LIGO-T2400377

Cosmic Explorer (CE)
Cost Estimate of Unstiffened and Ring - Stiffened Beam Tubes

(based on 1992-1994 cost data)

v1

Scope

Caveats

general

Sources

LIGO Fabrication Cost based on CBI documentation

N.B. : Costs below are for one LIGO Site (8 km of Tube)

Short Transport (Portland, OR to Hanford, WA) Case

This was the shortest transportation case considered by CBI but had the highest cost per mile.

In[224]:=
```
(* using Portland, OR to Hanford, WA rates*)
(*  costTransPerMile[BTsegmentLength]  *)
transMileageCosts = {{12.192, 2.03172}, {15.24, 2.03172}, {16.764, 2.68537},
   {18.288, 3.02828}, {19.812, 3.20449}, {21.336, 4.35449}, {22.86, 4.35449}};
costTransPerMile = Interpolation[transMileageCosts, InterpolationOrder → 1];
Off[InterpolatingFunction::dmval];
```

In[227]:=
```
(* LIGO BT is "interrupted" at the mid-station *)
armLength1 = 3987.155 - 2028.345;
armLength2 = 2006.155 - 47.345;
```

In[229]:=
```
armLength1 + armLength2
```

Out[229]=
```
3917.62
```

In[230]:=
```
(* including 1 spare tube segment per ~2km module *)
BTsegmentLength = {40, 50, 55, 60, 65, 70} 0.3048;
Clear[nTubes];
nTubes[BTL_] := 2 (Ceiling[armLength1 / BTL] + Ceiling[armLength2 / BTL] + 2);
```

In[231]:=
```
nTubesPerLoad = 4;
nLoads = nTubes[BTsegmentLength] / nTubesPerLoad;
```

In[233]:=
```
(* Portland, OR to Hanford, WA *)
miles = 227;
costTrans = nLoads * miles * costTransPerMile[BTsegmentLength];
```

In[235]:=
```
nTubeSegments = nTubes[BTsegmentLength]
nBellows = nTubes[BTsegmentLength] / 2
nSupports = nTubes[BTsegmentLength] - 4
nTubeInstalls = nTubes[BTsegmentLength] - 1
nLeakTests = nTubes[BTsegmentLength] + 1
nSites = 2;
```

Out[235]= {648, 520, 472, 436, 400, 372}

Out[236]= {324, 260, 236, 218, 200, 186}

Out[237]= {644, 516, 468, 432, 396, 368}

Out[238]= {647, 519, 471, 435, 399, 371}

Out[239]= {649, 521, 473, 437, 401, 373}

In[241]:=
```
costPerBellows = 3000;
costPerSupport = 3800;
costPerTubeInstall = 1500;
costPerLeakTest = 2200;
```

In[245]:=
```
costBellows = nSites nBellows costPerBellows;
costSupports = nSites nSupports costPerSupport;
costTubeInstall = nSites nTubeSegments costPerTubeInstall;
costLeakTests = nSites nLeakTests costPerLeakTest;
```

In[249]:=
```
totalCostInstall =
  (costTrans + costBellows + costSupports + costTubeInstall + costLeakTests) / 10^6;
```

In[250]:=
```
(* Compare to Table at bottom of pg. 60 of LIGO_DRD _ 9 _ITEM _ 2. pdf *)
(* reference table has errors especially in 1st 3 columns *)
```

In[251]:=
```
TableForm[Partition[Join[costTrans, costBellows,
    costSupports, costTubeInstall, costLeakTests], Length[BTsegmentLength]],
  TableHeadings → {{"Freight", "Bellows", "Supports", "Tube Install", "Leak Test"},
    {"40'", "50'", "55'", "60'", "65'", "70'"}}]
```

Out[251]//TableForm=

	40'	50'	55'	60'	65'	70'
Freight	74 714.5	59 956.1	71 930.3	74 928.7	72 741.9	91 927.6
Bellows	1 944 000	1 560 000	1 416 000	1 308 000	1 200 000	1 116 000
Supports	4 894 400	3 921 600	3 556 800	3 283 200	3 009 600	2 796 800
Tube Install	1 944 000	1 560 000	1 416 000	1 308 000	1 200 000	1 116 000
Leak Test	2 855 600	2 292 400	2 081 200	1 922 800	1 764 400	1 641 200

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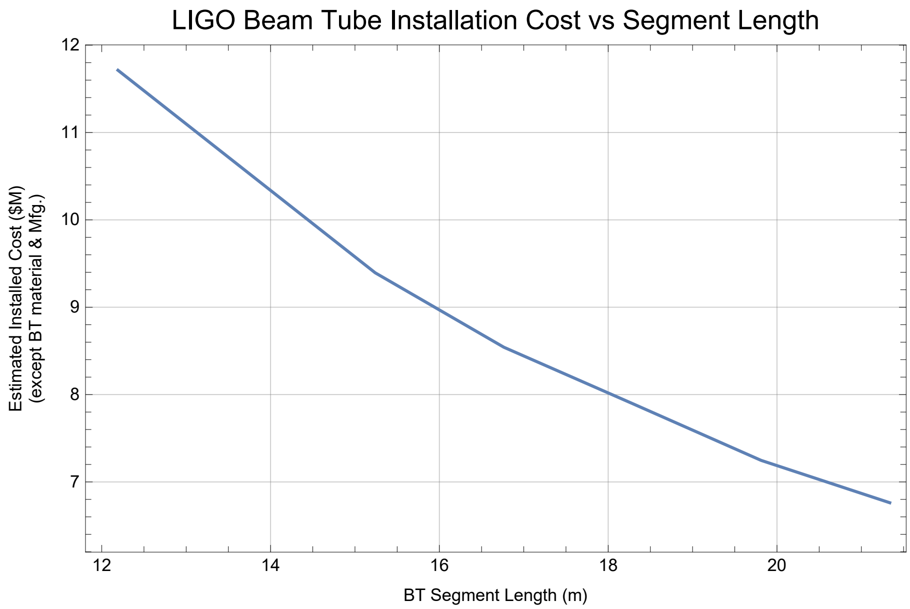
In[252]:=
```
(* Compare to Figure on pg. 61 of LIGO_DRD _ 9 _ITEM _ 2. pdf *)
```

In[253]:=
```
ListPlot[
 Transpose[Partition[Join[BTsegmentLength, totalCostInstall], Length[BTsegmentLength]]],
 Joined → True, Frame → True, FrameLabel → {"BT Segment Length (m)",
   "Estimated Installed Cost ($M)\n(except BT material & Mfg.)"}, GridLines → Automatic,
 PlotLabel → Style["LIGO Beam Tube Installation Cost vs Segment Length", 14]]
```

Out[253]=


In[254]:=
```
(* cost of the tube material and manufacturing is
 taken as the average of 5 steel manufacturer costs, +/- 11%
 Note that these costs are independent of tube segment length *)
costCoilMfg = (5 068 734 + 6 030 090 + 5 663 768 + 4 893 966 + 6 190 206) / 5 / 10^6 // N
```

Out[254]= 5.56935

In[255]:=
```
costSpiralWeldMfg =
 (3 870 944 + 548 800 + 262 904 + 4 303 000 + 106 650 + 296 466 + 1 809 792 + 208 867) / 3 / 10^6 // N
```

Out[255]= 3.80247

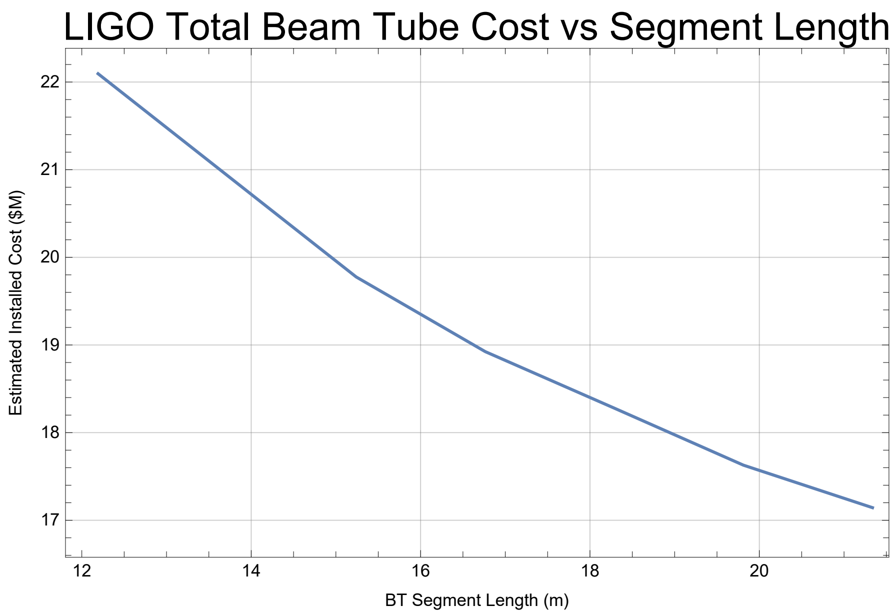
In[256]:=
```
nStiffeners = 19 552;
costPerInstalledStiffener = (34 + 41 + 80) / 3 // N;
costStiffeners = nStiffeners costPerInstalledStiffener / 10^6;
```

In[259]:=
```
totalCost = totalCostInstall + costCoilMfg + costSpiralWeldMfg + costStiffeners;
```

In[260]:=
```
(* Adding all costs together *)
```

In[261]:=
```
ListPlot[Transpose[Partition[Join[BTsegmentLength, totalCost], Length[BTsegmentLength]]],
 Joined → True, Frame → True, GridLines → Automatic,
 FrameLabel → {"BT Segment Length (m)", "Estimated Installed Cost ($M)"},
 PlotLabel → Style["LIGO Total Beam Tube Cost vs Segment Length", 20]]
```

Out[261]=



In[262]:=
```
pieData = Transpose[Partition[Join[costTrans / 10^6, costBellows / 10^6, costSupports / 10^6,
      costTubeInstall / 10^6, costLeakTests / 10^6, costStiffeners Table[1, {6}] ,
      costCoilMfg Table[1, {6}] , costSpiralWeldMfg Table[1, {6}] ], 6]] // N;
```

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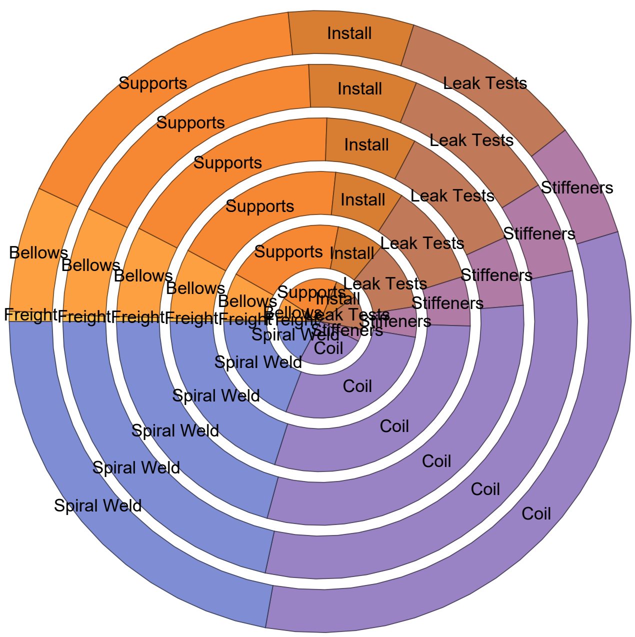
In[263]:=
```
PieChart[pieData, ChartLabels → {"Freight", "Bellows", "Supports",
   "Install", "Leak Tests", "Stiffeners", "Coil", "Spiral Weld"}, PlotLabel →
  Style["Relative Costs for Tube Segment Lengths:\n40',50',55',60',65',70'", 14]]
```

Out[263]=

Relative Costs for Tube Segment Lengths:
40',50',55',60',65',70'



In[264]:=

Long transport Case

LIGO Fabrication Cost based on LIGO Cost Book

CE Cost for varying tube segment length

Assume LIGO shell thickness and stiffener spacing, but vary the length of the tube segments.

Design Parameters

In[308]:=
```
(* not including spare tube segments *)
```

In[309]:=
```
armLength = 40000; (* m *)
```

In[310]:=
```
maxTubeSegmentLength = 20; (* m *)
BTsegmentLength = Table[i, {i, 20}] (* m *)
```

Out[311]=
```
{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20}
```

In[312]:=
```
selectLengths = {5, 10, 15, 20};
BTsegmentLength[[selectLengths]]
```
Out[313]=
```
{5, 10, 15, 20}
```
In[314]:=
```
nLengths = Length[BTsegmentLength];
BTdiameter = 1245; (* mm *)
skelp = 36 × 25.4; (* mm *)
nTubes = 2 Ceiling[armLength / BTsegmentLength];
BTthickness = 3; (* mm *)
BTmaterialDensity = 8 × 10^-6; (* 304L, kg/mm^3 *)
```
In[320]:=
```
milesFreight = 1000; (* miles *)
```
In[321]:=
```
stiffenerHeight = 1.75 × 25.4; (* mm *)
stiffenerWidth = (3 / 16) 25.4; (* mm *)
```

Freight

Freight only addresses transportation of tube segments from tube manufacturer to the site for installation.

Shipping of coils from foundry to bake facility, to finishing mill, to tube mfg are considered separately in the Coil Mfg costs.

https : // arcb.com/blog/things - to - know - about - heavy - haul - trucking

width < 8.6 ft (2.621 m)

Height < 13.6 ft (4.145 m)

Length < 53 ft (16.154 m) (but I guess the tubes can extend off the end of the bed)

Gross weight < 80,000 lb

This implies 4 long tubes per truck bed (2 wide x 2 high)

Each LIGO BT segment weighs about 2180 kg (4806 lb), so 4 tube segments < 20,000 lb

Packing density on flat bed:

If <= 4m length, stand up in 2 rows x 11

if >4m length, lay down in 2 rows x 2 levels, but ensure that the C.G. of the last tube is < 16m (bed length)

In[323]:=
```
(* packingDensity(tubeSegmentLength,nTubesPerLoad) *)
packingDensity = {{0, 88}, {1, 88}, {2, 44}, {3, 22}, {4, 22},
   {5, 12}, {6, 12}, {7, 8}, {8, 8}, {9, 8}, {10, 8}, {11, 4}, {12, 4},
   {13, 4}, {14, 4}, {15, 4}, {16, 4}, {17, 4}, {18, 4}, {19, 4}, {20, 4}};
nTubesPerLoad = Interpolation[packingDensity, InterpolationOrder → 0];
```

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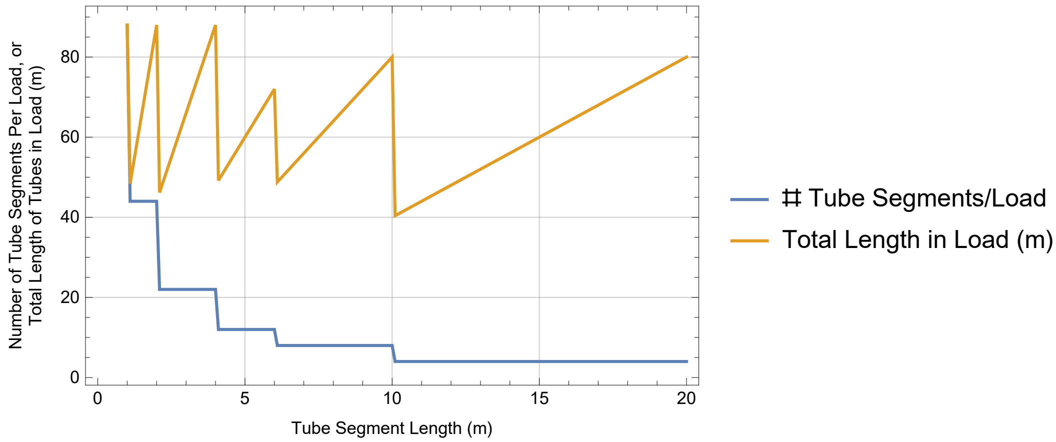
In[325]:=
```
ListPlot[{Table[{length, nTubesPerLoad[length]}, {length, 1, maxTubeSegmentLength, .1}],
  Table[{length, length nTubesPerLoad[length]}, {length, 1, maxTubeSegmentLength, .1}]},
 Joined → True, Frame → True, FrameLabel → {"Tube Segment Length (m)",
   "Number of Tube Segments Per Load, or\nTotal Length of Tubes in Load (m)"},
 GridLines → Automatic, PlotLegends → {"♯ Tube Segments/Load", "Total Length in Load (m)"}]
```

Out[325]=



1994 average freight costs as a function of tube length

https : // dcc.ligo.org/LIGO - C1900321

LIGO_DRD _ 9 _ITEM _ 2. pdf, pg.59 - 62

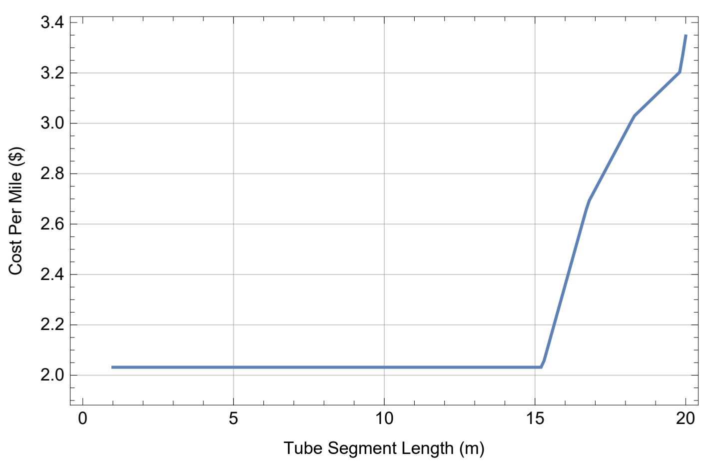
In[326]:=
```
transMileageCosts = {{12.192, 2.03172}, {15.24, 2.03172}, {16.764, 2.68537},
   {18.288, 3.02828}, {19.812, 3.20449}, {21.336, 4.35449}, {22.86, 4.35449}};
costTransPerMile = Interpolation[transMileageCosts, InterpolationOrder → 1];
Off[InterpolatingFunction::dmval];
```

In[329]:=
```
nLoads = Ceiling[nTubes / nTubesPerLoad[BTsegmentLength]]
```

Out[329]=
```
{910, 910, 1213, 910, 1334, 1112, 1429, 1250, 1112,
 1000, 1819, 1667, 1539, 1429, 1334, 1250, 1177, 1112, 1053, 1000}
```

In[330]:=
```
ListPlot[Table[{length, costTransPerMile[length]}, {length, 1, maxTubeSegmentLength, .1}],
 Joined → True, Frame → True,
 FrameLabel → {"Tube Segment Length (m)", "Cost Per Mile ($)"}, GridLines → Automatic]
```

Out[330]=



In[331]:=
```
costFreight = nLoads milesFreight costTransPerMile[BTsegmentLength] / 10^6 // N
```
Out[331]=
```
{1.84887, 1.84887, 2.46448, 1.84887, 2.71031, 2.25927, 2.90333, 2.53965, 2.25927, 2.03172,
 3.6957, 3.38688, 3.12682, 2.90333, 2.71031, 2.94711, 3.22318, 3.29539, 3.27547, 3.34635}
```

Bellows

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 252-255
See LIGO-C1900321, file LIGO_DRD_9_ITEM3.pdf, pg. 128-138
For the LIGO BT, the optimum BT length was determined to be 19.812 m (65' 0"). This optimum was based on a design goal to place the baffles at (or near) the support points. The baffle spacing was specified as 20 m, which was close to the optimum tube length for shipping and construction (19.812 m). The expansion joint spacing then had to be a multiple of 19.812 m.

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 255-271
CBI performed a trade study on the formed Bellows (thin-walled vs near full thickness).
Near full thickness bellows are preferred due to lower cost, fewer welds, higher torsion capacity, lower leak risk and lower damage risk. Near full thickness (0.100 in) bellows were just (barely) compliant enough so that additional convolutions were not needed (which would add cost).

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 263-265
Discussion of 3 forming methods: roll forming, expanding mandrel (punch forming) and hydroforming. Hydroforming is best but requires the most expensive NRE; best for large volume production.

Rather than attempt to re-design the Bellows (and estimate costs for these variations), in this simple cost estimate model, I'll assume that each Bellows "handles" the expansion from ~40m of tube, and the cost per Bellows, remains the same.

In[332]:=
```
nBellows = 2 armLength / 40
```
Out[332]=
```
2000
```

In[333]:=
```
costPerBellows = 3000;
costBellows = nBellows costPerBellows / 10^6 Table[1, {nLengths}] // N
```
Out[334]=
```
{6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6., 6.}
```

Supports

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat) :

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 252-255
See LIGO-C1900321, file LIGO_DRD_9_ITEM3.pdf, pg. 128-138
For the LIGO BT, the optimum BT length was determined to be 19.812 m (65' 0"). This optimum was based on a design goal to place the baffles at (or near) the support points. The baffle spacing was specified as 20 m, which was close to the optimum tube length for shipping and construction (19.812

m). The expansion joint spacing then had to be a multiple of 19.812 m.

Perhaps BT gravity sag as a function of BT segment length should be calculated to determine the number of required supports. For this simple cost model, I'll assume 1 Fixed Support and 1 Guided Support per Bellows (as is the case for LIGO). Since the CBI cost data doesn't differentiate between fixed and guided, a single support quantity and cost is used.

```
In[113]:= nSupports = 2 nBellows
Out[113]= 4000
```

```
In[114]:= costPerSupport = 3800;
costSupports = nSupports costPerSupport / 10^6 Table[1, {nLengths}] // N;
```

Leak Tests

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat)

```
In[116]:= nLeakTests = nTubes;
costPerLeakTest = 2200;
costLeakTests = nLeakTests costPerLeakTest / 10^6 // N;
```

Pump Ports

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat)
Pump Ports are not explicitly included in CBI's cost estimate (referenced above).
FWIW a hand written note on pg. 85 of LIGO_DRD_9_ITEM_3.pdf indicates that each Pump Port costs $3975

Since I don't know the number of required ports, I'll simply scale the LIGO Cost Book number by the CE Length/LIGO Length:

```
In[119]:= costPumpPorts = 1.83 (80 / 16) Table[1, {nLengths}]  // N;
```

Installation

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat) :

```
In[120]:= nTubeInstalls = 2 nTubes;
costPerTubeInstall = 1500;
costTubeInstall = nTubeInstalls costPerTubeInstall / 10^6 // N;
```

Coil Mfg Costs

1992 cost of the tube material and manufacturing is taken as the average of 5 steel manufacturer costs, +/- 11%
Note that these costs are (apparently) independent of tube segment length and thickness for the range under consideration by CBI for LIGO.
Assuming:
1) a coil weight of 30,000 lbm, which was the size ordered by CBI
2) no welding of coil ends
3) spiral welded tube, which requires tube spiral length plus 2 x skelp widths
4) 10% scrap recouped

https://dcc.ligo.org/LIGO-C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 105 & 247 (repeat):
Coil material procurement costs, including:
cost of coil material (304L)
transport cost to/from bake facility
bake cost
transport cost to/from finishing mill
outgas test costs
cost to level
cost to slit
transport to tube mfg
less cost of 10% scrap steel

Estimate of coil waste so that the number of 65 ft long tubes from a single coil (6) matches the quotes CBI received from spiral tube manufacturers. Corresponds to 1 skelp length at each end of 6 tubes, or 12 x skelp length waste
I’ve assumed that this as a constant waste weight per coil

In[123]:=
```
coilWeight = 30000 × 0.453592; (* kg *)
wastePerCoil =
  (Pi / 4) (BTdiameter^2 - (BTdiameter - 2 BTthickness) ^2) 12 skelp BTmaterialDensity // N;
wastePerCoil / coilWeight
```
Out[125]=
```
0.0755116
```

In[126]:=
```
BTsegmentWeightUncut = (Pi / 4) (BTdiameter^2 - (BTdiameter - 2 BTthickness) ^2)
    (BTsegmentLength 1000) BTmaterialDensity // N;
nTubesPerCoil = Floor[(coilWeight - wastePerCoil) / BTsegmentWeightUncut]
```
Out[127]=
```
{134, 67, 44, 33, 26, 22, 19, 16, 14, 13, 12, 11, 10, 9, 8, 8, 7, 7, 7, 6}
```

In[128]:=
```
nCoils = Ceiling[nTubes / nTubesPerCoil] // N
```

Out[128]=
```
{598., 598., 607., 607., 616., 607., 602., 625., 635.,
 616., 607., 607., 616., 636., 667., 625., 673., 636., 602., 667.}
```

In[129]:=
```
baseCostCoil = 27639; (* 304L *)
freightCostBake = 822;
costBake = 3000;
freightFinishingMill = 411;
costOutgasTest = 2650;
costLevel = 1500;
costSlit = 1800;
freightTubeMfg = 1370 / 2; (*2 coils per trip *)
```

In[137]:=
```
costCoilMfg = (baseCostCoil + freightCostBake + costBake + freightFinishingMill +
    costOutgasTest + costLevel + costSlit + freightTubeMfg) nCoils / 10^6
```

Out[137]=
```
{23.0272, 23.0272, 23.3737, 23.3737, 23.7203, 23.3737, 23.1812, 24.0669, 24.4519, 23.7203,
 23.3737, 23.3737, 23.7203, 24.4905, 25.6842, 24.0669, 25.9152, 24.4905, 23.1812, 25.6842}
```

Spiral Weld Mfg Costs

https://dcc.ligo.org/LIGO-C1900321

LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 113:

Spiral welded tube manufacturing cost is taken as the average of 3 manufacturing quotes/estimates for tube manufacturing + equipment costs + material overhead. Costs are not quoted as a function of tube segment length. Presumably shorter length tube segments would cost a little more due to the need to make more transverse cuts, but I don’t know this cost.

In[138]:=
```
costSpiralWeldMfg = Table[1, {nLengths}]
    (3870944 + 548800 + 262904 + 4303000 + 106650 + 296466 + 1809792 + 208867) / 3 / 10^6 // N;
```

Stiffener Mfg Costs

https://dcc.ligo.org/LIGO-C1900321

LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 139-141 & 282 (repeat):

BT stiffener material costs (material, painting & welding)

In[139]:=
```
stiffenerSpacing = 758; (* mm, baseline stiffener spacing == LIGO *)
nStiffeners = 2 armLength 10^3 / 758 // N
```

Out[140]=
```
105541.
```

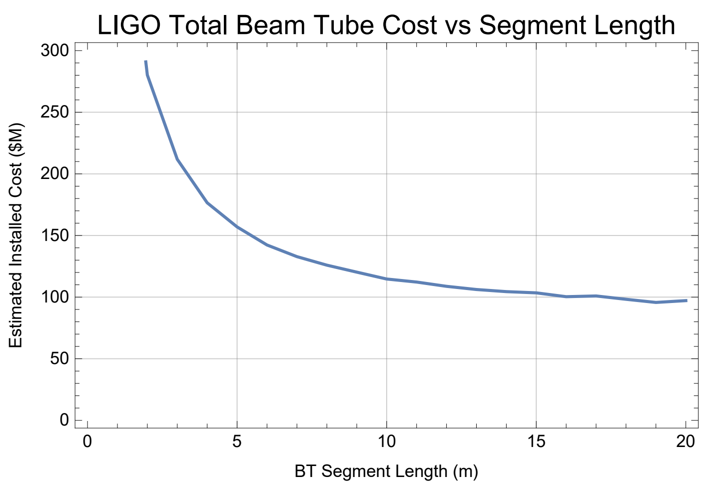
In[141]:=
```
thicknessBarStock = (3/16) 25.4; (* mm *)
lengthBarStock = 14 × 12 × 25.4; (* mm *)
unitWeightBarStock = 1.12 × 0.00148816; (* kg/mm *)
unitCostBarStock = 1.55/0.453592; (* $/kg *)
costStiffenerMaterial = lengthBarStock unitWeightBarStock unitCostBarStock;
costPerStiffenerMfg = (34 + 41 + 80) / 3 // N;
costFactorStiffenerMfg = costPerStiffenerMfg / costStiffenerMaterial;
costPerStiffenerWld = 15;
costStiffeners = Table[1, {nLengths}] nStiffeners
   (costPerStiffenerMfg costFactorStiffenerMfg + costPerStiffenerWld) / 10^6;
```

Total Costs (as a function of tube segment length)

In[150]:=
```
totalCost = costFreight + costBellows + costSupports + costTubeInstall +
   costLeakTests + costPumpPorts + costCoilMfg + costSpiralWeldMfg + costStiffeners;
```

In[151]:=
```
ListPlot[Transpose[Partition[Join[BTsegmentLength, totalCost], nLengths]],
 Joined → True, Frame → True, GridLines → Automatic,
 FrameLabel → {"BT Segment Length (m)", "Estimated Installed Cost ($M)"},
 PlotLabel → Style["LIGO Total Beam Tube Cost vs Segment Length", 14]]
```

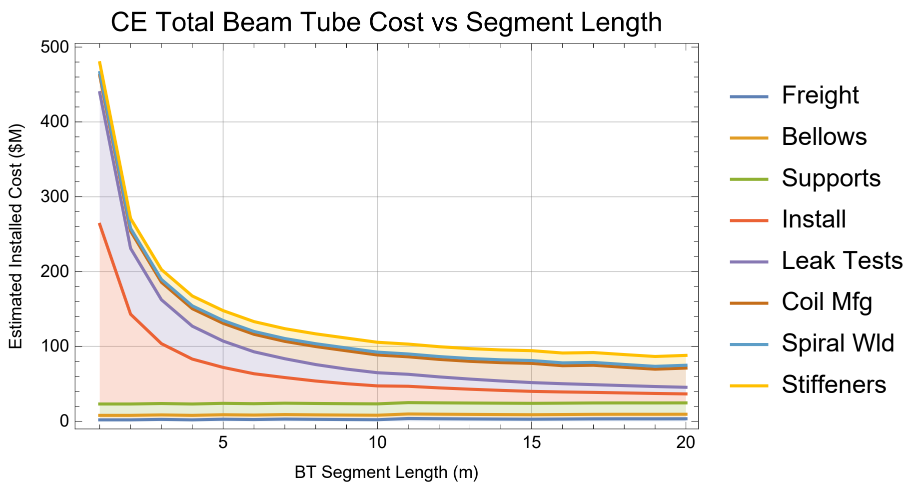
Out[151]=



In[152]:=
```
plotData = {Transpose[Partition[Join[BTsegmentLength, costFreight], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costBellows], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costSupports], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costTubeInstall], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costLeakTests], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costCoilMfg], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costSpiralWeldMfg], nLengths]],
   Transpose[Partition[Join[BTsegmentLength, costStiffeners], nLengths]]};
```

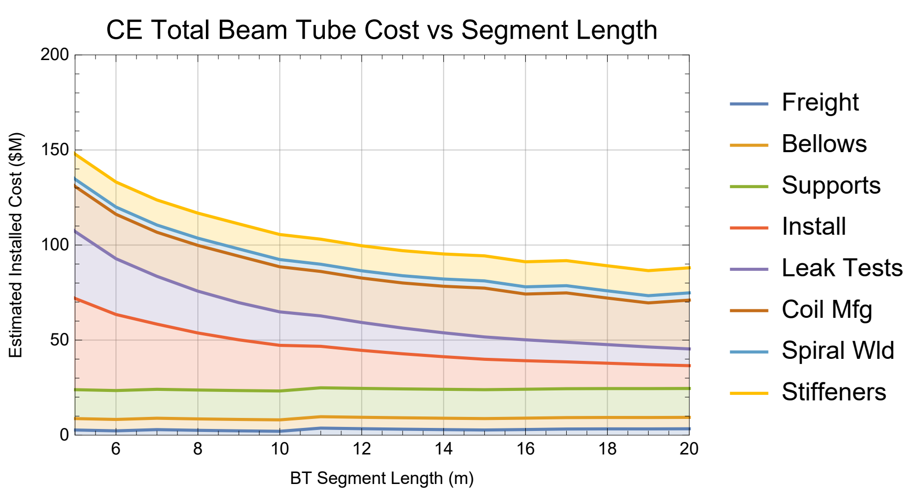
In[153]:=
```
StackedListPlot[plotData, Joined → True, Frame → True, GridLines → Automatic,
 FrameLabel → {"BT Segment Length (m)", "Estimated Installed Cost ($M)"},
 PlotLabel → Style["CE Total Beam Tube Cost vs Segment Length", 14],
 PlotLegends → {"Freight", "Bellows", "Supports",
   "Install", "Leak Tests", "Coil Mfg", "Spiral Wld", "Stiffeners"}]
```

Out[153]=



In[154]:=
```
StackedListPlot[plotData, Joined → True, Frame → True,
 GridLines → Automatic, PlotRange → {{5, 20}, {0, 200}},
 FrameLabel → {"BT Segment Length (m)", "Estimated Installed Cost ($M)"},
 PlotLabel → Style["CE Total Beam Tube Cost vs Segment Length", 14],
 PlotLegends → {"Freight", "Bellows", "Supports",
   "Install", "Leak Tests", "Coil Mfg", "Spiral Wld", "Stiffeners"}]
```

Out[154]=



In[155]:=
```
dataTable = Partition[Join[costFreight[[selectLengths]] / totalCost[[selectLengths]],
    costBellows[[selectLengths]] / totalCost[[selectLengths]],
    costSupports[[selectLengths]] / totalCost[[selectLengths]],
    costTubeInstall[[selectLengths]] / totalCost[[selectLengths]],
    costLeakTests[[selectLengths]] / totalCost[[selectLengths]],
    costCoilMfg[[selectLengths]] / totalCost[[selectLengths]],
    costSpiralWeldMfg[[selectLengths]] / totalCost[[selectLengths]],
    costStiffeners[[selectLengths]] / totalCost[[selectLengths]]], nSL];
```

```
••• Partition: Single or list of positive machine-sized integers expected at position 2 of
    Partition[{0.0172677, 0.0177165, 0.026197, 0.0344423, 0.0382267, 0.0523196, 0.057994, 0.0617549, 0.096841, ≪15≫,
      0.024226, 0.0331573, 0.0367534, 0.0391369, 0.0839412, 0.114888, 0.127348, 0.135606}, nSL].
```

In[156]:=
```
nSelectLength = Length[selectLengths];
headerString = Table[0, {nSelectLength}];
For[i = 1, i < nSelectLength + 1, i++,
  headerString[[i]] = TextString[BTsegmentLength[[selectLengths[[i]]]]]];
PercentForm[TableForm[dataTable, TableHeadings → {{"Freight", "Bellows", "Supports",
     "Install", "Leak Tests", "Coil Mfg", "Spiral Wld", "Stiffeners"}, headerString}], 2]
```

Out[159]//PercentForm=
```
Partition[
 {1.7%, 1.8%, 2.6%, 3.4%, 3.8%, 5.2%, 5.8%, 6.2%, 9.7%, 13%, 15%, 16%, 31%, 21%, 15%, 12%,
  22%, 15%, 11%, 9.1%, 15%, 21%, 25%, 26%, 2.4%, 3.3%, 3.7%, 3.9%, 8.4%, 11%, 13%, 14%}, nSL]
```

CE Cost for varying stiffener spacing

Shell thickness increases with increased stiffener spacing.

Tube segment length is a constant 20 m.

Import Stiffened Design Parameters

Import the file created by T2400351-v2 ASME section VIII division 1.nb

For varying stiffener spacing (L304L), provides corresponding :

shell thickness (t304L),

stiffener height (h304L),

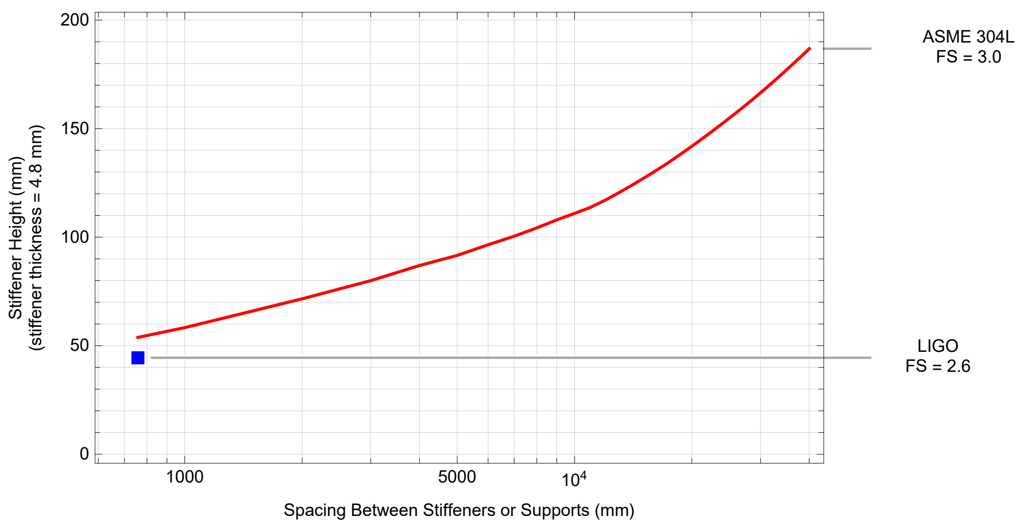
stiffener thickness (b304L)

for 1245 mm OD tube

In[335]:=
```
data = Import["ASMEdiv1CE304L.dat"];
L304L = data[[1]]
```

Out[336]=
```
{758, 1000, 2000, 3000, 4000, 5000, 6000, 7000, 8000, 9000, 10 000,
 11 000, 12 000, 13 000, 14 000, 15 000, 16 000, 17 000, 18 000, 19 000, 20 000,
 21 000, 22 000, 23 000, 24 000, 25 000, 26 000, 27 000, 28 000, 29 000, 30 000,
 31 000, 32 000, 33 000, 34 000, 35 000, 36 000, 37 000, 38 000, 39 000, 40 000}
```

In[337]:=
```
t304L = data[[2]]
```
Out[337]=
```
{3.3263, 3.73545, 4.85321, 5.7979, 6.47277, 7.35351, 7.91096, 8.54024,
 9.03984, 9.4595, 9.97078, 10.4541, 10.6829, 10.8296, 10.9287, 11.0051,
 11.0826, 11.1376, 11.1671, 11.1818, 11.1966, 11.2106, 11.2225, 11.2344,
 11.2464, 11.2584, 11.2704, 11.2824, 11.2945, 11.3023, 11.3038, 11.3053,
 11.3069, 11.3084, 11.3099, 11.3115, 11.313, 11.3145, 11.3161, 11.317, 11.317}
```
In[338]:=
```
b304L = data[[3]]
```
Out[338]=
```
{4.7625}
```
In[339]:=
```
h304L = data[[4]]
```
Out[339]=
```
{53.8122, 58.3276, 71.6007, 79.9638, 86.9274, 91.583, 96.4963, 100.431, 104.271, 107.936,
 110.95, 113.769, 117.112, 120.483, 123.809, 127.04, 130.12, 133.14, 136.128, 139.062, 141.9,
 144.654, 147.334, 149.94, 152.476, 154.946, 157.355, 159.707, 162.005, 164.269, 166.511,
 168.709, 170.864, 172.98, 175.056, 177.097, 179.102, 181.074, 183.015, 184.927, 186.815}
```
In[340]:=
```
nSpacings = Length[L304L]
```
Out[340]=
```
41
```
In[341]:=
```
stiffener304L = Transpose[Partition[Join[L304L, h304L], nSpacings]];
LIGOstiffener = {{758, 1.75 × 25.4}};
ListLogLinearPlot[{stiffener304L, LIGOstiffener}, Joined → True,
 Frame → True, FrameLabel → {"Spacing Between Stiffeners or Supports (mm)",
   "Stiffener Height (mm)\n(stiffener thickness = 4.8 mm)"},
 PlotLabels -> {"ASME 304L\nFS = 3.0", "LIGO\nFS = 2.6"}, PlotStyle → {Red, Blue},
 PlotMarkers → {{None}, {Automatic}}, GridLines → All]
```
Out[343]=



Design Parameters

In[344]:=
```
(* not including spare tube segments *)
```
In[345]:=
```
armLength = 40 000; (* m *)
```

```
In[346]:= maxTubeSegmentLength = 20; (* m *)
          BTsegmentLength = 20; (* m *)

In[348]:= selectSpacing = {1, 6, 11, 16, 21};
          nSelectSpacings = Length[selectSpacing];
          L304L[[selectSpacing]]
          t304L[[selectSpacing]]
          h304L[[selectSpacing]]

Out[350]= {758, 5000, 10000, 15000, 20000}

Out[351]= {3.3263, 7.35351, 9.97078, 11.0051, 11.1966}

Out[352]= {53.8122, 91.583, 110.95, 127.04, 141.9}

In[353]:= BTdiameter = 1245; (* mm *)
          skelp = 36 × 25.4; (* mm *)
          nTubes = 2 Ceiling[armLength / BTsegmentLength];
          BTmaterialDensity = 8 × 10^-6; (* 304L, kg/mm^3 *)

In[357]:= milesFreight = 1000; (* miles *)
```

Freight

Freight only addresses transportation of tube segments from tube manufacturer to the site for installation.

Shipping of coils from foundry to bake facility, to finishing mill, to tube mfg are considered separately in the Coil Mfg costs.

https : // arcb.com/blog/things - to - know - about - heavy - haul - trucking

width < 8.6 ft (2.621 m)

Height < 13.6 ft (4.145 m)

Length < 53 ft (16.154 m) (but I guess the tubes can extend off the end of the bed)

Gross weight < 80,000 lb

This implies 4 long tubes per truck bed (2 wide x 2 high)

Each LIGO BT segment weighs about 2180 kg (4806 lb), so 4 tube segments < 20,000 lb

Packing density on flat bed:

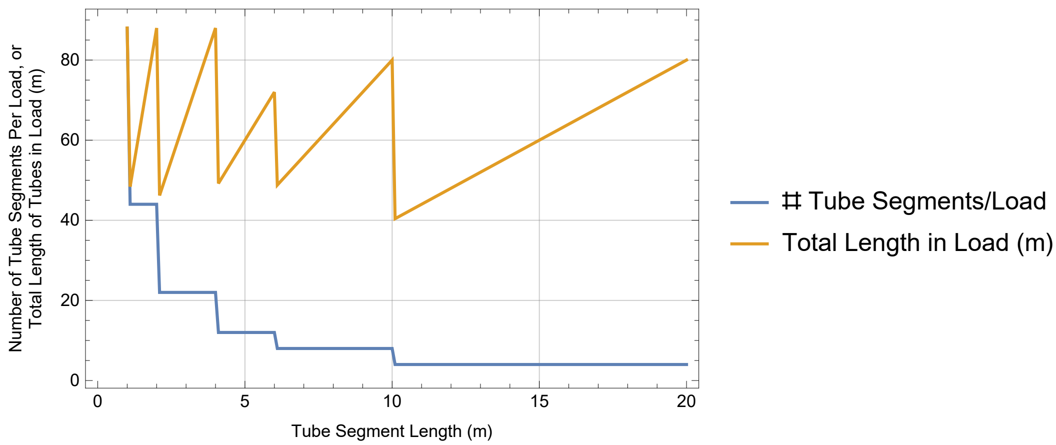
If <= 4m length, stand up in 2 rows x 11

if >4m length, lay down in 2 rows x 2 levels, but ensure that the C.G. of the last tube is < 16m (bed length)

```
In[358]:= (* packingDensity(tubeSegmentLength,nTubesPerLoad) *)
          packingDensity = {{0, 88}, {1, 88}, {2, 44}, {3, 22}, {4, 22},
             {5, 12}, {6, 12}, {7, 8}, {8, 8}, {9, 8}, {10, 8}, {11, 4}, {12, 4},
             {13, 4}, {14, 4}, {15, 4}, {16, 4}, {17, 4}, {18, 4}, {19, 4}, {20, 4}};
          nTubesPerLoad = Interpolation[packingDensity, InterpolationOrder → 0];
```

In[360]:=
```
ListPlot[{Table[{length, nTubesPerLoad[length]}, {length, 1, maxTubeSegmentLength, .1}],
  Table[{length, length nTubesPerLoad[length]}, {length, 1, maxTubeSegmentLength, .1}]},
 Joined → True, Frame → True, FrameLabel → {"Tube Segment Length (m)",
   "Number of Tube Segments Per Load, or\nTotal Length of Tubes in Load (m)"},
 GridLines → Automatic, PlotLegends → {"# Tube Segments/Load", "Total Length in Load (m)"}]
```

Out[360]=



1994 average freight costs as a function of tube length

https : // dcc.ligo.org/LIGO - C1900321

LIGO_DRD _ 9 _ITEM _ 2. pdf, pg.59 - 62

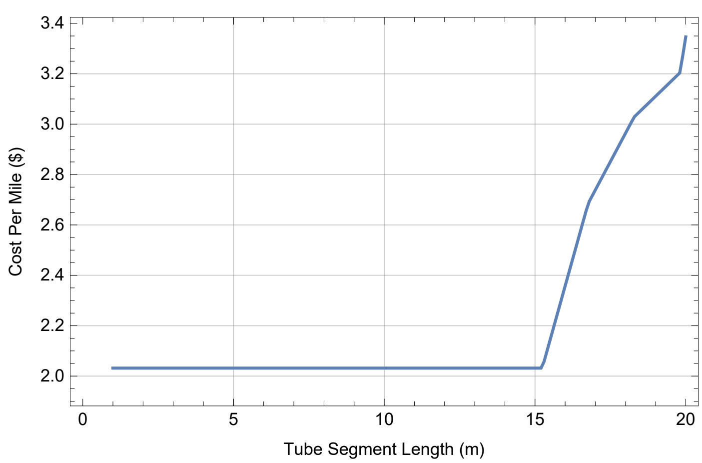
In[361]:=
```
transMileageCosts = {{12.192, 2.03172}, {15.24, 2.03172}, {16.764, 2.68537},
   {18.288, 3.02828}, {19.812, 3.20449}, {21.336, 4.35449}, {22.86, 4.35449}};
costTransPerMile = Interpolation[transMileageCosts, InterpolationOrder → 1];
Off[InterpolatingFunction::dmval];
```

In[364]:=
```
nLoads = Ceiling[nTubes / nTubesPerLoad[BTsegmentLength]]
```

Out[364]= 1000

In[365]:=
```
ListPlot[Table[{length, costTransPerMile[length]}, {length, 1, maxTubeSegmentLength, .1}],
 Joined → True, Frame → True,
 FrameLabel → {"Tube Segment Length (m)", "Cost Per Mile ($)"}, GridLines → Automatic]
```

Out[365]=



In[366]:=
```
costFreight =
  nLoads milesFreight costTransPerMile[BTsegmentLength] / 10^6 × Table[1, {nSpacings}] // N;
```

Bellows

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 252-255
See LIGO-C1900321, file LIGO_DRD_9_ITEM3.pdf, pg. 128-138
For the LIGO BT, the optimum BT length was determined to be 19.812 m (65' 0"). This optimum was based on a design goal to place the baffles at (or near) the support points. The baffle spacing was specified as 20 m, which was close to the optimum tube length for shipping and construction (19.812 m). The expansion joint spacing then had to be a multiple of 19.812 m.

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 255-271
CBI performed a trade study on the formed Bellows (thin-walled vs near full thickness).
Near full thickness bellows are preferred due to lower cost, fewer welds, higher torsion capacity, lower leak risk and lower damage risk. Near full thickness (0.100 in) bellows were just (barely) compliant enough so that additional convolutions were not needed (which would add cost).

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 263-265
Discussion of 3 forming methods: roll forming, expanding mandrel (punch forming) and hydroforming. Hydroforming is best but requires the most expensive NRE; best for large volume production.

Rather than attempt to re-design the Bellows (and estimate costs for these variations), in this simple cost estimate model, I'll assume that each Bellows "handles" the expansion from ~40m of tube, and the cost per Bellows, remains the same.

```
In[367]:= nBellows = 2 armLength / 40

Out[367]= 2000

In[368]:= costPerBellows = 3000;
          costBellows = nBellows costPerBellows / 10^6 Table[1, {nSpacings}] // N;
```

Supports

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat) :

See LIGO-C1900321, file LIGO_DRD_9_ITEM2.pdf, pg. 252-255
See LIGO-C1900321, file LIGO_DRD_9_ITEM3.pdf, pg. 128-138
For the LIGO BT, the optimum BT length was determined to be 19.812 m (65' 0"). This optimum was based on a design goal to place the baffles at (or near) the support points. The baffle spacing was specified as 20 m, which was close to the optimum tube length for shipping and construction (19.812 m). The expansion joint spacing then had to be a multiple of 19.812 m.

Perhaps BT gravity sag as a function of BT segment length should be calculated to determine the number of required supports. For this simple cost model, I'll assume 1 Fixed Support and 1 Guided Support per Bellows (as is the case for LIGO). Since the CBI cost data doesn't differentiate between fixed and guided, a single support quantity and cost is used.

In[370]:=
```
nSupports = 2 nBellows
```

Out[370]=
```
4000
```

In[371]:=
```
costPerSupport = 3800;
costSupports = nSupports costPerSupport / 10^6 Table[1, {nSpacings}] // N;
```

Leak Tests

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat)

In[373]:=
```
nLeakTests = nTubes;
costPerLeakTest = 2200;
costLeakTests = nLeakTests costPerLeakTest / 10^6 Table[1, {nSpacings}] // N;
```

Pump Ports

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat)
Pump Ports are not explicitly included in CBI’s cost estimate (referenced above).
FWIW a hand written note on pg. 85 of LIGO_DRD_9_ITEM_3.pdf indicates that each Pump Port costs $3975

Since I don't know the number of required ports, I'll simply scale the LIGO Cost Book number by the CE Length/LIGO Length:

In[376]:=
```
costPumpPorts = 1.83 (80 / 16) Table[1, {nSpacings}] // N;
```

Installation

https : // dcc.ligo.org/LIGO - C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 59 - 62 :
LIGO_DRD _ 9 _ITEM _ 3. pdf, pg. 155 - 156 (repeat) :

In[377]:=
```
nTubeInstalls = 2 nTubes;
costPerTubeInstall = 1500;
costTubeInstall = nTubeInstalls costPerTubeInstall / 10^6 Table[1, {nSpacings}] // N;
```

Coil Mfg Costs

1992 cost of the tube material and manufacturing is taken as the average of 5 steel manufacturer costs, +/- 11%
Note that these costs are (apparently) independent of tube segment length and thickness for the range

under consideration by CBI for LIGO.
Assuming:
1) a coil weight of 30,000 lbm, which was the size ordered by CBI
2) no welding of coil ends
3) spiral welded tube, which requires tube spiral length plus 2 x skelp widths
4) 10% scrap recouped

https://dcc.ligo.org/LIGO-C1900321
LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 105 & 247 (repeat):
Coil material procurement costs, including:
cost of coil material (304L)
transport cost to/from bake facility
bake cost
transport cost to/from finishing mill
outgas test costs
cost to level
cost to slit
transport to tube mfg
less cost of 10% scrap steel

Estimate of coil waste so that the number of 65 ft long tubes from a single coil (6) matches the quotes CBI received from spiral tube manufacturers. Corresponds to 1 skelp length at each end of 6 tubes, or 12 x skelp length waste
I've assumed that this as a constant waste weight per coil

```
In[380]:= coilWeight = 30000 × 0.453592; (* kg *)
wastePerCoil =
  (Pi / 4) (BTdiameter^2 - (BTdiameter - 2 BTthickness) ^2) 12 skelp BTmaterialDensity // N;
wastePerCoil / coilWeight

Out[382]= 0.0755116
```

Assuming Coil Weight is constant for varying tube thickness, as the stiffener spacing varies:

```
In[433]:= BTsegmentWeightUncut = (Pi / 4) (BTdiameter^2 - (BTdiameter - 2 t304L) ^2)
    (BTsegmentLength 1000) BTmaterialDensity // N;
nTubesPerCoil = Floor[(coilWeight - wastePerCoil) / BTsegmentWeightUncut]
nTubesPerCoil = (coilWeight - wastePerCoil) / BTsegmentWeightUncut

Out[434]= {6, 5, 4, 3, 3, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1, 1, 1, 1,
 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1}

Out[435]= {6.05968, 5.39772, 4.1583, 3.48342, 3.12193, 2.74996, 2.55734, 2.37011,
 2.24003, 2.14138, 2.03241, 1.93921, 1.89803, 1.87255, 1.8557, 1.84294,
 1.83017, 1.8212, 1.81645, 1.81408, 1.8117, 1.80945, 1.80755, 1.80565,
 1.80375, 1.80185, 1.79995, 1.79805, 1.79615, 1.79492, 1.79468, 1.79443,
 1.79419, 1.79395, 1.79371, 1.79347, 1.79323, 1.79299, 1.79274, 1.7926, 1.7926}
```

In[436]:=
```
nCoils = Ceiling[nTubes / nTubesPerCoil] // N
```

Out[436]=
```
{661., 742., 962., 1149., 1282., 1455., 1565., 1688., 1786., 1868.,
 1969., 2063., 2108., 2137., 2156., 2171., 2186., 2197., 2203., 2205.,
 2208., 2211., 2213., 2216., 2218., 2220., 2223., 2225., 2227., 2229., 2229.,
 2230., 2230., 2230., 2231., 2231., 2231., 2231., 2232., 2232., 2232.}
```

In[437]:=
```
baseCostCoil = 27639; (* 304L *)
freightCostBake = 822;
costBake = 3000;
freightFinishingMill = 411;
costOutgasTest = 2650;
costLevel = 1500;
costSlit = 1800;
freightTubeMfg = 1370 / 2; (*2 coils per trip *)
```

In[445]:=
```
costCoilMfg =
  (baseCostCoil + freightCostBake + costBake + freightFinishingMill + costOutgasTest +
     costLevel + costSlit + freightTubeMfg) nCoils Table[1, {nSpacings}] / 10^6;
```

Spiral Weld Mfg Costs

https://dcc.ligo.org/LIGO-C1900321

LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 113:

Spiral welded tube manufacturing cost is taken as the average of 3 manufacturing quotes/estimates for tube manufacturing + equipment costs + material overhead. Costs are not quoted as a function of tube segment length. Presumably shorter length tube segments would cost a little more due to the need to make more transverse cuts, but I don’t know this cost.

In[446]:=
```
costSpiralWeldMfg = Table[1, {nSpacings}]
    (3870944 + 548800 + 262904 + 4303000 + 106650 + 296466 + 1809792 + 208867) / 3 / 10^6 // N;
```

Stiffener Mfg Costs

https://dcc.ligo.org/LIGO-C1900321

LIGO_DRD _ 9 _ITEM _ 2. pdf, pg. 139-141 & 282 (repeat):

BT stiffener material costs (material, painting & welding)

In[447]:=
```
nStiffeners = 2 armLength 10^3 / L304L // N
```

Out[447]=
```
{105541., 80000., 40000., 26666.7, 20000., 16000., 13333.3, 11428.6, 10000., 8888.89,
 8000., 7272.73, 6666.67, 6153.85, 5714.29, 5333.33, 5000., 4705.88, 4444.44, 4210.53, 4000.,
 3809.52, 3636.36, 3478.26, 3333.33, 3200., 3076.92, 2962.96, 2857.14, 2758.62, 2666.67,
 2580.65, 2500., 2424.24, 2352.94, 2285.71, 2222.22, 2162.16, 2105.26, 2051.28, 2000.}
```

Assuming available bar stock every 1/4” in width for the chosen 3/8” thick bar

Should really choose next largest size, but here I’m selecting nearest width

In[448]:=
```
availableBarStockWidths = Table[2 + i .25, {i, 0, 15}] 25.4;
selectedBarStockWidths = Nearest[availableBarStockWidths, h304L];
thicknessBarStock = b304L; (* mm *)
```

Use the CBI cost estimate for LIGO stiffeners (1.75” high x 3/8” thick) to scale the cost of stiffeners of other dimensions:

In[451]:=
```
lengthBarStock = 14 × 12 × 25.4; (* mm *)
unitWeightBarStock = 1.12 × 0.00148816; (* kg/mm *)
unitCostBarStock = 1.55 / 0.453592; (* $/kg *)
costStiffenerMaterial = lengthBarStock unitWeightBarStock unitCostBarStock;
costPerStiffenerMfg = (34 + 41 + 80) / 3 // N;
costFactorStiffenerMfg = costPerStiffenerMfg / costStiffenerMaterial
```

Out[456]=
```
2.12585
```

In[457]:=
```
costStiffenerMaterial = unitCostBarStock selectedBarStockWidths / (1.75 × 25.4); (* $/kg *)
```

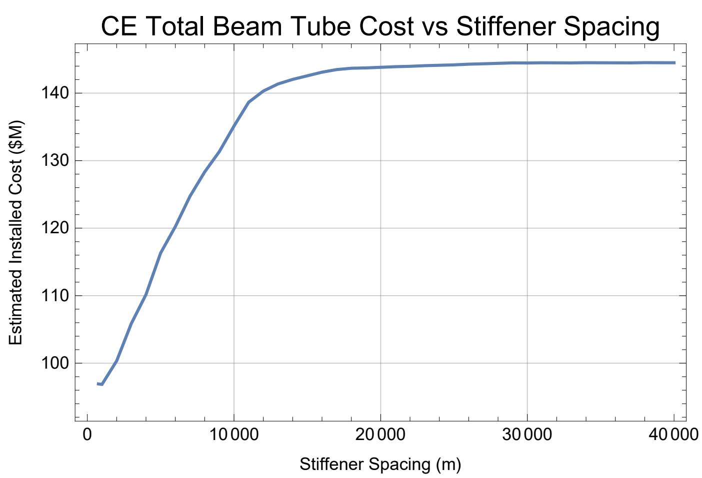
In[458]:=
```
costPerStiffenerWld = 15;
costStiffeners = Table[1, {nSpacings}] nStiffeners
   (costPerStiffenerMfg costFactorStiffenerMfg + costPerStiffenerWld) / 10^6;
```

Total Costs (as a function of stiffener spacing)

In[460]:=
```
totalCost = costFreight + costBellows + costSupports + costLeakTests +
   costPumpPorts + costTubeInstall + costCoilMfg + costSpiralWeldMfg + costStiffeners;
```

In[461]:=
```
ListPlot[Transpose[Partition[Join[L304L, totalCost], nSpacings]],
 Joined → True, Frame → True, GridLines → Automatic,
 FrameLabel → {"Stiffener Spacing (m)", "Estimated Installed Cost ($M)"},
 PlotLabel → Style["CE Total Beam Tube Cost vs Stiffener Spacing", 14]]
```

Out[461]=



In[462]:=
```
plotData = {Transpose[Partition[Join[L304L / 10^3, costFreight], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costBellows], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costSupports], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costLeakTests], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costPumpPorts], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costTubeInstall], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costCoilMfg], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costSpiralWeldMfg], nSpacings]],
   Transpose[Partition[Join[L304L / 10^3, costStiffeners], nSpacings]]};
```

```
In[464]:= costFreight[[1]]
Out[464]= 3.34635

In[465]:= costBellows[[1]]
Out[465]= 6.

In[466]:= costSupports[[1]]
Out[466]= 15.2

In[467]:= costLeakTests[[1]]
Out[467]= 8.8

In[468]:= costPumpPorts[[1]]
Out[468]= 9.15

In[469]:= costTubeInstall[[1]]
Out[469]= 12.

In[470]:= costCoilMfg
Out[470]= {25.4531, 28.5722, 37.0437, 44.2445, 49.366, 56.0277, 60.2635, 64.9998,
  68.7735, 71.9311, 75.8203, 79.4399, 81.1728, 82.2895, 83.0211, 83.5987,
  84.1763, 84.5999, 84.8309, 84.9079, 85.0235, 85.139, 85.216, 85.3315, 85.4085,
  85.4855, 85.6011, 85.6781, 85.7551, 85.8321, 85.8321, 85.8706, 85.8706,
  85.8706, 85.9091, 85.9091, 85.9091, 85.9091, 85.9476, 85.9476, 85.9476}

In[471]:= costSpiralWeldMfg[[1]]
Out[471]= 3.80247

In[472]:= costStiffeners
Out[472]= {13.1753, 9.98686, 4.99343, 3.32895, 2.49672, 1.99737, 1.66448, 1.42669, 1.24836,
  1.10965, 0.998686, 0.907897, 0.832239, 0.76822, 0.713347, 0.665791, 0.624179,
  0.587463, 0.554826, 0.525624, 0.499343, 0.475565, 0.453948, 0.434211, 0.416119,
  0.399475, 0.38411, 0.369884, 0.356674, 0.344375, 0.332895, 0.322157, 0.31209,
  0.302632, 0.293731, 0.285339, 0.277413, 0.269915, 0.262812, 0.256073, 0.249672}

In[480]:= costStiffeners[[1]] / totalCost[[1]]
Out[480]= 0.13593

In[481]:= costBellows[[1]] / totalCost[[1]]
Out[481]= 0.0619021

In[482]:= (costBellows[[1]] + costStiffeners[[1]]) / totalCost[[1]]
Out[482]= 0.197832
```

In[474]:=
```
StackedListPlot[plotData, PlotRange → {{0, 20}, {0, Automatic}},
 Joined → True, Frame → True, GridLines → Automatic,
 FrameLabel → {"BT Stiffener Spacing (m)", "Estimated Installed Cost ($M)"},
 PlotLabel → Style["CE Total Beam Tube Cost vs Stiffener Spacing", 14],
 PlotLegends → {"Freight", "Bellows", "Supports", "Leak Tests",
   "Pump Ports", "Install", "Coil Mfg", "Spiral Wld", "Stiffeners"}]
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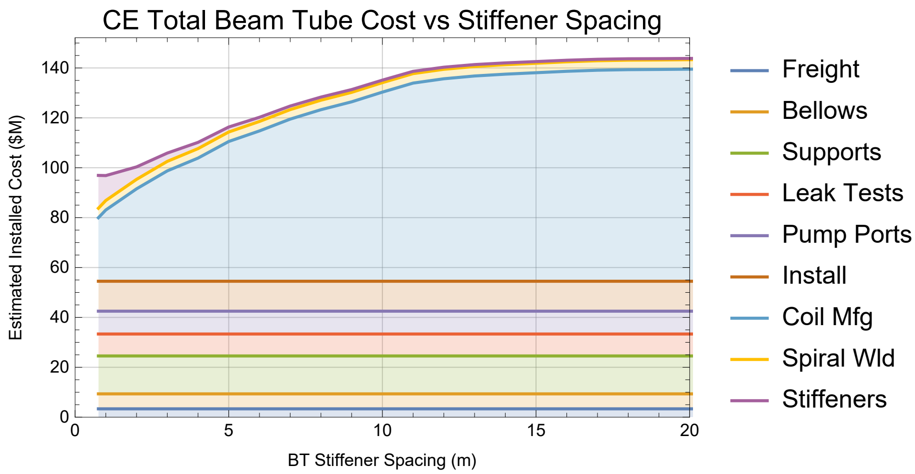
Out[474]=



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