CASING AND LINERS FOR DRILLING AND COMPLETION

DESIGN AND APPLICATION

SECOND EDITION

Ted G. Byrom
Casing and Liners for Drilling and Completion
Dedication

To Anne
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Acknowledgments

I owe very special thanks to Leon Robinson who encouraged the first edition of this textbook as the first in a series of textbooks that he envisioned as an encyclopedia of drilling technology. Simply put, his goal was to publish a record of current drilling technology before the “old timers” all retired and faded away. He recognized that a trend in more frequent personnel turnover was resulting in an industry cycle of having to continually reinvent drilling practices and technology that have been well known by earlier generations of engineers. His encouragement was invaluable to the first edition, and he continues to be an inspiration for this second edition.

Thanks also to Marc Summers for his valuable suggestions on additional load cases and their systematic organization, and so too, the many helpful suggestions of others who used the first edition in teaching casing design.

Finally, and especially, I extend my grateful appreciation to my editors, Katie Hammon, Kattie Washington, and Anusha Sambamoorthy whose enthusiasm and tireless efforts made this the smoothest publishing experience of my career.
Preface

This second edition represents a significantly revised and improved version of the first edition, and in many respects it is a new book. I have taught various aspects of casing design over more than twenty years, and for the past six I taught a 5-day basic casing design course from the first edition of this book. I felt that some changes in organization and approach would greatly enhance its value for engineers learning casing design. Hence, the present focus is on a clear and logical progression through the design/selection sequence and related practices followed by material on more advanced topics of casing performance mechanics and casing in directional and horizontal wells.

I have added some new material on loading cases and some additional perspective on approaches to design. Especially topical is the addition of a section on casing performance in hydraulic fracturing of horizontal wells, a relatively new application and one in which I have been consulting in the past few years. Along these lines, I have also added a brief overview of some aspects of rock mechanics as it relates to fracturing and horizontal wells in a separate appendix.

While the first edition contained much foundational matter such as units of measure, hydrostatics, and so forth, it was all interspersed throughout the main body of text. That order of presentation works well for an introduction to casing design, but once an engineer is past the fundamentals it makes for an amount of clutter for someone wanting to refer back specifically to the design/selection process. Consequently, I have moved most of the foundational material from the body of the text into appendices for easy study and reference. One might question the necessity for including such foundational material in a text like this, but having taught specific industry training courses for engineers over the past eighteen years, I can assure you that most of this material is essential. Engineers who approach casing design for the first time typically come from various disciplines and may or may not have any previous exposure to solid mechanics, but more importantly, it is an inescapable fact that we forget what we were taught if we are not using it on a regular basis. Those new to the topic of casing design should devote serious study to these appendices, and I highly encourage all to at least review them. In the appendices I have gone into greater depth and detail on some of the peripheral issues of casing than might seem necessary for those whose only interest is in basic level casing design, but I did so to enhance the value of the book as a fairly complete reference on the topic.

I have included scant material on pipe standards and specifications, especially in regard to connections, only what is essential to understand the process of casing design. The reasons for this are twofold, one is that standards and specifications change periodically and a book based heavily on them is out of date as soon as a new specification or standard is published, and the other is that most of the meager published data on oilfield tubulars is of a nominal or minimal performance nature and readily available elsewhere. My focus in this book is on the fundamental mechanics that will not change over time.
Finally and importantly, as with the first edition, I have tried to maintain a conversational style so that it may be easily read and understood by those seeking self education without the necessity of an instructor. There are many precautions and opinions sprinkled throughout, sometime homiletic in tone, but all based in real case histories, most of which could never find their way into print. I hope these add to the content. Overall, the reader should find this edition to be a much improved and more useful textbook.

Ted G. Byrom
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January, 2014
Preface to the First Edition

Hardly anyone reads a Preface. Please read this one, because this book is a bit different and what is written here is the actual introduction to the book. I never read a textbook that I really liked when I was a student. The main reason is that most authors seemed more interested in presenting the information with the goal of impressing colleagues rather than instructing the reader as a student of the subject. For a long time, I thought they were so smart that they could not relate to the ordinary student. I now know that is rarely true. You should know that I have reached a point in my career where no one is important enough that I need to impress, and certainly no money is to be made writing a textbook. My reason for accepting the task of writing this text is that I truly wanted to attempt to explain this subject in an understandable manner to the many petroleum engineers who need or want to understand it but at best received a couple of classroom lectures and a homework assignment on the subject from someone who never designed or ran a real string of casing in his life. I was in that same position some 44 years ago. This book is also intended for those coming into the oilfield from other disciplines and needing to understand casing design.

This book is not written in the style of most textbooks. That is because its main purpose is to teach you, the reader, about casing and casing design without need of an instructor to “explain” it to you. I would like you to read this as if you and I were sitting down together as I explain the material to you. While some of the material requires a little formality, I have tried to put it on a readable level that progresses through the various processes in a logical manner. I have also tried to anticipate, pose, and answer some of the questions you might ask in the process of our discussion.

The first five chapters of this book lay a foundation in basic casing design. It is, if you will, a recipe book for basic casing design. It goes into some detail at times, but overall its purpose is to actually teach an understanding of basic casing design. If you are not an engineer, and many casing strings are designed by nonengineers, do not be discouraged by the many equations you see. The information in this part should be sufficient to design adequate casing strings for the vast majority of the wells drilled in the world, and although the chapter on hydrostatics contains some calculus, none of it is beyond the capabilities of a second-year engineering student. The sixth chapter is about running and landing casing. Most of it is common sense, but there are some practical insights that are worth the time it takes to read.

Chapter 6 begins the discussion of slightly more advanced material. Some of this material is not covered in universities, except on a graduate level, but I have tried to present it so that any undergraduate engineering student should be able to understand it. The remaining chapters continue in the same vein.

I have not tried to cover everything about casing or casing design in this book. I have never had any aspirations of writing the definitive text on casing or any other subject, mostly because some aspects hold no interest at all for me. I have personally run and cemented close to a couple of hundred casing strings as a field drilling engineer, designed several hundred more, and been involved with several thousand
casing strings over my career. These have ranged from very shallow strings to a few over 23,000 ft. Never have I designed a string for a geothermal well, and my corrosion and sour gas experience is limited. Consequently, little is said about those subjects in this book. There are much better sources for that than what I could write on those particular topics.

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September, 2006
Acronyms

AEUB  Alberta Energy and Utilities Board
API   American Petroleum Institute
IADC  International Association of Drilling Contractors
ISO   International Organization for Standardization
SPE   Society of Petroleum Engineers

See Glossary for technical acronyms.
1.1 Introduction

In this textbook, we will explore the fundamentals and practices of basic casing design with some introduction to more advanced ideas and techniques. We will use a simple process that involves manual calculations and graphical plots. This is the historical method of learning casing design and will instill a depth of understanding. For the vast majority of casing strings run in the world this is still the method
employed. Those engineers already well founded in the process may use more advanced techniques and specific software. While there is some excellent software on the market that does casing design, one cannot really learn the process using software. This is not by any means a harangue about casing design software; some of it is excellent and quite sophisticated especially compared to the crude first attempts that hit the market. But the unwelcome fact is that many who are using it are overwhelmed by multipage, detailed printouts, half of which they do not even pretend to understand. And truth be told, many of the “support” personnel experience the same problem. Information is not knowledge if you do not understand it.

### 1.2 Design basics

Casing design is a bit different from most structural design processes in engineering because the “structure” being designed is a single tubular monolith of given outside diameter primarily supported from the top end. There is nothing to actually “design” in the conventional sense of structural engineering. Geometrically speaking, our structure is already designed. The available tubular sizes and strengths are standardized, so the design process maybe thought of as a two-step process:

1. Calculate the anticipated loads.
2. Selecting from the available standard tubes those with adequate strength to safely sustain those loads.

As simple as that may sound, casing design is still not a linear process. It is not a matter of calculating the anticipated loads and then selecting the casing. The selected casing itself is part of the load. Hence, the process must be iterated to account for that fact. Still, it is quite an easy process in the vast majority of cases.
The basic design/selection sequence in its iterative form might be listed in steps:

1. Determine depths and sizes of casing.
2. Determine pressure loads.
3. Apply design factors and make preliminary selection.
4. Determine axial loads and apply design factors.
5. Adjust preliminary selection for axial design loads.
6. Adjust for combined tension/collapse loading.

Some might not consider Step 1 a part of casing design, and technically that is true. That step might be done by someone other than the casing designer and not in conjunction with the actual design process. However, we are going to include it in our treatment because it is essential for us to understand how it is done and how the results affect our design process.

The actual design process starts with Step 2, where we calculate the pressure loads for various scenarios using basic hydrostatics. We do this for all the strings in the well.

In Step 3, we select the worst case pressure loading from the previous step and apply a design factor which gives us a margin to account for uncertainty in the loads and pipe strengths. The results of that are design pressure-load plots for each string of casing in the well. From these plots, we make preliminary selections of casing, which will safely sustain those design loads.

Because the axial load (weight) of the string is a function of the casing itself, we must then calculate it from the preliminary pressure-load selection. We then apply a design factor to the axial load and check to see if our preliminary selection has sufficient axial strength. If it does, Step 4 is complete and we skip Step 5. If it does not, then in Step 5, we must modify the preliminary selection so that it also satisfies the axial design load. When we modify the preliminary selection, we must recalculate the axial load for the modified string and apply our axial design factor again. We must also check to ascertain that the modified string still meets our pressure-load design requirements. So in this step, the process becomes iterative. It is not difficult though, because in the manual process, it is easy to visually see the values and minimize the iterations. Seldom are more than two iterations required.

Finally, in Step 6, we check for the effects of combined axial tension and collapse loading, often referred to as biaxial loading. This is a critical step even in basic casing design, because tension in a string reduces the collapse resistance of the casing. This step too may require several iterations because any change or adjustment in the casing selection always requires that all the loads be rechecked.

For your early reference, Step 1 is covered in Chapter 2, Step 2 in Chapter 3, and Steps 3-6 in Chapter 4. Chapter 5 covers the casing installation process, and the remainder of the chapters covers more advanced topics.

### 1.3 Conventions used here

There is in the petroleum literature a virtual plethora of odd terminology, incoherent physical units, mathematical inconsistencies, and so forth. I have tried to adhere to several principles in this book:

- A readable text
- A progressive sequence for learning and self education
- Sufficient background material in appendices
- Avoidance of acronyms except for organizational names (5) and those appearing in API/ISO standards (8) that you must necessarily understand plus only one other that is too common to not know (BOP)
Readability is essential for self-education, and I think, one of the most important features I have aimed for in this textbook. Perhaps I have oversimplified some concepts, but I prefer that to pedantic gibberish and superfluous acronyms that are more confusing than educational. And if the copy editor is successful at ironing out my convoluted sentence structure, you should find this book fairly readable.

1.3.1 Organization of book

The book is organized in a logical sequence that a beginner would follow to learn casing design, starting with the basics and proceeding to the more advanced topics. Chapters 2–4 illustrate basic casing design and Chapter 5 covers installation in the well. Having learned that material, the reader will have acquired the skills necessary for a fundamental level of casing design. That is the level of most who actually design the majority of casing strings in the world. Chapter 6 covers the details of casing strengths and performance, and Chapter 7 covers casing in deviated and horizontal wells. That latter chapter also contains materials on casing for hydraulic fracturing in horizontal wells.

Most of the referential and foundational materials on mechanics, hydrostatics, rock behavior, and so forth, have been moved to separate appendices so as not to clutter the logical progression of the design process and casing specific topics. Most of that material has been expanded in these appendices and should serve as handy reference or refresher for those needing it. I have also added an appendix with the most commonly used equations for easy access, rather than requiring a search through the text to locate them. Those equations that are boxed in the text are listed in this appendix along with their respective equation numbers from the text to facilitate locating the qualifications and discussions.

You will notice a number of redundancies in this text, and I can already imagine the number of times a reader may say, “He already said this!” While partly the result of my writing process, I have intentionally left some of these in place and added some. The reason is that it is seldom that anyone would read a text like this from beginning to end. More commonly one reads selectively those topics of concern or need, thus some of the pertinent precautions and qualifications mentioned elsewhere may be missed. I beg your patience when you encounter these.

1.3.2 Units and math

The problem with units in oilfield technology is that there are too many systems and hybrid systems in play, none of which use consistent units in oilfield applications. Here, I adhere to a simple underlying principle: all physical phenomena are independent of any units used to measure them. If we use consistent units from a coherent system, no conversion factors are necessary in properly stated physical formulas and equations. Importantly, none of the formulas or equations in this book require conversion factors if you use consistent units. There are no conversion factors included in any of the formulas, and it is left to you as a properly educated engineer to know when you need them. All that said, most of the global drilling and completion operations use the USC system (US Customary) of oilfield units, and we will bow to that custom here because it is the system of the vast majority of readers. The fundamental formulas will not require conversion factors, but our calculations will, and we will show them in the examples. Units of measure, physical constants, and material properties used in this text are covered in detail in Appendix B.

As in the first edition [3], I use specific gravity (specific density), \( \hat{\rho} \), (SG) for liquid density, where specific gravity is defined as \( \hat{\rho} \equiv \rho / \rho_{\text{wtr}} \), rather than the cumbersome lb/gal (ppg) of the USC system. This is done for ease of use in any unit system, where early in their education, every engineer committed
to memory that water density, $\rho_{wtr}$, is 62.34 lb/ft$^3$, 8.33 ppg, and 1000 kg/m$^3$. (We avoid the niceties of temperature variation as we seldom have that data anyway.)

Throughout the petroleum literature (SPE, API, IADC, etc.), there is a virtual hodgepodge of variable names, symbols, multiletter computer variables, mixed mode math, and grade school arithmetic, all of which are inconsistent and quite confusing. All math here will be in strict algebraic form with single-kernel, italicized letter/symbol variables. Nonitalicized subscripts will be used for further identification and clarification. Italicized subscripts will denote variable descriptors rather than names. Further, I will use mostly standard variable names from mechanics rather than from the petroleum literature as per ISO 80000-4 [2] to make this more universal for all readers. At first encounter, this may be a bit confusing to some, but Appendix A defines all the notation and variables used, so you should not have to search through the text to find a variable's definition where first used. A glossary of petroleum related terms and acronyms is also included. There are a few instances where the same symbols are necessarily used to represent different quantities, but those are quite local and should be obvious from the context. Where applicable to terms and abbreviations, I have adhered closely to the SPE Style Guide [4].

For those who have used the first edition of this text, I should call attention to two significant changes in usage. As before all of our pressure loads are defined in terms of a differential pressure across the casing wall. But in this edition, we will define that differential pressure in a single, consistent manner:

$$\Delta p = p_i - p_o \quad \begin{cases} < 0 & \rightarrow \text{collapse loading} \\ = 0 & \rightarrow \text{no differential loading} \\ > 0 & \rightarrow \text{burst loading} \end{cases} \quad (1.1)$$

where $p_i$ and $p_o$ are inside and outside pressure, respectively. This should avoid some confusion inherent in the previous edition. The second change is in the definition of the conversion factor, $g_c$, that converts pounds (mass) to slugs (mass). In this edition, I use $g_c = 1/32.174049$ slug/lb, which is the more conventional form (though there is no standard). This is the reciprocal of the value used in the earlier edition. More discussion on this is found in Appendix B.

**Roundoff**

The API rounds off pressure ratings to the nearest 10 psi, and we will follow that convention in most of our pressure load calculations. We will use the $\approx$ symbol to denote where we roundoff. However, there are a few places where we will not roundoff because intermediate results may have significance in further calculations, and where we want to illustrate something more clearly.

### 1.3.3 Casing used in examples

All of the design process and calculations will be illustrated with examples. Most are based on real wells. For the sake of simplicity and avoidance of commercialism, I limit all of the casing used in the designs to API threaded and coupled pipe (ST&C, LT&C, and Buttress). This does not constitute a recommendation, but utilizes the most widely used and standardized casing in the world. This book primarily addresses the design process and the mechanics employed, so I have purposely limited the amount of API/ISO standards covered because they can and do change periodically whereas the fundamental mechanics do not. Furthermore, I make scant mention of proprietary casing and connections because those standards are set by the individual manufacturer, not always readily available, and subject to change for marketing and business-related reasons.
1.4 Oilfield casing

Anyone reading this book is assuredly already familiar with the oilfield tubes (casing, tubing, drill pipe, and line pipe) referred to as Oil Country Tubular Goods or OCTG, the standardized tubes used in drilling, completion, and production applications. But for a refresher and consistency in our discussions, we include this brief and basic section on oilfield casing.

The steel tubes that become a permanent part of an oil or gas well are called casing, and the tubes that are removable, at least in theory, are referred to collectively as tubing, which are not covered in this book. Oilfield casing is manufactured in various diameters, wall thicknesses, lengths, strengths, and with various connections. The purpose of this text is to examine the process of selecting the type and amount we need for specific wells. But first, a question: What purpose does casing serve in a well? There are three:

- Maintain the structural integrity of the borehole.
- Keep formation fluids out of the borehole.
- Keep borehole fluids out of the formations.

It is as simple as that, though we could list many subcategories under each of those. Most are self-evident. Additionally, there are some cases where the casing also serves a structural function to support or partially support some production structure, as in water locations.

1.4.1 Setting the standards

By necessity, oilfield tubulars are standardized. Until recent times, the standards were set by the American Petroleum Institute (API) through various committees and work groups formed from personnel in the industry. Now, the International Organization for Standardization (ISO) is seen as taking on that role. Currently, most of the applicable ISO standards are merely the API standards, but that role may expand in the future. In this text, we refer primarily to the API standards, but it should be understood that there are generally identical standards, and in some cases, more advanced standards, under the ISO name.

It is important that some degree of uniformity and standardization is in force and that manufacturers be held to those standards through some type of approval or licensing procedure. In times of casing supply shortages, a number of manufacturers have entered the oilfield tubular market with substandard products. Some of these have resulted in casing failures where no failure should have occurred. Any casing purchased for use in oil or gas wells should meet or exceed the current standards as set for oilfield tubulars by the API or ISO.

Some casing on the market is not covered by API or ISO standards. Some of this non-API casing is for typical applications, some for high-pressure applications, high-temperature applications, low-temperature applications, and some for applications in corrosive environments. Many of these types of casing meet or exceed API standards, but one must be aware that the standards and quality control for these types of casing are set by the manufacturer. It probably should not be mentioned in the same paragraph with the high-quality pipe just referred to, but it should also be remembered that there are some low-quality imitations of API products on the market as well, including some with fraudulent API markings.

1.4.2 Manufacture of oilfield casing

There are two types of oilfield casing manufactured today: seamless and welded. Each has specific advantages and disadvantages.
 Seamless casing

Seamless casing accounts for the greatest amount of oilfield casing in use today. Each joint is manufactured in a pipe mill from a solid cylindrical piece of steel, called a billet. The billet is sized so that its volume is equal to that of the joint of pipe that will be made from it. The manufacturing process involves:

• Heating the billet to a high temperature
• Penetrating the solid billet through its length with a mandrel such that it forms a hollow cylinder
• Sizing the hollow billet with rollers and internal mandrels
• Heat treating the resulting tube
• Final sizing and straightening

The threads may be cut on the joints by the manufacturer or the plain-end tubes may be sent or sold to other companies for threading. The most difficult aspect of the manufacture of seamless casing is that of obtaining a uniform wall thickness. For obvious reasons, it is important that the inside of the pipe is concentric with the outside. Most steel companies today are very good at this. A small few are not, and which is one reason that API and ISO standards of quality were adopted. Current standards allow a 12.5% variation in wall thickness for seamless casing. The straightening process at the mill affects the strength of the casing. In some cases, it is done with rollers when the pipe is cool and other cases when the pipe is still hot. Seamless casing has its advantages and also a few disadvantages.

Advantages of seamless casing

• No seams to fail
• No circumferential variation of physical properties

Disadvantages of seamless casing

• Variations in wall thickness
• More expensive and difficult manufacturing process

 Welded casing

The manufacturing process for welded casing is quite different from that of seamless casing. The process also starts with a heated steel slab that is rectangular in shape rather than cylindrical. One process uses a relatively small slab that is rolled into a flat plate and trimmed to size for a single joint of pipe. It is then rolled into the shape of a tube, and the two edges are electrically flash welded together to form a single tube. Another process uses electric resistance welding (ERW) as a continuous process on a long ribbon of steel from a large coil. The first stage in this process is a milling line in the steel mill:

• A large heated slab is rolled into a long flat plate or ribbon of uniform thickness.
• Plate is rolled into a coil at the end of the milling line.

The large coils of steel “ribbon” are then sent to the second stage of the process, called a forming line.

• Steel is rolled off the coil and the thickness is sized.
• Width is sized to give the proper diameter tube.
• Sized steel ribbon is formed into a tubular shape with rollers.
• Seam is fused using electric induction current.
• Welding flash is removed.
• Weld is given an ultrasonic inspection.
• Seam is heat treated to normalize.
• Tube is cooled.
• Tube is externally sized with rollers.
• Full body of pipe is ultrasonically inspected.
• Tube is cut into desired lengths.
• Individual tubes are straightened with rollers.

This is the same process by which coiled tubing is manufactured, except coiled tubing is rolled onto coils at the end of the process instead of being cut into joints. Note that, in the welding process, no filler material is used; it is solely a matter of heat and fusion of the edges.

Welded casing has been available for many years, but there was an initial reluctance by many to use it because of the welding process. Welding has always been a matter of quality control in all applications, and a poor-quality weld can lead to serious failure. Today, it is both widely accepted and widely used for almost all applications except high-pressure and/or high-temperature applications. It is not used in the higher yield strength grades of casing.

**Advantages of welded casing**

• Uniform wall thickness
• Less expensive than seamless
• Easier manufacturing process
• Inspected during manufacturing process (ERW) and defective sections removed

Uniform wall thickness is very important in some applications, such as the newer expandable casing.

**Disadvantages of welded casing**

• High temperatures of welding process
• Possible variation of material properties caused by welding
• Possible faulty welds
• Possible susceptibility to failure in weld

Welded casing has been used for many years now. Many of the so-called disadvantages are perhaps more a matter of perception than actuality.

**Strength treatment of casing**

When a cast billet or slab is formed into a tube it is done at quite high temperature. The deformation that takes place in the forming process is in a plastic or viscoplastic regime of behavior for the steel. As it cools, its crystalline structure begins to form. Once the crystalline structure forms or begins to form, any additional plastic deformation to which we subject the tube will change its properties. The change may be minor or significant, depending on the constituents of the steel, the amount of deformation, and the temperature. Heating a tube above certain temperatures and cooling slowly allow the crystals to form more uniformly with fewer structural imperfections, called *dislocations*, in the lattice structure. The properties of the steel can be modified by the addition of certain constituents to the alloy and, to some extent, by controlling the cooling rate. One common process for enhancing the performance properties
of casing is to heat the tube above a certain temperature then quickly cool it by spraying it with water or some other cool fluid to strengthen and harden it (quenching), especially near the surface. The casing is then heated again, but to a lower temperature, and allowed to remain at that temperature for a period of time to allow “relaxation” of the steel to some specific lower hardness and strength (tempering). This process is called *quench and temper*, or QT for short, and is an inexpensive alternative to adding more expensive alloying constituents.

Some steels are said to get “stronger” when they are deformed plastically at ambient temperatures. This is part of the manufacturing process in some steels and is called *cold working*. Cold working typically increases the steel’s yield strength; however, it does not, in general, increase the ultimate strength. Straightening casing joints in the latter stages of the manufacturing process can also have an effect on the properties of the tube depending on whether it is done at “cool” temperatures or “warm” temperatures. It should be noted that any steel that is cold worked is no longer isotropic. Its yield strength will vary depending on the direction of the loading. For example, if a tube is cold worked by axially stretching, it may see an increase in tensile yield strength, but it will suffer a reduction in compressive yield strength. This elastic-plastic behavior will be discussed more fully in Appendix C.

### 1.4.3 Casing dimensions

Casing comes in an odd assortment of diameters ranging from 4-1/2 in. to 20 in. that may seem quite puzzling at first encounter, e.g., 5-1/2, 7, 7-5/8, 9-5/8 and 10-3/4 in. Why such odd sizes? All we can really say about that is that they stem from historical sizes from so far back that no one knows the reasons for the particular sizes any longer. Some sizes became standard and some vanished. Within the different sizes, there are also different wall thicknesses. These different diameters and wall thicknesses were eventually standardized by the API (and now ISO). The standard sizes as well as dimensional tolerances are set out in API Specification 5CT [5] and ISO 11960 [6].

**Outside diameter**

The size of casing is expressed as a *nominal diameter*, meaning that is the designated or theoretical outside diameter of the pipe. API and ISO allow for some tolerance in that measurement, and the specific tolerance differs for different size pipe. The tolerances for nonupset casing 4-1/2 in. and larger are given as fractions of the outside diameter in Table 1.1. Note that the amount of minimum tolerance for the outside diameter is much less than for the maximum tolerance. This is necessary to assure that standard threads cut on the joint will be of adequate depth and height.

For upset casing, Table 1.2 shows the current API and ISO tolerances measured 5 in. or 127 mm behind the upset.

<table>
<thead>
<tr>
<th>Nominal Outside Diameter, $d_o$(in.)</th>
<th>Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
</tr>
<tr>
<td>≥ 4-1/2</td>
<td>$+0.01d_o$</td>
</tr>
</tbody>
</table>
Table 1.2 Tolerance for *Upset* Casing Outside Diameter [5, 6]

<table>
<thead>
<tr>
<th>Nominal Outside Diameter, $d_o$ (in.)</th>
<th>Tolerances (in.)</th>
<th>Tolerances (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>&gt; 3-1/2 to 5</td>
<td>7/64</td>
<td>0.0075</td>
</tr>
<tr>
<td>&gt; 5 to 8-5/8</td>
<td>1/8</td>
<td>0.0075$d_o$</td>
</tr>
<tr>
<td>&gt;8-5/8</td>
<td>5/32</td>
<td>0.0075$d_o$</td>
</tr>
</tbody>
</table>

Table 1.3 Minimum Drift Mandrel Dimensions [5, 6]

<table>
<thead>
<tr>
<th>Nominal Outside Diameter (in.)</th>
<th>Mandrel Length</th>
<th>Mandrel Diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(in.)</td>
<td>(mm)</td>
</tr>
<tr>
<td>&lt; 9-5/8</td>
<td>6</td>
<td>152</td>
</tr>
<tr>
<td>9-5/8 to 13-3/8</td>
<td>12</td>
<td>305</td>
</tr>
<tr>
<td>&gt;13-3/8</td>
<td>12</td>
<td>305</td>
</tr>
</tbody>
</table>

*Inside diameter and wall thickness*

The inside diameter of the casing determines the wall thickness or vice versa. Rather than a specific tolerance for the amount at which the internal diameter might exceed a nominal value, the tolerance specified by API and ISO is given in terms of minimum wall thickness. The minimum wall thickness is 87.5% of the nominal wall thickness. The maximum wall thickness is given in terms of the nominal internal diameter, however. It specifies the smallest diameter and length of a cylindrical drift mandrel that must pass through the casing (Table 1.3).

The internal diameter of casing is a critical dimension. It determines what tools and so forth may be run through the casing. It is not uncommon to have to select a casing for a particular application such that the drift diameter is less than the diameter of the bit normally used with that size casing, even though the bit diameter is less than the nominal internal diameter of the pipe. In cases like this, it is a practice to drift the casing for the actual bit diameter rather than the standard drift mandrel diameter. This may be done with existing pipe in inventory, and those joints that will not pass the bit are culled from the proposed string. Or it may be done at special request at the steel mill, in which case there will be an extra cost. This procedure applies only to casing where the desired bit diameter falls between the nominal internal diameter and the drift diameter of the casing.

*Joint length*

The lengths of casing joints vary. In the manufacture of seamless casing, it all depends on the size of the billet used in the process. Usually, there is some difference in weight of the billets, and this results in some variation in the length of the final joints. One could cut all the joints to the same length, but that would be a needless expense and, in fact, would not be desirable. (Wire line depth correlation for perforating and other operations in wells usually depends on an electric device to correlate the couplings with a radioactive formation log; so if all the joints are the same length, it can cause errors in perforating or packer setting depths.) For ERW casing, it is much easier to make all of the joints the same length,
but there may still be some waste if that is done. Even if the joints vary in length, they need to be sorted into some reasonable ranges of lengths for ease of handling and running in the well. Three ranges of length are specified by API Recommended Practices 5B1 [7], Ranges 1, 2, and 3 (Table 1.4).

Most casing used today is in either Range 2 or 3, with most of that being Range 3. Range 1 is still seen in some areas where wells are very shallow, and the small rigs that drill those wells cannot handle longer pipe.

**Weights of casing**

The term *casing weight* refers to the linear “weight” of casing expressed as mass per unit length, such as kg/m or lb/ft. The use of the term *weight* is so common that we are going to use that term for now, but it should be understood that we are not talking about weight but linear density (mass per unit length), and we will use the symbol $\rho_\ell$ to so designate. One might logically assume that the published casing weight is determined by the density of the steel and the dimensions of the casing body. For instance, we may have a joint of 7 in. 26 lb/ft casing and reasonably assume from that our joint actually weighs 26 lb/ft. Our assumption would be wrong. The published value is the *nominal weight* of the casing, not the actual weight. For outdated reasons, the nominal weight of casing is based on a joint that is 20 ft in length (including coupling). It includes the total weight of the plain-end pipe plus the weight of a coupling, minus the weight of the metal cut away to make the threads on each end, and divided by 20 ft to give the nominal weight in terms of pounds per foot (or kg/m). And the threads used in that calculation are an obsolete thread that is no longer manufactured. In other words, casing almost never weighs the same as its nominal weight. Fortunately, the difference is small enough that in most cases of casing design, it is relatively insignificant. API Spec 5CT [5] has formulas for calculating the actual weight of a joint, but it requires specification of the thread dimensions, and so forth, and we are not going to concern ourselves with that here. One particular formula in API Spec 5CT and ISO 11960 sometimes is useful though, and that is a formula for calculating the nominal casing weight of plain pipe without threads or couplings:

$$\rho_\ell = \rho_s A_t \quad (1.2)$$

or more in the form used by the API

$$\rho_\ell = \rho_s \pi (d_o - t_w) t_w \quad \text{or} \quad \rho_\ell = \rho_s \frac{\pi}{4} (d_o^2 - d_i^2) \quad (1.3)$$

where

$\rho_\ell =$ linear density (mass per unit length), plain-end “casing weight”

$\rho_s =$ density of API carbon steel, 7850 kg/m$^3$ or 490 lb/ft$^3$

$A_t =$ cross-sectional area of the tube

$d_o =$ outside diameter

$d_i =$ inside diameter

$t_w =$ wall thickness

<table>
<thead>
<tr>
<th>Table 1.4 Length Range of Casing [7]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range 1</strong></td>
</tr>
<tr>
<td>(ft)</td>
</tr>
</tbody>
</table>