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BUILDING  
MECHANICAL INTEGRITY PROGRAMS  
INTO NEW PLANTS

by

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**1.0 COURSE INTRODUCTION**

Pipe, tanks, pressure vessels and other static mechanical equipment is usually designed per particular codes, and then manufactured, installed, operated and maintained by different companies. Today, it is not unusual to find equipment in service for over 50 years. Certainly that is well beyond the design engineer's design basis of "useful life", and introduces the possibility that the equipment has been subjected to service related incidents that were never considered in the design. Plant personnel are continually trying to answer a very difficult question:

***In an existing plant, how long can equipment be operated safely and reliably?***

When new plants are designed, there are decisions that can be made and tasks performed that make it easier for the above question to be answered with some confidence.

This course describes an approach to Life-Cycle Mechanical Integrity that should be initiated in the original Design Basis, and continued through the plant's operating life. Topics include:

- Definition of Mechanical Integrity (MI)
- Historical approach to MI at existing plants, to understand the site issues
- Driving forces to implement MI during the design phase
- Project Management fundamentals that allow MI to be designed into a new plant.
- Considerations for equipment and construction
- Information to be provided to Owner at commissioning
- Implementing an MI Plan after plant commissioning

MI in its broadest interpretation is a system and plant wide approach to all plant operating equipment. The focus in this course is on static equipment, particularly pipe, tanks and pressure vessels. Rotating equipment typically has manufacturer recommendations and is considered separately in plant maintenance.

In presenting MI concepts over the life cycle of the plant, the end goal of knowing the current equipment condition must always be kept in mind. For this reason, this presentation starts with an explanation of the MI tasks at an existing plant and describes the overall purposes and processes. Then the course returns to the beginning process of designing a plant to show how the end goals can be achieved.



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## **2.0 MECHANICAL INTEGRITY DEFINITIONS**

### **2.1 Mechanical Integrity Process**

**Mechanical Integrity is the process of assuring equipment is in satisfactory condition to safely and reliably perform its intended purpose.**

In the 1980's, Mechanical Integrity was implemented as an inspection program at some existing plants, to develop Predictive Maintenance plans. Given this history, it is understandable that in many people's minds, MI is a set of equipment inspection programs. However, in implementation and practice, MI impacts plant operations, maintenance, safety and plant reliability. To limit the concept to an inspection program only, limits the positive influence the results can have on the entire safety and profitability of a plant.

In discussing MI in this course, often references are made to particular equipment, such as a tank or pressure vessel. This approach is necessary to describe the MI process. The actual implementation is rolled up into more of a "System" viewpoint. For example, if a particular process train includes 20 piping systems, 3 tanks, 2 pressure vessels, 6 pumps, and assorted instrumentation, then the entire system must be considered. While each individual equipment item needs to function properly, the end goal is that the entire system operates well, and can be maintained, operated and inspected.

Table 2.1 lists some of the major activities associated with Mechanical Integrity in Conceptual Design, Preliminary Design, Detailed Design, Construction, Start-Up & Commissioning, Operations and Maintenance cycles of a plant. The reader may wish to review this table as the various project phases and activities are discussed. At this point in the course, this table is presented to emphasize that Mechanical Integrity is a continually evolving process in the design and operation of a plant.



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**TABLE 2.1: OVERVIEW OF MI TASKS THROUGH LIFE OF PLANT**

<b>CONCEPTUAL DESIGN</b>	<b>PRELIM. DESIGN</b>	<b>DETAIL DESIGN</b>	<b>CONSTR.</b>	<b>START-UP, COMMISS.</b>	<b>OPERATIONS</b>	<b>MAINT.</b>
Perform MI & Other Studies	Major Equip. Spec. & Purchased	Complete Equipment Purchases	Confirm All Delivered Equipment Meets Specs	Test All Systems per Procedures	Monitor Equipment Operates Within Design Conditions	Perform Scheduled Maintenance and Record Results by Equipment No.
Design Basis For Plant	Design In Conseq. Mitigation	Design In Conseq. Mitigation	Receive and File All Vendor Documents	Repair, Modify Procedures & Equipment, As Needed	Report All Excessive Temp / Press/ Vibration, Flow Rate Data to MI Data Base	Perform Non-Routine Maintenance and Record Results by Equipment No.
Design Basis for Major Systems	Design in Risk Mitigations	Design in Risk Mitigations	Install Equipment per Specs	Maintain Management of Change Procedures	Assess Risk / Consequence Based on Anomalies	Revise MI Plan Based on Maintenance Data
Preliminary Risk / Consequence Diagrams	Start Required Document Lists	Implement Document Requirement Procedures	Perform QA and Document	Report Equip Condition / Anomalies & Other Data to MI Data Base	Perform MI Inspections, Record Data & Evaluate	
	Modify Risk/ Conseq. Diagrams	Contractor Specs including Documents	Perform Any Baseline Tests for MI and Document	Based on Start-Up Experience, Modify Risk/ Consequence Diagrams	Modify MI Program Based on Operations and Inspection Data	
		Initiate Management of Change Procedures	Doc All Field Changes Per Management of Change Procedures	Fully Implement MI Program		
		Modify Risk / Conseq. Diagrams	Update Risk / Conseq. Diagrams			



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## **2.2 Roots of Mechanical Integrity**

In plant operations there are several approaches to equipment maintenance:

1. Maintain on a fixed schedule
2. Maintain when indications exist that there is a deterioration based on inspection, instrumentation, product quality, reliability, or some other measure
3. Maintain when it is predicted that deterioration has begun or is eminent
4. Maintain after the equipment breaks

Depending on the system in a plant, it may be that all four of these approaches are appropriately performed at one plant. For example, a large process system critical to plant availability and safety, should be inspected and evaluated differently, than service water and instrument air systems.

While safety was of some concern in the early days of MI, the primary driving force was cost, related to avoiding unplanned shutdowns, and to accurately predict the timing for major repairs and replacements. MI was inherently an “After the Fact” or “Catch-Up” activity that could only be as good as the historical record that existed on each piece of equipment.

## **2.3 Mechanical Integrity Programs at Existing Plants**

As part of Predictive Maintenance, inspection programs were performed on equipment that was known to, or expected to deteriorate. This begs the questions:

- How often should the inspections be performed?
- What type of inspections?
- How do we evaluate the results?
- What should be done when an anomaly is found?

To answer these questions, MI programs have been developed on a plant specific basis with the following steps:

- 1. Assess the Design Conditions compared to the Actual Operating Conditions**
  - a. Confirm the known design conditions
  - b. Compare the actual operating experience to the design conditions
- 2. Determine the information available compared to the needed information**



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- a. Are design calculations available?
- b. Is there a known history of cycles, pressures, temperatures and fluids?
- 3. What are the potential failure modes for each piece of equipment?**
  - a. Fatigue
  - b. Internal Corrosion
  - c. External Corrosion
  - d. Flow Accelerated Corrosion
  - e. High Temperature Creep
  - f. Metal Embrittlement
  - g. Flow Induced Vibrations
  - h. Externally Induced Vibrations
  - i. Excessive Pressure
  - j. Excessive Temperature (high or low)
  - k. Loosening or Failure of Support Bolts or Other Support Materials
  - l. An external event, such as seismic, high winds, floods
  - m. A combination of two or more of the above
- 4. Identify Any Of The Potential Failure Modes That Can Be Mitigated By Operational Procedures and Management Practices**
- 5. If There Would Be A Failure Of Equipment, Describe the Consequences of Failure**
  - a. To safety
  - b. To regulatory requirements
  - c. To plant reliability
- 6. Determine The Known Condition Of The Equipment**
  - a. History of maintenance
  - b. History of repairs and replacements
  - c. History of inspections
- 7. Determine the Risk of a Failure**
- 8. Plan Inspections and Other Activities to Obtain an Acceptable Risk Level**
- 9. Perform the MI Plan**
- 10. Assess the Inspection Results**
- 11. Develop Recommendations to Include:**
  - a. Repair
  - b. Replace
  - c. Modify Frequency and Type of Inspection
  - d. Accept Results and Leave Equipment As-Is
  - e. Modify Operational Procedures



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f. Modify Maintenance Procedures

**12. Document The Disposition Of All Recommendations**

**13. Consider Modification Of Operating Procedures, Or Maintenance Schedules To Minimize Risk**

**14. Develop A Long Term MI Plan For The Equipment, which basically recycles to step 1.**

This process in flow chart form can become extensive when all activities and possibilities are considered. Typically the complexity of the flow charts expands for high-risk equipment and compresses for relatively low risk equipment.

It is readily apparent that a well functioning MI Plan is an integral part of the plant operational and maintenance procedures. It is not a program that is just implemented during a shutdown or inspection cycle. As equipment is operated, inspected, maintained and repaired or replaced, it must be done as part of the overall MI plan to assure proper decisions are made, and all results and changes are well documented.

## **2.4 Equipment Inspections**

Inspection of existing equipment invariably finds “indications”. This is an inspector’s term for something outside the normal bounds, and its characterization depends on the type of inspection.

- A surface inspection by magnetic particle or dye penetrant exam looks for surface cracks
- A sub-surface inspection by ultrasonic inspection looks for “reportable indications” based on the appropriate db level. In examining a tank or pipe weld, the indication may be a rough surface at the root, lack of fusion at points in the weld, slag lines, porosity, cracks or other defects. Many of these indications occur in the original welding process and are not rejectable by original fabrication Codes. Other indications represent active deterioration that must be corrected.
- A thickness inspection, usually by straight beam ultrasonic, shows the measured metal or weld thickness. Until there are two data points at different times at the same location, it is difficult to determine if a thin measurement represents original fabrication error, or represents corrosion or erosion of the metal.
- A replica of a surface is taken on some welds to ascertain the level of deterioration in the grain structure. Replicas are most commonly used to evaluate creep damage on high temperature equipment.



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- A hardness test may be taken to evaluate embrittlement or softening of the base metal or weld metal.

The evaluation of each of these inspection results often requires the answer to the question,

***“How Has The Equipment Condition Changed Since The Last Inspection?”***

During the fabrication and construction phases, this baseline data could be made available. In the past, this data was often not saved, or it was in a format that was not useful. For example, a vendor might verify, “All measured thicknesses are greater than specified minimum.” If the actual data was written down and saved such that measurements can be related to specific locations, then the inspector that inspects the equipment 5 or 10 years later can make much more specific evaluations. Otherwise, assumptions must be made, and inspection frequency may be unnecessarily compressed because of possible thinning that does not really exist. (A more detailed explanation is provided in Section 2.5)

**2.5 Importance of Documents and Data**

If full design, operation, maintenance and inspection history is available, then the process is well defined. Experienced engineers and technicians can develop and perform an inspection plan. At major decision points, rational, well informed decisions can be made based upon knowledge. In the real world, rarely is all this information readily available. This forces assumptions, which creates additional risk. If the risk of the assumption is considered unacceptable, then additional calculations, inspections, or other activities may be performed to reduce this risk.

The lack of information is so prevalent in the performance of MI at existing operating plants, that there is an underlying basis to the process.



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### THREE LAWS OF MECHANICAL INTEGRITY

LAW

COROLLARY

	LAW	COROLLARY
1.	<b><i>IF THE INFORMATION IS NOT PROPERLY DOCUMENTED, THEN FOR ALL PRACTICAL PURPOSES, IT NEVER EXISTED.</i></b>	<b><i>IF DOCUMENTS ARE NOT PROPERLY FILED AND STORED, SOON THEY WILL NOT EXIST.</i></b>
2.	<b><i>THE LESS INFORMATION AVAILABLE WHEN A POTENTIAL PROBLEM IS DISCOVERED, THE MORE ASSUMPTIONS THAT MUST BE MADE.</i></b>	<b><i>RISK INCREASES UNLESS CONSERVATIVE ASSUMPTIONS ARE MADE.</i></b>
3.	<b><i>THE LESS INFORMATION AVAILABLE, THE MORE COSTLY TO MAKE A CORRECT DECISION, OR THE MOST COSTLY THE EFFECT OF THE DECISION WILL BE.</i></b>	<b><i>OWNER'S MANAGEMENT WILL BE FRUSTRATED BY COST OF NON-BUDGETED REPAIRS AND INSPECTIONS.</i></b>

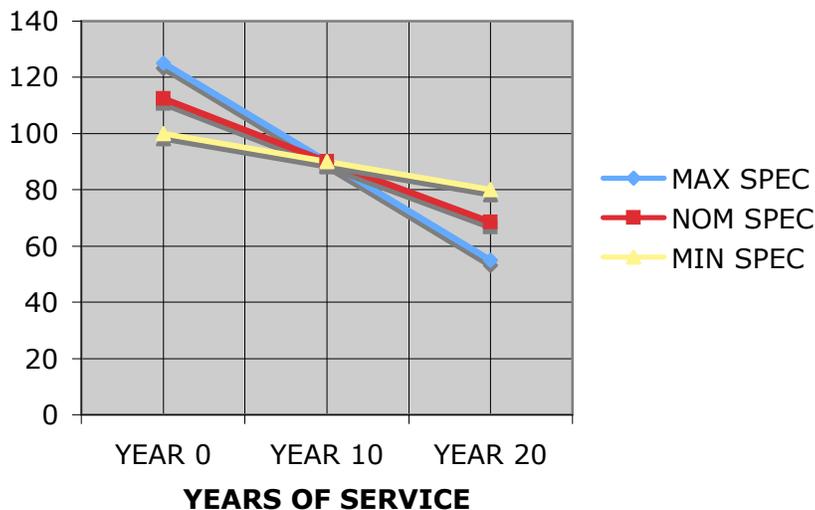
To illustrate these laws with some experiences:

1. A plant engineer was preparing an evaluation of some high-temperature – high-pressure pipe. When a search was made for original fabrication drawings that would have exactly located all the welds, the plant manager reported “All files associated with original pipe fabrication and installation had been thrown out since no one had looked at them for a couple of years.” The result was that to find and inspect all welds, all the insulation had to be removed, rather than just locally at each weld. Not only did this increase initial inspection cost, but also the possibility of knowing the original condition of each weld had been thrown away.
2. In a piping system in which thinning due to Flow Accelerated Corrosion was possible, the original measured fabrication thicknesses were not saved. After 10 years of operation, some measured thicknesses were 90% to 100% of the specified minimum thickness. By calculating the rate of thinning, an estimate can be made of expected remaining life. In this case replacement was required when measured thickness was less than 75% of specified minimum thickness. Without any original thickness measurements, assumptions had to be made. See Table 2.2.



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**TABLE 2.2 SAMPLE  
THICKNESS MEASUREMENTS,  
% OF MINIMUM SPECIFIED**



- A non-conservative assumption would be the original pipe was at specified minimum wall when installed, resulting in less than 1% wall loss per year – 15 or more years before the 75% thickness ratio is reached.
- A reasonable assumption would be that the original wall was nominal, or 12.5% greater than minimum specified. This would result in about a 2% to 2.5% loss of wall thickness per year – 7 years or more before the 75% threshold is reached.
- A conservative assumption would be to assume the original wall was 12.5% greater than nominal, resulting in up to 3.5% wall loss per year – less than 5 years before the 75% threshold is reached.
- The actual approach was to make the most conservative assumption, and schedule a new inspection within 2 years. Then the rate of wall loss could be more accurately predicted. Thus two inspections were scheduled within 2 years, when the second inspection could have been delayed 5 to 7 years.



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- If the initial inspection had found a wall loss to 80% of minimum specified, replacement would have been made on an emergency basis, instead of safely waiting for 12 to 18 months when the replacement could have been planned as part of a normal shutdown.
3. In investigating the condition of a piping system, plant personnel told the engineer that, “A few years ago there had been a pressure surge that had damaged some of the pipe supports and that some of the pipe welds were examined as a precaution.” The report written at the time did not detail which supports were damaged, how they were repaired, which welds were inspected, or what the results of the inspection were (except to say “No damage found at inspected welds.”) With this limited information, the engineer could not assume which welds were inspected and by which methods. While some useful inspections were probably performed, without detailed records they had no long - term value.

When developing a Mechanical Integrity program, always keep in mind that it should last for decades. The memory of individuals cannot be counted upon. In fact, the program and documentation needs to be able to survive different owners, and complete turnovers in plant personnel.



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### **3.0 MECHANICAL INTEGRITY DRIVING FACTORS**

#### **3.1 Disasters and Regulations**

While the implementation of Mechanical Integrity at plants is a logical improvement to plant safety and reliability, it has many driving forces that directly or indirectly affect the implementation.

There has been a long history of plant failures that have killed and injured plant personnel and civilians. In most cases, the plant personnel are those most at risk, such as the 2005 BP Texas City refinery explosion that killed 15 people. The most infamous disaster occurred in 1984 at a Union Carbide plant in Bhopal, India. Several thousand Indian civilians were killed immediately, and many more thousands have died later as the result of the toxic gas release. Disasters such as these led to governmental and industry insistence that accidents must be avoided.

In the United States, OSHA became directly involved by issuing Regulation 1910.119, in the early 1990's. Of the many requirements, there were three major programs that changed the operation of United States process facilities working with hazardous chemicals.

1. There must be a valid Process Safety Hazards Analysis
2. There must be a Mechanical Integrity Program
3. There must be a formal Management of Change (MOC) program documenting all physical and operational changes to the plant.

After the initial phase in period of these rules to bring existing plants to an acceptable level, the rules now apply to any facility containing hazardous chemicals in the prescribed quantities.

***ALL NEW FACILITIES THAT MUST MEET OSHA 1910.119 REQUIREMENTS, MUST HAVE A FUNCTIONING MECHANICAL INTEGRITY PROGRAM AT TIME OF COMMISSIONING.***

When OSHA 1910 became law, major petrochemical plants spent millions of dollars verifying and correcting their Process & Instrumentation Diagram's (P&ID's). In far too many cases, physical and undocumented changes had been made that allowed unacceptable pressures, temperatures or fluids to enter certain equipment.



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For example,

- Safety valves that were originally designed to protect equipment had been isolated from the equipment they were intended to protect by changes in pipe routing
- Safety valves were “gagged” since the operating pressures had been increased.
- Equipment contained materials that they were not designed to hold
- Instrumentation was not properly located to monitor the processes.
- Potential fire hazards were not covered with appropriate automatic fire safety equipment
- Many other physical changes existed, that upon careful examination, created unnecessary risk.

The procedures that typically exist today represent a major improvement in plant safety and personnel hazard awareness.

Mechanical Integrity procedures are not prescribed in OSHA 1910. The regulations allow plants to develop reasonable practices that attempt to assure equipment is suitable for its intended service. Since most plants covered by these rules are petrochemical and refinery plants, the American Petroleum Institute (API) has taken a major lead with the issuing of Standards, Guidelines and Recommended Practices. Other Code organizations around the world have contributed useful documents to assess the condition of equipment. See Table 3.1 for a partial listing of documents. By using these guidelines, plants can develop and implement their own MI program. While these API documents are primarily focused on hazardous chemical processes, they may also be used as a starting point for non-regulated equipment, such as high-pressure steam.

Since the legal requirements of OSHA 1910 are limited to hazardous chemicals there are many facilities that are not required to comply. However, at most facilities there are many types of equipment that could fail that would injure personnel, and it is difficult to ignore these possibilities in the 21<sup>st</sup> century. Thus, many owners have implemented portions of OSHA 1910 in practice, even if not legally required.



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**TABLE 3.1: MECHANICAL INTEGRITY REFERENCES**

<b>TITLE</b>	<b>ORG.</b>	<b>NUMBER</b>
<b>Calculation of Heater-Tube Thickness in Petroleum Refineries</b>	<b>API</b>	<b>RP 530</b>
<b>Recognition of Conditions Causing Deterioration or Failure</b>	<b>API</b>	<b>RP 571</b>
<b>Inspection of Pressure Vessels</b>	<b>API</b>	<b>RP 572</b>
<b>Inspection of Fired Boilers and Fired Heaters</b>	<b>API</b>	<b>RP 573</b>
<b>Inspection of Piping, Tubing, Valves &amp; Fittings</b>	<b>API</b>	<b>RP 574</b>
<b>Recommended Practice or Inspection of Atmospheric and Low Pressure Storage Tanks</b>	<b>API</b>	<b>RP 575</b>
<b>Inspection of Pressure Relieving Devices</b>	<b>API</b>	<b>RP 576</b>
<b>Recommended Practice for Inspection of Welding</b>	<b>API</b>	<b>RP 577</b>
<b>Recommended Practice for Positive Materials Identification</b>	<b>API</b>	<b>RP 578</b>
<b>Fitness-For-Service</b>	<b>API</b>	<b>RP 579</b>
<b>Recommended Practice for Risk Based Inspection</b>	<b>API</b>	<b>RP 580</b>
<b>Steels for Hydrogen Service at Elevated Temperatures and Pressures in Petroleum Refineries and Petrochemical Plants</b>	<b>API</b>	<b>RP 941</b>
<b>Avoiding Environmental Cracking in Amine Units</b>	<b>API</b>	<b>RP 945</b>
<b>Pressure Vessel Inspection code: Maintenance Inspection, Rerating, Repair and Alteration</b>	<b>API</b>	<b>510</b>
<b>Piping Inspection Code</b>	<b>API</b>	<b>570</b>
<b>Design and Construction of Large, Welded, Low -Pressure Storage Tanks</b>	<b>API</b>	<b>620</b>
<b>Welded Steel Tanks for Oil Storage</b>	<b>API</b>	<b>650</b>
<b>Tank Inspection, Repair, Alteration and Reconstruction</b>	<b>API</b>	<b>653</b>
<b>Alternative Methods to Area Replacement Rules for Openings Under Internal Pressure, Section VIII, Div. 1</b>	<b>ASME B&amp;PV CODE</b>	<b>Case 2168</b>
<b>Alternative Method of Calculating Maximum Allowable Stresses Based on a Factor of 2.5 on Tensile Strength, Section II &amp; Section VIII, Divs 1 &amp; 2</b>	<b>ASME B&amp;PV CODE</b>	<b>Case 2278</b>
<b>Alternative Rules for Determining Allowable Compressive Stresses for Cylinders, Cones, Spheres and Formed Heads, Section VIII, Divs 1 &amp; 2</b>	<b>ASME B&amp;PV CODE</b>	<b>Case 2286</b>
<b>Rules For In-Service Inspection of Nuclear Power Plant Components</b>	<b>ASME B&amp;PV CODE</b>	<b>Section XI</b>
<b>Multiple Standards for Material and Fabrication</b>	<b>ASTM</b>	
<b>Standard Practices for Cycle Counting in Fatigue Analysis</b>	<b>ASTM</b>	<b>E1049</b>
<b>Standard Test Method for Measurement of Fatigue Crack Growth Rates</b>	<b>ASTM</b>	<b>E647</b>
<b>Standard Guide for Examination and Evaluation of Pitting Corrosion</b>	<b>ASTM</b>	<b>E647</b>



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### 3.2 Non-Regulatory Driving Factors

While safety is the primary reason for government regulations, many owners are using all available resources to improve plant productivity and increase profits. Driving factors beyond the legal requirements for owners to implement MI programs include:

- Personnel safety is a primary consideration in the operation and maintenance at most plants.
- Plant productivity and profitability is directly linked to reliability. If there is critical equipment that is subject to degradation, even if it is not a safety hazard, then many plants will have an MI program in place to plan inspections and maintenance.
- If historical information is available when an anomaly is discovered, then accurate decisions may be possible to safely and quickly resolve the problem.
- An MI program is often required to comply with insurance requirements, or lowering insurance rates
- An MI program provides data to develop predictive maintenance capabilities (leading to lower costs)
- An MI program contributes to an “Integrated Plant Operational and Budgeting Process” that allows planning and minimizes reactions to unforeseen problems.
- An MI program provides a rational process to focus resources on the highest risk situations, and to limit the cost of inspections and maintenance.
- Implementation of MI provides saving on initial plant costs.
  - Unfortunately there is a fairly common practice associated with the initial operation. Due to the speed of the design / construction cycle, lack of prior planning, and contractual requirements with the design engineer; often the plant personnel “Will re-build the plant the way they can operate it, in the first 2 years after start-up.” Owner’s budgeting often allows for this, and it can be shown as maintenance costs, rather than capital improvements. Proper foresight and planning can avoid most of these unnecessary initial start-up costs.
- Implementation of MI during the design phase can save money later. Much of the fundamental design, analysis and inspection data is available during construction and commissioning. It must be catalogued and properly saved.



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#### **4.0 DESIGNING IN MECHANICAL INTEGRITY**

##### **4.1 Design Basis Considerations**

Over the past few decades, design engineering has advanced by considerations beyond the basic requirements of *PERFORMANCE*, which include stress, flow, and fabrication.

*CONSTRUCTABILITY* became a discipline to assess the questions of site versus field fabrication, accessibility during construction, sequencing of work and construction safety.

As plants became more complex and larger, clients insisted on carefully reviewing all designs for *OPERABILITY*. Personnel safety, ergonomics in the control room, access to valves and instrumentation in the plant, sophistication of alarms, and other considerations have become an every day consideration by design engineers.

Many owners require consideration of, *MAINTAINABILITY* in their designs. Downtime is generally lost revenue, and methods to assure quick access, and proper isolation of equipment that must be serviced is a normal design requirement.

With major accidents, the adoption of OSHA1910.119, and the owner's inherent desire to limit risk, the next logical level of design basis is to design Mechanical Integrity process into the plant. This process is to create the risk matrices described in Section 5.2 during the design phase, and start the long term MI program at that time.

When deciding to design MI into a new plant, there is a fundamental change in approach by the design engineer. The concept of designing for performance is not sufficient. The concept of designing for constructability is not sufficient. Even the approach of designing for operability and maintainability is not sufficient. The basic approach must be:

**DESIGN EQUIPMENT TO MEET THE REQUIREMENTS OF  
OPERATIONS, INSPECTION CYCLES AND SHUTDOWN CYCLES THAT  
THE OWNER INCLUDES IN THE DESIGN BASIS.**

Equipment that is critical to these rigorous requirements cannot be bought based on lowest purchase price, or even installed cost. It must be selected based on life cycle and maintenance



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cost. This certainly complicates the design engineers' job, as some of the following questions need to be answered.

1. If additional conservatism is added to a design (additional wall thickness, better alloy materials, stronger valve motor operators, additional instrumentation, etc.) does this really reduce the risk of unplanned outages?
2. Do these changes result in
  - a. Longer interval between planned shutdowns?
  - b. Reduced inspection and maintenance time during shutdowns?
  - c. Longer equipment life?
  - d. More reliable equipment operation?
  - e. Improved efficiency?
  - f. Lower maintenance and operating time and cost?
  - g. Reduced vibration or noise?
  - h. Enhanced safety to plant personnel?
  - i. Reduced environmental discharges to air, ground or water?
3. If the planned intervals between shutdowns can be extended, for example from 2 to 4 years, is there other equipment that now should be evaluated for upgrade? For example, if increasing the shutdown interval on a reactor from 2 to 5 years can be done, are there now safety valves inspections, catalyst regeneration, line clean-outs, pump maintenance or other systems that can be extended to 5 years? If not, will temporary by-pass systems need to be included to allow the plant to operate while some systems are maintained and inspected?
4. Will the risk of unplanned outages increase unacceptably if extended shutdowns are planned?
5. Are the additional installed costs of upgraded equipment justified based upon the long-term savings?
6. Are there some additional long-term benefits that may be difficult to quantify to justify upgraded equipment? Upgrades may improve plant safety, reduce noise and vibration, reduce insurance costs, or allow better access around the facility.
7. Are there any long-term negative impacts to the upgrades?
  - a. Is access reduced?
  - b. Is there a loss in efficiency or productivity after so many months without shutdowns?



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- c. Is operability made too complicated with additional valves, instrumentation or other equipment?

#### **4.2 Project Management of a Mechanical Integrity Based Plant**

Answering all these questions listed in Section 4.1 in a timely manner, in the rush of a fast-track design project is very much a stretch for most design engineering companies. This is expecting the design engineer to be knowledgeable about the operational and maintenance details of a plant. With few exceptions, this breadth of experience is not available in a single individual. Even with experience, the Owner has site-specific expectations on how to operate and maintain the plant.

The ultimate knowledge and decision making forces the approach that the Owner and consultants must interact continuously with the Design Engineer from the earliest concept, through detailed design, equipment procurement, fabrication, construction, commissioning and start-up. The Owner must bring the long-term operations and maintenance focus to the design project and insist on including their observations and comments in all aspects of the design and construction process.

Unfortunately, in an environment in which Owners want to limit risk to the capital improvement budget, this open-ended approach is very worrisome. Owners want very well defined costs, and many Owners would like jobs to be based on a fixed price Engineering – Procurement – Construction EPC contract. However, this ignores the benefits that might be achieved by designing in Operability, Maintainability and Mechanical Integrity into the project. Depending on the type of facility, it is very possible that more will be spent in 1 to 2 years on fuel, raw materials, operations and maintenance, than is spent on initial design and construction. When this is true, then the concept of designing on the basis of installed cost is inherently flawed.

Performing project management of a new plant can become very difficult in this type of environment, but it can be done properly, with minimal cost impact on the overall capital cost. This sounds a little like a politician claiming “We can increase spending on programs and cut taxes” during an election campaign. But, cost effective MI programs can be implemented with the following approach:



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1. Contractual terms that incentivize all groups to aim for the primary goal of a well operating plant that includes all Operability, Maintainability and Mechanical Integrity into the design, construction and commissioning phases. Unless the design is so well defined that a very specific specification has been written, fixed price quotes for this type of work is usually counterproductive.
2. Sufficient time and effort during the project definition / conceptual design phases must be allowed. There are specific front-end studies described in Section 5.1 that provide a Design Basis for the detailed design. The concept is to identify critical factors to the Owner such as reduce operating costs, increase efficiency, limit risks, extend time between outages, limit standard outage time, or increase safety. Formally study the critical processes and equipment in a plant and develop formal recommendations to be included in the design. These studies must be completed prior to initiating detailed design.
3. Owner must formally accept or reject the recommendations in determining the design basis for the plant and various systems.
4. Identify formal review and approval steps during the design and construction phases, and all parties hold to them. Time must be allowed for adequate review by interested groups, and for discussions to resolve all issues.
5. All parties must hold to the decisions made in these reviews – unless Owner and Design Engineer / Project Management agree to a late change and its impact on cost and schedule.
6. The critical team members from the Design Engineer, Owner and other stake holders should be
  - a. Experienced in their areas of responsibility
  - b. Open minded to listen to concerns of other perspectives
  - c. Imaginative to create and accept new ideas
  - d. Consistently responsible to the project (new people should not be brought in part way through the design and be allowed to second guess previous decisions)
7. All parties must be reasonable and knowledgeable enough to understand the acceptable level of depth that a decision can be made, even if not every design detail is known.
8. In some cases, there may be multiple solution paths that need to be considered beyond the initial studies. Allow these to happen if at all possible, to best resolve the issues.



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9. Recognize that even with these best efforts, the plant will probably still not be “perfect” from everyone’s viewpoint. There is a limit to the options and studies that are useful in the end.



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## **5.0 MECHANICAL INTEGRITY IN THE PROJECT DEFINITION PHASE**

### **5.1 Design Basis**

When planning for MI during a project, the engineer must try to postulate what could go wrong, and then try to avoid as many of the issues as possible. There may be instances in which the design becomes much more conservative than the minimum design code requirements. Sometimes these improvements are characterized as “Owner Preferences” based on their experience in operating similar plants. Taken to an extreme, this could greatly increase the initial plant cost and may not be cost effective. However, there are many improvements that have minor affects on cost at the early design phases, but which could be prohibitively costly as add-ons after the plant is built.

Design improvements can be appropriate for many cost or safety reasons:

- Increase life expectancy of the equipment to delay inspection, repair or replacement
- Increase interval between outages (referred to as “shutdowns” in some industries), to increase production days
- Totally avoid a known failure mechanism
- Reduce inspection or replacement requirements
- Protects plant personnel from potential failures by reducing the access requirements
- Protect plant personnel from potential failures by adding a secondary protection
- Provide early warning of impending failure, which can be justified for safety, and cost reasons
- Provide access for observations that will save money on scaffold or other access methods during operation

For any plant design, the Owner must provide a DESIGN BASIS. At a minimum this includes the size of the facility, input materials, expected output, site, applicable regulations, ambient conditions, basic process design, completion schedule and budgetary costs. Operability, Maintainability, Constructability requirements / preferences should be included, and are probably based on studies of performance at other units, available labor at the site, goals for availability, and other factors.

When Mechanical Integrity considerations are to be included these requirements must be added to the Design Basis. The list of questions in section 4.1 is not easily answered, and the design



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team must have guidance to achieve the Owner's goals. To achieve this end, additional studies must be performed during the development of the design basis. These preliminary studies go by different names, such as Front End Engineering Design (FEED), Front End Loading (FEL), preliminary design, or conceptual design. By whatever name is used, the MI requirements in the design basis must be defined prior to the release of the plant to detailed design and fabrication. These studies may take several months to perform, but without this effort, a full MI program cannot be implemented on a new project. Some examples of studies include:

1. Process studies with focus on safety and reliability comparisons
2. Process simplification to minimize equipment costs and reduce maintenance and inspection requirements without negatively impacting availability
3. Process/ safety studies to allow partial operation while maintenance is performed
4. Preventive maintenance study to reduce maintenance costs
5. Inspectability study to reduce inspection costs and allow on-line evaluations
6. Material selection studies to minimize potential for expected degradation phenomena
7. Quality studies to specify fabrication, inspection and erection requirements to minimize flaws and provide expected longer life before failure
8. Long term MI plan outline to provide a basis for all documentation requirements
9. Long term outage (shutdown) studies to design for a set schedule between planned outages, and the types of activities to be performed at each outage

The various studies may be performed in parallel, but they must eventually be integrated together. Some recommendations in one study may counter recommendations in another. For example: A process simplification study may recommend the reduction in pumps or tanks, but a maintenance study may recommend more equipment to allow partial or full operation while inspection and maintenance is performed on some equipment. Once these issues have been resolved, then the Owner should issue the Design Basis.

There will invariably be questions and judgments through the detailed design phase that may cause some modification to the Design Basis for certain equipment items. That is normal design process. With careful thought and planning, these changes can be minimized. When changes do occur, it will be implemented with a full knowledge of the compromises that are being made. These modifications to the Design Basis should be documented, as it may be important to plant personnel after commissioning to understand the long-term viability of the equipment.

## **5.2 Risk / Consequence Evaluations**



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During the Design Basis studies and throughout the design process, there will be a need to evaluate systems and equipment for Risk of Failure and Consequence of Failure. Definitions for Risk and Consequence are different for each plant and owner. Consequence may include safety, plant availability (profitability), environmental impact, permits or other legal requirements, or cost to operate and maintain. For clarity on critical systems, it may be appropriate to rate “Consequence” for all these considerations.

An example of why consequences must be identified for each plant: Due to availability of repair equipment, the Consequence of Failure may be much greater on the Northern slope of Alaska, compared to near a large industrial city.

See Figure 5.1 for a typical Risk/Consequence Diagram. For systems with low Risk of Failure and low Consequence of Failure, minimum standard design is usually acceptable.

For systems with high Risk of Failure and high Consequence of Failure, special studies may be appropriate to design out as many risks as possible, and to develop mitigation strategies to reduce the Consequences.

For all other systems with a mix of high to low Risk of Failure and high to low Consequence of Failure, engineering judgment is required to design out risks and/or develop mitigation strategies.

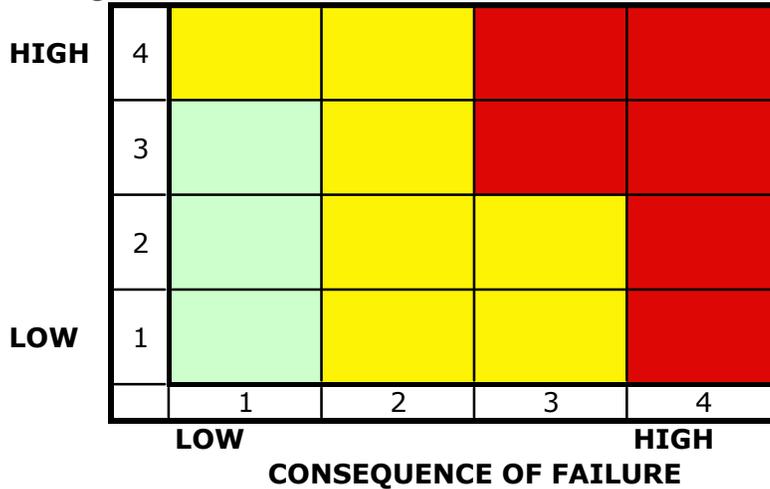
It is impossible to list all the possible risks, consequences and mitigation factors. In fact, once anyone thinks the list is complete, there will be new special circumstances. As an example of this method, see Table 5.1.



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**Figure 5.1: EXAMPLE OF RISK / CONSEQUENCE DIAGRAM**

**RISK OF EQUIPMENT FAILURE TO PERSONNEL SAFETY**



KEY	<span style="display: inline-block; width: 20px; height: 15px; background-color: #90EE90; border: 1px solid black;"></span>	STANDARD DESIGN, VISUAL INSPECTIONS ONLY
	<span style="display: inline-block; width: 20px; height: 15px; background-color: #FFFF00; border: 1px solid black;"></span>	MODIFIED DESIGN, ROUTINE VISUAL & PERIODICE NDE
	<span style="display: inline-block; width: 20px; height: 15px; background-color: #FF0000; border: 1px solid black;"></span>	RIGOROUS DESIGN FOR SAFETY, MANDATORY PERIODIC INSPECTIONS

**DEFINITIONS**

**SAFETY CONSEQUENCE**

- 1 Personnel Injury Highly Unlikely
- 2 Personnel Injury Possible First Aid Case
- 3 Personnel Injury Possible Hospitalization
- 4 Possible Loss of Life

**RISK OF FAILURE**

- 1 Potential Failure Modes Minimal
- 2 Some Potential Failure Modes
- 3 Expected and Known Failure Modes
- 4 Failure Nearly Certain Unless Intervention



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**Table 5.1: SAMPLE PRESSURE VESSEL RISK / MITIGATION ANALYSIS**

<b>RISK / CONSEQUENCE</b>	<b>FAILURE MODE</b>	<b>RISK REDUCTION</b>	<b>CONSEQUENCE REDUCTION</b>
Moderate / High	Internal Corrosion @ Nozzles	Increase corrosion allowance locally	Isolate vessel from nearby equipment
		Use chrome – moly material @ nozzles	Require special PPE for personnel in area
		Schedule wall thickness inspections on 6 month intervals	Since fire might be a consequence, design automatic foam system
		Provide inspection access at all nozzles	
	2 Phase Flow causes erosion of internal trays	Use hardened materials	Provide by-pass to allow inspection during reduced operation
		Study flows to properly locate trays	Develop strategy to evacuate fluid quickly for field inspections
			Provide extra access ports for inspection
Low/High	External Corrosion of support legs could cause catastrophic collapse	Evaluate best possible external coating or materials for protection	Provide redundancy in support scheme
		Develop skirt support design that allows for full ultrasonic inspection	



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These tables should be considered as “living documents” through the design phase, and for critical equipment should be part of the project documents that the owner has for permanent design records. As the design progresses, the table should be expanded and revised to make note of exact risk mitigations and consequence strategies that have been implemented. In some cases, the recommendations will not be implemented due to cost, schedule, or other engineering considerations. This should also be noted for the field personnel to understand.

As detailed design is developed, vendor drawings are reviewed, acceptance test criteria are written, they should be reviewed against this risk/consequence chart to assure recommendations are implemented. This is highly critical, as detailed weld procedures, fabrication methods, flange gasket selection, stress calculations, inspection methods and other details may greatly reduce or increase the risk of failure.



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## **6.0 DETAILED DESIGN PHASE**

While the integration of Mechanical Integrity into the detailed design process seems logical and reasonable, it should be recognized that current technology makes this much easier to do than in past decades. Some of the improvements that should be utilized in the process include:

- 3D modeling techniques to allow detailed analysis of access areas
- Analysis techniques to predict damage caused by releases of fluids
- DCS systems that allow real time linkage and long term storage of plant operating conditions
- Improved instrumentation at reduced costs which allow cost effective real time monitoring of more operating conditions
- “Smart P&ID’s” which assist in identifying equipment with particular systems and can be linked to data retrieval in the operating plants.
- Digital data base systems that allow more cost effective storage of large amounts of linked data from the design engineer, vendors, erector, and owner.

### **6.1 Equipment Design Basis**

With the overall plant Design Basis, and perhaps separate System Design Basis documents, individual equipment can be specified and design. Some of the typical specifications include:

#### **OPERATING AND ENVIRONMENTAL**

- All designs are based upon the operating conditions that should be expected. Operating Pressure, temperature, flow rates & fluid,
- Upset Pressure, temperature, flow rates & fluid
- Design Life, such as years of service, type of service, design cycles (partial and full cycles) and corrosion rate
- Environmental Conditions, such as external pressures, temperatures, soil, wind, flood, seismic zone and air quality
- Special Considerations: There are many possible considerations such as expected design and operating revisions, vibrations from nearby equipment, and noise limitations due to nearby residences or businesses,

Assumptions are often made about operating and upset conditions that lead to one set of design conditions that include all possible pressures and temperatures. Likewise, number of cycles and years of service are often not specifically stated. This is satisfactory for a large number of



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equipment items that may have at most 100 operating cycles per year. Even with a 50-year design life, this is only 5,000 cycles. Most design codes include 7,000 or more cycles in the basic equations and allowable stresses. However, for systems that are designed for batch loading, or are known to have imposed vibrations (mechanical or flow induced), then the number and type of design cycles must be specified.

## **6.2 Material Specifications**

The materials of construction and methods of fabrication and erection are dictated by the design basis above. Usually equipment is designed to perform as long as the plant design life. However, there may be cost or other considerations that provide for a design basis of particular equipment to be replaced in shorter periods of time. For example, a flow of coal or ash is highly erosive. Rather than purchase high grade hardened materials, it may be more cost effective to design pipes and valves to function for a few years, and plan on replacement.

Alternatively, carbon steel systems potentially subject to Flow Accelerated Corrosion (FAC) have been found to be nearly impervious to FAC when made of materials with a minimum of 1% chrome. In this case with a modest increase in material costs, the need for inspection is greatly reduced, and the potential for safety and availability problems are greatly reduced.

## **6.3 Inspectability**

One aspect of including MI in the design phase is INSPECTABILITY. This process is to identify the static equipment in a plant that will require inspection during its life, and as much as practical, reduce the future costs of these inspections. Criterion to include:

1. DOCUMENTATION OF ORIGINAL DESIGN, CALCULATIONS, FABRICATION, ERECTION AND INSPECTION DATA.
2. Provide reasonable access to primary inspection areas.
3. If visual observations are useful, assure permanent access to line of sight
4. If equipment needs to be isolated or entered for examination, assure valves, manways, boroscope access ports, quick access “blanket insulation” or other aides are included in the design.

## **6.4 Alternative Specifications**

From the Design Basis, there may be additional specifications to be included beyond standard code requirements. These could include access platforms, access ports, manways,



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instrumentation, insulation types for quick access, support requirements to minimize long - term damage, Quality Assurance (QA) and inspection, testing and documentation.

#### **6.5 Revise Risk /Consequence Chart**

At pre-determined points in the design phase, it is appropriate to review the risk / consequence charts for MI. Typical timing should be at completion of specifications, at receipt of vendor proposal packages, and upon receipt of vendor drawings. For each system, update the potential failure modes and determine if modifications should be made to the risk modification plans and equipment specifications.



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**7.0 EQUIPMENT SUPPLY**

Once equipment has been specified and ordered, the plan should be well set for fabrication, inspection, testing and erection. The simple statement is that the project team needs to follow through on the plan and install the equipment as specified. There are some requirements that deserve emphasis.

Equipment suppliers often have the data available that is required later, such as thickness data, and repairs that are made in the shop. Vendors may be surprised when asked to provide this data and are not prepared to perform the work to the specifications. Assure these requirements are agreed to prior to award. In some cases, the vendor may allow access to the Owner's team to actually record the data. In other cases, the vendor may be very helpful in organizing the data in the format the project team requires.

The vendors do not typically document shop repairs. However, when assessing equipment condition, this is the type of detail that is often very important. The vendor should be required to document special repairs on critical equipment.

When wall thickness data is required at specific locations on tanks, pipe and vessels a detailed plan is required to complete. Some of the questions include:

1. Will the equipment be insulated?
2. If insulated how will the exact location be know?
3. Should measurements be taken in the shop or in the field?
4. What format will the data be recorded in?
5. Metric or English units?
6. Will vendor, construction, QA, Owner, or other entity take measurements?
7. What is the database that will be used?
8. If equipment is insulated, will future measurements be made by going through the insulation, or by internal measurements, or through insulation measurements?
  - a. At one time, the common method for inspection was to drill out a 2" diameter hole in the insulation, measure the metal thickness and then install an insulation plug over the location. This method greatly limits the inspection locations.
  - b. Through insulation radiography is now used to look for thinning if the pipe is relatively small, around 6" diameter or less.



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- c. Some companies are marketing through insulation thickness readings using electro magnetic imaging. Thus, to obtain the right kind of baseline readings, it is best if the expected method for making MI readings later in the process is understood.
9. For flaw detection of welds, is radiography to be used, or perhaps a version of the computerized ultrasonic methods recently developed? Method used should be similar to that expected to be used later to allow detailed point-to-point comparisons.



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**8.0 TRANSITION TO OWNER**

The process of transferring ownership of a plant from contractor to owner is a complex task that must be well planned. Sometimes systems are transferred as they become available. Owner personnel usually work with contractor personnel in the commissioning and start-up activities. Usually there is schedule and cost pressures to get the plant on-line to meet funding and/or production deadlines. In the midst of these issues, sometimes documentation is considered a low priority – certainly documentation that may not be referred to again for years.

At this transition time, the documentation is available from equipment suppliers, contractors and commissioning personnel that tell later evaluators the original condition of the equipment, the types of operating conditions it was subjected to, and the original design criteria. There must be a system in place that accumulates this information, and all parties must adhere to the documentation system procedures.



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**9.0 SUMMARY**

The process of performing Mechanical Integrity should begin during the initial planning of the plant concept and included in the Design Basis of all systems and equipment. This life-cycle approach to MI allows the Owner to later make rational evaluations on the condition of equipment that will lead to decisions to

- Repair
- Replace
- Modify Inspection Frequency and Methods
- Accept Results and Leave Equipment As-Is
- Modify Operational Procedures
- Modify Maintenance Procedures

Detail design for MI should include considerations on how the equipment will be operated, inspected and maintained, to provide the highest reasonable plant availability and safety, for the lowest long-term cost.

All decisions, calculations, inspection data, material certifications and other design data should be properly documented and saved for future reference.

All of these tasks are intended to provide safe and reliable operation of every system in an operating plant.