PHENIX Stave Production

# Overview

This is a description of the associated cost spreadsheet and details of line items.

The ‘bottom lines’ are negotiable. The estimate presented is intended to be a tool by which we mutually understand the scope and costs of various activities and devise a plan that better defines the scope of work, and shares costs.

The associated spreadsheet has a lot of structure and is intended to be massaged to see how to fit the costs within an accepted limit and profile—after understanding scope. I have added ‘knobs’ for moving line items to contingency, and changing the year in which they occur (within obvious limits). I have also included the ability to zero-out various line items if they are deemed unnecessary.

Also, by changing the ‘year’ to ‘Hytec’ or ‘LANL’, the roll-up will reflect the hours (not cost as I don’t have their rates)—also whomever does the work should estimate the time required...

This is a short project so I did not, but I can later; add some splits in certain tasks to allow spreading over Fiscal Years within some granularity as to allow a funding profile to be generated. The best example is a production spanning more than one FY. The breaks I’m used to are 25%, 50% and the final part of 100% production—hopefully with reducing contingencies, but that is a whole other bailiwick.

Of course, this is only an estimate, and as it sums over a large number of items, small adjustments in the items can have a large impact. I have at most spent a solid minute, occasionally two, thinking about each line item’s details—there are more than 100 line-items... Consider this a ROM estimate.

Note that this is a manpower estimate, not a schedule—I built it to tie to a schedule more easily, but some tasks require ‘management interventions’ i.e. decisions for new directions which add to schedule, or insert check points which must be passed before proceeding. I will try to outline some of those impacts here.

## Contingency Planning

The first thing you should note is that the contingency levels, which I have explicitly estimated, approach 100%. This is in line with a ROM quote, but I hope to use this estimate as a tool to reduce this.

My experience has been that standard contingency levels i.e. 50% are good at the first go-thru. This represents my lack of understanding of the processes involved, and trying to reign in a non-final design. In seeing the larger contingency numbers, I realize that scope needs to be addressed. This is a work in progress, and should be reviewed. Various line items may be deemed unnecessary or excessive, but I include them for discussion, and after we scrub it, we might settle on a lower contingency rate, and perhaps a reduced scope.

By making the production section of this estimate close in structure to the ‘Prototype’, it is easy to project cost increases or savings learned during the prototype phase into production. If this is timed well, during a yearly cost-scrub, it is easy to zero non-essential explicit contingencies, and adjust the production estimates based on experience.

I have only included ‘explicit’ contingency. Contingency in the sense of a DOE program needs to be included in addition, but you might consider a more elaborate model to address this than simply applying a fixed ratio. My hope in defining explicit contingency items is to reduce overall contingency by providing a more accurate cost model.

# Engineering

This is nominally just a fabrication estimate; however some portions of the deliverables will require design work. Where appropriate, I have put this effort as separate line items, but some deliverables will require this—you will see them as having a mixture of labor types on one line. The two primary cases where this is true are described below.

## Design for Fabrication

This is the portion of engineering/designer work that is required to make/modify fabrication drawings and procedures for Tooling, Parts and Assemblies. For some parts additional analysis may be required for re-design to achieve acceptable geometries. For tooling, and parts, during prototype phase, I will embed this effort, in production it is assumed complete. The analysis I will include as separate line items as I think Hytec will likely play some role, though I will cost it as if LBNL is doing the work.

I have not included any designer work at this stage—if the project were larger, it might allow some cost savings by incorporating a designer.

## Oversight

All efforts will require some oversight. Frequently this is handled by physicists or other programmatically supported people, but for this I assume engineering labor. For some tasks I have explicitly included engineering oversight, but I have not included ‘Project’ oversight, which is usually 10-20% of an FTE for the duration of the project.

## Contingency

As the oversight function is required, but likely to overlap with design efforts during prototype work, it is likely acceptable to place ~20% of the ‘Base’ Engineering effort in contingency directly, but need to balance that with whatever contingency model we use. I have not done this in this estimate—we would have to progress to the scheduling phase for this to make sense.

# Material Batches

For machined parts, the material will be embedded in the part line item, however for some components/assemblies all parts will draw from one batch, and likely not soak up the full batch due to minimum order size or material expiration. I will denote batches separately as to better capture their full cost.

This is a different approach than for larger part productions—here we are up against minimum orders; otherwise I would cost material/part, however there are costs per batch regardless of quantity which do occur and these are outlined below.

Unfortunately, these batches approach $40k and their minimum size maximizes the overheads (tests and QA). This can be shared if other components are eventually produced from the same material.

## Expendables

Composite material processing uses expendable bagging materials, tape, film, et-al. The material cost in each part will be the cost of these expendables (based on tool area)—not the composite cost. These are cheap by area, but large in minimum orders. We usually share these across projects.

After summing all the parts’ use, it may be required to pull this up as a batch order depending on our current stocks and projects at the time—probably best handled in contingency… (only a few $k if needed)

Again, for large productions, this is usually brought up as a separate batch, but this is unfair for such a small area project. Will as best as possible average this cost over several projects.

## Composite Batch Estimate Structure

For this estimate, all material orders will cost the same ~$6k/material/batch (minimum orders). Might later be able to spread across other structures, but costed directly here.

In addition to the material order itself, which will include setup fees and the cost of the materials themselves, there are a number of required activities to properly accept and store the material. As these are shipped frozen, typically it requires additional M Tech time to coordinate the delivery, and opening of the materials—this is buried in the next task:

### Material Acceptance

Every roll needs to be entered into our Composites Database to track its ‘Out Time’ (time spent warm) to assure the materials stay in spec during the production. A few hours of Engineering are required to set up new material specs in the DB (subsequent batches do not require this). We will typically also do ‘Bleed Studies’ at this time which requires some additional engineering effort to determine the appropriate test samples. As part of the acceptance, several test panels are made taking a few days of M Tech time.

### Material Testing

As a bare minimum, at least one test panel from each material, with appropriate bleed technique, is sent out for analysis (Modulus/Fiber and Void Fraction). This is required to track batch variability—resin ratio will vary batch to batch from the vendor.

If target laminates are defined, it is usually wise to also include them here—e.g. a specifically oriented laminate as defined by the part(s). Feedback from this testing is currently required in your part specs.

### Iterations…

The bleed studies are a ‘shot in the dark’ at achieving the appropriate resin content. Usually after the first test results, an additional sample with targeted laminate and bleed procedure might need to be tested.

The spec on your parts does stipulate targeted testing of specific laminates—this necessitates additional testing. I have placed these in contingency, but you may require moving them to base (to be discussed with Hytec).

## Tube Material

Unless the tubes are round and COTS dimension, these will be custom extrusions. It is unclear to me whether we can start with a round (but targeted diameter) tube, and mold the D-Shape into it, or if the tube must be extruded in the D-Shape.

I think that either way, because a heated mold is already required to shape the bends on the tubes, that the cost difference is negligible for production parts—assuming that the cost of a custom extrusion is included. I go a step further and assume that custom extrusions are required for both Prototype and Production (assuming a design change in-between). I’ve put the Production extrusion in contingency.

The main uncertainty comes below in Tube Fabrication, where it is unclear how many iterations are required in the tooling.

### Prototype Options—not in cost estimate

Using COTS PEEK tubing, it may be possible to iterate on the bend geometries and mold profiles, however to achieve the final dimensional shape, likely requires a certain wall-thickness and tube circumference that aren’t free parameters for COTS tubing.

Prototyping with COTS seems a reasonable approach to determine mold shape, bend-parameters, and thermal processes, but will not yield a tube which can work in a prototype assembly (which needs to fit well in the Omega profile).

For the purpose of this estimate, I assume that this prototype effort is done elsewhere allowing us to minimize mold iterations, however we could do this work, but it is not costed in this estimate.

### Adhesives

Hysol and the other Loctite adhesive will have generally a 6mo shelf life. Depending on schedule several batches may need to be ordered. Assumed 1 for prototype and 2 for production

# Component Fabrication

Prototype and Production have overlaps in Schedule, but not cost—this will need to be addressed by understanding the goals of prototype activities (later discussion). The goal of the cost estimate and target schedule is to have the final prototypes be qualified as pre-production elements. This means going deep in the prototype phase—taking each element up to its production phase so that they can be assembled into prototype assemblies. This does put a lot of costs up front, but the goal is to reduce risks and contingency levels for production. It does however define which tasks can and cannot overlap based on management decisions.

## Note on Prototyping

Experience from ATLAS shows that 3-4 iterations are normal, if not 6-8... Some parts are higher risk than others and usually drive the iterations—here I think it will be the Omega. The tube is also high risk, but I don’t think the challenge—it’s a drop-in component in the assembly that doesn’t affect your critical dimensions—it’s development can proceed independently cost-wise, but will affect schedule for first prototype assembly.

## Thermal Tiles

These are simple parts. My plan is to cut them from large production sheets. Like any composite part, we will need to qualify the laminate. This speaks to the panel testing mentioned before—it is unclear how much you want to pre-load that testing and the tests required for this. I assume that for these, we can put testing in contingency. Once a process is identified which yields acceptable properties, this will be a quick production.

### Tooling

This already exists. We have re-usable tooling for flat plates, but there are some expendables used during cure.

#### Prototype

As mentioned before—need to assure properties to spec’ but assume we can ‘just make’ after initial test samples are accepted.

Will lay up several Panels in prototype, only some used, but each panel can yield up to 12 Tiles.

The costs for one-tile-size panel same as panel for 12. Including cost of additional panels allows for iterations—will directly include iterative panels in contingency.

#### Production

This is just an extension of prototype, but with less handling by the M Tech. Aimed at throughput, not assessing quality which should have previously been determined.

### QA Procedure

This is the cost driver during prototype—we need to determine how many tests you require. I will assume only one for the first panel, however your spec implies one test per production panel—need some clarification. I will only include one test.

Flatness spec of ‘free tile’ may cause problems. I am assuming that I do not need to provide survey data for every single tile (as specified in drawing). I do include fixtures and CMM time during the prototype phase to assure that we do not need to do this for production, but you may want to excise this from the cost estimate.

I have included no iterations or extensive measurements in the cost estimate—I assume these are easy to make, but have questions about the req’s specified in the drawings (which I ignore for these parts)

### Trim to shape

This is done on a router table. Cost driver is setup time, though only a couple hours per panel. See more setup time during prototype than production (one per iteration). Will need to include expendables—PCD cutters. Wear will dominate the trimmed part tolerance, so need to replace per panel

## Omega

This component is a cost driver and has several options to consider… The cured shape of the Omega will likely drive the flatness of the final assembly so designing a combined part/tool combination that yields an acceptably flat Omega is THE goal of the prototype activity. This is the bow and twist of the part. Crudely speaking, Bow is dominated by tool/part CTE mismatch, and Twist is dominated by the laminate. Estimating the cost involves some strategy toward honing in on a flat cured part, and I have opted for a more risky, but less costly approach (success oriented).

I am going to assume that I cannot change the laminate by much, which I believe will inherently twist, so I will need to make ‘anti-twisted’ tools—predicting this twist is difficult and usually iterative (requires making and measuring parts). I am also assuming to use Stainless Steel rather than Invar (should address delta-cost in contingency).

Freedom to iterate on the laminate might allow us a quicker approach to a flat part, but will require analysis of the part. I will include this as a line item and assigned it to Hytec. For instance with a 0/90 laminate, I can reduce the number of tooling iterations 2-fold—likely hit it the first time.

### Prototype Tooling

There will be an engineering analysis task to determine the base tool shape. Strategy mentioned above would make the first tool flat and un-twisted as to measure part twist and bow to feed into a re-machined tool. Will make tool for 5 parts with identical geometry—allows for increased statistics during test phase (and good number for production tooling).

Invar would be conservative to cost here, but this impacts cost of iterations (harder to machine and more expensive material). Prefer to handle this with increased contingency for this task. Another option is to us a ‘graphite’ tool, but this has impact on production as it would likely require re-machining several times mid production (frangible surface).

For the cost estimate I have explicitly put an Invar tool and iterations in contingency—might consider removing altogether with increased engineering (optimization needed).

### Prototype Fabrication

We will first pull a few sets of dummy parts off of tool to verify bag (bleed) technique. I will include a test (material property) in contingency at this phase. Bleed method will not change for tooling iterations.

Once we have determined that bleed and lamination techniques have settled can start pulling measurable parts off of tool and subject them to geometry tests to determine direction for tooling iteration.

This step needs to be repeated for each tool-iteration, perhaps multiple times for sufficient statistics—if laminate is also varied, need to increase number to account for statistics…

I have assumed direct convergence on this with 3 iterations and no laminate studies—perhaps the contingency on this part of the schedule needs to be higher than on others, but should discuss model.

### Qualification

For the Omega, this feeds into the overall assembly. At some point we need to determine what exactly ‘flat enough’ is. This points toward an accelerated approach toward making a full assembly before final iteration of the Omega Tool and Laminate. This is a schedule issue not addressed in the cost estimate, but more affects profile than cost.

 For the purposes of the cost estimate, I have assumed that this is largely a geometry measurement task which moves lock-step with the prototype fabrication (on a smaller sample)—regardless of the over-arching decision process. We will need to CMM measure these parts in some quantity to determine we have a tool/part satisfactory for production—this will require a Survey Fixture.

### Tooling Iteration

Experience has shown that for some parts this takes more iteration than anticipated. I’m proposing a minimum of 3 tools (first version inclusive). The 3rd iteration I think should come after a first full assembly to see if we need to do better, making it possible to later cut from costs.

Each iteration will require some engineering (perhaps Hytec but currently embedded, thus LBNL) and ‘Management’interaction—you need to assess quality and risk. Cost wise, these are clear line items—schedule-wise this is somewhat open loop.

### Production Tooling

This should be simply the final prototype tool, however depending on schedule, it might be desirable to replicate the tools to increase production rate. I will include in contingency, but I doubt that’s needed (see below).

### Fabrication

Once a production tool shape is defined, this is a very simple part and they are small. If a tool holds 5, we can do 5/day. This is less than the Thermal Tile, so unless staves become critical path, do not see need for second tool

NOTE: Drawing specifies that CMM Data is required for EVERY SINGLE PART—I have assumed this is a bogus requirement that can be assured during prototype phase. I have explicitly included a CMM task in Contingency, but we might want to zero this.

I have also assumed that the material specification test per part is also bogus and simply ignored it (not even in contingency)

### Trim Tooling

It is unclear if this (and the associated process) is necessary, but it depends ultimately on the assembly tolerances.

Because Part lamination tool is ‘un-flat’ a flat-nominal tool needs to hold the cured part during trimming. This is either a vacuum chuck or a router guide—they cost the same so choice unimportant.

Will include in Base costing, but depending on discussion of assembly tolerances, may be able to zero this.

### Part Trimming

Machine operation—using tool above. May not be required based on understanding of latter assembly tolerances. Included, but zero if not needed.

## Bent D-Tube

I’m assuming that the base development work on this is not a part of this estimate, but I do include substantial prototype work. First for fitting insertions and then a single end-bend to assure we understand the process, then a 5-up tool for production. That said, this is a development that we either need to be guided by or do ourselves—a topic for discussion.

Despite the development required, the actual processes for production are pretty clear after some discussions with people familiar with them. A heated mold is required, and some pre-bending work is required to actually fit the parts in the molds. The shape and parameters of the molds (and tube shape) are immaterial to the estimate. I have assumed that we both install and leak check the fittings

NOTE: above comments on Tubing Batches—has impact on prototype and production tool shapes, thus iteration.

### Tube Fittings

Straightforward aluminum lathe part(s)—may be either barb or a compression collar. Cost is the same…

May need both prototype and production batches, but design change and batch size issues are negligible—can be costed as simple parts on a per-part basis.

### Basic Prototypes

This is potentially a can of worms, but I include for discussion. Experience on ATLAS shows that a number of tests are required—after basic tube shaping and fitting termination. Need to assure that tube shaping and fitting termination don’t interact to produce leaks, but need to qualify each independently—particularly for PEEK which has shape-memory issues.

To first order, I’m going to assume that much of this is handled outside of this scope—i.e. bend radii, wall-thickness and bend parameter (thermal) studies. We can do this, but to do so would require more work than I’ve assumed here.

We will still require some prototyping to assure we can make leak tight fitting to tube junctions (that survive the bending process), and I’m guessing you will want data supporting that fact, thus require the work. I have explicitly included simple fitting tests (with leak checks) and fitting tests with bend. As an auxiliary test I have included CMM measurements after thermal cycling to assure that the ‘memory’ of the PEEK has been addressed with the thermal profile of the process.

An extension of the prototype work is to make a full length tube (two bends and two fittings). One of the requirements stipulated in the drawings is a thermal cycle. Experience from ATLAS has shown, at least for general confidence) that a ‘Torture Test’ of the final geometry is useful data to have. I have included these here for the tube fittings and prototype staves (to test the fittings). This test is stipulated for EVERY SINGLE STAVE ASSEMBLY (with associated CMM data). I hope to address that concern in the prototype phase and the ‘Torture Tests’ are part of this staged process.

Note that the scalar result of the tube torture test is ideally a leak rate, so leak testing is the main effort for the torture test (otherwise just being cycled).

### Prototype Tooling

The prototype tooling described here is only to qualify the bend and process—will make simple end geometry first (small tool) before making (pre) production tool

The scope of this may change depending on whether we become responsible for also developing the tube fabrication.

### Pre-Production Tooling

Unfortunately, to actually make an entire prototype assembly, we need a ‘production shape’ tube and thus tool. I target this as a 5-up tool so that it could act as a production tool. I reduce risk by prototyping the full production shape, but this will interact with the tube batches, which is more of a schedule than a cost issue, but should be mentioned.

I will include the cost of an additional production tool in contingency.

### Prototype Part Production

This comes in two phases—first with the prototype tooling to understand the process, then with the ‘pre-production tooling’ in sufficient quantities to make the first few prototype assemblies.

### Production

Production tool is wholly in contingency—may zero based on assessment of risks and other contingency items.

#### Tube Prep

Assume that all tooling to insert fittings is complete, but will assume that ‘pre-bending’ to fit into the mold is also included in this task—also cut to length.

#### Part Molding

The tool should accommodate 5 parts. Tool needs to be loaded with parts (which might need pressure manifold), and cured in a platen press. Nominally this is a small labor component, but yield may be an issue depending on how well we understand the process.

I have added 20 tubes in Contingency to address yield issues

### QA (Leak Checks)

On ATLAS, this proved to be very time consuming. I do not know what your leak spec is nor the pressures the system must see. Nominally this includes both a proof and leak test at every stage of the assembly. This can be overdone, but also underdone which puts it back on the critical path later, and with dire consequences.

I will only include a moderate amount of vacuum leak checking (no proof), but this is something which needs to be defined better.

## Mount Blocks

Simple Machined parts—assume PEEK, but simple production. Need to include cleaning/surface prep for later bonding—will appear as ‘Shop’ cost in bonded assembly.

While this item appears in the ‘components’ section of this paper, I will include it lower in the cost estimate—in the prototype and production stave assemblies.

# Deliverable Assemblies

This is the final assembly process. There are two strategies—accurate bonding or accurate machining. Either will cost about the same, but have differing procedures. In the end, it’s always the quality assurance requirements that can hang up a schedule…

I have made some assumptions about the assembly procedure. I do not know how the tube and omega will be joined to the tile. I have assumed that the back-side of the tube (omega side) is dry, and that the thermal compound and omega-to-tile adhesive are co-applied and co-cured. I have included in contingency an auxiliary tool and method (potting) which may be required based on what the tube shape and adhesive properties turn out to be—i.e. if my assumed procedure is impossible. This needs discussion.

I have pulled the tooling of each of the following assembly stages up into a ‘tooling section’ but these are described below.

Some Prototype Effort is suggested. I have assumed a run of 5, but this needs to be discussed, and has schedule impacts, i.e. how to get enough tooling early enough to actually make a full pre-production prototype…

I have also included in contingency an auxiliary batch of 20 staves to address yield issues, but this is a number which should be discussed (totally arbitrary on my part)

## Omega/Tube Sub-Assembly

This assembly assumes that both Omega and Tube are simultaneously bonded to the Thermal Tile. There is no cost difference to this tool or procedure if only the Omega is bonded and the Tube later potted in the void, however there would be the additional, approximately equal effort to later pot the tube into the omega. I have included this in contingency, but describe only the former below.

### Bond and Glue Application Fixture(s)

This is largely a block of Aluminum which sits in a robotic stage that holds both the tube and omega in place relative to the robot’s axes. Some programming and iteration is required to deposit the correct beads of differing adhesives (Loctite and Hysol adhesives will vary in deposition parameters). Some prototyping with glass-slides is required to tune the proper volumetric deposition. Aging thru batch life, particularly of the thermal compound, usually requires re-programming of the deposition rates.

## Bare Stave Assembly

This is everything but the mount reverences. I have assumed that this would be built first then the mount blocks attached. This gives the freedom of both bonding the blocks accurately or ‘willy-nilly’ and machining the required accuracy in place. I prefer an accurate bond tool, but depending on how the drawing tolerances are interpreted one is lower risk than the other. I have assumed accurate bonding (higher risk) and put accurate machining into contingency.

### Omega to Thermal Tile Bond Fixture and Procedure

This is nominally a ‘structural’ bond, i.e. does not require accuracy; however this depends on how the drawing is interpreted. I’m assuming the maximal leeway, but the cost difference is minimal—perhaps requires trimming of Omega and CMM survey of tool (this is where some discussion is required), but cost of tool is similar regardless.

Process is simple—load tool with parts (glue applied to omega/tube) and slap together. A Second tool is placed in contingency to increase rate, otherwise 1 per day.

### QA Data

Unclear what level of QC Documentation is required at this stage? I have included none, but allowed extra time during prototypes (5) to accrue bond-thickness, etc. Production has no QC for this step—assume tooling is qualified during prototypes.

## Stave with Mount Blocks

This is the final article. The drawings specify a dual level of QC, i.e. flatness before and after a thermal cycling regime for production parts. I have ignored this in deference to a thoroughly qualified set of prototypes whose cost I include. I have mentioned that I was unsure what procedure would best meet your tolerances as specified in your drawings and I discuss both methods below. I have included the ‘machining’ option in contingency.

I have added a step, not explicitly defined in the drawings, but inferred by one of the notes—coating of exposed cut surfaces with ‘epoxy’. On ATLAS we have used parylene coating—a vapor deposited poly-imide rather than manually trying to seal surfaces. I’m assuming this is to reduce possibility of graphite debris in the environment.

### Bond Fixture and Bonding

Cost model for this is same as for Omega to Thermal Tile—same size, and features, but includes additional CMM survey

Rate unclear, but only included 1 tool, thus 1/day—simple bond operation, so rate dominated by cure unless tool size or number increased.

### Machining Fixture

Datums as specified on drawing include Tile, Omega, and Mount Block Edge. One way to achieve this reference (if required)\_is to co-machine them with the mount hole feature. Need a vacuum chuck to achieve this. Might also need to adjust part sizes to allow them to be machined later—this is a process that needs some discussion

Currently all in contingency—both procedure and tooling

### Survey Fixture

Need some fixture to make survey of 50+ items routine. Discussion of details is important, but basically it’s a chunk of aluminum with machined features that has been surveyed on a CMM. Cost is easy, details are more difficult…

### QA Data

This is a potentially costly activity… As mentioned earlier, drawings stipulate geometry data req’s after thermal cycle—this doubles this activity, and adds labor for the thermal cycle. I have assumed that this is qualified during prototype, and only a final CMM measurement of each serial part is required

### Parylene Coating

This is to coat the surface of each final assembly with a non-conductive and encapsulating film to prevent shedding of conductive particles which might affect the wire/bump bonds of various electrical components within the detector. This is a batch process, and we need to provide a porous support structure which the vendor can place in their reaction chamber. This is the fixture cost, and I assume a batch of 10 units. Batch includes shipping/handling to and from vendor.

## Shipping

I know this seems trivial, but for ATLAS this was a large expense—boxes and shipping. I include only because it was in my template, but it is a few $k so seems reasonable to track…