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

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Low Technology Readiness Levels (TRLs) and high levels of uncertainty make it challenging to develop cost estimates of new technologies in the R&D phase. It is however essential for NASA to understand the costs and benefits associated with novel concepts, in order to prioritize research investments and evaluate the potential for technology transfer and commercialization. This paper proposes a framework to perform a cost-benefit analysis of a technology in the R&D phase. This framework was developed and used to assess the Advanced Near Net Shape Technology (ANNST) manufacturing process for fabricating integrally stiffened cylinders. The ANNST method was compared with the conventional multi-piece metallic construction and composite processes for fabricating integrally stiffened cylinders. Following the definition of a case study for a cryogenic tank cylinder of specified geometry, data was gathered through interviews with Subject Matter Experts (SMEs), with particular focus placed on production costs and process complexity. This data served as the basis to produce process flowcharts and timelines, mass estimates, and rough order-of-magnitude cost and schedule estimates. The scalability of the results was subsequently investigated to understand the variability of the results based on tank size. Lastly, once costs and benefits were identified, the Analytic Hierarchy Process (AHP) was used to assess the relative value of these achieved benefits for potential stakeholders. These preliminary, rough order-of-magnitude results predict 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. Compared to the composite manufacturing technique, these results predict cost savings of 35 to 58 percent; 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 AHP study results revealed that decreased final cylinder mass and improved 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.

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I. Introduction

COST estimating activities conducted within the NASA community typically occur during the project formulation phase, in order to "provide the basis for programming the total requirement and the recommended phasing of budgets."[1] This is commonly done with Life Cycle Cost Estimates (LCCE) validated by Independent Cost Estimates (ICE). Multiple methods and tools are available to produce these cost estimates[2], which are essential to the management of NASA projects.

However, the uniqueness of NASA's mission requires that a lot of R&D efforts occur prior to the project formulation phase. NASA's mission statement reminds us that the purpose of the Agency is to "drive advances in sciences, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality and stewardship of Earth."[3] Innovation and the development of next-generation technologies are key components of NASA's strategic plan and research is a defining function of the Agency. Fewer costing activities however occur during the R&D phase. High uncertainty in the concept definition, low Technology Readiness Levels (TRL), and the uniqueness of the concepts make it challenging to develop cost estimates using the conventional approaches. As NASA prioritizes research investments, it is however essential to understand the relation between costs and benefits for novel concepts, as well as the potential for technology transfer and commercialization. This paper proposes a framework to perform a cost-benefit analysis of a technology in the R&D phase. The framework was developed and used to assess the Advanced Near Net Shape Technology (ANNST) project. Supported by NASA's Game Changing Development Program, the ANNST project is exploring an alternative method for manufacturing single-piece integrally stiffened cryogenic tank cylinders using the single-step, integrally stiffened cylinder (ISC) process. This paper first provides an overview of the ANNST process, then presents the framework that was designed to perform the cost-benefit analysis and finally provides the results of the analysis.

II. The ANNST Process

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 ANNST process proposes 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 a 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.

III. Cost-Benefit Analysis Framework

A cost-benefit analysis of the ISC process was performed to support the definition of viable applications for the process and development of relevant business cases. The objective of the analysis was to assess 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.

Tools and methods commonly used to produce cost estimates in the mission formulation phase are not a good fit in the case of a cost estimate for a new process in the R&D phase. For example, 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. In the case of the ISC process, the novelty of the concept makes that there is no historical data for similar processes to which regression analysis could be applied. In addition, parametric cost estimating tools such as Project Cost Estimating Capability (more commonly known as PCEC), Price® Systems software or SEER® project estimation, are tailored to develop cost estimates of components and systems. They are not tailored to evaluate the cost of a new manufacturing process. Similarly, a grass root cost estimate is also difficult to produce due to the novelty of the concept.

In addition to the challenges associated with estimating the costs of the ISC process, the team found that there were also challenges tied to the evaluation of the derived benefits. Quantifying and analyzing the benefits of using the ISC process to manufacture cryogenic tanks is difficult given the low technology readiness level of the process. Hein[4] states 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." In order to overcome these challenges, the team had to develop a novel framework to assess both the costs and the benefits associated with the ISC process. This framework is presented in the following sections.

A. Case Study Selection

The costs and potential benefits associated with the ISC process were assessed in comparison to two other processes traditionally used to manufacture cryogenic tank cylinders: the conventional metallic and composite manufacturing techniques. 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 ISC 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 is representative 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 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 since the construction method for the stiffeners is not analogous to that of metallic tanks.

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, are usually supported by ring structures, but these elements were also ignored, along with fasteners, to simplify the geometry.

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.

B. Subject Matter Experts Interviews

Once the case study had been defined, Subject Matter Experts (SMEs) throughout NASA and industry where identified and consulted. Data was gathered by contacting and interviewing over 20 SMEs. Many of these SMEs 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. 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. Data gathered from these interviews enabled the team to develop the following products: a definition of the three manufacturing processes synthesized in flowchart form, mass estimates for the case study tank for all three manufacturing processes, capital costs estimates for the ANNST process, and production costs and schedule estimates for the case study tank for the three manufacturing processes. These results are presented in the following sections.

a. 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 1 lists the estimated materials and infrastructure requirements, and figures 2 to 4 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 2 to 4). These were compiled from conversations with the 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 1, 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.

Requirements

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

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

Figure 1. SME Estimated materials and infrastructure requirements

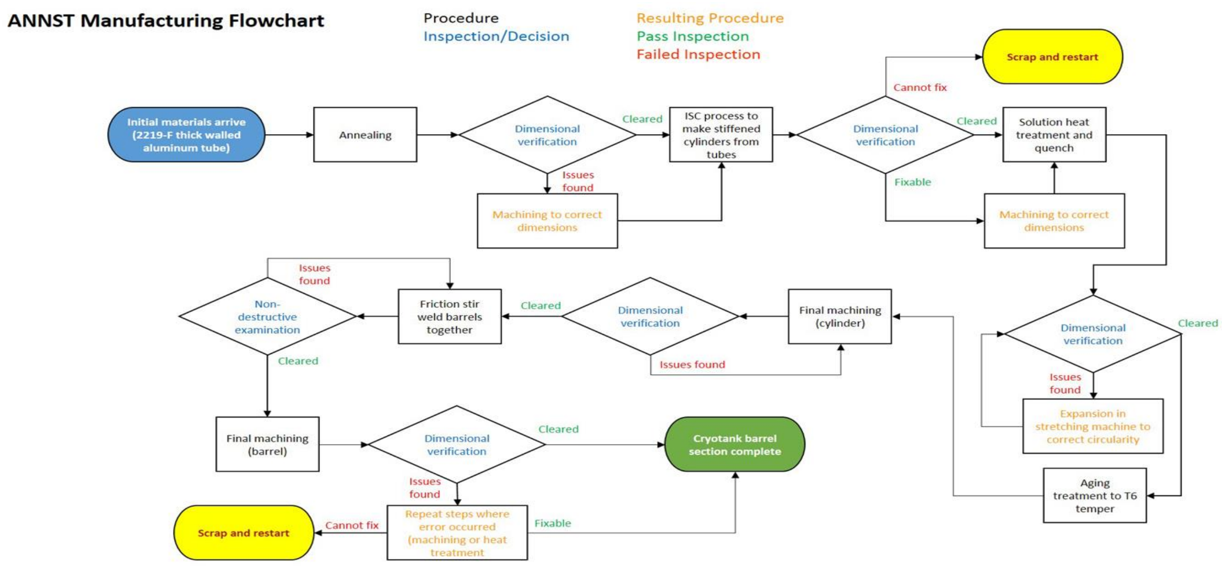

Figure 2. Manufacturing flowchart for the case study cylinder fabricated through the ANNST manufacturing method using the ISC process

Table 2. 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
Time (No setup time)			**47 days**
Total Time (Setup included)			**74 days**

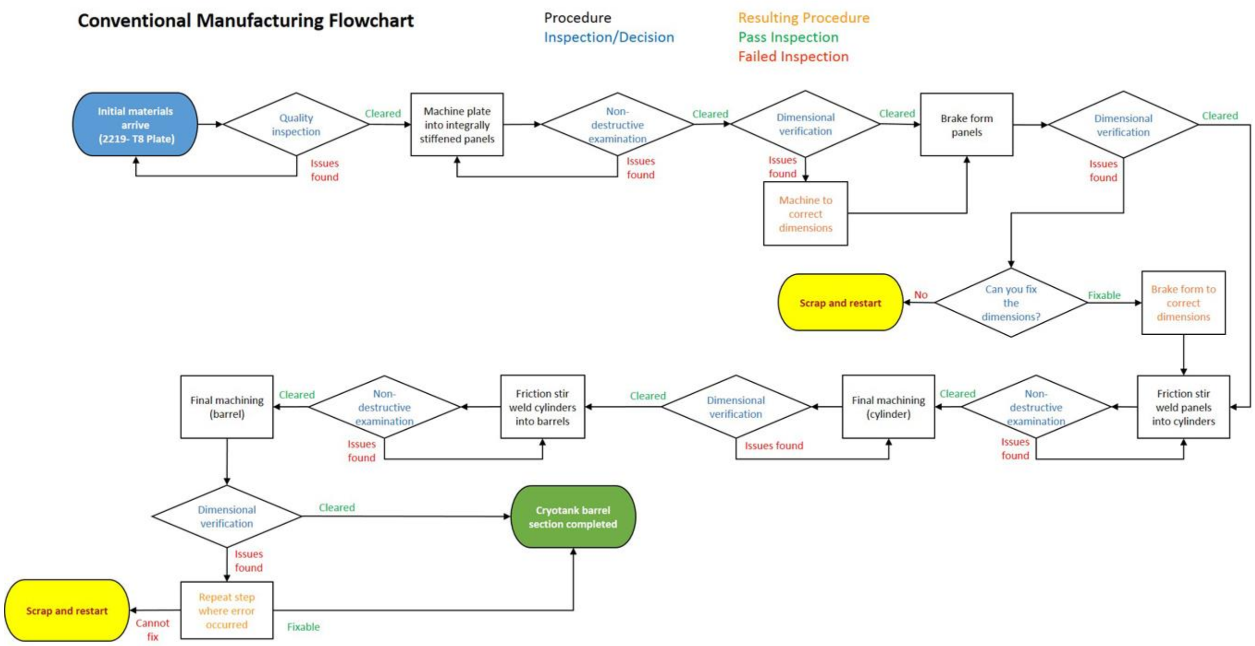

Figure 3. Manufacturing flowchart for the case study cylinder fabricated through the conventional metallic manufacturing process.

Table 3. 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
Time (No setup time)			**108 days**
Total Time (Setup included)			**147 days**

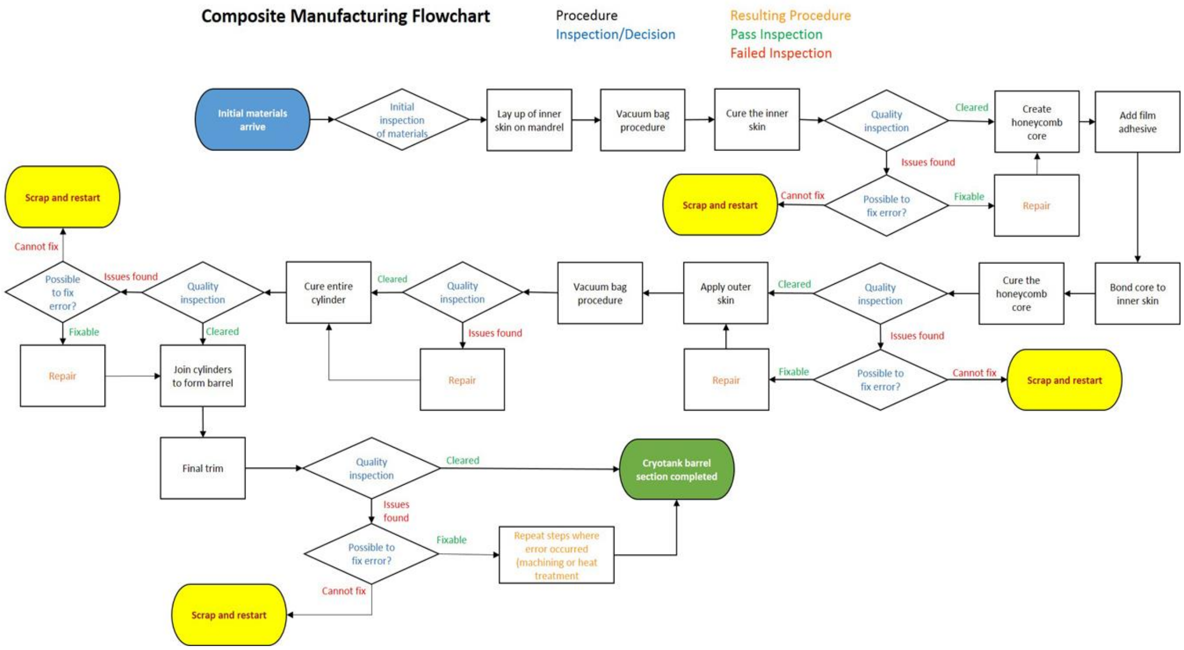

Figure 4. Manufacturing flowchart for the case study cylinder fabricated through the composite manufacturing method

Table 4. 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 weldof 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
Time (No setup time)			**70 days**
Total Time (Setup included)			**104 days**

b. Mass estimates

Mass estimates were calculated for the 16-foot diameter case study tank manufactured using the conventional and ANNST metallic methods and estimated from prior studies for 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 5 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 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.

Table 5. Estimated mass of the metallic tank fabricated using the conventional metallic and ANNST methods

Conventional Manufacturing

Length of the tank (in, ft)	480.00	40.00
Wall thickness (in, ft)	0.10	0.01
Outer diameter of tank (in, ft)	192.00	16.00
Inner diameter of tank (in, ft)	191.80	15.98
Volume of tank skin (in^3)	28,937.81	
Stiffener length (in, ft)	480.00	40.00
Stiffener height (in, ft)	0.75	0.06
Stiffener thickness (in, ft)	0.25	0.02
Number of stiffeners	60.00	
Total volume of Stiffeners (in^3)	5,400.00	
Total weld land length (in, ft)	3,729.56	310.80
Weld land thickness (in, ft)	0.22	0.02
Weld land width (in, ft)	4.00	0.33
Weld land vol. overlap (in^3)	28.16	
Vol. build-up at ends of cylinder (i	530.80	
Total number of welds	19.00	
Volume of welds (in^3)	3,784.65	
Total volume (in^3)	38,122.47	
Starting volume needed (in^3)	622,080.00	
Weight (lbs)	3,926.61	

(Plate dimensions are 10 ft by 13.5 ft by 2 inch)

Plate length (in, ft)	120.00	10.00
Plate width (in, ft)	162.00	13.50
Plate thickness (in, ft)	2.00	0.17
Cylinder circumference (in, ft)	603.19	50.27
Number of stiffeners	60.00	60.32
Number of vertical welds per barrel secti	4.00	3.72
Number of circumferential welds	3.00	3.00
Length of all vertical welds (in, ft)	1,920.00	160.00
Length of all circumferential welds (in, ft	1,809.56	150.80
Total length of welds (in, ft)	3,729.56	310.80
Total number of plates	16.00	

Amount of scrap material (in^3)	583,958
Percent scrap	94%

Legend:

(green)	*Input*
(blue)	*Computed*
(yellow)	*Output*

ANNST Manufacturing

Same tank skin volume (in^3)	28,937.81	
Same stiffener volume (in^3)	5,400.00	
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	
Total length of welds (in, ft)	603.19	50.27
Vol. build-up at ends of cylinder (i	530.80	
Volume from weld lands (in^3)	530.80	
Total volume (in^3)	35,399.42	
Starting volume (80% yield) (in^3)	35,470.36	
Weight (lbs)	3,646.14	

Material yield from ingot conversion	80%
Percent scrap	20%

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 Game Changing Development (GCD) Program Composite Cryotank Technology Demonstration (CCDT) project[5]. 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.

c. 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.

d. Cost Estimates by Analogy

Cost estimates were produced with the analogy method, which 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[1]. Table 6 provides a summary of the cost and schedule estimates obtained for the three manufacturing techniques for the given case study, based upon the SMEs interviews. A detailed breakdown is available in section A of the Appendix.

Table 6. Results from analogy method and SME estimates for cost and schedule for case study cylinders produced by the three manufacturing processes.

	Conventional Metallic	ANNST	Composite
Touch time, no set-up	108 days	47 days	70 days
Total time, includes set-up	147 days	74 days	104 days
Estimated cost	$1.55 million	$658,000	$1.01 million

C. Parametric Cost Estimate

In addition to the cost estimates derived from the data gathered through the SMEs interviews and produced by analogy, a rough order of magnitude parametric cost estimate was also developed. The parametric estimate produced for this cost-benefit analysis was done with the NASA Langley Research Center basis of estimate (BOE) tool. The BOE tool was selected over other parametric cost estimating tools—such as Project Cost Estimating Capability (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. The assumptions used to develop the cost estimate are listed in section B of the Appendix.

Table 7 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 7. Parametric cost estimate for the 16-foot diameter case study cylinder produced by the three manufacturing processes

16-ft diameter				ANNST Savings, %	
Cost in $K Real Year	Conventional Metallic	ANNST	Composites	Over Conv.	Over Comp.
Cylinder Mass, lbs.	**3,927**	**3,646**	**1,809**	**7.1**	**-101.6**
Total Cost, $K	**3,842**	**2,076**	**4,936**	**46.0**	**57.9**
· 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

D. 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 5. Mass calculations for 8-, 16-, and 27.5-foot diameter tanks manufactured using the ANNST and conventional methods, showed that tank weight is directly proportional to diameter.

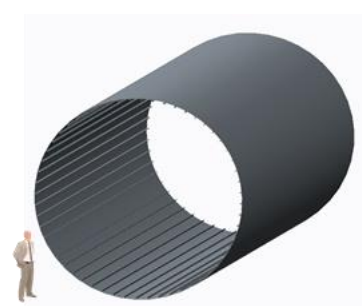

Figure 5. 16-foot integrally stiffened cylinder with scale

The difference in weight between the two methods remains about 7 percent for all three tank diameters. The relationship between tank diameter and both longitudinal weld length and mass was also directly proportional. 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. Mass calculations are available in section C of the Appendix.

The parametric cost analysis results for 8-, 16-, and 27.5-foot diameter tanks shown in table 8 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.

Table 8. Results from the Parametric Method for Cost and Schedule Estimates for Case Study Cylinders

8-ft diameter				ANNST Savings, %	
Cost in $K Real Year	Conventional Metallic	ANNST	Composites	Over Conv.	Over Comp.
Cylinder Mass, lbs.	**1,963**	**1,822**	**904**	**7.1**	**-101.5**
Total Cost, $K	**2,083**	**1,368**	**3,461**	**34.3**	**60.5**
· 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-ft diameter				ANNST Savings, %	
Cost in $K Real Year	Conventional Metallic	ANNST	Composites	Over Conv.	Over Comp.
Cylinder Mass, lbs.	**3,927**	**3,646**	**1,809**	**7.1**	**-101.6**
Total Cost, $K	**3,842**	**2,076**	**4,936**	**46.0**	**57.9**
· 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-ft diameter				ANNST Savings, %	
Cost in $K Real Year	Conventional Metallic	ANNST	Composites	Over Conv.	Over Comp.
Cylinder Mass, lbs.	**6,763**	**6,276**	**3,109**	**7.2**	**-101.9**
Total Cost, $K	**6,350**	**3,008**	**6,868**	**52.6**	**56.2**
· 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

Figure 6 shows cost curves for cylinders of the three diameters (8, 16 and 27.5 feet) produced with the ANNST method. 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 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 lesser rate of cost increase for tanks in the range of 8 to 27.5 feet as compared with tanks below 8 feet in diameter.

Figure 6. Scalability study results

E. Assessment of the value of the achieved benefits

Following the SMEs interviews, the rough order of magnitude parametric cost estimate and the scalability study, 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[6]. AHP models the decision problem through a hierarchical structure of the evaluation criteria, referred to herein as figures of merit (FOMs). 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 7 illustrates the decision problem model and table 9 provides the definitions of the FOMs.

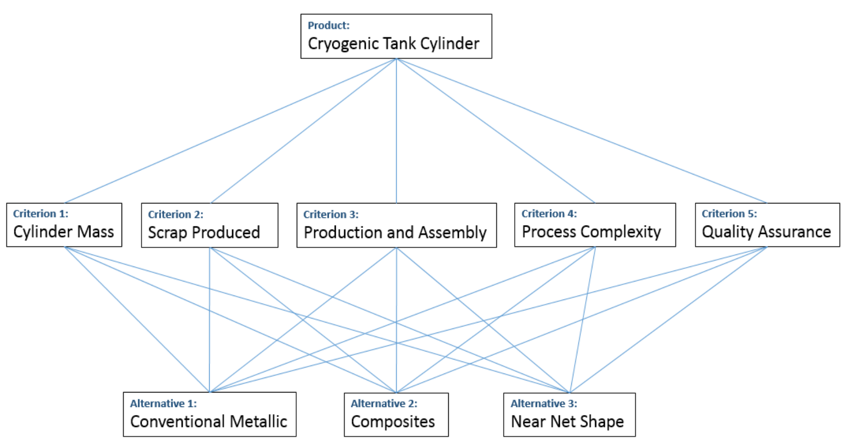

Figure 7. Model of the ISC Decision Problem

Table 9. 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, experts were contacted from three primary groups located across various NASA centers and industry: materials and structural researchers, systems engineers, and program managers. Results were obtained from six experts from each discipline, for a total of 18 sets of prioritized benefits. Each expert used a supplied MS Excel-based AHP tool to perform pairwise comparisons of the figures of merit. When performing a pairwise comparison, the user first selects which of the two FOMs is more 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 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.

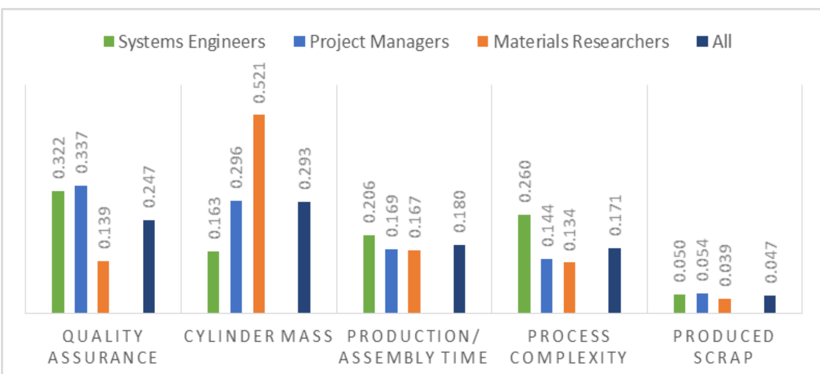

Figure 8. Prioritization of the figures of merit

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 for project managers 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 10 shows the combined weights for all SMEs, providing some insight into the prioritization of the potential benefits associated with the various manufacturing methods.

Table 10. 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

IV. Results

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. 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. 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.

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 3 and table 3. The ANNST method simplified those steps down to the one manufacturing step and two heat treatment steps by using the ISC process (figure 2 and table 2). In addition, when compared with composite manufacturing (figure 4 and table 4), 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 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 (Appendix) 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.

The results obtained with the AHP prioritization of benefits help interpret how these benefits are valued by various potential stakeholders. The prioritization shows 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 2 to 4 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.

V. Conclusion

Low Technology Readiness Levels (TRLs) and high levels of uncertainty make it challenging to develop cost estimates of new technologies in the R&D phase. A framework was developed to perform a cost-benefit analysis of the ANNST method for manufacturing single-piece integrally stiffened cryogenic tank cylinders. The analysis 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.

Appendix

A. Cost breakdown by analogy

Cost Breakdown	ANNST	Conventional	Composites
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)	**657,934**	**1,554,120**	**1,012,604**
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

Legend

(green)	Input
(light blue)	Output
(grey)	Not applicable
(yellow)	Total percentiles
*	Break out is "composite / resin / core"

B. Assumptions used for the parametric cost estimate with the BOE tool

- 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: 1/10th inch thick Aluminum, formed on tool. The manufacture of the tool is not considered here.
  - Conventional metallic method: 1/10th inch thick Aluminum. The cylinder is made by machining, brake forming and welding the Aluminum plate. Assumes 8 plates per 20-foot section, 10x1/4th 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. The first prototype is fabricated at ground specifications levels for structural testing, the 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.

C. Mass calculations for 8-, 16-, and 27.5-foot cylinders manufactured using the conventional metallic 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^3)	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^3)	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^3)	14.08		28.16		42.24	
Vol. build-up at ends of cylinder (in^3)	265.40		530.80		912.32	
Total number of welds	11		19		31	
Volume of welds (in^3)	1626.92		3784.65		6563.83	
Total volume (in^3)	19053.69		38122.47		65671.54	
Starting volume needed (in^3)	311040		622080		1088640	
Weight (lbs)	1962.53		3926.61		6764.17	
Amount of scrap material in^3	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^3)	14461.37		28937.81		49747.71	
Same stiffener volume (in^3)	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^3)	265.40		530.80		912.32	
Volume from weld lands (in^3)	265.40		530.80		912.32	
Total volume (in^3)	17692.17		35399.42		60932.34	
Starting volume (80% Yield) (in^3)	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	

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