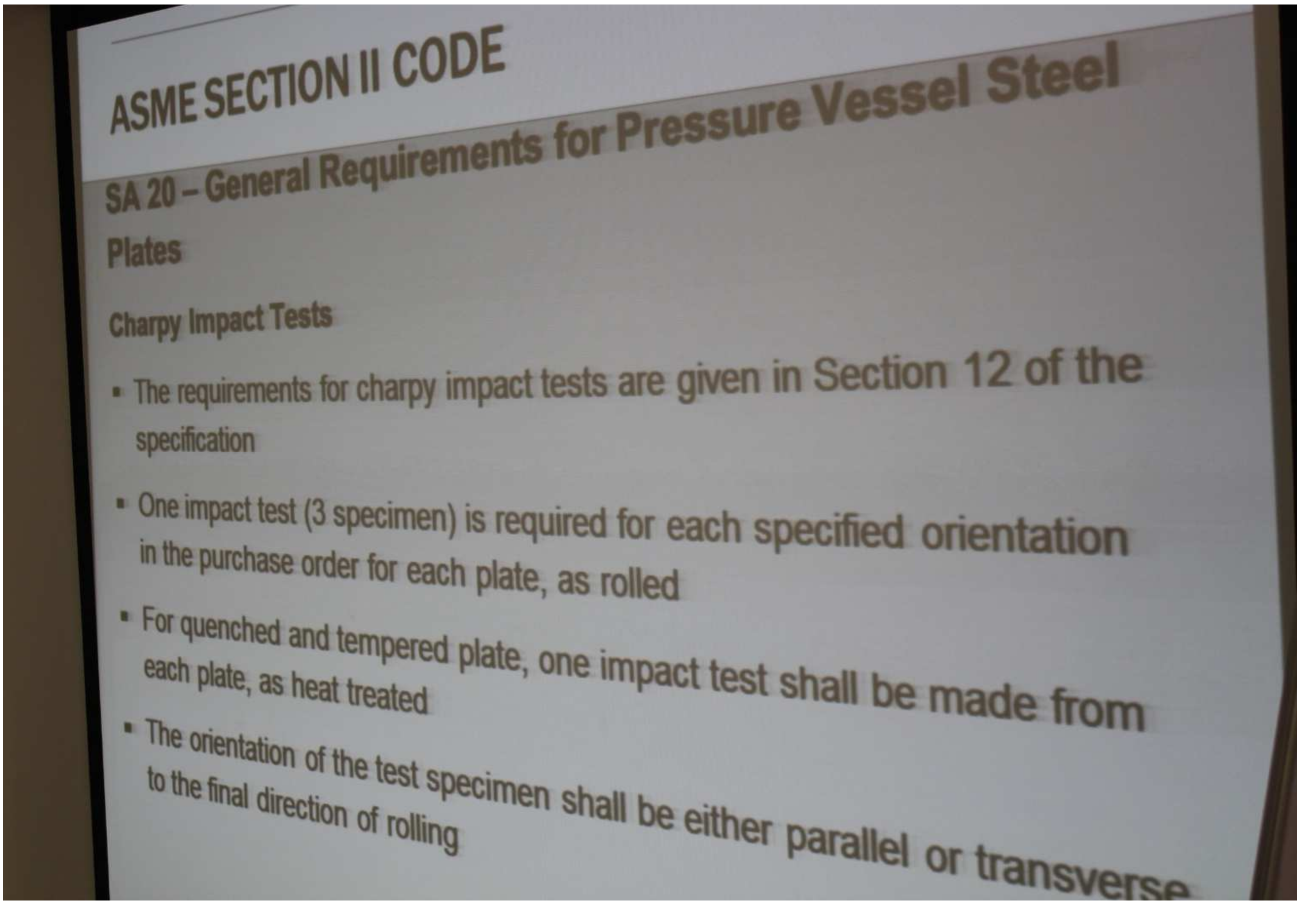
Pressure Vessel Newsletter

Volume 2015, October Issue



ASME SECTION II CODE

SA 20 – General Requirements for Pressure Vessel Steel Plates

Charpy Impact Tests

- The requirements for charpy impact tests are given in Section 12 of the specification
- One impact test (3 specimen) is required for each specified orientation in the purchase order for each plate, as rolled
- For quenched and tempered plate, one impact test shall be made from each plate, as heat treated
- The orientation of the test specimen shall be either parallel or transverse to the final direction of rolling

IN ASSOCIATION WITH

INTERGRAPH®

Serving the Pressure Vessel Community Since 2007

From The Editor's Desk:

[*This article is taken from August 23 issue of Houston Chronicle and edited for space. It was written by Alice Adams – Jobs Correspondent. The information here is applicable to US market.*]

The table below provides the projected employment growth and salaries in the engineering field as provided by the Bureau of Labor Statistics. These statistics are for mining and geological engineering, nuclear engineering, petroleum engineering, chemical engineering, environmental engineering, civil engineering, industrial engineering and mechanical engineering. Employment in many of these disciplines is affected by various factors.

Nuclear Engineering: Employment in nuclear power plants will be favorable because of safety upgrades.

Petroleum Engineering: Oil prices are a major determinant of employment growth and should be watched.

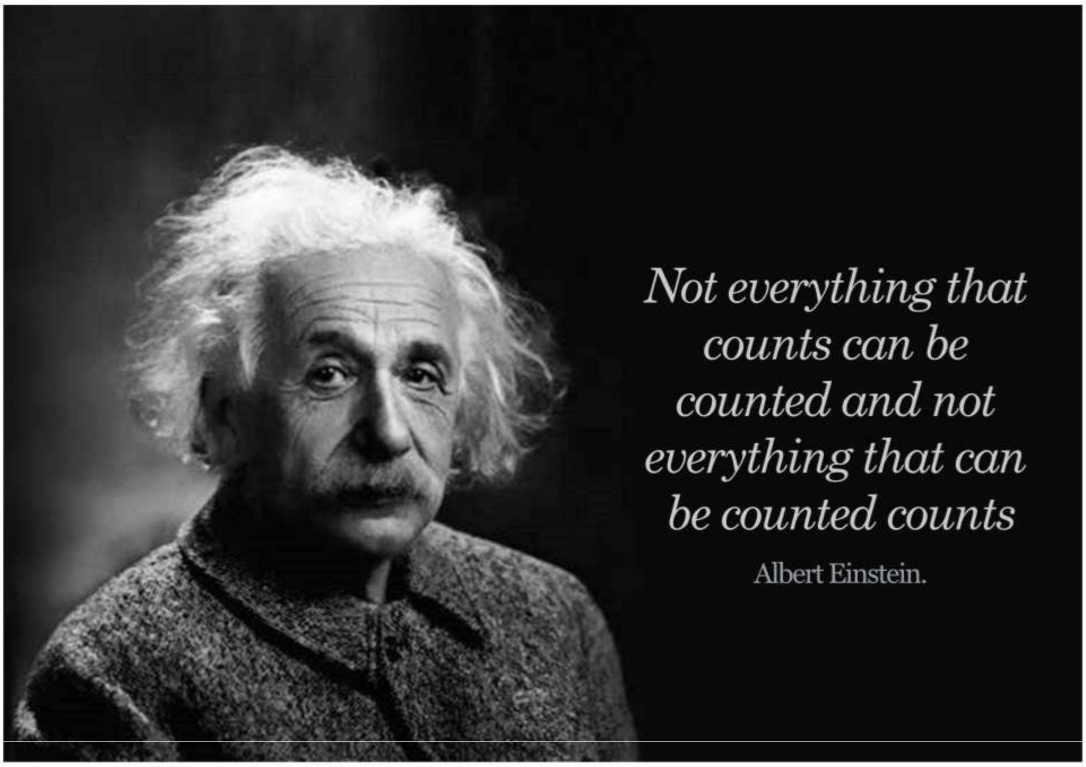
Chemical Engineering: Employment will be sustained by the ability to stay on the forefront of emerging technologies. This discipline is experiencing some migration into new fields, such as nanotechnology, alternative energies and biotechnology.

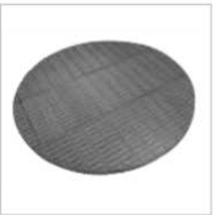
Environmental Engineering: The federal government's cleanup of contaminated sites is expected to help sustain demand for environmental engineers. Additionally, wastewater treatment is becoming a larger concern in areas of the country where new methods of drilling require the use and disposal of large volumes of water.

Civil Engineering: As infrastructure continues to age, civil engineers will be needed to manage projects to rebuild bridges, repair roads, and upgrade levees and dams. Plus, water systems must be maintained to reduce or eliminate leakage of drinkable water.

	Expected Growth from 2010 to 2020	Mean Salary (US $)	Top Salary (US $)
Mining and Geological Engineering	10%	96,000	149,000
Nuclear Engineering	10%	106,000	156,000
Petroleum Engineering	17%	149,000	186,000
Chemical Engineering	6%	104,000	158,000
Environmental Engineering	22%	85,000	122,000
Civil Engineering	19%	85,000	126,000
Industrial Engineering	6%	83,000	119,000
Mechanical Engineering	9%	85,000	123,000

In this issue…


Not everything that counts can be counted and not everything that can be counted counts
Albert Einstein.



WHAT ARE THE EFFECTS OF DIFFERENT ELEMENTS IN THE CHEMICAL COMPOSITION OF STEEL?

Carbon (C): Carbon is added to iron to make steel. In its pure form, iron is very soft and adding up to 2%carbon gives it toughness and strength. Structural steel plates typically contain about 0.15 to 0.3% carbon. As the amount of carbon increases in steel, the strength increases but the ductility decreases. So, iron with a lot of carbon added to it becomes very brittle and is unable to respond elastically to dynamic loading.

Silicon (Si): Silicon is added to carbon steels to help deoxidize, or *kill* them. That is, silicon helps to remove bubbles of oxygen from the molten steel. It is also useful in increasing strength and hardness but is less effective than manganese in doing so. Negatively for many uses, it also increases grain size so there is usually an upper limit on it.

Manganese (Mn): Manganese is probably the second most important alloying element after carbon in steel. Carbon has a large impact on strength, ductility and hardenability. Manganese helps to reduce oxides and also counteract the presence of iron sulfide. Steel makers, however, had to be careful that the level of carbon and manganese didn't get too high or the steel becomes too brittle and decreases weldability.

Phosphorus (P): In structural steel, phosphorus is considered to be an unwanted residual element. This is because most applications require very low or low phosphorus amounts. Phosphorus increases steel embrittlement which reduces the toughness and ductility of the metal. In uses this generally appears as cracks and fracture. High phosphorus in steel is a contributing factor to HIC cracking in wet H_2S environments.

Sulfur (S): Sulfur is another residual element in structural and pressure vessel steels. Sulfur decreases notch impact toughness, reduces weldability and decreases ductility. It generally appears as sulfide inclusions in the steel which decreases its strength.

Nitrogen (N): Nitrogen is a residual element for hot rolled steel plate. Generally, high levels of nitrogen will give the plate inconsistent mechanical properties and make welding more difficulty by increasing embrittlement in the heat affected zone (HAZ).

Copper (C): In structural steels, copper is primarily used as an alloying element as it will improve atmospheric corrosion resistance and help paint bond the steel. It also has a small impact on hardenability.

Nobium (Nb): Nobium is a key grain refining element in steel production. That is because it makes the grain size smaller, it simultaneously improves strength, toughness and ductility.

Vanadium (V): When added in the steelmaking process, vanadium helps to remove oxides and thus increases the yield strength and tensile strength of steel plates.

Titanium (Ti): Titanium in steel helps to keep grain size small and also helps manage inclusions by making them rounder.

Chromium (Cr): Chromium as an alloying element in steel helps increase its corrosion and oxidation resistance properties. When the percentage of chromium in steels exceeds 1.1%, a surface layer is formed that helps protect the steel against oxidation.

Nickel (Ni): Nickel is used to improve steel's corrosion resistance properties. It is a key component in stainless steels but at low concentrations found in carbon steels, it also helps to increase impact strength and hardenability.

Molybdenum (Mo): Molybdenum is used to increase the strength of boiler and pressure vessel steels at typical boiler operating temperatures of 400^{o}C. Typically, it is used in conjunction with chromium to provide strength and corrosion resistance at high temperature as well as increased creep strength.

Boron (B): Boron is added to fully killed fine grained steel to increase hardenability. This gives a benefit to the yield strength and toughness if the steel is fully hardened before tempering.

Zirconium (Zr): Zirconium is added to steel to modify the shape of inclusions. It helps them to become rounder (as opposed to elongated). The result is that toughness and ductility are improved when the plate is fabricated into a shell.

The following table illustrates the effects of alloying elements on the properties of steel. In this table, √ indicates that the element is advantageous with respect to the particular property, and x indicates that the element is harmful with respect to that property.

Desirabilty	Property	Carbon	Silicon	Manganese	Phosphorus	Sulfur	Nitrogen	Copper	Nobium	Vanadium	Titanium	Chromium	Nickel	Molybdenum	Boron	Zirconium	Iron
↑	Toughness	√			x	x			√				√		√	√	
↑	Strength	√	√			x			√					√			
↑	Ductility	x			x	x			√							√	
↑	Deoxidize		√	√						√		√					
↑	Hardness		√														
↓	Grain Size		x						√		√						
↑	Weldability			x		x	x										
↓	HIC Cracking				x												
↑	Mechanical Properties						x										
↓	Embrittlement				x		x										
↑	Corrosion Resistance							√				√	√				
↑	Paint Bonding							√									
↑	Yield Strength									√					√		
↑	Tensile Strength									√							
O	Inclusions										√					√	

Desirabilty	Property	Carbon	Silicon	Manganese	Phosphorus	Sulfur	Nitrogen	Copper	Nobium	Vanadium	Titanium	Chromium	Nickel	Molybdenum	Boron	Zirconium	Iron
↑	Hardenability							√					√		√		
↑	Creep Strength													√			
	Price/ Kg	24.00	2.50	1.60	300.00	500.00	5.61	8.28	180.00	14.33	8.00	9.59	54.00	30.00	11,140.00	1570.00	7.20

Source: Article by Denis Oakley written in September 2014, Oakley Steel website

RUPTURE HAZARD OF PRESSURE VESSELS

Improperly operated or maintained pressure vessels can fail catastrophically, kill and injure workers and others, and cause extensive damage even if the contents are benign. Many accidents to date demonstrate the potential danger of pressure vessels if they are not properly designed, constructed, operated, inspected, tested, or repaired. The higher the operating pressure and the larger the vessel, the more energy will be released in a rupture and the worse the consequences. It should be emphasized that the danger exists even if the vessel contents are not flammable, reactive or explosive

Factors in pressure vessel failure

The following conditions and factors have played major roles in pressure vessel accidents:

- Operation above the maximum allowable working and test pressures
- Improper sizing or pressure setting of relief devices
- Improper operation of relief devices due to faulty maintenance and failure to test regularly
- Failure of vessel due to fatigue from repeated pressurization, general thinning from corrosion or erosion, localized corrosion, stress corrosion cracking, embrittlement, holes and leaks
- Failure to inspect frequently enough
- Improper repair of a leak or other defect involving welding and annealing that embrittles and further weakens the vessel. Hazards posed by a vessel can be worse if repair welds are made without shutting down and de-inventorying the vessel. If a pressure vessel is repaired without removing the water, the quench effect of water can embrittle the steel.
- Over-pressurizing and failure of the vessel due to exothermic reaction or polymerization
- Vessel exposed to fire

Pressure vessel laws

Requirements for pressure vessels vary widely from state to state. Many states have a boiler law, but others do not. Even for those states that have a boiler law, typical practices (i.e. inspector requirements) for pressure vessels may vary. State boiler laws that require general adherence to ASME codes or National Board Inspection Code (NBIC) usually require the following for each pressure vessel:

- Registering with the state boiler and pressure vessel department
- Designing and constructing in accordance with ASME Section VIII, Division 1 which covers vessels operating between 15 psi and 3000 psi
- Marking the ASME Code on the vessel with specified information that includes the manufacturer, the serial number, the year built, and the maximum allowable working pressure for a specific temperature, and any special suitability such as for low temperature and poisonous gases or liquids
- Having the vessel approved for installation with the submission of drawings, specifications, welding details and calculations, and having an authorized inspector be satisfied with the welding and witness the testing
- Operating at pressures below the maximum allowable working pressure with pressure relieving devices set according to the ASME code; testing at regular intervals
- Periodically for corrosion and defects, and testing according to NBIC Manual for Boiler and Pressure Vessel Inspectors or API 510 for vessels in the petrochemical industry

- Repairing or altering only according to a plan approved by an authorized inspector and conducted by test-qualified welders. The inspector must be satisfied that the repairs are performed according to NBIC or API 510 and specify any necessary nondestructive and pressure testing. Increasing the maximum allowable working pressure or temperature is considered an alteration whether or not physical work is done.

In states with no pressure vessel law, good safety practices require that similar precautions be followed in the design, construction, welding, testing, marking, operation, inspection and repair of any pressure vessel. The ASME Code should be used for the design, construction, initial testing, and operation of pressure vessels. The NBIC or API 510 should be used for maintenance and inspection and subsequent testing. Boiler and machinery insurance companies, some pressure vessel suppliers, or jurisdiction-licensed independent contractors can provide authorized inspectors.

Pressure vessel hazard reduction

Pressure vessels must comply with all regulations, industry codes, and standards to keep vessels in safe condition to handle design pressures and temperatures. Areas to review could include, but are not limited to, the following:

Design: At a minimum, pressure vessels should be designed in accordance with ASME code for material contents of varying characteristics. Facilities should address any added concerns about the temperature and characteristics of vessel contents (e.g., toxic, corrosive, reactive, or flammable contents). When the vessel contents are changed from those the vessel is designed for, a risk analysis should be conducted to determine if it is still safe for the new material.

Certification of vessels: In states with a pressure vessel law, all pressure vessels must be certified by the relevant state authority as meeting requirements of the ASME code. When a pressure vessel cannot be constructed to comply fully with the ASME code, however, the NBIC provides a procedure by which the pressure vessel may get state approval without bearing the ASME symbol. This procedure includes submittal of drawings, calculations, welding procedures, service conditions, welding qualification and performance tests, and professional engineering certifications. This should be done before any construction begins.

When the facility finds an unmarked vessel or is about to bring one into a state, similar information plus the repair history should be submitted to the state pressure vessel authority for review and approval before use begins or continues.

When the pressure vessel is located in a state without a pressure vessel law, or is not marked with the ASME symbol, or there are doubts about the safety of the vessel, the information listed above should be submitted to a pressure vessel consulting engineer and authorized inspector for a safety review.

Inspection of vessels: The NBIC and API 510 require that the vessels be periodically inspected externally and internally. External inspections are made more frequently and involve visual and nondestructive examination. An internal inspection is more difficult to perform because it usually requires a confined space entry and the vessel must be taken out of service, cleaned and prepared. General or localized thinning of the internal walls due to corrosion or erosion is a potential problem and must be monitored, with the records kept of rate of thinning. When the vessel is reaching the end of its useful life, the period between inspections is shortened so that the vessel may be taken out of service before it may become dangerous. An internal test may also reveal stress corrosion, cracking, pitting, embrittlement, and other defects that could weaken the vessel. In addition to the vessel itself, the relieving devices must also be tested. When practical, this can be done in place for vessels containing non-hazardous substances; but for vessels containing hazardous substances without special controls (e.g., scrubbers), safety relief valves must be taken off to ascertain whether their settings are correct. How this can be done safely and conveniently should be considered.

Maintenance: In addition to maintenance requirements, the NBIC and API 510 include specific pre-heating and post-heating requirements. Large temperature differences the outside and the inside surface of the pressure vessel must be avoided to minimize embrittling or stressing the meatal. Nondestructive examinations may include radiographic, ultrasonic, liquid penetrant, magnetic particle, eddy current, visual checks, and leak testing.

Operation of Vessels: Operators should consider process start-up and shutdown conditions, possible process upsets, and any other unusual conditions that might cause overpressure problems. The ASME code includes recommended pressure differentials between safety valve set pressures and maximum allowable working pressure, as well as pressure differential settings of the relieving devices when there are multiple devices.

Evaluating potential explosion hazard

Facilities, particularly those without formal pressure vessel inspection programs, should survey their vessels, review pertinent history and data to identify hazards, and prevent vessel rupture or catastrophic failure.

1) Does the vessel operate above 15 psi, and was it designed, fabricated and constructed according to the ASME or any other applicable code?
   Is the vessel code labeled or stamped?
   Is the operating pressure and size of the vessel known?
2) Is the vessel maintained, inspected and repaired according to NBIC and/or API 510?
3) Are the ratings and settings of the relieving devices appropriate?
   Are the devices tested regularly and how recently?
4) Is the vessel inspected periodically?
   What are the criteria for inspection frequency?
   When it was last inspected externally? Internally?
   Did the inspection disclose general thinning of walls due to corrosion, localized corrosion, stress corrosion cracking, embrittlement, holes, leaks, or any other defects that required follow up?
   Were they followed up?
5) Has the vessel been repaired?
   Were the plan of repair, welding techniques and safety tests approved by a certified or authorized inspector?
   Was the welding done by a qualified welder?
   Were the welding performance qualification tests approved by an inspector?
   Was the vessel tested after the repair was completed?
6) Was the vessel down rated and were the necessary changes in operating conditions and relief device settings made?
7) Are exothermic reactions carried out in the vessels?
   Does the vessel have an emergency relief system to handle runaway reactions?

Source: Chemical Emergency Prevention & Planning Newsletter – March/ April 2008

BASIC INTRODUCTION TO FATIGUE

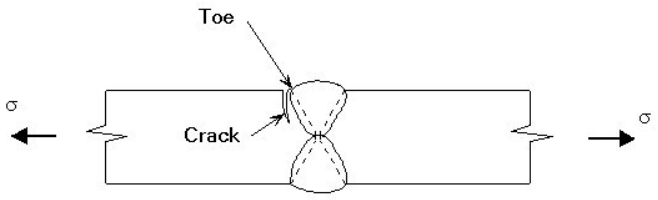
Nature of Fatigue

Fatigue is the mechanism whereby cracks grow in a structure. Growth only occurs under fluctuating stress. Final failure generally occurs in regions of tensile stress when the reduced cross-section becomes insufficient to carry the peak load without rupture. Although the loading on the structure is stationary, the crack does not grow under normal service temperatures. Many structures, such as building frames, do not experience sufficient fluctuating stress to give rise to fatigue problems. Others do, such as bridges, cranes, and offshore structures, where the live loading is a higher proportion of the total load.

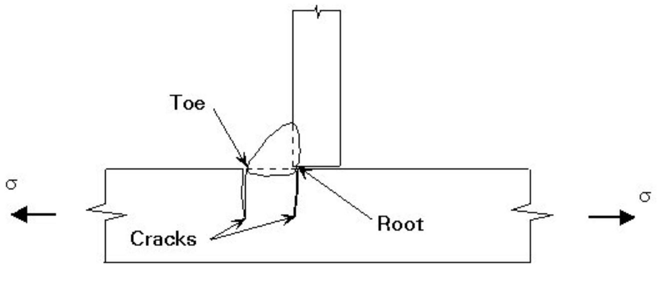
How Welds Fatigue

In welded steel structures, fatigue cracks will almost certainly start to grow from welds, rather than other details, because:

- Most welding processes leave minute metallurgical discontinuities from which cracks may grow. As a result, the initiation period, which is normally needed to start a crack in plain wrought material, is either very short or non-existent. Cracks therefore spend most of their life propagating, i.e. getting longer.
- Most structural welds have a rough profile. Sharp changes of direction generally occur at the toes of butt welds and at the toes and roots of fillet welds (See Figure 1). These points cause local stress concentrations of the type shown in Figure 2. Small discontinuities close to these points will therefore react as though they are in a more highly stressed member and grow faster.



Butt weld (Full penetration)



Fillet weld

Figure 1: Local Stress Concentrations at Welds

Crack Growth History

The study of fracture mechanisms shows that the growth rate of a crack is proportional to the square root of its length, given the same stress fluctuation and degree of stress concentration. For this reason fatigue cracks spend most of their life as very small cracks which are hard to detect. Only in the last stages of life does the crack start to cause a significant loss of cross-section area, as shown in Figure 3. This behavior poses problems for in-service inspection of structures.

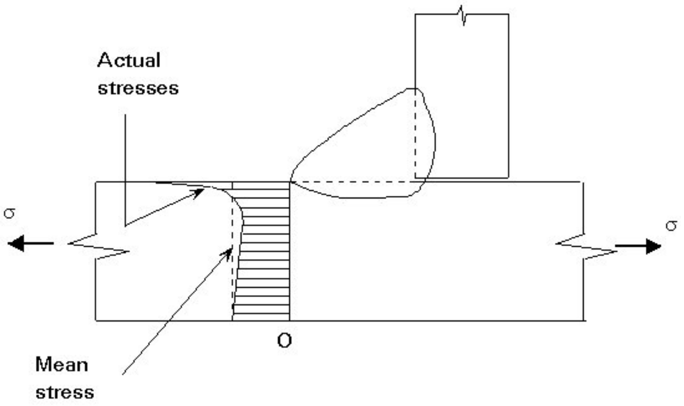


Figure 2: Typical Stress Distribution at Weld Toe

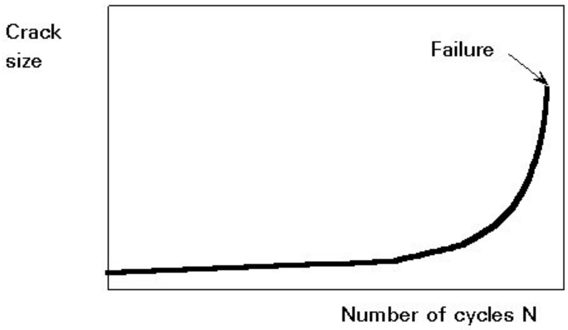


Figure 3: Typical Crack Growth Curve

FATIGUE STRENGTH

Definition of Fatigue Strength and Fatigue Life

The fatigue strength of a welded component is defined as the stress range ($\Delta\sigma_R$) which fluctuating at constant amplitude, causes failure of the component after a specified number of cycles (N). The stress range is the difference between the maximum and minimum points in the cycle, see Figure 4. The number of cycles to failure is known as the endurance or fatigue life.

Primary Factors Affecting Fatigue Life

For practical design purposes there are two main factors which affect the fatigue life of a detail, namely:

- The stress range ($\Delta\sigma_R$) at the location of crack initiation. There are special rules for calculating this range.
- The fatigue strength of the detail. This strength is primarily a function of the geometry and is defined by the parameter 'a', which varies from joint to joint.

The fatigue life (N), or endurance, in number of cycles to failure can be calculated from the expression:

$$N = a/\Delta\sigma_R^{m}$$

or

$$\log N = \log d - m \log \Delta\sigma_R$$

where m is a constant, which for most welded details is equal to 3. Predictions of life are therefore particularly sensitive to accuracy of stress prediction.

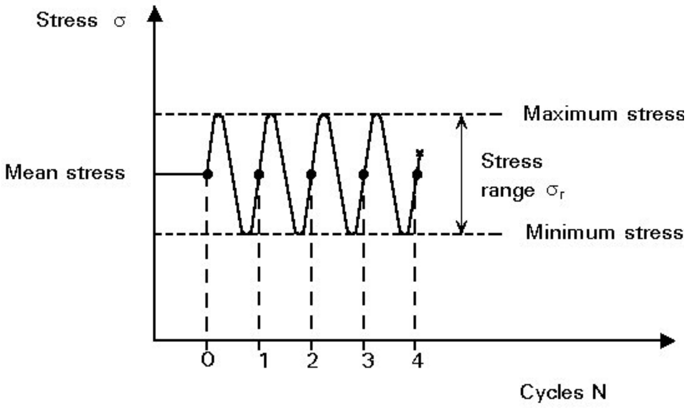


Figure 4: Constant Amplitude Stress History

S-N Curve

The expression linking N and $\Delta\sigma_R^m$ can be plotted on a logarithmic scale as a straight line and is referred to as an S-N curve. An example is shown in Figure 5. The relationship holds for a wide range of endurance. It is limited at the low endurance end by static failure when the ultimate material strength is exceeded. At endurances exceeding about 5-10 million cycles the stress ranges are generally too small to permit propagation under constant amplitude loading. This limit is called the non-propagating stress ($\Delta\sigma_D$). Below this stress range cracks will not grow.

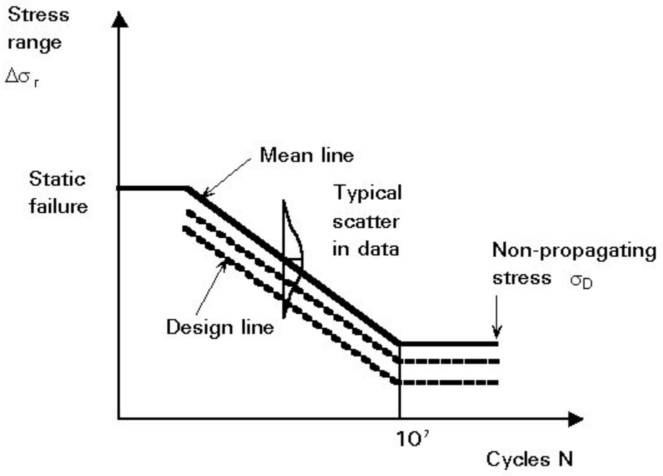


Figure 5: Typical S-N Curve for Constant Amplitude Tests

For design purposes it is usual to use design S-N curves which give fatigue strengths about 25% below the mean failure values, as shown in Figure 5. 'a' is used to define these lines.

Effect of Mean Stress

In non-welded details the endurance is reduced as the mean stress becomes more tensile. In welded details the endurance is not usually reduced in those circumstances. This behaviour occurs because the weld shrinkage stresses (or residual stresses), which are locked into the weld regions at fabrication, often attain tensile yield. The crack cannot distinguish between applied and residual stress. Thus, for the purposes of design, the S-N curve always assumes the worst, i.e. that the maximum stress in the cycle is at yield point in tension. It is particularly important to appreciate this point as it means that fatigue cracks can grow in parts of members which are nominally 'in compression'.

Effect of Mechanical Strength

The rate of crack growth is not significantly affected by variations in proof stress or ultimate tensile strength within the range of low alloy steels used for general purposes. These properties only affect the initiation period, which, being negligible in welds, results in little influence on fatigue life. This behavior contrasts with the fatigue of non-welded details where increased mechanical strength generally results in improved fatigue strength, as shown in Figure 6.

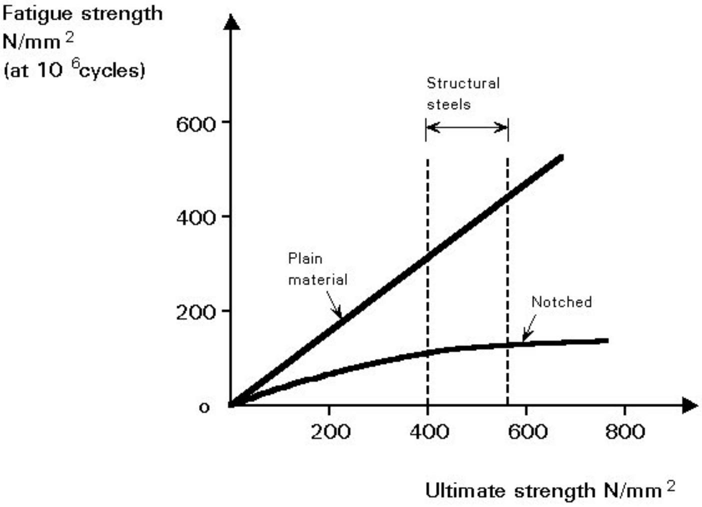


Figure 6: Effect of Mechanical Strength

CLASSIFICATION OF DETAILS

Detail Classes

The fatigue strength parameter (K_2) of different welded details vary according to the severity of the stress concentration effect. As there are a wide variety of detail in common use, details with similar K_2 values are grouped together into a single detail class and given a single K_2 value.

This data has been obtained from constant amplitude fatigue tests on simple specimens containing different welded detail types. For the most commonly used details, it has been found convenient to divide the results into fourteen main classes. The classes are:

Detail Category, $\Delta\sigma_c$(N/mm^2)	d	m
160	7.962×10^{12}	3
140	5.636×10^{12}	3

125	3.990×10^{12}	3
112	2.825×10^{12}	3
100	2.000×10^{12}	3
90	1.416×10^{12}	3
80	1.002×10^{12}	3
71	0.710×10^{12}	3
63	0.502×10^{12}	3
56	0.356×10^{12}	3
50	0.252×10^{12}	3
45	0.178×10^{12}	3
40	0.126×10^{12}	3
36	0.089×10^{12}	3

As shown in Figure 7, these classes can be plotted as a family of S-N curves. The difference in stress range between neighbouring curves is usually between 15 and 20%.

Detail Types

There are usually a number of detail types within each class. Each type has a very specific description which defines the geometry both microscopically and macroscopically. The main features that affect the detail type, and hence its classification, are:

- Form of the member:e.g. plate, rolled section, reinforcing bar.
- Location of anticipated crack initiation:The location must be defined with respect to the direction of stress fluctuation. A given structural joint may contain more than one potential initiation site, in which case the joint may fall into two or more detail types.
- Leading dimensions:e.g. weld shape, size of component, proximity of edges, and abruptness of change of cross-section.
- Fabrication requirements:e.g. type of weld process, any grinding smooth of particular parts of the joint.
- Inspection requirements:Special inspection procedures may be required on higher class details to ensure that detrimental welding defects are not present.

It should be noted that if fatigue is critical in the design, the extra controls on fabrication incurred by the last two requirements may increase the total cost significantly above that for purely static strength.

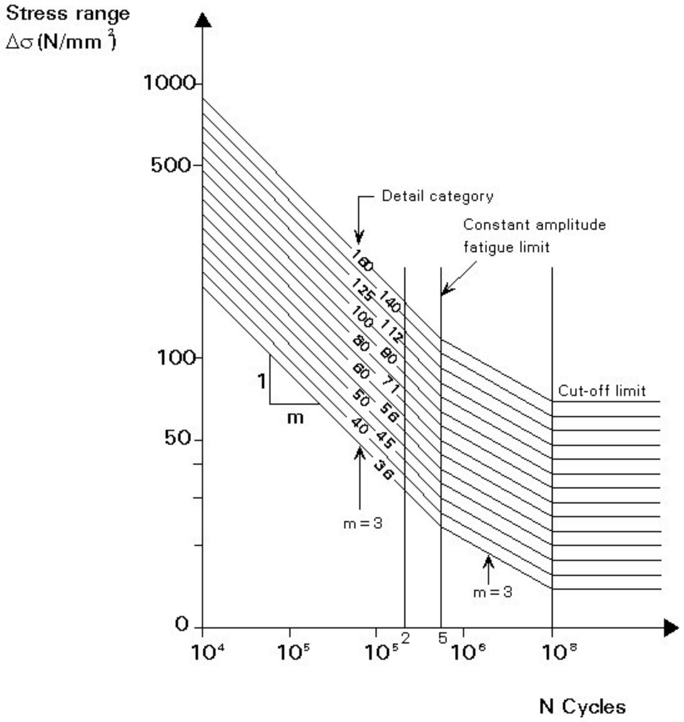


Figure 7: Family of Design S-N Curves

Commonly Used Detail Types

Figure 8 shows some of the most important details to look out for in welded steelwork. They are:

- Load carrying fillet welds and partial penetration butt welds. These details are category 36 for failure starting at the root and propagating through the throat.
- Welded attachments on edges. They are category 45. Note that the attachment weld may not be transferring any stress. Failure is from the weld toe into the member.
- Ends of long flat plates, e.g. cover plates are category 50.
- Most short attachments in the stress direction are category 80 or 71 as long as they are not at an edge.
- Transverse full penetration butt welds can range from category 12,5 to 36 depending on how they are made.
- Long continuous welds on site welded structures are found to be category 100.

It should be borne in mind that most potential fatigue sites on welded structures are found to be category 80 or below.

STRESS PARAMETERS FOR FATIGUE

Stress Area

The stress areas are essentially similar to those used for static design. For a crack starting at a weld toe, the cross-section of the member through which propagation occurs is used. For a crack starting at the root, and propagating through the weld throat, the minimum throat area is used, as shown in Figure 8a.

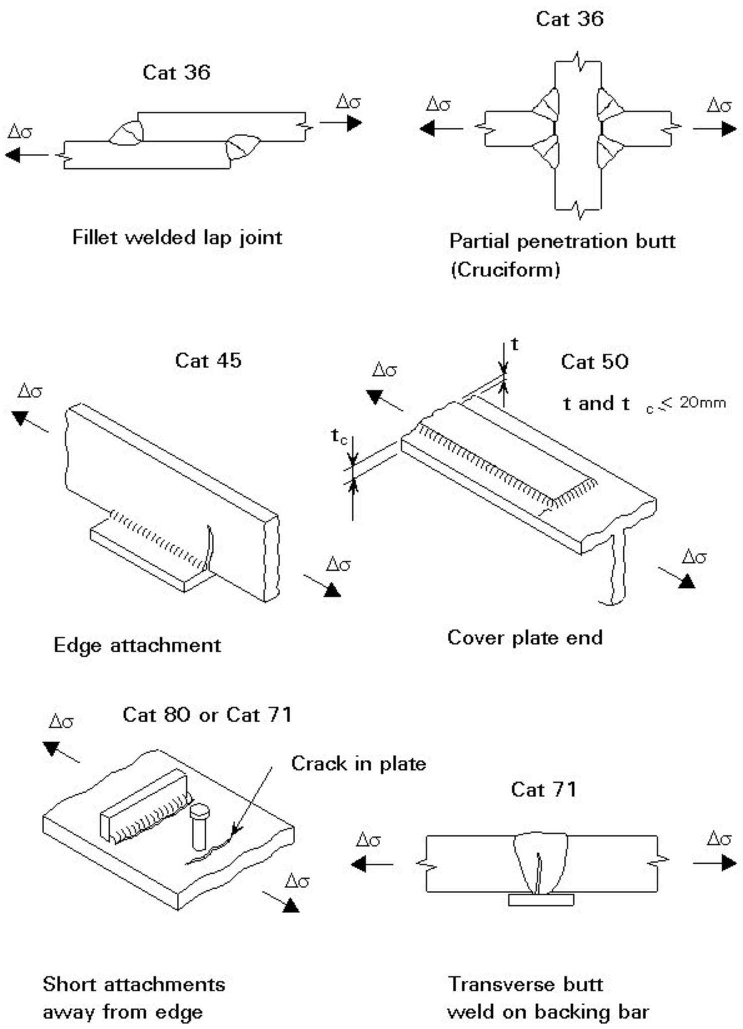


Figure 8a: Some Common Detail Types and Their Fatigue Categories

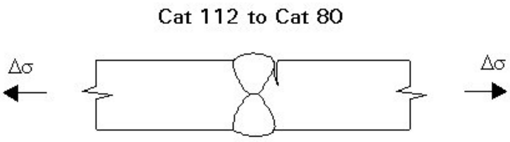
Calculation of Stress Range,$\Delta\sigma$

The force fluctuation in the structure must be calculated elastically. No plastic redistribution is permitted.

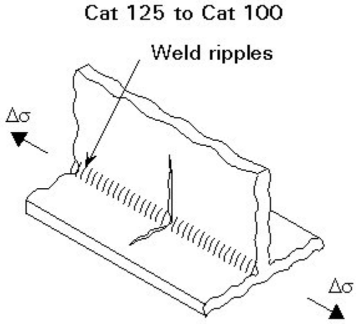
The stress on the critical cross-section is the principal stress at the position of the weld toe (in the case of weld toes cracks). Simple elastic theory is used assuming plane sections remain plane(See Figure 9). The effect of the local stress concentration caused by the weld profile is ignored as this is already catered for by the parameter 'd' which determines the weld class.

In the case of throat failures, the vector sum of the stresses on the weld throat at the position of highest vector stress along the weld is used, as in static design.

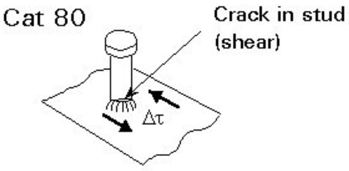
Exceptions to these rules occur in the case of unstiffened joints between slender members such as tubes. In this case the stress parameter is the Hot Spot Stress. This stress is calculated at the point of expected crack initiation, taking into account the true elastic deformation in the joint, i.e. not assuming plane sections to remain plane.



Transverse butt weld
(Welded from both sides)



Longitudinal Welds



Stud connector

Some Common Detail Types and Their Classes

Effects of Geometrical Stress Concentrations and Other Effects

Where a member has large changes in cross-section, e.g. at access holes, there will be regions of stress concentration due to the change of geometry. In static design the stresses are based on the net area as plastic redistribution will normally reduce these peaks at ultimate load. With fatigue this is not so, and if there is a welded detail in the area of the geometrical stress raiser the true stress must be used, as shown in Figure 10.

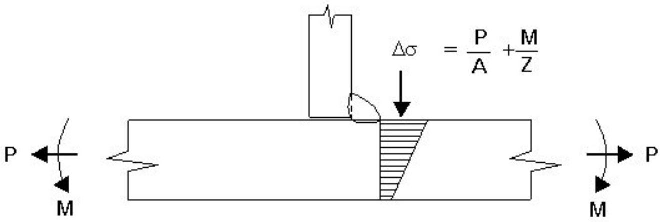


Figure 9: Design Stress Parameter for Cracks Propagating in Parent Material

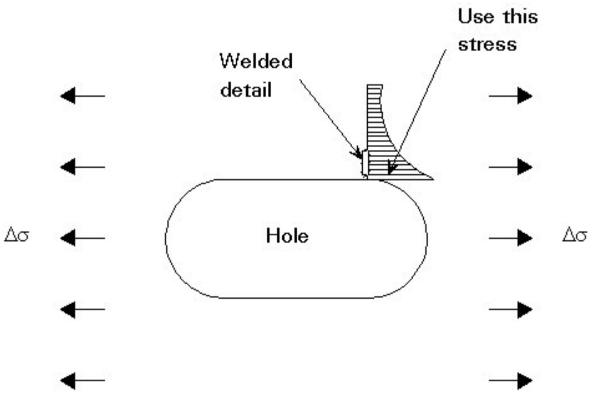


Figure 10: Design Stress Parameter for Cracks Initiating at Geometrical Stress Concentrations

Secondary Effects

Similarly any secondary effects, such as those due to joint fixity in latticed structures, and shear lag and other distortional effects in slender beams, are allowed for in calculating the stresses.

LOADINGS FOR FATIGUE

Types of Loading

Examples of structures and the loads which can cause fatigue are:

Bridges: Commercial vehicles, goods trains

Cranes: Lifting, rolling and inertial loads

Offshore structures: Waves

Slender chimneys: Wind gusting

The designer's objective is to anticipate the sequence of service loading throughout the structure's life. The magnitude of the peak load, which is vital for static design purposes, is generally of little concern as it only represents one cycle in millions. For example, highway bridge girders may experience 100 million significant cycles in their lifetime. The sequence is important because it affects the stress range, particularly if the structure is loaded by more than one independent load system.

For convenience, loadings are usually simplified into a load spectrum, which defines a series of bands of constant load levels, and the number of times that each band is experienced, as shown in Figure 11.

Slender structures, with natural frequencies low enough to respond to the loading frequency, may suffer dynamic magnification of stress. This magnification can shorten the life considerably.

CALCULATION OF DAMAGE

Under variable amplitude loading the life is estimated by calculation of the total damage done by each cycle in the stress spectrum. In practice the spectrum is simplified into a manageable number of bands, as shown in Figure 12.

The damage done by each band in the spectrum is defined as $\frac{n}{N}$where n is the required number of cycles in the band during the design life and N is the endurance under that stress range, see Figure 13.

If failure is to be prevented before the end of the specified design life, the Palmgren-Miner's Rule must be compiled with. This rule states that the damage done by all bands together must not exceed unity, i.e.:

$$\frac{n_1}{N_1} + \frac{n_2}{N_2} + \ldots\ldots \frac{n_n}{N_n} \leq 1$$

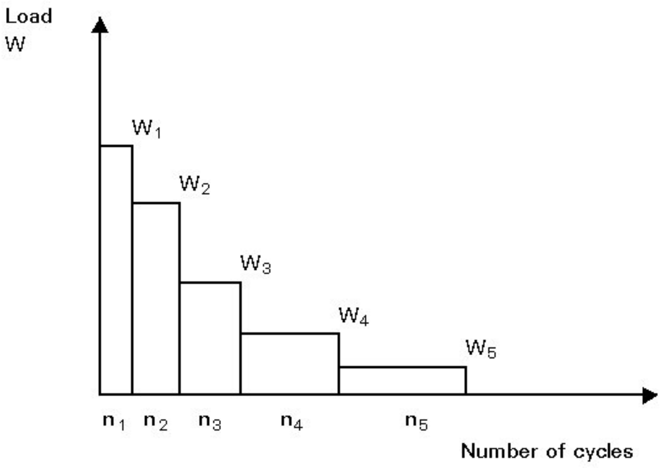


Figure 11: Typical Load Spectrum for Design

It should be noted that, when variable amplitude loading occurs, the bands in the spectrum with Δσ values less than $\Delta\sigma_D$ may still cause damage. Damage occurs because the larger amplitude cycles may start to propagate the crack. Once it starts to grow lower cycles become effective. In this case, the horizontal constant amplitude fatigue limit $\Delta\sigma_D$ shown in Figure 5, is replaced by a sloping line with a log gradient of $\frac{1}{m+2}$.

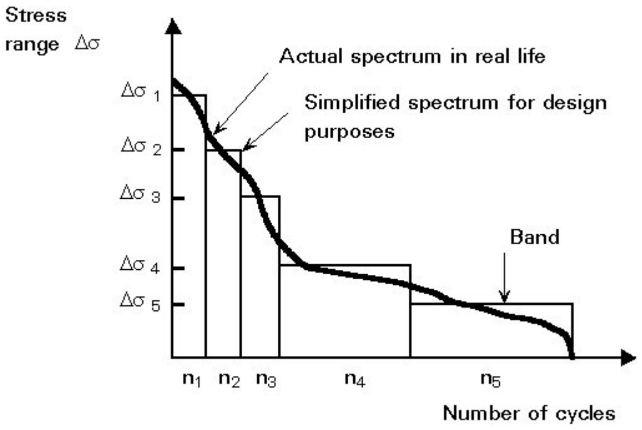


Figure 12: Simplification of Stress Spectrum

CONCLUDING SUMMARY

- Fatigue and static failure (whether by rupture or buckling) are dependent on very different factors, namely:
    - Fatigue depends on the whole service loading sequence (not one extreme load event).
    - Fatigue of welds is not improved by better mechanical properties.
    - Fatigue is very sensitive to the geometry of details.
    - Fatigue requires more accurate prediction of elastic stress.

- Fatigue makes more demands on workmanship and inspection.

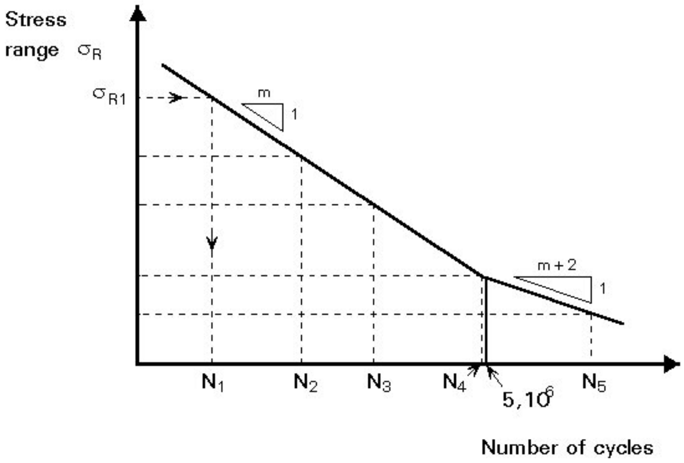


Figure 13: Determination of Endurance for Each Band

- It is therefore important to check early in the design whether fatigue is likely to be critical. Acceptable margins of safety against static collapse cannot be relied upon to give adequate safety against fatigue.
- Areas with a high live/dead stress ratio and low category 36 details should be checked first. The check must cover any welded attachment to a member, however insignificant, and not just the main structural connections. Note that this check should include welded additions to the structure in service.
- If fatigue is critical, then the choice of details will be limited. Simplicity of detail and smoothness of stress path should be sought.
- Be prepared for fatigue critical structures to cost more.

BUILDING A BETTER TOMMORROW

It is becoming less practical for many companies to maintain in-house engineering staff. That is where we come in – whenever you need us, either for one-time projects, or for recurring engineering services. We understand the codes and standards, and can offer a range of services related to pressure vessels, tanks and heat exchangers.

Training & Development

Consulting Services

CoDesign
Engineering

Pressure Vessels ● Heat Exchangers ● Tanks
Oil & Gas ● Power ● Chemical ● Petrochemical ● Fertilizer