CHAPTER TWO

THEORETICAL BACKGROUND

2-1: History of Pressure Vessels

Numerous boiler explosions took place through the late 1800s and early 1900s. This led to the enactmentof the first code for construction of steam boilers bythe Commonwealth of Massachusetts in 1907. Thissubsequently resulted in the development andpublication of the ASME Boiler and Pressure VesselCode in 1914, which sought to standardize thedesign, manufacturing, and inspection of boilers andpressure vessels. In 1921 the National Board ofBoiler and Pressure Vessel Inspectors was organizedto promote consistent inspection and testing. Thepublication of the section on locomotive boilers alsoappeared in 1921. The ASME (AMERICAN SOCIETY OF MECHANICAL ENGINEERS) and theASTM (AMERICAN SOCIETY FOR TESTING AND MATERIALS)material specification merged in 1924. The firstpublication of Section VIII ‘‘Unfired PressureVessels,’’ appeared in 1925. This document wasreferred to as one of a theoretical factor of safety of5. The petroleum industry did not consider it to beadequate for their purposes and also desired betterutilization of available materials. The year 1928 sawthe advent of welded pressure vessels. For higherpressures the welded shells were made thicker than70 mm. These required non-destructive examination(NDE) before service. In 1934, a joint API–ASMECommittee published the first edition of an unfiredpressure vessel code specifically for the petroleumindustry. In 1952 these two separate codes mergedinto a single code – the ASME Unfired

PressureVessel Code, Section VIII. The ASME PressureVessel Code, Section VIII Division 2: ‘‘AlternativeRules for Pressure Vessels,’’ was published in 1968 and the original code became Section VIII Division 1: ‘‘Pressure Vessels.’’ A considerable boost was provided to the understanding of the basic behaviour of pressure vessel components following the development of the nuclear power program in the U.S. and Europe in the late 1950s and early 1960s.

Similar developments can be found in the British, French, German and Japanese codes, to name but a few. By 1960 the need for a code for pressure vessels for commercial nuclear plants became imperative.
This resulted in publication of the 1963 Edition, Section III: ‘‘Nuclear Pressure Vessels.’’ This was a design by analysis code with a theoretical safety factor of 3. After the publication of Section III: ‘‘Nuclear Pressure Vessels’’ in 1963, it was necessary to modify Section VIII for general pressure vessels. ASME Code Section VIII Division 2: ‘‘Alternate Rules for Pressure Vessels’’ appeared as a result and provided a theoretical factor of safety of 3.

In 1971, Section III: ‘‘Nuclear Power Components’’ were classified as (a) pumps, (b) valves, and (c) piping. The stress limits for emergency and faulted conditions were introduced. In addition, the addenda of 1971 added storage tanks. The addenda of summer 1972 introduced Appendix G on non-ductile failure.
The Appendix F On evaluation of faulted conditions was included in the addenda of winter 1972. The design of component supports and core support structures appeared in the addenda of winter 1973. [7, 8]

2-2: ASME Code Contents

ASME Section III Division 1 is devoted entirely to nuclear power components and also contains the rules for the design of nuclear pumps and valves. The recognition of concrete reactor and containment vessels led to the publication of the Section II Division 2 code in 1975. Three subsections (NB, NC and ND) of ASME Section III Division 1 cover the design and construction of equipment of Classes 1, 2, and 3, respectively. The most stringent is Class 1, which requires design by analysis. Class 2 permits design by analysis as well as the use of formulas. Class 3 prescribes design by formula, and is equivalent to Section VIII Division 1. The designer evaluates the safety function of each pressure vessel and applies the appropriate code class. Design of supports for Section III Division 1 vessels are not prescribed in the ASME Code. Section III has a subsection NF, which prescribes the design of supports for Class 1, 2 and 3 pressure vessels. The addenda of winter 1976 changed the nomenclature of design, normal, upset, testing and faulted conditions to level A, B, C and D service conditions. In the 1982 addenda, the fatigue curves were extended to 1011 cycles. In the 1996 addenda, the design rules for high-temperature service were incorporated.

In 1976Division 3 was published which contained rules on transport of irradiated materials. The need for uniform rules for in-service inspection of nuclear power plants led to the issuance of the 1970 edition of Section XI: ‘‘Rules for In-service Inspection of Nuclear Plant Components.’’ The organization of the ASME Boiler and Pressure Vessel Code is as follows: [1, 2, 3, and 6]

1. Section I: Power Boilers.
2. Section II: Material Specification:

   i. Ferrous Material Specifications – Part A.
   ii. Non-ferrous Material Specifications – Part B.
   iii. Specifications for Welding Rods, Electrodes, and Filler Metals –Part C.
   iv. Properties – Part D.
3. Section III Subsection NCA: General Requirements for Division 1 and Division 2
   i. Section III Division 1:
      a. Subsection NA: General Requirements.
      b. Subsection NB: Class 1 Components.
      c. Subsection NC: Class 2 Components.
      d. Subsection ND: Class 3 Components.
      e. Subsection NE: Class MC Components.
      f. Subsection NF: Component Supports.
      g. Subsection NG: Core Support Structures.
      h. Appendices: Code Case N-47 Class 1: Components in Elevated Temperature Service.
   ii. Section III, Division 2: Codes for Concrete Reactor Vessel and Containment.
4. Section IV: Rules for Construction of Heating Boilers.
5. Section V: Non-destructive Examinations.
6. Section VI: Recommended Rules for the Care and Operation of Heating Boilers.
7. Section VII: Recommended Guidelines for Care of Power Boilers.
8. Section VIII:
   i. Division 1: Pressure Vessels – Rules for Construction.
   ii. Division 2: Pressure Vessels – Alternative Rules.

9. Section IX: Welding and Brazing Qualifications.
10. Section X: Fiberglass-Reinforced Plastic Pressure Vessels.
11. Section XI: Rules for In-Service Inspection of Nuclear Power Plant Components.

The rules for design, fabrication and inspection of pressure vessels are provided by codes that have been developed by industry and government in various countries. The design and construction codes all have established rules of safety governing design, fabrication and inspection of boilers, pressure vessels and nuclear components. These codes are intended to provide reasonable protection of life and property and also provide for margin for deterioration in service. Table 2-1 also includes the ASME Boiler and Pressure Vessel Code. Some of the significant features of the latest version of the ASME Code Section III are:

- Explicit consideration of thermal stress
- Recognition of fatigue as a possible mode of failure
- The use of plastic limit analysis
- Reliable prediction of ductile failure after some plastic action.

2-3: Role of Finite Element in Pressure Vessel Design

There is a continuous attempt to understand all failure modes, and provide rational margins of safety against each type of failure. These margins are generally consistent with the consequence of the specific mode of failure. A word or two about the impact of technological advances in pressure vessel design should be mentioned. The last three decades have seen great strides made in the improvement of digital computations. In the 1960s the use of computers began to make an impact on design and analysis of Pressure vessels.

Table 2-1: Design & Construction Codes for Pressure Vessels [8]

Country	Code	Issuing authority
U.S.	ASMEBoiler&Pressure Vessel Code	ASME
U.K.	BS1515Fusion Welded Pressure Vessels BS5500Unfired Fusion WeldedPressureVessels	British Standard Institute
Germany	AD Merblatter	ArbeitsgemeinschaftDruckbehalter
Italy	ANCC	AssociazioneNationalePerIlControllo Peula Combustione
Netherlands	Regeis Voor Toestellen	Dienst voor het Stoomvezen
Sweden	Tryckkarlskommissionen	SwedishPressure Vessel Commission
Australia	AS1200:SAABoilerCode AS1210Unfired Pressure Vessels	Standards Association of Australia
Belgium	IBNConstructionCode for Pressure Vessels	Belgian Standards Institute
Japan	MITI Code	Ministry of International Trade and Industry
France	SNCTConstruction Code for Unfired Pressure	Syndicat National de la Chaudronnerie et de la Tuyauterie Industrielle

The rapid development of finite-element software has remarkably impacted the detailed design of pressure vessel components. These developments along with continuing increase in computing speed and storage capacity of the computer have really made the design process extremely quick and at the same time have led to very accurate design assessment. Initially in the early to mid-1970s, detailed finite-element analyses were generally performed for confirmatory analyses.

Today these tasks are routinely accomplished in an interactive mode. The three dimensional finite element analysis programs using solid elements are rapidly replacing plate, shell, and two-dimensional programs for routine structural design analysis of pressure vessels. In addition the concepts of computer-aided design (CAD) and computer-aided manufacturing (CAM) are being integrated.

2-4:Safety Aspects

In spite of some of the most rigorous, well-conceived safety rules and procedures ever put together, boiler and pressure vessel accidents continue to occur. In 1980, for example, the National Board of Boiler and Pressure Vessel Inspectors reported 1972 boiler and pressure vessel accidents, 108 injuries and 22 deaths. The pressure vessel explosions are of course rare nowadays and are often caused by incorrect operation or poorly monitored corrosion.

The design and construction cures are dependent upon the formulation and adoption of good construction and installation codes and standards.

Thus the ASME Pressure Vessel Code requires that all pressure vessels be designed for the most severe coincident pressure and temperature expected during the intended service. There can be no deviation from this requirement, even if the severe condition is short term and occurring only occasionally. Bush has presented statistics of pressure vessels and piping failures in the U.S., Germany and the UK.3 He has concluded that a 99 percent confidence upper boundary for the probability of disruptive failure to be less than 1 _ 10–5 per vessel year in the U.S. and Germany. According to his study, periodic inspection is believed to be a significant factor in enhancing pressure vessel reliability, and successful applications of ASME Boiler and Pressure Vessel Codes (Sections I and VIII) are responsible for the relatively low incidence of non-critical failures early in life. Pierre and Bayle authored an international perspective of the design of pressure vessels in 1924.

Section VIII – Pressure Vessels Division 1 provides requirements applicable to the design, fabrication, inspection, testing, and certification of pressure vessels operating at either internal or external pressures exceeding 15 psig. Such vessels may be fired or unfired. This pressure may be obtained from an external source or by the application of heat from a direct or indirect source, or any combination thereof. Specific requirements apply to several classes of material used in pressure vessel construction, and also to fabrication methods such as welding, forging and brazing.

Division 1 contains mandatory and non-mandatory appendices detailing supplementary design criteria, non-destructive examination and inspection acceptance standards. Rules pertaining to the use of the single ASME certification mark with the U, UM and UV designators are also included.

Division 2 requirements on materials, design, and non-destructive examination are more rigorous than in Division 1; however, higher design stress intensify values are permitted. These rules may also apply to human occupancy pressure vessels typically in the diving industry.

Rules pertaining to the use of the single ASME certification mark with the U2 and UV designators are also included.

Division 3 requirements are applicable to pressure vessels operating at either internal or external pressures generally above 10,000 psi. It does not establish maximum pressure limits for Section VIII, Divisions 1 or 2, or minimum pressure limits for this Division. Rules pertaining to the use of the single ASME certification mark with the U3 and UV3 designator are also included. [4]

2-5: General Description of Pressure Vessel Design Code [1]

2-5-1: UG-1 Scope

UG is a part of ASME code which describes the design of pressure vessel. The requirements of part UG are applicable to all pressure vessels and vessel parts and shall be used in conjunction with the specific requirements in subsections B and C and the Mandatory Appendices that pertain to the method of fabrication and the material used.

2-5-2: UG-4 General Materials

When specifications, grades, classes, and types are referenced, and material specification in Section-2, part A or Part B is a dual-unit specification (e.g., SA- 516/SA-516M), the design values and rules shall be applicable to either the U.S. Customary version of the material specification or the SI unit version of the material specification. For e.g. when SA-516M Grade 485 is used in construction, the design values listed for its equivalent, SA-516 Grade 70, in either the U.S. Customary of metric section-2, Part D (as appropriate) shall be used.

2-5-3: UG-27 (C) Cylindrical Shells

The minimum thickness for maximum Allowable working pressure of one-half cylindrical shells shall be the greater thickness of lesser pressure as given by:

i. Circumferential stress (Longitudinal joints); When the thickness does not exceed one-half of the inside radius, or p does not exceed 1.25SE.
ii. Longitudinal stress (Circumferential joints) When the thickness does not exceed one-half of the inside radius, or P does not exceed 1.25SE.

2-5-4: UG-99 (b) Hydrostatic Test

Vessels designed for internal pressure shall be subjected to a hydrostatic test pressure which at every point in the vessel is at least equal to 1.3 times the maximum allowable working pressure to be marked on the vessel multiplied by the lowest ratio (for the material of which the vessel is constant) of the stress value S for the test temperature on the vessel to the test stress value S for the design temperature (see UG-21). All loadings that may excite during this test shall be given consideration.

2-5-5: UG-32 (F) Ellipsoidal Heads

The required thickness of a dished head of semi ellipsoidal form, in which half of the minor axis (inside depth of the head minus the skirt) equals one-half of the inside diameter of the head skirt. An acceptable approximation of 2:1 ellipsoidal head is one with a knuckle radius 0.17D and a spherical radius of 0.90D.

2-5-6: UG-32 (F) Hemispherical Heads

When the thickness of a hemispherical head does not exceed 0.356L or P does not exceed 0.665SE.

2-5-7: UG 40 Limits Of Reinforcement

The limits of reinforcement, measured parallel to the vessel wall, shall be at a distance, on each side of the axis of the opening, equal to the greater of the following:

i. The diameter d of the finished opening.
ii. The radius of the finished opening plus the vessel wall thickness, plus the nozzle wall thickness.

2-5-8: UG-45 Nozzle Neck Thickness

i. **As per type UG-45(a):** the minimum wall thickness of a nozzle neck or the other connection (including access openings and opening for inspection) shall not be less than the thickness computed from the applicable loadings in UG-22 plus the thickness added for allowable for correction and threading, as applicable (see UG-31 C 2), on the connection.

ii. **UG-45(b):** Additionally, the minimum thickness of a nozzle neck of other connection (except for access opening and openings for inspection only) shall not be less than the smaller of the nozzle wall thickness as determined by the applicable rule in(b)(1) or (b)(3) below, and the wall thickness as determined by (b)(4) below.

iii. **UG-45(b)(1):** for vessels under internal pressure only, the thickness (plus correction allowance) required for pressure (assuming E=1.0) for shell or head at the location where the nozzle neck or other connection attaches to the vessel but in no case less than the minimum thickness specified for the material in UG-16(b)

iv. **UG-45(B)(2):** For vessels under external pressure only, the thickness (plus correction allowance) obtained by using the external design pressure as an equivalent internal design pressure (assuming E=1.0) in the formula for the shell or head at the location where the nozzle neck of other connection attaches to the vessel but in no case less the minimum thickness specified for the material in UG-16(b);

v. **UG-45 (b) (3):** for vessels designed for both internal and external pressure, the greater of the thickness determined by (b) (1) or (b)(2) above;

vi. **UG-45 (b) (4):** the minimum thickness of standard wall pipe plus the thickness added for correction allowance on the connection; for nozzles larger than the largest pipe size included in ASME B36, 10M, the wall thickness of that largest size plus the thickness added for correction allowance on the connection.

2-5-9: UG-16 (b) General Design

As per (b) of UG-16 (b) minimum thickness of pressure retaining components, The minimum thickness of shells and heads used in compressed air service, steam service, and water service, made from material listed in table UCS-23, shall be 3/32 in (2.5 mm) exclusive of any correction allowance.

2-5-10: UG-22 Loadings

As per type(c) Superimposed static reactions from weight of attached equipment, such as motors, machinery, other vessels, piping, linings, and insulations:

i. Internal.

ii. Vessel supports, such as lugs, rings, skirts, saddles, and legs.

2-6: Finite Element Method (FEM)

Fundamentals of Finite Element Analysis are intended to be the text for a senior level finite element course in engineering programs. The most appropriate major programs are civil engineering, engineering mechanics, and mechanical engineering. The finite element method is such a widely used analysis-and-design technique that it is essential that undergraduate engineering students have a basic knowledge of the theory and applications of the technique.

The finite element method (FEM), sometimes referred to as finite element analysis (FEA), is a computational technique used to obtain approximate solutions of boundary value problems in engineering. Simply stated, a boundary value problem is a mathematical problem in which one or more dependent variables must satisfy a differential equation everywhere within a known domain of independent variables and satisfy specific conditions on the boundary of the domain. Boundary value problems are also sometimes called field problems. The field is the domain of interest and most often represents a physical structure. The field variables are the dependent variables of interest governed by the differential equation. The boundary conditions are the specified values of the field variables (or related variables such as derivatives) on the boundaries of the field.

Depending on the type of physical problem being analysed, the field variables may include physical displacement, temperature, heat flux, and fluid velocity to name only a few. [9]

2-7: ANSYS

The ANSYS program has many finite element analysis capabilities, ranging from a simple, linear, static analysis to a complex, nonlinear, transient dynamic analysis and it also has branched into several packages or programs related to it and have their properties and use them in the work of analysis appropriate for each type. General procedure for Finite Element Analysis:

(1) Preprocessing.

(2) Solution.

(3) Post processing.

ANSYS Workbench is a new modern interface with more up to date functions, for example, the integration of CAD geometries. There are many modules in workbench such as static structural analysis, modal analysis (vibration analysis), thermal analysis etc. Atypical ANSYS analysis has three distinct steps:

i. Build the model.

ii. Apply loads and boundary conditions and obtain the solution.

iii. Review the results.