Mitigating “Dimensional Drift” in Industrial Construction Work Processes

Applying State of the Art Dimensional Technology to Industrial Construction Work Processes

The Design Process:

The goal in chemical process design is to produce a plant design that is optimal with respect to cost and performance. Plant performance involves a broad range of criteria. A good process design must not only exhibit an optimal balance between capital and operating costs; it must also exhibit operability characteristics which will allow economic performance to be realizable in a practical operating environment. Operability considerations include flexibility, controllability, reliability, and safety.

Process Design:

In chemical engineering, process design constitutes the design of chemical processes for the desired physical and chemical transformation of materials. Process design is central to chemical engineering, and is considered the summit of the chemical engineering discipline, incorporating all the technical and financial considerations required for the construction and operation of a facility.

Process design applications include the design of new facilities and the modification and expansion of existing facilities. The process design exercise starts at a conceptual level and ultimately ends with the design basis for all the construction documents that will be produced in the detail design phase of the project.

Detail Design:

The product of the detail design phase is the construction package that will be used to build the facility. The dimensional integrity of these construction documents varies widely depending on how the dimensional data is captured, validated, and reported. Equipment, piping and structural steel must fit together with other new and existing components in the construction phase as to facilitate the function of the process design. This collective installation of elements, at the surface, appears to be more intuitive than challenging but experience teaches otherwise. ***The intent of this paper is to define the issues and circumstances that lead to dimensional problems in detail design and the proposed technical and administrative remedies required to address these problems.***

Dimensional Errors and Tolerances:

There are actually two possible root causes whenever a "bust" or miss-closure during the installation phase of the project is experienced. Both are equally problematic.

- Fit-up problems due to dimensional errors in design, fabrication and field erected components
- Fit-up problems due to accumulated tolerances in design, fabrication and field erected components

A dimensional error is different from a tolerance in that dimensional errors are due to a lack of precision in the measurement process that results in dimensional data that is not correct. Examples are the measuring and recording of as-built conditions incorrectly in the field or failing to interpret a design document properly and not building the associated component or components as specified.

On the other hand, a tolerance is the deviation from a standard; *especially***:** the range of variation permitted in maintaining a specified dimension. The allowable deviation in industrial applications in many cases is set by the precision limits of the fabrication and installation work processes.

In our industry, we commonly refer to "shop tolerances" as the maximum allowable deviation from design standards acceptable in a component. Shop tolerances for heavy industrial applications are usually set at 1/8". Given the scale of the elements, the precision of the fabrication equipment and the measurement technology utilized, 1/8" is the best possible precision obtainable in a shop environment. It is important to remember this is the best tolerance that can be achieved and tolerances in many cases exceed 1/8" and when they do there is an increased incidents of dimensional problems.

Both dimensional errors and accumulating tolerances can result in the failure to install elements without the revision of one or more of the elements.

There are three distinct project phases where dimensional errors and tolerance accumulation occur:

- **Design:** These are errors that occur in the measurement of existing equipment and piping. When these errors are incorporated in the design documents, fabrication will, by definition, not be compatible with existing piping and equipment in the field.
- **Fabrication:** Errors, such as, fabricating a left hand instead of the right hand that was required are common in every project. Owners typically do not perform extensive dimensional QA/QC in fabrication shops. Errors in interpreting and following fabrication documents frequently go undetected resulting in rework in the field.
- **Installation of field fabricated elements:** The layout of equipment foundations, supports and structural steel are common sources of error. Layout of cut lines on piping and equipment can also be challenging. When these errors occur, the results are usually systemic and pervasive.

Every fabricated element (equipment, piping, structural steel, concrete foundations) has some dimensional tolerance or deviation from the design documents. There are no perfect matches with respect to design. Examples of common deviation from design that cause fit-up problems are:

- Deviated flange rotation
- Piping configuration
- Nozzle projections
- Nozzle locations with respect to elevation and orientation
- Rolling offset angles
- Prescribed level or slope of piping
- Component located out of the plumb, level, and square grid
- Foundations off coordinate, off elevation and out of rotation
- Equipment anchor bolt patterns out of orientation with respect to nozzles and other connections

These are only a few of the possible and even likely errors that are experienced on every project. Deviations due to tolerance occur in all of the project phases. These deviations are not considered errors unless they exceed the allowable tolerances prescribed in the specifications for any given component. It is important to remember that even when tolerances are within the acceptable range, ultimately a bust may occur because tolerances are accumulative making a bust more likely with an increase in the number of components to be assembled. This occurrence is commonly and colorfully expounded by "***Klipstein's Law****"* which states:

"Tolerances will accumulate unidirectionally toward a maximum difficulty in assembly"

Mitigation and Control of Dimensional Drift:

Given that accumulating tolerances and human error are experienced on every project, a methodology for controlling it beyond traditional methods is needed. It is important to note that ***a comparison to the original design document will not provide the dimensional certainty required for fit-up***. That comparison would only be effective if all of the following were true for all components:

- Detailed design documents must precisely match as-built conditions
- Fabricated components must precisely match fabrication drawings
- Field constructed components and assemblies must precisely match design documents
- Tolerances (which are random) must occur in a manner that will offset each other in a given assembly rather than in an accumulative manner

If any of the above is not true, and for some elements it will not be true because of dimensional drift, rework will be experienced. Furthermore, for errors that occur, early in the project, such as as-builting existing piping and equipment, the probability of repetitive rework is significantly increased. Often when there is a design error the result is a pervasive, systemic fit-up problem affecting an entire circuit/system.

Also it is important to understand that when these errors do occur, ultimately they must be corrected. The question is not will they be corrected, but under what circumstance and by who. If these errors are left for discovery late in the project by the field contractor, the remedy will be left for the field contractor to resolve. Some of problems associated with this approach are:

- In some cases, when miss-closures are relatively small, piping and equipment are forced to fit introducing stresses on piping and equipment. This frequently leads to future maintenance problems, premature failure, unscheduled shutdowns, and possible safety issues.
- When busts are discovered in the construction phase, there is no opportunity to provide a global remedy. A field contractor can only evaluate one spool at a time which may lead to multiple, unnecessary revisions to piping and structural steel. When cad models are used to identify and mitigate fit-up problems, key spools can be located and revised before field contractor mobilization in the field avoiding repetitive unnecessary revisions during installation. This work process not only reduces the number of revisions required but eliminates the need to stop the scheduled work while revisions are made.
- When busts are discovered during the construction phase, several undesirable work practices are forced into the work processes. Cutting and grinding in elevated structures or in process areas. Hold over of cranes and other construction equipment. Increased man-hours with the associated impact to schedule and budget. Identifying and revising key spools early avoids these problems and allows the revision to be made offsite in a fabrication facility or, at worst, in the laydown yard.

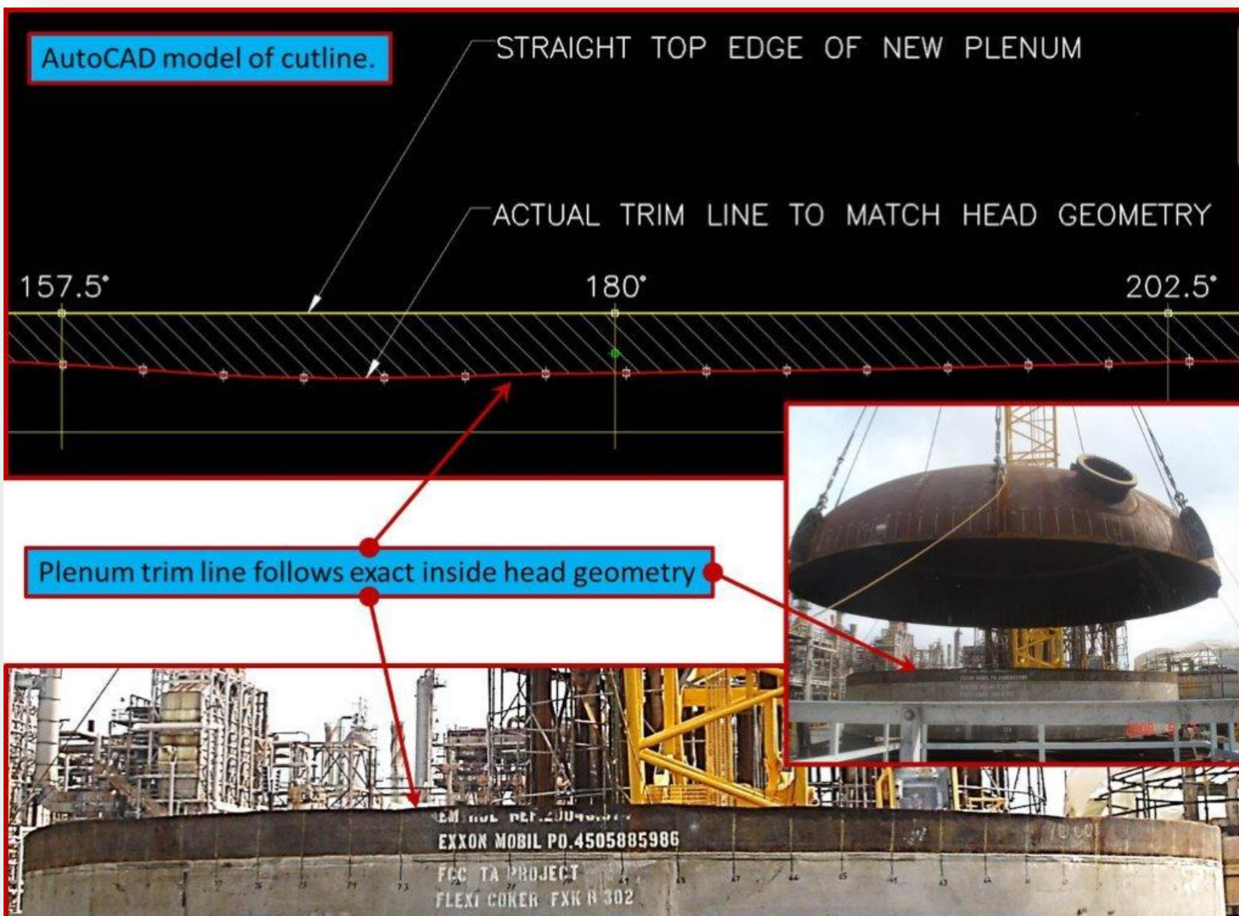
The only reliable methodology for eliminating rework is to control or manage dimensional drift as the project progresses. The most important part of any measurement system is the mechanism that provides for the comparative analysis of the data collected. Given that revision will occur when required, the goal at this point is not the conformity to the construction documents, but to install all components in a workman like manner.

Given that all elements have a tolerance and are by definition dimensionally deviated from the design documents, the goal is to determine if the element will or will not fit with the other dimensionally deviated elements in an assembly. The inability to track the accumulation of tolerances and errors as the project progresses by traditional methods is why rework is so prevalent in industrial construction applications today.

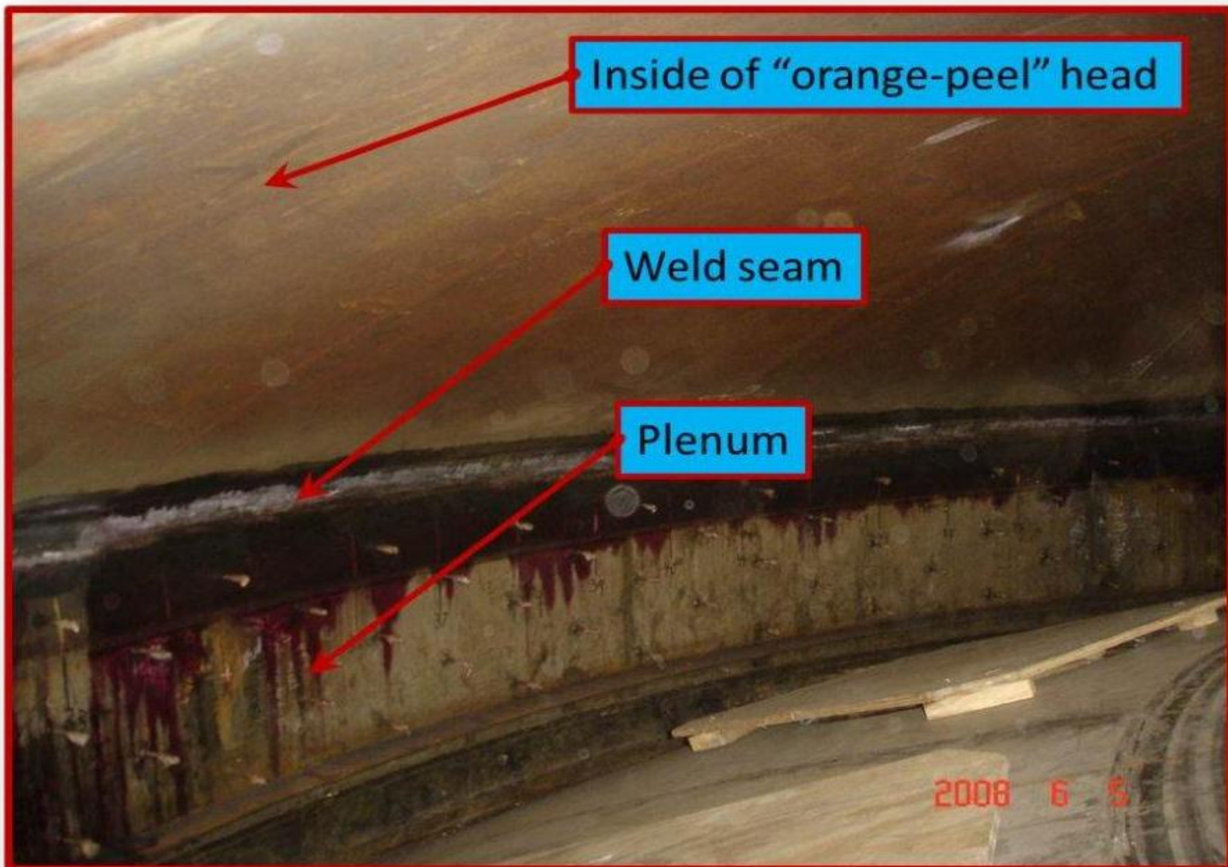
Control of Dimensional Drift requires the ability to look at the, “Dimensionally Deviated**”** system as a whole and track how elements are connecting or not connecting and the best recourse for any problems that will result in a bust.

When precise electronic measurements are processed into 3D models, these models can be assembled in model space providing an electronic “trial fit” of the elements. If the individual 3D models precisely match the actual fabricated components, the electronic assembly will predict the success or failure of the fit-up in the field.

Furthermore, the trial fit will provide data required for the revision of one or more elements in order to avoid rework in the field. The deviations due to accumulating tolerances and the irregular profile of an orange peel head are predicted and documented in the illustration given below.



After the 3D model is developed, a Mylar wraparound template is generated to guide the constructor in the final modification of the plenum to head connection. The final cutline can be identified and completed away from process areas, preferably in a fabrication facility. This integration of an electronic drafting platform and precise 3D models of the elements to be connected is the answer to controlling and mitigating dimensional drift. The combination of technologies provides the ability to detect and correct dimensional miss-closures before the shutdown of operating units or the mobilization of manpower resources in the field. Utilizing this important step reduces the financial liabilities experienced by the owner during shutdown. A typical weld seam for a plemun to head connection utilizing these techniques is given below.



According to a recent Energy Information Administration report, operating companies and turnaround professionals agree that the leading cause for turnaround overruns is the dimensional revision of piping, equipment and structural elements. This ongoing problem is perpetuated by the inability to identify and correct the dimensional errors in piping and equipment that adversely affect assembly in the field before installation or bringing the elements into close proximity using traditional methods.

This challenge is further compounded by the size, scale, and complexity of heavy industrial systems and components. Distortion due to thermal cycling and creep can also add to the dimensional complexity of components that are operating in the field at elevated temperatures making fit-up with new elements difficult.

It is common for operating companies to experience major turnarounds where cost, schedule, and safety issues spiral out of control. A recent survey of FCCU operators summarized the operating experiences for 28 FCCUs. Turnaround durations tended to be longer than planned, with an average slippage of 5 days. For each day the turnaround exceeded the scheduled outage, the average cost per day was 2 million dollars making the average additional cost for FCCU turnaround due to schedule overruns 10 million dollars.

When executing major turnarounds, the financial and technical risks are such that no event or scenario that can be controlled should be left to chance. Mitigation and control of these root causes of overruns should be the principal concern of any turnaround execution plan.

Traditional Measurement Methods - Laser Scanning/Point Cloud Technology:

Traditional dimensional control methods, primarily laser scanning, lacked the precision and flexibility required for this high resolution work process. A technology that can provide precise, comprehensive dimensional control is required to implement the zero rework approach. The dominant dimensional tool utilized in the petrochemical and refining industry today is laser scanning/point cloud technology. Laser scanning is the primary measurement device employed by engineering companies to produce models for detail design. Even though point cloud technology dominates the market place, laser scans have limitations associated with how the dimensional data is captured, processed into models, and later on in the project utilized for detailed design purposes.

The ease and speed of the random mass data acquisition method utilized by laser scans incurs definite precision limitations. When dimensionally complex components are involved, the dimensional uncertainty associated with laser scans requires the use of field adjustment methodology during installation. The adjustment of components in the field requires additional time and craftsman manpower resources, putting the schedule and budget at risk. Laser scans can provide useful dimensional information, but cannot define all elements to the point of fit-up without adjustment or revisions. A system with greater precision and flexibility is required to track and mitigate dimensional drift.

Leave-Long Field Fit Methodology:

The availability and accuracy of “as-built” documentation is critical to a turnaround’s cost, schedule, and safety performance. As-built accuracy is dependent upon dimensional control work processes and procedures, and their respective limitations. Because of traditional measurement methodology’s inability to measure accurately enough to provide a fit-up, particularly for dimensionally challenging components, an installation technique has been developed, as a “work around” to address the problem. For dimensionally complex piping systems, one design/installation approach is the “leave-long field fit” method. This methodology requires that selected components be fabricated with additional length. Piping is installed sequentially while modifying the leave long spools to obtain proper fit-up. When working with boilermaker components, field fits, slotting, and field drilling bolt holes along with increased cutting, grinding, dogging, and welding are some of the activities used to install elements with potential dimensional deficiencies.

These techniques are essentially trading the devil you know for the devil you don’t. That is, substituting the planned modifications associated with field adjustment methodology for the unplanned, undefined, difficult to resolve, rework that invariably arises due to the inability to precisely measure and fabricate components with complex geometries. This field adjustment methodology provides some control of the schedule, but obtains that control by a planned increase in “fit-up tasks” to accommodate final field adjustment installation methodology.

To achieve the goal of a minimum outage, a comprehensive and meticulous dimensional control method incorporating all project phases is required. Effective post engineering dimensional checks to control the accumulation of tolerances in the fabrication phase is critical. Fabricated and field constructed elements must also be dimensionally captured, modeled, and trial fit in model space to verify fit-up can be achieved. Any dimensional deviation in fabricated components due to collective shop tolerances or fabrication errors must be captured before turnaround and modified for fit-up as a pre-turnaround activity. By preparing all components for installation in this manner, the construction scope of work during shutdown is reduced to the weld up/bolt up of the new and existing elements. This concept of zero rework/zero modification work process is primary in minimizing the turnaround window and also provides important safety benefits by eliminating numerous crane lifts as well as the cutting and grinding in elevated structures associated with traditional leave long-field fit methods to achieve fit-up.

A Combination of High Resolution Dimensional Control is Required to Achieve Zero Rework:

As previously discussed, laser scans, although dominate in the industry, cannot provide the precision or flexibility required to achieve a zero rework project. To insure that all components in all project phases will fit, total station point shots and photogrammetry is required. The increased precision delivered by this combination of dimensional methodology provides the basis for design checks, fabrication checks, and construction field support. The comprehensive use of these two diverse and independent precision measurement systems to dimensionally define and monitor all project phases is essential for high resolution dimensional control methodology. Both of these measurement systems provide significant precision advantages over laser scanning technology.

The photogrammetry system currently utilized is an adaptation of a measurement technology first developed by the National Aeronautics and Space Administration (NASA) for all measurements taken in outer space since 1970. The technology captures dimensional data by extracting three-dimensional information from two-dimensional digital images and total station point shots. A recent NASA application of this work process provided a methodology to locate and measure the defect in damaged heat shield tiles on the space shuttle. Tile damage measuring less than 1 mm was detected at a range of 600 feet.

A software interface between these state of the art electronic measurement tools (digital cameras and total stations) and the dominant electronic design tools used today (AutoCAD® and Microstation®) is also part of the system. The software transfers the dimensional data captured with total station point shots or by digital images into model space of the drafting software of choice. Model development is aided by algorithms developed for this purpose and trial fitting occurs in the model space utilizing either of the electronic drafting platforms listed above.

Conclusions:

The use of advanced dimensional control technology has proven methods to reduce field activities such as cutting and grinding components in elevated structures. The technology provides a zero defect work process on most projects regardless of dimensional complexity. Many project tasks that are traditionally performed on the jobsite today can now be fabricated and dimensionally verified offsite in the fabricators shop before shipment. Reducing the number of project tasks and activities is the best way to improve safety. If tasks are eliminated, particularly unplanned rework related tasks, there is no opportunity for a worker to be injured performing those tasks. If a planned task is eliminated from the project scope of work, fewer workers and construction equipment are required to complete the construction scope of work. This reduced density of activities, people, and equipment directly facilitates improved safety.

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