Casing-Cost Optimization for Complex Loading Situations

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Summary

Casing can be the single most expensive item of an oil well and, in many cases, can be designed in a cheaper way. We present the optimization procedure, method, and algorithm to minimize cost of a combination casing string. The algorithm is general and can be used with any commercial program, provided a few modifications are made for it to be used as a subroutine. To demonstrate its use, a commercial package (that can handle complex load calculations) is tested and the results confirm the effectiveness of the optimization procedure. We present two complete examples that include cost predictions for multiple combination casing strings by use of an extensive database of price and casing properties for the $9^5/_8$-in. (with 27 different casing types) and the 7-in. casing (with 64 different types). With such a great casing database from which to select, it would be very hard to obtain the cheapest string by trial and error.

Introduction

Many oil companies and a few service companies have specialized in calculating casing loads for complex situations such as (1) setting multiple strings through creeping salt sections, (2) tough corrosion environments (H_2S, etc.), (3) situations for which accurate stress knowledge is required (deep wells, etc.), (4) cementing, production, and well-control loads, (5) thermal expansion loads, (6) collapse, burst, and impact loads, (7) casing wear, (8) running loads in directional, extended reach, and horizontal wells, (9) buckling, and (10) a combination of the above.

No company, however, has published the answer to the question: What is the cheapest possible casing string to be used that meets all load requirements? We address this question in our research.

Wojtanowicz and Maidla[1] addressed the optimization of casing design for vertical and directional wells by using Prentice's [2] method for load calculations. Although Prentice's load calculation method is appropriate in many situations, it does not cover the complex load situations described earlier.

Many commercial programs are available today that use sophisticated numerical techniques to estimate the loads of a combination casing string that can be handled only by computers. The commercial programs themselves are not the topic of discussion but, instead, are seen here as a necessary input to the main optimization program outlined in this work.

Price/Weight Conflict

The casing designer always faces the problem of having to choose between selecting the cheapest or the lightest casing for the bottom section of the casing string. If selecting the cheapest, the penalty will be paid by the sections above that will have to support larger axial loads.

Fig. 1 best explains the impact of this decision on its final cost. The best choice might be some intermediate casing weight between the weight of the cheapest one and the lightest one. This is possible because there is an overlap in casing properties in going from lighter to heavier weights because of the different grades of steel from which to choose.

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Casing-Optimization Method

We have slightly modified the theory and optimization procedure outlined by Wojtanowicz and Maidla.[1] It is basically the same, although the procedure was carried one step further; see Step 7 in the sequence described in the next section.

In this paper, we have opted to avoid the mathematical notation because we believe there is a simpler and more effective way to present the algorithm being just as rigorous in its completeness.

The method, illustrated in **Fig. 2,** makes use of a commercial program that must be able to calculate loads along the entire length of the casing string and provide, as an output, the actual safety factors for burst, collapse, yield, and the buckling condition, for any predetermined length interval.

The optimization procedure is described in a stepwise fashion, using the aid of examples and figures. The first step is to divide the combination string in two parts, as **Fig. 3** shows. To run the commercial program, an arbitrary defined casing is used for the Casing "A" (normally assumed to be the strongest tube and thread in the casing database). The bottom part (Casing "B") is the one to be designed. **Tables 1 through 4** provide a hypothetical example of a selection process for the Casing "B."

How To Find Casing "B"

1. The commercial program is run for this condition, using for the lower part of the string all casings in the database.
2. All casings are selected for which design factor (the desired minimum safety factor selected by the casing designer) is smaller than the actual safety factor (ratio between the corrected rating of a casing property by the to which it will be subjected).
3. The selected casings are separated in groups of actual weight (see Table 1).
4. For each weight group, the cheapest casing is selected (Table 2).
5. The cheapest casing is identified within the group remaining after the previous step.
6. The cheapest casing is selected as well as the ones that are lighter than it (Table 3).
7. All casings of greater price than any lighter one are excluded—these are the options for Casing "B" (Table 4).
8. These partial results are kept in memory.

Next Step After Finding "B." Take another step of length ΔL in the design process (**Fig. 4**). The length increment ΔL can be any fraction of L_{min} determined by the user. For small numbers of ΔL values (e.g., 40 ft) and long casing strings, the program could run for many hours on a 486DX2/66 before the result is known (this also depends on the speed of the commercial programs to determine the loads). Values of ΔL between 250 and L_{min} have shown to be appropriate in our research. Also the value of L_{min} is selected to limit the number of sections (this will be demonstrated in presented field examples).

The optimization procedure to determine Casing "C" (Fig. 4) is identical to the one described for Casing "B." Of course, there will be a particular Casing "C" for each Casing "B" previously determined.

Note 1: Casing "C" could be equal to casing "B." This is the reason why ΔL is normally smaller than L_{min}.

Note 2: If casing "C" is not equal to casing "B" and ΔL is less than L_{min}, then the length of "C" should be made equal to L_{min} and the calculations should be repeated. This simple procedure reduces the computational time significantly.

Note 3: After all "C" casings are determined for each casing "B," the numbers of partial solutions (N_{ps}) in memory will be

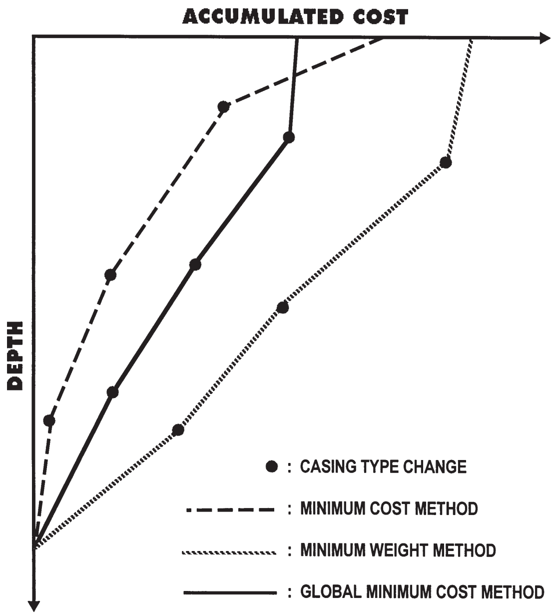

Fig. 1—Price/weight conflict.

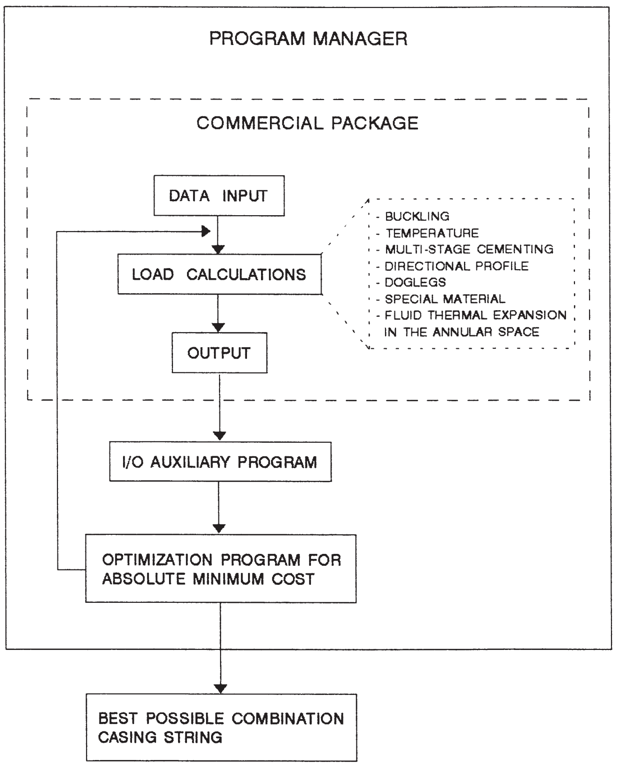

Fig. 2—The role of the commercial package in the optimization procedure.

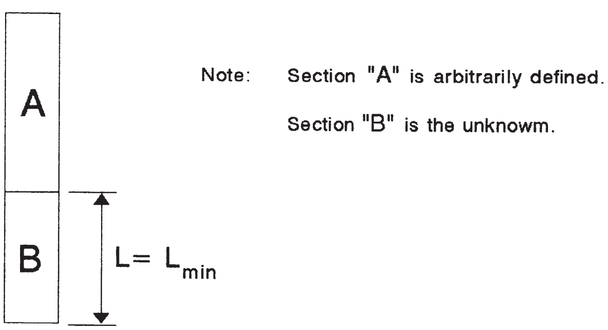

Fig. 3—Casing-optimization procedure.

TABLE 1—CASING-OPTIMIZATION EXAMPLE

Weight, lbm/ft	10	12	14	16	18
Price, $/100 ft	1310	1420	1100	1740	1959
	1200	1525		1348	1351
	1311	1628		1000	1266
		1300		1944	1899
				1641	1205

TABLE 2—CASING-OPTIMIZATION EXAMPLE

Weight, lbm/ft	10	12	14	16	18
Price, $/100 ft	1200	1300	1100	1000	1205

TABLE 3—CASING-OPTIMIZATION EXAMPLE

Weight, lbm/ft	10	12	14	16
Price, $/100 ft	1200	1300	1100	1000

TABLE 4—CASING-OPTIMIZATION EXAMPLE

Weight, lbm/ft	10	14	16
Price, $/100 ft	1200	1100	1000

$$N_{ps} = \sum_{i=1}^{N_B} (N_C)_i , \qquad (1)$$

where N_B is the number of Casings "B" and $(N_C)_i$ is the number of Casings "C" for each "B."

The procedure continues by adding casings "D," "E," etc., until $\Delta L_A \leq L_{min}$. Assuming at this point that the casing being designed is casing "M," then

$$(\Delta L_M)_n = (\Delta L_M)_{bd} \div \Delta L_A , \qquad (2)$$

where ΔL_M is the length of section "M." At this point, ΔL_A has been incorporated in ΔL_M and the entire combination string is finally defined.

Field Case Studies

Two field case studies will be used to demonstrate the usefulness of the optimization procedure.

First Field Case Study (Example 1)—A Medium Depth Well That Penetrates a Creeping Salt Section. The well plan (**Fig. 5**) shows the complete casing and cement program. The casing to be designed is the $9^5/_8$-in. string (depth interval is 0 to 8,900 ft).

Data used to determine the loads.

1. Undisturbed earth temperatures where surface is 50°F and static bottom hole temperature (BHT) is 170°F (at 11,800 ft).

2. Backup pressure data, where (1) the mud deteriorates with time, (2) there is an equivalent mud density of 9 lbm/gal, (3) there

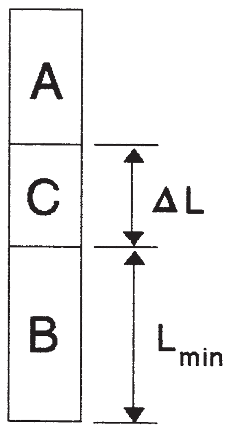

Fig. 4—Casing-optimization procedure.

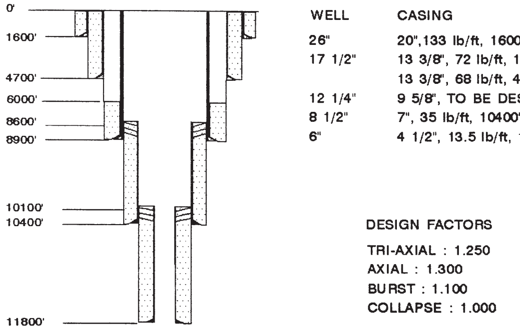

Fig. 5—Casing-design study of the 9 $^5/_8$-in. string that penetrates a creeping salt section.

is good cement behind the casing, and (4) there are no permeable zones behind the casing.

3. Vertical well with a maximum dogleg severity, superimposed over the entire well, of 2°/100 ft.
4. Cement top is 6,000 ft.
5. Hole size is 12.25 in.

Load Case 1.1: Complete Evacuation With External Mud (14 lbm/gal) and Salt Load. See **Table 5.**

Load Case 1.2: Gas Kick.

1. Depth of influx is 10,400 ft.
2. Kick volume is 50 bbl.
3. Shut-in drillpipe pressure is 270 psig.
4. Mud density is 14 lbm/gal.
5. Formation fracture gradient at the casing shoe is 17 lbm/gal.
6. Gas specific gravity is 0.7.
7. Mud surface temperature is 100 °F.
8. Mud temperature at gas influx is 130 °F.
9. Bottom hole assembly is only 5-in. drillpipe.

Load Case 1.3: Displacement to Gas. Many companies use a full column of gas inside the casing as a burst-design criterion. This example is just such a case caused by a high-pressure gas zone encountered near the total depth of the 8½-in. hole. This criterion is conservative because a full column of gas in the drilling annulus is indicative of losing control of a kick. These types of design criteria can be excessive and not cost effective for high-temperature, high-pressure wells.

TABLE 5—DATA FOR LOAD CASE 1.1

Depth (ft)	Internal Pressure (psig)	External Pressure (psig)
0	0	0
6,499	0	4,722
6,500	0	6,500
7,000	0	7,000
7,001	0	5,087
8,900	0	6,467

1. Gas gradient is 0.1 psi/ft.
2. Next hole section, where there is an equivalent pore pressure density of 14.5 lbm/gal, depth is 10,400 ft, and formation fracture gradient at the casing shoe is 17 lbm/gal.

Load Case 1.4: Production Tubing Leak at Surface.

1. Surface pressure is 4,400 psig.
2. Completion fluid density is 10.2 lbm/gal.

We ran the casing-design program by using the casing database shown in **Table 6** and selecting only buttress threads.

The first design was run with a minimum allowable casing length of 900 ft and a ΔL of 250 ft. **Table 7** shows the results.

The minimum cost of the combination casing string for the constraints presented earlier is $275,940 weighing in air 435,150 lbf. It contains six sections that might not be strategically interesting depending on the cost of the string with less sections. This was achieved by changing the minimum allowable casing length to 2,000 ft. **Table 8** shows the results.

By reducing the number of sections from six to three, there is a price increase of $23,343 or 8.46%; the economic advantage is significant.

We also ran the casing-design program considering all threads in the database and a minimum allowable casing length of 2,000 ft. **Table 9** shows the results. Notice that basically the design is the same with the only difference being the change in threads; the price, however, is cheaper.

TABLE 6—9$^5/_8$-in. CASING PRICE AND PROPERTIES*

Price	Weight (lbm/ft)	Grade	NN	Burst (psi)	Collapse (psi)	Bodyield (lbf)	M	ID (in.)
1,740.12	36.00	K55	3	3,520	2,020	423,000	1	8.921
1,826.23	36.00	K55	3	3,520	2,020	489,000	2	8.921
1,905.60	40.00	K55	3	3,950	2,570	486,000	1	8.835
1,952.81	36.00	K55	3	3,520	2,020	564,000	3	8.921
1,999.88	40.00	K55	3	3,950	2,570	561,000	2	8.835
2,138.47	40.00	K55	3	3,950	2,570	630,000	3	8.835
2,565.56	40.00	N80	6	5,750	3,090	737,000	2	8.835
2,743.75	40.00	N80	6	5,750	3,090	916,000	3	8.835
2,879.99	43.50	N80	6	6,330	3,810	825,000	2	8.755
2,983.77	43.50	N80	6	6,330	3,810	1,005,000	3	8.755
3,014.47	47.00	N80	6	6,870	4,750	905,000	2	8.681
3,131.24	40.00	C95	7	6,820	3,330	847,000	2	8.835
3,223.84	47.00	N80	6	6,870	4,750	1,086,000	3	8.681
3,349.03	40.00	C95	7	6,820	3,330	1,074,000	3	8.835
3,405.16	43.50	C95	7	7,510	4,130	948,000	2	8.755
3,421.44	47.00	S95	13	8,150	7,100	1,053,000	2	8.681
3,431.34	53.50	N80	6	7,930	6,620	1,062,000	2	8.535
3,642.00	43.50	C95	7	7,510	4,130	1,178,000	3	8.755
3,669.66	53.50	N80	6	7,930	6,620	1,244,000	3	8.535
3,679.12	47.00	C95	7	8,150	5,080	1,040,000	2	8.681
3,732.44	53.50	C75	4	7,430	6,380	999,000	2	8.535
3,835.01	47.00	C95	7	8,150	5,080	1,273,000	3	8.681
3,984.63	53.50	P110	8	10,900	7,930	1,422,000	2	8.535
3,993.71	53.50	C75	4	7,430	6,380	1,166,000	3	8.535
4,187.92	53.50	C95	7	9,410	7,330	1,220,000	2	8.535
4,263.55	53.50	P110	8	10,900	7,930	1,710,000	3	8.535
4,479.20	53.50	C95	7	9,410	7,330	1,458,000	3	8.535

*M1 = STC, M2 = LTC, M3 = BUTT, NN = grade

TABLE 7—EXAMPLE 1—CASING DESIGN OF THE 9⅝-in. STRING FOR L_{min} = 900 FT.

Depth (ft)	Grade	Weight (lbm/ft)	Thread	Price ($/100 ft)
0 to 2,000	C-95	43.5	BUTT	3,058.05
2,000 to 3,000	C-95	40.0	BUTT	2,912.00
3,000 to 5,000	N-80	43.5	BUTT	2,751.38
5,000 to 6,000	N-80	47.0	BUTT	2,972.75
6,000 to 7,000	C-95	53.5	BUTT	3,761.05
7,000 to 9,000	N-80	53.5	BUTT	3,383.88

Total Price: $275,940.32
Total Weight in Air: 416,150.00 lbf

TABLE 8—EXAMPLE 1—CASING DESIGN OF THE 9⅝-in. STRING FOR L_{min} = 2000 FT.

Depth (ft)	Grade	Weight (lbm/ft)	Thread	Price ($/100 ft)
0 to 2,800	C-95	43.5	BUTT	3,058.05
2,800 to 4,800	N-80	47.0	BUTT	2,972.75
4,800 to 6,800	C-95	53.5	BUTT	3,761.05

Total Price: $299,283.45
Total Weight in Air: 435,150.00 lbf

TABLE 9—EXAMPLE 1—CASING DESIGN OF THE 9⅝-in. STRING FOR L_{min} = 2000 FT.

Depth (ft)	Grade	Weight (lbm/ft)	Thread	Price ($/100 ft)
0 to 2,800	C-95	43.5	LTC	2,857.95
2,800 to 4,800	N-80	47.0	LTC	2,777.70
4,800 to 6,800	C-95	53.5	LTC	3,514.95

Total Price: $279,689.55
Total Weight in Air: 435,150.00 lbf

Second Field Case Study (Example 2)—A Deep North Sea Well. The well plan (**Fig. 6**) shows the complete casing and cement program. The casing to be designed is the 7-in. tieback string (depth interval is 0 to 15,000 ft).

Data used to determine the loads.

1. Undisturbed earth temperatures, where the surface is 40°F and static BHT is 380°F (at 17,500 ft).
2. Backup pressure data, where the mud gradient is 17.5 lbm/gal and there is good cement behind the casing.
3. Mildly deviated well (22°).
4. Cement top is 13,000 ft.

Load Case 2.1: Evacuated Casing.

1. 100% evacuated.

Load Case 2.2: Pressure Test.

1. Surface pressure is 12,000 psig.

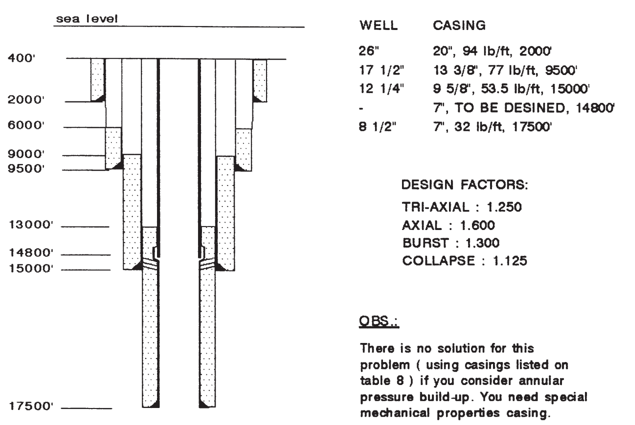

Fig. 6—Casing-design study of a deep 7-in. production-tieback for a deep offshore North Sea directional well.

2. Well fluid is 17.5 lbm/gal.

Load Case 2.3: Tubing Leak.

1. Surface pressure is 11,800 psig.
2. Completion fluid density is 10 lbm/gal.

Load Case 2.4: Long Term Production. Load Case 2.4 is a data "link" to the results of a production simulation.

1. Completion fluid density is 10 lbm/gal.
2. Mud line temperature is 236°F.
3. Temperature at 17,500 ft is 380°F.
4. Time period is 5 years.

Note: The increase in temperature owing to production causes the entire uncemented portion of the 7-in. production tieback to go into compression with a maximum dogleg as a result of buckling of 4.3°/100 ft at the top of the cement.

Load Case 2.5: Acid Job

1. Completion fluid density is 10 lbm/gal.
2. Surface temperature is 70°F.
3. Temperature at 17,500 ft is 380°F.

Load Case 2.6: Postproduction Acid Job. Load Case 2.6 is a link to the temperature results of a acid job simulation performed after the well had been producing for a long period of time. All other variables are identical to the initial acid job (Load Case 2.5), which was performed in a cooler wellbore. The case illustrates the importance of considering prior thermal history in stress analysis.

1. Completion fluid density is 10 lbm/gal.
2. Surface temperature is 77°F.
3. Temperature at 17,500 ft is 380°F.
4. Time period is 5 years.

Load Case 2.7: Tubing Leak With Temperature.

1. Surface pressure is 11,800 psig.
2. Casing temperature profile is the same as long-term production.

We ran the casing design program by use of the casing database shown in **Table 10.** The threads used in this database are buttress, although extreme line threads could be the preferred choice for this particular well.

The program was run with a minimum allowable casing length of 1,800 ft, and a ΔL of 250 ft. **Table 11** shows the results.

The minimum cost of the combination casing string is $472,809 weighing in air 466,200 lbf. Note that for this particular design, there is no solution if annular pressure buildup as a result of fluid thermal expansion (in all casing annular spaces) is considered.

The commercial program also suggests that the casing should be landed with an additional tension of 416,020 lbf if buckling is to be avoided in all load scenarios studied.

Conclusions

The casing method and procedure showed that a practical program can be built to take advantage of the commercial programs in the market today, such that the cheapest casing can always be designed that meets all mechanical constraints. We demonstrated this achievement through the design and analysis of two field examples.

Nomenclature

ΔL = length step in the casing design process
L_{min} = smallest length that is acceptable to the casing designer
N_{ps} = number of partial solutions
N_B = number of Casings "B"
$(N_C)_i$ = number of Casings "C" for each "B"

Subscripts

n = new
bd = being designed

Acknowledgments

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TABLE 10—7-in. CASING PRICE AND PROPERTIES

Price	Weight (lbm/ft)	Grade	NN	Burst (psi)	Collapse (psi)	Bodyyield (lbf)	M	ID (in.)
1,028.79	20.30	H40	1	2,720	1,970	176,000	1	6.456
1,054.91	20.30	K55	3	3,740	2,270	254,000	1	6.456
1,954.91	20.30	K55	3	3,740	2,270	281,000	2	6.456
1,173.96	20.30	K55	3	3,740	2,270	316,000	3	6.456
1,194.09	23.00	K55	3	4,360	3,270	309,000	1	6.366
1,253.22	23.00	K55	3	4,360	3,270	341,000	2	6.366
1,340.14	23.00	K55	3	4,360	3,270	366,000	3	6.366
1,750.23	23.00	C75	4	5,940	3,750	416,000	2	6.366
1,872.75	23.00	C75	4	5,940	3,750	499,000	3	6.366
1,608.00	23.00	N80	6	6,340	3,830	442,000	2	6.366
1,719.76	23.00	N80	6	6,340	3,830	532,000	3	6.366
1,962.77	23.00	C95	7	7,530	4,140	505,000	2	6.366
2,099.36	23.00	C95	7	7,530	4,140	632,000	3	6.366
1,331.17	26.00	K55	3	4,980	4,320	364,000	1	6.276
1,397.08	26.00	K55	3	4,980	4,320	401,000	2	6.276
1,493.97	26.00	K55	3	4,980	4,320	415,000	3	6.276
1,950.89	26.00	C75	4	6,790	5,220	489,000	2	6.276
2,087.45	26.00	C75	4	6,790	5,220	566,000	3	6.276
1,792.53	26.00	N80	6	7,240	5,410	519,000	2	6.276
1,917.10	26.00	N80	6	7,240	5,410	604,000	3	6.276
2,187.98	26.00	C95	7	8,600	5,880	593,000	2	6.276
2,340.23	26.00	C95	7	8,600	5,880	717,000	3	6.276
2,082.71	26.00	P110	8	9,960	6,230	693,000	2	6.276
2,228.50	26.00	P110	8	9,960	6,230	830,000	3	6.276
2,119.42	29.00	C75	4	7,650	6,730	562,000	2	6.184
2,267.78	29.00	C75	4	7,650	6,730	634,000	3	6.184
1,947.75	29.00	N80	6	8,160	7,320	597,000	2	6.184
2,083.08	29.00	N80	6	8,160	7,320	676,000	3	6.184
2,277.37	29.00	C95	7	9,690	7,830	683,000	2	6.184
2,542.77	29.00	C95	7	9,690	7,830	803,000	3	6.184
2,262.62	29.00	P110	8	11,220	8,530	797,000	2	6.184
2,421.00	29.00	P110	8	11,220	8,530	929,000	3	6.184
2,763.84	29.00	V150	9	15,300	9,800	1,049,000	2	6.184
2,957.31	29.00	V150	9	15,300	9,800	1,243,000	3	6.184
2,325.85	32.00	C75	4	8,490	8,200	633,000	2	6.094
2,488.66	32.00	C75	4	7,930	8,200	699,000	3	6.094
2,137.55	32.00	N80	6	9,060	8,610	672,000	2	6.094
2,286.06	32.00	N80	6	8,460	8,610	745,000	3	6.094
2,609.01	32.00	C95	7	10,760	9,750	768,000	2	6.094
2,790.52	32.00	C95	7	10,050	9,750	885,000	3	6.094
2,483.00	32.00	P110	8	12,460	10,780	897,000	2	6.094
2,656.81	32.00	P110	8	11,640	10,780	1,025,000	3	6.094
3,033.03	32.00	V150	9	16,990	13,020	1,180,000	2	6.094
3,245.34	32.00	V150	9	15,870	13,020	1,370,000	3	6.094
2,544.05	35.00	C75	4	8,660	9,670	703,000	2	6.004
2,722.13	35.00	C75	4	7,930	9,670	763,000	3	6.004
2,338.08	35.00	N80	6	9,240	10,180	746,000	2	6.004
2,500.52	35.00	N80	6	8,460	10,180	814,000	3	6.004
2,853.77	35.00	C95	7	10,970	11,650	853,000	2	6.004
3,052.31	35.00	C95	7	10,050	11,650	920,000	3	6.004
2,715.94	35.00	P110	8	12,700	13,020	996,000	2	6.004
2,906.06	35.00	P110	8	11,640	13,020	1,096,000	3	6.004
3,317.57	35.00	V150	9	17,320	16,230	1,310,000	2	6.004
3,549.80	35.00	V150	9	15,870	16,230	1,402,000	3	6.004
2,762.11	36.00	C75	4	8,660	10,680	767,000	2	5.920
2,955.46	38.00	C75	4	7,930	10,680	822,000	3	5.920
2,538.49	38.00	N80	6	9,240	11,390	814,000	2	5.920
2,714.85	38.00	N80	6	8,460	11,390	876,000	3	5.920
3,098.38	38.00	C95	7	10,970	13,440	931,000	2	5.920
3,313.94	38.00	C95	7	10,050	13,440	920,000	3	5.920
2,948.74	38.00	P110	8	12,700	15,140	1,087,000	2	5.920
3,155.15	38.00	P110	8	11,640	15,140	1,096,000	3	5.920
3,601.94	38.00	V150	9	17,320	19,240	1,430,000	2	5.920
3,854.08	38.00	V150	9	15,870	19,240	1,402,000	3	5.920

ented, does not necessarily reflect any position of Petrobrás or Enertech and is subject to correction by the authors.

References

1. Wojtanowicz, Andrew K., Maidla, Eric E.: "Minimum Cost Casing Design for Vertical and Directional Wells," *JPT* (Oct. 1987) 1269; *Trans.*, AIME, **283.**
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TABLE 11—EXAMPLE 2—7-in. TIEBACK CASING DESIGN

Depth (ft)	Grade	Weight (lb/ft)m	Thread	Price ($/100ft)
400 to 13,000	V-150	32.5	BUTT	3,245.34
13,000 to 14,800	V-150	35.0	BUTT	3,549.80
Total Price: $472,809.24				
Total Weight in Air: 466,200.00 lbf				

SI Metric Conversion Factors

bbl	$\times$ 1.589 873	E − 01	$= m^3$
ft	$\times$ 3.048*	E − 01	= m
°F	(°F–32)/1.8		= °C
gal	$\times$ 3.785 412	E − 03	$= m^3$
in.	$\times$ 2.54*	E + 00	= cm
lbf	$\times$ 4.448 222	E + 00	= N
lbm	$\times$ 4.535 924	E − 01	= kg
psi	$\times$ 6.894 757	E + 00	= kPa

*Conversion factor is exact.

SPECA

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Maidla