ME 217A - Design for Manufacturability
Project Report

SLAC-B Team
(NLC Waveguides)

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1. Executive Summary

The Stanford Linear Accelerator Center (SLAC) is a national basic research laboratory, probing the structure of matter at the atomic scale with x-rays and, at much smaller scales, with electron and positron beams. The laboratory is operated by Stanford University under contract from the United States Department of Energy (DOE).

Having pioneered the technology of linear colliders and accelerators, the Stanford Linear Accelerator Center (SLAC), in collaboration with other laboratories, is planning a powerful new instrument (the Next-Linear Collider, or NLC) that will provide a frontier facility for basic research on elementary particles. Stretching some 30 kilometers, it will smash electrons into their antimatier counterparts, creating exotic new particles from pure energy. The NLC has not yet been approved for funding by the Department of Energy.

A component of the NLC, called the RF (Radio Frequency) DLDS (Delay Line Distribution System) Waveguide System, will consist of 176 kilometers of precise, high purity evacuated tubing to carry microwave power from the power sources (called Klystrons) to the accelerator structure. SLAC has successfully constructed a test section of a DLDS Waveguide System at a facility called the NLCTA (Next Linear Collider Test Accelerator). However, the full-scale NLC Waveguide will need 500 times more tubing than the NLCTA Waveguide. A more economical design, construction, and installation process needs to be defined for the large-scale production of the NLC Waveguide. The purpose of this report is to provide the Product Definition for this NLC Waveguide Assembly, and to document the factors that went into the product definition.

We have applied a number of Design for Manufacturability tools, including benchmarking, the Value Graph, Functional Analysis, QFD Phases I and II, Cost Worth Analysis, Fishbone Assembly Sequence, DFA (Design for Assembly) Calculations, FMEA (Failure Modes and Effects Analysis) and SMA (Service Modes Analysis). We then used these tools to create the Product Definition.

The Product Definition details the required customer specifications for the Waveguide tube material, tube geometry/tolerances, and tube cleanliness. These constraints are governed by strict requirements for effective transfer of microwave power through the Waveguide system. They came from the primary customers of the NLC (Physicists, Engineers, and Technicians at SLAC).

Alternatives in tube fabrication, tube joining design and process, tube cleaning process, tube installation, and tube section length are then discussed. Ultimately, we will recommend an optimal combination of these parameters, but that is beyond the scope of this report. A follow-up report detailing the optimum design will be published in several months.
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3. Background

3.1 Profile/Products

SLAC (The Stanford Linear Accelerator Center) is a research laboratory that is operated by Stanford University. It gets its funding from the DOE (Department of Energy). Founded in 1962, SLAC began operation four years later upon completion of the Linac (Linear Accelerator). At SLAC, the structure of matter is studied by 1,600 visiting physicists and scientists each year.

A staff of over 1,200 people operates the Center’s major experimental facilities. These facilities include:

• The Linac, a two mile long electron accelerator.
• The Final Focus Test Beam, a facility researching future accelerator design.
• PEP II, An Asymmetric B-Factory.
• SSRL (Stanford Synchrotron Radiation Laboratory)
• NLCTA (Next Linear Collider Test Accelerator)

In addition to these test facilities, SLAC is involved in a number of research projects, including the NLC (Next Linear Collider). The NLC will be ten times longer and more powerful than the SLC. SLAC has created the NLCTA in order to test the key operating characteristics of the main Linac, this Linac will make up 60% of the future NLC’s length.

3.2 Market/Competition

SLAC’s business is to provide a research facility to both academic and industrial researchers from around the world. Competition comes from other similar laboratories like the Fermi National Accelerator Laboratory and the Brookhaven National Laboratory. Such labs compete for prestige and limited funds for scientific research from the Federal Government and the DOE.
Currently there is an initiative to design the best configuration for the NLC. Many Universities and Laboratories/Institutions are working to create optimized designs that can meet the energy requirements of this NLC. Thus there is informal competition for funding between these factions.

This is not competition in the conventional sense, as there is also collaboration between the facilities, including sharing of ideas and information. For example, in the design of the NLC, the Stanford research group has collaborators in Europe and Japan (KEK). Differing opinions with respect to project priorities and final construction location create a healthy competition for decision-making power and technology. However, the value of the collaboration to pool resources outweighs the costs of internal competition.

3.3 Requirements/Constraints

The technology currently exists to build an NLC that meets the power requirements. However, there are opportunities to reduce the cost of the current designs. Thus the features/functionality of the design are constrained, and cost must be optimized.

Approval for the NLC project depends on acceptance by the DOE, followed by passing of its budget in congress. SLAC’s current design greatly exceeds the DOE’s entire annual budget for ALL high-energy physics projects combined. The current Waveguide design represents about 2% of the total cost of the SLAC NLC design. However, design for manufacturability in the Waveguide system will help move the NLC project closer to an acceptable total cost.
4. Problem Statement

The proposed Waveguide consists of a delay line system made up of 176 kilometers of 4.75 inch diameter high purity tubing. The application of Design for Manufacturability will enable a better understanding of cost drivers and cost reduction opportunities. Potential opportunities exist in the selection of tube material, tube geometry/tolerances, tube fabrication, tube joining design and process, tube cleaning process, and tube section length. All of these constraints, except tube length, are governed by strict requirements for effective transfer of microwave power through the Waveguide system.

The material constraints are:

- Electrical Conductivity (to minimize power loss)
- Diffusion rate of Hydrogen (to minimize vacuum contamination)
- Manufacturability (ease of fabrication)
- Oxidation Rate (affects time to evacuate)
- Cost (minimize)
- Strength

Materials under consideration include Copper, Aluminum, or an alloy of these.

The geometric constraints are:

- Circularity
- Straightness
- Surface Finish
- Concentricity

The physicists have provided the geometric constraints that limit tube fabrication options, in that the required tolerances can only be met with certain processes. The processes currently under consideration include extruding and roll forming.

The tube joints need to perform the following functions:

- Provide an ultra-high vacuum seal
- Provide tube-to-tube alignment
- Provide structural integrity
• Allow microwaves to pass without losses (creates certain internal geometric constraints)
• Prevent “Virtual Leak” where gas molecules are trapped in non-sealed metal-to-metal chambers
• Maintain internal cleanliness

Joint methods under consideration include Conflat flanges (bolted joints currently used in the NLCTA), brazing, and e-beam welding. The current DLDS waveguide design for the NLC call for over 42,000 joints, so decreasing the cost of the joint could have a significant impact on the total system cost.

The Waveguide system demands that the tubing be extremely clean. There are a number of critical cleaning steps needed in order to meet the functionality requirements. There may be opportunities for cost reduction in the cleaning process.

The wall thickness of the Waveguide tubing also needs to be determined. It was arbitrarily set at .125” for the NLCTA. The main factors driving the decision on wall thickness is the cost of the raw material versus the robustness of the tubing.

The last design consideration is the length of tubing sections used. This parameter is related to a number of the other design factors, including joint design, tube fabrication process, cleaning process, and ease of installation. The joint design may enable shorter tube sections, but this increases the number of joints. Conversely, a longer tube section reduces the number of joints, but may add shipping, handling, and installation complexity. One possibility is to manufacture very long tube sections on-site and eliminate shipping concerns. The capability of the chosen manufacturing method to produce the desired length of tubing is also a design factor. The selected length of tubing sections also affects the size of the cleaning tanks required, in addition to the method of assembly and installation.

The Waveguide project challenge is to meet all of the above requirements, while minimizing cost and considering other factors such as design for variety, serviceability, and recycling.
5. Analysis and Discussion

5.1 Benchmarking

The purpose of benchmarking is to develop a set of parameters to evaluate the performance of other products that attempt to fill the same need in a similar way. Benchmarking for the NLC’s Waveguide is somewhat different than benchmarking for consumer goods products, in that no other “NLC” currently exists. However, there are benchmarking opportunities.

First, internal benchmarking was conducted against previously constructed accelerators like the NLCTA and the SLC. Also, other facilities that use extensive amounts of tubing, such as the Trans-Alaskan pipeline, were examined. Finally, since it may be cost-effective to manufacture tubing on-site, other tubing manufacturers and methods were considered as competitors in benchmarking.

The first category of benchmarking includes previously constructed accelerators, such as the SLC and the NLCTA. The SLC is the existing 2-mile long linear accelerator near Stanford campus. An archival documentary video, that was made in the 60’s, of the fabrication and assembly process used for the SLC’s accelerator structure revealed the techniques of copper tube joining, cleaning, and installation. This revealed a brazing process that may prove to be cost effective over Conflat flanges. The cleaning process, while very thorough, appeared somewhat cumbersome and inefficient; there may be room for improvement. The second accelerator that was benchmarked was the NLCTA (a working prototype of a cross-section of the NLC, also at the SLAC facility), which is the first accelerator to actually use Waveguide delay line technology. In this facility, high purity extruded copper tubes were used, with section lengths of five meters. These tubes were shipped from Japan. Conflat flanges were used to make the joints.

The second benchmarking category includes structures that use large lengths of tubing. One
project that involved construction and assembly of extensive amounts of tubing is the Trans-Alaskan Pipeline. One of the world's greatest civil engineering projects, the construction of this pipeline carries petroleum 1,285 km from northern Alaska to the ice-free port of Valdez. Though the pipeline’s geometric shape is not nearly as crucial for the functionality of the system as with the Waveguide, the Trans-Alaskan Pipeline provides a good comparison of producing, shipping, and joining tubing of an extremely large quantity. The main design constraint faced by the Trans-Alaskan Pipeline engineers that was applicable was the tube section lengths. They chose 40 ft. (12.2 meter) long sections, largely due to shipping considerations (i.e. a tractor-trailer’s maximum shipping length is approximately 40 ft. without taking special measures.) If other design considerations call for as much as forty-foot length tubing, the Alaskan pipeline has proven that shipping tubing of this length is feasible. However, sections longer than that may become a shipping issue.

The last benchmarking activity involves comparing different tube fabrication processes. The chosen process must meet all of the dimensional and material requirements, and the feasibility of on site production must also be considered. Tube fabrication processes that were benchmarked include extrusion forming, roll forming (with mandrel pull post-roll), and centrifugal casting with grinding. End configurations were machined or formed as well. The benchmarking practice revealed that centrifugal casting is unable to meet length and internal finish requirements, and hydroforming lends itself more to formation of complex shapes of smaller size that the tubing in question here. Further research of extrusion forming and roll forming will be conducted to determine the best process solution.

These benchmarking activities led us to a baseline design configuration essentially matching that of the NLCTA. This baseline design will be used as assumptions for the remainder of this document. This decision was made based on the fact that the NLCTA is a functional prototype of the NLC, and also represents the most mature working design configuration to date. The assumptions include:

- Tube Geometry and Material Selection (per NLCTA Print Specifications)
• Tube Manufacturing Process (Extruded & redrawn)
• Tube Joining Method (Conflat Flanges)
• Tube Segment Lengths and Location (Off-site, 5 meter lengths)

The only assumption made that was not based on the NLCTA was the tube cleaning method. The baseline cleaning process that was chosen matches that of the SLC process, since the SLC represented a higher volume production environment than the NLCTA. The NLCTA used a cleaning process matching that of Klystron manufacturing, which is most likely overkill for this application.

5.2 Customer Requirement Definition

This section details the benefits of the tools used to help define the customer requirements.

5.2.1 Value Graph

The main benefit of constructing the Value Graph for the Waveguide (See Attachment #1) is derived from the activity itself. Although the ‘why?’ portion was fairly well defined before the use of the tool, the ‘how?’ portion revealed some interesting insights. It helped organize the customer requirements and relate system components and engineering measurements to those requirements. In addition, it created a platform to work from in generating the Function-Structure Map and QFD Phase I.

5.2.2 Functional Analysis

The Function-Structure Map (See Attachment #2), like the Value Graph, seemed to add most of its value through the activity of creating it. In addition to preparing team members for effectively carrying out QFD analysis, it allowed for clearly visualized relationships between the system functions and the structure.

5.2.3 QFD (Phase I)

The Quality Function Deployment of the NLC Waveguide relates the customer requirements
(derived from interviews with various personnel at the SLC) to the engineering metrics, which are designed to quantitatively measure the requirements. From the QFD [See Attachment #3], we observed that ‘joint vacuum limit’ (a measure of the maximum vacuum that a particular joint design will handle) has the highest relative weight. This metric rose to the top of the list because it affects a great number of the customer requirements. The unique nature of the Waveguide assembly did not lend itself to a comparison to other projects, so this portion of the QFD was not performed.

5.2.4 QFD (Phase II)
In the second phase of the Quality Function Deployment [See Attachment #4], the main components of the Waveguide (the tube and the joint) were broken down further in an attempt to determine with greater resolution where the real customer value lies. The parts were then compared with the engineering metrics and relative weights derived from phase I. The results of this analysis shows that the tubes hold 44% of the relative weight of the design, while the other four parts make up the remaining 56% in approximately equal portions.

5.3 Cost-Worth Analysis
The Cost-Worth Analysis was completed by breaking the price of each Waveguide component down to a cost/meter [See Attachment #5]. Because the Conflat flange joint has an inherent assembly cost, and a different type of flange would have a different assembly cost, we rolled the labor cost of joint assembly into the associated component costs. In order to maintain the consistency of the cost vs. worth results, the assembly costs of the tubing are also included. A table summarizing the source of these costs and the associated assumptions can be seen in Attachment #5a. Our analysis revealed cost/worth ratios for the various components. Each component was then plotted to show the relationship between its cost and worth. These results indicated, somewhat surprisingly, that the tubing is the primary candidate for cost reduction with a cost/worth of 1.61. The stainless-steel portion of the conflat flange follows as a close second with a cost/worth of 1.46. However, the combined cost/worth of all the joint components yields a cost/worth ratio of 0.54. While these results indicate that the joint as a whole is a
candidate for enhancement, it is unlikely that this step will be taken. The conflat flange is already extremely robust, and the entire system is above target costs.

### 5.4 Assembly Process Definition

This section details the results of the tools used to help define the assembly process and related issues.

#### 5.4.1 Fishbone Assembly Sequence

The Fishbone Diagram [See Attachment #6] reveals the serial nature of the process that needs to be applied in order to build the Waveguide system. There are, in effect, no sub-assemblies. Based on the NLCTA, we made the assumptions that the tubing is received without machined ends. Conflat flanges are used to join the tubes, and the tubes are purchased. The cleaning process was assumed to match that of the accelerator structure for the original 2 mile SLAC linear accelerator. A large number of steps are required in preparing/cleaning the tubing; it was assumed that each one requires a fixture, although there may be an opportunity to share a common fixture, depending on the layout of the cleaning facilities. Other steps include machining the tube ends to accept the Conflats, and welding and brazing the Conflat flanges to the ends of the tubing before cleaning. After cleaning, the tube sections are transported to the site, and finally the sections are joined via Conflat flanges using 20 nuts and bolts and a copper gasket.

#### 5.4.2 DFA Calculations

While DFA calculations were performed with the assumptions listed previously [See Attachment #7], this tool did not add substantial value to the project. The DFA tool normally applies to high-volume, labor-intensive products, which does not describe the Waveguide. However, the tool did allow for documentation of assembly times and cycle times for the steps involved in building the Waveguide.

### 5.5 Failure Modes and Effects Analysis
5.5.1 Function-based FMEA- See Attachment #8

5.5.2 VOC-based FMEA- See Attachment #9

5.5.3 Pareto Chart- See Attachment #10

The Pareto Chart was created by plotting the RPN vs. the cause of the failure. The Pareto chart revealed that the top 4 causes (which were 11% of the total causes) resulted in 39% of the cumulative RPN values. Because the FMEAs were created with rough estimates (i.e. values of 1, 3, or 9), the cumulative values show linear trends over various regions. If more information were available to create a more detailed FMEA, a stronger trend might appear in the cumulative values. Of the top 4 causes that were identified, 3 of them were associated with being able to join the tube in a manner that ensures that the Waveguide remains straight, concentric, and smooth. This indicates that the joining process will be key to having a quality end result.

5.6 Service Considerations

This section details the results of the tools used to define service-related issues.

5.6.1 Service Mode Analysis

The FMEA indicated that the top 3 potential failures involve the joining of the tubes and contamination in the tubes. These failures can lead to three different service modes: patching leaks at joints, replacing tubes, and replacing joints.

The FMEA indicates that joints which don’t meet specification to be the greatest risk. A variety of geometric issues could lead to this RPN of 81, our highest value. Any of these issues could then result in a leak at a joint, which may require repair or patching. It is important to note that patching would only occur in a desperate situation, where timing was critical, because a patch could lead to many other issues that will be explored in the spring term.
Contamination of the system due to solid particles also received a very high RPN in the FMEA. An unclean manufacturing or installation process, in combination with an inadequate cleaning process could create this kind of contamination. The root of the high RPN lies in the issue’s high severity and occurrence. Dirty manufacturing processes are common for tubing and SLAC’s experience indicates difficulty in cleaning processes and maintaining component cleanliness before and during installation. Severity for such a contamination problem would be high because contamination can cause dielectric breakdown (arcing) that will damage the system. This damage could result in needing to replace an entire section of tubing.

5.6.2 Serviceability Analysis Worksheet

A serviceability analysis worksheet was created [See Attachment #11] to analyze the costs that the NLC could expect to see from each of the major types of required service. The typical format of the worksheet was altered to deliver this result instead of an expected total life-cycle cost. Because the likelihood of the failures being considered are not yet understood, it seemed more appropriate to write the serviceability requirements as an expected cost to the NLC per failure.

The serviceability analysis worksheet reveals that the expected service costs for leak patching, joint replacement, and pipe replacement are $7262.50, $7853.33, and $7887.07, respectively. Allowing the system to cool and returning the system to vacuum takes days to perform. This time period is where the true cost of serviceability lies, and while there is a great deal of labor connected to this effort, other less quantifiable cost must be considered. During this time the community of physicists that is performing experiments on the NLC will have to wait until the repairs are completed. As mentioned before, it difficult to quantify this cost. However, there is no doubt that it is extremely significant since the NLC will offer a very unique opportunity to work on a high-power linear collider.

Further discussions with members of the SLAC community have revealed that the serviceability issue needs to be further visited. In particular, it appears that it may be impossible to service
either tube sections or joints, once they are installed. This is due to the inherent design of the Waveguide, [See Attachment #17] which lacks the axial compliance to slide sections in or out, and does not even allow access to many of the tubes until others are first removed. As such, the tubing and joints simply are not serviceable, regardless of the joint design. This makes the initial quality of the components of paramount importance.

5.7 Variety/Complexity, and Recycling Issues

There are no design for variety issues involved in the Waveguide design because all of the parts that are produced will be identical. The main benefit of design for variety lies with supply chain and inventory management, which do not apply to this scenario.

There are two components of the Waveguide that will need to be considered when looking at recycling issues. An over-riding concern when addressing recycling of either of these components is whether they have become radioactive during their years of service. While it is unknown at this time how much of the waveguide will become radioactive, this issue would have to be addressed before the parts could be recycled. If the parts are radioactively safe, it should be fairly simple matter to recycle the two components. The first component is the copper tubing that makes up the main body of the Waveguide. Because the copper tubing in the Waveguide needs to meet an extremely high purity standard, it should be easy to recycle once it is removed from the NLC. Recycling the tubing by selling it on the copper market will also most likely prove to be cost effective. The second component of the Waveguide is the Conflat flanges, which will also be removed when the Waveguide life cycle is over. Upon removal, they could be broken down into their primary components of stainless steel flanges, copper gaskets, and silver plated stainless steel nuts and bolts. Again, because of the purity of these components, they should be fairly easy to resell/recycle. However, a copper Flange design would eliminate the need to remove the flanges for material separation when recycling.
6. Product Definition

6.1 Product Definition Tools

In this section, detailed product requirements and potential opportunities for improvements in the NLC project will be identified.

The following tools were used to help form the product definition

- Product Definition Assessment Checklist
- Customer Value Chain Analysis
- Project Priority Matrix
- Customer Interviews

These tools helped to define the scope, priorities, and detailed specifications of the Waveguide system, as well as to generate project documentation.

6.1.1 Product Definition Assessment Checklist

The Product Definition Assessment Checklist [See Attachment #12] was filled out early in the project stage (January 25). For the most part, the team was in agreement that there was a high degree of discomfort in the status of most of the items, such as understanding need, competitive analysis, product positioning, etc. This helped the team to focus on these elements during the interviews with the SLAC personnel. These interviews helped the team build a substantially higher degree of comfort. Perhaps an updated PDA reflecting this could be part of the next phase of the project.

6.1.2 Customer Value Chain Analysis

The Customer Value Chain Analysis [See Attachment #13] helped to visualize and clearly document all of the major customers involved in the NLC. Starting internally, the requirements of the Physicists, Engineers, and Technicians within the SLAC Waveguide Team need to be met.
Additionally, the Waveguide team members are a potential customer to a number of material providers, including the sourced supplier of copper tubing, flange/joining hardware, tube-cleaning equipment, and other installation hardware. These have the traditional money/complaints traded for material goods relationship. A similar relationship exists with the construction crew hired to actually perform installation of the Waveguide, although they are providing a service rather than material goods.

The Waveguide team’s budget comprises a portion of the NLC project team’s total budget. This team, in turn, has customers at the Department of Energy, which interfaces with Congress, who is ultimately paid by the taxpayers. In return, all of these parties have the opportunity to benefit from information and discoveries that are made at the NLC.

6.1.3 Project Priority Matrix

![Project Priority Matrix]

The Project Priority Matrix helped to clarify the priorities for the NLC’s Waveguide system. In this case, there is no question that the feature content MUST be met; otherwise the NLC would be inoperable, which is not acceptable. This results in the features being the constrained factor. Furthermore, due to budgetary constraints, cost must be optimized. These first two results
indicate that ‘time’ must be accepted, which is permissable because the traditional “time-to-market” financial issues do not apply here.

6.1.4 Customer Interviews
The above tools helped to clearly define the project scope and goals. Customer Interviews were then conducted with a number of internal customers [See Attachment #14] to obtain and document the requirements of the NLC’s Waveguide System, and the potential opportunities for improvement.

6.2 Detailed Product Definition
The detailed product definition includes:

- Tube Geometry and Material Selection
- Tube Manufacturing Process
- Tube Joining Method
- Tube Segment Lengths and Location
- Tube Cleaning Process
- Installation

Again, the baseline assumption for this definition is that the design matches that of the NLCTA, and the cleaning process matches that of the original accelerator structure in the SLC.

6.2.1 Geometry and Material Selection
The Waveguide system must meet all of the following functional requirements that were developed for the NLCTA: [See Attachment #15 – Prints]

DIMENSIONAL:
- Circularity: 0.005”
- Straightness: 0.010” per 24” length
- Surface Finish: 32 Micron RMS
- Concentricity: 0.005” joint-to-joint
• Wall Thickness: Arbitrarily set at 0.125” +/- 0.010” for the NLCTA. It could be changed if required.

MATERIAL:
• Oxygen-free, Electronic (OFE) Copper Alloy UNS Number C10100
• Chemical and metallographic Properties to conform to ASTM F68-93 Metallographic Class 1.
• Circular OFE copper Per PS-290-291-02.

Note that while the Physicists provided these requirements, the specifications that are driving cost and/or limiting process selection need to be identified. A study may reveal major cost savings opportunities, which could warrant detailed testing to see if any decrease in precision or purity is tolerable. The same is true of material selection.

6.2.2 Manufacturing Process Selection
Currently, in order to meet the above requirements, SLAC is importing tubes from Japan where they are extruded. Roll forming with mandrel pull post roll could be considered as a means of cost reduction, but dimensional tolerances may preclude the use of this process.

6.2.3 Tube Joining Method
The NLCTA baseline uses Conflat flanges to join sections of waveguide tubing together. They consist of stainless steel flanges that are welded/brazed to the machined ends of the copper tube sections. These stainless steel flanges include a knife-edge feature that embeds into a copper gasket inserted between the flanges and is clamped by 20 silver-plated nut/bolt combinations. [See Attachment #16- Prints] To meet flange-to-flange concentricity requirements, the outer diameter of the flanges are custom machined, and a fixture ring is placed around the flanges before bolting. These flanges have the following benefits:
• Extremely Reliable (not a single leak with 50 in use on the NLCTA’s delay line, and a history of using thousands on different UHV SLAC projects)
• Serviceable in Principle (Bolts used to make the attachment)
• Proven Design in this application
• Does not require cleaning after joint is made
• Provides positive feedback when the joint is good

The fact that cleaning is not required after the joint is made allows for the use of shorter cleaning tanks, as well as shorter final tube sections. This eases installation of the tube sections down the NLC tunnel.

Unfortunately, Conflat flanges are expensive (Material alone is $110 per piece including fasteners and gasket at the NLCTA) due to their complexity. They are also relatively labor-intensive to install.

While the Cost/Worth Analysis revealed that the tubing is the primary candidate for adding value, the tube joining method may also represent a major cost reduction opportunity in absolute terms. The joints need to perform the following functions ultra-reliably:

• Provide a vacuum seal
• Provide tube-to-tube alignment
• Provide structural integrity
• Allow for microwaves to pass without losses (creates certain internal geometric constraints)
• Prevent “Virtual Leak” where gas is trapped inside the vacuum system

Alternative joint designs under consideration include brazing, and e-beam welding (in a local vacuum). There are several considerations in the selection of these processes. The first is that they may require the design of a new, unproven joint; however, SLAC does have some experience with brazed joints. The second consideration is the fact that they may require cleaning after the joining operation. This increases the required length of the cleaning tanks, and longer sections of tubing will need to be transported down the NLC tunnel. This may have a negative impact on installation. The third point about brazed or welded joints is the fact that they are non-serviceable. However, the current SLC RF system is vented, on average, only once every four years, and the venting process is performed at valves, not at the tube joints.
Additionally, the Conflat flanges cannot be easily serviced in the current waveguide system design for the NLC, due to a lack of lateral compliance and the lack of accessibility of the flanges. Thus serviceability of the tube joints is probably a non-issue under the current design-layout for the waveguide because drastic measures would need to be taken to service any type of joint that would be used.

6.2.4 Tube Segment Lengths

The length of tube segments is another design variable that could affect cost substantially. The baseline length of the tube segments is five meters, which is a shippable and manageable length using hand installation. However, this requires a great number of joints. The design must be optimized by weighing the ease of shipping and handling against the number of joints. This plays a role in whether the tubes could be cost-effectively manufactured on sight as well, since they would not need to be shipped.

6.2.5 Tube Cleaning Method

As shown in the Fishbone Diagram, there are a great many steps involved in obtaining the level of cleanliness required for the Waveguide. However, there may be opportunities to reduce or eliminate some steps. There may also be ways to increase efficiency in the cleaning process, such as running fluid through the inner diameter, rather than dipping in tanks. This method may enable the running of cleaning fluids sequentially through the same fixtured tube. Furthermore, the length of tube section that needs to be cleaned could also play a role in the selection and complexity of the cleaning process.
7. Plan of Attack and Conclusions

7.1 Project Challenges
There are several major challenges facing the SLAC–Waveguide team. The first challenge is the determination of actual, realistic product requirements. Many of the current requirements were created with a great deal of stringency to ensure that the final product would work. Less precise specifications may well be allowable, but have never been tested. Furthermore, the design is continually evolving. This makes it difficult to pinpoint the product definition. Confirming that our specifications are realistic is challenging because of limited communication between, and among, the different disciplines at SLAC.

Another challenge is that many of the design variables have interdependencies. When considering the cost of the Waveguide, design variables include length of tube, number of joints, cleaning process, and type of joint. For example, since the number of joints is a cost driver, then reducing the number of joints is desirable. However, this would result in lengthening the tube sections, which then makes it more difficult to clean, ship, handle, and install. An optimization to minimize cost will need to be performed.

The final challenge is the fact that the NLC has yet to be approved by the United States Congress to receive funding. The current budget estimate to build the accelerator is phenomenally large. Unless the accelerator’s cost can be reduced by a factor of five, the NLC will not become a reality.

7.2 Project Direction
The SLAC-Waveguide team will attempt to complete the following tasks for ME217B:

<table>
<thead>
<tr>
<th>TASK</th>
<th>TARGET COMPLETION DATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final selection of material</td>
<td>4/7/00</td>
</tr>
<tr>
<td>Complete Cost Model</td>
<td>4/14/00</td>
</tr>
<tr>
<td>Event Description</td>
<td>Date</td>
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<tr>
<td>-----------------------------------------------</td>
<td>------------</td>
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<td>Joint Alternatives Selected</td>
<td>4/14/00</td>
</tr>
<tr>
<td>Visit tube-manufacturing facility</td>
<td>4/21/00</td>
</tr>
<tr>
<td>Select viable tube process</td>
<td>4/28/00</td>
</tr>
<tr>
<td>Detail Tube Installation Process</td>
<td>5/5/00</td>
</tr>
<tr>
<td>Final report completed</td>
<td>6/2/00</td>
</tr>
</tbody>
</table>

In order to meet this timing, it is imperative that the team makes a swift decision on a tube-manufacturing site that is appropriate for a plant tour. Additionally, detailed cost information is required to complete the cost model.

### 7.3 Contingency Plans

Unexpected problems are sure to appear. However, the SLAC Waveguide team has a number of options to ensure that the project remains on schedule. The project liaison, Jeff Rifkin, has proven to be an excellent source of information, either by providing his expertise, or by networking to the expert contact. The coach of the project, Vikash Goyal, is currently employed by SLAC and worked on a SLAC project for the completion of ME217 last year. Vikash has experienced some of the same difficulties that await us and has the ability to predict these pitfalls and guide us in the right direction. If the need arises for drastic measures, the scope of the project could be modified to be more manageable for the time frame given.

A contingency plan for the product itself is to simply use the design and process that were used in the construction of the NLCTA.
8. Acknowledgements

Jeff Rifkin, Project Liaison
Vikash Goyal, Project Coach
Professor Kos Ishii, Instructor
Professor Mark Martin, Instructor
Chris Adolphsen, Main Linac Systems Coordinator
Sammy Tantawi, Physicist
Chris Nantista, Physicist
John Cornuelle, Deputy for Mechanical Systems
Karen Fant, Engineer
Mike Neubauer, Engineering Manager
Carl Rago, Engineer
Bobby McKee, Engineer
9. References

1. SLAC Website (http://www.slac.stanford.edu)

2. U.S. Department of Energy Website (http://www.doe.gov/)


   6 September 1999
Waveguide Value Graph

Run Computer Model

Learn about the components of atoms

Run Physics Experiments

Have Fun?

Accelerate Particles

Transfer Energy

Hold Vacuum

Manufacture Electronics components

Guide Waves

Waveguide

Efficient

Safe

Reliable

Serviceable

Easy to Install

Surface Roughness/Conductivity

Wall Thickness

Vacuum Capacity

Cleanliness (particulate levels)

Length

Weight

Joints

Tubing

Pumps

Hardware

WHAT

WHY

HOW
# PHASE I QFD

**NLC Waveguide**

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Customer Weights</th>
<th>Tube and Joint Roundness</th>
<th>Tube and Joint Concentricity</th>
<th>Tube Straightness</th>
<th>Tube Interior Surface Finish</th>
<th>Tube Conductivity</th>
<th>Wall Thickness</th>
<th>Joint Vacuum Limit</th>
<th>Tubing Material Outgassing</th>
<th>Tube Weight</th>
<th>Mean Time to Remove Joint</th>
<th>Mean Time to Remove Tube</th>
<th>Mean Time Assemble Joint</th>
<th>Tube Length</th>
<th>Exterior Surface Oxidation</th>
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## Technical Targets

- Tube and Joint Roundness: < 0.01"
- Tube and Joint Concentricity: < 0.005"
- Tube Straightness: <0.001" per 24"
- Tube Interior Surface Finish: <0.02 micrometers
- Tube Conductivity: <0.125" +/− 0.010"
- Wall Thickness: >ASTM F68-93, 1
- Joint Vacuum Limit: >10^-9 Torr
- Tubing Material Outgassing: <100 lbs
- Tube Weight: <2 hr.
- Mean Time to Remove Joint: >20 ft.
- Mean Time to Remove Tube: <20" length (in)
- Mean Time Assemble Joint: >10 minutes
- Tube Length: <25% after 1 yr
- Exterior Surface Oxidation: >18% after 1 yr

## Raw Score

- Able to Transfer Power: 81
- Reliability: 70
- Able to hold Vacuum: 84
- Safety: 93
- Serviceability: 84
- Installability: 84
- Cosmetics: 84

## Relative Weight

- Able to Transfer Power: 6%
- Reliability: 5%
- Able to hold Vacuum: 5%
- Safety: 5%
- Serviceability: 5%
- Installability: 5%
- Cosmetics: 5%
## PHASE II QFD

### NLC Waveguide

### Part Characteristics

<table>
<thead>
<tr>
<th>Engineering Metrics</th>
<th>Phase I Relative Weights</th>
<th>Tube</th>
<th>Conflat Flange- Stainless Steel</th>
<th>Conflat Flange- Cu Ring</th>
<th>Bolts (20/flange)</th>
<th>Nuts (20/flange)</th>
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<td>Mean Time Assemble Joint</td>
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<td>Exterior Surface Oxidation</td>
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<td>9</td>
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</tbody>
</table>

| Raw score                            | 6.0                      | 2.4  | 1.8                            | 1.8                   | 1.8               | 1.8             |

| Relative Weight                      | 44%                      | 17%  | 13%                            | 13%                   | 13%               | 13%             |
QFD Cost - Worth Diagram
(based on 5 meter tube sections)
<table>
<thead>
<tr>
<th>Component</th>
<th>Base Cost</th>
<th>Discount</th>
<th>Scrap Rate</th>
<th>Labor Minutes</th>
<th>Labor at $50/hr and Processing</th>
<th>Cost/ Meter</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube</td>
<td>$50</td>
<td>10%</td>
<td>1</td>
<td>N/A</td>
<td>$50</td>
<td>$95.00</td>
<td>Base cost is from $2/lb for raw coper and 25lb/meter. Tube wall thickness is .125&quot;. Labor is an assumption to cover manufacturing and installation</td>
</tr>
<tr>
<td>Flange - Steel</td>
<td>$220</td>
<td>30%</td>
<td>1</td>
<td>20</td>
<td>$16.67</td>
<td>$34.13</td>
<td>Base Cost from catalog. Labor time to braze and weld</td>
</tr>
<tr>
<td>Cu Ring</td>
<td>$4.80</td>
<td>30%</td>
<td>1.2</td>
<td>0.1</td>
<td>$0.08</td>
<td>$0.82</td>
<td>Base Cost from catalog. Labor time to install.</td>
</tr>
<tr>
<td>Nuts &amp; Bolts</td>
<td>$22</td>
<td>30%</td>
<td>1.2</td>
<td>7.5</td>
<td>$6.25</td>
<td>$2.47</td>
<td>$22 for set of Nuts and Bolts. Final costs is for just 1 set of Nuts or Bolts</td>
</tr>
</tbody>
</table>
Fish Bone Diagram

Tube Section ~(20-40 ft)

↓ F  ☮ Quality Check Tubes

↓ F  ☮ Machine Tube Ends (x2)

↓ F  ☮ Chemically Clean Tubes

↓ F  ☮ Warm Conflat Flange (x2)  
(Thermal Expansion)

↓ F  ↓ Insert Conflat Flanges onto Tube Ends

↓ F  ☮ Cusil Weld Conflat Flange to Tube Ends (x2)

↓ F  ☮ Braze Conflat Flange to Tube Ends (x2)

↓ F  ☮ Chemically Clean Tube Assemblies

↓ F  ↓ Transport to Site

↓ F  ↓ Insert Copper Gasket

↓ F  ☮ Apply Locator Ring on OD

↓ F  ↓ Insert bolts (x20)

↓ ☮ Assemble 20 nuts

↓ ☮ Bake-Out

Finished Assembly

Legend

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>☮</td>
<td>Screw Down/Rotate</td>
</tr>
<tr>
<td>☮</td>
<td>Weld</td>
</tr>
<tr>
<td>☮</td>
<td>Braze</td>
</tr>
<tr>
<td>☮</td>
<td>Clean</td>
</tr>
<tr>
<td>↓</td>
<td>Insert Down</td>
</tr>
<tr>
<td>←</td>
<td>Insert Side</td>
</tr>
<tr>
<td>F</td>
<td>Fixture</td>
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<tr>
<td>☮</td>
<td>Machine</td>
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<td>Quality Control</td>
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<td>Heat</td>
</tr>
<tr>
<td>☮</td>
<td>Microwave Energize</td>
</tr>
<tr>
<td>Part/Operation Description</td>
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<tr>
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<td>1 Fixture Tube Section</td>
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<tr>
<td>2 Cusil Weld Conflat Flange (X2)</td>
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<tr>
<td>3 Braze Conflat Flange (X2)</td>
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<tr>
<td>4 Immulsion &amp; Water Rinse</td>
<td>360</td>
</tr>
<tr>
<td>5 Alcohol Dip &amp; Water Rinse</td>
<td>360</td>
</tr>
<tr>
<td>6 Bright Dip &amp; Water Rinse</td>
<td>360</td>
</tr>
<tr>
<td>7 50% Hydrochloric Acid &amp; Water Rinse</td>
<td>360</td>
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<tr>
<td>8 Cyanide Dip &amp; Water Rinse</td>
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<tr>
<td>9 High Temp., High Purity Water Rinse</td>
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<tr>
<td>10 Blow w/ Nitrogen</td>
<td>360</td>
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<tr>
<td>11 Dry at 150 degree C</td>
<td>3600</td>
</tr>
<tr>
<td>12 Transport to Site</td>
<td>300</td>
</tr>
<tr>
<td>13 Insert Copper Ring</td>
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</tr>
<tr>
<td>14 Install 20 Bolts</td>
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</tr>
<tr>
<td>15 Assemble 20 Nuts</td>
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</tr>
</tbody>
</table>

Cleaning Steps

**Step 1:** Draw the Assembly Sequence Diagram
- **Summary Statistics**
  - NUP = number of unique parts
  - TOP = total no. of operations
  - TAT = total assembly time
  - NP = no. of parts = sumprod.(L,N)
  - Tavg = avg time/operation = TAT/(sumRep)
  - Pmin = min # parts = NP - sumprod.(L,N,O)
  - AR = Assembly rating = 2.35 * NP/TAT
  - PE = Part Efficiency = Pmin/NP

**Step 2:** List Parts & operations in order (left column)

**Step 3:** Enter times from Estimated DFA Time Chart

**Step 4:** Sum time per part/oper. in column K
- Enter no. of repetitions for each operation in col. L
- Enter K*L in col. M

**Step 5:** Enter a 1 in col. N if a part was inserted during operation
- Enter a 1 in col. O if part or operation can be eliminated

**Step 6:** Calculate Summary Statistics
<table>
<thead>
<tr>
<th>Function or Requirement</th>
<th>Potential Failure Modes</th>
<th>Potential Causes of Failure</th>
<th>Occurrence</th>
<th>Local Effects</th>
<th>End Effects on Product, User, Other Systems</th>
<th>Severity</th>
<th>Detection Method/Current Controls</th>
<th>Detection RPN</th>
<th>Actions Recommended to Reduce RPN</th>
<th>Responsibility and Target Completion Date</th>
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<tbody>
<tr>
<td>Conductive</td>
<td>Low Conductivity</td>
<td>Impure Material</td>
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<td>Local Effects</td>
<td>End Effects on Product, User, Other Systems</td>
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<tr>
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<td></td>
<td>Not Enough Joints</td>
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<td>Open Larger Section to Air During Service</td>
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1.5 Pareto Chart

- Dirty Manufacturing Process
- Smooth Joining
- Concentric Joining
- Slow Installation Process
- Material Choice
- Thickness of Pipe
- Weak Joints
- Processing
- Expensive Joints
- Difficult Transport
- Complex Joints
- Permanent Joints
- Bulky Joints
- Impure Material
- System Opens to Air
- Virtual Leak
- Mfg. Process
- Installation
- Support Structure
- Processing
- Expensive Materials
- Not Enough Joints
- Exterior Oxidation
- Exterior Dirt
- Poor Material Selection

RPN

Cause

Cummulative %
## Modified Service Modes Analysis

<table>
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<tr>
<th>Labor Steps</th>
<th>Time (min)</th>
<th>Labor (Rate $50.00)</th>
<th>Part (Cost $0.00)</th>
<th>Total Step Costs (LSC)</th>
<th>Total Step Cost</th>
<th>Total # of Steps</th>
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<tr>
<td>Recognize leak from vacuum issue or power loss/spike.</td>
<td>5.00</td>
<td>$50.00</td>
<td>$0.00</td>
<td>$4.17</td>
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<td>Shut down system and allow system to cool</td>
<td>1,440.00</td>
<td>$50.00</td>
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<td>$1,200.00</td>
<td>$1,200.00</td>
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<td>Search for leak with hydrogen sniffer.</td>
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<td>Patch leak</td>
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<td>Unbolt joint</td>
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<tr>
<td>Unbolt joints on either side of the faulty joint</td>
<td>15.00</td>
<td>$50.00</td>
<td>$0.00</td>
<td>$12.50</td>
<td>$12.50</td>
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<tr>
<td>Unbolt joints on either side of the faulty pipe</td>
<td>15.00</td>
<td>$50.00</td>
<td>$0.00</td>
<td>$12.50</td>
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<td>Remove the two sections of piping that contain the faulty joint</td>
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<td>Remove the piping section</td>
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<td>Cut off bad flange sections.</td>
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<td>Cusil weld and braze on new flange sections.</td>
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<td>Return system to vacuum</td>
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### Total Step Cost

- Patch Leak: $7,262.50
- Replace Joint: $7,853.33
- Replace Pipe: $7,887.08
- Total: $23,002.92
## SLACB- Waveguide

**Internal Customer List & Function**

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<tr>
<th>Name</th>
<th>Notes</th>
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<td><strong>Management</strong></td>
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<tr>
<td>Chris Adolphsen</td>
<td>SLED system/waveguide, Budget, also design specs.</td>
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<tr>
<td>Sammy Tantawi</td>
<td>Waveguide/Tube functional req.</td>
<td>Tdes, Tmtl, Tjoin, Tquant</td>
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<td>Chris Nantista</td>
<td>Tube &amp; joining detail design</td>
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<tr>
<td>Perry Wilson</td>
<td>theory</td>
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<td><strong>Design</strong></td>
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<td>Waveguide/Tube functional req.</td>
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<td>Marc Ross</td>
<td>Made SLC Work</td>
<td>Tinst, Tmnt</td>
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<tr>
<td>User</td>
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<td>Keith Jobe</td>
<td>Made SLC Work</td>
<td>Tinst, Tmnt</td>
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<tr>
<td>Nan Phinney</td>
<td>NLC</td>
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<td><strong>User</strong></td>
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<td>Klystron Mfg, In charge of shop</td>
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<td>Tubing</td>
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<td>Tubing Install process</td>
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<td>Mike Neubauer</td>
<td>management</td>
<td>Tdes, Tmtl, Tmfg, Tjoin, Tinst, §§</td>
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<td>Tubing Install process</td>
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<td>Rose Santana</td>
<td>In Vacuum Dep't.</td>
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<td><strong>Jack-of-All Trades</strong></td>
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<tr>
<td>All</td>
<td>Jeff Rifkin</td>
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**Functions:**

- Tquant = Number of tubes
- Tdes = Tube Design
- Tmtl = Tube Material
- Tjoin = Tube Join
- Tmfg = Tube Manufacturing
- Tinst = Tube Installation Process
- Tmnt = Tube Maintenance
- §§ = Budget
NOTES:

1. MATERIAL: THE FINISHED TUBING SHALL BE MADE FROM AND MEET ALL THE REQUIREMENTS OF OXYGEN FREE ELECTRONIC grade COPPER ALLOY UNS NUMBER C71500, CHEMICAL AND METALLURGICAL PROPERTIES TO CONFORM TO ASTM F68-93 METALLURGICAL CLASS 1.


3. SURFACE FINISH: INSIDE SURFACE FINISH SHALL BE 32 MICROINCHES OR BETTER WITH NO SCRATCHES, DENTS, NICKS OR PITS. INSIDE SURFACE MUST ALSO BE FREE OF INCLUSIONS, COLD LAPS AND GALLING.

4. STRAIGHTNESS: MAXIMUM CURVATURE (DEPTH OF ARC) IS 0.008" FOR ANY 24" PORTION OF THE TOTAL LENGTH OR 0.002" FOR ANY 120" PORTION OF THE TOTAL LENGTH.

5. ROUNDNESS: THIS IS EQUAL TO AN INNER DIAMETER ROUNDNESS TOLERANCE OF 0.008" AS DEFINED BY THE DIFFERENCE BETWEEN THE MAJOR AND MINOR DIAMETERS AT ANY ONE CROSS SECTION.


7. SHAPING: DUE TO THE SOFT NATURE OF THE COPPER TUBES, PACKING PROCEDURES AND SHIPPING CONTAINERS MUST BE DESIGNED AND CONSTRUCTED TO PREVENT DAMAGE IN TRANSIT. CARE MUST BE TAKEN TO PROTECT THE COPPER TUBE SURFACES FROM ANY INDENTATIONS, INCLUSIONS AND DEFORMATION DUE TO HANDLING. THE TUBES MUST BE PROTECTED FROM MOISTURE, CORROSION AND CONTAMINATION.
Main Linac Tunnel with 4 by 2-Mode DLDS