

Ultra-low cost coil fabrication approach for ARIES-ST

L.M. Waganer^{a,*}, D.A. Deuser^a, K.T. Slattery^a, G.W. Wille^a, F. Arcella^b,
B. Cleveland^b

^a *The Boeing Company, St. Louis, MO, USA*

^b *AeroMet Corporation, Eden Prairie, MN, USA*

Abstract

The extremely large capital expense of fusion power core components has severely diminished the overall attractive features of fusion-generated electrical power. A fresh examination of possible new manufacturing techniques yielded two ultra-low cost methods to fabricate the massive toroidal field (TF) coils of the ARIES-Spherical Torus (ARIES-ST) conceptual power plant. These innovative fabrication approaches are estimated to reduce the capital costs of the TF centerpost and return leg shell by an order of magnitude from conventional fabrication processes. This capital cost reduction will, in turn, reduce the cost of electricity by approximately 10%.

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Keywords: Toroidal field; ARIES-ST; Coil fabrication

1. Introduction

The investigation of the fabrication approaches and detailed costing of the toroidal field (TF) coil system did not begin early in the design phase of ARIES-Spherical Torus (ARIES-ST). Rather, the ARIES-ST conceptual design evolved from parametric studies to optimize the plasma size and shape to yield lowest cost of electricity while satisfying the necessary plasma physics requirements. Only after the plasma and design parameters were largely established and the configuration was nearly final did the TF coil

fabrication approach and economic evaluation commence.

The ARIES system code [1,2] has been used over many years to evaluate a series of tokamak conceptual designs with many plasma configurations and power core system variations. This code has evolved as the various conceptual power plant designs have been evaluated. The code models and adjusts the physics parameters of the plasma, magnetic field and coil configurations, power core component engineering parameters, and general power core configuration and determines the capital and operating costs of the entire power plant to arrive at an optimized cost of electricity.

To efficiently examine the multidimensional parameter space mentioned above, the level of detailed cost estimating is constrained to the level of a system (instrumentation and control) or a component (power supply or poloidal field coil).

* Corresponding author. Address: Boeing High Energy Systems, Mail Code S111-1300, P.O. Box 516, St. Louis, MO 63166, USA. Tel.: +1-314-233-8617.

Historically, costs for these systems or components have been estimated by several researchers, as documented in Starfire [3] and ARIES-RS [2]. Cost estimating relationships for these systems and components have been developed employing the significant cost drivers, thus enabling parametric cost modeling for use in system analysis codes. These cost estimating relationships are usually based on one or more statistically significant parameters (weight, power, current, stored energy) that estimate the system or component cost with a reasonable degree of accuracy.

Normally, the significant capital cost elements in tokamak reactors are the nuclear power core (first wall, blanket, shielding, coils, and ancillary systems), reactor plant equipment (power supplies, heat transfer and transport systems, etc.), and plant buildings, roughly in equal parts. The content of the latter two categories is based upon conventional electrical power generation experience and little can be done to modify or reduce these designs and costs. For conventional tokamak fusion power plants, the emphasis has been on improving performance and reducing the cost of the power core. The tokamak power core is roughly divided into three large, similar-sized capital cost accounts: the first wall, blanket, and shielding system; the coil system; and all other ancillary systems (heating, current drive, vacuum pumping, support structure, etc.). So the emphasis is to improve the performance in all areas of the conventional power core because they contribute rather equally to the cost of electricity.

In the case of the spherical torus [4–10], the optimal configuration generally favors a low aspect ratio of 1.4–1.6 that causes the plasma to be very tall and very close to the centerpost. All the coil current for the toroidal field coil system must flow through the centerpost. There are differing opinions by researchers as to whether it is better to shield or not shield the centerpost [7]. It is not feasible to have a power-generating or tritium-breeding blanket on the inboard area of the centerpost. So the blanket and shield system of the spherical torus is not as extensive and costly compared to the conventional tokamak. However, the cost of the TF coil system has increased significantly as it has grown in height. Trade

studies generally favor a normally conducting TF coil as opposed to superconducting coils, but the sheer size and complexity determine and drive the system costs higher than the traditional tokamak design.

In this light, the ARIES-ST team thought it would be worthwhile to conduct a study of the evolving TF coil design. Boeing was commissioned to review the design approach, develop a fabrication concept for the centerpost and return shell, and prepare a cost estimate. The main purpose was to validate the fabrication technique and capital cost for the dominant cost item in the plant.

2. Costing groundrules

The design basis is the ARIES-ST centerpost and the complete shell return (as opposed to discrete return legs). The costs are estimated in current 1998 dollars. The plant is assumed to be the tenth of a kind plant, so all developmental problems have been solved and no development costs are applicable to this unit. Appropriate learning curves are included in the unit costs.

3. Design basis

The design basis for the ARIES-ST centerpost and TF return shell is shown in Fig. 1. The return TF coil system could have been discrete coils, but to obtain low aspect ratio plasma, the outer legs are relatively close to the outer surface of the plasma. If it were necessary to move the legs outboard to obtain more clearance, the entire size of the TF coil system becomes very large. With the discrete coils relatively close to the plasma, TF field ripple was a concern. So a continuous shell approach for the TF return currents was adopted. There is also a need for a vacuum shell in this region, so the shell could also function as that element.

As shown in Fig. 1, there are four parts to the TF coil system. The 30-m-long centerpost is comprised of a tapered section in the upper region to electrically mate with the outer shell, a straight cylindrical section that is in close proximity with

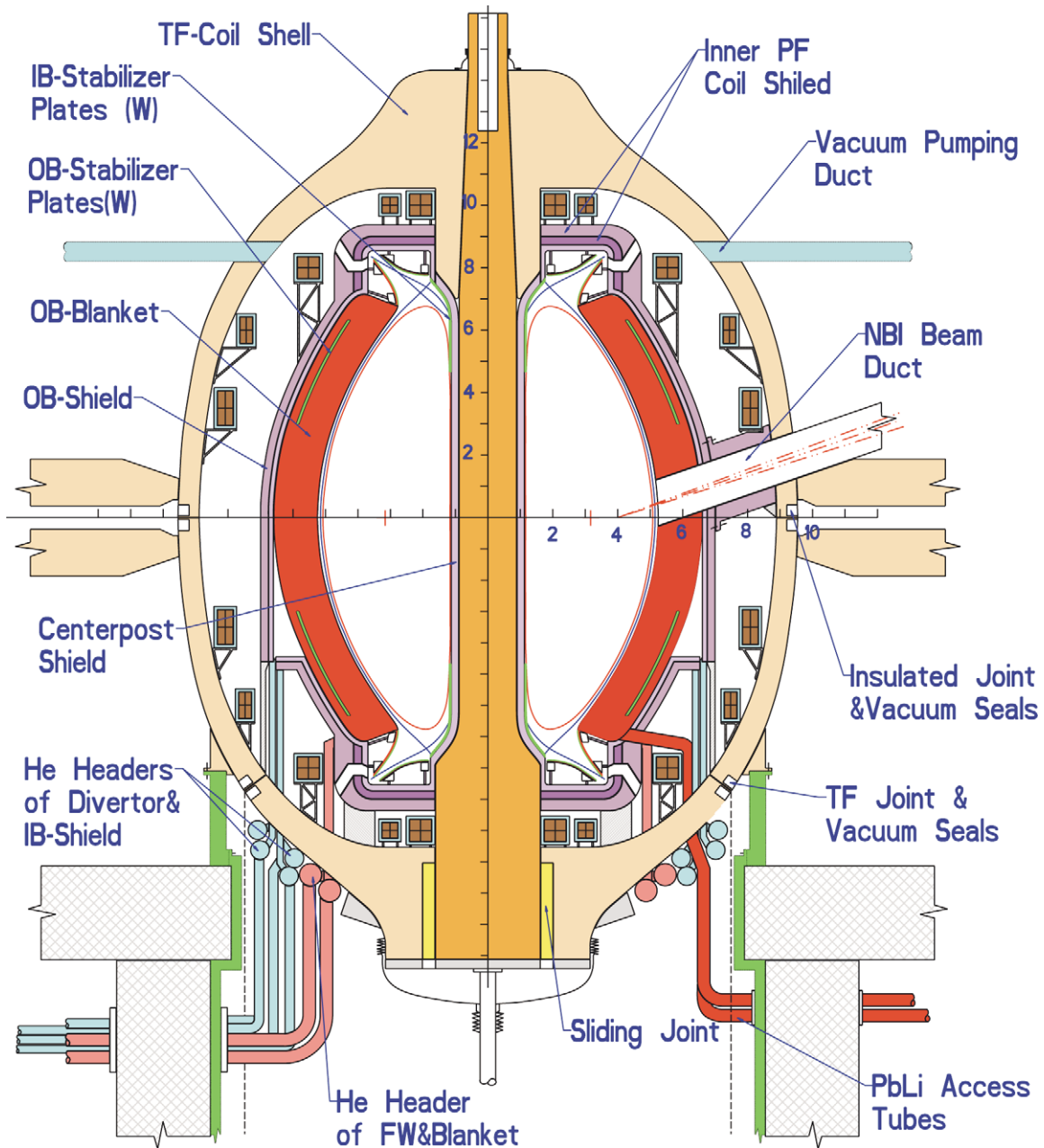


Fig. 1. Elevation view of ARIES-ST power core.

the plasma, and a larger cylindrical section at the bottom to increase the conductive area to the maximum extent to lower ohmic losses. The 30-m, unitary centerpost is constructed of high-conduc-

tivity copper. It is cooled with low-temperature water in a single pass configuration. The centerpost is comprised of roughly 85% copper and 15% water. This part weighs approximately 0.851×10^6

kg. As mentioned earlier, there is shielding for the region close to the plasma, but that is not a part of the TF coil system.

The outer shell has three distinct parts. An upper shell extends from the top of the centerpost to the midplane where it is connected to one of the power supply busbar leads. The middle shell extends from midplane, where the other busbar connection is made, down to a maintenance break. The third shell is from the maintenance break down to the lower connection to the centerpost. This shell is removable during maintenance actions. The outer shells could be made from either copper or aluminum. Copper is more conductive than aluminum but it would be heavier for the same effective conductivity. The thickness of the aluminum shell would be adjusted to yield the proper coil resistance and recirculating power losses. Again, the shells would be water cooled with an overall 15% water fraction.

4. Conventional fabrication approach

The conventional method of constructing the copper centerpost assembly with internal water passages would be to fabricate wedges with grooves for the coolant and then weld the entire assembly in a fixture to minimize distortion. This would be a difficult and costly technique involving extensive welding and inspection. The overall length of the assembly is 30 m, which would require several joints to form the entire length. The diameter of the central region is 1.6 m while the lower section is 3.35 m. Welding is recommended only on the outer surface areas. The inner joint conceivably could be joined with a hot isostatic pressed assisted diffusion bonding process, but there is a current size limitation of around 1.5 m diameter and 3 m in length. It is unlikely this will ever be feasible for a 3.5 m monolithic component 30 m in length. Diffusion bonding with axial pressure would not be feasible because of extreme forces needed for the large cross-sectional area. At present, the only conventional fabrication approach that might be feasible, but very costly, would be to change the design to welded, built-up radial layers with integral cooling

passages. The cost to conventionally fabricate this part is well over \$80/kg, thus this 0.851×10^6 kg assembly would likely cost \$70M to \$100M or more. Since this component must be replaced on a two to three year basis, this is a recurring cost item.

The thicker cross-sections of the TF shells (up to 2.5–3.0-m thick) at the top and bottom complicates the fabrication approach. The most likely approach is to cast the TF shells in smaller pieces and then join sectors together by welding. The internal water passages are difficult to reliably join. If aluminum is chosen, separate stainless steel coolant tubes may be necessary for high reliability and long-term operation. There is also a concern about obtaining a reliable bond between the tube and the base metal to assure effective heat transmission across the bond line. The unit cost to fabricate such an aluminum component might well be over \$100/kg. The total weight of the three aluminum shells is 2.69×10^6 kg, which would yield a total cost of \$270M or more. If it were constructed of copper, the cost would be significantly higher.

The conclusion is that a conventional approach is not an attractive and cost-effective way to fabricate these components primarily because of the complexity and difficulty in joining details. Instead alternative, innovative fabrication technologies were investigated.

5. Ultra-low cost fabrication approaches

The use of an improved fabrication process to yield an improved product at perhaps a lower cost depends upon the advent and evolution of new techniques, along with an application that is suitable. In the case of the ARIES-ST toroidal field coils, the components seem to be well suited to two new fabrication techniques that are being developed.

The first fabrication process is laser or plasma arc forming, which melts powdered metals and deposits them where required to form the part. The second process is an in-place spray casting of molten metals. Both will be explained in more detail below. Both of these processes provide the

benefit of being able to adapt to the large size of the ARIES-ST coils. The parts are ‘continually being built up’ rather than joined together from many detailed pieces.

5.1. Laser or plasma arc forming

The laser or plasma arc forming process is derived from the earlier stereolithography processes to construct solid models directly from CAD drawings. In that process, a laser beam scans the surface of a liquid resin to harden a layer of resin onto a substrate just below the liquid surface. The laser illuminates just the areas representative of the first layer of the solid model. Then the substrate is lowered the thickness of the just-constructed layer. The laser then solidifies the next layer and so on until the complete solid model is fabricated. These solid models are useful for prototypes and model construction. This process has now been extended into metals and other more substantial materials for more robust prototypes and limited production components.

The next logical step has been to extend this technology to the fabrication of larger structural parts. The Advanced Research Laboratory at

Penn State [11] in cooperation with John Hopkins University Applied Physics Laboratory [12] and MTS Systems Corporation [13] have developed a laser-based process to fabricate structural components of titanium alloys under DARPA/ORN sponsorship. Under a Cooperative Research and Development Agreement with the Army Research Laboratory, AeroMet Corporation [14], a subsidiary of MTS Systems Corporation, installed a large-scale laser forming system built for ARL by MTS. In 1998, Boeing and Grumman both awarded AeroMet contracts to fabricate parts made from a titanium alloy, Ti–6Al–4V, to be used on aircraft. Fig. 2 from DARPA shows recent progress to obtain material properties, namely fatigue strength. The test results to date lie in the range of the high end of traditional cast and the low end of wrought titanium. It is anticipated that copper could be laser fabricated and exhibit properties slightly less than wrought material.

So why would laser forming be an improvement over conventional techniques? As an example, when aircraft transitioned from wood to metal airframes, the then-traditional fabrication process was to use sheet metal panels and skins with bent up sheet metal angles to form bulkheads and

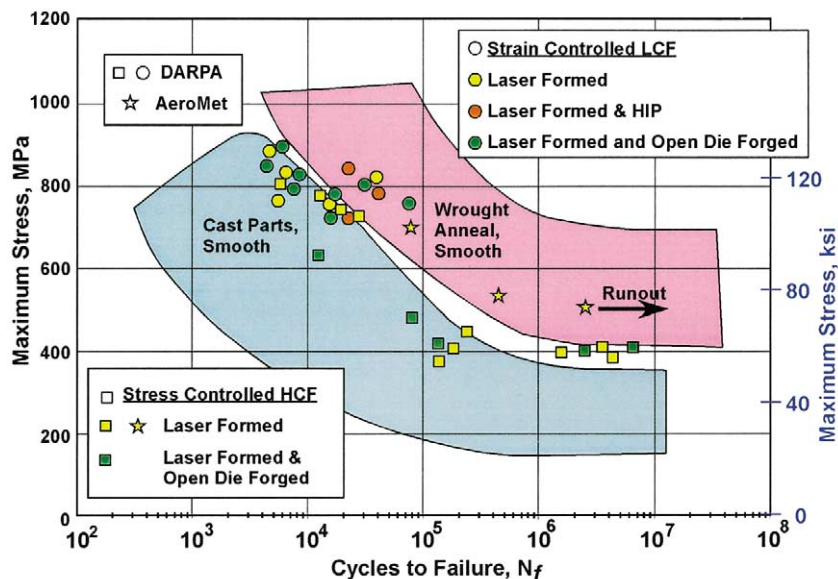


Fig. 2. Fatigue testing results of laser-formed specimens.

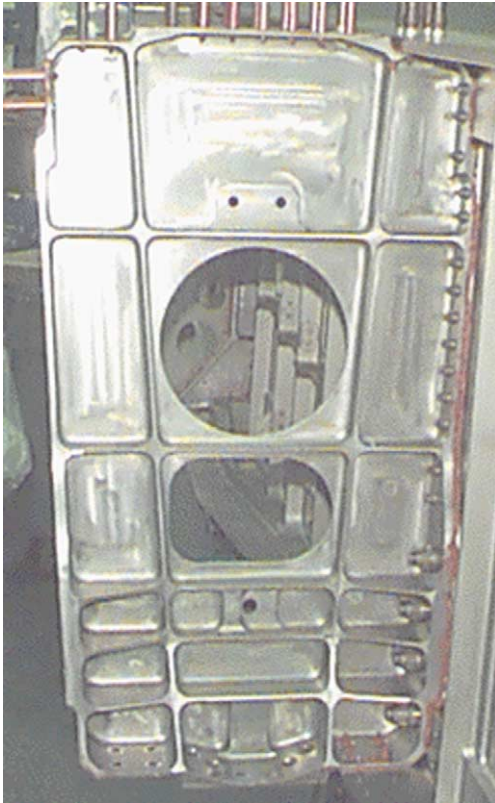


Fig. 3. Typical titanium-machined aircraft part.

stiffened skin panels fastened with rivets. Interchangeability was poor on this process and there was a lot of fixturing and hand fitting (costly). This was the way aircraft were constructed for over 30 years. This process can be characterized by starting with a thin panel and increasing the section thickness for the required strength and stiffness. The next fabrication process to be adopted was the machining of bulkheads and structural members to make them lightweight, even though a majority of the material had to be removed. Fig. 3 shows an aircraft bulkhead machined from Ti-6Al-4V plate, which illustrates the degree of complex machining necessary on some parts. The material costs were higher and certainly the machining time was much increased; but as most machining operations were automated, overall costs were reduced. As the interchangeability of the parts was enhanced, the production costs were lowered. The next evolutionary improvement is high-speed machining of the parts to reduce the time to produce the part.

The laser forming process, shown schematically in Fig. 4, is closer to the original stiffened skin process in that it starts with a thin panel or skin of the required thickness. Then a stream of powdered

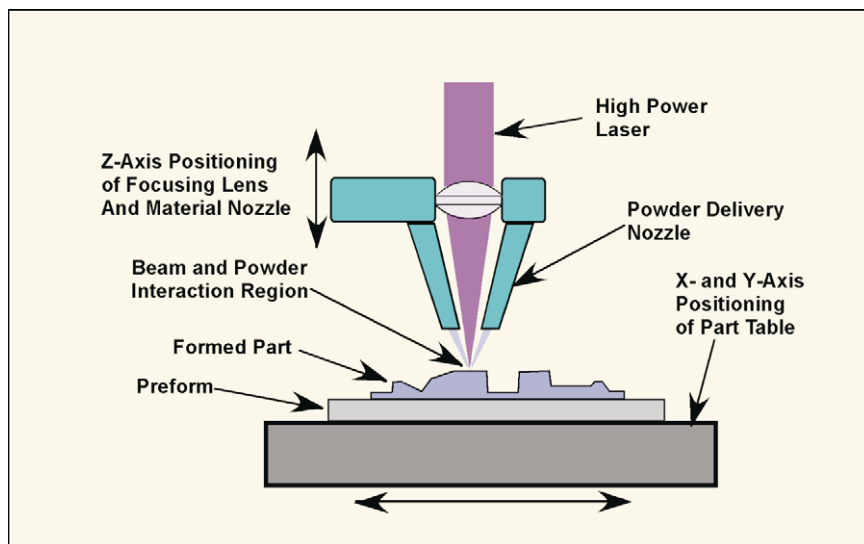


Fig. 4. Schematic of laser forming process.



Fig. 5. Typical laser-formed parts produced by AeroMet.



Fig. 6. An as-formed titanium part illustrating the laser forming condition.

metal is directed toward the part and a laser melts the metal onto the substrate. As in the stereolithography process, the new material is applied only where required to form the 3-D part. The application rate of the material is limited only to the power of the laser and the compatibility with the material. Plasma arc sources seem to be better suited to copper at present. There is little wastage of material. Surface finishes are typically 32–64 $\mu\text{in.}$ and may be as good as 10 $\mu\text{in.}$ But to obtain these finishes, the application rates are reduced.

Fig. 5 illustrates a few typical titanium parts produced by AeroMet Corporation. Some are in as-built condition and others have been lightly machined to final shape. A much larger part is shown in Fig. 6 in the as-formed condition ready for final machining.

The laser forming process is ideally suited to construct the copper centerpost, shown in Fig. 7. It is a rather simple geometry of cylinders and cones with multiple, continuous coolant passages from the top to the bottom of the part. The bulk of the part with the integral coolant passages could easily be fabricated with this highly automated process. An initial blank or preform will be used to start the process at the bottom. It is estimated that 20 kg per hour of material could be deposited by a single forming head. It would be proposed that a set of 10 such laser forming heads would be simultaneously directed to deposit each layer by layer of material. Present experience on stopping and restarting a single laser forming head poses no problems in material properties or composition. The operation of 10 multiple heads should be feasible. If a high surface finish is desired, dedicated laser heads could be assigned for that desired fabrication. At the rate of 200 kg/h and 24-h operation, the 0.85-M kg part could be completed

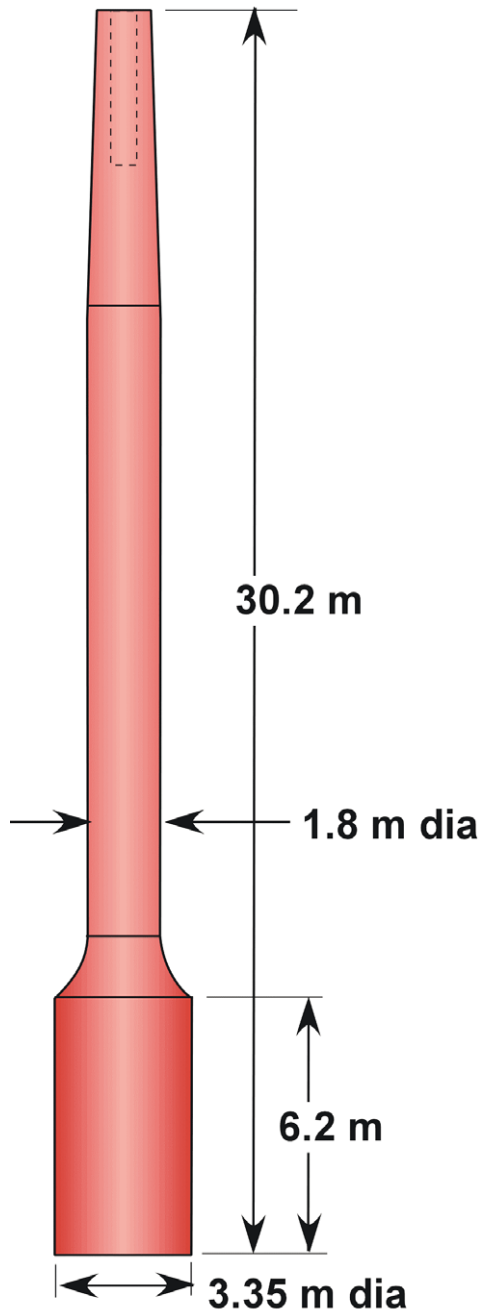


Fig. 7. Centerpost geometry.

in roughly one-half year, assuming no down time for maintenance and refurbishment. Allowing a generous allowance for downtime, the fabrication time would be 8 months or so.

Fig. 8 schematically illustrates how the centerpost would be gradually grown from the initial preform. First, the large 3.35-m diameter cylinder would be constructed with the integral coolant passages. Then the tapered cylinder would be grown with the coolant passages being transitioned to those in the central 1.6-m diameter cylinder. Finally, the top tapered section would be added. Any errors detected during construction could be machined away and new material would be deposited. No water leaks are permitted at the surface of the centerpost. Leakage between coolant passages is not anticipated, but some leakage could be tolerated. Due to the overall size and weight of the part, it is anticipated that the part would be fabricated on the reactor site because shipping such a large component would be very difficult. Since the lifetime of the centerpost is approximately 2 full-power years, the fabrication time is well matched to the component lifetime. Replacement of the centerpost would be accomplished as documented in a maintenance plan in Ref. [4].

5.2. Spray casting

Both aluminum and copper materials were considered for the outer return TF shell. The aluminum was lighter for the same coil resistance (adding additional aluminum material to compensate for its inherent lower conductivity.) It was also more likely to be cheaper to fabricate, thus aluminum was selected as the material of choice for the outer shell.

Conceivably, the outer shell could be constructed with the same laser forming process as mentioned above. But because the weight of a TF shell is more than three times as much as the centerpost, the time and cost to construct would be correspondingly higher. So another fabrication option with a faster time to construct was considered.

Spray casting of a molten metal involves holding the metal just above the melting temperature, atomizing it, and spraying it onto a preform structure. This process is being evaluated as a method to construct large component parts, as would be the case for the TF return coil shell. This

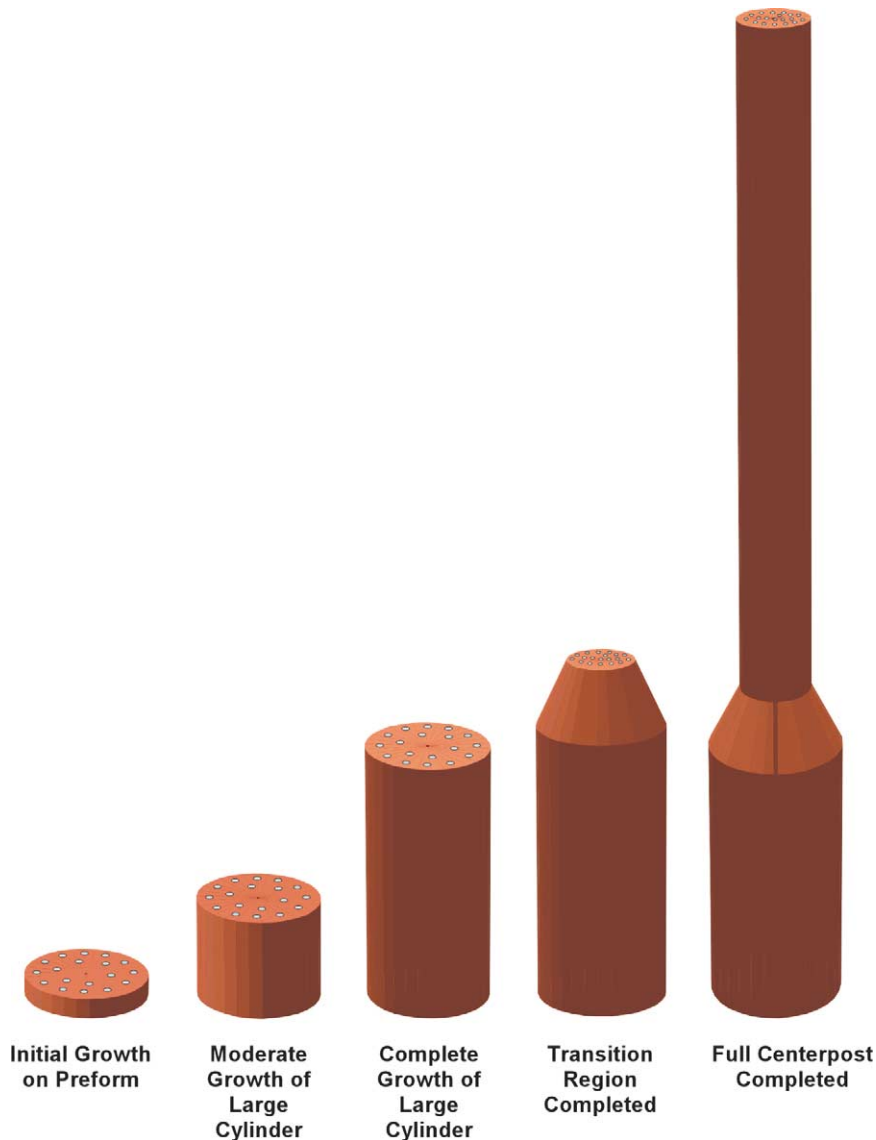


Fig. 8. Growth of centerpost.

process has fast deposition rates, estimated to be up to 0.5 kg/s per head. To fabricate these shells, four heads are used to help speed the process, yielding 7200 kg/h at full production rate. In calculating labor hours required, an efficiency factor of 50% was assumed with an operator and an assistant or inspector (only normal shifts required). This would enable all three shells to be spray cast in less than 6 months.

As a result of the faster deposition rate, the finish detail is reduced. If a smooth finish or precision dimensions are needed, some limited local machining will be required at the electrical connection and support points. On the TF return shells, this final finish will only be required locally at the flanges and joints with the interfacing hardware, such as the busbars and vacuum pumps.

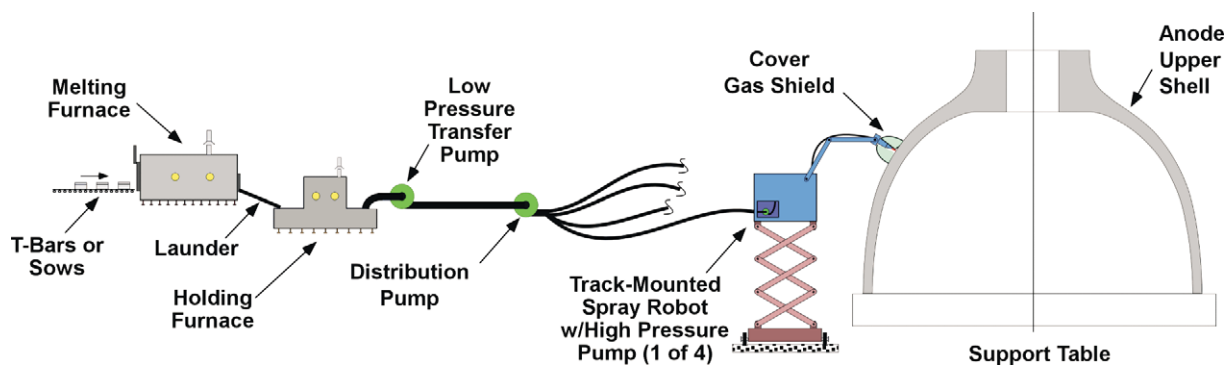


Fig. 9. Overall spray cast process.

This process requires a preform structure to initiate the process. This is a desirable feature for the TF shell since the preform can serve as the power core vacuum vessel. A thin (1/2 in. or 2 cm) shell will be the interior preform structure and also serve as the vacuum vessel. An inspection can verify vacuum integrity before initiating the spray casting process. A separate cost estimate will be conducted for this element because it will be fabricated in a conventional manner. The vacuum vessel will be constructed as a separate component, but after the vacuum inspection is concluded and the spray cast process starts, it will be an intimate part of the TF shell.

The vacuum vessel (and spray cast shell) (Fig. 1) also consists of three parts: upper, middle, and lower. The vacuum vessel will be the most interior portion of the TF shell, with the spray cast aluminum being added to the exterior of the shell. For the present cost estimate, no cutouts or ports are assumed. Individual vacuum vessel segments (for example, 30 orange slices, 15 m $\times$ 2 m for the upper half) will be bump formed into the approximate hemispherical elements and welded to form the upper hemisphere. The flat pattern elements can be arranged to minimize waste. Because of the size of the finished parts, the parts will be welded and inspected on site.

The upper hemisphere would be spray cast in its final orientation and perhaps in its final position in the power core. The final weight of the vacuum vessel and spray cast shell is 1.56×10^6 kg, assuming 85% mass fraction to allow for 15%

coolant. The two lower shell elements will probably be spray cast in an inverted position with trunnions added to assist in handling and inverting the large components. The weights are 0.584×10^6 kg and 0.584×10^6 kg for the middle and lower sections, respectively. A wastage allowance of 5% is allowed for the spray cast process. The aluminum material would have slightly lower material properties than a standard casting process. This property degradation would be compensated in the design analysis process.

It is not advisable for the coolant to be in direct contact with aluminum. Therefore, it is planned to embed stainless steel tubes in the aluminum shell to distribute the water. As the shell is being fabricated, the tubes can be placed in position. The aluminum is spray cast around the tubes, embedding them in the aluminum structure to cool the volumetric heating of the high-energy neutrons.

Fig. 9 schematically illustrates the spray cast process. Large 1000–1200 pound T-bars or sows of the appropriate aluminum alloy (e.g., 5000 series) are loaded into the melting furnace. The aluminum is a high conductivity alloy with low impurity content to minimize transmutation products. The gas-fired melting furnace operates in a batch mode with a capacity in the 100 000-pound class. The melted aluminum is transferred to a holding furnace that precisely controls the liquid metal temperature. A low-pressure pump removes the liquid aluminum from the holding furnace and transfers it to a distribution pump. This distribu-

Table 1
Laser (or plasma arc) formed centerpost cost estimate

Cost elements	Metric units	English units
Mass of centerpost, 85% Cu, 15% H ₂ O (11/98 strawman)	8.51×10^5 kg	1.87×10^6 lb
Mass including 5% wastage	8.94×10^5 kg	1.97×10^6 lb
Deposition rate with 10 laser heads (20 kg/h for each head)	200.00 kg/h	440.00 lb/h
Elapsed time (total mass/rate)	186.18 d	
Setup time	250.00 h	
Build labor time, 1 operator+0.5 assistant	6702.41 h	
Inspection and rework (25%)	1675.60 h	
Total labor hours	8628.02 h	
Fabrication cost @ \$150/h include site premium and overtime	\$1 294 202	
Material unit cost ^a	\$2.86 \$/kg	\$1.30 \$/lb
Material cost	\$2 555 853	
Energy requirement/head @ 20 kg/h (heating and melting)	3.75 kW	
Energy input/head @ 20% conversion efficiency	18.75 kW	
Total energy consumption, 10 heads	932 054 kW h	
Total energy cost @\$0.10/kWh	\$93 205	
Copper powder storage container	\$50 000	
Copper powder transport system	\$25 000	
Assembly fixture and vertical positioning system	\$125 000	
Horizontal positioning system (coarse control)	\$60 000	
Vernier raster system (10+frame)	\$250 000	
Laser forming heads 10 @ \$45 000 ea)+spares	\$500 000	
Power supplies, 200 kW total	\$100 000	
Argon shield	\$24 000	
Argon supply and recovery system	\$20 000	
Computer	\$25 000	
Hardware cost	\$1 179 000	
Subtotal	\$5 122 261	
Contingency (20%)	\$1 024 452	
Prime contractor fee (12%)	\$737 606	
Total	\$6 884 319	
Unit cost	\$8.09 \$/kg	

Assume construction within Reactor Building. See Act 21.02, Reactor Building cost account.

^a \$0.72/lb + \$0.50/lb (alloying/processing) + \$0.08 shipping.

tion pump sends the liquid metal through heated lines to the spray robots with high-pressure pumps for atomizing and spraying the metal onto the preform surface. These robots are probably track-mounted and can access the entire perimeter surface of the shells. A cover gas shield is necessary to minimize addition of atmospheric impurities. This gas shield will probably be a local shield. The cover gas is recovered and recycled in a dedicated system.

6. Detailed cost estimates

The cost estimates contained herein are considered detailed when compared to previous estimates encountered in fusion conceptual designs. But the estimates are not considered detailed when compared to those associated with a construction project. These processes are quite speculative in

Table 2
Vacuum vessel cost estimate

Cost elements	Metric units	English units
Mass of 1/2 in.-thick plates, including wastage	4.18×10^4 kg	9.19×10^4 lb
Material cost, \$5/kg 5052 or 5002 plate	\$208 825	
Bump forming: 90 panels $\times$ 60 h/panel	5400 h	
On-site weld setup, 6 mo $\times$ 6 people $\times$ 160 h/mo	5760 h	
Weld prep, 90 panels $\times$ 2 h/m + setup 10 h/panel $\times$ 90 panels	4776 h	
Segment welding, 900 m $\times$ 0.1312 h/m 25% efficiency	472 h	
Weld inspection, 900 m $\times$ 1 h/m	900 h	
Helium leak check, 900 m $\times$ 0.5 h/m	450 h	
Final cleaning for vacuum service	1500 h	
Total labor hours	19 258 h	
Fabrication cost @ \$120/h include site premium	\$2 310 960	
Subtotal	\$2 519 785	
Contingency (20%)	\$503 957	
Prime contractor fee	\$362 849	
Total	\$3 386 591	
Unit cost of finished mass (39 776 kg)	\$85.14 \$/kg	

Table 3
Sparry cast TF shell cost estimate (W.J. Schafer, Inc.)

Cost elements	Metric units	English units
Mass of three shell components (new CAD weight values)	2.69×10^6 kg	5.92×10^6 lb
Mass including 5% wastage	2.82×10^6 kg	6.21×10^6 lb
Deposition rate per head	0.50 kg/s	1.10 lb/s
Number of spray heads, operational	4	
Deposition rate, 4 heads	2.00 kg/s	4.40 lb/s
Elapsed time (including 50% efficiency and 10% startup)	35.96 d	
Setup time	120.00 h	
Build labor time at 50% efficiency, 1 operator + 1 associate or inspector	1569.17 h	
Inspection and rework	400.00 h	
Total labor hours	2089.17 h	
Fabrication cost @ \$150/h include site premium and overtime	\$313 375	
Material unit cost (\$0.60/lb + \$0.25/lb for alloying and shipping)	\$1.87 /kg	\$0.85 /lb
Material cost, aluminum	\$5 281 815	
Coolant tubes, stainless steel	\$50 000	
Energy cost, natural gas for furnaces (use elapsed time)	800 \$/d	
Energy cost for pumps	240 \$/d	
Energy cost total	\$37 398	
Melting furnace ^{a,b} , 126 000 lb capacity, natural gas	\$550 000	
Installation of melting furnace ^a	\$225 000	
Holding furnace ^{a,b} , 60 000 lb capacity, natural gas	\$140 000	
Installation of holding furnace ^a	\$70 000	
T-bar handling system	\$25 000	
Transfer pumps, 4 @ \$16k each + 1 spare	\$80 000	
Heated transfer piping	\$100 000	
Spray robots ^b , 4 @ \$100k each	\$400 000	
Atomizing heads with high pressure pumps ^b , 4 @ \$100k each	\$400 000	
Spare parts, robots and atomizing heads (10% factor)	\$80 000	
Argon shields, 4	\$24 000	
Argon supply and recovery system	\$20 000	
Robot rail system	\$100 000	
Spray casting computer and installation	\$50 000	
Shell handling fixtures	\$100 000	
Hardware costs	\$2 364 000	
Subtotal	\$8 046 588	
Contingency (20%)	\$1 609 318	
Prime contractor fee	\$1 158 709	

Table 3 (Continued)

Cost elements	Metric units	English units
Total	\$10 814 615	
Unit Cost	\$4.02 /kg	

Assume construction within Reactor Building, See Act 21.02, Reactor Building cost account. Furnaces located in temporary buildings, See Act 91, Construction Services and Equipment cost account.

^a Furnace cost data provided by Dave Nelson, Frank W. Schaefer, Inc. Dayton, OH.

^b Secondary use possible.

that they have only been demonstrated on small components (compared to the scale of the parts referenced herein).

The costs are developed based on a mature design and mature fabrication technology. Both processes are assumed to be highly automated with minimal operator or inspection oversight. The costs are reported in 1998 dollars.

To assure the estimate is conservative, the process hardware costs associated with the laser (or plasma arc) forming and spray casting processes are included as direct capital costs. In the case of the laser (or plasma arc) forming of the centerpost, the process hardware cost might best be included in an operating capital cost since this part is frequently replaced as part of the routine maintenance plan. The process hardware cost for the spray cast TF shell probably should be included as part of the Construction Services and Equipment Account (Account 91) since it is anticipated to be a one-time construction item. The equipment (furnaces and other ancillary equipment) could be rented for the initial construction or leased to a third party after construction has been completed. But for the present estimate, they are both included.

To account for possible material wastage, an allowance of 5% was added to the material quantities purchased. In turn, these increased material quantities were used in the labor estimates. An efficiency factor of 50% was used in the spray cast rates because of the lack of experience on parts of this scale. Allowances for inspection

Table 4
Spary cast TF shell cost estimate (SECO/WARWICK)

Cost elements	Metric units	English units
Mass of three shell components (new CAD weight values)	2.69×10^6 kg	5.92×10^6 lb
Mass including 5% wastage	2.82×10^6 kg	6.21×10^6 lb
Deposition rate per head	0.50 kg/s	1.10 lb/s
Number of spray heads, operational	4	
Deposition rate, 4 heads	2.00 kg/s	4.40 lb/s
Elapsed time (including 50% efficiency and 10% startup)	35.96 d	
Setup time	120.00 h	
Build labor time at 50% efficiency, 1 operator + 1 associate or inspector	1569.17 h	
Inspection and rework	400.00 h	
Total labor hours	2089.17 h	
Fabrication cost C \$150/h include site premium and overtime	\$313 375	
Material unit cost (\$0.60/lb + \$0.25/lb for alloying and shipping)	\$1.87 \$/kg	\$0.85 \$/lb
Material cost, aluminum	\$5 281 815	
Coolant tubes, stainless steel	\$50 000	
Energy cost, natural gas for furnaces (use elapsed time)	800 \$/d	
Energy cost for pumps	240 \$/d	
Energy cost total	\$37 398	
Melting furnace ^{a,b} , 90 000 lb capacity, natural gas	\$750 000	
Installation of melting furnace ^b	\$800 000	
Holding furnaces ^{a,b} , 60 000 lb capacity, natural gas	\$600 000	
Installation of holding furnace	\$500 000	
T-bar handling system	\$25 000	
Transfer pumps, 4 @ \$16k each + 1 spare	\$80 000	
Heated transfer piping	\$100 000	
Spray robots ^b , 4 @ \$100k each	\$400 000	
Atomizing heads with high pressure pumps ^b , 4 @ \$100k each	\$400 000	
Spare parts, robots and atomizing heads (10% factor)	\$80 000	
Argon shields, 4	\$24 000	
Argon supply and recovery system	\$20 000	
Robot rail system	\$100 000	
Spray casting computer and installation	\$50 000	
Shell handling fixtures	\$100 000	
Hardware costs	\$4 029 000	
Subtotal	\$9 711 588	
Contingency (20%)	\$1 942 318	
Prime contractor fee	\$1 398 469	

Table 4 (Continued)

Cost elements	Metric units	English units
Total	\$13 052 375	
Unit Cost	\$4.85 \$/kg	

Assume construction within Reactor Building, See Act 21.02, Reactor Building cost account. Furnaces located in temporary buildings, See Act 91, Construction Services and Equipment cost account.

^a Furnace cost data provided by Al Reinhart, SECO/WARWICK, Meadville, PA.

^b Secondary use possible.

and rework were provided. An overall contingency allowance of 20% was added to the total estimate cost, including material, labor, process energy, and process hardware. A prime contractor fee of 12% was also included.

6.1. Centerpost cost estimate

The cost estimate for the copper centerpost is shown in Table 1. Each cost element is shown along with a brief explanation of the basis for the estimate.

6.2. Vacuum vessel cost estimate

The cost estimate for the conventional construction of the aluminum vacuum vessel is shown in Table 2. Each cost element is shown along with a brief explanation of the basis for the estimate. This estimate is segregated even though it is an integral part of the TF shell.

6.3. TF shell cost estimate

Two cost estimates for the aluminum TF shell are shown in Table 3 and Table 4. Two furnace manufacturers provided cost estimates of melting and holding furnaces. The estimates provided by these vendors are only ROM costs based on their interpretation of the necessary requirements and should not be viewed as comparable bids. Instead, they should be considered likely cost ranges. Each

Table 5
TF coil cost summary

Component	Finished mass (Mkg)	Total cost (M\$)	Unit cost (\$/kg)
Centerpost	0.851	6.88	8.09
Vacuum vessel	0.040	3.39	85.15
TF shell (average cost)	2.690	11.93	4.44 (average)
TF coil system	3.581	22.20	6.20 (average) 5.89 (minimum) 6.51 (maximum)

cost element is shown along with a brief explanation of the basis for the estimate.

6.4. Total toroidal field coil estimate

The costs of the TF coil system shown in Table 5 are very attractive when compared to those associated with more conventional fabrication techniques. Constructing the vacuum vessel using conventional techniques results in a fabrication cost of \$85/kg. If the centerpost and the TF shell are also fabricated by conventional means, the cost will be approximately ten times higher than shown in Table 5.

7. Summary

The innovative fabrication techniques of laser forming and spray casting offer an ultra-low-cost approach for the centerpost and TF coil shell. Sometimes this is referred to as ‘additive’ machining, which captures the sense that material is added only where necessary. These parts are very well suited to these techniques in that they are simple continuous structures, have moderate stresses, and have distributed internal cooling passages. Toroidal field coils of spherical torus reactors are not the only structures that might utilize these technologies. Due to the significant cost and time advantages that these ultra-low-cost processes offer, it is recommended that these technologies be developed and applied to these and other structures.

References

- [1] (a) F. Najmabadi, R.W. Conn, et al., ‘The ARIES-I tokamak fusion reactor study—The final report,’ UCLA report UCLA-PPG-1323 (1991).; (b) R.W. Conn, F. Najmabadi, et al., ‘ARIES-I: A steady-state, first-stability tokamak reactor with enhanced safety and environmental features,’ Proceeding of the Thirteenth Conference on Plasma Physics and Controlled Nuclear Fusion Research, Washington, DC (October 1990), International Atomic Energy agency, Vienna (1991) 659.
- [2] C.G. Bathke, Systems analysis in support of the selection of the ARIES-RS design point, *Fusion Eng. Des.* 38 (1997) 59.
- [3] C. Baker et al., ‘Starfire—A commercial tokamak fusion power plant study,’ Argonne National Laboratory Report ANL-FPP-80-1 (1980).
- [4] F. Najmabadi and the ARIES Team, ‘Overview of ARIES-ST spherical torus power plant study,’ *Fusion Eng. Des.*, in press.
- [5] S. Jardin, ‘Physics basis for spherical torus power plants,’ *Fusion Eng. Design*, in press.
- [6] M.S. Tillack, X.R. Wang, J. Pulsifer, ‘Fusion power core engineering for the ARIES-ST power plant,’ *Fusion Eng. Des.*, in press.
- [7] L. El-Guebaly, the ARIES Team, ‘ARIES-ST nuclear analysis and shield design,’ *Fusion Eng. Design*, in press.
- [8] H.Y. Khater, E.A. Mogahed, I.N. Sviatoslavsky, et al., the ARIES Team, ‘ARIES-ST safety and design analysis,’ *Fusion Eng. Des.*, in press.
- [9] W. Reiersen, et al., ‘The Toroidal-Field Coil Design for ARIES-ST,’ *Fusion Eng. Design*, in press.
- [10] L. Bromberg, ‘Superconducting poloidal field magnet engineering for ARIES-ST,’ *Fusion Eng. Des.*, in press.
- [11] ‘Advanced Research Laboratory at Penn State Home Page’ at <http://www.arl.psu.edu/core/laser/freeform.html>.
- [12] ‘John Hopkins University Applied Physics Laboratory Home Page’ at <http://www.jhuapl.edu/>.
- [13] ‘MTS Systems Corporation Home Page’ at <http://www.mts.com/>.
- [14] ‘AeroMet Home Page’ at <http://www.aerometcorp.com/>.