	US ATLAS HL-LHC Upgrade BASIS of ESTIMATE (BoE)	**Date of Est:** **03/05/2020 DRAFT**
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		Docdb #: HL-LHC-doc-328-v20 **DRAFT**

WBS number: 6.2.1	**WBS Title: Strips Tracker Stave Cores**

WBS Dictionary Definition:

This WBS item is for the fabrication of the stave cores for the barrel strips tracker. The cores are the thermal and mechanical support structures for the barrel modules (WBS 6.2.4). The cores also include the electrical services between the end-of-stave electrical connections, and all the modules. These services are contained on a copper kapton laminate “Bus Tape” which is manufactured as a flexible PCB as part of this activity. The stave cores are composed of a lamination – from top-to-bottom – of the copper-kapton bus tape, a carbon fiber facing, honeycomb, carbon foam, titanium cooling pipe, a carbon fiber facing, and another bus tape.

This WBS item covers the prototype, pre-production and production of the stave cores and their components. The USA will supply 50% of the barrel stave cores installed in the detector (the rest will be fabricated in the UK) totaling 196 units. The participating institutions are LBNL, Yale University, Iowa State University, and the University of Massachusetts Amherst. The tasks include: procurement and inspection of the tapes, fabrication, test, and inspection of the facings (LBNL 6.2.1.2.1), procurement and preparation of internal components, and lamination of the cores (Yale 6.2.1.5.2), and quality assurance (Iowa State 6.2.1.6.3, UMass Amherst 6.2.1.10.1). The completed stave cores are sent to BNL where they are used in stave electrical assembly (WBS 6.2.5).

Estimate Type (check all that apply – see BOE Report for estimate type by activity):

___ Existing Purchase Order or Work Completion
_X_ Engineering Build-up
_X_ Extrapolation from Actuals
_X_ Analogy
_X_ Expert Opinion

Supporting Documents (including but not limited to): Attachments X-Y
Attachments 1-8

Details of the Base Estimate (Explanation of the Work)

Summary

The stave core assembly is composed of a lamination – from top-to-bottom – of the copper-kapton bus tape, a carbon fiber facing, honeycomb, carbon foam, c-channels, end closeouts, titanium cooling pipe, a carbon fiber facing, and another bus tape. Locking points are inserted for final installation into the barrel. See Figure 1 for details.

The bus tape is purchased from a vendor, inspected, and measured for physical dimensions at Lawrence Berkeley National Laboratory (LBNL). Following inspection, the bus tape is co-cured onto a carbon fiber facing and measured again. The co-cured tape is expected to stretch within tolerable limits. After co-cure, the facings are sent to Yale University (Yale) to for core assembly. The facing is further tested at Yale for electrical continuity and high voltage resistance. Yale fabricates the necessary honeycomb and carbon foam parts needed for core assembly from raw materials purchased from vendors. C-channels, end closeouts, titanium cooling pipe, and locking points are supplied by the United Kingdom (UK). The parts are laminated together with epoxy to form a core. The core is testing for physical dimensions, structural integrity, thermal properties, electrical continuity, and high voltage resistance. Cores that pass all tests satisfactorily are sent to Brookhaven National Laboratory (BNL) for module loading.

The US is responsible for supplying the UK with bus tapes, honeycomb, and foam. As mentioned previously, the UK supplies c-channels, end closeouts, titanium cooling tubes, and locking points. See figure 2 for details.

Work prior to the Preliminary Design Reviews (PDR)

Stave core prototype design and construction initially began at LBNL and BNL a decade ago. By 2018, the project also included Yale, Iowa State University (ISU), and University of Massachusetts Amherst (UMass). Multiple varieties and sizes of cores were assembled to test structural, thermal, and electrical properties. LBNL focused on bus tape design and co-curing procedures; BNL, ISU, and UMass on quality assurance and control techniques; Yale on core assembly.

A similar effort was being conducted by colleagues in the UK—Oxford, Liverpool, Sheffield, Lancaster, and Queen Mary. In 2016, the responsibility for the final core design was awarded to the UK. The first version of the core held 13 modules per side and included several iterations of bus tapes. From 2016-2018, 26 of these cores were assembled—16 in the UK and 10 in the US.

At LBNL, co-cure methods were scrutinized, and results compared to those in the UK. QA/QC testing systems were developed at ISU following work previously done at BNL. The testing methods consisted of local flatness measurements, detection of delamination in the structure, and determination of thermal properties. In addition to assembling 10 cores, Yale duplicated the ISU testing systems. UMass began planning the construction of a robot to test electrical properties of the facings and completed cores. Major components of the robot, stages and drives were purchased through Yale.

Prior to the PDRs, a base change was made to increase the length of the cores to include 14 modules per side. This increase in length did not significantly change the base design of the core.

Bus tapes and cores are covered under separate PDR's within the ATLAS Upgrade Structure. The bus tape PDR was successfully completed in April 2018 and the stave core PDR in October 2018. Satisfactory completion of both PDRs designated the start of the 14-module prototyping phase. The reviews specified a set of action items to be completed before the FDR that included locking point and overall core stability, cooling modeling and performance, co-curing methodology, and delamination detection.

Prototype Phase

The prototyping phase is used to demonstrate that the designs of the bus tapes and cores meet structural, thermal, and electrical specifications. Assembly, procurement and testing (QA/QC) procedures are finalized. The prototyping phase concludes with a Final Design Review (FDR).

LBNL purchases tapes of the new 14 module design, sends half to the UK, and co-cures facings for core assembly at Yale. Dimensional measurements are made to determine if the bus tape length falls within established specifications following co-cure. LBNL continues to improve the co-cure process in conjunction with the UK, a PDR action item. Yale fabricates one set of new 14-module core tooling and improves the thermal imaging and flatness testing stations. Six prototype cores are assembled and tested. Four cores are sent to BNL for module loading. ISU continues quality assurance efforts by performing slow and fast thermal cycling tests re quired for quality assurance (QA). ISU completes a thermal Finite Element Analysis (FEA) of the End of Stave (EOS) region, where the cooling requirements are most critical. UMass constructs and commissions the tape testing robot that measures electrical continuity and high voltage resistance of the co-cured bus tape and completed cores. The robot moves to Yale following commissioning.

The thermal imaging system consists of an acrylic box, chiller, and thermal camera. The core is cooled via the chiller and bad glue lines in the foam appear as thermal hot spots. A thermal profile of each core can be obtained and compared to the thermal FEA, a PDR action item. The flatness measuring system incorporates the use of a coordinate-measuring machine (CMM) at Yale. The use of a CMM substitutes for the ISU system, which demonstrated reliability issues during implementation at Yale. This system uses a laser that projects a structured illumination pattern consisting of closely spaced parallel lines projected onto the surface and imaged. The ISU system will primarily be used for delamination studies of the honeycomb following a large number of temperature cycles, a PDR action item. These tests on Core #2r, a core with intentionally placed defects, determined the need for a high granularity test such as ultrasound or x-ray is not required. Successful pull tests on wire bonds with defective glue joints performed in the UK also supported this conclusion.

The bus tape FDR occurred in September 2019. Vendor selection and bus tape Y-distortion were identied as follow-up actions. The core FDR occurred in February 2020. Initial reports are the review was successful, but the official report has not been released. Successful completion of the FDRs initiates the Pre-production phase.

Pre-production Phase:

As part of the international ATLAS tracker construction project, pre-production is used to demonstrate production quality for all components and to satisfy and document site qualification requirements. This requires all processes and quality assurance methods to be in place over the course of pre-production. Pre-production will culminate in the Production Readiness Reviews for bus tapes and cores, expected in late 2020 and early 2021.

Vendor selection is an action item from the FDR, after Altaflex changed business direction. Altaflex has work with the project for more than 10 years. A vendor search found 5 companies capable of producing bus tapes this long. Tapes from all five companies were purchased and electrically and mechanically tested. LBNL plans to place small orders with 2 vendors early in pre-production, then choose a single vendor for production based on quality and pricing.

The second action item from the FDR was Y-distortion issues with the bus tape after co-cure. LBNL is developing tooling to correct this distortion by using pins to hold the tape in place on the jig.

Yale plans to fabricate an additional set of assembly tooling needed for production. Lamination and testing of 10 pre-production cores are planned. Throughout the process, procedures will be tuned to gain efficiencies in all processes. Training and practice are focused on optimizing the build and inspection processes to meet the required throughput which is expected for the production phase. UMass will supply un-costed labor to Yale in support of electrical testing of the facings and stave cores.

The PRR for the bus tapes is scheduled for September 2020 and the core PRR for February 2021. Successful completion is needed to progress to Production.

Production Phase

Production is planned to begin in January 2021 for bus tapes and June 2021 for cores. The goal of production is to produce the components and laminated staves as quickly as possible. The total number required from the USA is 196, however, we plan for a 5% yield loss due to either thermo-mechanical failures of the core, or electrical assembly failures during subsequent module loading. This yield is calculated based upon experience assembling stave cores both in the USA and in a parallel effort in the UK, adjusted for the difference between prototype and production yields based on past experience, and experience with module loading and electrical performance. Therefore, 227 cores will be constructed. The number of cores delivered to BNL is 206. See Table 1 for component quantities and yield factors.

The US is responsible to provide the UK with 491 bus tapes as well as enough honeycomb and carbon foam to build 227 cores. The UK provides c-channels, end closeouts, titanium cooling pipes, and locking points to the US. See Figure 2 for details.

The stave cores will be loaded with modules at BNL over the full course of the production period. The maximum length of that period is set by the rate of module production and stave core loading and is explained in the BOE for modules. It is however more efficient and economical to fabricate the stave cores in a shorter period during by saturating the available effort and completing the project as quickly as possible. We require an output of 6-7 completed cores per month over a 3-year production period to meet this requirement. This corresponds to approximately one completed core every 3-4 days.

The final design of the bus tape is the responsibility of the UK but will be fabricated by the chosen vendor following pre-production trials; total quantity of 982. The tapes will be inspected at LBNL on an optical system already developed as part of generic R&D for future high throughput detector projects. The expectation is that tapes can all be produced within two years.

The current schedule and cost estimates are based on the previous agreements with Altaflex. The estimates may change with a new vendor.

According to the vendor (Altaflex):

"…we would start with 25 pieces the first month and gradually increase to 50 or more within a few months. After about six months, we should be able to ship approximately 100 pieces per month"

Accordingly, we would allow the ramp to occur early in production and plan to receive 100 cables per month for the duration until the full production is complete (Altaflex will produce, and we will inspect all the bus tapes needed for the ATLAS barrel (100%) but we will send 50% of them to the UK.) This production will therefore complete in FY22.

As discussed previously, the tapes are known to change length during co-cure. For this reason, the design of the tape is calibrated to the tape fabrication such that the tapes arrive appropriately dimensioned. Prior to co-cure, the tapes will be inspected on the custom optical system to screen for the proper pre-cure length, at LBNL. With 100 tapes arriving per month we plan to inspect ten per day. The LBNL optical inspection system requires 10 minutes to scan a single tape. Experience from the R&D has shown that about 10% of the tapes are out-of-spec for length and therefore an overage will be ordered. Work is underway to determine the electrical yield and the appropriate factors for that as well, however the vendor does an electrical inspection, so this factor is expected to be small. Subtle electrical failures (ie: hairline cracks in traces) may only manifest after the stretch during co-cure so will be inspected on the Oxford tape robot at Yale and are included in the yield calculation for facings.

The tapes and facings will be co-cured at LBNL. Respecting the yield loss which may occur during co-cure, in electrical inspection, and with completed cores, we will produce 227 pairs of facings, to supply 206 cores to BNL [Table 1]. LBNL also supplies the same number of facing pairs (227) to the UK. This factor is determined from experience during the co-cure R&D and prototyping phase. The co-cure process occurs overnight in an autoclave at elevated temperature and pressure. We plan to co-cure 5 facings per overnight batch. In this way, all the facings can be completed within about 2 years, allowing for some downtime for the autoclave and its periodic use for other projects. Prior to co-cure the layups and bus-tapes have to be prepped and stacked.

While the tapes will have been inspected at LBNL before co-cure, they will next be inspected at Yale using the tape testing robot. This inspection will confirm whether a) the tapes have stretched appropriately based upon the pre-production calibration, and b) whether any fissures have opened in the traces due to the stretching process. This inspection requires 2 hours per facing. Once the facings have passed the inspection process they are ready to be laminated into a stave core.

The additional components – foam channels, honeycomb, c-channel, will be fabricated from raw materials in the Yale shops, at a rate which matches the 6-7 cores laminated, per month. Closeouts, locking points, housings, and cooling pipe assemblies will be provided by the UK.

The lamination of the stave core includes several gluing and curing steps. The cures occur at room temperature, overnight. These cures extend the lamination and testing processes over 7-8 days. Consequently, to meet the 3-4 days/core rate we run the process in parallel with multiple cores in a staggered production line.

Once the stave core is completed it will again be inspected on the tape robot for dimensional and electrical characteristics. It will then undergo additional inspections to probe thermal characteristics, and mechanical properties.

Table 1: Component Quantities and Yield Factors in Production

ITEM	Quantity	Yield Factor
US Staves in ATLAS	196	1.05
US Staves to be delivered to CERN	206	
US Staves to be assembled at BNL	206	1.10
Core to be assembled at Yale	227	
Facings supplied to Yale (cores x 2)	454	1.08
Bus tapes needed at LBNL	491	
Bus tapes needed for production (US & UK)	982	
Total bus tapes to order	982	

A stave core overall assembly drawing is shown in Figure 3 but the full detail and separate components is covered in a set of 64 drawings.

Figure 1: Barrel Stave Core

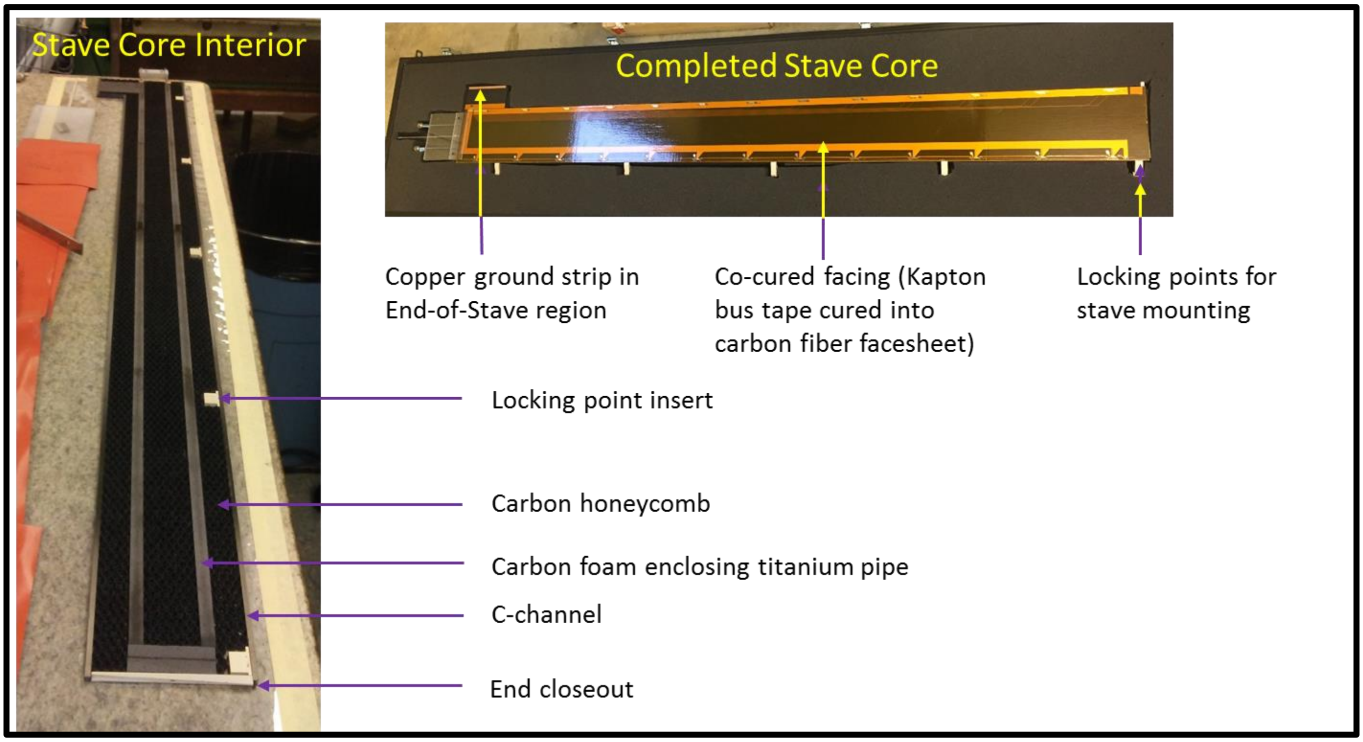


Figure 2: US and UK Component Responsibilities

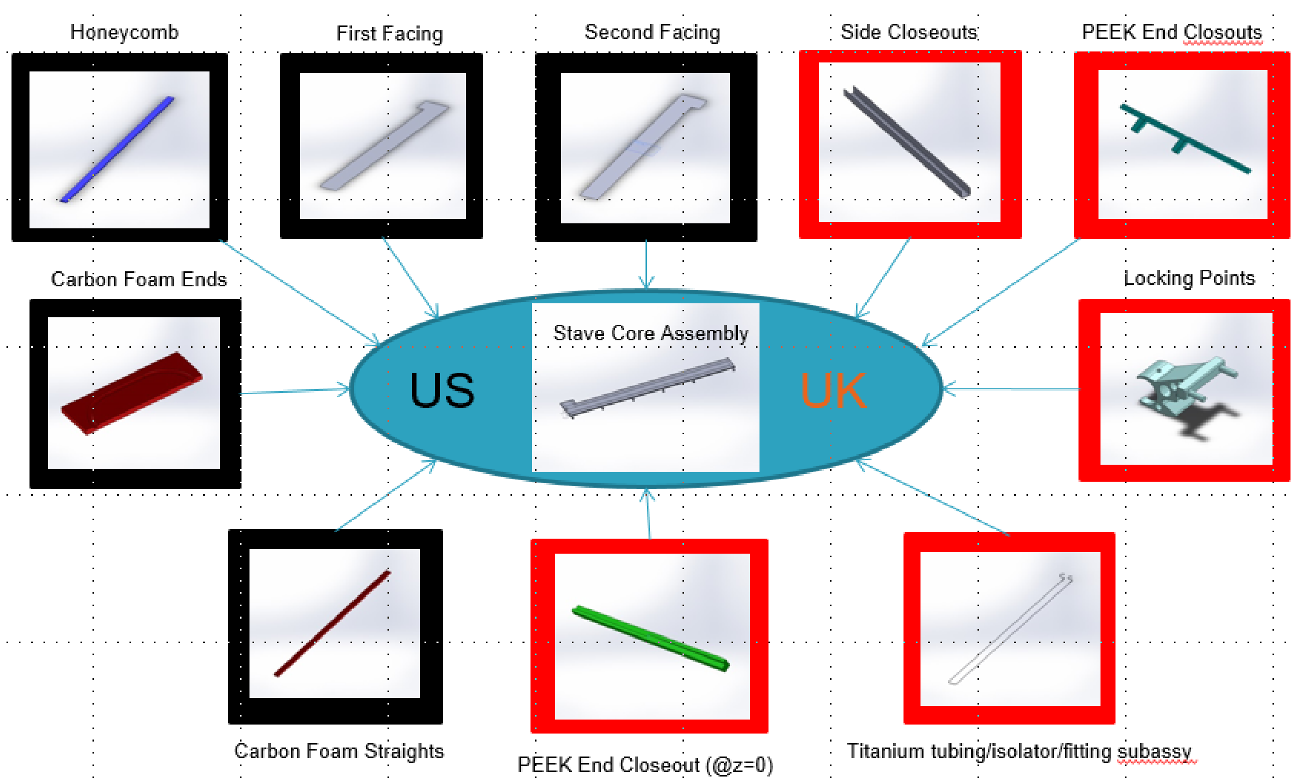
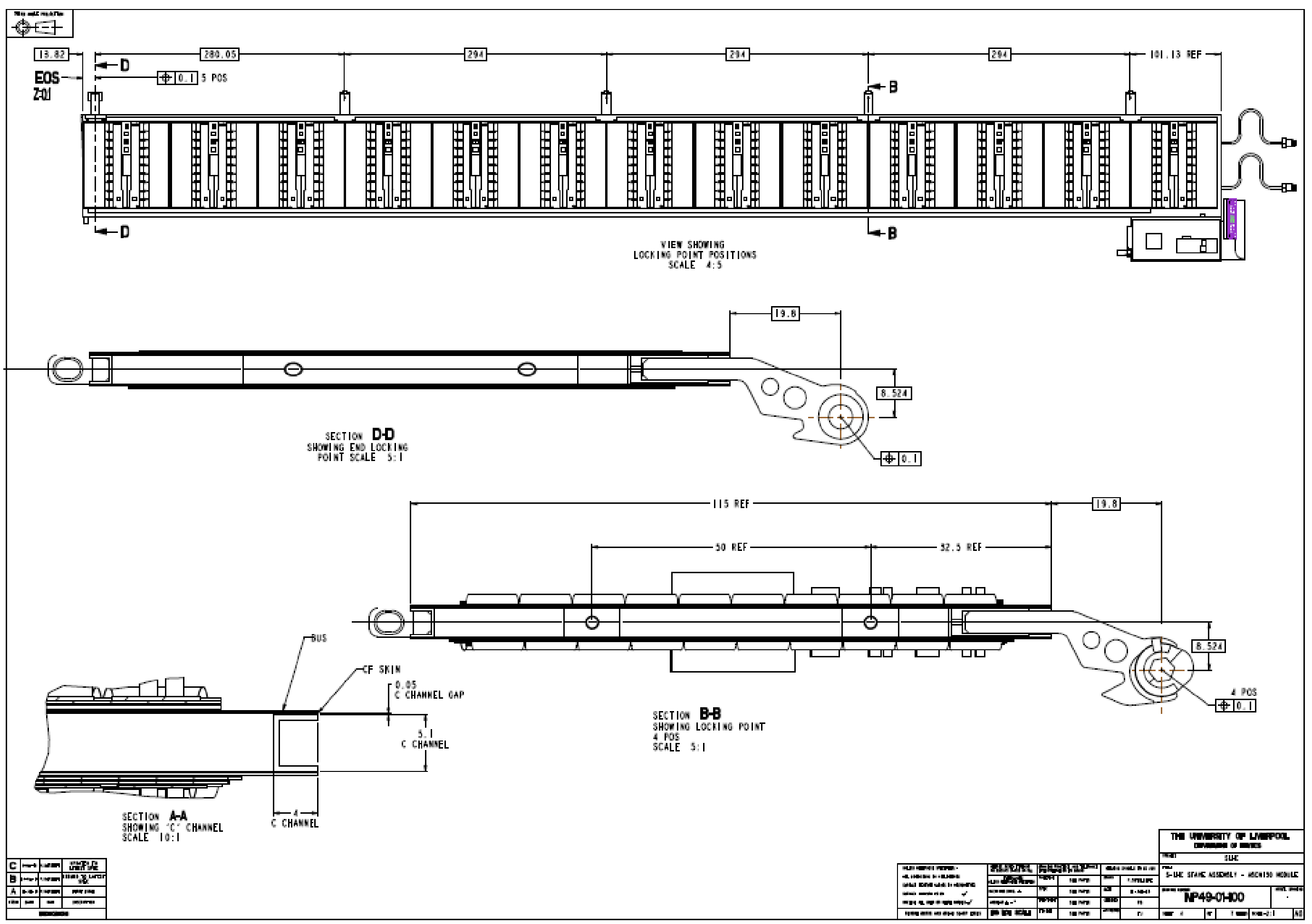


Figure 3: Stave Core Assembly Drawing



Cost Estimate Description

Table 2 is an output from P6 that lists total labor hours and direct material costs, separated into categories of engineer, equipment, materials, technician and un-costed.

Table 2: Labor Hours and Materials

	Lbr Hours	MAT Base	TRAV Base
6.02.01.02.01 / LBNL Stave Core LBNL - Facings & Bus Tapes	**5,164**	**322,563**	
ENG	680		
EQUIP		74,220	
MAT		248,343	
SCI	954		
TECH	3,530		
6.02.01.05.02 / YALE Stave Core Yale - Stave Cores Laminated	**24,476**	**930,327**	**16,974**
ENG	5,058		
EQUIP		448,937	
MAT		481,390	
SCI	1,586		
TECH	17,832		
TRAVF			16,974
6.02.01.06.03 / IAST Stave Core Iowa State - Stave Cores Inspection Sy	**6,828**		
SCI	6,340		
TECH	488		
6.02.01.10.01 / UMAS Stave Core UMAS	**1,416**	**2,971**	
ENG	758		
MAT		2,971	
SCI	658		
6.02.01.32 / LBNL Stave Core LBNL - CD-3a	**332**	**81,477**	
ENG	56		
MAT		81,477	
SCI	112		
TECH	164		
6.02.01.35 / YALE Stave Core Yale - CD-3a	**1,988**	**748,800**	
ENG	358		
EQUIP		589,860	
MAT		158,940	
SCI	60		
TECH	1,570		
6.02.01.90 / YALE L3 Project Management	**2,897**		
ENG	1,943		
SCI	954		
Grand Total	43,101	2,086,138	16,974

<u>Prototype Phase Costs</u>

Prototype phase material cost estimates are listed in the BOM (attachment 1, items 1-5, 8-9) and detailed in attachments 2-3 and 5-6. The cooling loop, locking points, housings, c-channels, and end closeouts are sourced from our colleagues in the UK as an in-kind trade, we do not cost these. The US provides the UK with bus tapes. Labor estimates are determined from similar work completed with 13-module cores, approximately 120 labor hours for assembly and testing.

LBNL purchases prototype bus tapes from vendors. [Table 3]. Half of the bus tapes are shipped to the UK. Tapes are co-cured and shipped to Yale for prototype core assembly. Other tapes are retained for QA testing. Labor estimates for prototype work at LBNL is 0.3 FTE; technician, engineer, and scientist.

Table 3: Prototype Core Material Costs

Item	Source	WBS	Part Name	Att	Unit Price	Quantity	Cost
5	Altaflex	SC200328M, 342M, 352M	Bus Tape	3	$ 870	34	$ 29,769
7	Ultracor	SC500700M	Honeycomb	5	$ 984	17	$ 17,275
8	Allcomp	SC500710M	Carbon Foam	6	$ 338	17	$ 6,900
			Total Cost				$ 53,944

Yale fabricated one set of assembly tooling. Further modifications and upgrades to the thermal imaging and flatness measuring systems were made. UMass constructs and commissions the tape testing robot [Table 4]. Labor required to complete these tasks is shown in Table 5.

Table 4: Tooling and Testing System Costs

Item	Institution	WBS	Part Name	Attachment	Unit Price
1	Yale	SC500658M, 709M	Thermal imaging station	2	$ 22,800
2	Yale	SC500664M, 703M, 739M	Assembly tooling	2	$ 48,300
3	Yale	SC500681M, 749M	Flatness station	2	$ 14,200
4	UMass	A70240M	Tape testing robot	2	$ 2,800
		TOTAL			$ 88,100

Table 5: Labor for Tooling and Testing Systems

Tooling/Fixtures	Institution	Labor Hrs
Flatness testing station	Yale	456
Thermal testing station	Yale	548
Tape testing robot	Yale	104
Tape testing robot	UMass	1416
Assembly tooling	Yale	336
Documentation	Yale	498
Total		3358

Yale assembles 6 prototype cores and ships 4 to BNL for module loading. The remaining 2 cores are used for QA testing. Honeycomb and foam costs are listed in Table 3. Assembly labor is listed in Table 6.

Table 6: Labor Hours for Core Assembly

CORE	WBS	# cores	Assembly (hrs)	Ave (hrs/core)
1	SC500745	1	200	200
2	SC500771	1	120	120
3	SC500805	1	128	128
4	SC500810	1	120	120
5	SC500850	1	120	120
6	SC500940*	1	120	120
		6	808	135

*prototype core 6 only

Pre-production Phase Costs

Material cost estimates for the pre-production phase are listed in the BOM (attachment 1, items 2, 5) and detailed in Attachments 2-3. The cooling loop, locking points, housings, c-channels, and end closeouts are sourced from our colleagues in the UK as an in-kind trade, we do not cost these. The US provides the UK with bus tapes, 2 per core. Enough honeycomb and foam remain from the prototype phase. Labor estimates are based on similar work completed on 13-module cores, approximately 120 hours per core for assembly and testing.

LBNL purchases 71 bus tapes, inspects, and sends half to the UK [Table 7]. Of the remaining, 32 are co-cured, inspected, and shipped to Yale for core assembly [Table 8].

(need to update table to BP-31)

Table 7: Pre-Production Core Material Costs

Item	Source	WBS	Part Name	Att	Unit Price	Quantity	Cost
5	Altaflex	SC200360M, 385M, 394M, 398M	Bus Tape	3	870	71	$ 62,324
			Total Cost				$ 62,324

Table 8: Labor Estimates for Co-cure

Batch	WBS	# Tapes	# Co-cure	Total (hrs)	Ave (hrs)
1	SC200387	16	8	134	17
2	SC200396	16	8	134	17
3	SC200398	16	8	134	17
4	SC200400	16	8	134	17

Yale fabricates additional assembly tooling needed to meet the demands of production [Table 9]. Ten pre-production cores are assembled and tested. Testing includes thermal imaging for detection of foam delamination and determination of thermal properties. Flatness measurements are performed on a CMM.

Labor required for assembly and testing of cores during pre-production are listed in Table 10. UMass provides 1un-costed labor for electrical testing using the robot tape tester.

Table 9: Fixture/Tooling Costs

Item	Institution	WBS	Part Name	Attachment	Unit Price
2	Yale	SC500890M	Assembly tooling	2	$ 70,000
		TOTAL			$ 70,000

Table 10: Pre-Production Labor Hours Summary—Core Assembly at Yale

CORE	WBS	# cores	Assembly (hrs)	Ave (hrs/core)
1	SC500940*	1	169	169
2, 3, 4	SC500990	3	353	118
5, 6, 7	SC501060	3	353	118
8, 9, 10	SC501090	3	353	118
		10	1228	123

*pre-prod core 1 only

<u>Production Costs</u>

Component costs are detailed in the BOM (items 6-9) included in Attachment 1. Individual quotations are provided in Attachments 3-6. The cooling loop, locking points, housings, c-channels, and end closeouts for 227 cores are sourced from our colleagues in the UK as an in-kind trade, we do not cost these. The US provides 491 bus tapes as well as honeycomb and foam for 227 cores. Estimated material costs during production are outlined in Table 11.

Labor estimates for bus tape inspection and co-cure, as well as core assembly and testing has been studied in the prototyping phase and documented in “Stave Core Assembly”, a CERN EDMS document (Feb 2020). Comparisons have also been made to core assembly times provided by the UK. The US and UK agree that the lamination process takes 5-6 days. Experience at Yale determined that nearly half a day is needed for individual component receipt, inspection, and preparation. Circuit testing times were provided by Oxford and estimated at a total of a full day per core, which includes initial testing of bus tapes and the full core. Experience at ISU demonstrated that 1 day is needed to complete all thermal and mechanical inspections. In total, the core assembly process takes 7-8 days (approximately 120 labor hours). Revisions to these estimates may be made as experience is gained during the pre-production phase.

Table 11: Production M&S Costs

Item	Source	WBS	Part Name	Att	Unit Price	Quantity	Cost
6	Altaflex	SC200474M	Bus Tape	3	$ 598	50	$ 30,000
6	Altaflex	SC200475M	Bus Tape	3	$ 598	680	$ 407,000
6	Altaflex	SC200485M	Bus Tape	3	$ 598	252	$ 166,000
7	Tencate	SC200510M	Pre-preg	4	$ 556	68	$ 37,800
7	Tencate	SC200720M	Pre-preg	4	$ 556	70	$ 39,000
7	Tencate	SC201000M	Pre-preg	4	$ 556	54	$ 30,000
7	Tencate	SC201210M	Pre-preg	4	$ 556	54	$ 30,000
8	Ultracor	SC501204M	Honeycomb	5	$ 984	151	$ 149,000
8	Ultracor	SC501600M	Honeycomb	5	$ 984	151	$ 149,000
8	Ultracor	SC501940M	Honeycomb	5	$ 984	152	$ 149,000
9	Allcomp	SC501210M	Carbon Foam	6	$ 338	147	$ 49,816
9	Allcomp	SC501610M	Carbon Foam	6	$ 338	151	$ 51,312
9	Allcomp	SC501950M	Carbon Foam	6	$ 338	156	$ 52,852
			Total Cost				$ 1,340,780

Production labor costs are grouped into two parts: co-cure and inspection at LBNL and parts preparation, core assembly, and testing at Yale. The co-cure process consists of the following steps:

- Receive bus tapes at LBNL
- Optical inspection (0.6 hr/tape)
- Ship 50% to UK (0.2 hr/tape)
- Multiple co-cure process (4 hrs/tape)
- Optical inspection (2 hrs/facing)
- Ship to Yale (1hr/facing)

The process was developed during the 13-module prototyping phase and extended to include multiple co-cure simultaneously during pre-production. Co-cure prep includes cutting and sorting the carbon fiber sheets, preparing tape, flash break, and plastic sheets for blocking, masking, and vacuum bagging. Co-cure is performed in an autoclave at elevated temperature and pressure. Co-cure activities are overseen by an un-costed research scientist and directly supervised by a mechanical engineer. A software development engineer will support the inspection aspect. The remaining work will occupy a single dedicated technician.

Production quantity will ramp up during the first 6 months of production to a stable level. Production will be completed in roughly 18 months. Table 12 summarizes the estimated labor hours needed to inspect tapes, co-cure multiple tapes, inspect facings, and ship to Yale. The average time needed to co-cure a tape and facing is estimated at 6 hours.

Table 12: Labor Hours Summary—Tape Inspection and Co-Cure at LBNL

Batch	WBS	Tapes #	Inspect (hrs)	Ave (hrs)	Co-cure #	Co-cure (hrs)	Inspect (hrs)	Total (hrs)	Ave (hrs)
1	SC200490, 510, 520	25	32	1.3	12	48	32	80	7
2	SC200560, 580, 590	25	20	0.8	13	56	24	80	6
3	SC200630, 650, 660	25	20	0.8	12	48	68	116	10
4	SC200700, 720, 730	50	32	0.6	25	74	32	106	4
5	SC200770, 790, 800	50	32	0.6	25	44	32	76	3
6	SC200840, 860, 870	50	32	0.6	25	58	32	90	4
7	SC200910, 930, 940	100	52	0.5	50	204	86	290	6
8	SC200980, 1000, 010	100	52	0.5	50	204	86	290	6
9	SC201050, 1070, 080	100	52	0.5	50	204	86	290	6
10	SC201120, 1140, 1150	100	52	0.5	50	204	86	290	6
11	SC201190, 1210, 1220	100	52	0.5	50	204	86	290	6
12	SC201260, 1280, 1290	100	52	0.5	50	204	86	290	6
13	SC201340, 1360, 1370	100	52	0.5	50	204	86	290	6
14	SC201410, 1430, 1440	57	52	0.9	29	204	86	290	10
	Totals	982	584	0.6	491	1960	908	2868	6

At Yale, the stave core assembly and testing process consists of the following steps, followed by the associated number of labor hours in parenthesis (120 labor hours in total):

- Day 1: receipt, inspection, and preparation (16 hrs.)
  - foam, c-channels, and honeycomb components
  - locking points and inserts
  - pipe assemblies
  - facings (tape testing robot)
- Day 2: glue tube/foam subassembly (16 hrs.)
- Day 3: glue tube/foam subassembly, c-channel, locking point inserts, end closeouts to facing (16 hrs.)
- Day 4: glue honeycomb core (16 hrs.)
- Day 5: machine the partially built core and glue on the top facing (16 hrs.)
- Day 6: testing (16 hrs.)
  - facings (tape testing robot)
  - thermal
- Day 7: Complete thermal testing (16 hrs.)
  - Glue locking points
- Day 8: Flatness testing (8 hrs.)

The assembly process of a single core is dominated by the drying time of the epoxy, usually set to dry overnight. To meet the demands of production (1 core every 3-4 days), 3 assembly lines are planned, all running in parallel. The assembly lines will also run in parallel with inspections, testing, and shipping. The assembly process will be supervised by mechanical engineers. The preparation, lamination, machining, cleaning, and inspecting tasks will require the efforts of multiple technicians. This parallel process will be implemented and refined near the end of pre-production.

Table 13 summarizes the labor hours for each batch of cores. The rate of assembly slowly ramps-up during production and is completed in 3 years. The average time to assemble and test a core is estimated at 71 hours.

Table 13: Labor Hours for Core Assembly

Batch	WBS	# cores	Assembly (hrs)	Ave (hrs/core)
1	SC501290	10	898	90
2	SC501360	12	898	75
3	SC501400	12	928	77
4	SC501440	12	928	77
5	SC501480	12	928	77
6	SC501520	12	928	77
7	SC501670	13	928	71
8	SC501730	13	928	71
9	SC501770	13	928	71
10	SC501810	13	928	71
11	SC501840	14	928	66
12	SC501870	14	928	66
13	SC502010	14	928	66
14	SC502060	14	928	66
15	SC502090	14	928	66
16	SC502120	14	928	66
17	SC502150	14	928	66
18	SC502180	7	489	70
	Totals	227	16205	71

Scientific (uncosted) Labor

Scientific or un-costed labor plays a very important role in all phases of the project. At LBNL, a scientist provides expertise and oversight in support of the co-cure process. At Yale, an engineer provides oversight and management of core lamination, inspection, and testing systems. At ISU, a professor, post-docs, and graduate students contribute software development to the quality control process. Software development for the Oxford tape robot is provided by professors and graduate student from UMass Amherst. UMass involvement will continue throughout the production phase at Yale.

Shipping Costs

Typical shipping cost estimates are referenced in Attachment 7: tapes from LBNL to the UK, facings from LBNL to Yale, and cores from Yale to BNL and ISU. It may be desirable at times to hand deliver cores from Yale to BNL directly. A quotation is also included for a suitable shipping case.

Travel Costs

At Yale, costs are budgeted to cover travel for an engineer to the 2 main ATLAS meetings each year (ITk and/or AUW) typically at CERN. Travel costs are listed in Appendix 8.

Assumptions:

- Availability of bus tapes (single vendor)
- Sufficient availability of low density foam (single vendor)
- Availability of titanium cooling pipes from the UK

Schedule:

- Schedule is provided by P6

Risk Analysis: in risk registry

Comments: N/A

Attachments:

- Attachment 1: Bill of Materials
- Attachment 2: Estimate:
- Attachment 3: Vendor Quote: Bus tapes
- Attachment 4: Vendor Quote: CF facings
- Attachment 5: Vendor Quote: Honeycomb
- Attachment 6: Vendor Quote: Carbon Foam
- Attachment 7: Shipping Cost Estimate
- Attachment 8: Cost of Travel

Attachment 1: Bill of Materials

Item	Institution	Source	Part Name	Part #	Attachment	Qty/Stave	Unit Price	Quantity	Cost
1	Yale	Various	Thermal imaging station	Not assigned	2	N/A	$ 22,800	1	$ 22,800
2	Yale	TBD	Assembly tooling	Not assigned	2	N/A	$ 118,300	1	$ 118,300
3	Yale	Various	Flatness station	Not assigned	2	N/A	$ 14,200	1	$ 14,200
4	UMass	Various	Tape testing robot	Not assigned	2	N/A	$ 2,800	1	$ 2,800
5	LBNL	Altaflex	Proto/Pre-prod bus tape	RHS-14, LHS-14	3	2	$ 870	105	$ 92,093
6	Yale	Altaflex	Production Bus Tape	RHS-14, LHS-14	3	2	$ 598	982	$ 603,000
7	LBNL	Tencate	Carbon fiber facing material	K13D2U	4	1.836 m3	$ 556	245	$ 136,800
8	Yale	Allcomp	Foam	NP49-01-108, 125, 141, 142, 155	5	339 cc	$ 338	454	$ 153,980
9	Yale	Ultracor	Honeycomb	NP49-01-114, 115, 116, 140, 143	6	0.139 m3	$ 984	454	$ 447,000
			Totals						$ 1,590,973

Attachment 2: BTTR purchase order (to be added)

Attachment 3: Vendor Quotation: Bus Tapes (to be updated when vendor selection is made. Current P6 cost and schedule based on this quotation.)

Note: One pair of tapes per stave core. $845 ($FY17) each at pre-production quantities, $598 ($FY17) for production quantities.

Quotation

Altaflex

Carl Haber
Lawrence Berkeley Labs
MS 50B-5239
One Cyclotron Road.
Berkeley, CA 94720

Altaflex
336 Martin Avenue
Santa Clara, CA 95050
Phone: (408) 727-6614
Fax: (408) 988-8009

Quotation for Flexible Printed Circuits

Date	Quote Number	Terms	Salesperson
9/20/2017	21955	Net 30	Ferdie Robancho frobancho@altaflex.com

Description	Quantity	Lead Time	Price
PN: RHS-14	25 pieces	4 weeks	$845.00 each
PN: LHS-14	25 pieces	4 weeks	$845.00 each

Set up	Amount
Prototype Tooling	$543.75

Notes:

FOB Santa Clara

Subject to state and local sales tax if not for resale purposes
Valid resale certificate number required & statement are for resale purposes)
NRE and tooling is subject to state and Santa Clara County sales tax (9.00%)

Please Include Ship Method and account number (FedEx, UPS, DHL, etc) with Purchase Order
Sales Tax is Included on Tooling Per California Sales Tax & Usage Regulation 1525.1 and
Revenue and Taxation Code Sections 6007-6009.1 and 6010.5

Quotation Valid for 30 Days

Quotation

Carl Haber
Lawrence Berkeley Labs
MS 50B-5239
One Cyclotron Road.
Berkeley, CA 94720

Altaflex
336 Martin Avenue
Santa Clara, CA 95050
Phone: (408) 727-6614
Fax: (408) 988-8009

Quotation for Flexible Printed Circuits

Date	Quote Number	Terms	Salesperson
9/20/2017	21956	Net 30	Ferdie Robancho frobancho@altaflex.com

Description	Quantity	Lead Time	Price
PN: RHS-14	495 pieces*	25 pcs per month	$598.00 each
PN: LHS-14	495 pieces*	25 pcs per month	$598.00 each

Set up	Amount
Prototype Tooling	$543.75

Notes:

Parts are in individual pieces
Quotation is for bare flex circuit only

Lead time is in working days (Monday – Friday, excluding holidays)
FOB Santa Clara

Subject to state and local sales tax if not for resale purposes
Valid resale certificate number required & statement are for resale purposes)
NRE and tooling is subject to state and Santa Clara County sales tax (9.00%)

Please include shipping method and account number on purchase orders.

Please Include Ship Method and account number (FedEx, UPS, DHL, etc) with Purchase Order
Sales Tax is Included on Tooling Per California Sales Tax & Usage Regulation 1525.1 and
Revenue and Taxation Code Sections 6007-6009.1 and 6010.5

Quotation Valid for 30 Days

Attachment 4: Vendor Quote: Carbon Fiber Facings

(to be updated when new vendor quotation is received. Quantity of required material is also different from below. Current P6 cost and schedule uses information below.)

Note: The stave facings are 1.45m x 0.15m per layer. The facing needs 3 layers and the estimated wastage is 40%. The area needed per facing is 0.918 m^2. Two facings are required for each core. Cost per core is 1.836 x \$303 (\$FY17) = \$556. The quotation from the Tencate Advanced Composites is below.

TENCATE

ADVANCED COMPOSITES

Quotation

Bill To:
Lawrence Berkeley National Lab
Accounts Payable Dept.
1 Cyclotron Rd, MS971-AP
or APinvoice@lbl.gov
Berkeley, CA 94720
USA

Contact	Eric Anderssen
Phone	510-219-1480
Email Address	ecanderssen@lbl.gov

Page	1 of 2
Date	11/17/2016
Quotation Number	Q003016
Customer Reference	ALICE and LHCb
Salesperson	Kendall Oblak
Customer Service Representative	DeAnna Memeo
Mode of Delivery	Customer Routing
Delivery Terms	Collect
Payment Terms	NET30
Expiration Date	12/16/2016

Item Number	Description	Specification	Quantity Unit	Unit Price	Total Charges
99999	EX-1515/K13C2U 65 gsm, 32% RC, 12" NOTE: FAW is at/below the threshold of producing a cosmetically appealing product using this resin/fiber combination. TenCate will produce on a BEST EFFORTS BASIS.		140.00 m2	408.2900	57,160.60
99999	EX-1515/K13C2U 45 gsm, 40% RC, 12" NOTE: FAW is at/below the threshold of producing a cosmetically appealing product using this resin/fiber combination. TenCate will produce on a BEST EFFORTS BASIS.		140.00 m2	303.1700	42,443.80
810011	Dry Ice		2.00 ea	75.0000	150.00
810013	Dry Ice Temperature Recorder		2.00 ea	100.0000	200.00

Shipping Lead Time: 7 weeks after receipt and acknowledgement of order, pending raw material availability at time of order placement.
Mechanical Testing: None specified. If mechanical testing is required a test fee will apply.
TenCate Standard Certification. Testing requirements not specified.

TenCate will provide the following goods and / or services as stated. The pricing is warranted to be the same as that given to other customers for identical quantities under identical conditions and circumstances.

2450 Cordelia Road
Fairfield, CA 94534
USA

Tel 1-707-359-3400
Fax 1-707-359-3459
http://www.tencate.com/

ISO 9001
AS 9100
Registered

Attachment 6: Vendor Quote: Carbon Foam

Note: The amount of carbon foam needed is approx. 400cc with an estimated wastage of 100%. A $2400 quotation ($FY17 = $2190) from Allcomp is provided below for a 2360cc block of foam. Based on this quote of $1.02/cc, corrected to $0.93/cc ($FY17), the cost per stave is $371.

ALLCOMP

209 Puente Ave. City of Industry, CA 91746
Tel: 626-369-1273, Fax: 626-369-3543

1/1/2020

Product Catalog and Pricing
Allcomp low density K9 Hi-K Carbon Foam

Product Description:

Allcomp low-density 130 ppi high conductivity K9 carbon foam with density at 0.23 g/cc ± 0.03 g/cc and with a minimum thermal conductivity at 20 W/m.K in the thickness direction. Standard size is 12"x12"x1" thick. At least one 1"x1" size sample is taken from one corner of the block for conductivity verification. Higher density K9 foam is available upon special request. Please reference Appendix.

Price (effective Jan 1, 2020)

$ 2,900 per piece for quantity of one (1) block
$ 2,800 per piece for quantity of two (2) – five (5) blocks
$ 2,650 per piece for quantity of six (6) – ten (10) blocks
$ 2,500 per piece for quantity of eleven (11) - twenty (20) blocks
$ 2,400 per piece for quantity above twenty (20)

For smaller blocks, please use $35/ in3 price.

Delivery

To meet high demand over the next 2 years, Allcomp is currently scheduled to begin delivering **20-30** blocks of K9 foam per month starting **April 2020**. Allcomp plans to coordinate with each buyer to schedule the delivery based on customer's needs and our production schedule. We deeply appreciate the corporation and support.

Terms and Conditions

Our payment terms are (1) in US Dollars and (2) net 30 days with approved credit. Failure to pay within the stated period will result in a late charge of 1.5% per month calculated on any outstanding balance. The FOB point is City of Industry California. We encourage foreign buyer to make & provide the necessary shipping arrangement upon shipping.

Contact Person:

Mr. Wei Shih at 626-369-1273 x 102, wei.shih@allcomp.net
Mr. Bill Miller at 505-298-7633, bill.miller@allcomp.net

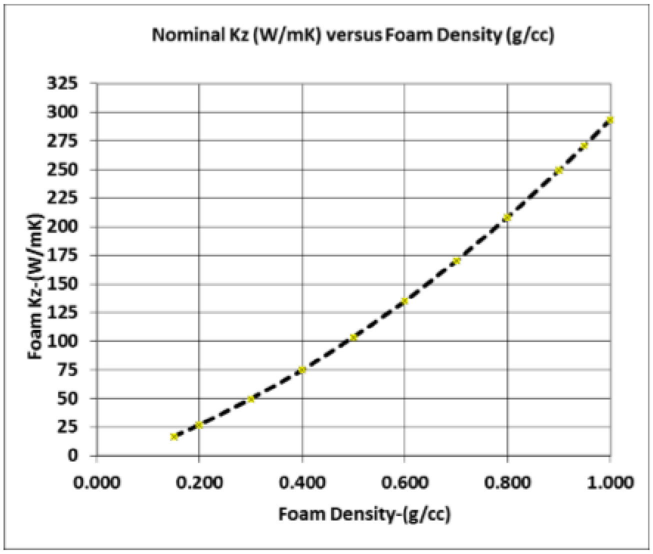
1

209 Puente Ave. City of Industry, CA 91746
Tel: 626-369-1273, Fax: 626-369-3543

Product Catalog and Pricing
Higher Density K9 foam

Description

Allcomp can provide higher density K9 foam for special applications. These materials offer higher thermal conductivity as illustrated below.



Pricing and Delivery

Size: 12"x12"x1", at least one 1"x1"x1" size sample will be taken from one corner of the block for conductivity verification

Density g/cc	Pricing $/ block, FOB Los Angles	Delivery 4.5 month ARO estimated
0.25-0.35 g/cc	$3,150	Upon Request
0.36-0.45 g/cc	$3,600	Upon Request
0.46-0.60 g/cc	$4,000	Upon Request

Upon receiving firm order, delivery will be provided based on quantity and density requirements.

Attachment 5: Vendor Quote: Honeycomb

Note: The amount of 5.5mm thick honeycomb needed for each stave core is 0.126 m^2, with an estimated wastage of 10%. A $2054 quotation ($1874, corrected to $FY17) from Ultracore is provided on page for 0.252m^2. This corresponds to a cost per stave of $1027.

ULTRACOR
Engineered Specialty Honeycomb

2763 BOEING WAY
STOCKTON, CALIFORNIA 95206
WWW.ULTRACORINC.COM

DATE:	February 19, 2020
ATTN:	Mr. Jeffery Ashenfelter
COMPANY:	Yale University
FROM:	Stan Wright
PHONE:	209-983-3744
RE:	**Quote Number: Q-42408**

Ultracor is pleased to provide the following proposal for UCF-328-1/4-3.0.

Qty	Description	Unit	Price	Total
80	UCF-328-1/4-3.0 685mm X 368.3mm X 5.5mm thickness tolerance of ± 0.006"	slice	$2,054	$164,320

Conditions:

Delivery:	35 weeks ARO
Pricing:	Valid until March 31, 2020
Terms:	Net 30
FOB:	Stockton, CA

Ultracor hopes to be of service to Yale University. Please call me if you have any questions, or require additional information.

Sincerely,

Stan Wright
209-983-3744
stan@ultracorinc.com

Doc 7.2.2_Rev E

AS9100:2016 Certified

Attachment 7: Shipping Cost Estimate

Shipping Case:

Shipping Address

William Emmet
Yale University Physics Department
Wright Lab WLW305
266 Whitney Ave
New Haven, Connecticut 06520
United States
203-432-3384

Billing Address

William Emmet
Yale University Physics Department
Wright Lab WLW305
266 Whitney Ave
New Haven, Connecticut 06520
United States
203-432-3384

Your Order Contains...

Cart Items	SKU	Qty	Item Price	Item Total
Impact Case 6214A for Black Powder Rifle (Choose a Color: Raw Aluminum)	6214A	1	$389.99 USD	**$389.99 USD**
			Subtotal:	**$389.99 USD**
			Shipping:	**$61.89 USD**
			Grand Total:	**$451.88 USD**
			Payment Method:	Authorize.net

ICC Case Store
http://icc-case.com/

ICC Case Store is powered by BigCommerce. Launch your own store for free with BigCommerce.

Shipping Quote: CF Facings LBNL to Yale

Ship From	Ship To	
United States	United States	Number of Packages: 1
NEW HAVEN	BERKELEY	Total Shipment Weight: 20 lbs
06511	94720	Packaging Type: Your Packaging
		Currency: USD

Modify Shipment Information

Estimated Cost by Service

Service and Total Price (All Packages)	
Ground	$73.66
3 Day Select	$140.75 *
2nd Day Air	$192.59 *
Next Day Air Saver	$259.46 *
Next Day Air Early AM	$303.38 *
Next Day Air	$272.18 *

The UPS Store

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Package Type: Your Packaging

Package 1	Weight 20 lbs
	Length 15 in
	Width 5 in
	Height 62 in

Shipping Quote: Stave Core Yale to BNL, ISU

SHIPMENT SUMMARY

Shipment Information

Sender
Yale University
Jeff Ashenfelter
WL207
272 Whitney
New Haven CT 06511
United States

Recipient
Brookhaven National Lab
Dr. David Lynn
Physics Department
Mail Stop 510A
Upton NY 11973-5000
United States

Order No	: 104946892
Order Date	: 5/12/2017 11:03:43 AM
Tracking No	: 786549226829
Service	: FedEx First Overnight
Ship Date	: 5/12/2017
Scan Date	:
Scan Activity	: No information at this time.
Signed By	:

Shipment Ref	:
Bill Type	: Prepaid
Package	: CUSTOM - 20 lbs 15x5x62 (inches)
Additional Svc[1]	: DV - 5000 USD DO

Shipment Amount Information

Original Estimated Charge

Freight Charge	USD 89.42	
Fuel Surcharge	USD 1.34	
Declared Value	USD 47.50	
Additional Handling	USD 9.00	
Transaction Charge	USD 0.75	
Estimated Total		**USD 148.01**

Disclaimer : *The charges shown here are estimated charges only. Actual charges may differ based on actual weight, dimensions or other accessorial charges.*

[1] **Legend**
Email : S - Shipper, R - Recipient, DC - Delv Confirm
SRQ/SRL - Adult Signature /Signature Release : PK/DO - Pickup/Drop-Off : DV - Declared Value
DI - Dry Ice : DG - Dangerous Goods : SD - Saturday : RD - Residential : HS - Hold
IP - Inside Pickup : ID - Inside Delivery

Ship From	Ship To	
United States	United States	Number of Packages: 1
NEW HAVEN	AMES	Total Shipment Weight: 20 lbs
06511	50011	Packaging Type: Your Packaging
		Currency: USD

Modify Shipment Information

Estimated Cost by Service

Service and Total Price (All Packages)	
Ground	$56.97
3 Day Select	$109.13 *
2nd Day Air AM	$191.08 *
2nd Day Air	$168.79 *
Next Day Air Saver	$232.73 *
Next Day Air Early AM	$273.85 *
Next Day Air	$242.65 *

Package Type: Your Packaging	
Package 1	Weight 20 lbs

Attachment 8: Travel

Yale Travel

Average Cost to and from CERN (5-day Meeting)	
AIRFARE	$1,300.00
CERN Hostel	$300.00
Per Day Per diem	$300.00
Taxi's etc..	$100.00
TOTAL APPROX	$2,000.00

Average Cost to and from OXFORD (3-day Meeting) England	
AIRFARE	$1,400.00
Hotel (approx $135/nt)	$405.00
Per Day Per diem	$180.00
Taxi's etc..	$100.00
TOTAL APPROX	$2,085.00

Average Cost to and from LBNL (3 day Meeting) – Berkeley, CA	
AIRFARE	$650.00
Hotel (Av $165/nt)	$495.00
Per Day Per diem	$180.00
Taxi's etc..	$100.00
TOTAL APPROX	$1,425.00

Average Cost to and from BNL (2 day Meeting)—Upton, NY	
Ground Transporation	$145.00
Hotel (av $140/nt)	$280.00
Per Day Per diem	$120.00
TOTAL	$545.00