April 2004 • NREL/SR-500-35546

Subcontractor Report

WindPACT Rotor Design Study: Hybrid Tower Design

Period of Performance:
June 29, 2000 – February 28, 2004

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Kirkland, Washington

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1 INTRODUCTION

1.1 Background

Wind energy has the lowest overall cost of all renewable energy sources and is now almost competitive with conventional energy sources, even without environmental credits. The dramatic decrease in the cost of energy (COE) from wind over the past two decades is due to improvements in aerodynamics, materials, controls, electronics, and in the balance-of-station costs, such as interconnection and maintenance.

In 2000, the National Renewable Energy Laboratory (NREL) launched the Wind Partnerships for Advanced Component Technologies (WindPACT) program to examine ways in which the cost of wind energy could be reduced a further 30% to approximately \$0.03/kWh. The purpose of this program is to explore advanced technologies for improving machine reliability and decreasing the overall COE.

The cost of a wind turbine tower can represent as much as 20% of the cost of an entire megawatt-scale horizontal axis wind turbine (HAWT) and as much as 10% of the total COE. The tower is a major cost component, and its design is important: Its structural properties are key to the response of the rotor; its height determines the wind regime that the rotor experiences; it allows access to the turbine nacelle and rotor; and it houses components of the electrical connection and the control and protection systems.

Most large wind turbines currently installed in the United States use self-supporting steel tubular towers. The diameter of these tubes is limited by the maximum size that can be transported by road, which is approximately 4.3 m. The base dimensions of a truss tower are not restrained by this limit, but trusses may require more maintenance and may not be aesthetically acceptable. Guyed tube towers have been used, but they represent additional foundation costs and inconvenience. Addressing these limitations may lead to an alternative that avoids the problems. For this reason, the WindPACT Rotor Design Study [1] was modified to include a study of a hybrid tower to determine the technical and economic feasibility of such a design.

1.2 Current and Past Practice

In the past, many methods have been used to support horizontal and vertical axis wind turbines. The most common approach for vertical axis wind turbines (VAWTs) has been to use guy cables for the upper bearing while the lower connection remains close to the ground. Rigid truss frames have also been used for VAWTs but with limited success.

Small HAWTs usually required a ratio of height to diameter (H/D) greater than that for larger HAWTs in order to gain the same benefit of higher wind speeds. This meant that small HAWTs more often employed supporting guy cables, which are likely to be more cost-effective than a freestanding tube or truss when the H/D ratio exceeds about 2.0.

In the 1980s, when many 50- to 100-kW machines were installed in California, truss towers were common. Although a stiff support can be offered to the nacelle in this way, truss towers were considered an attraction to birds, leading to a possible increase in avian mortality. In addition, truss towers were considered less aesthetic than single-tube towers. As a result of these and other factors, self-supporting tube towers have become the standard for utility-scale wind turbines. Although the tubes are generally made of steel or concrete, steel tubes have become the standard, especially in developed countries with high labor costs.

The towers for large HAWTs are sometimes categorized according to the fundamental natural frequency of the combined system [2]. Systems with a natural frequency below the rotor speed (1P) are classed as “soft-soft”; those with natural frequencies between 1P and nP (where n is the number of blades) are “soft”; and a frequency above nP identifies the tower as “stiff.” Some think that soft-soft towers will more successfully attenuate the fatigue loads throughout the system. However, this relationship has not been firmly proven, and most large wind turbines use soft towers.

This study focuses on large HAWTs, which can be considered to have rated powers above 1.0 MW, although even this is well below the higher ratings that most manufacturers now sell. Such machines have hub heights greater than 50 m; the highest reach about 80 m. A major limitation of the use of steel tubes for heights above about 80 m is that the base diameter must fit within the maximum dimension that can be transported by road. This limit is about 4.3 m in the United States. Any larger diameter may require sectioning and field assembly by bolting or welding. The former may be unsightly and expensive; the latter may increase the costs of obtaining adequate quality assurance.

To circumvent the problem of transporting large steel sections, one recent study [3] examined the concept of combining an upper steel tube with a concrete lower tube. That study concludes that at some scales, the use of cast-in-place or precast concrete for the lower tube will be cost-effective.

1.3 Scope

The current study examines an alternative type of hybrid design, one that considers a combination of steel tube, steel truss, and guy cables (Figure 1-1). It may be called a "stayed" design due to the analogy with the support of sailing ship masts.

This study is limited to an examination of configurations suited to supporting a 1.5-MW rotor and nacelle at a hub height of 84 m. These values make the tower comparable with the 1.5-MW WindPACT baseline tower [1]. However, the width of the spreader beams, the height of the truss, and the shape of the tube are varied to optimize the configuration.

1.4 Objectives

The objectives of this study are to:

- Construct a simple mathematical model of the stayed tower to allow trade-offs between the dimensions to optimize the configuration
- Carry out preliminary design of the major components and to prepare drawings
- Obtain cost estimates for all components
- Draw conclusions regarding the cost-effectiveness of this type of configuration
- Identify the strengths and weaknesses of the design concept.

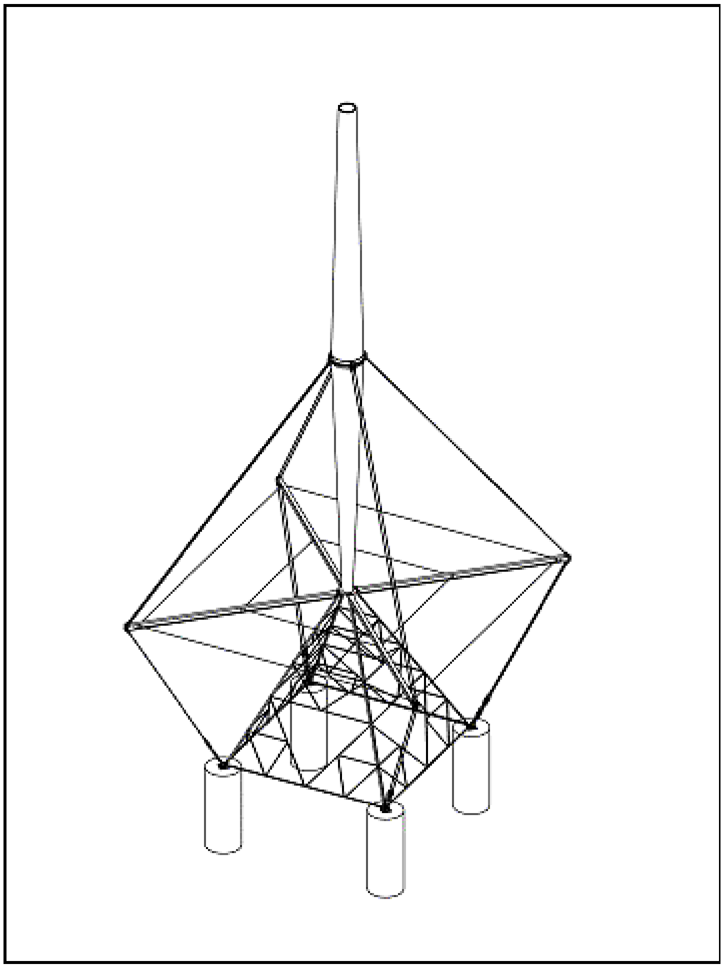


Figure 1-1. Representative stayed tower configuration.

The staff of the National Wind Technology Center (NWTC) originated the concept of combining a lower truss and an upper tube, with the latter supported by stayed cables. The motivations behind the concept shown in Figure 1-1 are to:

- Avoid the restriction of a 4.3-m diameter for the tube base
- Use the larger footprint of a truss for the lower parts of the tower
- Combine this larger footprint with guy cables to support the upper tube.

2 APPROACH

2.1 Selected Configuration

The basic configuration model and nomenclature used to model the concept are shown in Figure 2-1.

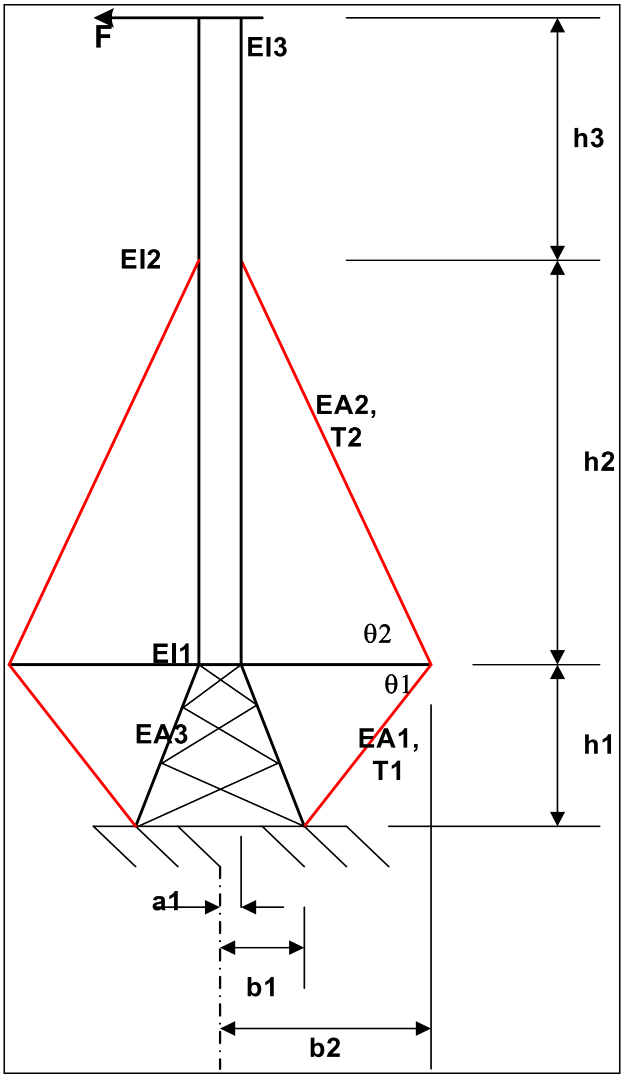


Figure 2-1. Two-dimensional layout of hybrid tower.

The location at which the guy cables are connected to the tube is fixed such that distance h3 is equal to the rotor radius below the hub height to ensure blade-cable clearance.

The following key design variables were identified:

- The length of the spreader beams
- The base dimension of the truss
- The height of the connection between truss and tube (i.e., the height of the truss)
- The stiffness of the guy cables.

Early in the project, the connection between the truss, the spreader beams, and the tube was identified as a key component. This component must be a casting to accept the multiple connections, and the moment transferred to the tube will affect not only the tube but also the design of the casting. The value of this moment should be as low as possible.

2.2 Initial Design Spreadsheet

The hybrid tower sketched in Figures 1-1 and 2-1 is a highly redundant structure because there are multiple load paths, except in the upper part of the tube. An exact analysis of the internal forces due to a given external load is, therefore, a complex calculation best done by a computer code such as a finite element analysis. However, to avoid the added cost of this process and to facilitate analysis of many configurations, as much of the analysis as possible was completed by hand and by spreadsheet calculations. This was justified by the objective to arrive at a cost estimate to determine whether the concept merits further pursuit.

We made the following assumptions to perform this simplified analysis:

1. The upper cables are distinct from the lower cables and have their own set of end attachments.
2. The spreader beams are infinitely stiff members pinned at each end.
3. The truss is also very stiff, and the top of the truss does not translate.
4. The bending stiffness of the tower can be represented by a torsional spring at the base of the tube.
5. The tube is of constant cross section and stiffness (this was later modified).
6. The loading on the tower is a single lateral load at the hub height.

These assumptions make the hybrid tower a once-indeterminate structure, and it is possible to solve for all the member forces using the Solver feature in an Excel spreadsheet. The input to the spreadsheet consisted of:

- Lateral force at hub height
- Truss height
- Width of the truss base
- Span of the spreader beams
- Axial stiffness of the cables
- Bending stiffness of the tube
- Cross section area of main truss members.

The spreadsheet output included the forces in all the components. We used this information to calculate the lateral motion at the hub and to compare it with the stiffness of a conventional tower. In addition, the spreadsheet performed some preliminary design, such as the mass of the cables, the tube, the truss, and the spreader beams (by making assumptions about the governing criteria).

In practice, a preload will be applied to the cable system to ensure that no cables become slack under the influence of normal operating loads. For extreme loads, such as from the 50-year return wind loading, it is permissible to allow the downwind cables to become slack. The preload was chosen so that under the 50-year predicted characteristic thrust at the yaw bearing, the downwind guy cables were reduced to zero tension (assuming that the response of the system, including the cable tension, remained linear).

2.3 Final Spreadsheet Design

It is usually possible to arrive at a set of guy cable stiffness and tube flexibility that results in zero bending at the base of the tube under the influence of a lateral load at hub height. Figure 2-2 shows how the bending effects at the tube base due to cable extension only are of opposite nature to that of the lateral load only. The spreadsheet was, therefore, set up to solve for the cable size that would result in zero total rotation at the tower base and, hence, zero base-bending moment. In this solution, the distribution of bending stiffness in the tube is important, and it is no longer acceptable to approximate the tube as having constant stiffness. The formulas in the spreadsheet were corrected to reflect the tapered nature of the tube. This, in turn, meant that tube diameter and wall thicknesses at the top, at the cable restraint, and at the base were required as input.

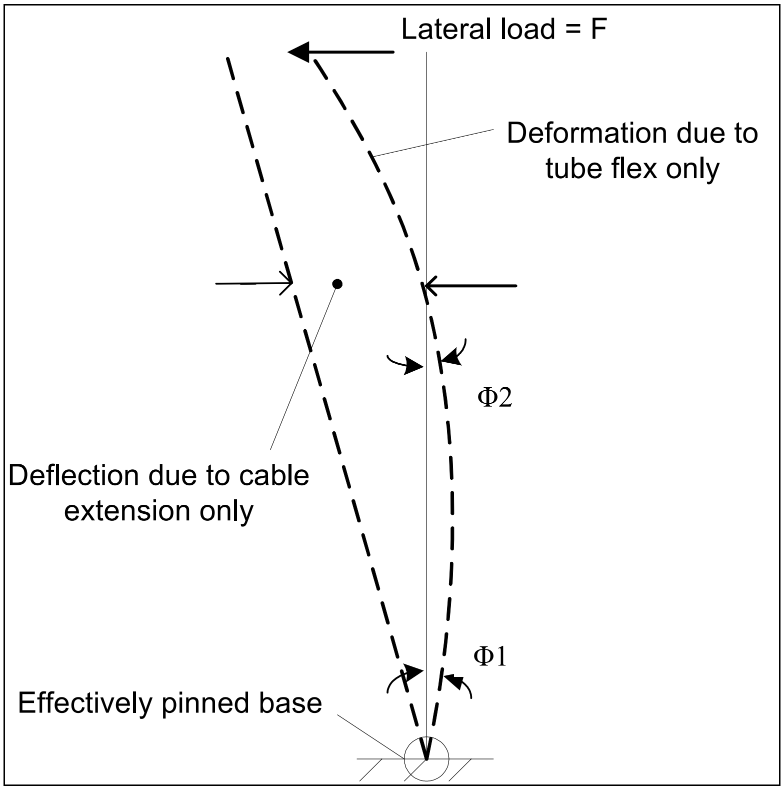


Figure 2-2. Displacements of tube due to tube flexing and cable extension.

2.3.1 Spreadsheet Calculations

The following calculations assume that the wind loading is aligned with one of the guys and refer to the two-dimensional sketch in Figure 2-2.

The tube base is regarded as pinned, so the change in upper cable tensions, T2, due to the applied lateral load, F, is

$$\mathrm{T2} = \frac{\mathrm{F(h2 + h3)}}{\mathrm{h2}\cos(\theta 2)}\,.$$

From this, the tension, T1, in the lower cables is calculated as

$$\mathrm{T1} = \mathrm{T2}\frac{\sin(\theta 2)}{\sin(\theta 1)}\,.$$

The extension in the lower cables gives rise to a vertical displacement, d1, at the ends of the spreader beams of

$$\mathrm{d1} = \frac{\mathrm{T1\ h1}}{\mathrm{EA1}\ \sin^2(\theta 1)}$$

and the lateral displacement at the attachment to the tube is

$$d2 = d1 \tan\theta 2 + \frac{T2\ h2}{EA2\ \cos^2(\theta 2)} .$$

The maximum compression in the spreader beam is

$$\text{compression} = T1\ \cos(\theta 1) + T2\ \cos(\theta 2) .$$

The stiffness of the cables and tube must be proportioned so that there is zero final rotation at the tube base (because the connection of the tube to the truss will, in reality, be a rigid one, and the truss is considered very stiff). This requires calculation of the rotation due to the cable extension of the cables and due to the flexing of the tube. For small angles, the rotation due to the cable extension is simply

$$\phi = {}^{d2}\!/_{h2} .$$

The rotation due to the tube flex is more complex to calculate. We have that

$$\phi 1 + \phi 2 = \int \frac{M_z dz}{EI} \quad \text{and} \quad \phi 2\ h2 = \int_0^{h2} \frac{M\ dz}{EI}$$

where $M = F\ h3\ {}^{z}\!/_{h2}$

$$EI = EI1\left[1 + (\beta - 1)\frac{z}{h2}\right]$$

and $\beta = \dfrac{EI2}{EI1}$

where $\varphi 1$ is the tube rotation at the tube base and $\varphi 2$ is the rotation of the tube at the cable connection. The solution for $\varphi 1$ is

$$\phi 1 = \frac{Fh3}{EI1} \int_0^{h2} \frac{\left(1 - {}^{z}\!/_{h2}\right) {}^{z}\!/_{h2}}{\left[1 + (\beta - 1) {}^{z}\!/_{h2}\right]} dz ,$$

which can be evaluated numerically. First, the value of EI1 was selected, and then the Excel Solver routine was used to solve for the cable cross section that satisfied the condition that

$$\phi 1 + {}^{d2}\!/_{h2} = 0 .$$

The lateral displacement, d3, at the rotor hub height can be calculated with reference to the same Figures 2-1 and 2-2 and is a superposition of the displacement due to cable extension and flexure of the tube. This leads to

$$d3 = d2 \frac{(h2 + h3)}{h2} + \phi 2\ h3 + \int_0^{h3} \frac{M\ z\ dz}{EI}$$

where $$\phi 2 = \frac{Fh3}{EI1} \int_0^{h2} \frac{\left(z/_{h2} \right)^2}{1 + (\beta - 1) z/_{h2}} dz$$

and $$M = F\,h3\, z/_{h3}$$

$$EI = EI3 \left(1 + (\alpha - 1)\, z/_{h3} \right)$$

$$\alpha = EI2/_{EI3}$$

2.4 Component Design Process

Some design capability was included in the spreadsheet. For example, the total mass of the steel tube was calculated from the dimensions supplied for the tube sections. In addition, the cross section of the horizontal spreaders was estimated based on the buckling capacity of the flanges using a safety factor of 2.0 in conjunction with the characteristic loads. The mass of the main truss members was calculated from the given cross section, and an estimate was made for the bracing members.

2.5 Cable Dynamics

A check was carried out to avoid the upper or lower sets of cables "galloping" due to excitation of their fundamental natural modes by the 1P or 3P harmonics from the rotor. This calculation considered the range of tensions that would occur during normal operation of the wind turbine. Figure 2-3 shows typical plots for the upper cables of the fundamental natural frequencies together with the change in axial stiffness with cable tension. The operating rotor speed is approximately 20 rpm, or 0.33 Hz, and 3P is at 1.0 Hz. Hence, the natural frequency of the cables will be well above the dangerous harmonics except at the very lowest tension; that condition will occur very infrequently and is likely to correspond with a stationary rotor. The natural frequencies of the lower cable will be greater than those of the upper cables and will, therefore, be further above the 1P and 3P harmonics.

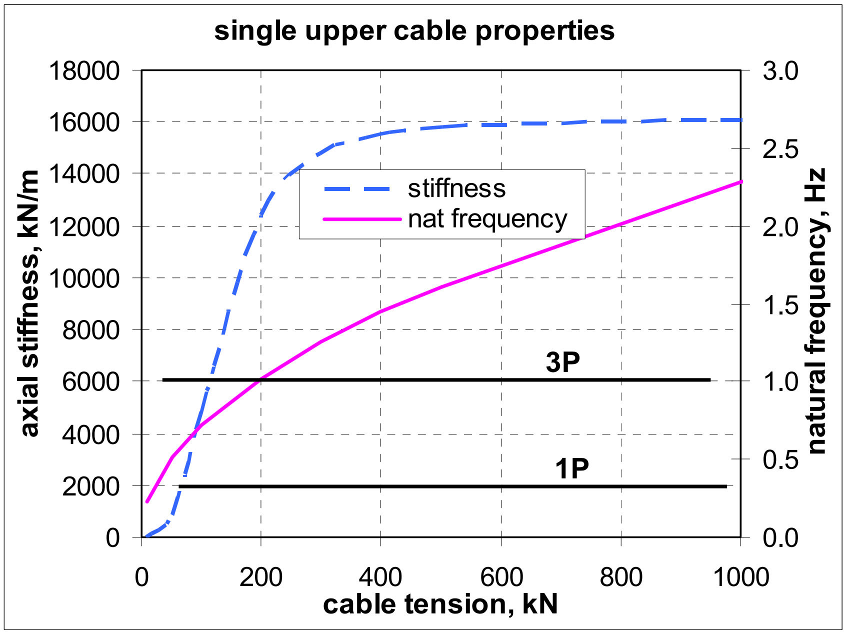


Figure 2-3. Natural frequency and axial stiffness vs. tension for the upper guy cables.

The axial stiffness of the cable was calculated from the expression [4]:

$$k = \left[\frac{\ell}{EA} + \frac{\rho^2 \ell^3 \cos^2\theta}{12T^3} \right]^{-1}$$

and the fundamental natural frequency (Hz) was calculated from [4]

$$f = \frac{1}{2\,\ell}\sqrt{\frac{T}{\rho}}$$

where ρ = mass density per unit length, T= tension in cable, and *l* = cable length.

3 ANALYSIS AND DESIGN

3.1 Outline Geometries

The outline geometries considered are summarized in Table 3-1. They fall into three groups that correspond to the single parameter varied in each case. Those parameters are the length of the spreader beam, the width of the truss base, and the height of the truss.

Table 3-1. Outline Geometries Considered

Group #	Spreader Beam Length (m)	Truss Base Half-Width (m)	Truss Height (m)
1	15	10	20
Variation of spreader	20	10	20
beam length	25	10	20
	30	10	20
2	25	10	20
Variation of truss	25	5	20
width	25	15	20
3	25	10	15
Variation of truss	25	10	20
height	25	10	25

The outlines corresponding to Groups 1, 2, and 3 are shown in Figures 3-1, 3-2, and 3-3, respectively.

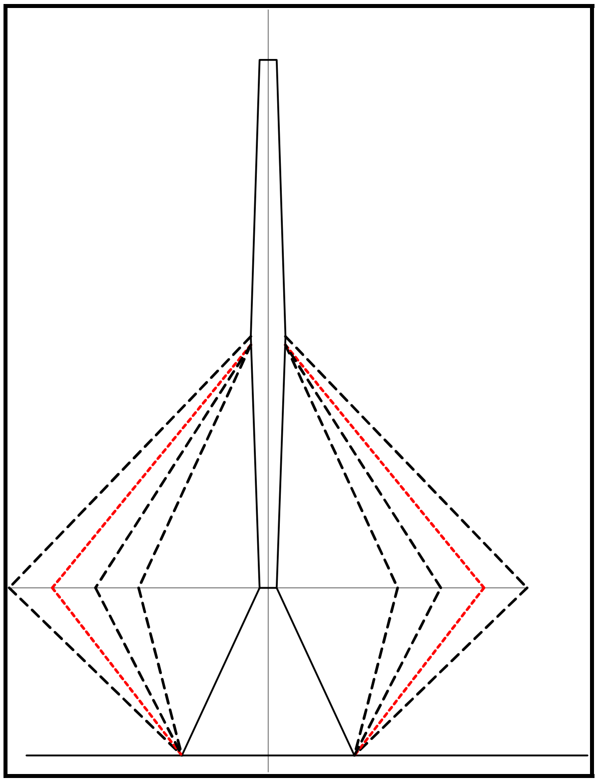


Figure 3-1. Outlines of Group #1: variation of spreader beam length.

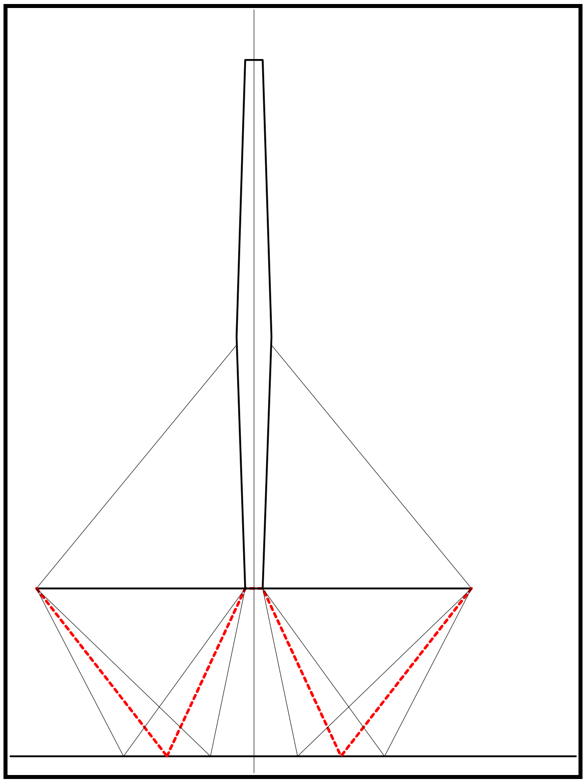


Figure 3-2. Outlines of Group #2: variation of truss base width.

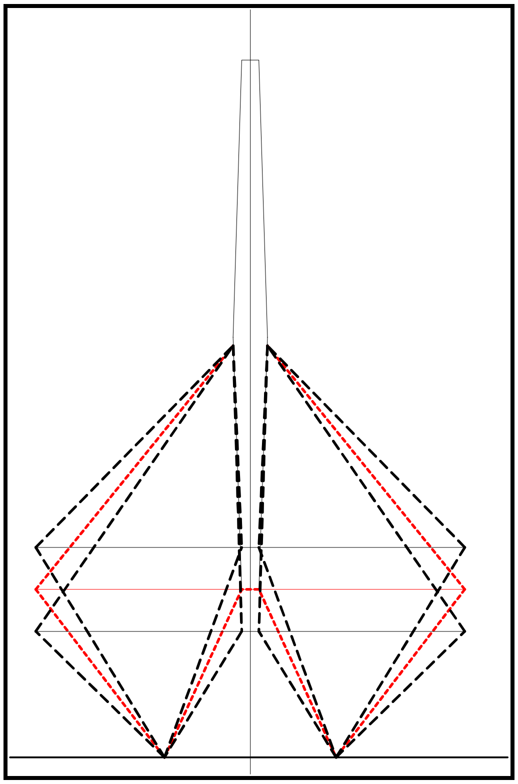


Figure 3-3. Outlines of Group #3: variation of truss height.

3.2 Selection of Configuration

We examined the dependence of several system properties on the governing dimensions such as truss height, truss width, and spreader beam length. The selected properties are:

- Minimum preload in the cables. The preload was selected such that the minimum cable load under peak lateral rotor load (436 kN) was zero.
- Maximum cable tension. As for the minimum tension, this calculation assumed a linear response between load and tension change.
- Lateral stiffness at the tower top. This calculation assumed a rigid truss but considered the flexibility of the tube and the cables.
- Maximum compression in the spreader beams. The design of the beam was governed by stability under peak compression.
- Estimate of the total mass of the assembly (excluding cables). This was a rough estimate of total masses, using approximate design of the spreader beam.
- Cross section of each cable pair. The cables are in pairs and the cross section values refer to the combination of both cables.
- Diameter of the base of the tube. This was fixed at 1200 mm with a thickness of 8 mm. These dimensions led to acceptable answers for other properties, such as the cable cross sections.

One limiting property was the size of the cables. The cost of the cables increases rapidly with diameter, especially the cost of the end sockets and other end fittings. The maximum acceptable cable size was 2½ inches (63 mm), which corresponds to an effective cross section for a pair of approximately 5000 mm^2. A preferred maximum cross section was 4000 mm^2, corresponding to a pair of 57-mm cables.

Figure 3-4 shows the variation in the key properties as a function of the spreader beam length (Group #1). If the cable cross section is to be within 4000 mm^2, then the beam length must be 25 m or more. The longer beam lengths are associated with lower cable tensions but with higher beam compression, which leads to higher overall mass.

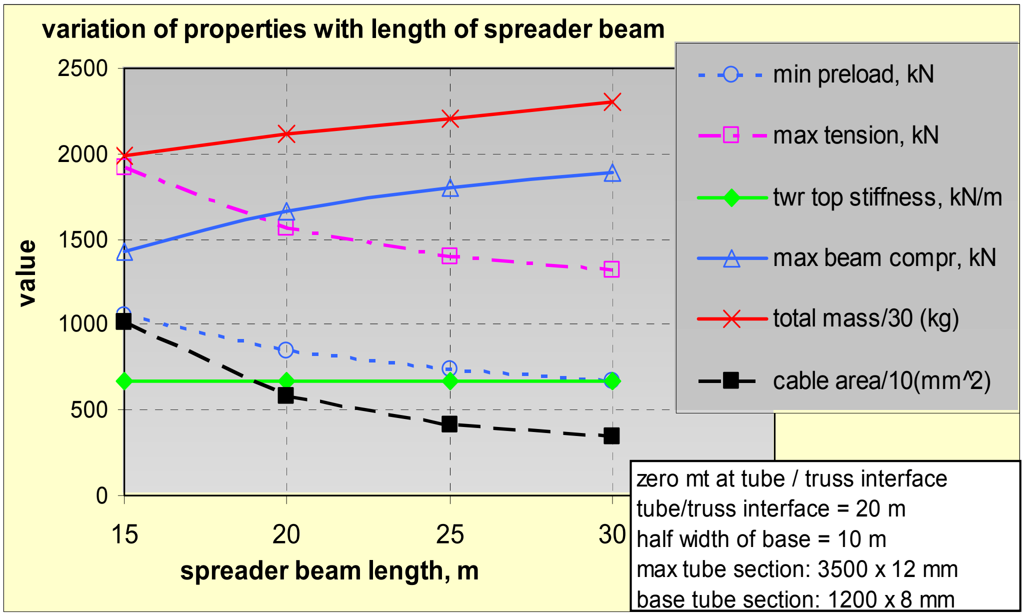


Figure 3-4. Variation of key properties with length of spreader beam (Group #1).

Figure 3-5 illustrates the results of Group #2, in which the width of the truss base was varied while the spreader beam length was maintained at 25 m and the truss height at 20 m. The increasing width is associated with lower beam compression and lower cable tensions.

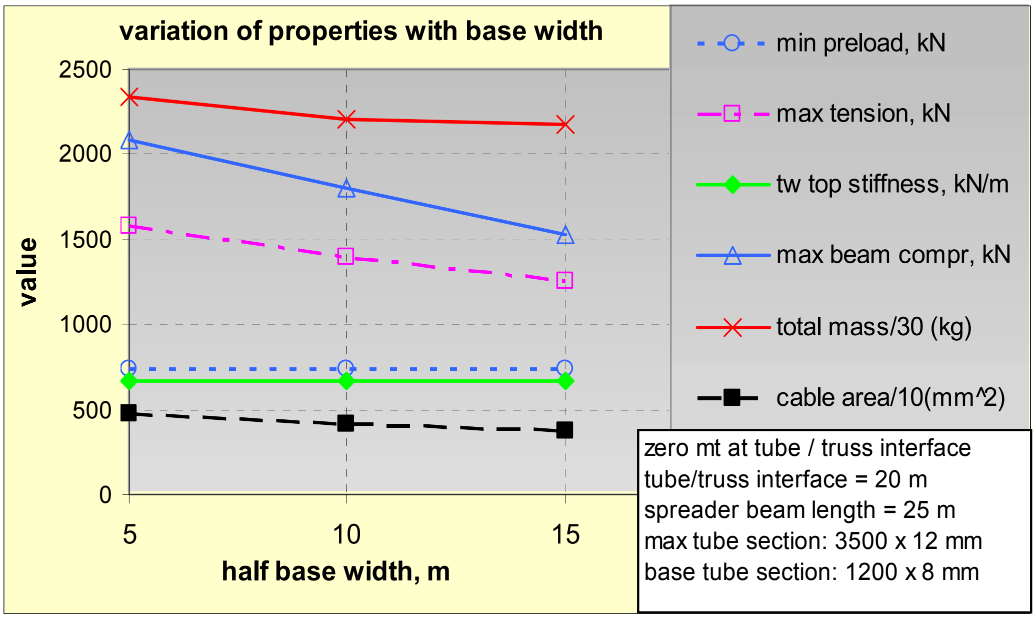


Figure 3-5. Variation of key properties with truss base width.

Figure 3-6 illustrates the results of Group #3 in which the height of the truss base was varied while the spreader beam length was maintained at 25 m and the truss half-width at 10 m. The increasing height is associated with lower maximum cable tension, lower beam compression, and higher hub-lateral stiffness.

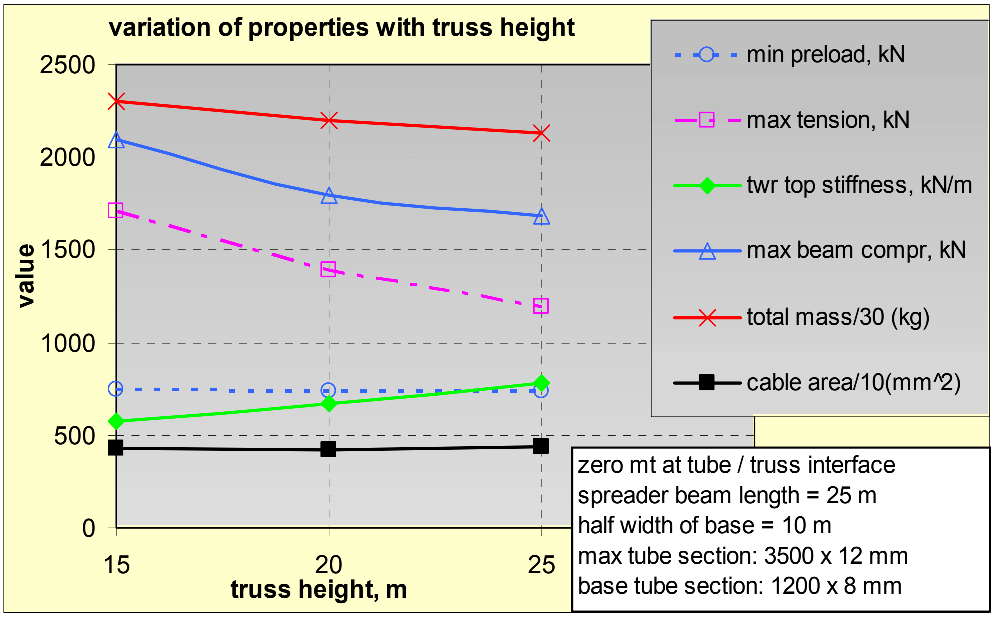


Figure 3-6. Variation of key properties with truss height.

3.3 Natural Frequency of Wind Turbine

The fundamental natural frequency of the complete wind turbine system is predominantly one of tower sway and is affected strongly by the tower stiffness. The tower stiffness will, therefore, determine whether the tower is classed as soft-soft (fundamental natural frequency less than 1P), soft (natural frequency between 1P and 3P), or stiff (natural frequency greater than 3P).

We estimated that a hub lateral stiffness of 600 kN/m offered by the tower (typical of the results presented above), assuming a head mass of 87,000 kg, would lead to a fundamental natural frequency of about 0.37 Hz. If the rated speed of the rotor is 20 rpm, then this natural frequency is 1.11P, which is barely sufficient to place it in the soft category. However, this calculation indicates that variations in some of the basic parameters could change the tower category from soft to soft-soft.

3.4 Selection of Configuration for Costing

After examining the full range of configurations, we selected a single configuration for final drafting and costing. The dimensions of that configuration are listed in Table 3-2. A number of trade-offs must be made among cable size, compressive loads, overall stiffness, etc. These were considered in this selection.

Table 3-2. Configuration Dimensions Selected for Final Costing

Item	Units	Dimension
Total height	m	84.0
Height of truss/tube interface	m	20.0
Half-width of base of truss	m	10.0
Length of one spreader beam	m	25.0
Height of tube/cable connection	m	49.0
Diameter of cables	mm	57
Pretension in each cable of each pair	kN	370
Tube section at top	mm	2000 x 8
Tube section at cable attachment	mm	3500 x 13
Tube section at bottom	mm	1200 x 8

The key decision drivers were the spreader beam length and the base width.

Figure 3-4 shows that the required cable stiffness and size decrease with the length of the spreader beam. For the cable diameter below 57 mm to be considered reasonable, the spreader beam must have a minimum length of 25 m.

Figure 3-5 shows that a decreased base width is associated with higher compressive loads in the spreader beam, higher initial cable tension, and higher required cable size. A smaller truss footprint will also lead to higher foundation loads. This suggests that a half-width no less than 10 m is desirable. Further increasing the footprint of the truss will lead to longer and less stable bracing members.

Table 3-3. Masses of Subassemblies of the Selected Configuration

Item	Total Mass (kg)
Spreader beams (4)	13,790
Upper tube	27,096
Lower tube	22,600
Truss assembly	14,487
Upper cables and fittings	7,880
Lower cables and fittings	5,136
Base castings (4)	3,916
Tube-truss casting	1,138

4 COST ESTIMATES

We approached several suppliers to determine the estimated costs for 100 units that will affect the overall cost of fabricating and assembly. Rough cost estimates reflect the feasibility nature of the study, so all results are approximate. The suppliers approached and the responses received are summarized in Table 4-1.

Table 4-1. Summary of Vendors Approached for Cost Estimates

Item	Supplier	Response
Steel fabrication	DMI Industries 420 East Main Ave. West Fargo, ND 58078 701-282-6959	No response
	Trinity Structural Towers, Inc. Thomas Holt Dallas, TX 75207 214-589-8382	No response
	Beaird Industries, Inc. Steve Rogers 601 Benton Kelly St. Shreveport, LA 71106 318-671-5400	$155-k/turbine
Castings	St Marys Foundry Steve Barry 405 E South St. St Marys, OH 45885 419-394-3346	$5691 for tube-truss casting. $1896 for each of four truss base castings
Cables and fittings	Williamsport Wirerope Works, Inc. Rick Perry 100 Maynard St. Williamsport, PA 17701 570-326-5146	$107-k/turbine; includes all end fittings
Field assembly	D.H. Blattner & Sons Paul Chandler 400 County Road 50 Avon, MN 56310 320-356-7351	$20-k/turbine minimum. Crane mobilization extra. See Appendix.

A comparison with the equivalent costs from the WindPACT baseline 1.5-MW rotor [3] is given in Table 4-2.

Table 4-2. Comparison of Costs with WindPACT Baseline

Item	WindPACT Baseline [1]	Hybrid Tower
Total mass (including cables)	122,000 kg	96,000 kg
Fabrication (including castings and cable assemblies)	$179,000	$275,275
Tower transportation	$37,500[1]	$40,000[2]
Assembly	$7,500	$20,000[3]
Foundations	$63,000[5]	$20,000[4]
Total cost	$257,000	$355,275

Notes:

1. This value was obtained from a $25/kW estimate used in the WindPACT logistics report [5].
2. This value was selected to be similar to the corresponding value for the conventional tower because the total masses are similar but the hybrid towers comprise more parts.
3. D.H. Blattner & Sons supplied the cost estimate for assembly of the hybrid tower. The estimate does not include the cost of crane mobilization and demobilization.
4. D.H. Blattner & Sons supplied the cost estimate for the hybrid tower footings. The estimate was based on the company's experience with similar foundations.
5. The cost of the foundation for the single tube assumes that the Patrick & Henderson single-pile foundation is used.

5 Discussion and Conclusions

5.1 Discussion

The hybrid tower assembly is a highly redundant structure that requires a finite element analysis for an accurate solution. However, the approximate analysis performed for this project is a valid approach for an initial solution. The analysis also recognizes that any bending moment transferred from the base of the tube through the casting will greatly increase the complexity and cost of that connection but that it is usually possible to proportion the cables and the tube sizes to eliminate any bending at this key connection.

The height of the connection between the tube and the cables is dictated by the need to allow passage of the rotor blades, which are assumed to have a radius of 35 m. However, the truss height can be varied, and Figure 3-6 shows the effects of changing this height. As the height increases, the cable preload, the spreader beam compression, and the total mass are reduced, while the overall lateral stiffness is increased. Therefore, an increase of the truss height to about 25 m should be considered, despite the slight increase in required cable size.

The cost estimates for the hybrid tower show that the total fabrication costs are expensive and may ensure that this concept remains less cost-effective than the single steel tube. If the costs of the cable assemblies are neglected, then the costs of fabricating the parts for the hybrid tower are similar to those for the conventional tower. However, the cables add another $100,000 to the cost of each turbine because 16 cables and end fittings are required for each tower.

The design of the spreader beams is controlled largely by stability under the large compressive loads. In this project, we decided to restrain the possible buckling in the horizontal plane by including two sets of cables between the system of beams. These cables are of nominal diameter, and their cost is not great, but including them will add to the assembly time.

This study has been sufficient to identify (but not fully solve) some of the technical problems associated with this hybrid concept. These include the challenges listed in Table 5-1.

Table 5-1. Technical Challenges Associated with Hybrid Tower

Technical Challenge	Comments
Ensuring near-zero bending moment at base of tube under all conditions	Requires the correct selection of cable stiffness. Extreme conditions may not satisfy this state.
Designing spreader beams to withstand buckling	These long members must carry high compressive loads. More careful design may lead to weight saving.
Applying preload to cables	Each cable must have some adjustment device, which can be expensive. The cables in each of the two principal directions must be pretensioned independently.
Designing attachments to the tube (requires detailed stress analysis)	Stress concentrations will lead to fatigue failure.
Allowing maintenance access to the nacelle	Maintenance personnel must first climb the truss and then enter the tube, which is barely large enough to accommodate one person.
Designing electrical connection	The main cable must transfer from the tube to the truss.
Installing parts	More parts implies more time required for assembly. Pretensioning can be time consuming.
Accommodating crane requirements	The hybrid tower does not lend itself to a self-erection procedure. The crane requirements are not reduced.

One purpose of this project is to open a possible approach to very tall towers for which a single-tube design will be problematic. The investigation has shown the hybrid concept to be viable and that it could be used to construct very tall towers (more than 100-m hub height) while avoiding the problem of large base-tube diameters. However, the hybrid configuration does not naturally lend itself to a self-erection process for the tower or for the nacelle and rotor; in fact, the presence of the spreader beams and cables could make such a scheme more difficult. Instead, the crane requirements will be the same as for a conventional tower.

5.2 Conclusions

The overall conclusions of the study are:

- The concept of a hybrid tower, incorporating a truss, tube, stays, and cables, appears to be technically feasible.
- The bending moment at the connection between the tube and the truss can be reduced to near zero by correct sizing of the cables and tube.
- The spreader beams constitute a subassembly with considerable mass. This is due to the large compressive load that must be carried and the unsupported length, which leads to stability problems. The cost of this assembly might be reduced by a more careful design.
- Although the maximum tube diameter has been reduced from that of a single-tube design, the mass of the total assembly has been reduced by only about 25% (see Table 4-2).
- The cable assemblies are expensive (especially the cost of the end fittings) and require careful installation.
- Cables are supplied in pairs for redundancy, to aid handling, and because of limited cable sizes.
- If this scheme is not combined with a self-erecting scheme for the tower and nacelle, the concept does not appear to facilitate higher hub heights.
- The overall cost of a hybrid design is likely to be greater than that of a single-tube design. This is due to the higher cost of fabrication and the higher assembly costs.

6 REFERENCES

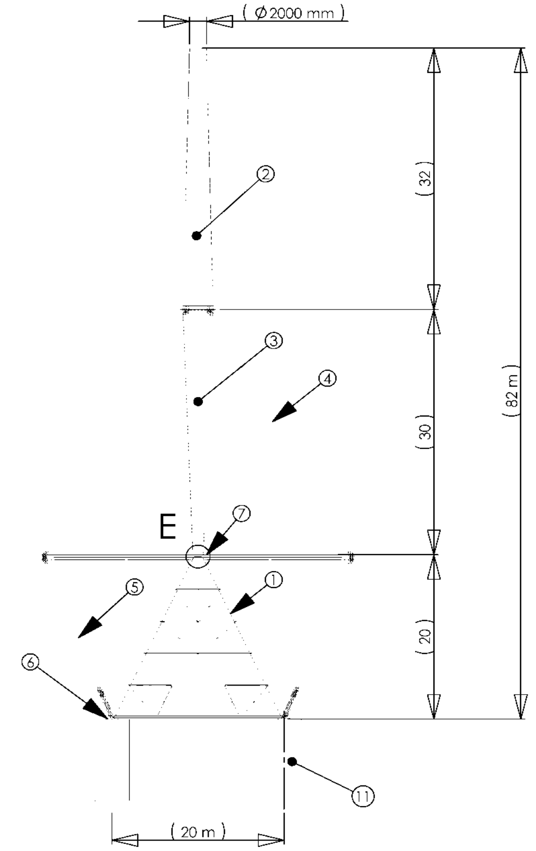
1. Malcolm, D.J.; Hansen, A.C. *WindPACT Turbine Rotor Design Study.* NREL/SR-500-32495. Work performed by Global Energy Concepts LLC, Kirkland, WA, and Windward Engineering, Salt Lake City, UT. Golden, CO: National Renewable Energy Laboratory, August 2002.
2. Frederick, G.R.; Savino, J.M. "Summary of Tower Designs for Large Horizontal Axis Wind Turbine." *ASME Energy Source Technology Conference and Exhibition Proceedings, February 1986, New Orleans, Louisiana.* . DOE/NASA/20320-68. NASA Lewis Research Center, 1986.
3. Berger/ABAM. *Evaluation of Design and Construction Approaches for Economical Hybrid Steel/Concrete Wind Turbine Towers*. Draft Report, NREL Subcontract YAM-2-31235-01.
4. Madugula, M.K.S. (Ed.). *Dynamic Response of Lattice Towers and Guyed Masts*. Reston, VA: ASCE, 2002.
5. Smith, K. *WindPACT Turbine Design Scaling Studies, Technical Area 2: Turbine, Rotor, and Blade Logistics*. NREL/SR-500-29439. Work performed by Global Energy Concepts LLC, Kirkland, WA. Golden, CO: National Renewable Energy Laboratory, June 2001.

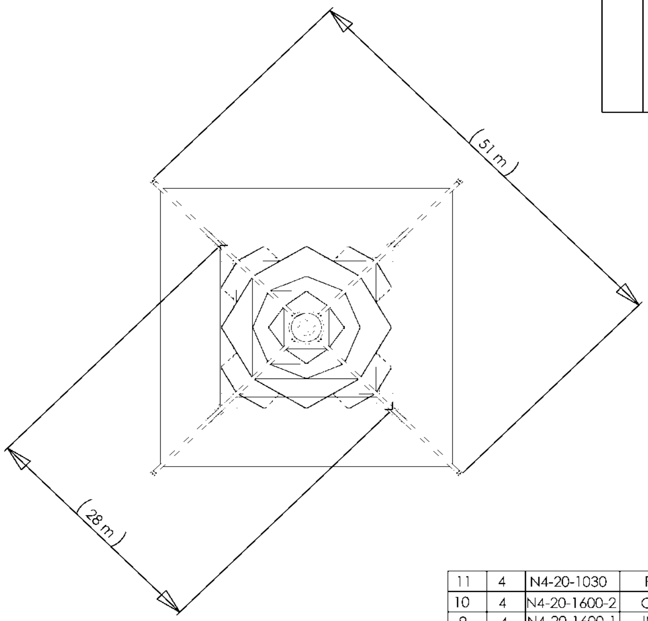
Appendix A

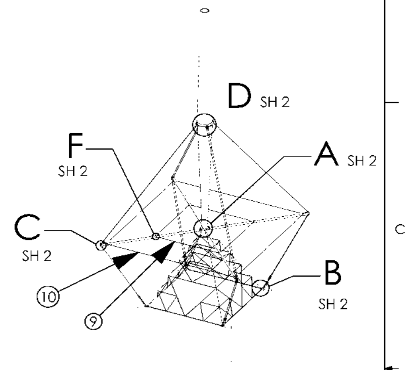
Drawings of Proposed Hybrid Tower

NOTES:
1. TOWER WEIGHT DOES NOT INCLUDE PILINGS

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
	A	A1. CHANGE SPREADERS A2. ADD SPREADER BRACING CABLES A3. MODIFY TRUSS TOP CASTING A4. MODIFY DOUBLER PLATES A5. CHANGE UPPER AND LOWER CABLE LENGTHS		







ITEM	QTY	PART NO.	TITLE	MATERIAL	WEIGHT
11	4	N4-20-1030	PILING	CEMENT	TBD
10	4	N4-20-1600-2	OUTER BRACE CABLE	ASTM A586	39.2
9	4	N4-20-1600-1	INNER BRACE CABLE	ASTM A586	22.3
8	16	N4-20-1021	DOUBLER	ASTM A36	14
7	4	N4-20-1020	SPREADER	ASTM A36	4,620
6	4	N4-20-1010	CASTING, LEG BASE	ASTM A536	905
5	8	N4-20-1500	LOWER CABLE ASSEMBLY	ASTM A586	1395
4	8	N4-20-1400	UPPER CABLE ASSEMBLY	ASTM A586	1031
3	1	N4-20-1300	LOWER TUBE ASSEMBLY	ASTM A36/A546	22,600
2	1	N4-20-1200	UPPER TUBE ASSEMBLY	ASTM A36/A546	27,096
1	1	N4-20-1100	TRUSS ASSEMBLY	ASTM A242/A536	14,365

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR:
.X ± 0.5°
.XX ± 0.1°
LENGTH
.X ± 1 mm
.X ± 0.5mm
.XX ± 0.1mm
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
PER COMPONENT
FINISH
PER COMPONENT
DO NOT SCALE DRAWING

NEXT ASSY	USED ON
APPLICATION	

	NAME	DATE
DRAWN	DAR	6/4/2003
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

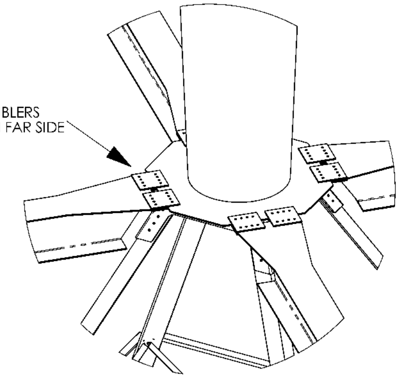
COMMENTS:

GLOBAL ENERGY CONCEPTS, LLC

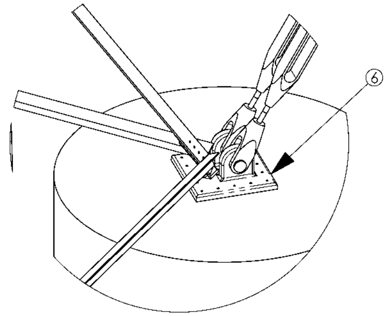
TITLE:

STAYED TOWER
ASSEMBLY

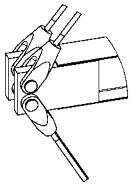
SIZE B
N4-20-1000
REV A
SCALE: NONE
WEIGHT: 101,500 kg *
SHEET 1 OF 2



A (1 : 50)

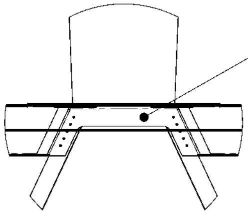


DETAIL B
SCALE 1 : 50



DETAIL C
SCALE 1 : 50

DETAIL F
SCALE 1 : 50



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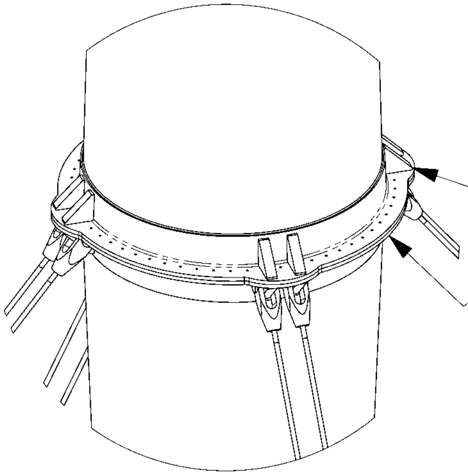


D (1 : 50)

GLOBAL ENERGY CONCEPTS, LLC

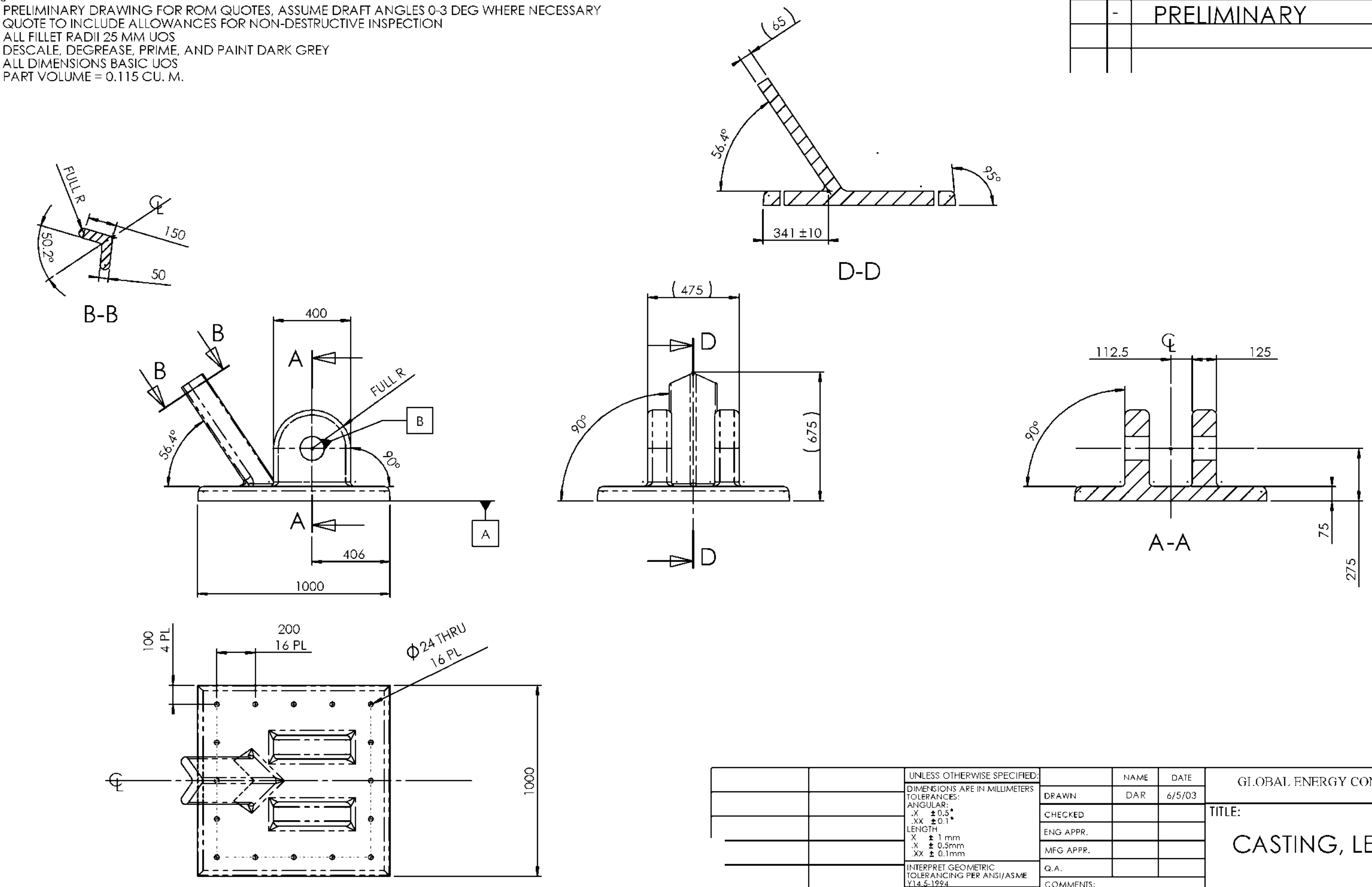
TITLE:
STAYED TOWER

SIZE	PART NO.	REV
B	N4-20-1000	A
SCALE: NONE	WEIGHT: 101,500 kg	SHEET 2 OF 2

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES, ASSUME DRAFT ANGLES 0-3 DEG WHERE NECESSARY
2. QUOTE TO INCLUDE ALLOWANCES FOR NON-DESTRUCTIVE INSPECTION
3. ALL FILLET RADII 25 MM UOS
4. DESCALE, DEGREASE, PRIME, AND PAINT DARK GREY
5. ALL DIMENSIONS BASIC UOS
6. PART VOLUME = 0.115 CU. M.

REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	PRELIMINARY		



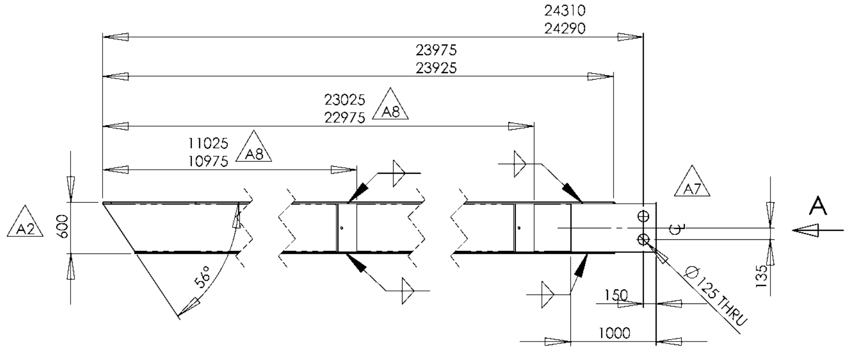
UNLESS OTHERWISE SPECIFIED:		NAME	DATE	GLOBAL ENERGY CONCEPTS, LLC
DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: .X ±0.5° .XX ±0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm	DRAWN	DAR	6/5/03	TITLE: CASTING, LEG BASE
	CHECKED			
	ENG APPR.			
	MFG APPR.			
INTERPRET GEOMETRIC TOLERANCING PER ANSI/ASME Y14.5-1994	Q.A.			
MATERIAL ASTM A536 GR. 5	COMMENTS:			SIZE B | PART NO. N4-20-1010 | REV -
FINISH PER NOTE				
DO NOT SCALE DRAWING				SCALE: NONE | WEIGHT: 905 kg | SHEET 1 OF 1

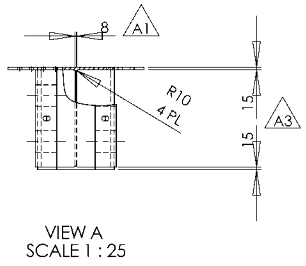
NEXT ASSY	USED ON
APPLICATION	

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES, ASSUME DRAFT ANGLES WHERE NECESSARY
2. QUOTE TO INCLUDE ALLOWANCES FOR NON-DESTRUCTIVE INSPECTION
3. ALL FILLET RADII 5 MM UOS
4. DESCALE, DEGREASE, PRIME, AND PAINT WHITE EPOXY, 5 MIL MIN PAINT THICKNESS
5. DEBUR AND/OR BREAK SHARP EDGES

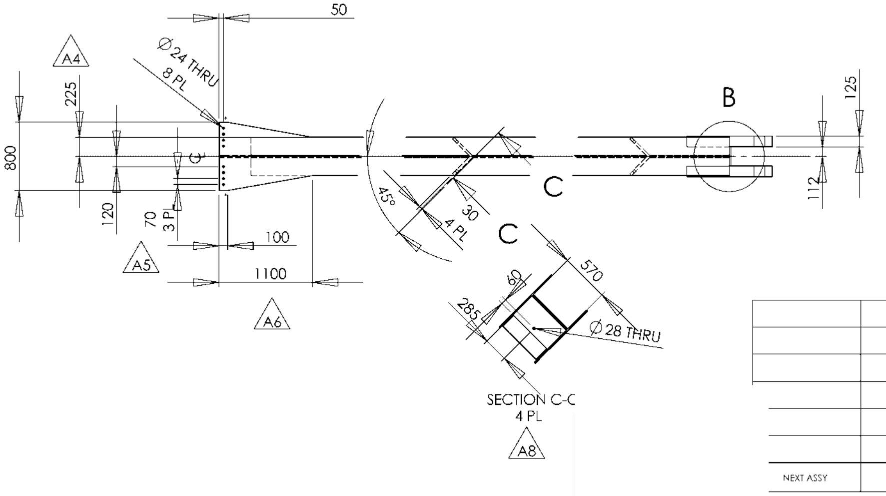
REVISIONS

REV.	DESCRIPTION	DATE	APPROVED
A	A1. CHANGED WEB THICKNESS A2. CHANGED WEB HEIGHT A3. CHANGED FLANGE THICKNESS A4. CHANGED FLANGE WIDTH A5. CHANGED HOLE SPACING A6. INTRODUCED FLANGE TAPER A7. CHANGED CABLE ATTACH BRACKETS A8. ADDED CROSS BRACE BRACKETS	12/21/03	

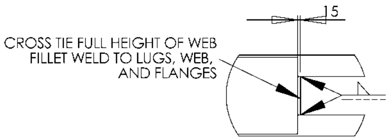




VIEW A
SCALE 1 : 25



SECTION C-C
4 PL



DETAIL B
SCALE 1 : 25

UNLESS OTHERWISE SPECIFIED:		NAME	DATE	GLOBAL ENERGY CONCEPTS, LLC
DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: X ± 1° .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm	DRAWN	DAR	6/10/03	TITLE:
	CHECKED			SPREADER
	ENG APPR.			
	MFG APPR.			
INTERPRET GDT PER: ANSI Y-14.5-1994	Q.A.			
MATERIAL ASTM A36	COMMENTS:			SIZE B N4-20-1020 REV A
FINISH PER DWG NOTES				
DO NOT SCALE DRAWING				SCALE: NONE WEIGHT: 12,194 kg SHEET 1 OF 1

NEXT ASSY | USED ON
APPLICATION

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES, ASSUME DRAFT ANGLES WHERE NECESSARY
2. DESCALE, DEGREASE, PRIME, AND PAINT WHITE EPOXY, 5 MIL MIN PAINT THICKNESS
3. DEBUR AND/OR BREAK SHARP EDGES
4. MATERIAL: ASTM A36 PLATE, 15mm THICK

REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED
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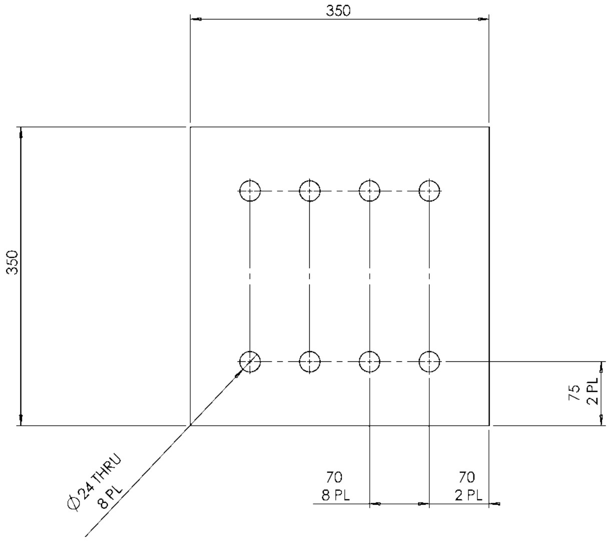
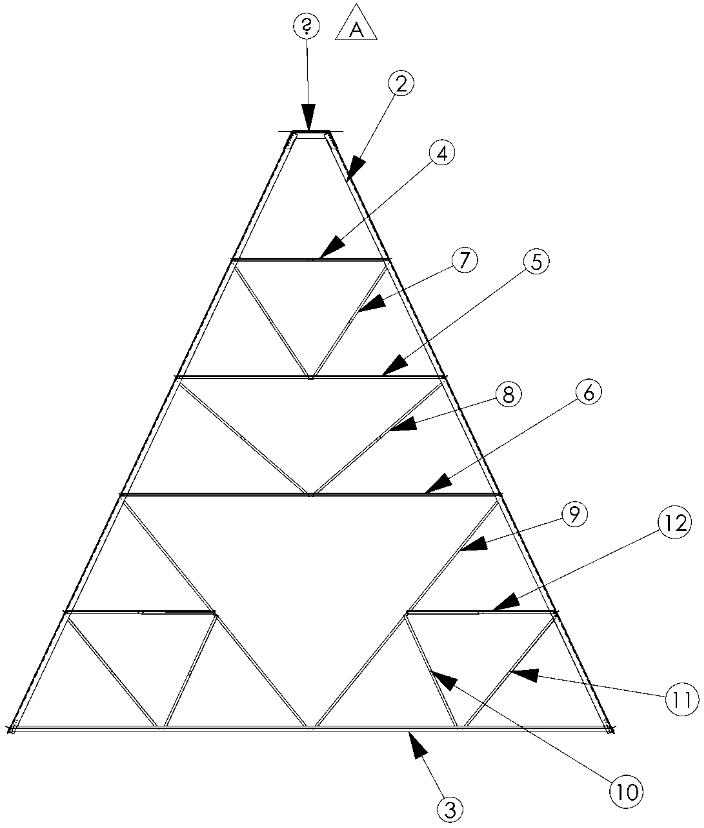


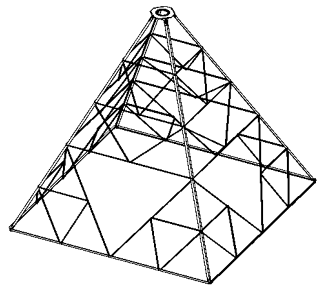
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	GLOBAL ENERGY CONCEPTS, LLC
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: X ± 1° .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm	DRAWN	DAR	6/11/03	TITLE: DOUBLER
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GDT PER: ANSI Y-14.5-1994	Q.A.			
	N4-20-1000	MATERIAL PER NOTES	COMMENTS:			SIZE B · N4-20-1021 · REV A
NEXT ASSY	USED ON	FINISH PER DWG NOTES				
APPLICATION		DO NOT SCALE DRAWING				SCALE: NONE · WEIGHT: 26.8 KG · SHEET 1 OF 1

NOTES:

1. ALL DIMENSIONS IN MM UOS
2. ALL WEIGHTS IN KG UOS
3. GALVANIZE ALL STRUCTURAL SHAPES PER SPEC XXXX AFTER DRILLING
4. INSTALL ALL BRACES WITH A MINIMUM OF TWO M22 GRADE 5 BOLTS
5. A SEE TOP CASTING DETAIL DRAWING

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	PRELIMINARY		





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2	N4-20-1102	4	2385	ASTM A242	STR. STL. ANGLE, 100.42 DEG
3	N4-20-1103	4	19781	ASTM A242	STR. STL ANGLE, 150X150X15, 90 DEG
4	N4-20-1104	4	5090	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
5	N4-20-1105	4	8754	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
6	N4-20-1106	4	12418	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
7	N4-20-1107	8	4946	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
8	N4-20-1108	8	6090	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
9	N4-20-1109	8	10560	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
10	N4-20-1110	8	4612	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
11	N4-20-1111	8	5264	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG
12	N4-20-1112	8	4893	ASTM A242	STR. STL. ANGLE, 75X75X8, 90 DEG

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
PER BOM

FINISH
PER NOTES

NEXT ASSY | USED ON

APPLICATION

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DAR	6/5/03
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

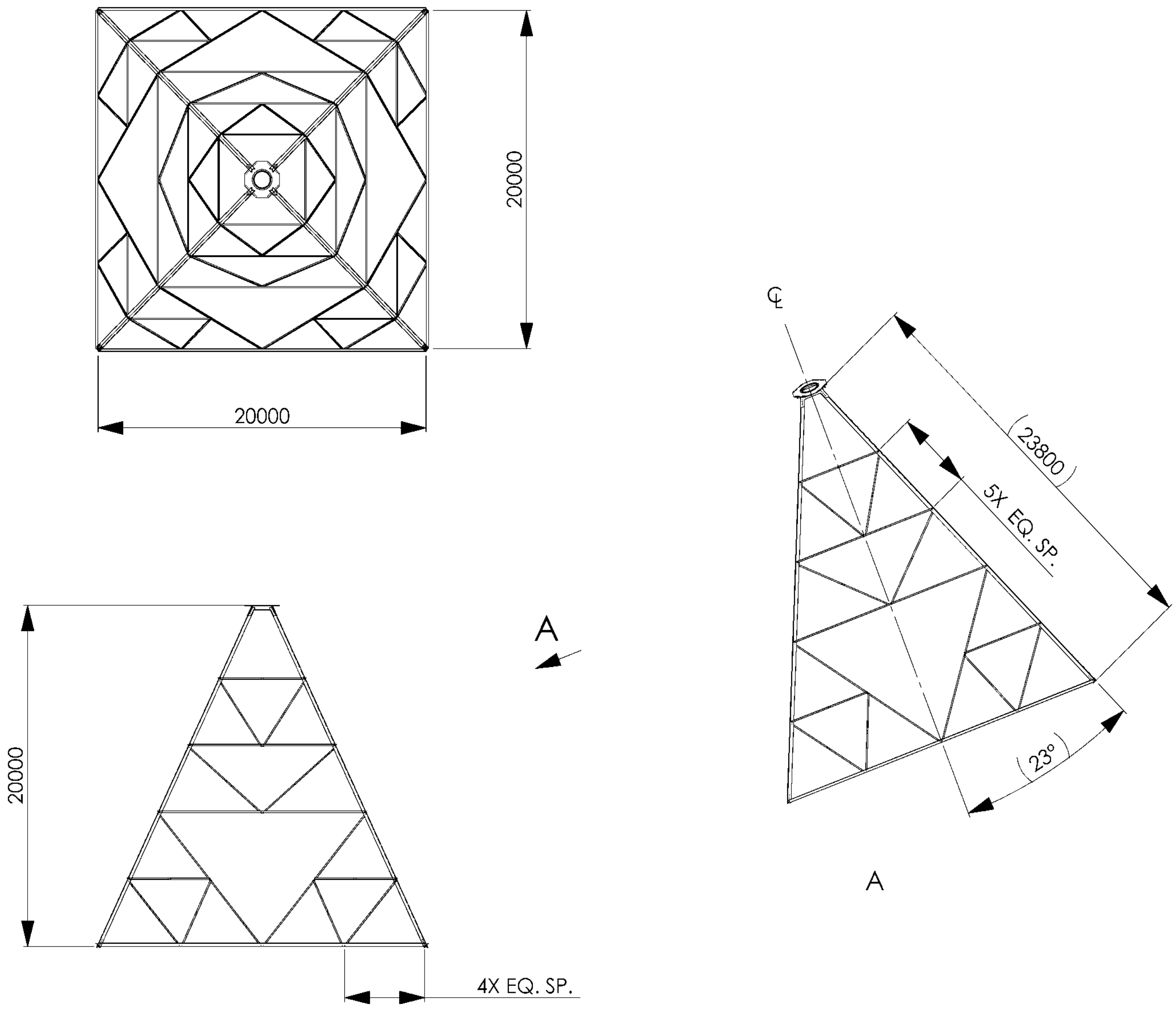
GLOBAL ENERGY CONCEPTS, LLC

TITLE:

Truss Assembly

SIZE	PART NO.	REV
B	N4-20-1100	-

SCALE: NONE | WEIGHT: 14,487 kg | SHEET 1 OF 2



GLOBAL ENERGY CONCEPTS, LLC

TITLE:

TRUSS ASSEMBLY

SIZE **B**
PART NO. N4-20-1100
REV -
SCALE: NONE
WEIGHT: 14,487 kg
SHEET 2 OF 2

NOTES:

1. PRELIMINARY DRAWING FOR ROM QUOTES, ASSUME DRAFT ANGLES WHERE NECESSARY
2. VOLUME: .1460 m^3
3. (PRELIMINARY) APPLY EPOXY PRIMER AND WHITE EPOXY PAINT
4. ALL FILLET RADII 15mm UOS

REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED
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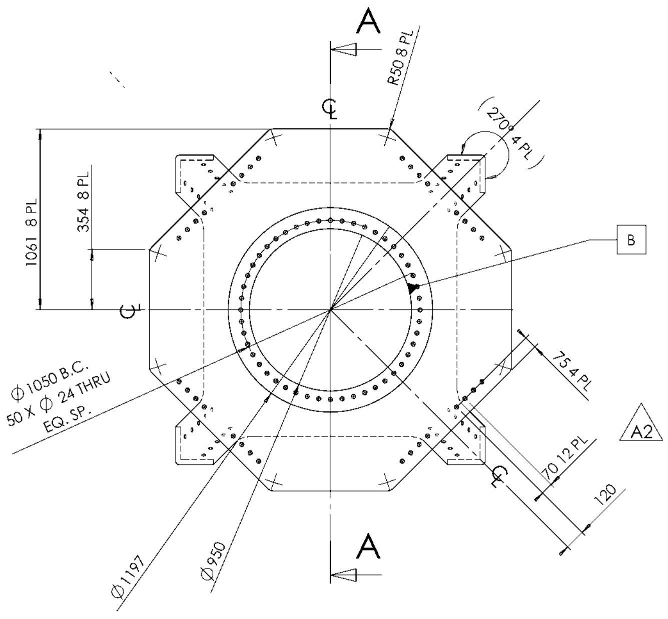
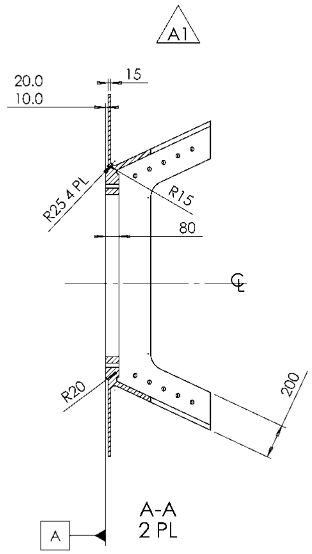
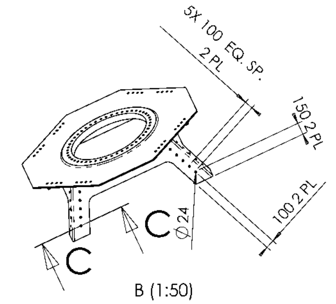
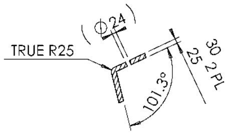




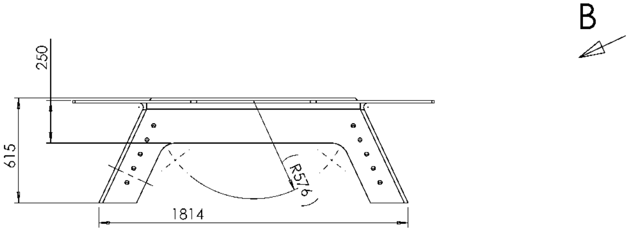
A-A
2 PL



B (1:50)



C-C



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
FRACTIONAL±
ANGULAR: ± .5°
X ± 1 mm
.X ± 0.5mm
.XX ± 0.1mm
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL ASTM 536 Gr. 5
FINISH PER NOTES
NEXT ASSY | USED ON
APPLICATION
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DAR	6/6/2003
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:

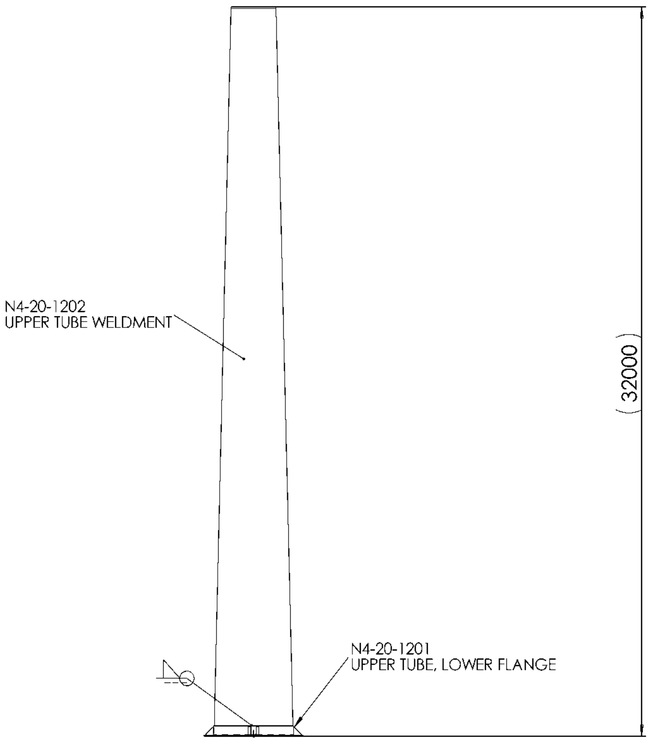
TRUSS TOP CASTING

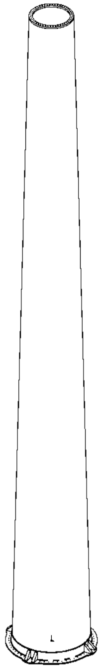
SIZE **B** PART NO. N4-20-1101 REV A

SCALE: NONE | WEIGHT: 1142 kg | SHEET 1 OF 1

REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	PRELIMINARY		





	NAME	DATE	GLOBAL ENERGY CONCEPTS, LLC	
DRAWN	DAR	6/16/03		
CHECKED				
ENG APPR.				
MFG APPR.				
Q.A.				
COMMENTS:				

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR:
.X ± 0.5°
.XX ± 0.1°
LENGTH
X ± 1 mm
.X ± 0.5mm
.XX ± 0.1mm

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL PER ITEM

FINISH PER NOTES

DO NOT SCALE DRAWING

NEXT ASSY	USED ON
	N4-20-1000

APPLICATION

TITLE:

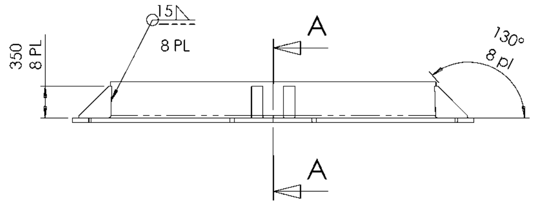
UPPER TUBE ASSEMBLY

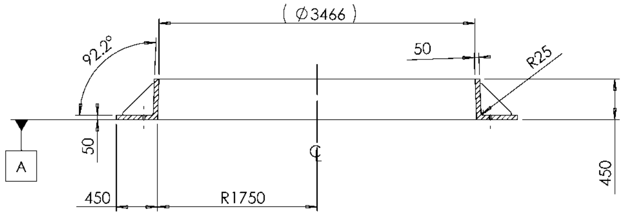
SIZE	PART NO.	REV
B	N4-20-1200	-

SCALE: NONE WEIGHT: XXXX SHEET 1 OF 1

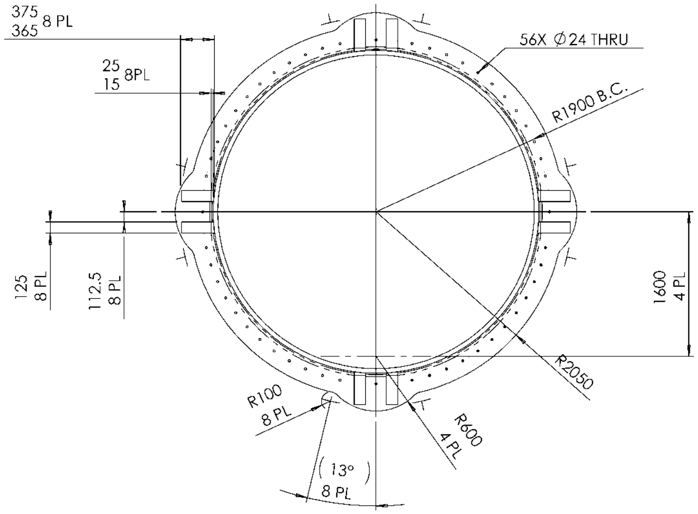
NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES
2. QUOTE TO INCLUDE ALLOWANCES FOR NON-DESTRUCTIVE INSPECTION
3. DESCALE, DEGREASE, PRIME, AND PAINT WHITE

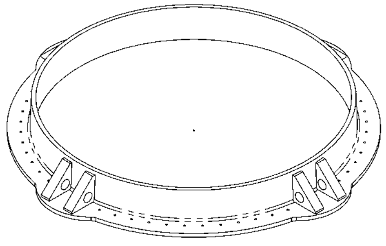
REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
		PRELIMINARY		





A-A





		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm	DRAWN	DAR	6/9/03
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
	N4-20-1200	MATERIAL ASTM A514 GR. Q	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

GLOBAL ENERGY CONCEPTS, LLC

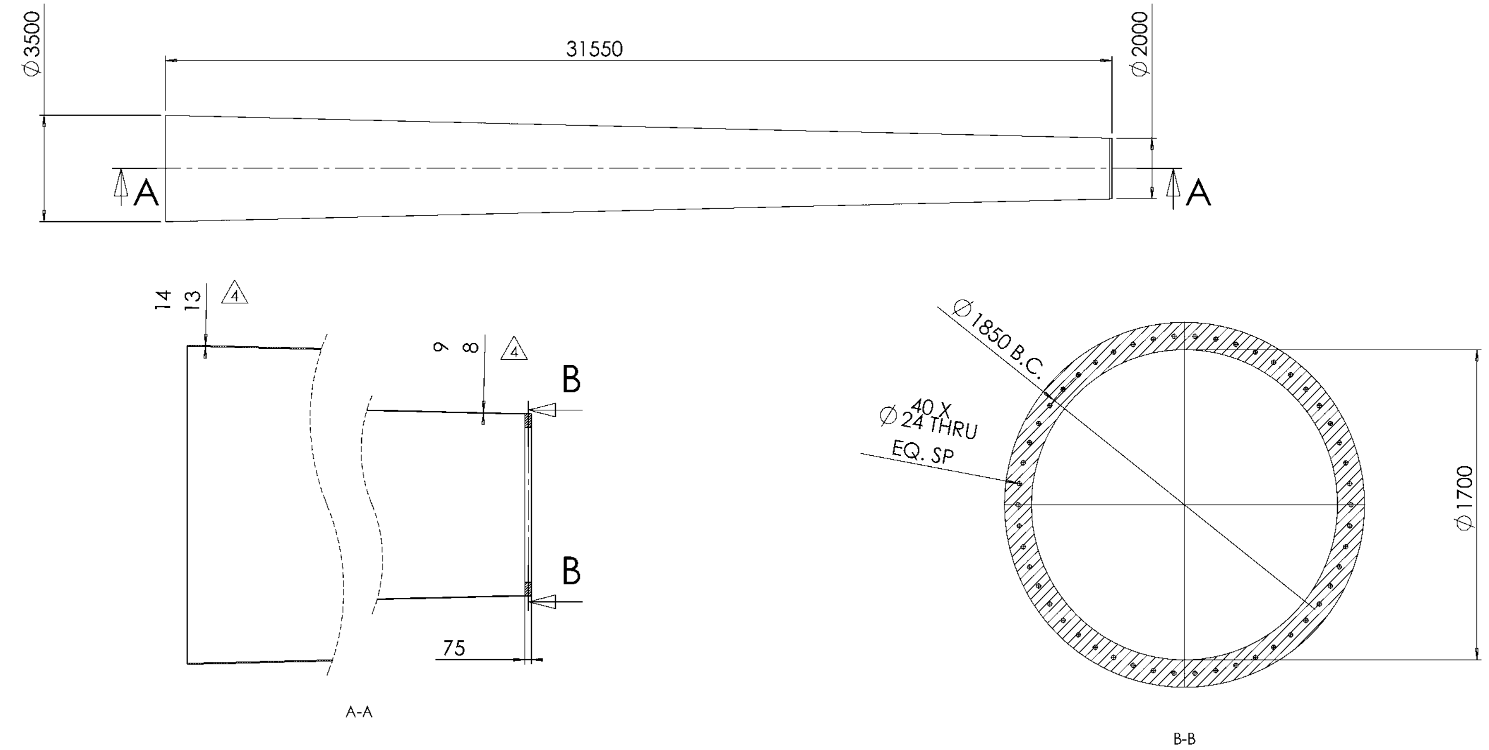
TITLE:
UPPER TUBE
BOTTOM FLANGE

SIZE **B**	N4-20-1201	REV -
SCALE: NONE	WEIGHT: 3736 kg	SHEET 1 OF 1

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES
2. DEBUR AND/OR BREAK SHARP EDGES
3. DESCALE, DEGREASE, PRIME, AND PAINT WHITE EPOXY, 5 MIL MIN PAINT THICKNESS

WALL THICKNESS DRAWN AS NOMINAL VALUES. ACTUAL TUBE MAY BE STEP-TAPERED WELDMENT
△4

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
		PRELIMINARY		



		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: X ± 1° .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm	DRAWN	DAR	6/18/2003
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		THIRD ANGLE PROJECTION INTERPRET GDT PER ANSI Y14.5 94	Q.A.		
	N4-20-1200	MATERIAL ASTM A36	COMMENTS:		
NEXT ASSY	USED ON	FINISH PER DWG NOTES			
APPLICATION		DO NOT SCALE DRAWING			

GLOBAL ENERGY CONCEPTS, LLC

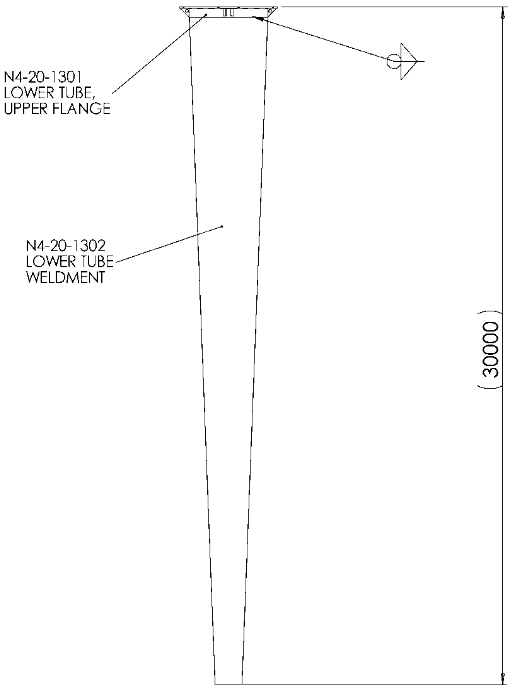
TITLE:

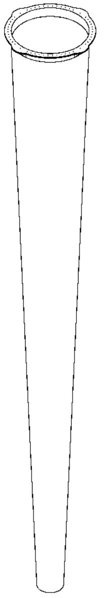
UPPER TUBE
WELDMENT

SIZE **B** N4-20-1202 REV -

SCALE: NONE WEIGHT: 23,263 kg SHEET 1 OF 1

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	PRELIMINARY		



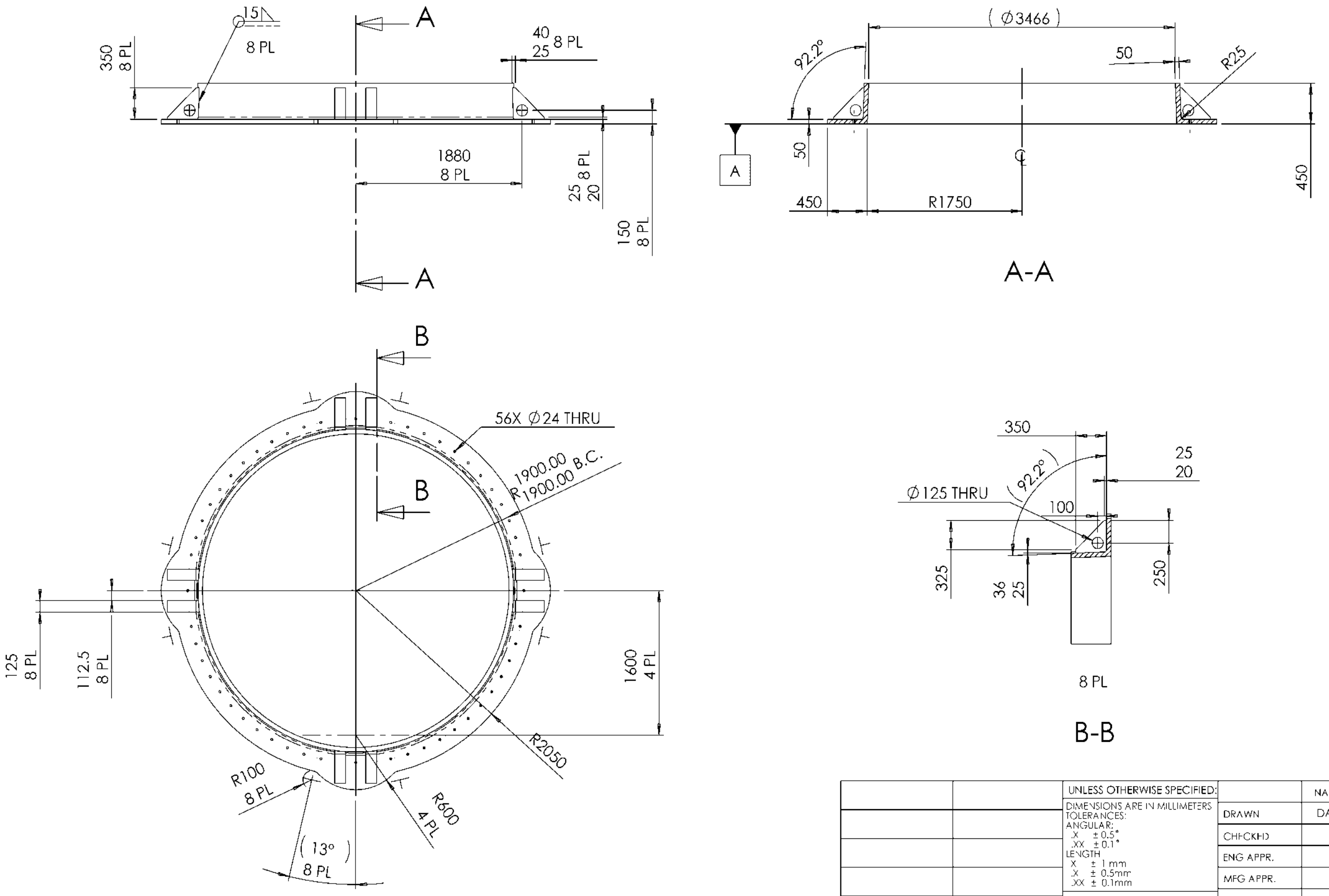


		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	GLOBAL ENERGY CONCEPTS, LLC
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm	DRAWN	DAR	6/17/03	TITLE: LOWER TUBE ASSEMBLY
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
	N4-20-1000	MATERIAL PER ITEM	COMMENTS:			SIZE B PART NO. N4-20-1300 REV -
NEXT ASSY	USED ON	FINISH PER NOTES				
APPLICATION		DO NOT SCALE DRAWING				SCALE: NONE WEIGHT: 22,600 kg SHEET 1 OF 1

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES
2. QUOTE TO INCLUDE ALLOWANCES FOR NON-DESTRUCTIVE INSPECTION
3. DESCALE, DEGREASE, PRIME, AND PAINT WHITE

REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED
		PRELIMINARY		



		UNLESS OTHERWISE SPECIFIED:
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm
		INTERPRET GEOMETRIC TOLERANCING PER:
	N4-20-1300	MATERIAL ASTM A514 GR. Q
NEXT ASSY	USED ON	FINISH PER NOTES
APPLICATION		DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	DAR	6/10/03
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

GLOBAL ENERGY CONCEPTS, LLC

TITLE:
BOTTOM TUBE
UPPER FLANGE

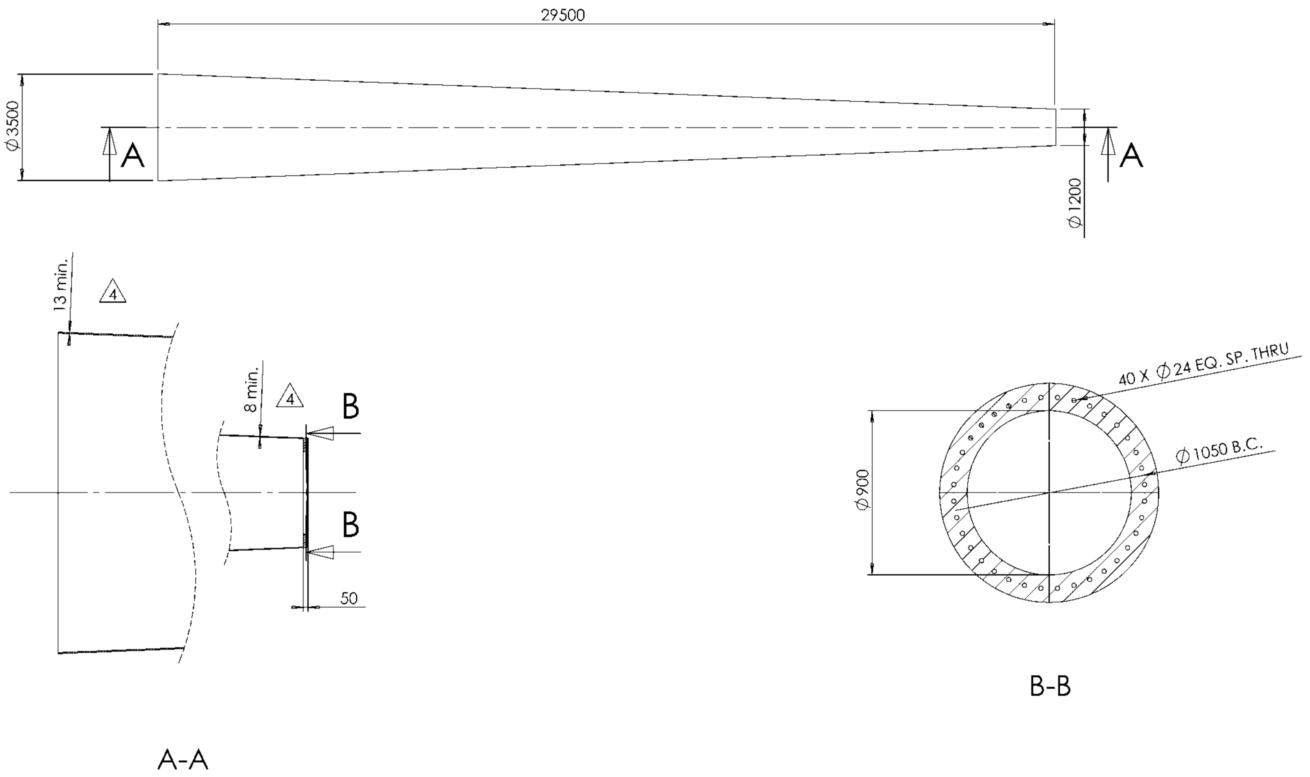
SIZE B
PART NO. N4-20-1301
REV -

SCALE: NONE
WEIGHT: 3735 kg
SHEET 1 OF 1

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES
2. DEBUR AND/OR BREAK SHARP EDGES
3. DESCALE, DEGREASE, PRIME, AND PAINT WHITE EPOXY, 5 MIL MIN PAINT THICKNESS

WALL THICKNESS DRAWN AS NOMINAL VALUES. ACTUAL TUBE MAY BE STEP-TAPERED WELDMENT
△4

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	PRELIMINARY		



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
TOLERANCES:
ANGULAR:
X ± 1°
.X ± 0.5°
.XX ± 0.1°
LENGTH
X ± 1 mm
.X ± 0.5mm
.XX ± 0.1mm
INTERPRET GDT PER:
ANSI Y-14.5-1994
MATERIAL
ASTM A36
FINISH
PER DWG NOTES
DO NOT SCALE DRAWING

N4-20-1300		
NEXT ASSY	USED ON	
APPLICATION		

	NAME	DATE
DRAWN	DAR	6/18/2003
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

GLOBAL ENERGY CONCEPTS, LLC

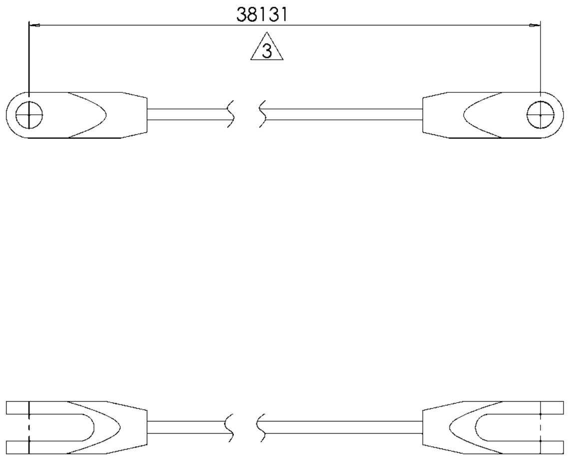
TITLE:
LOWER TUBE
WELDMENT

SIZE B
N4-20-1302
REV -
SCALE: NONE
WEIGHT: 18,837 kg
SHEET 1 OF 1

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES
2. MATERIAL: ∅ 57mm (2.25 in) PER ASTM A586, STAINLESS OR GALVANIZED WIRE ROPE WITH SWAGED OPEN END CLEVISES. MINIMUM BREAKING STRENGTH = ______________.

△3 LENGTH MEASUREMENT AFTER PRELOAD OF ________________.

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
		PRELIMINARY		



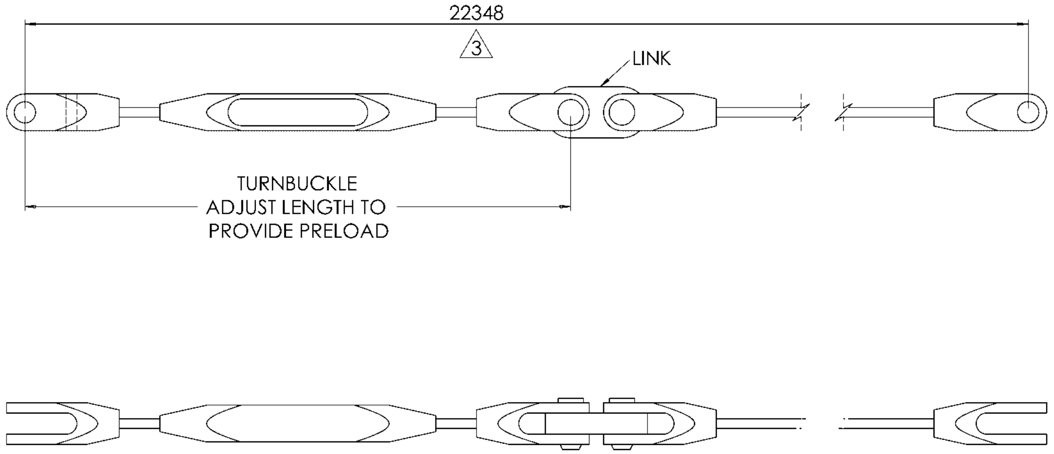
		UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: X ± 1° .X ± 0.5° .XX ± 0.1° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.1mm		NAME	DATE	GLOBAL ENERGY CONCEPTS, LLC
			DRAWN	DAR	6/17/2003	TITLE: UPPER CABLE
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GDT PER: ANSI Y-14.5-1994	Q.A.			
	N4-20-1000	MATERIAL SEE NOTES	COMMENTS:			SIZE B N4-20-1400 REV -
NEXT ASSY	USED ON	FINISH PER DWG NOTES				
APPLICATION		DO NOT SCALE DRAWING				SCALE: NONE WEIGHT: 1021 kg SHEET 1 OF 1

NOTES

1. PRELIMINARY DRAWING FOR ROM QUOTES. TURNBUCKLE AND LINK IS REPRESENTATION OF ADJUSTABLE ASSEMBLY ONLY. MANUFACTURER'S SUGGESTIONS ARE WELCOME.
2. MATERIAL: ∅57mm (2.25 in) PER ASTM A586, STAINLESS OR GALVANIZED WIRE ROPE WITH SWAGED OPEN END CLEVISES. MINIMUM BREAKING STRENGTH = ______________.

△3 LENGTH MEASUREMENT AFTER PRELOAD OF ________________.

REVISIONS				
ZONE	REV.	DESCRIPTION	DATE	APPROVED
	A	CHANGED LENGTH	12/12/03	



		UNLESS OTHERWISE SPECIFIED:	NAME	DATE
		DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: X ± 1° .X ± 0.5° .XX ± 0.[illegible]° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.[illegible]mm	DRAWN DAR	6/12/2003
			CHECKED	
			ENG APPR.	
			MFG APPR.	
		INTERPRET GDT PER: ANSI Y-14.5-1994	Q.A.	
	N4-20-1000	MATERIAL SEE NOTES	COMMENTS:	
NEXT ASSY	USED ON	FINISH PER DWG NOTES		
APPLICATION		DO NOT SCALE DRAWING		

GLOBAL ENERGY CONCEPTS, LLC

TITLE:

LOWER CABLE ASSEMBLY

SIZE B | N4-20-1500 | REV A

SCALE: NONE | WEIGHT: 1395 kg | SHEET 1 OF 1

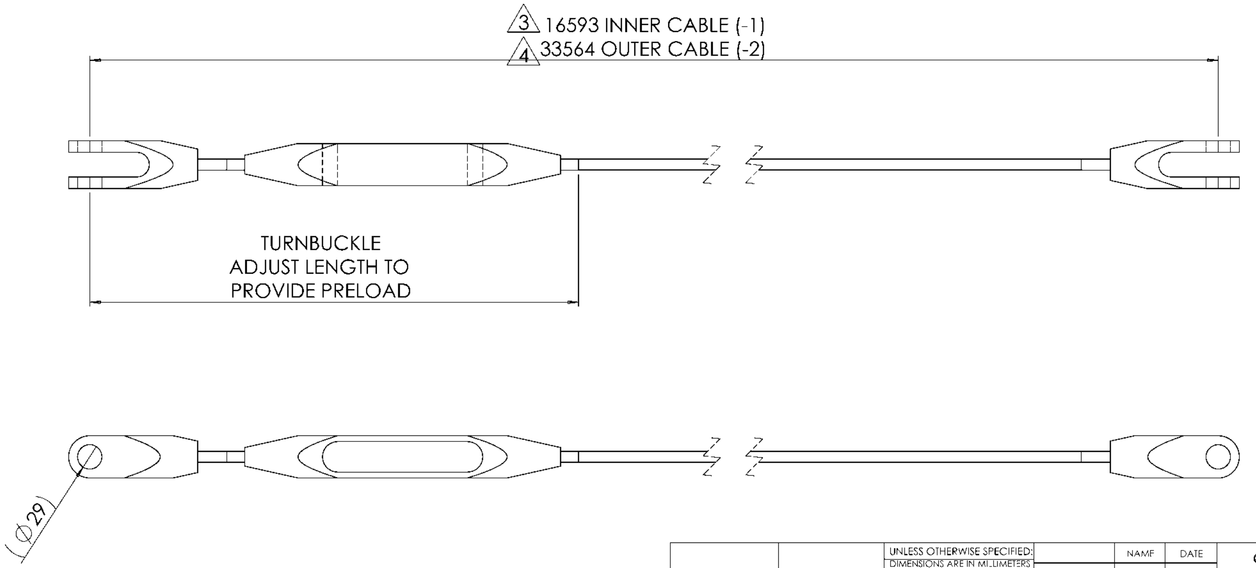
REVISIONS

ZONE	REV.	DESCRIPTION	DATE	APPROVED
	-	PRELIMINARY		

NOTES
1. PRELIMINARY DRAWING FOR ROM QUOTES. TURNBUCKLE AND LINK IS REPRESENTATION OF ADJUSTABLE ASSEMBLY ONLY. MANUFACTURER'S SUGGESTIONS ARE WELCOME.
2. MATERIAL: ∅12.5mm (0.50 in) PER ASTM A586, STAINLESS OR GALVANIZED WIRE ROPE WITH SWAGED OPEN END CLEVISES. MINIMUM BREAKING STRENGTH = ______________.
3. WEIGHTS: INNER (-1) 22.3 kg
   OUTER (-2) 39.2 kg

△3 INNER BRACE CABLE (-1) LENGTH MEASUREMENT AFTER PRELOAD OF _______________.

△4 OUTER BRACE CABLE (-2) LENGTH MEASUREMENT AFTER PRELOAD OF _______________.



		UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN MILLIMETERS TOLERANCES: ANGULAR: X ± 1° .X ± 0.5° .XX ± 0.[illegible]° LENGTH X ± 1 mm .X ± 0.5mm .XX ± 0.[illegible]mm		NAME	DATE
			DRAWN	DAR	12/21/03
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GDT PER: ANSI Y-14.5-1994	Q.A.		
	N4-20-1000	MATERIAL SEE NOTES	COMMENTS:		
NEXT ASSY	USED ON	FINISH PER DWG NOTES			
APPLICATION		DO NOT SCALE DRAWING			

GLOBAL ENERGY CONCEPTS, LLC

TITLE:
SPREADER BRACE
CABLE ASSEMBLY

SIZE B
N4-20-1600-X
REV -

SCALE: NONE
WEIGHT: see notes
SHEET 1 OF 1

REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE April 2004	3. REPORT TYPE AND DATES COVERED Subcontractor Report June 29,2000–February 28, 2004

4. TITLE AND SUBTITLE
WindPACT Rotor Design Study: Hybrid Tower Design

5. FUNDING NUMBERS
WER4.3509
YAT-0-30213-01

6. AUTHOR(S)
Malcolm, D.J.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Global Energy Concepts LLC
5729 Lakeview Dr. N.W., Suite 100
Kirkland, WA 98033

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Renewable Energy Laboratory
1617 Cole Blvd.
Golden, CO 80401-3393

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NREL/SR-500-35546

11. SUPPLEMENTARY NOTES
NREL Technical Monitor: J. Cotrell

12a. DISTRIBUTION/AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The cost of a wind turbine tower can represent as much as 20% of the cost of an entire megawatt-scale horizontal axis wind turbine (HAWT) and as much as 10% of the total cost of energy. The tower is a major cost component, and its design is important: Its structural properties are key to the response of the rotor; its height determines the wind regime that the rotor experiences; it allows access to the turbine nacelle and rotor; and it houses components of the electrical connection and the control and protection systems. Most large wind turbines installed in the United States use self-supporting steel tubular towers. The diameter of these tubes is limited by the size that can be transported by road (approximately 4.3 m). The base dimensions of a truss tower are not restrained by this limit, but trusses may require more maintenance. Guyed tube towers have been used, but they represent additional foundation costs and inconvenience. Addressing these limitations may lead to an alternative that avoids the problems. For this reason, the WindPACT Rotor Design Study was modified to include a study of a hybrid tower to determine the technical and economic feasibility of such a design.

14. SUBJECT TERMS
wind energy; wind turbine; tower; hybrid tower; WindPACT

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL