ILC CAVITY FABRICATION OPTIMIZATION FOR HIGH PRODUCTION *

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Abstract

In 2006, Advanced Energy Systems, Inc. (AES) performed a US based industrial Cost Study of RF units in production quantities sufficient for the International Linear Collider (ILC) [1]. We found that the cost of the SRF cavities was a significant driver at about 16% of the total cryomodule cost. In late 2007, AES carried out a more detailed study specifically oriented toward optimizing the high production methods of only the SRF cavities. We have optimized many of the machining and welding steps to take advantage of automated operations where possible. Our high production cost estimates were derived from actual machining, welding and parts handling times. These values were then applied with learning as appropriate to more automated operations to reduce labor costs. We found that in an ideal Factory setup dedicated to ILC production, the cost per SRF cavity might approach $14K. In addition, the type and size of e-beam welding machines was optimized. We found that the use of all single chamber welders covering three specific sizes was most cost effective. Details of steps leading to the stated conclusions are presented herein.

SUMMARY

Cost results presented herein are from a study based upon an ideal Virtual Factory dedicated to ILC high production. This data is in no way representative of current production costs at AES or any other company.

We find that for a production quantity of 6000 cavities the total estimated touch labor can be as low as 528K hours. We have high confidence in being able to achieve this value with a dedicated factory due to the amount of detail in the baseline data. Included are touch labor time values and measured machining times, welding sequences with measured times for each step, the inclusion of a worker productivity factor, a more accurate estimate of expendables use and the inclusion of machine operational maintenance factors.

In addition to the direct touch labor as stated, we add 180K hours for unattended operations that include automated machining and welding system stand-by time during parts cool down. Although it is well known that cost reductions can be obtained by means of automating certain processes, availability of the actual cost parameters is not readily available from subcontract shops. We have therefore taken an analytical approach to derive the estimated cost for automated (unattended) machining. We remove the direct labor and fringe costs associated with the worker in our Virtual Factory and leave the burdens for operation. This value is about 48% of the full rate. Further cost reduction may be realized because we do not require the same support and management labor for an automated or unattended process. The result used in our study is that an automated operation costs about 28% of an equivalent manned operation.

Based upon projects similar in nature and duration to the cavity production for ILC we also apply the addition of support labor and management labor taken at 40% and 12% respectively of the touch labor estimate. The results of this study are summarized in Table-1 showing a possible unit cost of around $14K per cavity using assumed burdened labor rates for the various labor categories in a dedicated Virtual Factory.

Table 1: Possible Cost per Cavity in a Virtual Factory

Cost Category	Hours	Assumed Rates ($/hr)	Cost ($)
Touch	88	80	7,040
Unattended	30	40	1,200
Support	35	100	3,500
Management	11	170	1,870
Expendables & Maintenance			425
TOTALS	**164**		**14,035**

NOTE: Excludes cost of subcontracting and shipping

When we expand the production quantity to 18000 units, the cost per cavity is only slightly changed to $13.7K since essentially all of the learning and production optimization has been achieved earlier in the run. Therefore having three sources for production as currently planned for ILC is a good choice from the reliability and scheduling point of view with little effect upon cost. In terms of the distribution of costs into the various key processes, the results of the study are shown in Table-2.

Table 2: Cost Distribution by Process

Process Category	Percent
Machining	59
Buffered Chemical Polishing	8
Electron Beam Welding	21
Radio Frequency Tuning	5
Special Inspections	1
Hydroforming Half Cells	3
Expendables & Maintenance	3

In reference 1 we proposed using all single chamber welders. In this more recent study, we quantified the differences between the two types of EBW approaches with more detail including initial capital cost and cost to operate. It was determined that for a production quantity

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of 6000 cavities the capital cost without any burdens was \$10.6M using the single chamber approach compared to \$12.6M using the dual chamber approach. The operating cost for the single chamber approach is roughly 27% less than for the dual chamber approach primarily because of the lower number of vacuum pumping systems. Further consideration must be given to the fact that dual chamber welders are less reliable than single chamber machines because of their inherent complexity and a single machine failure will result in a larger reduction in production capacity for that type of architecture.

FABRICATION ANALYSIS

Each and every fabrication step was examined with a goal toward reducing cost in a high production environment. We started with shop work orders used for production of prototype cavities at AES to define all of the necessary steps. For each fabrication step we utilized tested and measured CNC machining and/or welding times along with measured touch labor times for handling and manual operations to develop baseline data. The baseline data was modified with learning for high production and/or automated machining as applicable. Our approach permitted learning factors to be applied to all repetitive manual operations thereby reducing labor hours per part in a high production environment. In contrast, machining and welding times are governed by cutting speeds and weld rates for niobium and Nb55Ti alloys and are fixed regardless of production quantity. In some cases we improved the overall efficiency of these steps by utilizing alternate machining techniques that require less manned attendance and/or by multiple parts processing (batch mode) facilitated by proper tooling.

To enable the systematic analysis of all of the various manufacturing steps a spreadsheet model was established. Key equations to the spreadsheet are described with inputs as defined in Table-3.

Table 3: Definition of Inputs for Each Step to Production Analysis Spreadsheet

$T_{i/o}$	Measured in & out touch time for the 1st cycle
N_{pt}	Total number of parts to be produced
N_{cycle}	Number of parts handled per cycle
$\mathbf{N_w}$	Number of workers per day
$\mathbf{N_{mach}}$	Number of machines
f	Learning factor (taken as 0.90 herein)
N_{pday}	Required peak production rate (parts/day)
T_{sp}	Machine spindle time/cycle
J	Machine labor factor – percentage of manned time for the operation
$T_{nr/m}$	Non-recurring time per machine – setup & programming
S	Yield, taken as 0.95 from experience
T	Productivity taken as 0.90 typically

The model begins with the determination of average in and out touch time for each fabrication step for the production run with learning applied to our baseline data as follows:

$$T_{i/o\ avg} = T_{i/o} \times [N_{pt} /(N_{cycle} \times N_w)]^{\log(f)/\log(2)}$$

where the initial value of N_w is assumed. We then calculate the machining labor time per cycle as:

$$T_{mach} = J \times T_{sp}$$

The number of required cycles/day is then determined and rounded to the next full number by:

$$L = N_{pday}/ N_{cycle}$$

This is followed by determination of the total non-recurring time as:

$$T_{nr} = N_{mach} \times T_{nr/m}$$

where the value of N_{mach} is initially assumed and then iterated in the spreadsheet. Total machine run time per day is then determined by:

$$T_{mach} = T_{sp} \times L / S$$

Next total recurring labor per day for each operation is determined by:

$$T_{rec} = (T_{i/o\ avg} + T_{mach}) \times L / S$$

Based upon 14 hours of actual run time (2 shifts) per day for each machine, considering startup and shutdown, the number of machines required to achieve the production rate is found with the following relationship

$$N_{mach} = T_{mach} / 14$$

and then iterated and rounded up. The number of workers per day to run the machine is defined by

$$N_w = T_{rec} / 8$$

and rounded up. Finally the total labor is found by:

$$T_{tl} = \{T_{nr}+ [N_{pt}/N_{cycle} \times (T_{mach}+T_{i/o\ avg})/S]\} / T$$

In addition we determine the total unattended machining time by:

$$T_{tl\ unattended} = L \times T_{sp} - T_{tl}$$

provided $T_{tl\ unattended}$ is not less than zero.

Estimated costs for the various operations are then simply determined by multiplying the hours for each category of the step by the applicable rate for The Factory that is utilized. A simple summation is conducted at the end of the spreadsheet. Costs for tool bit replacement and machine general maintenance were parametrically calculated based upon machine run times from the spreadsheet. The amount of BCP acid was determined from component processing experience at AES and costed by supplier quotes of bulk mixed product.

ELECTRON BEAM WELDER TRADE

We optimized the size of the welding machines for the individual types of welding configurations and put them into size categories that bracket numerous welding cycle types. To accomplish this task we looked at the various types of tools that are currently being used by AES for fabrication of ILC cavities. We also considered how these tools might be modified for high production. In each case we determined the number of parts that could be handled during each welding step for a given size machine to minimize the number of pump downs and subsequent cool downs. The following ground rules were applied:

- Either single or double chamber welding machines are used throughout the production cycle
- Operator at 100% attendance except during the cool down
- Welding employs semi-universal tools that can handle multiple subassemblies for a given weld cycle
- Each set of parts has a unique set of holding attachments that are compatible with the tool
- Learning of 90% is applied to all touch labor steps

Three (3) sizes of welders were identified. The smallest having inside weld chamber dimensions of 30W X 30H x 24L inches, the next is 36W X 36H X 50L and the largest is 60W X 24H X 120L. The smallest machine handles egg crate type tooling and is used for making small part horizontal welds. The medium sized machine handles the bulk of the welding and utilizes one 10 position Ferris wheel type tool. The largest machine is for the final assembly welding of multiple quad dumbbell sections and end-groups into the cavity assembly, holding two (2) complete assemblies for a given pump down cycle.

The medium sized welding machine handles a single Ferris wheel tool. The wheel indexes the axes of the sub-assemblies to be welded while unique part holders for each type weld can be rotated 360 degrees as well providing for complete circumferential welding. Another tool provides only axial rotation for making equator welds for final cavity assembly. The large welding machine is configured to accommodate two (2) of these tools for a given pump down cycle. Simple egg crate type tooling is used to hold all of the parts that can be welded using only X and Y movement by means of the welding machine internal table.

Budgetary equipment costs and estimated welding chamber pump out times to 3 X 10^{-5} torr as provided by PTR Technologies are shown in Table-4.

Table 4: Welding Machine Budgetary Costs

	Single Chamber ($K)	Dual Chamber ($K)	Pump Out (min)
Small	600	1050	10
Medium	650	1130	20
Large	825	1450	35

These systems will all have vapor shields in the chamber that can be replaced within an hour. Pump down times are dramatically affected by chamber cleanliness thus the need for shield refurbishment.

Other issues with dual chamber welders that have not yet been accounted for in our cost trade are as follows:

- Maintenance cost of the large gate doors and long lead replacement if damaged
- Motor assemblies in chamber will need to be located in the table base (connecting/disconnecting electrical connections in the vacuum chamber would be difficult)
- Any down time would have a greater effect upon interrupting production
- Extra over all maintenance

To arrive at machine utilization requirements individual weld cycle times were derived using actual weld parameters from AES historical data on ILC cavity welds. When studying the differences between single and dual chamber welding machines with regard to cycle times we assumed all steps were identical except for the cool down cycle time. For single chamber welders this was kept at 60 minutes based upon actual experience while for dual chamber welders this time became only 5 minutes to allow for transfer of the welded items into the second vacuum chamber for cool down. The results of our study are summarized in Table-5.

Table 5: Summary of Welder Trade-off Study

	Single	Dual
No. of Small Welders	3	2
No. of Medium Welders	11	8
No. of Large Welders	2	1
Total Capital Cost ($M)	10.6	12.59
No. of Pumped Chambers	16	22
Diff. in Oper. Cost	1	1.38
Diff. in Touch Labor	1	1.016

The single chamber approach is still recommended for the ILC cavity production requirements based upon capital equipment and operating costs as well as availability/reliability of the production line.

ACKNOWLEDGEMENT

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REFERENCES

[1] J. Sredniawski, “Cost Study for Production of ILC Type RF Units”, Fermi National Accelerator Laboratory, Purchase Order #569640, March 6, 2007.