## Appendix A: Literature Review and Associated NASA Projects Summaries

<b>CBA Literature Review (references not cited in text)</b>			
<b><i>Author</i></b>	<b><i>Title</i></b>	<b><i>Year</i></b>	<b><i>Summary</i></b>
Gerdsri, Nathasit; Kocaoglu, Dundar	“Applying AHP to Build a Strategic Framework for Technology Roadmapping”	2007	Concept of “Technology Development Envelope” to apply AHP to emerging technology.
Lin, Than; Lee, Jae-Woo; Bohez, E.L.J.	“New Integrated Model to Estimate the Manufacturing Cost and Production System Performance at the Conceptual Design Stage of Helicopter Blade Assembly”	2012	Production-focused cost-benefit analysis outlining types of costs in production; mentions 70% of production costs are determined at conceptual stage.
Thengane, Sonal; et al.	“Cost Benefit Analysis of Different Hydrogen Production Technologies Using AHP and Fuzzy AHP”	2014	Production-focused cost-benefit analysis using AHP.
Ting, Pang; Xiao-hong, Shan; Guo-rui, Jiang	“Research on Risk Assessment of Emerging Technology: Industrialization Based on Gray Clustering”	2012	Establishes risk assessment index for environment, technology production, capital, management, and market through risk assessment with AHP.
Wijnmalen, Diederik	“Analysis of Benefits, Opportunities, Costs, and Risks (BOCR) with the AHP-ANP: A Critical Validation”	2007	BOCR Model in AHP

<b>Associated NASA Projects</b>	
<i>Topic</i>	<i>Summary</i>
COSTADE	Ability to cost forecast without historical data. Focuses on design variables that account for the majority of the cost in production. COSTADE is a multidiscipline tool which integrates design and manufacturing decisions helping to reduce the design cycle time; captures major process centers using process step level cost equations; provides framework to collect knowledge gained in fabrication; captured the synergy between design, process, and cost.
Ares V EDS	Two design concepts for the Ares V interstage. One metallic and one composite. Designs and results of analysis were used to determine lifecycle cost estimates for the two interstage designs, based on industry provided cost data for similar launch vehicle components. Study found that there was approximately a 35-percent mass savings for a composite Ares V interstage concept; significant upfront costs for composite concept. Also, annual production costs show the composite concept is 45 percent lower than the production costs compared to the metallic concept; so all this coupled with mass savings corresponds to cost savings of \$100M over the life of the project.
Boeing 777/787 Aluminum Composite	Aluminum performance has increase in order to compete with composites. Al-Li have higher strength, fracture, and fatigue/corrosion resistance. Composites not preferred compared to metal in the wings and fuselage due to higher certification and production costs, as well as low resistance to impact.
Composite Cryotank	A 5.5-m diameter composite tank design and fabricated as part of NASA's Composite Cryogenic Tank research program. The design used carbon fiber with epoxy resin and a fluted core concept. Boeing was contracted to design and fabricate the tank.
Shuttle ET Handbook	Broke down the manufacturing process for both the LH <sub>2</sub> barrel section as well as the LO <sub>2</sub> barrel section. In addition, provide measurements to be used in our case study such as the minimum plate thickness, weld land thickness, and other measurements specific to the conventional manufacturing of cryogenic tanks.

## Appendix B: SME Individual, Group, and Aggregate Results

Group Affiliation	Quality assurance	Cylinder mass	Production/ assembly time	Process complexity	Produced scrap	Consistency Index
Systems Engineer	3.74	3.38	0.64	0.54	0.23	0.09
Systems Engineer	1.43	0.73	1.39	2.57	0.27	0.07
Systems Engineer	1.11	0.29	2.36	3.12	0.42	0.03
Systems Engineer	1.83	1.89	0.52	3.76	0.21	0.09
Systems Engineer	0.90	0.34	3.50	1.82	0.51	0.05
Systems Engineer	5.16	1.84	0.89	0.47	0.25	0.09
<b>Systems Engineers (6)</b>	<b>1.92</b>	<b>0.97</b>	<b>1.23</b>	<b>1.55</b>	<b>0.30</b>	
Program Manager	3.16	3.09	0.45	0.82	0.28	0.05
Program Manager	1.40	4.08	0.73	0.58	0.42	0.05
Program Manager	3.32	0.27	1.38	1.38	0.58	0.02
Program Manager	1.70	2.91	0.70	1.20	0.24	0.05
Program Manager	1.82	2.61	1.74	0.35	0.34	0.09
Program Manager	1.48	1.18	1.93	1.48	0.20	0.10
<b>Program Managers (6)</b>	<b>2.02</b>	<b>1.77</b>	<b>1.01</b>	<b>0.86</b>	<b>0.32</b>	
Materials/ Manufacturing	1.48	2.95	1.07	1.07	0.20	0.08
Materials/ Manufacturing	1.06	5.80	0.87	0.56	0.33	0.08
Materials/ Manufacturing	0.32	1.97	4.58	1.11	0.32	0.08
Materials/ Manufacturing	2.17	4.43	0.84	0.54	0.23	0.09
Materials/ Manufacturing	0.38	3.74	1.36	1.75	0.3	0.05
Materials/ Manufacturing	1.90	3.94	0.49	1.00	0.27	0.06
<b>Materials Researchers (6)</b>	<b>0.96</b>	<b>3.60</b>	<b>1.16</b>	<b>0.93</b>	<b>0.27</b>	
Group Affiliation	Quality assurance	Cylinder mass	Production/ assembly time	Process complexity	Produced scrap	Consistency index
<b>Total</b>	<b>1.55</b>	<b>1.84</b>	<b>1.13</b>	<b>1.07</b>	<b>0.30</b>	
<b>Normalized Total</b>	<b>0.247</b>	<b>0.293</b>	<b>0.180</b>	<b>0.171</b>	<b>0.047</b>	



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