INNOVATIONS IN MOORING CABLE SOLUTIONS

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Abstract

Tried and tested steel cable products offer a mooring solution with long term experience and performance data. The suspended weight of steel mooring components presents a challenge as floating exploration & production facilities move into increasing water depth raising the issue of perceived limits for steel cables. Therefore Bridon continues to actively address solutions for ultra deep water with a focus on increased strength, reduced weight and improved endurance.

Advances in mooring system design have developed mooring arrangements, using proven technology steel components, which are both technically and economically suitable for 2000 metres (6500 feet) water depth. The potential for improvements to strength to weight ratio suggests that the use of steel products in increasingly deep-water locations can be achieved. Having gained experience through consultancy and design roles during the supply of 52 permanent mooring projects, supporting evidence established through numerous research programs and theoretical analysis, Bridon will continually challenge the perceived limiting parameters.

This paper will discuss the recent improvements in strength to offer a 25% lighter weight solution than that defined within DNV Certification Note 2.5, dramatically increasing the depths in which steel product can economically be used.

Current usage limitations of polyester mooring ropes results in the need for connection to steel mooring line segments. Understanding the interactions of these differing components and development of products to service this application is critical. This paper addresses the future of ultra-deep mooring systems through consideration of the complementary roles of steel and fibre mooring ropes.

Following the recent MMS approval of the use of FPSOs in the Gulf of Mexico s further expanding market demand, Bridon aims to continue to support the requirements of all oil explorations and extraction applications with a critical focus on the demanding mooring system application.

1.0 Introduction

Demands on exploration and production are driving the installation of facilities in ever increasing water depths. Conventional catenary moorings are currently planned for utilisation in depths of around 2000 metres (6500 feet). In deep water the extended mooring cable lengths result in greater self weights which influence both operational and installation loads.

Through the development of products with a greater strength to weight ratio, both system and deployment loads can be minimised. Continued improvements to strength suggest that the use of technically proven steel products in increasingly deep water locations will remain viable.

2.0 Deep Water Application of Steel Mooring Systems

In catenary systems (figure 1), the floating structure moves laterally in response to environmental loads. The overall compliance and hence station keeping performance is determined by the water depth, the weight of the mooring line and the mean tension. In depths beyond 1000 metres, the vertical load component can become significant due to a fundamental feature of the catenary mooring system weight (Firth 1997).

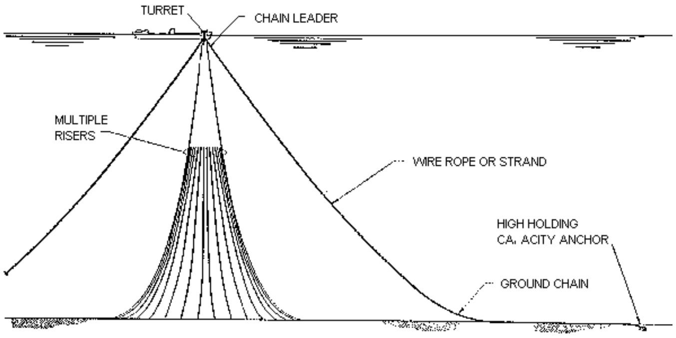

Figure 1 — Conventional Catenary Mooring

Semi taut and inverted catenary mooring arrangements (figure 2) introduce buoyancy to the mooring system. The result being a potential 40% reduction in resultant turret force and 25% reduction in resultant anchor leg force (Blair et al 1995) when compared to an equivalent conventional catenary arrangement. Sorrel et al (1997) suggests that through utilising the semi taut arrangement, the operational depth of a steel system is extended to 2000 metres.

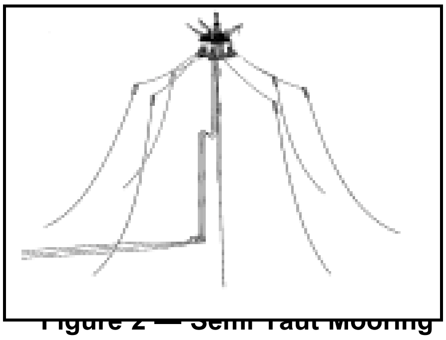

Figure 2 — Semi Taut Mooring

It is apparent the continued use of steel mooring line components remains possible with increasing water depth maintaining the confidence provided by proven technology. Nevertheless, continuing improvements in strength to weight ratio not only support the extension to useful depth range, but offer a more cost effective solution —reductions in mooring system loads can be utilised through maximisation of topside equipment.

3.0 Technological Advances

Increased strength or conversely reduced cable self weight has been achieved through advancing manufacturing techniques, availability of specialised materials and developments in engineering design.

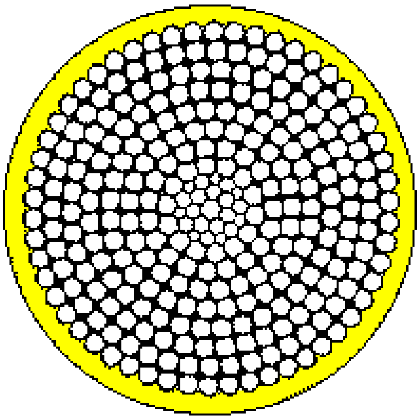

Figure 3 — Spiral Strand Mooring Cable Cross Section

3.1 Wire Performance

The finished wire rope or strand strength is governed by the properties of the component wires. The stranding operation of spinning the wires together cannot generate tensile strength above that provided by the component wire, hence control and development of the wire properties is essential in achieving improvements in strength to weight ratio. The key parameters which dictate the finished wire tensile strength include the feed material composition, heat treatment conditions and the wire drawing process.

3.1.2 Feed Material

In wire drawing, the quality of the finished product is governed by the quality and properties of raw materials. Considering the metallurgical properties required for cable manufacture and considering the expense and availability of exotic materials, the options for feed materials are limited to developments in micro-alloyed, high carbon / high silicon steels. Through careful control of the chemical composition and lead patenting conditions in the manufacturing process a feed material of homogeneous structure is achieved from which the final strength can be generated.

Bridon has recently completed a development program to meet the challenge of manufacturing a10% higher strength final hot dip galvanised (A-class) wire than that utilised in the Bridon SPR2*plus* range of spiral strands, which maintains good ductile properties and is suitable for spinning into finished cable. This wire product forms the essential building block of the Bridon *Xtreme* Spiral Strand range.

The feed material for Xtreme is a high silicon steel which has been developed in conjunction with our steel supplier, Corus and is the result of a continuing partnership in steel development which has given a continual improvement in final wire tensile strength.

3.1.1 Wire Drawing Process

The finished wire ultimate tensile strength (UTS) is achieved through the combination of the number and sequence of drawing dies and the reduction in diameter achieved by each.

Maximising cold working of the wire generates maximum UTS and in general this means that the smaller the finished wire diameter, the greater the potential tensile strength. Processing in this manner requires a high level of control to prevent loss of other properties such as ductility and surface finish.

Improvements in strand or rope breaking load are achieved through utilising a greater number of smaller diameter higher tensile wires. Mooring industry standards do not specify a minimum wire diameter. However, wire diameter selection is a balance between tensile strength, constructional balance and corrosion resistance. Firstly, availability of galvanic protection is proportional to the diameter of the wire. Secondly, the increased ratio of surface area to cross sectional (load bearing) area demonstrates the greater corrosion effect on a smaller diameter wire.

3.2 High Strength Mooring Cables

The rope making industry has led the way in specification development and data is published within DNV certification note 2.5. Previous developments in wire manufacture have enabled a 15% increase in the DNV CN 2.5 published spiral strand breaking load figures. With the introduction of the Bridon *Xtreme* Spiral Strand Range this now achieves a 25% improvement over the DNV figures, a 10% improvement over the current industry norm based around Bridon SPR2*plus* (figure 4) Alternatively this can be translated as a 25% weight saving - the original breaking loads being achieved with smaller diameter strands.

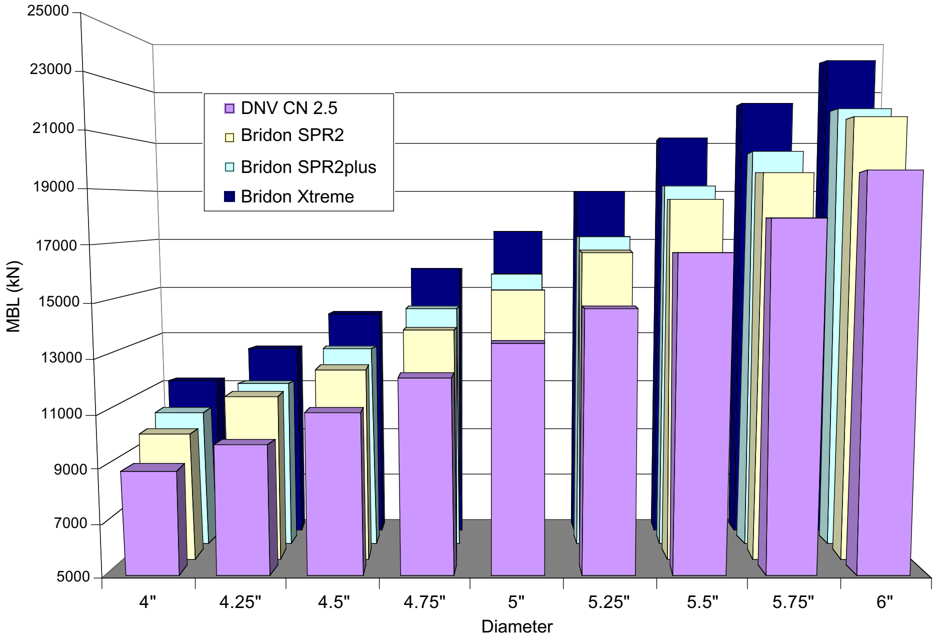

Figure 4 — Spiral Strand Strength Progression

Xtreme has been extensively tested throughout the manufacturing process i.e. rod and wire properties and finally minimum breaking load and fatigue testing. Two full scale fatigue tests have been conducted on 100mm diameter Xtreme spiral strand with an MBL of 1100 tonnes (10,791kN) — Appendix 1.

Current developments in six strand ropes for drilling rig operations have achieved breaking loads 30% higher than the API 9A minimum or conversely a 30% lighter, smaller rope. It is expected that the wire developments recently attained can be utilised to similar effect for drawn galvanised six strand wire ropes.

3.3 Cable Terminations

It is essential the termination strength at least matches the cable. Advances have been made in cable termination design with higher strength materials enabling higher strength products to match cable strength developments. Closed sockets have been developed facilitating the direct connection between cable and chain removing the need for additional connector plates.

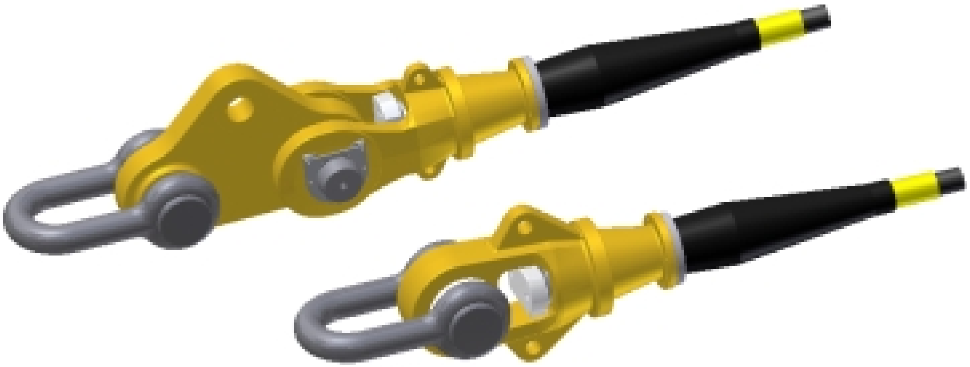

Figure 6 — Cable Termination Options

Future work is envisaged based on increased material strength and geometry changes to allow ease of connection to other more standard mooring system components.

4.0 Mooring Systems Weight Savings

Lighter weight products will allow designers to increase the water depth in which steel products are economically and logistically viable or allow more cost effective development of shallower water locations.

The typical overall submerged weight saving achievable for a twelve leg spread moored system of 2000 metre mooring cables each of 1000 tonne breaking load for a typical for a West Africa FPSO system, can be estimated at 100 tonne reduction in static load. Similar comparison for a Gulf of Mexico typical Spar system with nine 1200 metre mooring cables each of 1600 tonnes breaking load can now be achieved utilising cables contributing 10% less to the system static loads.

5.0 Complementary Role of Synthetic Fibre & Steel Moorings

5.1 Limitations

Synthetic fibre ropes offer the highest strength to weight ratio performance currently available. However, as the fine fibre filaments are susceptible to damage through abrasion there are usage limitations.

In a taut moored arrangement the lower end of the mooring cable is connected directly to an anchor and will be embedded in the seabed and subject to considerable wear action. Therefore, currently available fibre mooring materials are not suitable for the lower 150 - 200 metres of the mooring line above the seabed. At the upper end similar constraints are apparent as fibre products are not suitable for long term use with winches and sheaves. Furthermore, the potential for marine growth in the first 50 -100 metres below the splash zone prohibits the use of fibre product in this section.

Although various coatings, filters and treatments are being investigated to protect the fibre, the products currently available are typically suitable for use in the central taut segment away from the seabed, mechanical handling and marine life.

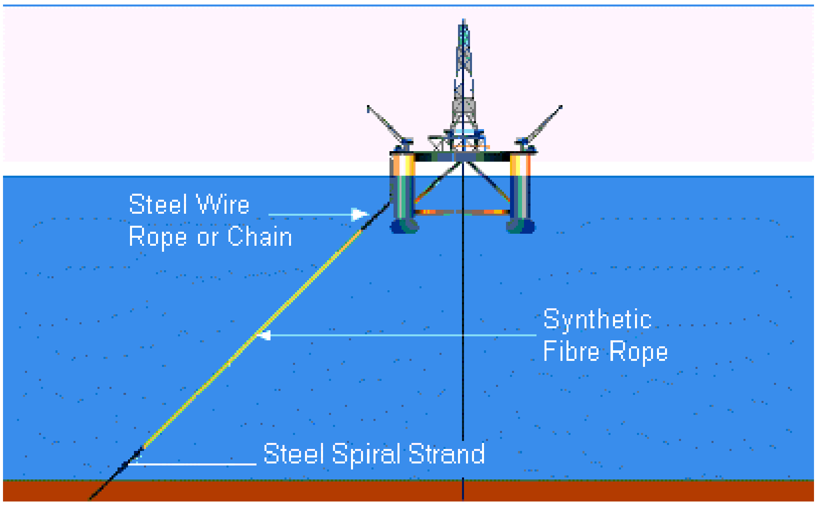

Figure 6 — Taut Moored System

5.2 Supporting Role of Steel

The constraint of the fibre product leaves the question of how to complete the connection between the anchor and the vessel. For the upper connection, the requirement for a flexible work-hardy product results in the use of either chain segments and stoppers or six strand rope with rotary winch systems. The lower segments are purely structural in usage; hence there is the potential to use a spiral strand in addition to six strand rope and chain. The narrow profile of the spiral strand offers the added advantage of reduced drag when utilised in an anchor forerunner application.

With the taut moored arrangement and the low weight synthetic cables, the introduction of steel into the system serves the critical purpose of providing weight to maintain the tension in the overall mooring line. Hence a requirement for cables with a low strength to weight ratio exists, contrary to the physical requirements of a conventional catenary mooring system.

5.3 Fibre & Steel in Series

When connecting any non-similar components in series the effect of each on the others must be carefully considered. Experience to date has suggested that the two critical factors in a combined taut moored system are torsion and fatigue performance.

5.3.1 Tension-Torsion Fatigue

Six strand ropes will rotate when axially loaded. Fibre ropes having a very low torsional stiffness and thus provides no resistance to the rotation generated by the six strand rope. The fibre rope effectively acts as a low friction swivel. The fibre rope is largely unaffected by the imposed rotation. However, the continued tension torsion fatigue loads have been proven to dramatically reduce the life span of the six strand rope (Chaplin et al 1999). In conventional catenary systems six strand wire rope is prevented from rotation by the inherent torsional stiffness of mooring chain, hence the reduced torsion tension fatigue life is not apparent.

Six strand rope is now considered unsuitable for long term use connected in series with fibre ropes. Torsionally balanced constructions such as spiral strand and chain, which do not generate rotation when loaded, are recommended in this scenario.

5.3.2 Tension-Tension Fatigue

Due to the restoring forces originating from the elasticity of the polyester rather than the weight of steel, taut moored systems are subject to higher tension fatigue loadings than a conventional catenary system. Both fibre mooring ropes and spiral strand show excellent performance in tension-tension fatigue loading. Standard mooring chain shows a much reduced performance in fatigue and in order to achieve the necessary performance the chain must be oversized (Snell et al 1999). Where minimising self weight is a critical driver, having to oversize the heavy chain components is not desirable.

6.0 Conclusions

Advances in mooring system design have developed mooring arrangements, using proven technology steel components, which are both technically and economically suitable for 2000 metres water depth. Recent developments in spiral strand design can now offer a further 10% reduction in weight when compared to the current industry norm.

Fibre systems offer the highest strength to weight ratio allowing exploration into ultra deep locations. In order to protect the sensitive fibre product against wear, the use of steel is still apparent in such taut systems. Spiral strand offers the most cost effective, weight conscious and technically advantageous solution to the connection between anchor and fibre rope.

Although the future for ultra deep mooring can be seen to be pursuing the trend for synthetic solutions, the supporting role of steel cable is essential to its success. The continuing developments in spiral strand strength will continue to assist engineering companies and operators with the economical development of offshore prospects.

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Chaplin, Rebel & Ridge (1999) Let s Not Twist Again. Offshore Engineer March 1999.

Snell, Ahilan & Versavel (1999) Reliability of mooring systems: application to polyester moorings. 31st OTC Conference May 1999 (Paper 10777).

Appendix 1: Bridon *Xtreme* High Strength Spiral Strand - Fatigue Performance

Two full scale fatigue tests have been carried out as described below,

Objective:
To establish the fatigue performance of Spiral strand comprising of high silicon chemistry final hot dip galvanised (A class) 5.0mm / 5.3mm diameter wires — Bridon *Xtreme* Spiral Strand .

Procedure:
Test completed at DMT, Bochum procedure on their horizontal 6MN fatigue testing machine in accordance with the Bridon procedure CP024.

Cable partially lubricated during manufacture (inner layers only) during sample preparation additional light lubricant (Brilube 30) was sprayed onto the surface. Additional lubricant was sprayed during sample testing.

Test sample length: 4 metres approx.
Terminations: Cylindrical dummy sockets.
Cable MBL: 1100 tonnes
Test 1: Load case, 30% mean load with –10% fluctuating load.
Test 2: Load case, 20% mean load with –10% fluctuating load.
Load frequency: 2 Hz.

Result:
Test 1: 384,650 cycles but the test was stopped whilst the sample could still support the upper load.
Test 2: 808,279 cycles achieved prior to the sample no longer being able to support the upper load.

Discussion:
Based on the API RP 2SK: $NR^M = K$ (equation 6.10)

Where:
N = Number of cycles
R = Tension range (double amplitude) to nominal breaking strength
M = Slope of T-N curve (5.05 for spiral strand)
K = intercept of T-N curve
Lm = ratio of mean load to MBL

	Test 1	**Test 2**
Test conditions	30%–10%	20%–10%
Lm	0.3	0.2
$K = 10^{(3.25-3.43Lm)}$	166	366
M	5.05	5.05
R	0.2	0.2
Expected N	**562,220**	**1,239,595**
Achieved N	**384,650**	**808,279**

The next lower band for fatigue assessment in accordance with API RP 2SK is the six / multi-strand assessment.

The M and K parameters are amended for six strand wire rope giving predicted cycles to failure as follows:

	Test 1	**Test 2**
Test conditions	30%–10%	20%–10%
Lm	0.3	0.2
$K = 10^{(3.20-2.79Lm)}$	231	438
M	4.09	4.09
R	0.2	0.2
Expected N	**166,878**	**316,418**
Achieved N	**384,650**	**808,279**

Hence, we can conclude the Xtreme spiral strand performs in excess of the six strand wire rope assessment.

Therefore we have an upper and lower bound limit between which the Xtreme spiral strand can be assessed.

To confirm the gradient factor (M) further testing will be required, two further tests at each mean load as a minimum would be necessary.

Alternatively, if we assume the M factor for spiral strand (5.05) is applicable for the Xtreme construction we can aim to establish a new K factor. This can then be proven as further fatigue testing is completed.

$K = 10^{(a - b.Lm)}$ hence $\log K = (a - b.Lm)$

Again using $NR^M = K$

	Test 1	**Test 2**
Test conditions	30%–10%	20%–10%
Achieved N	**384,650**	**808,279**
R	0.2	0.2
M	5.05	5.05
Lm	0.3	0.2
Therefore:		
K	114	238
Log K	2.055	2.378

Hence we can estimate $a = 3.024$
And $b = 3.230$

Therefore, for Xtreme, we can let: $K = 10^{(3.024-3.23Lm)}$

For a point of comparison a typical fatigue assessment for a Gulf of Mexico Spar was completed using the current spiral strand, six strand wire rope and the newly developed Xtreme M and K parameters. The resultant design lives were as follows:

	Standard Spiral Strand	**Xtreme Spiral Strand**	**Six Strand Wire Rope**	**Fittings***
Life span	1.8×10^6 yrs	1.2×10^6 yrs	2.2×10^5 yrs	9.45×10^4 yrs

* Fittings are assessed as chain and hence remain unaltered for each of the above cases.

Conclusions and Recommendations

The Xtreme spiral strand fatigue performance is in excess of the fatigue performance of equivalent breaking load six strand wire rope as defined by API RP 2SK.

For a typical Gulf of Mexico Spar assessment of the Xtreme spiral strand in accordance with the six strand parameters suggests the terminations will remain as the limiting factor in fatigue life assessment of the completed cable assembly.

If the assumption of the same curve gradient for standard spiral strand and Xtreme spiral strand is acceptable, assessment can be made utilising the newly developed K factor equation for Xtreme.

Appendix 2: Provisional data sheet

Nominal Diameter (in/mm)	Xtreme Spiral Strand MBL (kN)	Increment over SPR2*plus* (kN)	Nominal Weight/metre (kgs) Unsheathed	Sheathed	Nominal Weight/metre (kgs) submerged	Nominal Steel Area (mm^2)	Sheathing Thickness (mm)	Axial Stiffness (MN)
2.5" (65mm)	4680	11.4%	21.3	23.0	17.9	2562	6	423
2.625" (68mm)	4915	10.4%	22.4	24.2	18.7	2689	6	444
2.75" (70mm)	5355	10.4%	24.4	26.3	20.4	2901	8	479
2.875" (73mm)	5705	10.2%	26.1	28.0	21.8	3096	8	511
3.00" (76mm)	6225	10.2%	28.4	30.4	23.8	3377	8	557
3.125" (79mm)	6785	11.4%	30.4	32.5	25.4	3614	8	578
3.25" (82mm)	7235	10.5%	33.0	35.1	27.5	3917	8	627
3.375" (86mm)	7930	10.3%	36.2	38.7	30.2	4300	8	688
3.50" (90mm)	8750	10.2%	39.9	42.9	33.4	4747	10	760
3.625" (92.5mm)	9265	10.4%	42.2	45.3	35.3	5020	10	803
3.75" (95.5mm)	9850	10.3%	44.9	48.1	37.5	5341	10	855
3.875" (98mm)	10445	10.4%	47.6	51.0	39.8	5656	10	905
4.00" (102mm)	11255	9.6%	51.6	55.3	43.1	6139	11	982
4.125" (105.5mm)	11935	9.8%	54.7	58.4	45.7	6499	11	1040
4.25" (108mm)	12560	9.9%	57.5	61.3	48.0	6834	11	1093
4.375" (111.5mm)	13345	10.0%	61.0	65.0	51.0	7254	11	1161
4.50" (114mm)	13995	9.5%	64.2	68.3	53.6	7640	11	1222
4.625" (118mm)	14940	9.9%	68.4	72.6	57.1	8130	11	1280
4.75" (121.5mm)	15800	10.0%	72.2	76.5	59.7	8589	11	1353
4.875" (124mm)	16580	10.0%	75.9	80.3	63.4	9014	11	1420
5.00" (127mm)	17330	10.2%	79.1	83.6	66.0	9403	11	1481
5.125" (131mm)	18500	10.3%	83.3	87.9	69.6	9899	11	1534
5.25" (133mm)	18970	10.5%	86.8	91.5	72.4	10314	11	1599
5.375" (137.5mm)	20080	9.9%	92.5	97.3	77.2	10991	11	1704
5.50" (141mm)	21080	9.9%	97.5	102.4	81.5	11609	11	1799
5.625" (144mm)	21795	9.7%	101.3	106.3	84.6	12034	11	1865
5.75" (146.5mm)	22430	9.6%	105.1	110.2	87.7	12515	11	1940
5.875" (147.5mm)	22880	9.5%	107.2	112.4	89.5	12718	11	1971
6.00" (153mm)	24165	9.5%	114.5	119.7	95.5	13616	11	2110