Fabrication of Metallic Pressure Vessels

Owen R. Greulich and Maan H. Jawad

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Owen R. Greulich
Consultant

Maan H. Jawad
Global Engineering & Technology, LLC

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To our wives

Cathy Greulich

Dixie Jawad

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Preface

Pressure vessels are fabricated in thousands of facilities throughout the world. The fabrication processes differ from company to company, and even from plant to plant for the same company. Even within the same plant, construction of similar vessels will at times be performed in different ways for a variety of reasons.

Some companies produce large quantities of the same or essentially duplicate vessels. They typically develop designs that lend themselves to high production rates, as well as specialized tooling and processes to optimize production of those designs.

Other manufacturers specialize in pressure vessels for a particular function, such as heat exchanger vessels, and design their processes, tooling, and facilities around the type of product produced.

Still other fabricators make a specialty of constructing unique vessels. For these organizations, nearly every product is different from every other, covering a range of sizes, configurations, thicknesses, and purposes. Their business often comes from research organizations or from businesses that use very limited numbers of vessels for special applications, which cannot typically be obtained off the shelf. While using many of the same tools and machines as other manufacturers, fabrication of each vessel is planned as an individual project.

The volume of information that engineers need to absorb to work in the current environment has increased, and at the same time the opportunities for experience in manufacturing environments have in many cases decreased. The authors of this book, recognizing a dearth of readily available information in the field, felt that it would be useful to share their long experience in pressure vessel fabrication with a consolidated reference in this area.

The topics in this book cover various processes required in the fabrication of process equipment. This material will give the reader a broad understanding of the steps required in fabricating pressure vessels and includes such topics as cutting, forming, welding, machining, and testing. Each chapter presents a specific fabrication step and details its characteristics and requirements. Equations, charts, tables, figures, and other aids are presented, where appropriate, to help the reader implement the requirements in actual fabrication. Additional data is presented in the appendices at the end of the book as an aid to the user.

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Many of the weld symbols in the book were obtained courtesy of the American Welding Society with the help of Peter Potela. Photographs of weld equipment were supplied by CB&I Storage Solutions with the help of Koray Kuscu and Dale Swanson. A photo of a pipe beveler was supplied by E. W. Wachs with the help of Keith Polifka.

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1
Introduction

1.1 Introduction

The fabrication of process equipment involves a straightforward but complex sequence of operations that is developed and refined by industry or by individual manufacturers over the years. Each successful manufacturer of such equipment will have its own ways of working and will differ from others in the details of how processes are performed and level at which documentation becomes formalized, but the essential elements remain the same.

Some fabricators of process equipment have a standard product line, either available off the shelf or made to order. Those that do not have a product line and that bid for individual jobs within their field(s) of expertise are referred to as job shops or custom fabricators. Whether fabricating a piece of equipment on a job shop basis or producing a standard product, the organization must develop a design, procure or produce the component parts, and assemble them, all the while ensuring quality and maintaining quality assurance documentation.

1.2 Fabrication Sequence

To provide a background for the remaining chapters, which delve into the details of each aspect of pressure vessel fabrication, consider a large pressure vessel for a process application. The fabrication process flow proceeds as follows:

The pressure vessel manufacturer receives a request for quotation from the procurement organization for a petro-chemical plant. A job file will be created and a project engineer or estimator will be assigned.

If the design of the pressure vessel is fully defined by the purchaser, including all dimensions, materials, interfaces, etc., then the bidding process will be straightforward. However, if just interfaces and process requirements are provided, then this will allow the fabricator leeway to use its particular experience, efficiency, or capability. Either way a job file will be created to document what is required and what has been accomplished. This allows keeping track of preliminary analyses, decisions, and details, and it ensures that work and research such as sourcing of unusual components done at the bidding stage does not have to be repeated if the company is successful in getting the job.

More sophisticated customers, such as oil refineries and larger chemical companies, may provide a fairly refined design and will often have their own design specification. Such company

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specifications usually include requirements that may increase the cost of fabrication over that of a minimal design. The further details are usually based on company experience indicating that long term overall costs are reduced by the additional requirements. Others will leave much of the design to the fabricator, just defining interfaces and process requirements such as temperature, pressure, volume and envelope dimensions, and chemical compatibilities. Or they may provide the design of a vessel that is being replaced but still allow some design and fabrication flexibility for the new vessel.

If only limited design information is received, then a preliminary design must be roughed out to produce a cost estimate. Even if the design is fully defined, the fabricator will still need to resolve items including many of the weld details, weld processes, and things such as whether a nozzle is fabricated using a pipe and a flange or a long welding neck (LWN) flange. Not every detail needs to be worked out at this stage, but there needs to be sufficient resolution of the design that a reasonable cost estimate can be produced. Accuracy should be precise enough that the company can be confident of making a profit on the job and at the same time be competitive on price and delivery. Extra time invested at this point can often find ways to keep overall fabrication costs down, resulting in a higher bid success rate and helping ensure that no unpleasant surprises occur after receipt of a contract.

This book will not address the details of developing a bid on process equipment except to note that accurate bidding involves a thorough understanding of what it takes to produce the required equipment, and enough clarity in the estimate to ensure that all aspects of the effort are covered. Fabricators with standard products may use sophisticated internal estimating programs to develop pricing information. Other fabricators rely on the background and experience of their estimators to put together material and labor costs for each and every job, and some use standard industry programs to assist.

Once the order is actually received, the design and process flow will be finalized and a quality assurance package begun.

If not already accomplished at the bid stage, trade-offs will be assessed, such as stronger material or additional inspection such as radiography or ultrasonic testing to allow increased joint efficiency to reduce vessel wall thickness. This can reduce total material weight and the amount of welding required. Some parts of the design may be decided based on shorter lead times for one option than for another. Some are based on the particular equipment and capabilities available within the company. Others are based simply on cost. After all aspects of the design have been defined, a detailed material list will be produced. This may be done using in-house or specialized industry software, or it may be done by hand. Any material not available from stock must be procured, and process flow may be adjusted accordingly.

It is usual to identify long lead time items and contract for them immediately. Typically, these include heads (if not made in-house), special valves, filters, and forgings, any mill orders, anything made of exotic materials, and anything else that was identified during the bid stage as requiring extra time. Some custom manufacturers may stockpile such items as exotic materials and exotic weld supplies in anticipation of future orders to minimize lead time and get an edge over their competitors.

Weld procedures may be developed at this time if they are not available, as coupons can then be produced and tested in parallel with the wait for materials and components without extending the overall schedule.

Also, at this time quality assurance personnel develop plans for the required inspections, tests, and hold points that will take place throughout fabrication. This will include a number of dimensional inspections, verification that reported test results are compliant with applicable requirements, verification of process control of welding and other processes, and review of radiographs and other nondestructive examination (NDE) results. Review by the Authorized Inspector will be included if the work involves an ASME code stamp, which for a pressure vessel it almost certainly does.

Additionally, this is when the layout department is likely to become involved. The layout department personnel have a thorough understanding of geometry, trigonometry, fabrication, and some of the behavioral characteristics of materials while they are being fabricated. They are trained in how to lay out intersections of such items as pipe or cone sections with heads or shells. The layout department will plan for efficient use of materials, produce detailed layouts for the heads and shell sections, mark locations and contour cutouts for nozzle installations, etc. The first part of this effort takes place in the flat, when shell sizes and weld bevels are prepared. Other parts occur throughout fabrication. Shell layout will include allowance for weld shrinkage.

As the material arrives, it will go through a receiving inspection and be checked for compliance with specifications, with material mill test reports and other documentation placed in the quality assurance file. Early arrivals are often stockpiled but segregated from non-code materials that have not gone through quality assurance acceptance until enough components are available to begin work and continue through the flow without unnecessary starts and stops. Even if shell plates are available from stock, it is usual to postpone cutting them until the heads arrive so that actual head dimensions can be measured, or to request a "taping" (a measurement of the circumference) from the head manufacturer prior to shipping. This allows the shell diameter to be adjusted if needed, from its nominal dimension to permit an optimal fit to the heads. This slight adjustment to the shell circumference is often necessary since it is difficult to bring the head circumference to a precise dimension during forming due to the three-dimensional nature of the head. The difference is usually fairly insignificant, but even an eighth of an inch (3.2 mm) of diameter can make fit up and welding more, or less, efficient.

The shell sections are rolled subsequent to cutting to size and beveling for welds. Their longitudinal joints (straight seams) will be tacked into alignment, and then welded. The heat and stresses of welding will cause a certain amount of shrinkage and distortion. This may be, to some extent, controlled by alternating weld passes on the inside and outside of the weld. However, if distortion is excessive after welding, the shells will be reworked with hydraulic rams or will be re-rolled to bring them back within tolerance. Working from the zero point on each shell course, nozzles and other appurtenances will be laid out full scale on the plates, with indications as to weld preps as needed.

The *fitter* assembles the shell courses, referred to as "courses" or "cans," to each other and to the heads. Circumferential shell welds are usually welded on positioning rolls to allow welding to be performed in the flat position, which is the preferred position because it is the easiest orientation for producing high volumes of high-quality weld. Next, nozzles will be fabricated, and reinforcing pads laid out, cut, and formed, then fit in place and welded, either preceded or followed by fitting and welding of supports.

Note that while this description looks simple, the work involves a high level of training and skill on the part of the layer out, fitter, and welder. The fitter has the job of fitting and tacking together the assembly within fairly tight tolerances and the welder must be able to produce hundreds of feet of weld with the least amount of rejectable indications.

Nozzles, for example, must be laid out and then fit accurately in the holes cut in the shell sections, correctly oriented, with the proper projection, and with bolt patterns on the flanges in the correct orientation. This is essential in order they fit correctly with piping that may already exist in the field or that may be assembled elsewhere. The fitter will typically install "spiders" and other braces to minimize distortion such as shells going out of round or nozzles sinking excessively during welding. The welder also has a part, controlling his welding within the parameters of the Welding Procedure Specification, in accordance with which he has already demonstrated the ability to produce top quality welds. The welder also maintains preheat and interpass temperatures and speed of progression, and makes in process adjustments as his experience dictates to maximize productivity, avoid weld defects, and control distortion.

After welding is completed, the welds will be inspected. Common inspection methods include the following:

1) Visual.
2) Magnetic particle for ferromagnetic materials such as steel.
3) Dye penetrant for either magnetic or nonmagnetic materials.
4) Dimensional inspections.
5) Radiography.
6) Ultrasonic examination.

It is usual to do these inspections before any required post weld heat treatment (PWHT), even if they are required after PWHT as well, so that any needed repairs can be completed prior to final heat treatment. This is because repair of a defect found after PWHT will normally require repair and an additional heat treatment. Such additional heat treatment can be costly as well as have the potential to reduce material mechanical properties.

After PWHT and required final NDE, any final machining that is needed takes place. Intermediate machining processes may already have taken place if thick welds require J-grooves or if unique machining is required because of special configurations. Also, for vessels such as heat exchangers requiring tubesheets or other special components, machining of these tubesheets and components is accomplished in parallel with other work on the vessel.

Next, the vessel will be pressure tested when inspections and NDE demonstrate compliance with all requirements. Pressure testing is done either by a hydrostatic test, which is preferred for safety reasons, or by a pneumatic test. Although failures are not anticipated, access is usually restricted during such tests due to the potentially high levels of stored energy. This is especially true during pneumatic tests, but even though water is considered an incompressible fluid, the energy stored by compression of water or other liquid and any trapped air and the stretch of the metallic shell can result in a significant hazard during such tests.

Once the pressure test is completed and all other quality requirements are verified, the vessel is ready for final cleaning and application of any required paint, conversion finishes, anodizing, or other surface treatments. A name plate describing various vessel parameters is then attached to the vessel, indicating compliance with the applicable code and other requirements.

Finally, with fabrication, inspection, NDE, and testing completion, and coatings applied, the pressure vessel is readied for shipment. Shipment may include low level pressurization with a clean, dry, inert gas, sometimes referred to as "pad pressure." It is used to ensure that nothing is sucked into the vessel on cold days and to prevent condensation. Shipment also includes blocking or cribbing, special supports, possible packaging, and tie-down on the truck, railcar or barge for shipping.

Once the product arrives at the customer's facility, it will often undergo further inspection to ensure that all of the requirements have been met and that there has been no damage during shipping. The Quality Assurance package, when supplied, will be reviewed in detail and placed on file. Only then can the vessel be installed and put into service.

1.3 Cost Considerations

The cost of a pressure vessel is a function of many parameters. In areas where labor is costly, it is often the biggest single factor, but many decisions by both the designer and fabricator influence overall cost. The most effective design from a cost standpoint will be one in which schedule, cost and availability of materials, cost and capability of labor, inspection options, and available equipment and tooling are all considered. In addition, short versus long term product cost considerations may need to be discussed with the customer.

It follows that the designer will either have some experience in all of these areas or will work closely with people who do. Similarly, the shop management will be familiar with a wide range of production techniques, including means of cutting and machining, forming, fixturing and fit up, welding, heat treatment, inspection and testing, cleaning, painting and other surface treatments, and packaging and shipping options and requirements.

If large numbers of vessels of the same or similar designs are fabricated, design and fabrication choices will be different from those involving fabrication of a single unit.

The particular capabilities of a vessel fabricator often make one variation of a design more cost effective than another, and if the designer is not directly associated with the fabricator, it makes sense for these two parties to discuss design options with an eye on cost reduction.

This book is not about fabrication cost estimating, and this chapter does not address actual product cost. It, however, addresses a number of considerations affecting the cost of an overall pressure vessel fabrication to help the user, designer, and fabricator make judicious choices regarding design and fabrication approaches.

1.3.1 Types of costs

For a business, one way of dividing costs is to separate them into either capital or operating costs. Capital costs are the one-time expenses such as purchase of land, construction of a plant, and major equipment purchases that are expected to last a long time. A small hand grinder, for example, would not be considered a capital cost, while the costs of constructing a building or purchasing a large forge would be. Operating costs are the other costs of being in business, including wages and salaries, real estate expenses (rent, taxes, etc.), materials, furniture, consumables, maintenance, etc.

This way of looking at expenses is useful in understanding what things cost overall, and it might be enough for a company with a single product line. For calculating and controlling costs of production of individual products in a job shop, it is usually easiest to work with burdened labor rates that represent the hourly cost of performing an operation, plus material and other direct costs of a particular job, plus capital costs. The burdened labor cost includes such items as direct wages, cost of vacations and holidays, social security and other tax cost, sick leave, and pension or 401k plans.

Some companies use a single rate for essentially all personnel whose time is charged to a job, while others charge a rate that varies by function or even by the individual assigned to the job. Sometimes costs are broken down further to identify and charge for specific assets outside of the burdened labor rate. This is most likely to occur in a case in which an asset of particularly high value is used only on some jobs. In such a case, dividing its cost among all jobs would subsidize those jobs that require this equipment at the expense of those that don't. The result would be extremely competitive prices on the jobs requiring this equipment, but a lack of competitiveness on those that don't need it.

Companies arrive at burdened labor and equipment rates in different ways, but the intent is to allocate costs in a way that allows bidding jobs, recovering costs, and making a reasonable profit. Because the fabrication environment is competitive, it is important to understand enough about the individual cost elements that (1) wise trade-offs between design approaches can be made to ensure competitiveness, and (2) accurate total cost of a particular fabrication can be identified for pricing purposes and to ensure a reasonable profit.

1.3.2 Design choices

1.3.2.1 Major cost decisions – long term choices

Some design choices must typically involve the customer because they involve significant product cost differences that can only be amortized over the long run. An example of this occurs with a vessel that will contain a corrosive medium. In this case, material choices may make a significant difference in short term vessel costs. A vessel might be fabricated with a corrosion allowance, anticipating that at the end of some term (approximately five years, for example) the vessel will simple be replaced. Another approach would be to fabricate it entirely of a material that does not undergo corrosion in its particular internal and external environments, or to clad it with such a corrosion-resistant material. The cost of fabricating a pressure vessel of high alloy steel or other material may be significantly greater – perhaps double or more – than that of a fabrication using steel. If a more expensive product allows essentially unlimited life versus five years for the steel pressure vessel, then amortizing the cost of the single vessel versus initial vessel purchase plus replacements, and downtime and labor for the replacement, can make the farsighted decision attractive. Whichever way this decision goes, all other cost issues still apply.

1.3.2.2 Labor–material trade-offs

Some choices regarding materials simply minimize material costs. Others have the additional advantage of reducing labor. A third category reduces costs by eliminating whole operations. A fourth category is to increase labor in situations where labor cost is minimal and material cost can be reduced without a comparable increase in cost of labor.

1.3.2.3 Selecting a less expensive material

Cost reduction by minimizing material cost is represented by a situation in which two different metal alloys of different costs (per unit weight) result in the same wall thickness. This occurs when either the wall is fixed (for example, when a minimum wall is required for handling or for stiffness reasons), or when rounding from the required minimum wall to the next stock thickness results in the same fabricated thickness for both. If there is no other operational reason to use a more expensive material (SA 516-70, for example, rather than SA-36), then the obvious choice is a less expensive one.

1.3.2.4 Selection of a material with a higher allowable stress

In a given class of materials, using one with a higher allowable stress is beneficial in pressure vessels with high pressures and larger diameters. For example, use of SA 516-70 rather than SA 285C reduces wall thickness. The cost of material may remain about the same, since SA 516-70 is more expensive per pound than SA 285C, a fact somewhat balanced by the lesser amount of material used. The reduction in wall thickness reduces cost in multiple ways, however. The time needed for rolling the vessel shell and forming the heads is less. The thickness of welds and therefore weld volume and welding time are diminished. Handling costs may be less. And depending on the fluid medium, the reduction in vessel weight might lead to smaller or thinner supports or saddles.

1.3.2.5 Component selection to eliminate operations

Design changes to eliminate whole operations are options to be considered. This category includes selection of vessel diameter to coincide with standard pipe sizes and the use of integrally reinforced designs. Figure 1.1 shows a detail of a hemispherical head where additional material on the outside is left in place to minimize machining cost.

If a shop rolled and welded vessel shell or nozzle can be replaced by a piece of off-the-shelf pipe, whether seamless or welded, then the costs for layout, crimp, and individually rolling that shell are all included in the pipe cost, which is typically produced in a dedicated facility that only produces pipe, but does it very efficiently. When this can be done, the material cost of the completed shell section is often little more than the material cost of the unrolled shell plate. A further benefit is that standard caps may then be available for use as vessel heads. These, too, being mass produced, will likely be significantly less expensive that custom-formed heads.

When nozzles beyond a certain size penetrate a vessel wall, reinforcement is required to take the pressure loads that would otherwise have been transmitted through the material cut from the shell or head for placement of the nozzle. The ASME code puts limits on what material may be counted as contributing to this load carrying capability. Simple area replacement is typically used, provided that the reinforcing material is of strength equal to or greater than that of the material it is replacing. There are numerous ways of providing this material. Because the code allows essentially any material within a certain distance to be counted, any excess material in the shell itself, the nozzle wall, the weld, added reinforcing pads, or shell inserts, may be considered.

The best means of providing reinforcing beyond that inherent in the design is often fairly obvious, but in some cases a cost estimate for more than one approach may be needed to evaluate the trade-off.

If a vessel has a limited number of penetrations requiring reinforcement, accepting the labor and material cost of providing reinforcement on a few nozzles may be inexpensive compared to providing a heavier shell that results in an integrally reinforced design. When a vessel has many nozzle

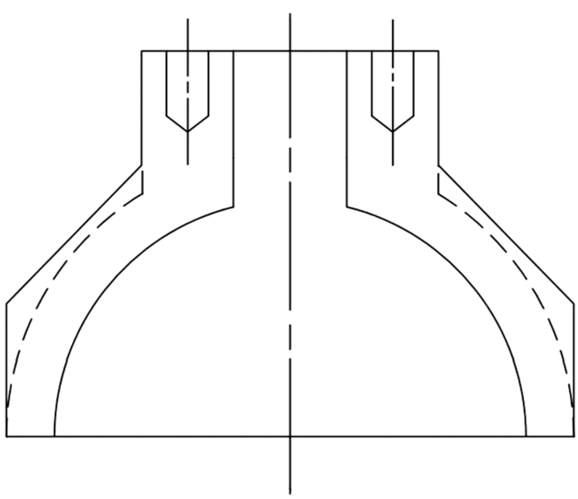

Figure 1.1 Outside machining of a hemispherical head

penetrations requiring reinforcement, however, the labor associated with providing that reinforcement may far exceed the additional cost of a heavier shell wall and thicker shell and nozzle to shell welds. If most or all of the nozzles requiring reinforcement are located in the same area, it may make sense to make one shell course thicker than the others to provide integral reinforcement.

Another way of providing additional nozzle reinforcement when a flanged nozzle is required is the use of LWN flanges. If the nozzle protrusion is not excessive, then unless the cost of labor is extremely low or the cost of material extremely high (e.g., high nickel materials for their corrosion resistance or high temperature strength), it will almost always be more economical to use an LWN flange than to add a reinforcing pad. The neck of an LWN flange normally has an outside diameter equal to the hub diameter of a slip-on flange, and it may be ordered in a variety of lengths. Thus, particularly if it is acceptable to allow the nozzle to protrude into the vessel, an LWN flange can almost always fulfill the need for additional reinforcement. While the cost of an LWN flange is significantly greater than that of either a slip-on or a welding neck flange, it has the advantage of eliminating the following costs: flange to nozzle weld, reinforcing (or insert) plate, reinforcing or insert plate layout, forming of reinforcing plate, drilling and tapping of reinforcing plate vent hole, fit up of reinforcing plate, and welding of reinforcing plate both to the shell and to the nozzle.

1.3.2.6 Enhanced inspection for higher joint efficiency

Enhanced inspection to increase joint efficiency can result in a significant reduction in wall thickness on a heavy wall vessel. This, in some cases, sufficiently reduces the wall thickness to allow the use of the next smaller stock thickness, thereby reducing material and other fabrication costs. When inspection has not been performed to allow 100% joint efficiency of shell longitudinal or head welds, however, then locating shell longitudinal or head welds so that welds aren't included in zones used for reinforcement may, in some cases, be enough to eliminate the need for extra reinforcement, since the excess material in the shell can be counted based on the 100% joint efficiency of the parent material.

Major considerations in deciding whether to perform inspections to reduce other costs include the cost of the inspection, the anticipated labor and material cost savings, and the level of confidence that the welds will pass inspection the first time. If inspection shows that weld repairs are required, all savings in labor and material may be wiped out by the cost of repairs and reinspection, resulting in no benefit to the fabricator and a loss in terms of schedule, and tolerances may be affected as well.

Example 1.1 This example illustrates an actual vessel for which the design approach eliminated a large number of operations as well as fabrication risk by using a much heavier wall than originally specified.

The heavy wall vessel shown in Figure 1.2 is 16 ft long, 30 in. diameter, 4 in. nominal wall, with flat bolted heads, 88 total penetrations, and the full shell length machined inside. Figure 1.3 shows the side views of the same vessel. The vessel might have been fabricated of much thinner material, but was fabricated this way to reduce cost.

The vessel was originally designed using a 1-3/4 in. thick shell with a number of heavier shell plate inserts with blind drilled and tapped holes for attaching instrumentation. The original design also had an added heavy section at each end with drilled and tapped holes for installation of cover flanges. The fabricator evaluated four approaches before making a proposal. Each approach included the large nozzles welded into fabricated shell sections. The four approaches were (1) as designed originally; (2) a centrifugal casting with flats machined and drilled and tapped for small