ARIES-CS COIL STRUCTURE ADVANCED FABRICATION APPROACH

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One of the key factors that determine the competitiveness of any power plant is its capital cost. The premise for this study is that a more compact stellarator concept should result in a fusion power plant with lower capital costs that retains the attractive features of a stellarator with costs comparable to those of a tokamak power plant.

One of the design innovations in the ARIES compact stellarator is a continuous monolithic coil structural shell conforming to the shape of the modular coils. This shell is structurally analyzed for electromagnetic and gravity forces to achieve tailored material thicknesses over the surface of the toroid. Fabricating such a complex structure with conventional means would be very challenging and costly.

A new fabrication technology is "additive manufacturing" to create unique shapes directly from the computer-aided design definition file. Component size is not a limiting factor with this highly automated fabrication process. Multiple material deposition heads create the coil structure in a timely manner to near net shape. Heat treatment will remove residual stresses, followed by final machining of the internal coil grooves and attachment features. The fabrication cost was estimated to be less than one-third of the traditional fabrication methods.

KEYWORDS: *ARIES-CS, advanced fabrication, additive manufacturing*

Note: Some figures in this paper are in color only in the electronic version.

I. INTRODUCTION

Conventional stellarator fusion reactor designs typically have been very large aspect ratio machines with large major radii. These larger-radii power cores, because of their size and volume, have been very costly to construct. The ARIES compact stellarator (ARIES-CS) study[1] investigates approaches to make the stellarator power core more compact and affordable (lower capital costs). Fabrication of the coils and coil structures is one of the more costly elements of the power core. Usually coils and coil structures account for one-third of the total power core cost and are typically in the range of $400 million in 1994 dollars for the ARIES stellerator power plant study.[2]

Modular stellarators have field period sets of high–field strength coils that are highly shaped and nonplanar. The electromagnetic (EM) forces acting on the coils and coil structure are extremely complex and not repeatable except for field periods. Traditionally, national and international stellarator experiments and conceptual power plants are designed with each coil having its own supporting structure that mimics the coil shape, with structural connections between adjacent coil structures to form a field period structural assembly. Fabrication and assembly techniques on current stellarator experiments have resulted in the toroidal coil structure being one of the most expensive power core components.

The ARIES-CS power plant study[3] took a different design approach and developed a monolithic toroidal coil structure for each field period. Reference 3 is a companion technical paper that provides the design approach and basis for the conceptual design. Details of the design requirements and constraints for the coil structure are provided in that publication. The trade-off of different design approaches is discussed and the logic for the final structural approach is provided. A continuous convoluted toroidal tube is adopted to support the modular coils within grooves located on the internal surface of the tube. The tube is thickened on the sides and outside of the coils away from the plasma. The part thickness between coils is appropriately sized for the local stresses and

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deflections. Thus, the volume, mass, and cost of the toroidal field coil structure is optimized precisely for the local EM forces. Additional tailoring of the structure is accomplished for the necessary access ports and support features.

The large, monolithic toroidal coil structure is truly massive even in the ARIES-CS design. The hollow undulating toroidal structure has an inner radius varying from 3.0 to 6.5 m, an outer radius varying from 11.0 to 13.5 m, and a thickness varying from 0.2 to 0.3 m. Each field period component (one of three) weighs around 1000 tonnes. Fabricating this type of structure with conventional methods may not be possible and, at best, would be very challenging and costly. Its complexity is magnified with varying thicknesses and curvatures throughout the field period. A built-up assembly of many individual investment casting components might be possible, but nothing of this scale has been attempted. Significant assembly costs and risks are inherent in a complex assembly with many detailed components. A new fabrication technology[4,5] was evaluated on ARIES-CS that is called *additive manufacturing*. This new technology creates unique shapes directly from the computer-aided design (CAD) model definition with minimal final machining. Component size is not a limiting factor given adequate capital and program support during component growth. The process is highly automated with minimal labor to monitor the fabrication process and manufacturing quality. Multiple material deposition heads are used to create the coil structure in a timely manner to near net shape.

Low-temperature, long-exposure heat-treating methods are used to remove residual stresses in the field period structure after the part growth deposition. Following heat treatment, the internal coil grooves and attachment features are machined to final dimensions. Then the cable-in-conduit conductor (CICC) winding pack cables[3] are installed into the internal grooves. The cables are secured in the dado grooves with a closure plate that is welded to support the coil cables. The extensive use of automation to create the complex part shape and install the superconducting cable allows the structure to be built to a cost close to 1.5 times the raw materials cost.

II. DEFINITION OF THE MODULAR STELLARATOR TOROIDAL COIL STRUCTURE

The governing design approach is to use a large monolithic continuous shell for the coil structure rather than using numerous small discrete components assembled and joined to produce the final structural assembly. Assemblies and joined structures would have high load concentrations and excess weight because of inefficient design compromises. Penetrations would have to be accommodated by altering the connecting structures. The individual coil structures are very complicated structures that support the coil cables and provide cooling to the cables. A continuous, monolithic coil structure provides some additional nuclear shielding to power core components outside the coil structure; however, the additional shielding benefit is difficult to quantify. The continuous structure should be a more efficient, lighter weight structure to restrain the coils and provide a more tailored cooling capacity for the coil structure.

Figure 1 illustrates the final coil structural configuration[3] for a single field period, without and with installed coils. The parting lines are located at the three field period interfaces of 0, 120, and 240 deg. Large primary maintenance ports span these field period interfaces.

The EM forces on the high–field strength coils are generally in a direction away from the plasma and to the side of each coil, but not inward toward the plasma. This is the rationale for placing the coils in the interior grooves with a small cover plate just to hold the coils in place. The coil structure is thickened outboard of each coil to resist the relatively high outward EM forces.

Structural analyses[3] are conducted on these structures to determine the local stresses and deflections and thus the optimal thickness of the coil structure. Figure 2 shows a cross-section view through one of the coils and surrounding coil support structure. The nominal thickness of the structure is 0.20 m between coils and 0.28 m outboard of coils, but this varies depending on the local stresses and deflections. Given the local thicknesses and the configuration shown in Figs. 1 and 2, the nominal

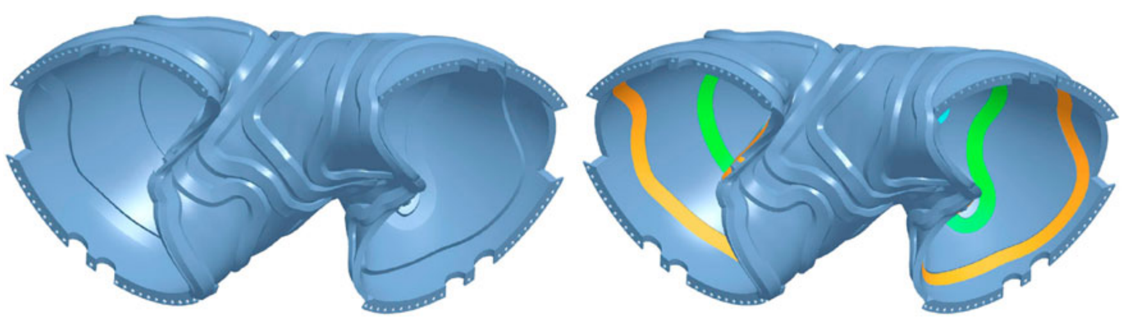

Fig. 1. Coil structure without and with coils in the internal grooves.

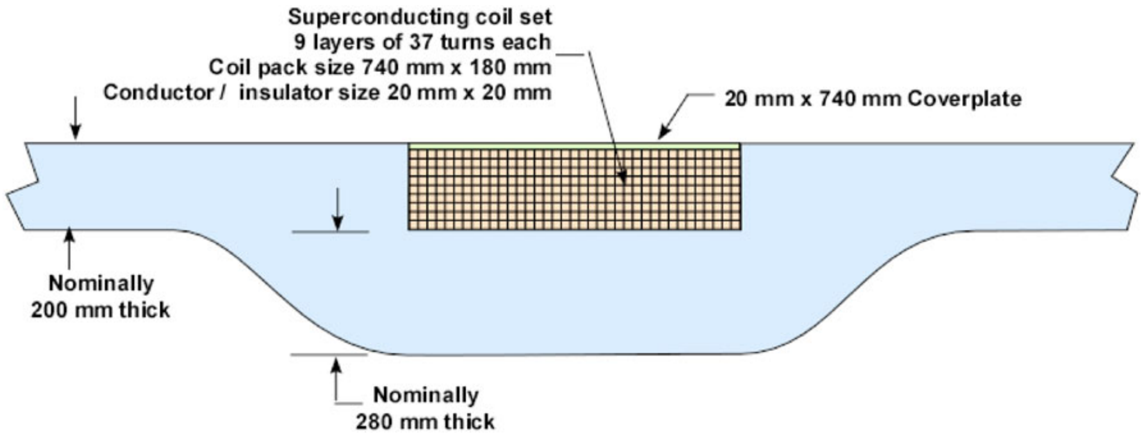

Fig. 2. Toroidal field coil cross section through the coils.

final mass of each field period is ~1000 tonnes of the selected JK2LB low-carbon, boron steel. The rationale for choosing the structural material JK2LB is given in the companion paper, "ARIES-CS Magnet Conductor and Structure Evaluation."[3] Table I in that paper[3] provides the material design properties. Reference 6 documents the material composition and mechanical properties at the operating conditions of 4 K after heat treatment for the production of Nb_3Sn. Weld metal properties are also included. I am sure that other more attractive metal systems will be developed before this reactor is designed in 30 to 40 years, but for the present assessment, this is determined to be the best material for the assessment. The effects of δ-ferrite formation in welded JK2LB or martensitic transitions are not fully characterized and will have to be investigated before this process and material are adopted.

III. EXAMINATION OF DIFFERENT FABRICATION APPROACHES

Several fabrication approaches could be attempted to fabricate the coil structure. The geometry of the coil is such that there are no identical surface parts in a field period except for an up-down mirror image reflecting around the 60-deg position. Figure 3 shows the progression of coil cross sections over one field period. Thus, the learning curve effects are minimal (i.e., quantity of three per reactor) for fabricating the field period with an assembly of many individual piece parts. All components and joining fixtures for a built-up field period structure are distinctly different and unique.

One candidate approach would be to form plates that approximate the shape of the inner coil surfaces and weld these plates to form a continuous ring that mimics the coil shape. Then thinner plates could be welded together to connect and form the remainder of the monolithic shell. The edges of the plates would be complex shapes (nonrectangular and nonstraight line segments) to construct the undulating toroid. The thickness of these plates would have to be selected to match the desired local thicknesses. Heat treatment of the complete field sector would be needed to reduce the welding stresses. Then the internal coil grooves would be machined into the thicker plate sections. If the interior or exterior surface geometry is critical, additional machining will be required to eliminate the surface discontinuities at the welded junction of the flat plates or further shaping of the plates would be required. This is not a vacuum-tight structure,

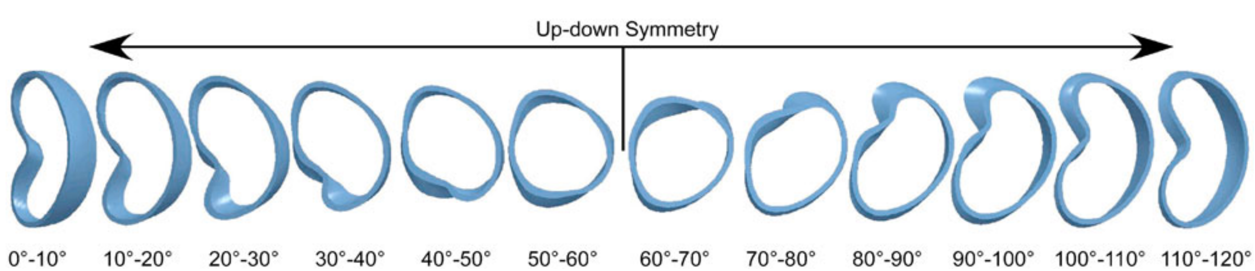

Fig. 3. Progression of coil structure shapes over a field period.

so leak-tight welding is not a requirement. However, high-quality welding would be required for strength purposes. Even if automated welding were used to a great extent, there would be substantial hand work and thousands of small individual piece parts. This approach is highly unlikely to be cost competitive or effective.

A second approach is to forge or explosively form larger sections of the structure to near net shape. This manufacturing method might be feasible, were it not for the varying thicknesses over the entire toroid surface. The folded surfaces and the required coil groove accuracy would be very difficult to achieve with forged or explosively formed parts. This does not seem to be a feasible approach.

A third approach would be the use of a thicker forged or stamped piece deformed to a rough shape that is then highly machined to the final shape. This is done on aircraft wing spars and bulkheads, with 90 to 95% of the part high-speed machined away to the final shape. Since the finished coil structure mass for a single field period is roughly 1000 tonnes, the cost of the raw material is a concern with this approach. The quantity of material needed for this approach is many times the final mass. Material costs, even when a high recycling fraction is assumed, would be excessive even without considering the high machining costs.

A fourth approach would be to use castings, such as an investment or sand casting. The molds can be formed in several different ways, many of which can be generated directly from the CAD definition to reduce cost and increase part reproducibility. These castings can produce parts that have reasonably close tolerances with minimal waste material. The current size of castings is somewhat limited (up to 40 to 50 tonnes for Type 316 LN stainless steel sand castings), but in the future, much larger sizes might be possible. Many castings would have to be joined together to form a complete field period. Dimensional accuracy, risk of defects in castings, and consistently high joint strength might be difficult to achieve. Again, the fabrication process involves a large number of parts with significant labor. Heat treatment would be necessary, followed with three-dimensional (3-D) machining. The cost of this approach would be lower than that for formed part assemblies, but it would still be too high to be cost effective.

In summary, the complexities of the chosen structural shape, as shown in Fig. 3, do not lead to a reasonably priced, conventional fabrication approach.

Additive manufacturing, a relatively new manufacturing process, appears to be a better fabrication method for this component. In general, the raw material is deposited in the correct position by a computer-generated part definition. The material is heated, melted, or activated so as to harden in place and "grow" the near-net shape part, layer by layer. Stereolithography was the first demonstration and practical application of this technology. With stereolithography, the raw material is a photo-sensitive liquid plastic. A laser scans the liquid surface with the image of a part section cut to harden the material onto a platform at the liquid surface. The base platform is lowered to expose another liquid layer and the laser builds another layer on top of the first, continuing to build the entire plastic component in the shape of the three-dimensional CAD image. This process can produce detailed, net shape components of thermoset plastic materials with minimal human intervention other than the CAD part definition. This is a very useful means to quickly and rather inexpensively build a prototype or test model in plastic. The next evolution of this technology was to use metal powders that are sintered by a laser into a more durable final piece part. The next-generation advancement was to use metallic wire or powders as the raw material that is melted into a continuous weld bead per the CAD definition. This has been done to create flight-worthy structural aircraft parts, as shown in Fig. 4.

A 2007 initiative of the Department of Defense's Manufacturing Technology (ManTech) Program is to "Use laser additive manufacturing to reduce cost and cycle time for aerospace structural components such as wing carry through structures and bulkheads." The process of creating parts directly from raw materials using computer-aided design and manufacturing is still in its infancy, but it holds great promise for efficient creation of complex parts. The ARIES-CS coil structure has several physical attributes that favor the additive manufacturing approach:

1. The complex part shape is difficult to build with conventional fabrication methods, and highly convoluted shapes have high complexity factors. Additive manufacturing has a relatively small complexity cost factor.

2. Although the coil structure comprises many unique subelements, there are only three sets of identical parts (one per field period) that provide minimal learning curve effects. Additive manufacturing is completely automated and cost effective, with little savings from learning curve effects. The numerically controlled (NC) programming will have been accomplished, validated, and costed on the initial production units on the early power plants; hence, no cost for NC programming was considered in this estimate.

3. The coil structure conceivably can be constructed as a single component for each field period.

4. High surface quality, requiring finish machining, is required only within the coil grooves and at interfaces between field periods, ports, and support points.

IV. FABRICATION OF THE COIL STRUCTURE

Additive manufacturing has been successfully demonstrated in the fabrication of intermediate-size, high-quality, and military primary structural components.

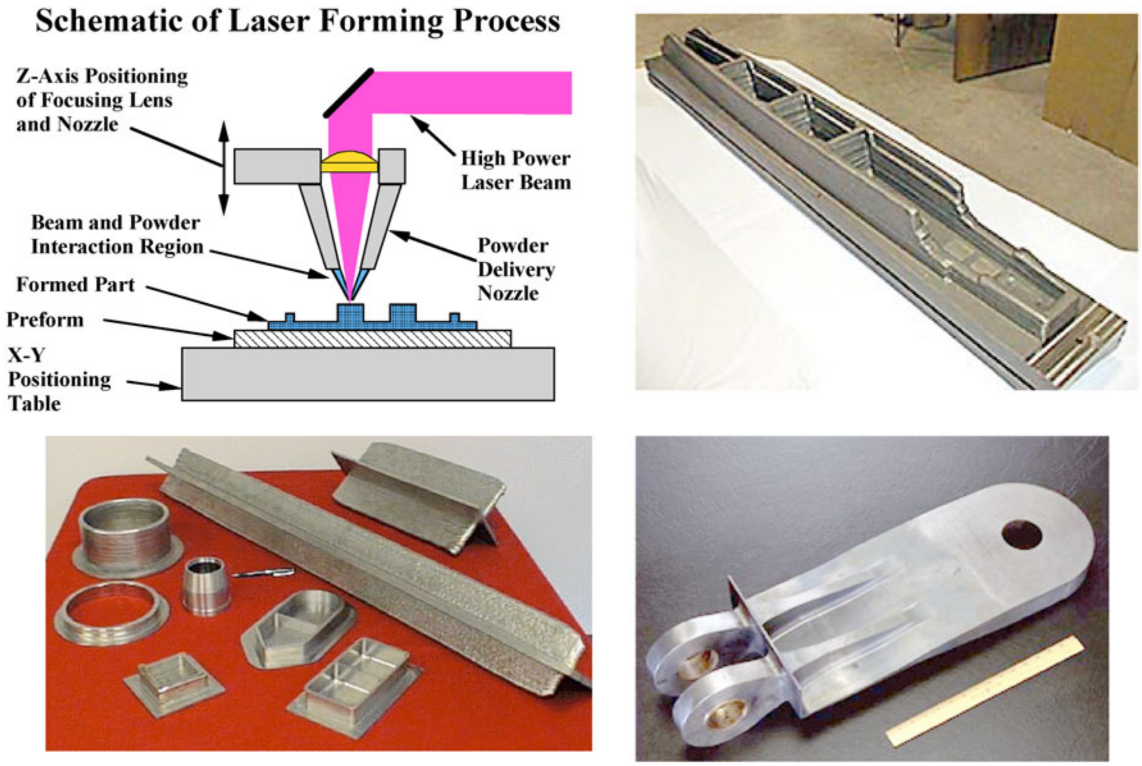

Fig. 4. Schematic of arc deposition process, layered buildup, and finished components.

Components of a complexity similar to that of the ARIES-CS coil structure have been produced using this technology, although they are a much smaller size ($\sim$3 to 4 m). There are, however, no inherent size limitations in additive machining. The fabrication of components can be stopped and restarted with no ill effects. Any weld defects detected with nondestructive testing can be ground out or machined away and repaired. The only limitation is the speed of material buildup. At present, titanium can be deposited at the rate of 10 kg/h. It is assumed that in 30 to 40 years, the rate would be in excess of 20 kg/h for steel. Adjusting the number of robots used enables construction within the desired manufacturing time.

For depositing the JK2LB low-carbon, boron steel, a wire form raw material is preferred over powered metal. Lasers could melt the wire material, but currently the deposition efficiency is inadequate. A plasma arc is a more efficient means of melting the wire at the needed deposition rate and material yield. Figure 5 shows how planar features are constructed through successive layered deposition. Overhanging or cantilevered features are constructed with assistance from cooled slip plates to provide a base upon which the overhanging features can be fabricated. The near-net shapes of the coil grooves are constructed by locally starting and stopping the deposition.

The deposition of the coil support structure begins with laydown on a prepared supporting substrate. Figure 6 shows the buildup of the structure beginning at the base and building to the top. Slip plates are used to create the lower and upper overhang areas. The grooves will be created as the buildup progresses.

As mentioned earlier, the size of the structure requires multiple deposition heads working simultaneously to fabricate the part in a reasonable time. It is estimated that nine deposition robots would be used in a round-the-clock operation, plus a spare to work on difficult areas. Each robot is assigned a particular region (inboard or outboard) of the structure, as shown in Fig. 7.

After the field period structure is fabricated, the structure is heat treated to remove induced welding stresses. Heat treatment is accomplished at a relatively low temperature for an extended time frame, approximately one month. Because of the size of the structure, many insulated heating blankets are used to uniformly heat the entire structure. A heat-treating oven of this size would probably be impractical for this size part. It is also desirable to have the fabrication on-site; therefore, the oven would have to be transported to site, which may also be impractical. After the heat treatment process, the entire structure is mapped to determine that all dimensional requirements have been met. If not, it can be locally reworked and re–heat treated.

Following heat treatment and inspection, the grooves and other mating surfaces are finish machined. Most interior and exterior surfaces will probably not require any finish machining. Gantry-mounted milling machines might

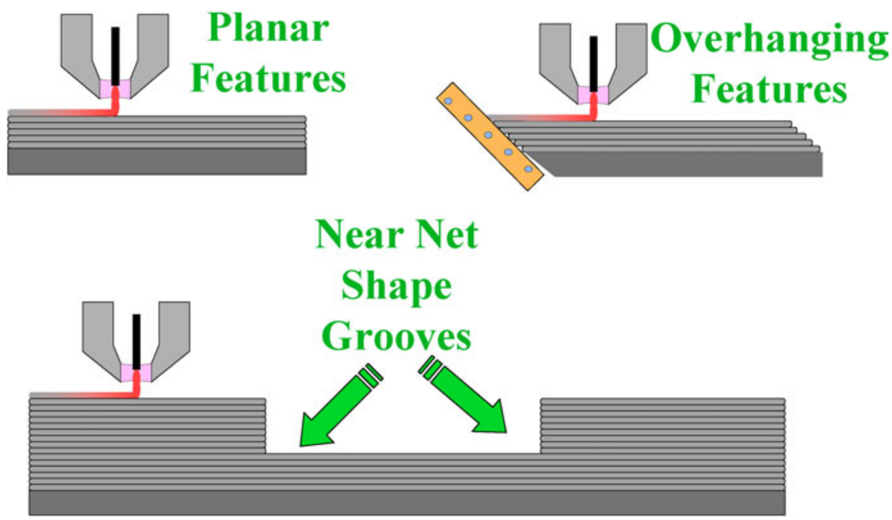

Fig. 5. Construction of coil features with additive manufacturing.

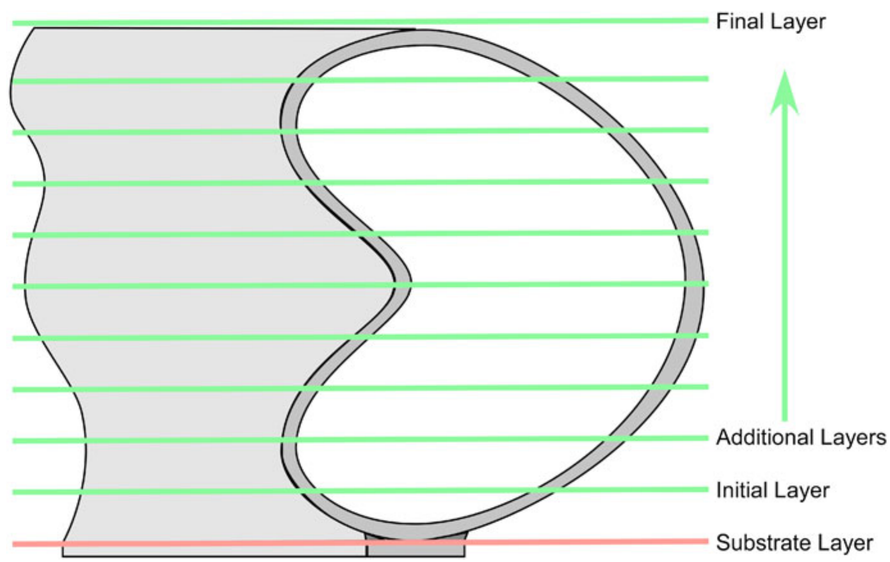

Fig. 6. The coil structure fabrication will initially deposit material on a base substrate. Fabrication will build up layers to the top of the structure for complete closeout.

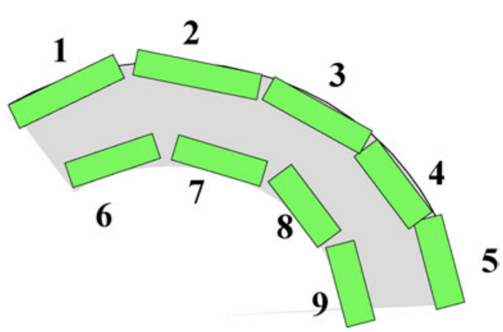

Fig. 7. Assignment of deposition robots to fabricate a field period structure.

be used, but their access inside the structure is limited. Cantilevered milling heads might result in deflections with poor dimensional accuracy when milling the grooves. Instead, it is recommended that guide rails be attached near the sides of the grooves, as shown in Fig. 8.

These guide rails follow the contour of the grooves and the inner toroid surface and allow the milling machine to follow the guide rails. Flexible track designs may be used. The machine path is determined by the CAD definition. Local fiducial reference marks with laser positioning systems will achieve the desired accuracy of the grooves. The near-net shape of the groove structure

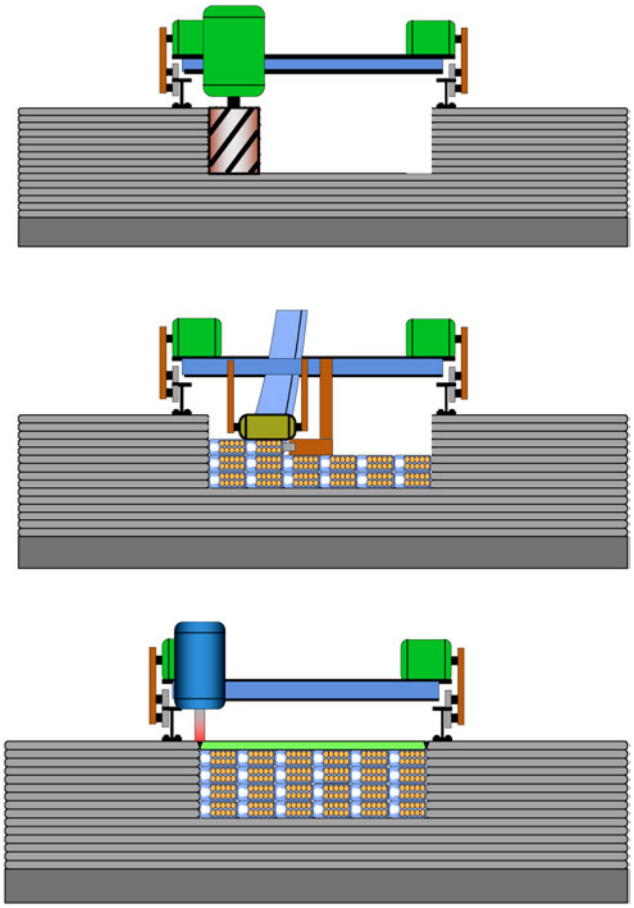

Fig. 8. Steps in milling grooves, installing coil cables, and securing coil cover plates.

will allow shallow machine cuts on the groove side walls and floor with low milling forces.

The same guide rails can be used to form and guide the coil conductor cables into the grooves using an automated process, as shown in Fig. 8. The conductor is a 20 mm × 20 mm continuous cable with prewrapped insulation on the exterior of the cable. There can be as many as 37 conductor turns per layer and up to seven layers in each coil groove. The number of conductor turns in each coil varies according to the type of coil[3] (e.g., M1, M2, or M3). The technique of the conductor installation and the installation speed will have to be determined in the research and development phase. For the present analysis, the winding rate is conservatively estimated to be 5 m/h. After all the cables are installed, another machine with a welding head can secure the thin cover plate over the coil cables. Laser or friction stir welding the cover plates is recommended; however, there are other fastening techniques that could work. These machining and cable installation steps are highly automated, which helps ensure part consistency, accuracy, and low fabrication costs.

The size and mass (1000 tonnes) of one field period structure suggests that the field period coil structure should be fabricated at the construction site. As shown in Fig. 9, the initial field period structure begins fabrication with the arc weld deposition at the far left position. When completed, the fully deposited component is moved to a second position where the heat treatment is carried out. Meanwhile, the second field period begins the deposition process. After the deposition of field period 2 and heat treatment of field period 1 is complete, they are moved to

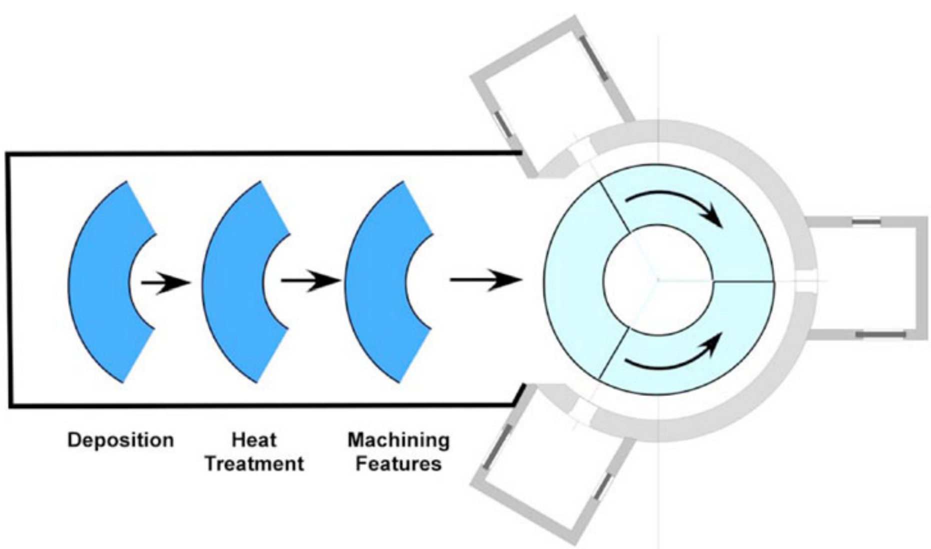

Fig. 9. Sequence of deposition, heat treatment, and machining features in preparation for installation into the power core.

the next stations, where the machining commences on field period 1 and heat treatment on 2. At the same time, the deposition of field period 3 starts. One-third of the bioshield is left open for the field period coil structures to be moved in and rotated into final position.

V. ESTIMATED COST OF COIL STRUCTURE FABRICATION AND COIL CABLES INSTALLATION

To determine if this advanced fabrication has positive cost benefits, a preliminary cost estimate has been prepared. The cost is provided in 2006 U.S. dollars, but in the systems cost summary,[1] the system costs are reported in 2004 dollars. As stated earlier, the final fabricated mass of a single field period is approximately 1000 tonnes of special low-carbon, boron steel, JK2LB. This alloy is being used in some of the International Tokamak Experimental Reactor (ITER) coil systems; its usage is still very low for the steel industry. In bar form, this steel is estimated to cost around $10/kg, which would be presently representative for a large quantity purchase of a specialty steel. The chemistry for JK2LB is very similar to PH stainless steel, which currently costs around $10/kg for bar material form. The weld wire form would be roughly double that cost, or $20/kg. These costs are representative of a specialty steel product that has been used on a demo plant, perhaps a prototype plant, and at least nine prior commercial plants before this tenth-of-a-kind power plant; hence, the steel companies will have significant experience producing large quantities (3000 tonnes/plant) of this specific steel.

On-site fabrication of the coil structure is planned. The build time is driven by the assumed deposition rate (20 kg/h) of each deposition robot and the number of robots working simultaneously (ten robots for the data shown plus two spare robots). Table I shows the key fabrication elements that influence the fabrication cost during the deposition phase. With 10 robots operating, the combined deposition rate is 200 kg/h. Assuming a deposition robot availability factor of 85%, the overall deposition rate is reduced to 170 kg/h. Thus, the total deposition time for a single field period structure is 245 days. Representative costs for the robots, platforms, and control systems result in a cost of $8 million for the deposition phase. The amortized cost of the fabrication hardware is $198/h, assuming that these robots and other equipment could be amortized over six field periods (two plants). Additional cost of electricity (power consumption) and cost of four operators and inspectors is added along with an overhead factor of 1.5. This yielded a fabrication cost of $25.9 million for a single field period coil support structure or $77.9 million for the entire coil structure.

The next step is to stress relieve each field period coil structure. Details of this operation are shown in Table II. With this material, the part is at temperature for

TABLE I

Estimated Time and Cost to Fabricate One Field Period of Coil Support Structure

Segment weight (kg)	1 000 000
Wire unit cost ($/kg)	$20
Material cost	$20 000 000
Deposition rate per robot (kg/h)	20
Number of deposition robots	10
Deposition rate (kg/h)	200
Up time (availability)	0.85
Deposition time (days)	245
Robot unit cost ($/robot)	$500 000
Total robot cost with 2 spares	$6 000 000
Raising platform cost	$1 000 000
Control system cost	$1 000 000
Deposition system cost	$8 000 000
Amortization (segments)	6
Amortization cost ($/h)	$227
Electricity unit cost ($/kWh)	$0.05
Electricity usage per robot (kW)	100
Electricity cost ($/h)	$50
Operator cost/h ($/h)	$100
Number of operators	4
Labor cost ($/h)	$400
Overhead factor	1.5
Deposition rate ($/h)	$1 015
Deposited segment cost	$25 970 588

TABLE II

Steps and Cost of Stress Relief for One Field Period

Segment weight (kg)	1 000 000
Stress relief time (days)	30
Insulation	$2 000 000
Heating system	$2 000 000
Heat treat system cost	$4 000 000
Amortization (segments)	6
Amortization cost ($/h)	$926
Electricity unit cost ($/kWh)	$0.05
Electricity usage (kW)	10 000
Electricity cost ($/h)	$500
Operator cost/h ($/h)	$100
Number of operators	1
Labor cost ($/h)	$100
Overhead factor	1.5
Heat treat rate ($/h)	$2 289
Stress relief cost	$1 648 000

30 days. It is estimated that this step requires $2 million in heating systems and $2 million in insulating blankets. These heating systems and insulating blankets should be relatively inexpensive elements, but the surface area to be covered is extensive. Again it is assumed that this equipment could be used for six segments, so the heating system is amortized over six field periods (segments). Electricity usage for the stress relief heating is estimated. Only one person is required per shift to monitor the heating systems and temperature control, so there is minimal labor cost. The cost of stress relieving one field period is $1.65 million.

The cost to machine the grooves for the superconducting coils on the interior of the coil structure is summarized in Table III. The total coil groove length of each field period is 263.8 m. Two milling machines are mounted on guide rails attached to the interior of the structure on each side of the groove. Rough and finish milling cuts on the groove side walls and floor are required to achieve the correct dimensions and location for the grooves. A machine availability of 85% is assumed. The rough machining for a complete field period should be completed in 24 days. Finish machining the groove floor takes several passes with an end mill cutter, whereas the sides require only a single pass each for a side mill cutter. The total finish machining can be completed in 7 days. Extra costs include amortized milling machine costs, labor, and overhead charges. The cost to machine the coil grooves in a field period is estimated to be $682 000.

TABLE III

Cost of Rough and Final Machining of the Coil Grooves for One Field Period

Length of channel (m)	263.8
Depth of channel (m)	0.194
Width of channel (m)	0.743
Fraction roughout	0.25
Amount of rough machining (kg)	74 718
Rough machining rate (kg/h)	77.28
Up time	0.85
Number of milling machines	2
Rough machining time (days)	23.7
Floor finishing feed rate (m/h)	6.980
Cutter diameter (m)	0.106
Total length of cut (m)	1 847
Up time	0.85
Floor finishing time (days)	6.5
Sidewall finishing rate (m/h)	24
Total length of cut (m)	527.6
Up time	0.85
Sidewall finishing time (days)	0.5
Total machining time (days)	30.7
Milling machine cost	$2 000 000
Amortization (segments)	25
Amortization cost ($/h)	$217
Operator cost/h ($/h)	$100
Number of operators	4
Labor cost ($/h)	$400
Overhead factor	1.5
Machining rate ($/h)	$926
Coil channel machining cost	$682 369

The next step after finishing the grooves is to install (or wind) the wound superconducting cable and install the cover plate. The cost of the cable and integral insulation is included in the toroidal field coil cost account as a separate item and is not included in these calculations. The conventional practice is to manually wind higher-flexibility superconducting cables and insulating materials onto mandrels and add epoxy to secure the cables and then transfer the winding pack onto the supporting structure. This is a very time-consuming and labor intensive practice, which is not conducive to high-precision, repeatable fabrication. A new approach is being used for insulating the coil cables by using an inorganic insulating tape that is impregnated with a ceramic binder. The ceramic insulating tape is applied to the conductor cable prior to winding the cable into the support grooves with automated winding equipment. This automated process is highly repeatable and will be much faster and more accurate than hand winding. Even at the relatively slow pace of 5 m/h, the winding operation on a segment can be completed in 152 days. After the winding process is completed and the cover plate installed, the entire structure is heat treated to react the Nb_3Sn, during which the ceramic binder melts. When the structure cools, the binder hardens and mechanically restrains the cables in the groove. No separate insulation or impregnation steps are needed. Table IV shows the installation steps, times, and costs to install the cable and the cover. The total groove length for a field period is ~264 m, which will be used to determine the cover material and installation costs. The length of each coil and number of turns per coil of each coil type (M1, M2, M3) are used to determine the length of conductor in each field period. The rate of installation of the 20 mm × 20 mm conductor cable is uncertain at this time. For the present, it is conservatively assumed to be a rate of 5 m/h or 80 mm/min. Multiple installation machines are required to obtain reasonable installation times and costs. Increasing the number of installation machines continues to decrease the time and cost, but it is felt that six machines is probably the limiting number that can be effectively utilized. The total installation cost for the cable and cover installation is estimated to be $2.4 million for a field period.

Following the installation of the winding pack and the installation of the cover plate, the installed Nb_3Sn conductor[3] is heat treated at 850 to 950 K (577 to 677°C) for a period of about 200 h (Ref. 7) to achieve the proper final reaction condition in the Nb_3Sn conductor. Reference 7 is documenting a fabrication process for low ac

TABLE IV

Cost of Coil Cable and Cover Installation for One Field Period

Cable installation and friction stir weld speed (m/h)	5
Number of installation or welding machines	6
Coil length/field period (m)	263.8
Cover width (m)	0.743
Cover thickness (m)	0.02
Mass of cover/field period (kg)	38 807
Unit cost ($/kg)	$10
Cover material costs	$388 071
Length of M1 coil (2 required, left and right) (m)	45.8
Length of M2 coil (2 required, left and right) (m)	45.1
Length of M3 coil (2 required, left and right) (m)	41.0
Number of turns in M1	270.0
Number of turns in M2	338.0
Number of turns in M3	328.0
Sum of length of Mx coil times 2 times number of turns (m)	82 115.6
Up time	0.75
Cable installation time/field period (days)	152.07
Coil cover installation and welding (days)	0.49
Complete coil and cover installation (days)	152.55
Installation machine cost/machine	$2 500 000
Amortization (segments)	25
Amortization cost ($/h)	$164
Operator cost/h ($/h)	$100
Number of operators	2
Labor cost ($/h)	$200
Overhead factor	1.5
Machining rate ($/h)	$546
Installation cost/field period	$2 386 463

TABLE V

Cost of Cryogenic Coil Heat Treatment for One Field Period

Segment weight (kg)	1 000 000
Stress relief time at 850 to 950 K (days)	8.3
Insulation (use same insulation from stress relief)	$0
Heating system (reuse heating system)	$0
Heat treat system cost	$0
Amortization (segments)	6
Amortization cost ($/h)	$0
Electricity unit cost ($/kWh)	$0.05
Electricity usage (kW)	2 778
Electricity cost ($/h)	$139
Operator cost/h ($/h)	$100
Number of operators	1
Labor cost ($/h)	$100
Overhead factor	1.5
Heat treat rate ($/h)	$358
Cryogenic coil heat treatment cost	$71 667

loss strand for a future ITER application. The same procedure, insulation, and heating equipment that were used for the prior stress relief process are now utilized for the superconducting cable reaction process, but at lower temperatures and shorter durations. The cost of coil heat treatment for a field period is minimal at $72 000, as shown in Table V.

The superconducting coil structure is designed to operate at cryogenic temperatures while providing support for the modular toroidal field coils. The power core components interior to the coil structure, namely, the blanket, shield, manifold/hot structure, and vacuum vessel, provide the majority of the neutron shielding during operation. However, there is some small amount of bulk neutron heating that reaches the coil structure during operation, varying from 1.5 mW/cm^3 on the inner surface to <0.1 mW/cm^3 on the outer surface. This level of heating is removed by using circulating low-temperature gaseous helium through integral cooling tubes or machined channels. The lowest-cost approach might be to solder or braze coolant tubes to the outside surface. But it is felt that a more technically conservative design approach would be to cut small coolant channels and manifolds into the outer surface of the coil structure as detailed in Table VI. This procedure ensures a high-quality conductivity heat transfer from the coil structure to the coolant. Nominally, the channels are 25 mm × 25 mm with generous corner radii. The assumed length of the cooling channel per field period is 2360 m, which equates to an average of 10 channels per coil winding. The heating is slightly higher on the structure at the larger radii and

TABLE VI

Cost of Cooling Channel Machining for One Field Period

Length of channels (ten times as many as coils) (m)	2 638
Depth of channel (m)	0.025
Width of channel (m)	0.025
Number of milling machines	2
Machining rate (m/h)	6.980
Up time	0.85
Channel machining time (days)	9
Milling machine cost	$2 000 000
Amortization (segments)	25
Amortization cost ($/h)	$720
Operator cost/h ($/h)	$100
Number of operators	4
Labor cost ($/h)	$400
Overhead factor	1.5
Machining rate ($/h)	$1 680
Cooling channel machining cost	$373 391

there is a greater distance between coils at the larger radii, so more cooling channels are provided there. The use of machined channels enables tailored placement of coolant channels and distribution headers. With two milling machines assumed, the channel machining time is 9 days at a cost of $373 000, as summarized in Table VI.

The cooling channel is covered to form a closed, leak-tight channel by welding a cover plate in place. The cooling channel is machined with a lip on both sides to accommodate the cover plate. The welding is accomplished with friction stir welding or some other form of welding. The two welding machines used in the cover plate operation complete a field period structure in 12 days at a cost of $415 000. The detailed cost estimate is provided in Table VII.

Summing all the cost elements in the coil structure results in a total fabrication cost per segment (field period) of $31 million U.S., as shown in Table VIII. This equates to only $31/kg for the fabricated cost of a very complicated and very large structure with high-accuracy placement of superconducting coils. This is a very low-cost approach. The majority of the cost is in the raw material, which accounts for $20/kg of the finished structure. The labor and fabrication overhead cost is only one-half of the raw material cost. This result is only possible with advanced automation, minimal machining, and high material yields. The duration of three years for the fabrication of all three field periods is compatible with the schedule to construct and assemble the power core. If a shorter fabrication time is required, additional deposition robots (i.e., more capital assets) can be employed. This additional equipment cost would likely be partially or wholly offset by lower direct and indirect labor costs.

TABLE VII

Cost of Closeout of Cooling Channel for One Field Period

Friction stir weld speed (m/h)	5.334
Number of installation machines	2
Coil length (m)	2 638
Up time	0.85
Coil installation time (days)	12.12
Installation machine cost	$2 000 000
Amortization (segments)	25
Amortization cost ($/h)	$550
Operator cost/h ($/h)	$100
Number of operators	4
Labor cost ($/h)	400
Overhead factor	1.5
Machining rate ($/h)	$1 425
Cooling channel closeout cost	$414 552

TABLE VIII

Summary of Cost and Time to Fabricate Toroidal Coil Structure

Fabrication total cost and time		
Cost/segment		$31 475 363
Cost/mass segment ($/kg)		$31.48
Cycle time to complete segment 1[a] (days)		512
Additional time for each segment (deposition) (days)		245
Total time for three segments (days)		1 002
Fabrication elements	Days	Cost
Deposition	245	$25 970 588
Stress relief	30	$1 648 000
Coil channel machining	3	$682 369
Coil cable and cover installation	153	$2 386 463
Cryogenic coil heat treatment cost	8	$71 667
Cooling channel machining	9	$373 391
Cooling channel closeout	12	$414 552
Segment totals	488	$31 547 029
Total, three segments	978	$94 641 088

[a]Including 4 days to move from each station to station.

Table VIII indicates that the bulk of the fabrication cost is in the deposition process ($25.9 million/segment), which is dominated by the cost of raw material ($20 million/segment). The coil cable installation is the second highest-cost element at $2.4 million/segment, being influenced by many cable turns and layers to form the individual coils. The stress relief operation on the large segments is the next-highest-cost element ($1.6 million/segment). These stress relief costs are driven by the amortized heating system and power consumption costs. The machining of the coil grooves and the cooling channels and the closeout of the cooling channels are relatively minor cost and schedule elements.

VI. SUMMARY AND CONCLUSIONS

The intent of this study element is to investigate advanced fabrication technologies that may appropriately apply to one of the compact stellarator's most expensive and complex components, the innovative toroidal coil support structure. Lowering the cost and time to build this structure helps to facilitate a more competitive cost of electricity.

Additive manufacturing is the process of creating a metallic part by depositing materials according to CAD instructions. Structures are literally grown, as opposed to the more traditional assembly and joining of detailed parts. Components are built up to near-net final configuration, rather than the conventional approach of removing material from a larger form of material. This coil structure has many attributes that are synergistic with the use of additive manufacturing. The structure would be very difficult and costly to fabricate with conventional technologies because there are no identical geometrical elements within the field periods and only three field periods. The design intent to have a single monolithic structure for each field period is very suitable for additive manufacturing since the deposition can fabricate the entire field period with no joining of subassemblies required, and hence higher part accuracies. Additive manufacturing is ideal since the deposition is directly linked to the CAD definition, with no complexity factors necessary. Any defect or dimensional change can easily be corrected through additional welding and/or machining.

Machining the interior coil grooves would be difficult using conventional gantry or cantilevered milling machines because of limited access inside the toroid and reach to the midpoint of the field period. A rail system is selected to support and guide small milling heads to cut the coil grooves and to install the superconducting coil cables in the grooves.

Estimates of the cost and time to fabricate the coil structure and install the coils using advanced technologies show a significant cost and schedule advantage as compared to a conventional fabrication approach for the coil structure, as estimated in the ARIES stellarator power plant study[2] using similar costing ground rules. The installed cost of the coil structure for this advanced fabrication approach is less than one-third the cost of the conventional approach and is only 50% above the raw material cost.

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