# FIXED EQUIPMENT NEWSLETTER

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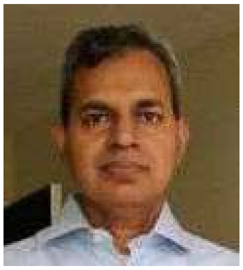
# Preventing Pressure Vessel Accidents



Pressure vessel related accidents might never be fully eliminated; however, we can work towards significantly reducing the risk and likelihood of such accidents occurring. The pressure vessel accidents can be prevented by:

- Designing, fabricating and constructing pressure vessels to comply with applicable codes and standards.
- Operating the vessel at pressure below the maximum allowable working pressure with proper pressure setting of relief devices.
- Periodically testing and inspecting the vessel as well as the relief devices in order to detect corrosion or erosion of the vessel that can cause holes, leaks, cracks, general thinning of the vessel walls or any other defects.
- Keeping records of inspection reports and monitoring potential problem, so that the vessel may be taken out of service before it becomes dangerous.
- Ensuring that alterations or repairs of vessels are only done by competent and authorized persons and the repairs meet the accepted industry quality standards for pressure vessel repair.
- Providing safety training for employees on job hazard and anticipated conditions that could jeopardize their safety or the safety of others.
- Periodically provide training for operators on vessels operating procedures to avoid over pressurizing, as well as providing them with adequate and suitable instructions for vessel safe operations.

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.

**Ramesh K Tiwari**
ramesh.tiwari@codesignengg.com

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# MECHANICAL INTEGRITY – FIXED EQUIPMENT

## INTRODUCTION

Mechanical Integrity can be defined as the management of critical process equipment to ensure it is designed and installed correctly and that it is operated and maintained properly. Mechanical Integrity is one of fourteen elements included in the Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) standard. The other elements are:

1. Employee Participation
2. Process Safety Information
3. Process Hazard Analysis
4. Operating Procedures
5. Training
6. Contractors
7. Pre-start Safety Review
8. Mechanical Integrity
9. Hot Work Permit
10. Management of Change
11. Incident Investigation
12. Emergency Planning and Response
13. Compliance Audits
14. Trade Secrets

OSHA identifies the intent of a "Mechanical Integrity" program "*is to assure that equipment used to process, store or handle highly hazardous chemical is designed, constructed, installed and maintained to minimize the risk of releases of such chemicals. This requires that mechanical integrity program be in place to assure the continued integrity of process equipment. The elements of a mechanical integrity program include the identification and categorization of equipment and instrumentation, development of written maintenance procedures, training for process maintenance activities, inspection and testing, correction of deficiencies in equipment that are outside acceptable limits defined by the process safety information, and development of a quality assurance program.*"

Mechanical Integrity includes equipment/assets such as pressure vessels, storage tanks, piping systems, and associated hardware (valves, fittings, etc.), relief devices, and emergency shutdown/control systems. It encompasses the activities necessary to ensure that equipment/assets are designed, fabricated, installed, operated and maintained in a way that provides the desired performance in a safe, environmentally protected, and reliable fashion.

In the early 1900s, the need to protect workers and the public from the hazards of boilers and pressurized equipment became apparent, so the industry began to develop design standards. After World War II, a number of industry consensus standards were developed by the National Board Inspection Code (NBIC). By the 1980s, the American Petroleum Institute (API) led industry efforts to develop and implement important Mechanical Integrity standards, while the federal government also turned its regulatory attention to Mechanical Integrity. API, industry, and the regulators have addressed Mechanical Integrity head-on since the early-90s, particularly through the OSHA's PSM program and the Environmental Protection Agency's Risk Management Program, as well as many additional Standards and Recommended Practices (RPs) published by API.

## EQUIPMENTS

### Pressure Vessels

API 510: Pressure Vessel Inspection Code: In-Service Inspection, Rating, Repair, and Alteration

Covers the in-service inspection, repair, alteration, and rerating activities for pressure vessels and the pressure-relieving devices protecting these vessels. This inspection code applies to most refining and chemical process vessels that have been placed in service. This includes:

- Vessels constructed in accordance with an applicable construction code;
- Vessels constructed without a construction code (non-code)—a vessel not fabricated to a recognized construction code and meeting no known recognized standard;
- Vessels constructed and approved as jurisdictional special based upon jurisdiction acceptance of particular design, fabrication, inspection, testing, and installation;
- Non-standard vessels - a vessel fabricated to a recognized construction code but has lost its nameplate or stamping.

RP 572: Inspection Practices for Pressure Vessels

Supplements API 510 by providing pressure vessel inspectors with information that can improve skills and increase basic knowledge of inspection practices. This recommended practice (RP) describes inspection practices for the various types of pressure vessels (e.g. drums, heat exchangers, columns, reactors, air coolers, spheres) used in petroleum refineries and chemical plants. This RP addresses vessel components, inspection planning processes, inspection intervals, methods of inspection and assessment, methods of repair, records, and reports. API 510 has requirements and expectations for inspection of pressure vessels.

### Piping Systems

API 570: Piping Inspection Code: In-Service Inspection, Rating, Repair, and Alteration of Piping Systems

Covers inspection, rating, repair, and alteration procedures for metallic and fiberglass reinforced plastic (FRP) piping systems and their associated pressure relieving devices that have been placed in service. This inspection code applies to all hydrocarbon and chemical process piping covered in 1.2.1 that have been placed in service unless specifically designated as optional per 1.2.2. This publication does not cover inspection of specialty equipment including instrumentation, exchanger tubes, and control valves.

However, this piping code could be used by owner/users in other industries and other services at their discretion. Process piping systems that have been retired from service and abandoned in place are no longer covered by this “in-service inspection” Code. However abandoned in place piping may still need some amount of inspection and/or risk mitigation to assure that it does not become a process safety hazard because of continuing deterioration. Process piping systems that are temporarily out of service but have been mothballed (preserved for potential future use) are still covered by this Code.

RP 574: Inspection Practices for Piping System Components

Supplements API 570 by providing piping inspectors with information that can improve skill and increase basic knowledge of inspection practices. This recommended practice describes inspection practices for piping, tubing, valves (other than control valves), and fittings used in petroleum refineries and chemical plants. Common piping components, valve types, pipe joining methods, inspection planning processes, inspection intervals and techniques, and types of records are described to aid the inspectors in fulfilling their role implementing API 570. This publication does not cover inspection of specialty items, including instrumentation, furnace tubulars, and control valves.

**Heat Transfer Equipment**

Std. 530: Calculation of Heater-Tube Thickness in Petroleum Refineries

Specifies the requirements and gives recommendations for the procedures and design criteria used for calculating the required wall thickness of new tubes and associated component fittings for fired heaters for the petroleum, petrochemical, and natural gas industries. These procedures are appropriate for designing tubes for service in both corrosive and non-corrosive applications. These procedures have been developed specifically for the design of refinery and related fired heater tubes (direct-fired, heat-absorbing tubes within enclosures). These procedures are not intended to be used for the design of external piping. This standard does not give recommendations for tube retirement thickness; Annex A describes a technique for estimating the life remaining for a heater tube.

RP 538: Industrial Fired Boilers for General Refinery and Petrochemical Service

Specifies requirements and gives recommendations for design, operation, maintenance, and troubleshooting considerations for industrial fired boilers used in refineries and chemical plants. It covers waterside control, combustion control, burner management systems (BMSs), feedwater preparation, steam purity, emissions, etc.

Std. 560: Fired Heaters for General Refinery Service

Specifies requirements and gives recommendations for the design, materials, fabrication, inspection, testing, preparation for shipment, and erection of fired heaters, air preheaters (APHs), fans, and burners for general refinery service. Covered sections include Purchaser's and Vendor's Responsibilities; Design Considerations (Process, Combustion and Mechanical); Materials of Construction; Tubes and Tube Supports; Headers, Piping, Terminals, and Manifolds; Loads and Allowable Stress; Refractory Linings and Castable Design and Construction; Structures and Appurtenances; Stacks, Ducts and Breeching; Burners, Dampers and Controls; Fan Drives; Sootblowers; Instruments and Connections; Shop Fabrication and Field Erection; Inspection and Testing; Air Preheat Systems; Efficiency Measurement; and Noise Measurement.

RP 573: Inspection of Fired Boilers and Heaters

Covers the inspection practices for fired boilers and process heaters (furnaces) used in petroleum refineries and petrochemical plants. The practices described in this document are focused to improve equipment reliability and plant safety by describing the operating variables which impact reliability and to ensure that inspection practices obtain the appropriate data, both on-stream and off-stream, to assess current and future performance of the equipment.

RP 575: Inspection Practices for Atmospheric and Low-Pressure Storage Tanks

Covers the inspection of atmospheric and low-pressure storage tanks that have been designed to operate at pressures from atmospheric to 15 psig. Includes reasons for inspection, frequency and methods of inspection, methods of repair, and preparation of records and reports. This recommended practice is intended to supplement Std. 653, which covers the minimum requirements for maintaining the integrity of storage tanks after they have been placed in service.

Std. 660: Shell-and-Tube Heat Exchangers

Specifies requirements and gives recommendations for the mechanical design, material selection, fabrication, inspection, testing, and preparation for shipment of shell-and-tube heat exchangers for the petroleum, petrochemical, and natural gas industries. This standard is applicable to the following types of shell-and-tube heat exchangers: heaters, condensers, coolers, and reboilers. It is not applicable to vacuum-operated steam surface condensers and feed-water heaters.

Std. 661: Petroleum, Petrochemical, and Natural Gas Industries Air-cooled Heat Exchangers

Gives requirements and recommendations for the design, materials, fabrication, inspection, testing, and preparation for shipment of air-cooled heat exchangers for use in the petroleum, petrochemical, and natural gas industries. This standard is applicable to air-cooled heat exchangers with horizontal bundles, but the basic concepts can also be applied to other configurations.

Std. 663: Hairpin-type Heat Exchangers

Specifies requirements and gives recommendations for the mechanical design, materials selection, fabrication, inspection, testing and preparation for shipment of hairpin heat exchangers for use in the petroleum, petrochemical and natural gas industries. Hairpin heat exchangers include double-pipe and multitube type heat exchangers.

Std. 664: Spiral Plate Heat Exchangers

Specifies requirements and gives recommendations for the mechanical design, materials selection, fabrication, inspection, testing, and preparation for shipment of spiral plate heat exchangers for the petroleum, petrochemical, and natural gas industries. It is applicable to standalone spiral plate heat exchangers and those integral with a pressure vessel.

**Storage Tanks**

Std. 620: Design and Construction of Large, Welded, Low-pressure Storage Tanks

This standard covers the design and construction of large, welded, low-pressure carbon steel above ground storage tanks (including flat-bottom tanks) that have a single vertical axis of revolution. This standard does not cover design procedures for tanks that have walls shaped in such a way that the walls cannot be generated in their entirety by the rotation of a suitable contour around a single vertical axis of revolution.

The tanks described in this standard are designed for metal temperatures not greater than 250 °F and with pressures in their gas or vapor spaces not more than 15 lbf/in.2 gauge.

Std. 650: Welded Tanks for Oil Storage

This standard establishes minimum requirements for material, design, fabrication, erection, and inspection for vertical, cylindrical, aboveground, closed- and opentop, welded storage tanks in various sizes and capacities for internal pressures approximating atmospheric pressure (internal pressures not exceeding the weight of the roof plates), but a higher internal pressure is permitted when additional requirements are met. This standard applies only to tanks whose entire bottom is uniformly supported and to tanks in non-refrigerated service that have a maximum design temperature of 93 °C (200 °F) or less.

RP 651: Cathodic Protection of Aboveground Petroleum Storage Tanks

Presents procedures and practices for achieving effective corrosion control on aboveground storage tank bottoms through the use of cathodic protection. This RP contains provisions for the application of cathodic protection to existing and new aboveground storage tanks. Corrosion control methods based on chemical control of the environment or the use of protective coatings are not covered in detail.

When cathodic protection is used for aboveground storage tank applications, it is the intent of this RP to provide information and guidance specific to aboveground metallic storage tanks in hydrocarbon service. Certain practices recommended herein may also be applicable to tanks in other services. It is intended to serve only as a guide to persons interested in cathodic protection. Specific cathodic protection designs are not provided. Such designs should be developed by a person thoroughly familiar with cathodic protection practices for aboveground petroleum storage tanks.

This RP does not designate specific practices for every situation because the varied conditions in which tank bottoms are installed preclude standardization of cathodic protection practices.

RP 652: Linings of Aboveground Petroleum Storage Tank Bottoms

Provides guidance on achieving effective corrosion control by the application of tank bottom linings in aboveground storage tanks in hydrocarbon service. It contains information pertinent to the selection of lining materials, surface preparation, lining application, cure, and inspection of tank bottom linings for existing and new storage tanks. In many cases, tank bottom linings have proven to be an effective method of preventing internal corrosion of steel tank bottoms.

Provides information and guidance specific to aboveground steel storage tanks in hydrocarbon service. Certain practices recommended herein may also applicable to tanks in other services. This recommended practice is intended to serve only as a guide and detailed tank bottom lining specifications are not included.

This recommended practice does not designate specific tank bottom linings for every situation because of the wide variety of service environments.

Std. 653: Tank Inspection, Repair, Alteration, and Reconstruction

Covers steel storage tanks built to Std. 650 and its predecessor Spec 12C. It provides minimum requirements for maintaining the integrity of such tanks after they have been placed in service and addresses inspection, repair, alteration, relocation, and reconstruction.

The scope is limited to the tank foundation, bottom, shell, structure, roof, attached appurtenances, and nozzles to the face of the first flange, first threaded joint, or first welding-end connection. Many of the design, welding, examination, and material requirements of Std. 650 can be applied in the maintenance inspection, rating, repair, and alteration of in-service tanks. In the case of apparent conflicts between the requirements of this standard and Std. 650 or its predecessor Spec 12C, this standard shall govern for tanks that have been placed in service.

## PROCESSES

### Risk-based Inspection

RP 580: Risk-Based Inspection

Provides users with the basic minimum and recommended elements for developing, implementing, and maintaining a risk-based inspection (RBI) program. It also provides guidance to owner-users, operators, and designers of pressure-containing equipment for developing and implementing an inspection program. These guidelines include means for assessing an inspection program and its plan. The approach emphasizes safe and reliable operation through risk-prioritized inspection. A spectrum of complementary risk analysis approaches (qualitative through fully quantitative) can be considered as part of the inspection planning process. RBI guideline issues covered include an introduction to the concepts and principles of RBI for risk management and individual sections that describe the steps in applying these principles within the framework of the RBI process.

RP 581: Risk-Based Inspection Methodology

Provides quantitative procedures to establish an inspection program using risk based methods for pressurized fixed equipment including pressure vessel, piping, tankage, pressure relief devices (PRDs), and heat exchanger tube bundles. RP 580 provides guidance for developing Risk-Based Inspection (RBI) programs on fixed equipment in refining, petrochemical, chemical process plants, and oil and gas production facilities. The intent is for RP 580 to introduce the principles and present minimum general guidelines for RBI, while this recommended practice provides quantitative calculation methods to determine an inspection plan.

The calculation of risk outlined in RP 581 involves the determination of a probability of failure (POF) combined with the consequence of failure (COF). Failure is defined as a loss of containment from the pressure boundary resulting in leakage to the atmosphere or rupture of a pressurized component. Risk increases as damage accumulates during in-service operation as the risk tolerance or risk target is approached and an inspection is recommended of sufficient effectiveness to better quantify the damage state of the component. The inspection action itself does not reduce the risk; however, it does reduce uncertainty and therefore allows more accurate quantification of the damage present in the component.

**Fitness-for-Service**

Std. 579-1/ASME FFS-1: Fitness-For-Service

Fitness-For-Service (FFS) assessments are quantitative engineering evaluations that are performed to demonstrate the structural integrity of an in-service component that may contain a flaw or damage or that may be operating under a specific condition that might cause a failure. This standard provides guidance for conducting FFS assessments using methodologies specifically prepared for pressurized equipment.

The guidelines provided in this standard can be used to make run-repair- replace decisions to help determine if components in pressurized equipment containing flaws that have been identified by inspection can continue to operate safely for some period of time. These FFS assessments are currently recognized and referenced by the API Codes and Standards (510, 570, and 653), and by NB-23 as suitable means for evaluating the structural integrity of pressure vessels, piping systems, and storage tanks where inspection has revealed degradation and flaws in the equipment. The methods and procedures in this standard are intended to supplement and augment the requirements in API 510, API 570, Std. 653, and other post-construction codes that reference FFS evaluations such as NB-23.

**Damage Mechanisms**

RP 571: Damage Mechanisms Affecting Fixed Equipment in the Refining Industry

Provides background information on damage that can occur to equipment in the refining process. It is intended to supplement Risk-Based Inspection (RP 580 and Publ. 581) and Fitness-for-Service (Std. 579-1/ASME FFS-1) technologies developed in recent years by API to manage existing refining equipment integrity. It is also an excellent reference for inspection, operations, and maintenance personnel. This RP covers over 60 damage mechanisms.

Each write-up consists of a general description of the damage, susceptible materials, construction, critical factors, inspection method selection guidelines, and control measures. Wherever possible, pictures are included and references are provided for each mechanism. In addition, generic process flow diagrams have been included that contain a summary of the major damage flow mechanism expected for typical refinery process units.

RP 585: Pressure Equipment Integrity Incident Investigation

Provides owner/users with guidelines and recommended practices for developing, implementing, sustaining, and enhancing an investigation program for pressure equipment integrity incidents. This recommended practice describes characteristics of an effective investigation and how organizations can learn from pressure equipment integrity incident investigations. This RP is intended to supplement and provide additional guidance for the OSHA Process Safety Management (PSM) Standard 29 CFR 1910.119 (m) incident investigation requirements, with a specific focus on incidents caused by integrity failures of pressure equipment.

RP 970: Corrosion Control Documents

Provides users with the basic elements for developing, implementing, and maintaining a Corrosion Control Document (CCD) for refining, and at the owner's discretion, may be applied at petrochemical and chemical process facilities. A CCD is a document or other repository or system that contains all the necessary information to understand materials damage susceptibility issues in a specific type of operating process unit at a plant site.

CCDs are a valuable addition to an effective Mechanical Integrity Program. They help to identify the damage mechanism susceptibilities of pressure containing piping and equipment, factors that influence damage mechanism susceptibilities, and recommended actions to mitigate the risk of loss of containment or unplanned outages.

This recommended practice provides the owner/user with information and guidance on the work processes for development and implementation of CCDs for the owners'/users' process units.

## CORROSION AND MATERIALS

### Welding

RP 577: Welding Processes, Inspection, and Metallurgy

Provides guidance to the API authorized inspector on welding inspection as encountered with fabrication and repair of refinery and chemical plant equipment and piping. Common welding processes, welding procedures, welder qualifications, metallurgical effects from welding, and inspection techniques are described to aid the inspector in fulfilling their role implementing API 510, API 570, Std. 653 and RP 582. The level of learning and training obtained from this document is not a replacement for the training and experience required to be an American Welding Society (AWS) Certified Welding Inspector (CWI).

RP 582: Welding Guidelines for the Chemical, Oil, and Gas Industries

Provides supplementary guidelines and practices for welding and welding related topics for shop and field fabrication, repair, and modification of the following:

- Pressure-containing equipment, such as pressure vessels, heat exchangers, piping, heater tubes, and pressure boundaries of rotating equipment and attachments welded thereto;
- Tanks and attachments welded thereto;
- Non-removable internals for process equipment;
- Structural items attached and related to process equipment;
- Other equipment or component items, when referenced by an applicable purchase document.

This document is general in nature and augments the welding requirements of ASME BPVC Section IX and similar codes, standards, specifications, and practices, such as those listed in Section 2. The intent of this document is to be inclusive of chemical, oil, and gas industry standards, although there are many areas not covered herein, e.g. pipeline welding and offshore structural welding are intentionally not covered. This document is based on industry experience, and any restrictions or limitations may be waived or augmented by the purchaser.

### Corrosion and Materials

RP 932-B: Design, Materials, Fabrication, Operation, and Inspection Guidelines for Corrosion Control in Hydroprocessing Reactor Effluent Air Cooler (REAC) Systems

Provides guidance to engineering and plant personnel on equipment and piping design, material selection, fabrication, operation, and inspection practices to manage corrosion and fouling in the wet sections of hydroprocessing reactor effluent systems. The reactor effluent system includes all equipment and piping between the exchanger upstream of the wash water injection point and the cold, low-pressure separator (CLPS). The majority of these systems have an air cooler; however, some systems utilize only shell-and-tube heat exchangers. Reactor effluent systems are prone to fouling and corrosion by ammonium bisulfide ($NH_4HS$) and ammonium chloride ($NH_4Cl$) salts.

RP 934-A: Materials and Fabrication of 2 1/4Cr-1Mo, 2 1/4Cr-1Mo-1/4V, 3Cr- 1Mo, and 3Cr-1Mo-1/4V Steel Heavy Wall Pressure Vessels for High-Temperature, High-Pressure Hydrogen Service

Presents materials and fabrication requirements for new 2 1/4Cr and 3Cr steel heavy wall pressure vessels for high-temperature, high-pressure hydrogen service. It applies to vessels that are designed, fabricated, certified, and documented in accordance with ASME BPVC, Section VIII, Division 2, including Section 3.4, Supplemental Requirements for Cr-Mo Steels and ASME Code Case 2151, as applicable. This document may also be used as a resource when planning to modify an existing heavy wall pressure vessel.

Materials covered by this recommended practice are conventional steels, including standard 2 1/4Cr-1Mo and 3Cr-1Mo steels, and advanced steels, which include 2 1/4Cr-1Mo-1/4V, 3Cr-1Mo-1/4V-Ti-B, and 3Cr-1Mo-1/4V-Nb-Ca steels. This document may be used as a reference for the fabrication of vessels made of enhanced steels

(steels with mechanical properties augmented by special heat treatments) at purchaser discretion. However, no attempt has been made to cover specific requirements for the enhanced steels.

RP 934-C: Materials and Fabrication of 1 1/4CR-1/2Mo Steel Heavy Wall Pressure Vessels for High Pressure Hydrogen Service Operating at or Below 825 °F (441 °C)

Presents materials and fabrication requirements for new 1 1/4Cr-1/2Mo steel heavy wall pressure vessels and heat exchangers for high-temperature, high- pressure hydrogen service. It applies to vessels that are designed, fabricated, certified, and documented in accordance with ASME BPVC, Section VIII, Division 1 or Division 2. This document may also be used as a resource for equipment fabricated using 1Cr-1/2Mo Steel. This document may also be used as a resource when planning to modify an existing heavy-wall pressure vessel. The interior surfaces of these heavy wall pressure vessels may have an austenitic stainless steel or ferritic stainless steel weld overlay or cladding to provide additional corrosion resistance.

RP 934-E: Recommended Practice for Materials and Fabrication of 11/4Cr-1/2Mo Steel Pressure Vessels for Service above 825 °F (440 °C)

Includes materials and fabrication requirements for new 11/4Cr-1/2Mo steel and 1Cr-1/2Mo pressure vessels and heat exchangers for high temperature service. It applies to vessels that are designed, fabricated, certified and documented in accordance with ASME BPVC Section VIII, Division 1. This document may also be used as a resource when planning to modify existing pressure vessels. The interior surfaces of these pressure vessels may have an austenitic stainless steel, ferritic stainless steel, or nickel alloy weld overlay or cladding to provide additional corrosion resistance. This recommended practice is applicable to wall (shell) thicknesses from 1 in. (25 mm) to 4 in. (100 mm). Integrally reinforced nozzles, flanges, tubesheets, bolted channel covers, etc. can be greater than 4 in. (100 mm). At shell or head thicknesses greater than 4 in. (100 mm), 11/4Cr-1/2Mo and 1Cr-1/2Mo has been shown to have difficulty meeting the toughness requirements given in this document, but this does not preclude the use of this alloy if these properties can be met or if the equipment is designed with stresses below the threshold for brittle fracture.

TR 934-G: Design, Fabrication, Operational Effects, Inspection, Assessment, and Repairof Coke Drums and Peripheral Components in Delayed Coking Units

Includes information and guidance on the practices used by industry practitioners on the design, fabrication, operation, inspection, assessment, and repair of coke drums and peripheral components in delayed coking units. The guidance is general and does not reflect specific details associated with a design offered by licensors of delayed coking technology, or inspection tools, operating devices/components, repairs techniques, and/or engineering assessments offered by contractors. For details associated with the design offered by a licensor or services provided by contractors, the licensor or contractor should be consulted for guidance and recommendations for their design details and operating guidance. This document is a technical report and as such provides generally used practices in industry and is not an API recommended practice for coke drums in delayed coking units.

RP 583: Corrosion under Insulation and Fireproofing

Covers the design, maintenance, inspection, and mitigation practices to address external corrosion under insulation (CUI) and corrosion under fireproofing (CUF). The document discusses the external corrosion of carbon and low alloy steels under insulation and fireproofing, and external chloride stress corrosion cracking (ECSCC) of austenitic and duplex stainless steels under insulation. The document does not cover atmospheric corrosion or corrosion at uninsulated pipe supports, but does discuss corrosion at insulated pipe supports.

The purpose of this RP is to:

- help owner/users understand the complexity of the many CUI/CUF issues,

- provide owner/users with understanding the advantages and limitations of the various NDE methods used to identify CUI and CUF damage,
- provide owner/users with an approach to risk assessment (i.e. likelihood of failure, and consequence of failure) for CUI and CUF damage, and
- provide owner/users guidance on how to design, install, and maintain insulation systems to avoid CUI and CUF damage.

RP 939-C: Guidelines for Avoiding Sulfidation (Sulfidic) Corrosion Failures in Oil Refineries

Applies to hydrocarbon process streams containing sulfur compounds, with and without the presence of hydrogen, which operate at temperatures above approximately 450 °F (230 °C) up to about 1000 °F (540 °C). A threshold limit for sulfur content is not provided because within the past decade significant corrosion has occurred in the reboiler/fractionator sections of some hydroprocessing units at sulfur or H2S levels as low as 1 ppm. Nickel based alloy corrosion is excluded from the scope of this document. While sulfidation can be a problem in some sulfur recovery units, sulfur plant combustion sections and external corrosion of heater tubes due to firing sulfur containing fuels in heaters are specifically excluded from the scope of this document.

Bull. 939-E: Identification, Repair, and Mitigation of Cracking of Steel Equipment in Fuel Ethanol Service

Discusses stress corrosion cracking (SCC) of carbon steel tanks, piping, and equipment exposed to fuel ethanol as a consequence of being in the distribution system, at ethanol distribution facilities, or end user (EU) facilities where the fuel ethanol is eventually added to gasoline. Such equipment includes but is not limited to storage tanks, piping and related handling equipment, and pipelines that are used in distribution, handling, storage, and blending of fuel ethanol. However, data for pipelines in ethanol service is limited and caution should be used when applying guidelines from this document that have been derived mainly from applications involving piping and tanks in ethanol storage and blending facilities. SCC of other metals and alloys is beyond the scope of this document, as is the corrosion of steel in this service.

RP 941: Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants

Summarizes the results of experimental tests and actual data acquired from operating plants to establish practical operating limits for carbon and low alloy steels in hydrogen service at elevated temperatures and pressures. The effects on the resistance of steels to hydrogen at elevated temperature and pressure that result from high stress, heat treating, chemical composition, and cladding are discussed. This recommended practice (RP) does not address the resistance of steels to hydrogen at lower temperatures [below about 400 °F (204 °C)], where atomic hydrogen enters the steel as a result of an electrochemical mechanism.

This RP applies to equipment in refineries, petrochemical facilities, and chemical facilities in which hydrogen or hydrogen-containing fluids are processed at elevated temperature and pressure. The guidelines in this RP can also be applied to hydrogenation plants such as those that manufacture ammonia, methanol, edible oils, and higher alcohols.

RP 945: Avoiding Environmental Cracking in Amine Units

Discusses environmental cracking problems of carbon steel equipment in amine units. This publication provides guidelines for carbon steel construction materials, including, fabrication, inspection, and repair, to help ensure safe and reliable operation. The steels referred to in this document are defined by the ASTM designation system, or equivalent materials contained in other recognized codes or standards. This document is based on current engineering practices and insights from recent industry experience.

## OTHER MECHANICAL INTEGRITY DOCUMENTS FOR FIXED EQUIPMENT

### NACE Documents

Corrosion & Material Documents

- MR0103 Materials Resistant to Sulfide Stress Cracking in Corrosive Petroleum Refining Environments
- SP0114 Refinery Injection and Process Mix Points
- SP0169 Control of External Corrosion on Underground or Submerged metallic Piping Systems
- SP0170 Protection of Austenitic Stainless Steels and Other Austenitic Alloys from Polythionic Acid Stress Corrosion Cracking During a Shutdown of Refinery Equipment
- SP0296 Detection, Repair, and Mitigation of Cracking in Refinery Equipment in Wet H2S Environments
- SP0403 Avoiding Caustic Stress Corrosion Cracking of Refinery Equipment and Piping
- SP0472 Methods and Controls to Prevent In-Service Environmental Cracking of Carbon Steel Weldments in Corrosive Petroleum Refining Environments
- Publication 34103 Overview of Sulfidic Corrosion in Petroleum Refining
- Publication 34108 Carbonate SCC
- Publication 34109 Crude Distillation Unit—Distillation Tower Overhead System Corrosion

Tanks

- SP0205 Recommended Practice for the Design, Fabrication, and Inspection of Tanks for the Storage of Petroleum Refining Alkylation Unit Spent Sulfuric Acid at Ambient

Pressure Vessels

- SP0590 Prevention, Detection & Correction of Deaerator Cracking ASME Documents
- ASME PCC-1 Guidelines for Pressure Boundary Bolted Flange Joint Assembly
- ASME PCC-2 Repair of Pressure Equipment and Piping

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**References:**

Mechanical Integrity: Fixed Equipment Standards & Recommended Practices - API

# FLEXIBLE SHELL ELEMENT EXPANSION JOINTS

[*This article is a summary of Mandatory Appendix 5 of the ASME Section VIII, Division 1.*]

Flexible shell element (FSE) expansion joints are designed to provide flexibility for thermal expansions and also functions as pressure-containing elements. Typical single layer FSE expansion joints are shown in Figure 1 and are limited to applications involving only axial deflections.

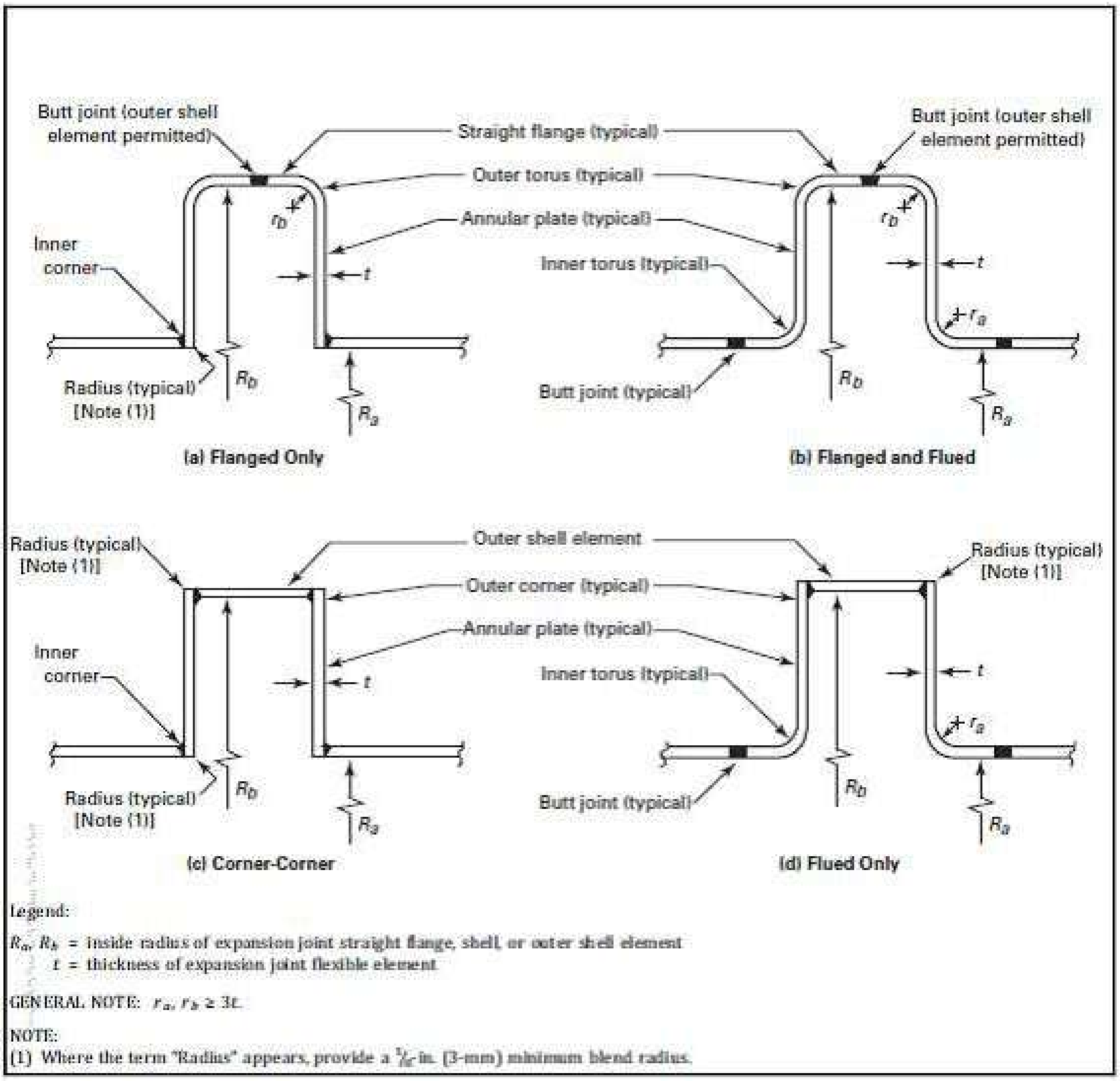


**Figure 1: Typical Flexible Shell Element Expansion Joints**

In all vessels with expansion joints, the hydrostatic end force caused by pressure and/or the joint spring force is contained by restraining elements (i.e., tube bundle, tubesheets or shells, external bolting, anchors etc.).

**DESIGN**

When carbon and low alloy steels are used for pressure-retaining components, minimum thickness exclusive of corrosion allowance is 0.125 in.

Elastic moduli, yield strengths, and allowable stresses are generally taken at operating temperatures when designing FSE expansion joints subjected to thermal loads. The design of flexible elements of the expansion joint must satisfy the following stress limits. These stress limits must be met both in corroded and noncorroded conditions.

1. MECHANICAL LOADS ONLY: Mechanical loads include pressure and pressure-induced axial deflections. The maximum stress in the joint is limited to 1.5S.
2. THERMALLY INDUCED DISPLACEMENTS ONLY: The maximum stress in the joint is limited to $S_{PS}$.
3. MECHANICAL LOADS PLUS THERMALLY INDUCED DISPLACEMENTS: The maximum stress in the joint is limited to $S_{PS}$.

The knuckle radius $r_a$ or $r_b$ of any formed element is at least three times the element thickness t as shown in the Figure 1. Extended straight flanges between the inner torus and the shell and between both the outer tori are permissible. An outer shell element between the outer tori is also permissible.

The calculation of the individual stress components and their combinations are performed by a method of stress analysis. The spring rate of the expansion joint may be determined either by calculation or by testing.

**FABRICATION**

The flexible element may be fabricated from a single plate (without welds) or from multiple plates or shapes welded together. When multiple plates or shapes are used to fabricate the flexible element, the following requirements apply:

1. Welds must be butt-type full penetration, Type (1).
2. Welds must be ground flush and smooth on both sides. For flexible elements to be formed, this must be done prior to forming.

The flexible element can then be attached to the shell, to the mating flexible element, or to the outer shell element. The circumferential weld in these attachments must be as follows:

1. Butt welds must be full penetration, Type (1).
2. Corner joints must be full penetration welds with a covering fillet and no backing strip. The covering fillet must be located on the inside of the corner and must have a throat at least equal to 0.7 times the minimum thickness of the element being joined, or 1/4 in. It is permitted for the corner weld to be full penetration through either element being joined.

Nozzles, backing strips, clips or other attachments cannot be located in highly stressed areas of the expansion joint. These are the inner torus, annular plate and outer torus. Nozzles and other attachments located in the outer straight flange or outer shell elements must satisfy the axial spacing requirements of Figure 2.

The welds within the shell courses adjacent to the flexible elements must be full penetration butt welds, Type (1) for a distance of $2.5\sqrt{Rt}$ where 'R' is $R_a$ or $R_b$, and 't' is thickness of the shell or outer shell element as applicable.

**MARKINGS AND REPORTS**

When expansion joint is provided, following additional data is included on the Data Report:

1. Uncorroded and corroded spring rate
2. Axial movements (+ and -) and associated loading condition, if applicable.

3. That the expansion joint has been constructed to the rules of Appendix 5 of the ASME Section VIII, Division 1 Code.

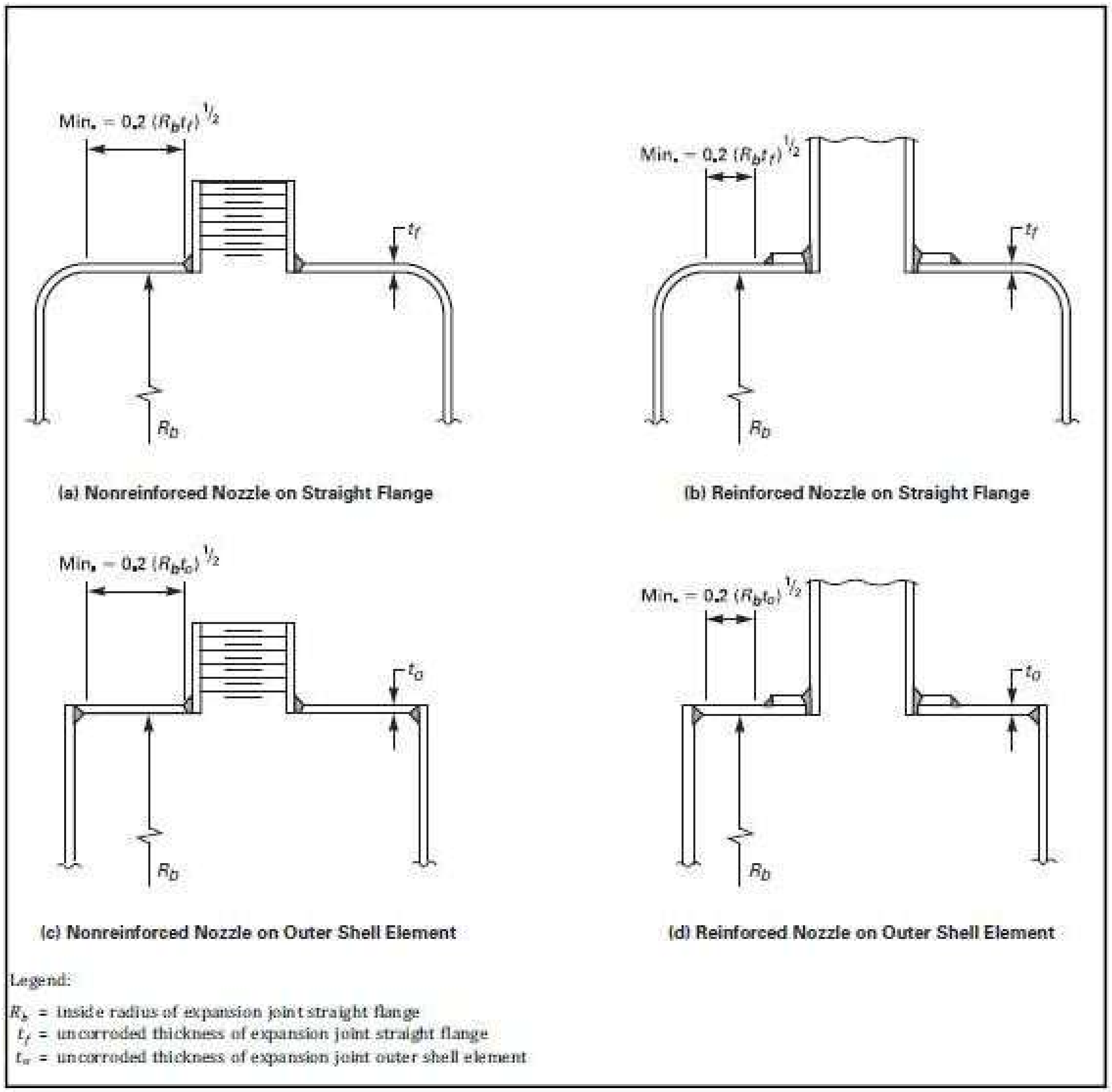


**Figure 2: Typical Nozzle Attachment Details Showing Minimum Length of Straight Flange or Outer Shell Element**

When expansion joint is provided by a parts manufacturer, he must identify the vessel for which the expansion joint is intended on the Partial Data Report.

**References:**

ASME Boiler & Pressure Vessel, Section VIII, Division 1 – Appendix 5

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# SOFT SENSOR FOR DEGRADATION MONITORING AND PREDICTIVE MAINTENANCE

**CONTRIBUTIONS FROM: Utsav Kumar, Soham Kulkarni, Prem Kumar Lakkabathula**

## INTRODUCTION

Challenge:

The downstream oil and gas industry uses multiple equipment setups that show degradation over the course of operational runs. A few key equipment that fall under this category are heat exchangers, compressors, pumps, reboilers, and evaporators. Such degrading equipment account for more than 50% of all equipment in a downstream oil and gas plant and play a crucial role in modulating both efficiency and quality. Any significant decline in performance of such equipment may limit the overall efficiency leading to equipment changeover or even untimely plant turnaround, therefore incurring unnecessary financial loss. To avoid such inadvertent scenarios, there has been a constant effort to monitor such degrading equipment. The pursuit to monitor fouling has inspired industry researchers to work towards a solution, although accomplishing the same has several challenges:

- Unavailability of all required variables around equipment to perform first principle calculations.
- In cases where first principle calculations can be performed, some key assumptions/approximations have to be made which diminish the accuracy of the model.
- Widely used software tools require both equipment specification and process data for model development. In addition, they require high volumes of data to learn equipment characteristics and may still be unreliable in case of process variation.
- Using multiple univariate or bivariate charts to analyze fouling trend is a tedious task and requires deep process understanding.

Approach:

The advent of Industry 4.0, catapulted by advancement of machine learning (ML) algorithms and its ever-increasing application in oil and gas industry, has allowed industry researchers to develop and deploy novel data-based solutions. In a nutshell, majority of the challenges discussed in the previous section can be addressed via an ML approach. Further, the oil and gas industry has been storing a lot of underutilized operations data for long periods. Thus, there is a lot of scope for the ML approach to succeed given its potential, market demand, and process data availability.

In this area, we propose a soft sensor framework that can be adapted to most of the degrading equipment discussed above. The core idea is to develop a multivariate model that learns the correlation among predictor variables and between predictor and dependent variable(s) (fouling indicator). The soft sensor is trained to identify deviation in the process induced particularly by fouling, muting the effect of various kinds of other normal process variations. Further, the degree of deviation between current and clean data (without fouling) is calculated to assess the severity of fouling. A detailed discussion on various aspects of Soft Sensor framework is covered in the following sections. The overall work is sub-divided into the following:

- Soft Sensor Development
- Soft Sensor in Real Life (Reboiler/Heat Exchanger)
- Automation and Scalability
- Broad Applicability
- Conclusion

## SOFT SENSOR DEVELOPMENT

Data Acquisition: Data from historical runs of the equipment is acquired. For setting up a model, a minimum of one complete run is required. In case an important variable is unavailable, a complimentary variable that qualitatively represents the actual variable is adopted.

Data Preparation: Data cleansing is done via process understanding (separating downtime and uptime) and multivariate outlier technique (outlier detection). Subsequently, data is categorized into clean and fouled sections. A section of data is deemed clean when there is minimal or no fouling, whereas data is considered foul when there is considerable increase in fouling; this is separated via a threshold. For a single run, the threshold between clean and fouled data is obtained via a combination of process understanding and exploratory data analysis (EDA). For multiple runs, statistical cut-points provide threshold numbers that are similar to first principle approach.

Feature Engineering: Using dimensionality reduction techniques, latent variables (LVs) are derived to efficiently capture system variability. LVs can be either linear or nonlinear combinations of predictor variables. Predictor variables that have minimal or no effect on equipment performance are discarded.

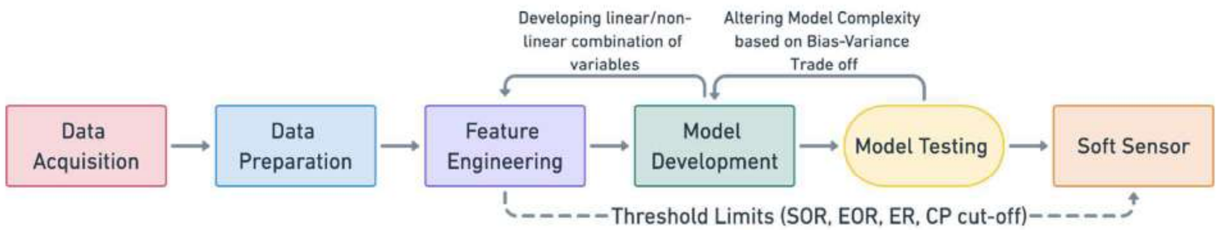



**Figure 1: Soft sensor development methodology (general schema)**

Degree of Fouling (DOF): For soft sensor development, variable deviating during the course of fouling are identified as dependent variables. A similarity between the actual and predicted value of dependent variables (with no fouling assumption) is utilized to capture fouling trends and transformed to a single score (monotonic behavior) termed as Degree of Fouling (DOF). Since, DOF is a relative number with reference to a benchmark (clean system), DOF values are qualitative representations of fouling, and higher DOF reflects higher fouling and vice versa.

Model Development: Clean data is divided into train and test sets and multivariate regression analysis is performed on train sets to capture system characteristics. Based on model performance on test sets combined with bias-variance trade-off analysis, optimal model complexity is determined, while achieving the desired accuracy. The complexity in the model can be introduced in the form of nonlinearity at two levels: developing non-linear combination of variables during feature engineering, or building a non-linear relationship between the predictor and dependent variable(s), or a combination of both. Generally, model development iteration starts with an assumption of linearity and then based on performance, model complexity is increased.

Model Testing: A continuous iteration between model development, feature engineering, and model accuracy is performed until an expected accuracy is attained.

Threshold Calculation: DOF is sub-divided into three regions:

- Clean Phase (CP): CP is the initial period between SOR (Start of Run) and CP cut-off when the system shows minimal or no fouling.
- Fouling Phase (FP): FP is the region between CP cut-off and EOR (End of Run). A system is assumed to reach EOR when it starts limiting the overall operation.

- Extended Phase (EP): EP is the region between EOR and ER (Extended Run). ER is the threshold when the system is finally taken offline. Thus, EP depicts the operating region with reduced load as the system has already surpassed limiting conditions.

For multiple runs, corresponding threshold values are estimated statistically. For fewer runs, a hybrid approach of first principle and statistical cut-off is deployed.

**Key Insights**:

Soft sensor readings integrated with historical runs and post data analysis are projected on a Dashboard to derive key insights on fouling.

- Early Fouling Indication**:** Soft sensor readings facilitate proactive implementation of required measures through DOF and rate of DOF.
- Fouling Comparison**:** DOF for the current run can be compared to previous run(s) to assess quality of operation and fouling status.
- Regularizing Antifoulant Dosing**:** The real time DOF rate helps to regularize antifoulant flow rate.
- Estimating Remaining Useful Life (RUL)**:** Parametric or nonparametric curve fitting is performed on selected observation window to estimate RUL. RUL estimation supports the decision-making process for turnaround or changeover depending upon the system.

## SOFT SENSOR IN REAL PROCESS (HEAT EXCHANGER)

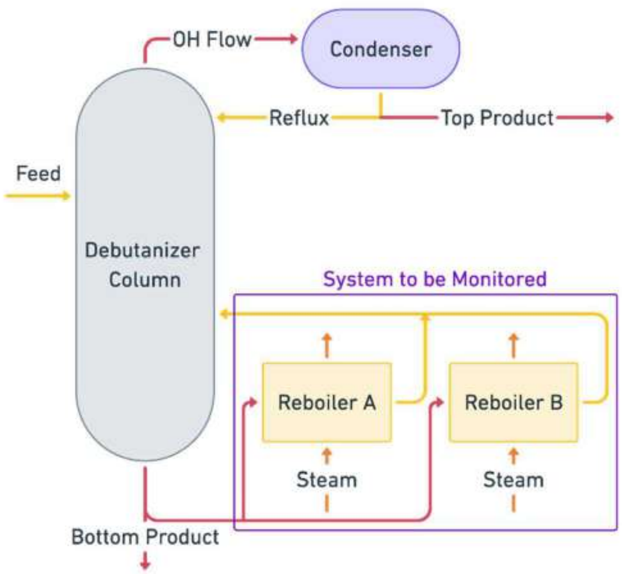
System: To demonstrate the functionality and effectiveness of the Soft Sensor framework, a debutanizer reboiler system is analyzed using the proposed methodology. A reboiler is a common equipment in downstream distillation processes prone to fouling. The block diagram for the process and reboiler system under study is shown in Figure 2. In brief, a debutanizer column separates the lighter components (C1-C4) (recovered from top) from its heavier counterparts (bottom residual). The feed to the reboiler is heavy C6+ compounds and over the period reboiler exhibits considerable amount of fouling. The debutanizer columns under study have two reboilers, A and B, where, at a given instant, a single reboiler is online and the other is in standby. An analysis on run length shows that reboilers A and B have vastly scattered run lengths and it is critical to estimate RUL and fouling progression in these reboilers (Figure 2).

Objective: Utilize a soft sensor to assess fouling in a real time operation; provide insights on rate of DOF and progression in fouling. Further, predicting RUL to ensure an optimized changeover scheduling.

Variable Selection and Soft Sensor Development: Process variables around the system boundary are selected and missing variables are represented by their respective complimentary variables. LP Steam Valve OP is selected as dependent variable to develop fouling tracker, i.e. DOF. A detailed description of the variables considered in Soft Sensor development is presented in Figure 2. Data from previous runs is segregated into clean and fouled sections. From iterative analysis, the threshold for CP cut-off is selected as 6 (DOF units). Process data below and above this threshold is considered as clean and fouled respectively. A multivariate linear regression is developed on clean data between independent and dependent variables, learning the characteristics of clean system. Subsequently, the deviation between predicted and actual value of dependent variable is transformed into DOF and captured in Soft Sensor.

Results and Discussion:

The current discussion focuses on Reboiler B and its existing runs for further investigation. Based on Soft Sensor output, a DOF plot for current run is developed and respective thresholds (SOR, CP cut-off, EOR and ER) are marked (Figure 3A). The significance of each threshold limit has been discussed in previous section. For reboiler B, threshold limits have been estimated statistically and verified from process understanding. As mentioned in the previous section, DOF does not have a quantitative significance but it qualitatively emulates the progression in equipment fouling. Hence, for reboiler B, DOF resonates degradation in the heat transfer coefficient. However, the true value of heat transfer coefficient is generally unknown thus, finding the correlation between heat transfer coefficient and DOF is improbable.




| Process Variables | Description |
|---|---|
| LP Steam Flow | Flow Rate of Steam into Reboiler |
| LP Steam Pressure | Captures saturation level and heat transfer capacity |
| LP Steam Battery Limit Temperature | Alternate variable to capture steam inlet T |
| Column Feed Flow I | Primary Feed Stream to Debutanizer |
| Column Feed Flow II | Secondary Feed Stream to Debutanizer |
| Column Bottom Temperature | Proccess inlet T to Reboiler |
| LP Steam Valve Opening | Dependent Variable |

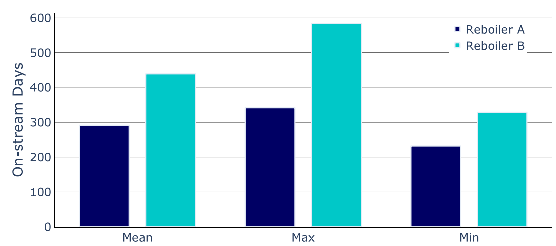



**Figure 2: (Left) Block diagram of the process; (Top Right) List of independent and dependent variable(s) considered for soft sensor development; (Bottom Right) Runlength comparison for exchanger A and B**

DOF and thresholds will be unique for every system, hence, DOF plots can't be compared across different systems. Although, DOF can be compared across historical runs of the same system (Figure 3B). Such comparative analysis allows the operator to track the positioning of current run relative to historical runs. In Figure 3B, a similar comparison is drawn between reboiler B's current run and its predecessor runs. At a glance, the quality of current run looks closer to its best run, implying that performance of current run is reasonable. As mentioned previously, DOF comparison can be grouped with the rate of DOF to provide early fouling indication in real time.

The DOF curve for reboiler B makes an s-shaped curve with a long tail (Figure 3A). The tail is noticeable up until CP cut-off threshold, following which there is a significant increase in DOF and it flattens as it approaches EOR or ER threshold. Performing RUL prediction when the system is in CP (Clean Phase) region will provide an abstract number, therefore, real time monitoring is mainly supported by DOF, rate of DOF, and comparison plots during this period. Additionally, the RUL prediction in the initial period of operation isn't resourceful, instead DOF status and its progression are more critical to ascertain quality of operation and flagging discrepancy. As the system enters FP (Fouling Phase) region, RUL indicator is brought online to provide an accurate changeover date along with the previously mentioned fouling indicator. Given the intricacy of RUL prediction, a window option for curve fitting is implemented. In Figure 3C, an appropriate window is selected and a best fit curve (using mean squared error) is selected from the available options of parametric and non-parametric curves.

The trendline obtained from the best fit is extended till it intersects the EOR and ER threshold (Figure 3D). A 95% confidence interval is adopted to measure the uncertainty around the prediction. A continuous prediction of RUL reported by the Soft Sensor guides the operator to a plan changeover accordingly. In the absence of an RUL predictor, operator tends to opt for an early changeover, incurring unnecessary financial loss. For e.g., the RUL for a current run is estimated to be (462 +/- 3) days assuming EOR threshold as changeover point, although, the system was taken offline after 448 days, leading to a loss of (14 +/- 3) days.

Overall, the case study highlights various levels of information that can be unlocked via the Soft Sensor framework to monitor and control fouling, and optimize the changeover process.

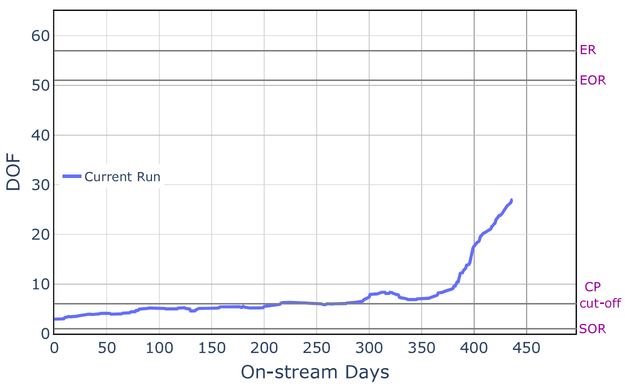



*Figure 3A: DOF curve for exchanger B with thresholds*

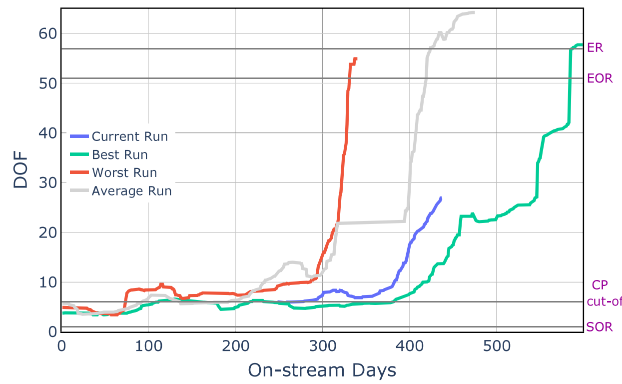



*Figure 3B: DOF comparison with previous runs*

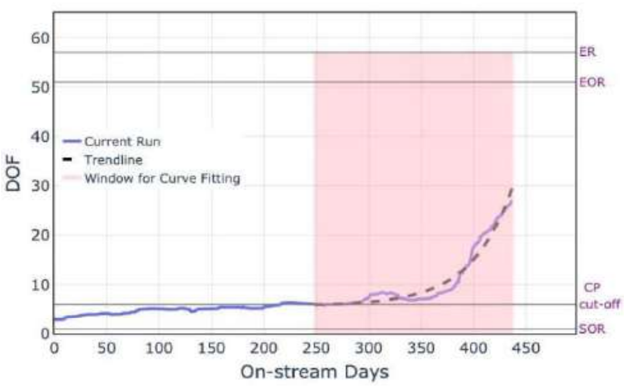



*Figure 3C: Window selection for curve fitting*

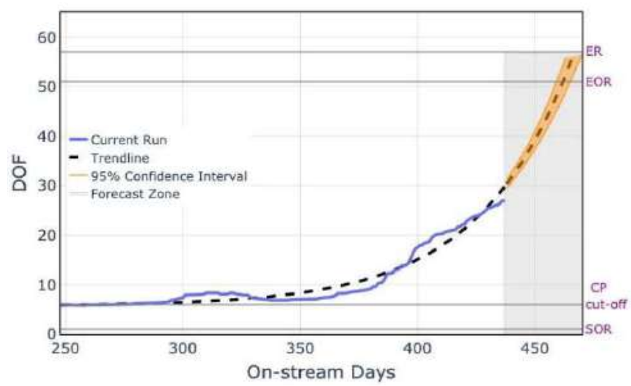



*Figure 3D: Forecasting RUL for EOR and ER conditions*

## AUTOMATION, VISUALIZATION AND SCALABILITY

To ensure that the Soft Sensor model is accessible to a wide range of users with and without an analytics background, an intuitive frontend is designed to enhance user experience (Figure 4). The following features have been embedded to cater to various user requirements.

- User Level Interface: (Section 1) The interface is developed to serve multiple users at a time. Any registered user can log into the portal and access the Soft Sensor modules.
- 360 Degree Analytics**:** (Section 2) The product offers an all-round evaluation of the degrading system via options described as below:
    - **Home:** Provides the option to run the Soft Sensor module on the listed system and given input dataset. To select the specific system required, the user can refer to Section 4 i.e. “HX Selection”. The latest input data can be uploaded via the “Upload” tab next to Input File (Section 3). The Download option allows the

user to examine previous data. In addition, all the required files to setup the module are kept under Config Files (Section 3) and can be accessed by designated user.

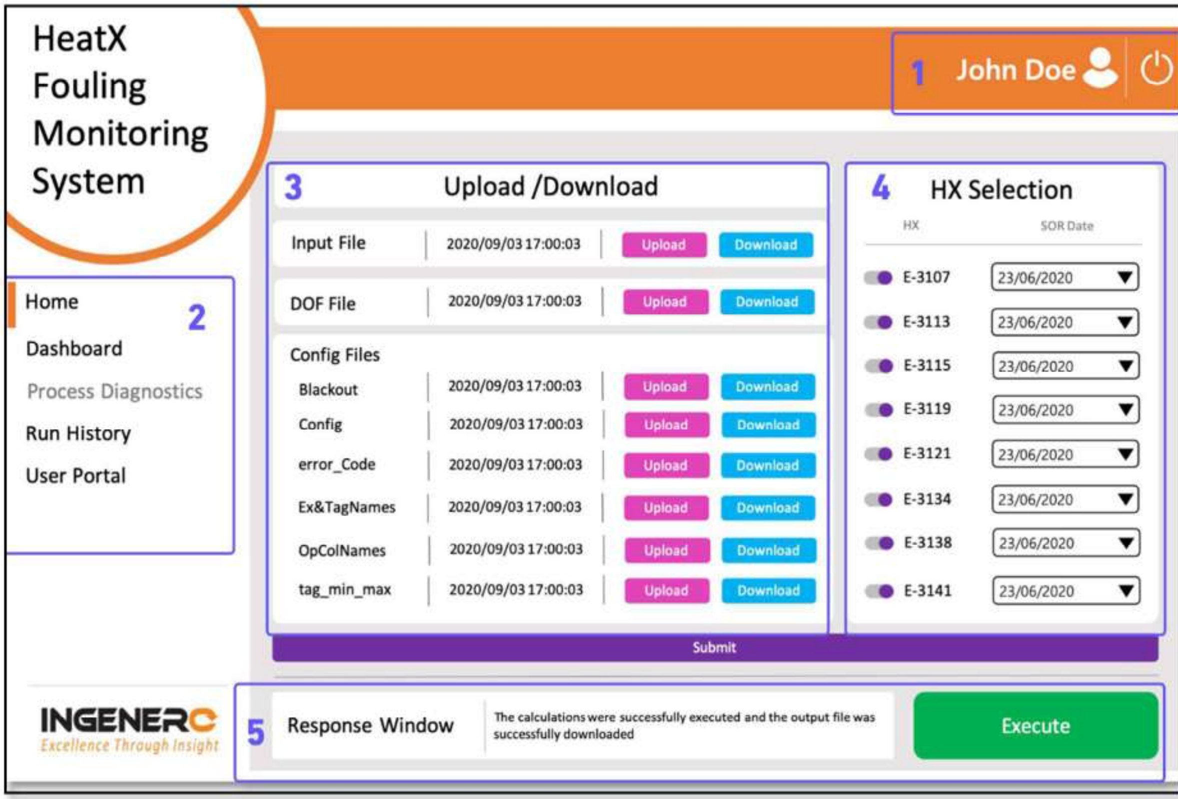



**Figure 4: Layout of front end to automate Soft Sensor for multiple equipment**

- **Dashboard:** The DOF output from the Soft Sensor can be qualitatively visualized through the Dashboards. More detailed insights like rate of DOF, DOF comparison with prior runs, RUL prediction etc. can also be accessed through the "Dashboard" tab. A bird's eye snapshot of some systems which are monitored through the dashboard is shown in Figure 5.
- **Run History:** To track the Soft Sensor runs performed across users, a user can avail information such as time of last run, status of the run and also the changes made to the configuration files.
- **User Portal:** The user portal addresses the administrative requirements of hierarchical user management.

- **Response Window:** (Section 5) The response window displays the progression status of the Soft Sensor run. Any discrepancy in user provided information or run time error will be highlighted through an error message in response window.

The developed product has a flexible framework to add new systems with ease. Simultaneously, the overall product and related I/O format are customizable based on user requirements.

## BROAD APPLICABILITY

The Soft Sensor framework and the underlying technique have a broad spectrum of applicability. The case study presented in this work provides information specific to a reboiler but the model can be extended to other degrading systems like compressors, pumps, all types of process exchangers, and catalysts in catalytic reactors. The Soft Sensor framework can also be used to formulate complex interdependent degrading systems and derive a singular degradation metric for a combined system comprising of several subsystems. Ingenero has executed and validated Soft Sensors for above mentioned systems with real-life data.

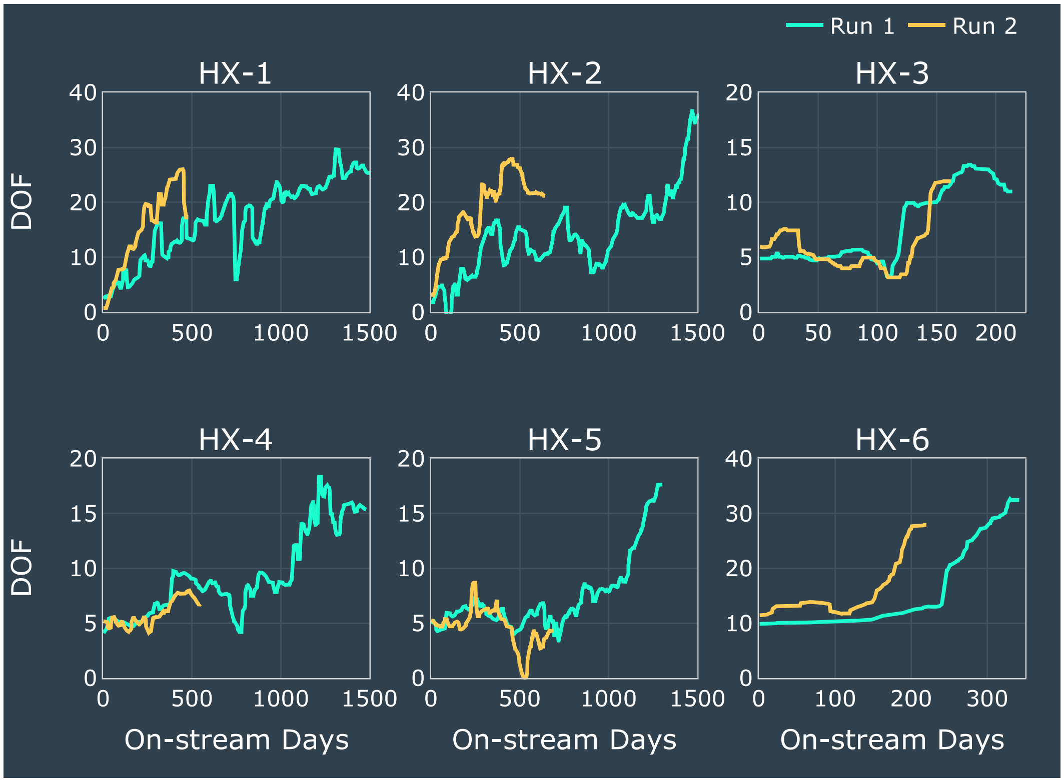



**Figure 5: Snapshot of dashboard used for monitoring multiple systems simultaneously**

## CONCLUSION

The work presented in this paper encapsulates a general "Soft Sensor for fouling" framework that can be implemented to monitor fouling progression in inherently degrading systems. A concept of monotonic variable termed DOF is developed to capture fouling via multivariate linear/nonlinear regression. A multivariate outlook ensures that a fouling induced process shift is isolated from normal operation. The DOF, rate of DOF, DOF comparison (with previous runs), and RUL prediction provide an early fouling indication and run length estimation. An application of the same is presented using a reboiler changeover study, indicating early changeover in the absence of Soft Sensor guidance. At present the Soft Sensor framework has been successfully extended to multiple process systems including charged gas compressors, reboilers, and catalyst degradation. The framework has been automated to develop a customizable product that enhances user experience and provides the required information with minimal efforts. The product has been kept flexible to include addition of the new system and is resilient to any user specific or I/O errors.

The immediate work is focused on developing a Process Diagnostics feature for front end (Figure 4 Section 2). It will entail the user about the system parameters which are most contributing towards system degradation and guide them to take proactive actions. It will also flag the instances where system shows abruptly high fouling rate and prompts user action. Lastly, it will provide actionable recommendations based on the RUL estimation.

In order to progressively evolve Soft Sensor framework, the techniques underneath the framework are being refined with feedback from users and self-testing to increase its robustness. Similarly, common customization requirements from users are being absorbed into base product. Depending on the process complexities, alternate algorithms for model building and RUL prediction are being explored to improve accuracy, performance, and reliability of Soft Sensors.

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***Utsav Kumar*** *is a Data Scientist with experience in developing and deploying AI/ML models across diverse industry segments, including Cement, Carbon Black, and Oil & Gas. He received his Bachelor's and Master's degrees from Indian Institute of Technology, Kanpur. He continued his research work at Vanderbilt University, focusing on high performance computing, Monte Carlo & molecular dynamics simulation and optimization. Utsav is a cricket enthusiast and ardently follows the NBA.*

***Soham Kulkarni*** *is a Chemical Engineer and seasoned Analytics Consultant with 5 years of domain experience in digital manufacturing. In his role, he empowers and transforms his petrochemical clients with analytics tools that achieve sustainable growth.*

***Prem Kumar*** *is a Data Analyst. He has a Bachelor's degree in Chemical Engineering from the National Institute of Technology, Warangal and a Master's degree in Chemical Engineering from the Indian Institute Of Technology, Roorkee.*

# HEAT EXCHANGER FOULING: ONLINE MITIGATION METHODS (PART 2)

*The following article is the second part in a two part series addressing broad categories of mitigation methods of heat exchanger fouling – this part addresses mechanical fouling mitigation methods. The first part in the previous issue of the newsletter addressed chemical fouling mitigation methods.*

## INTRODUCTION

A number of mechanical mitigation techniques have been developed which generally are based on one of the following mechanisms:

a. Short-time overheating of the heat transfer surfaces. The different thermal expansion of tubes and tube deposits may cause cracking of the deposit

b. Mechanical vibration of heat transfer surfaces

c. Acoustical vibration of heat transfer surfaces

d. Increased shear stress at fluid deposit interface.

e. Reduced adhesion of deposits

## LIQUID FLOW

Most of the commonly used fouling mitigation techniques have been developed for the tube-side liquid in shell and tube heat exchangers. Even though attempts have been made to develop mechanical online mitigation devices for non-tubular heat exchangers, their installation has not penetrated the market.

### Reversal of Flow Direction

Regular reversal of the flow direction in conjunction with a short-time increase of the flow velocity is sometimes used as a method to mitigate the formation of weak deposits. Figure 1 shows that this procedure reduces the fouling resistance, but only for a short period of time. A much better performance could be achieved by operating at a higher flow velocity.

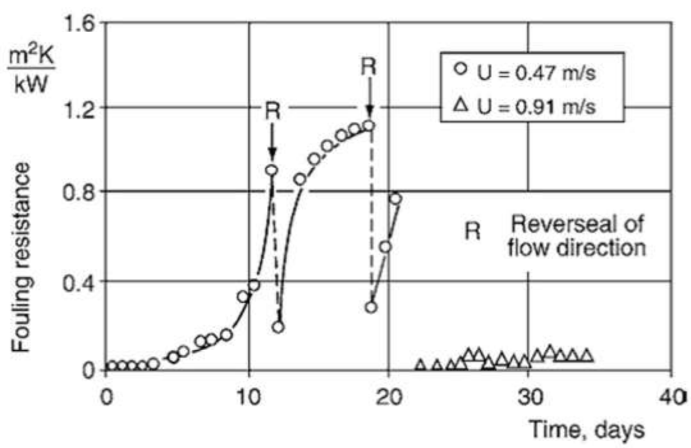


**Figure 1: Continuous Cleaning by Reversal of Flow Direction**

### Gas Rumbling

Deposits with moderate stickability to the heat transfer surfaces (e.g., particulate, and some biological deposits) can be dislocated and washed out by increasing the fluid shear forces for a short time, in regular time intervals. This can be achieved by increasing the flow velocity, if enough pump capacity is available. More effective is, however, to introduce compressed air or nitrogen into the liquid system. The resulting highly turbulent gas-liquid two-phase flow can provide shear forces and pressure fluctuations, which are substantially higher than for single phase flow. Gas rumbling is commonly used in cooling water applications.

### Ultrasound

On the laboratory scale, some success has been achieved in removing/inhibiting deposits by ultrasonic vibrations. So far, however, technical limitations have prevented the extrapolation of these results into industrial practice.

### Tube Inserts

Tube corrugations and tube inserts can increase the plain tube heat transfer coefficient by a factor of 2–15. This is achieved by reducing the average thermal boundary layer thickness. As deposition rates for most fouling mechanisms are inversely dependent on fluid wall shear stress and heat transfer surface temperature, reduction of the viscous and thermal sublayer thickness may also considerably reduce fouling. It must be considered that, for constant mass flux, the increased thermal efficiency is always accompanied by an increased pressure drop per unit length; therefore, these inserts work best for flow in the laminar or transitional flow regime. In combination with further reduction of flow velocity (i.e., tube passes) design variations may be possible where significant improvements of heat transfer can be achieved with no or little increase in pressure drop. Typical inserts are twisted tapes, coil inserts Figure 2 and wire matrix inserts Figure 3.

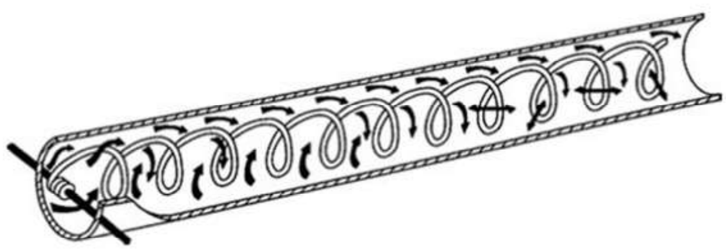

**Figure 2: Spiral Insert**

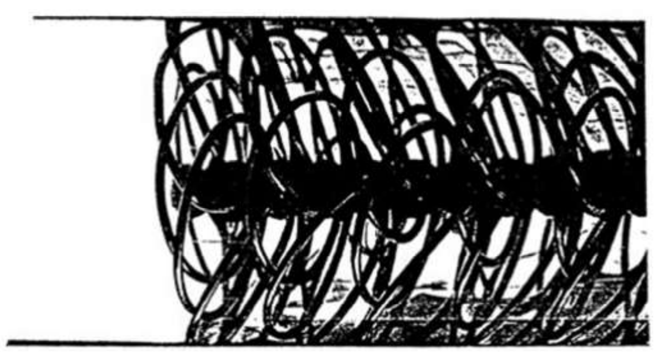

**Figure 3: Wire Insert**

**Continuous Transport of Cleaning Devices through Tubes**

These methods require major modifications of the flow system and are, therefore, best implemented in the design stage. However, they have the advantage that exchangers may be kept clean over long periods of time. All systems work best if applied to an initially clean heat exchanger.

A number of companies have developed continuous tube cleaning systems using small nylon brushes which are inserted into each tube, see Figure 4. These brushes are pushed through the tubes by the fluid flow. For continuous operation and optimum cleaning efficiency, the flow direction has to be reversed about every 8 hours. Life expectancy of the brushes is about 5 years. It is claimed that the time for amortization is between 8 and 16 months.

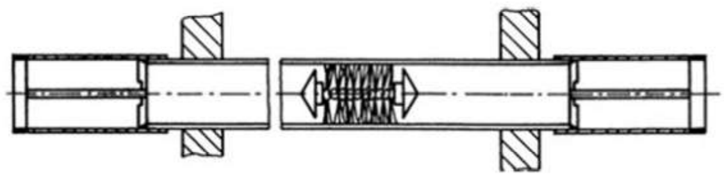

**Figure 4: Continuous Cleaning System with Wire Brush System**

There are many examples for the successful application of the brush tube cleaning system. However, their most effective installation is in smaller, water-cooled heat exchangers, for example, for the central air-conditioning systems of office buildings, hotels, or hospitals.

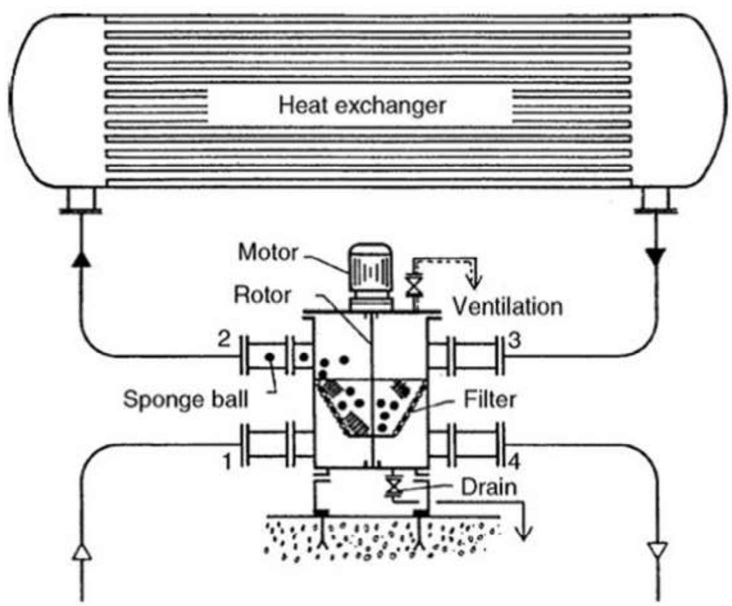


**Figure 5: Typical Layout of Sponge Ball Cleaning System**

For large installations, more consistent results were obtained with a system where sponge balls with a rough surface are circulated through the heat exchanger, see Figure 5. The diameter of the sponge balls is slightly larger than the inside diameter of the tubes and the system is designed such that each tube sees a sponge ball every 5 to 10 minutes. Since the diameter of the sponge balls decreases with time and because of inevitable ball losses through the screening system, the sponge balls have to be replaced regularly. For hard and adherent deposits, carborundum coated sponge balls can be used. According to the manufacturers, application of sponge ball systems may reduce the fouling resistance to close to 0. The application of sponge ball systems is limited to temperatures below 120°C. Several companies supply sponge ball systems and complete maintenance packages with different levels of complexity, size, and cost.

Online cleaning systems are not effective against stones, clamshells, etc. and need upstream devices to remove debris and macroscopic organic matter from the incoming water.

**GAS FLOW**

Online mechanical techniques vary greatly, but soot blowers are the most popular for gas-side use. Some of other techniques such as scrapers, rappers, and chains work well in special applications but are not as readily available. Two common types of soot blowers are jet soot blowers and sonic soot blowers.

- The jet type of soot blower operates by emitting pulses of steam, air or water at programmed intervals directed at the tubes and/or down tube lanes to dislodge the deposits and re-entrain them in the gas stream. These soot blowers work best if used frequently, thus avoiding the build-up of material. When build-up occurs, it insulates the surface from the coolant, allowing a temperature rise that can produce a glassy deposit. Glassy deposits are much harder to dislodge and frequently require shutdown for their removal. Jet soot blowers come in two types:
    i. The fixed position rotating type is installed inside the heat exchanger, and
    ii. The retractable type periodically passes an externally mounted nozzle through the heat exchanger. The fixed position soot blowers require little additional floor space, but they can usually not be used if the temperature exceeds 1000°C. As more than 100 soot blowers may be installed in large fired boilers, steam, and pressurized air consumption may cause considerable costs.
- According to the manufacturers, installation, and operation costs of sonic soot blowers are only 10% of those of jet soot blowers. Sonic soot blowers perform best in the cooler regions of furnaces or in other apparatus where glassy phases of deposits are not encountered. They operate by emitting sound pressure waves that loosen the particulates and allow them to be carried away with the gas stream. Under normal operations, sonic horns need only sound for 15–30 s every 10–30 min. Horns are constructed of materials that can withstand temperatures up to 1000°C. Sonic soot blowers may not, however, be able to loosen the harder deposits that can be removed by the high velocity steam, air or water jets. Sonic soot blowers are available at sonic or infrasonic range.

For very sticky deposits or if jet soot blowing may cause the temperature to drop below the acid dew point, 5 mm diameter cast iron spheres may be poured over the pipe arrangement. For extremely severe gas-side fouling problems, fluidized bed technology should be considered as an alternative.

The control of operating conditions is a very important consideration in the prevention of gas-side fouling. Some of the most important controls are:

- Maintain surface temperature above acid dew-point temperature
- Control amount of excess air, which governs the conversion of $SO_2$ to $SO_3$ and hence the amount of $H_2SO_4$ formed
- Control combustion parameters such as fuel injection pattern, fuel injection schedule and fuel viscosity
- Use fuel/air premixing to eliminate soot production
- Quench hot flue gases to solidify molten and soft particles to prevent attachment at cooler heat transfer surfaces

The control of combustion conditions is a difficult task due to the great variability in the quality of fuel supplies. Variability of fuel characteristics is a particular problem for those industries that burn waste products.

## OTHER DEVICES FOR FOULING MITIGATION

Particulate fouling is usually mitigated by the addition of surfactants or dispersants. If the surface tension is reduced, large particle agglomerates can break down into smaller particles, which tend less to sedimentation. Dispersants impart like charges to both the heat transfer surface and the particles and reduce deposition. For cooling water applications polyacrylates or polysulfonates are used with molecular weights between 2000 and 3000 g/mol. The addition of polyphosphates to reduce scaling may cause a slight reduction of the dispersion of particulates.

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**References:**

VDI Heat Atlas

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# EFFECTS OF ALLOYING ELEMENTS IN STEEL

Alloying elements are added to effect changes in the properties of steels. The purpose of this article is to cover some of the different alloying elements added to the basic system of iron and carbon, and what they do to change the properties or effectiveness of steel.

### (Al) ALUMINUM

When added to molten steel, mixes very quickly with any undissolved oxygen and is therefore considered one of the most common deoxidizers in making steel. Aluminum also is used to produce a fine grain structure and to control grain growth.

### (B) BORON

Boron is added to steel in small amounts of 0.0005 to 0.003% to improve hardenability without loss of ductility. In combination with other alloying elements, boron acts as an "intensifier", increasing the depth of hardening during quenching. Its effectiveness is most noticeable at lower carbon levels.

### (C) CARBON

Presence of carbon in iron is necessary to make steel. As carbon content increases, there is a corresponding increase in tensile strength, and resistance to wear and abrasion. The hardness of steel is increased by the addition of more carbon, up to about 0.65%. Wear resistance can be increased in amounts up to about 1.5%. Beyond this amount, increases of carbon reduce toughness and increase brittleness. Additionally, as carbon content increases, steel becomes increasingly responsive to heat treatment. The carbon content in steel defines its classification as follows:

- Low Carbon – under 0.4 percent
- Medium carbon – 0.4 to 0.6 percent
- High carbon – 0.7 to 1.5 percent

Carbon is the single most important alloying element in steel.

### (Cb) COLUMBIUM

Columbium in 18-8 stainless steel has a similar effect to titanium in making the steel immune to harmful carbide precipitation and resultant inter-granular corrosion. Columbium bearing welding electrodes are used in welding both titanium and columbium bearing stainless steels since titanium would be lost in the weld arc, whereas columbium is carried over into the weld deposit.

### (Co) COBALT

Cobalt Increases strength and hardness, and permits higher quenching temperatures and increases the red hardness of high speed steel. It also intensifies the individual effects of other major elements in more complex steels.

### (Cr) CHROMIUM

Like carbon, chromium helps the response to heat treatment. An increase in depth of hardness is also noticed with its use. It also increases tensile strength, toughness, resistance to wear and abrasion, and scaling at elevated temperatures. Used in conjunction with other alloys, chromium is one of the popular alloying elements.

Probably one of the most well-known effects of chromium on steel is the tendency to resist staining and corrosion. Steels with 14 percent or more chromium are referred to as stainless steels. A more accurate term would be stain resistant. Stainless tool steels will in fact darken and rust, just not as readily as the non-stainless varieties.

**(Cu) COPPER**

The addition of copper in amounts of 0.2 to 0.3 percent primarily improves steels resistance to atmospheric corrosion. It also helps in some degree to increase tensile and yield strengths with only a little loss in ductility.

**(Fe) IRON**

Although it lacks strength, iron is very soft and ductile, and does not respond to heat treatment to any degree. Iron is the primary element in steel. With the addition of other alloying elements, required mechanical properties can be achieved.

**(Mn) MANGANESE**

Manganese is present in most commercially made steels and is next to carbon in its importance in steel making. Manganese slightly increases the strength of ferrite, and also increases the hardness penetration of steel in the quench by decreasing the critical quenching speed. This also makes the steel more stable in the quench. Steels with manganese can be quenched in oil rather than water, and therefore are less susceptible to cracking because of a reduction in the shock of quenching.

**(Mo) MOLYBDENUM**

Molybdenum increases the hardness penetration of steel, slows the critical quenching speed, and increases high temperature tensile strength (i.e., it has good creep resistance).

**(Ni) NICKEL**

Nicket increases strength and toughness and has good fatigue resistance. Steels with nickel usually have more impact resistance than steels where nickel is absent. This is true especially at lower temperatures. Nickel also tends to help reduce distortion and cracking during the quenching phase of heat treatment.

**(Nb) NIOBIUM**

In low carbon alloy steels, Niobium lowers the transition temperature and aids in a fine grain structure. Niobium retards tempering and can decrease the hardenability of steel because it forms very stable carbides. This can mean a reduction in the amount of carbon dissolved into the austenite during heat treating.

**(P) PHOSPHORUS**

Phosphorus is seldom deliberately added to steel but is carried as a residual or incidental element. When it is added it is usually for the purpose of machinability. Phosphorous is present in all steels and tends to increase resistance to corrosion while increasing yield strength.

**(Pb) LEAD**

Lead is used in steel to improve machinability. In small amounts of .15 to .35% and finely divided and distributed, it has no known effect on the mechanical properties of steel.

**(S) SULFUR**

Sulfur is usually found in all steels and like phosphorus is considered a residual element. When added purposely it substantially increases machinability. The amount for this purpose is usually from .06 to .30%. Sulfur is considered the basic element for free machining steels. It is, however, detrimental to the hot forming properties.

**(Si) SILICON**

Silicon is used as a deoxidizer in the manufacture of steel. In amounts up to 1% it has a marked strengthening and toughening effect. In higher amounts it produces electrical resistance and gives high magnetic permeability.

**(Te) TELLURIUM**

The addition to approximately .05% tellurium to leaded steel improves machinability over the leaded-only steels.

**(Ti) TITANIUM**

Titanium is added to 18-8 stainless steels to make them immune to harmful carbide precipitation. It is sometimes added to low carbon sheets to make them more suitable for porcelain enameling.

**(W) TUNGSTEN**

Used in small amounts, tungsten combines with the free carbides in steel during heat treatment, to produce high wear resistance with little or no loss of toughness. High amounts combined with chromium gives steel a property known as red hardness. This means that the steel will not lose its working hardness at high temperatures. An example of this would be tools designed to cut hard materials at high speeds, where the friction between the tool and the material would generate high temperatures.

**(V) VANADIUM**

Vanadium is a strong deoxidizer and promotes fine grain structure during heat treatment. It helps steel resist softening at elevated temperatures and seems to resist shock better than steels without it.

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**References:**

Various internet sources.

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# DISHED COVER (BOLTED HEADS)

The rules for the design of dished covers is provided in the section 1-6 of Mandatory Appendix 1 (Supplementary Design Formulas) of the ASME Section VIII, Division 1. Appendix 1 provides rules for four (4) different types of dished covers – in this article, we will discuss in detail type (d) illustrated in Figure 1. Formulas for determining thicknesses of the flange and the spherical head are provided.

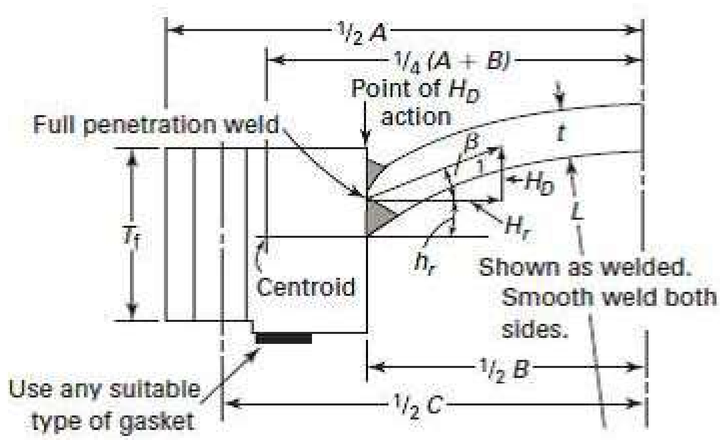



**Figure 1: Dished Cover Fabricated from Ring Flange and Spherical Head**

Dished Cover Dimensions

| | | | |
|---|---|---|---|
| Outside diameter of flange | A | | in |
| Inside diameter of flange | B | | in |
| Bolt circle diameter | C | | in |
| Inside spherical or crown radius | L | | in |
| Flange thickness | $T_f$ | | in |
| Radial distance from bolt circle to inside of flange | $h_D$ | | in |
| Lever arm for force $H_r$ | $h_r$ | | in |

Design Information

| | | | |
|---|---|---|---|
| Design pressure | P | | psig |
| Design temperature | T | | °F |
| Maximum allowable stress | S | | psi |
| Modulus of elasticity | E | | psi |

**Spherical Head Thickness**

a) For pressure on the concave side,

$$t = \frac{5 \text{ x P x L}}{6 \text{ x S}}$$

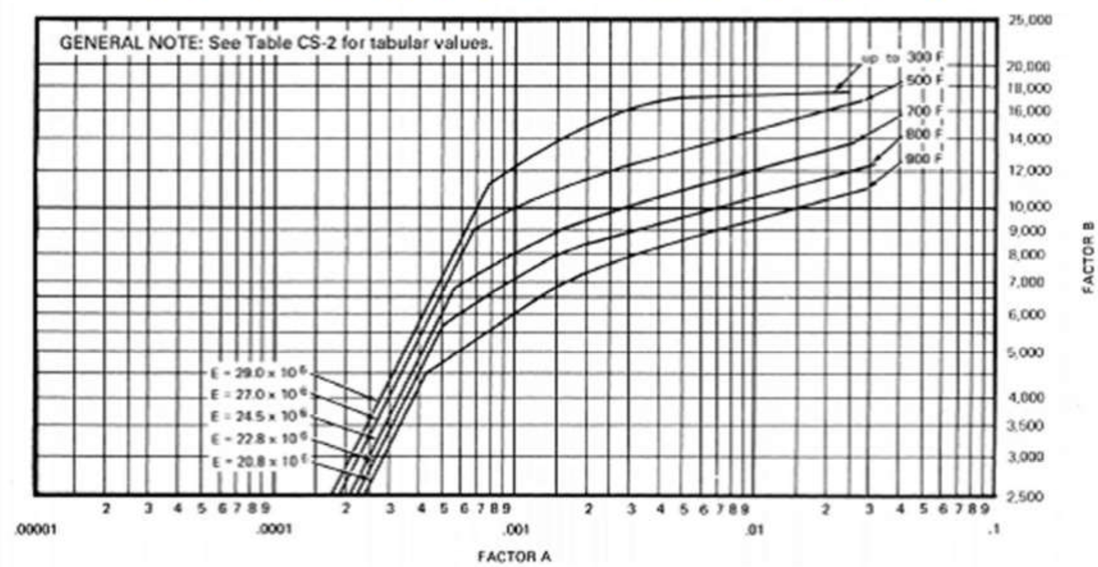
b) For pressure on the convex side, head thickness is determined based on UG-33(c) using the outside radius of the spherical head segment. Paragraph UG-33(c) provides a procedure for determining required thickness of hemispherical head having pressure on the convex side (external pressure). This procedure is identical to the procedure outlined in the paragraph UG-28(d) for determining thickness for a spherical shell, and involves the following steps:

Step 1- Assume a value for t (a good place to start is the value of t just calculated for the pressure on the concave side) and calculate the value of factor A.

$$A = \frac{0.125}{(R_o/t)} \qquad \text{where, } R_o = L + t$$

Step 2- Using this value of A, use the material chart for the material under consideration to determine the value of B at the design temperature.

**Figure CS-2**
**Chart for Determining Shell Thickness of Components Under External Pressure Developed for Carbon or Low Alloy Steels With Specified Minimum Yield Strength 30,000 psi and Higher**




GENERAL NOTES:

(a) The external pressure charts do not account for reduction of buckling strength due to creep under long-term loads. The effect of creep on buckling shall be considered at temperatures for which allowable stresses are shown italicized in Tables 1A, 1B, 5A, and 5B, and in boldface in Tables 2A and 2B.

(b) The external pressure chart assigned for a particular material is obtained from stress tables 1A, 1B, 2A, 2B, 5A, and 5B under the column for External Pressure Chart No. for that material and is mandatory, with the exception of Tables 5A and 5B.

**Figure 2: Material Chart**

The material chart for Figure CS-2 in the ASME Section II, Part D is shown above as Figure 2. The actual material chart to be used will depend on the material for the head. For example, if the material is SA-516-70, the material chart to be used will be indicated in the properties provided in Table 1A under the column titled “External Pressure Chart No.”

If B can be determined from the chart, then the maximum allowable external working pressure, $P_a$ can be calculated as:

$$P_a = \frac{B}{(R_o/t)}$$

If B cannot be determined from the material chart, then the maximum allowable working pressure, $P_a$ can be calculated as:

$$P_a = \frac{0.0625 \text{ x } E}{(R_o/t)^2}$$ where, E = Modulus of Elasticity at design temperature

The value of E can be read directly from the material chart

Step 3- Compare $P_a$ with the external pressure. If $P_a$ is smaller, select a larger value for t and repeat the procedure.

**Flange Thickness**

$$T = F + \sqrt{F^2 + J}$$

where, $F = \frac{PB\sqrt{4L^2 - B^2}}{8S(A-B)}$, and

$$J = \left(\frac{M_o}{SB}\right)\left(\frac{A+B}{A-B}\right)$$

$M_o$ is calculated both for the operating condition and the gasket seating condition, and the larger of the two is used in the equation for J.

Operating Condition

| | | | | |
|---|---|---|---|---|
| Gasket Dimensions and Factors | Gasket width | N | | |
| | Basic gasket seating width | $b_o$ | N/2 | |
| | Effective gasket seating width | b | $= b_o$ when $b_o \leq \frac{1}{4}$ *in.*<br>$= \frac{\sqrt{b_o}}{2}$ when $b_o > \frac{1}{4}$ in. | |
| | Diameter at location of gasket load reaction | G | = Mean diameter of gasket contact face when $b_o \leq \frac{1}{4}$ in.<br>= Outside diameter of gasket contact face less 2b when $b_o > \frac{1}{4}$ in. | |
| | Gasket factor | m | | |
| | Gasket factor | y | | |

| | | | | |
|---|---|---|---|---|
| Moment $M_D$ | Hydrostatic end force on area inside of flange | $H_D$ | $0.785\ B^2\ P$ | |
| | Radia distance from bolt circle to inside of flange ring | $h_D$ | | |
| | Component of moment due to $H_D$ | $M_D$ | $H_D \times h_D$ | |

| | | | | |
|---|---|---|---|---|
| Moment $M_G$ | Total hydrostatic end force | $H$ | $0.785\ G^2\ P$ | |
| | Total joint contact surface compression load | $H_p$ | $2b \times \pi GmP$ | |
| | Minimum required bolt load for operating condition | $W_{m1}$ | $H + H_p$ | |
| | Gasket load for operating condition | $H_G$ | $W_{m1} - H$ | |
| | Radial distance from gasket load reaction to the bolt circle | $h_G$ | $(C - G)/2$ | |
| | Component of moment due to $H_G$ | $M_G$ | $H_G \times h_G$ | |

| | | | | |
|---|---|---|---|---|
| Moment $M_T$ | Difference between total hydrostatic end force and the hydrostatic end force on the area inside of flange | $H_T$ | $H - H_D$ | |
| | Radial distance from bolt circle to the circle on which $H_T$ acts | $h_T$ | $H_T h_T$ | |

| | | | | |
|---|---|---|---|---|
| Moment $M_r$ | Angle formed by tangent to the centerline of dished cover thickness at its point of intersection with the flange ring and a line perpendicular to the axis of the dished cover | $\beta_1$ | $\arcsin\left[\frac{B}{2L+t}\right]$ | |
| | Radial component of membrane load in the spherical segment acting at the intersection of the inside of flange ring with the centerline of dished cover thickness | $H_r$ | $H_D \cot \beta_1$ | |
| | Lever arm of force $H_r$ about the centroid of flange ring | $h_r$ | | |
| | Component of moment due to $H_r$ | $M_r$ | $H_r\ h_r$ | |

| | | | | |
|---|---|---|---|---|
| | **Total moment** | $M_o$ | $M_D + M_G + M_T + M_r$ | |

Gasket Seating Condition

For gasket seating, the total flange moment $M_o$ is given by the equation,

$$M_o = W\frac{(C-G)}{2}$$

Use the greater of the values of $M_o$ for operating condition and gasket seating condition to calculate the thickness of the flange.

**References:**


ASME Boiler & Pressure Vessel Code, Section VIII, Division 1 – Mandatory Appendix 1-6

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# FUN WITH NUMBERS

*This article is for those readers that love mathematics. Here is a collection of some fun “numbers-related” facts plucked from the book “A Passion for Mathematics” by Clifford Pickover. Hope you will enjoy them.*

**DROWNING IN PI DIGITS**

The digits of pi beyond the first few decimal places are of no practical or scientific value. Four decimal places are sufficient for the design of the finest engines; ten decimal places are sufficient to obtain the circumference of the earth within a fraction of an inch if the earth were a smooth sphere.

**DEFINITION OF EULER’S NUMBER ‘e’**

The constant *e* is the base of the natural logarithm. It is approximately equal to:

$e$ = 2.71828 18284 59045 23536 02874 . . .

Along with π, *e* is the most important constant in mathematics since it appears in countless mathematical contexts. Roughly 2 billion digits of *e* have been determined.

Euler’s number can be defined as follows:

$$e = \sum_{k=0}^{\infty} \frac{1}{k!}$$

In other words, the number *e* can be defined as the sum of a series in which the series terms are the reciprocals of the factorial numbers: $e = 1/0! + 1/1! + 1/2! + \ldots = 2.7182818284590 \ldots$ (Recall that for a positive integer *n*, *n*! is the product of all the positive integers less than or equal to *n*. 0! is equal to 1.) Here’s another way to look at it. Euler’s number, *e*, is the limit value of the expression (1 + 1/*n*) raised to the *n*th power, when *n* increases indefinitely:

$$e = \lim_{n\to\infty}\left(1 + \frac{1}{n}\right)^n = 2.71828 \ldots$$

The symbol *e* was first used by the Swiss mathematician Leonhard Euler (1707–1783). The symbol *e* also appeared in his 1736 *Mechanica*, perhaps inspired by the word *exponential*.

**SPECIAL CLASS OF NUMBERS**

For many years, mathematicians have studied this cool class of numbers. Here’s how to understand them. If a number is less than the sum of its proper divisors, it is called *abundant*. (A positive proper divisor is a positive divisor of a number *n*, excluding *n* itself.) As an example, the proper divisors of 12 are 1, 2, 3, 4, and 6. And these proper divisors add up to 16. The number 12 is less than 16, so 12 is abundant. The first few abundant numbers are 12, 18, 20, 24, 30, 36, . . . The first odd abundant number is 945. (Its prime factorization is 945 = 33 × 5 × 7, and the sum of its factors is 975.)

## THE AMAZING 1/89

Although not widely known, the decimal expansion of 1/89 (0.01123 . . .) relates to the Fibonacci series when certain digits are added together in a specific way. Examine the following sequence of decimal fractions, arranged so that the right-most digit of the $n^{th}$ Fibonacci number is in the $(n + 1)^{th}$ decimal place:

| n | |
|---|---|
| 1 | .01 |
| 2 | .001 |
| 3 | .0002 |
| 4 | .00003 |
| 5 | .000005 |
| 6 | .0000008 |
| 7 | .00000013 |
| | .0112359 . . . |

Unbelievably, 1/89 = 0.01123595505617977528089887640449438202247191 . . .

Fantastic! Why should this be so? Why on Earth is 89 so special?

## PRIME TRIANGLE

In the seventeenth century, mathematicians showed that the following numbers are all prime:

31

331

3331

33331

333331

3333331

33333331

At the time, some mathematicians were tempted to assume that all numbers of this form were prime; however, the next number in the pattern - 333,333,331 - turned out not to be prime because 333,333,331 = 17 X 19, 607,843.

## 73,939,133

Amazingly, this is the largest number known such that all of its digits produce prime numbers as they are stripped away from the right!

73939133

7393913

739391

73939

7393

739

73

7

**DEFINITION OF A CYCLIC NUMBER**

A cyclic number, *C*, is an integer that - when multiplied by any number from 1 to the number of digits of *C* - always contains the same digits as *C*. Also, these digits will appear in the same order but begin at a different point. An example will clarify this. 142,857 is cyclic because

1 × 142,857 = 142,857

2 × 142,857 = 285,714

3 × 142,857 = 428,571

4 × 142,857 = 571,428

5 × 142,857 = 714, 285

6 × 142,857 = 857,142

Here are two more cyclic numbers: 588,235,294,117,647 and 52,631,578,947,368,421. Notice that these numbers can be constructed from certain primes in the following way. For example, 1/7 = 0.142857 . . . , 1/17 = 0.0588235294117647. . . , and 1/19 = 0.052631578947368421 . . . It has been conjectured, but not yet proven, that an infinite number of cyclic numbers exist.

**666 EQUATION**

$666 = 1^3 + 2^3 + 3^3 + 4^3 + 5^3 + 6^3 + 5^3 + 4^3 + 3^3 + 2^3 + 1^3$

$666 = 3^6 - 2^6 + 1^6$

$666 = 2^2 + 3^2 + 5^2 + 7^2 + 11^2 + 13^2 + 17^2$ (Sum of the squares of the first seven primes)

Examine the prime factors of 666 = 2 × 3 × 3 × 37 and add their digits. You get 18 = 6 + 6 + 6.

$666 = 6 + 6 + 6 + 6^3 + 6^3 + 6^3$

# BUILDING A BETTER TOMMORROW

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