All Sealing Problems can be Fixed

A Guide to Leak-free Sealing

David Clover, Advanced Sealing and Supply Company
David Reeves, Chevron USA

Submitted to the
National Petrochemical and Refiners Association
December, 2010

It's no secret. Every operating plant – whether a chemical processing plant, a paper mill, a refinery or nuclear facility – has occasional upsets, outages and yes, even leaks. We'd like to pretend they don't happen – and we don't talk about it openly outside our tight inner circles – but they do happen. Yet advancements toward the goal of leak-free sealing cannot be made by ignoring these occurrences. Rather, by studying these events – by coming to understand the root causes involved – we can establish the systems, materials and procedures needed to eliminate them.

This paper looks at one end-user's experience in unraveling and resolving persistent, long-term leak sources in the refining industry, and shows how their methodologies can benefit others willing to follow their steps. We will look at how two different cases were resolved using the following protocol:

1. Define the Problem
2. Collect Data and Identify the Root Cause
3. Test Possible Solutions (Lab and Field)
4. Write Specifications
5. Roll out to the Field for Implementation

Case 1: Heat Exchanger Leakage

1. Define the Problem

The first step in resolving any problem is to define it. The better the problem is understood – the better the scope of it is identified – the more readily it can be resolved. With that aim in mind, one major refining company determined in the mid-1990's to conduct a study of leaks in all its North American refineries. The results were eye-opening. They found that:

- Flange leaks were the 3rd most frequent repair item in refineries,
- Flange leaks had the 2nd highest dollar cost associated with them ($9,000,000 spend in five refineries over 5 years),
- Large refineries could lose $3,000,000 worth of production per year due to flange leaks,
- About 40% of all the heat exchangers developed some level of leakage in their 3-to-5 year service cycle.

Upon review of their findings it was clear that heat exchanger leaks were having an appreciable impact on the operating costs and profitability of the refinery. This was further exacerbated by the high cost of field repairs needed to keep key systems operational when a major exchanger leak occurred. The custom-fabricated exchanger clamps frequently exceeded $50,000.

Numerous "solutions" to the problem of leaking heat exchangers had already been developed, and were aggressively being marketed to the refining industry. These proposed solutions included:

- Belleville washers,
- Nubbins,
- Double nubbins,
- Graphoil-wrapped gaskets,
- Rotobolts,
- Supernuts,
- Thicker flanges,
- Temperature control during start-up,

- Remachining flanges,
- Tensioning,
- Smaller diameter studs,
- Spiralwound gaskets,
- Insulating before start-up, and
- Air Impact guns

And while some of these “solutions” seemed to help more than others – at least in specific applications - the problems of leaking heat exchanger gaskets persisted, leading to the conclusion that the root causes had not yet been fathomed or addressed.

2. Collect Data and Identify the Root Causes

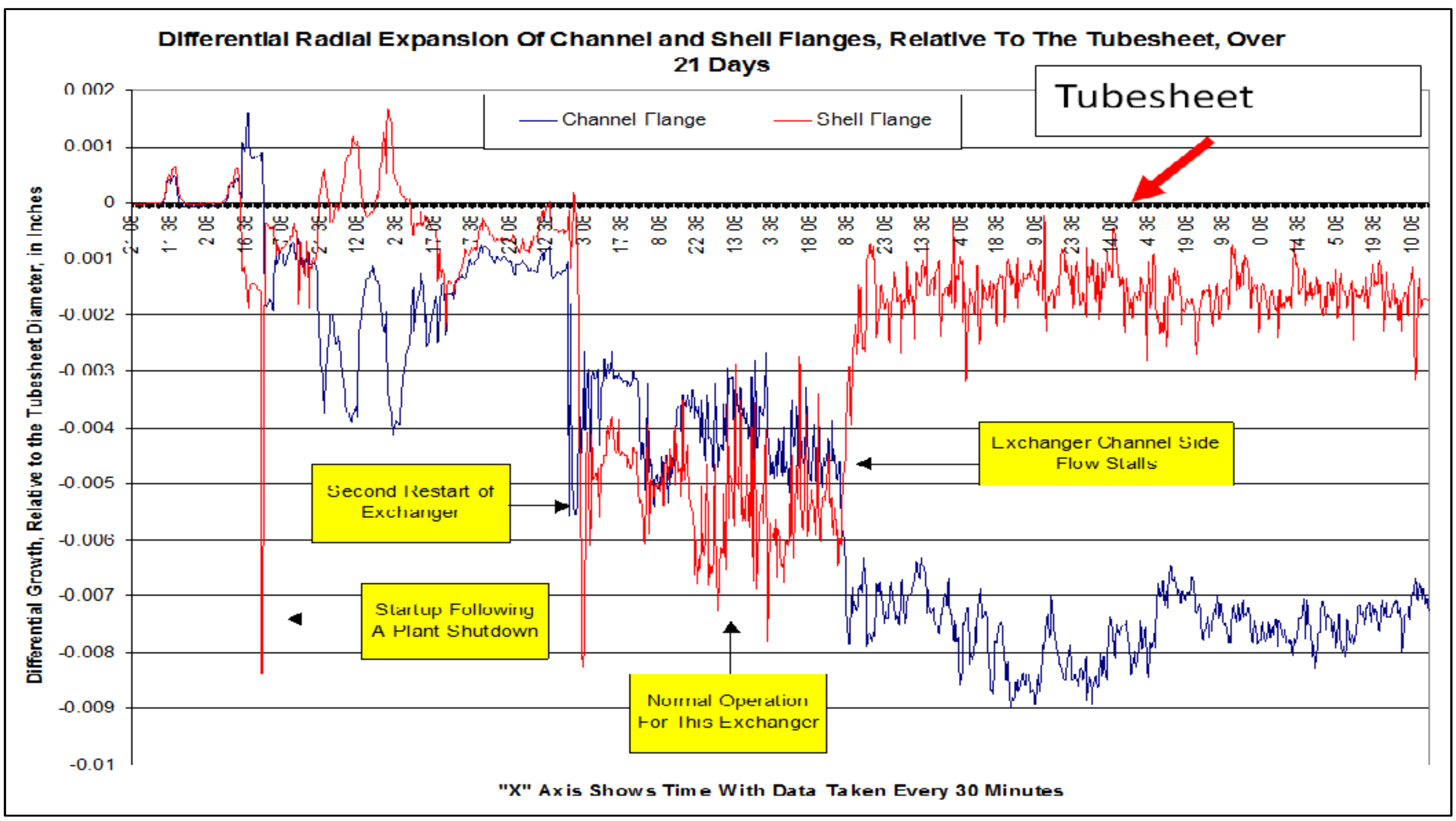
The co-author of this paper took on the task of determining the root causes of this leakage, determining appropriate fixes for these problems, and implementing these fixes system-wide.

To collect the data needed to analyze this problem, data David turned to one of the most persistently problematic pieces of equipment at his availability – E-510A, a jet-fuel reboiler on the side of a fractionating column. This exchanger had leaked immediately upon start-up for 25 years, regardless of precautions taken. He began to systematically measure and record any thermal event that could possibly affect sealing of this exchanger. For 22 months data was collected every 15 minutes, measuring all process temperature changes, the input and output temperatures of both fluid streams, the temperature of the outside of the tubesheet, as well as the outside of both of the flanges abutting the tubesheet. Environmental impacts, like rainfall, were also recorded. A series of load cells was put in place to directly read the stress on four of the studs that were used to load the flanges that sandwiched the tube-sheet.

The data generated over the next two years clearly revealed the root causes of gasket failure and joint leakage. One of these root causes had not been previously understood at all, and the other – which had only been understood qualitatively – could now be shown quantitatively. This data has led to advancements that have revolutionized the sealing of large diameter flanges in the refining industry.

The first of these root causes is Differential Radial Shear. The table below shows the genesis of this key advancement. In this chart the temperature of the tubesheet is artificially held to be zero, while the temperatures of the channel flange and the shell flange are shown as fluctuations relative to that zero line.

As you can see, the “X” axis is a 21-day plot, while the

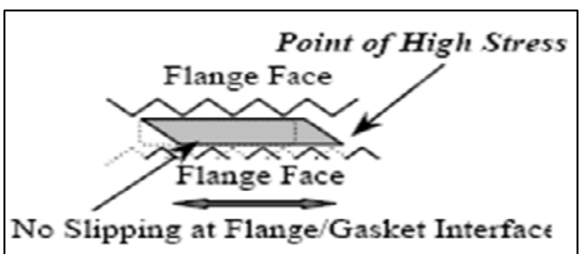


"Y" axis has been converted by the coefficient of thermal expansion into growth and shrinkage of the flange relative to the tubesheet. This enables one to easily see the very dynamic nature of heat exchanger joints, where relative growth and shrinkage between the flanges on either side of the gasket – on the order of 0.002" – happens repeatedly, and where temperature upsets in the system can result in very rapid differentials of up to 0.010". Data from larger exchangers has shown these movements to be in the range of .035", while the Coke drum flanges can move as much as .25" per cycle per day.

One needn't spend too much time viewing this data to see that the gasketed joints that have always been considered static are, to the contrary, quite dynamic. Even during the normal steady-state operation of this exchanger routine temperature fluctuations resulting in 0.002" growth and shrinkage of the flanges occur 14,000 times per year. It is impossible to ignore the cumulative effect of such dynamic movement on the gasket that seals between these elements. In fact, it was calculated that over the course of just one year the total differential "scrubbing" that occurs at this interface amounts to over 28" of movement.

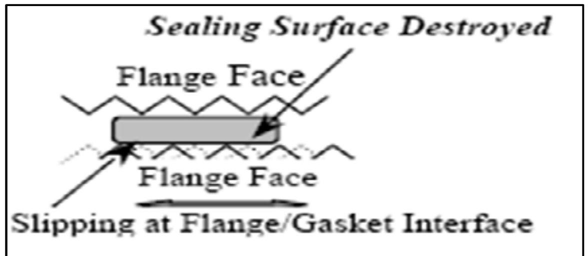
Since this scrubbing action is applied back and forth across the radius of gasket, it was essential to confirm the evidence of shear forces at work on the samples of failed double-jacketed gaskets that had been collected. To accomplish this, David enlisted the help of Dr. Warren Brown.

Dr. Brown reviewed David's data and the samples of failed gaskets and hypothesized that there were two major modes of failure that could be induced by the measured differential in radial growth. The first of these could occur when the gasket was firmly gripped by the flanges on both sides, and was forced to flex back and forth as the flanges moved relative to each other. At the point of flexure, fatigue would develop leading to the rupture of the gasket at that point.



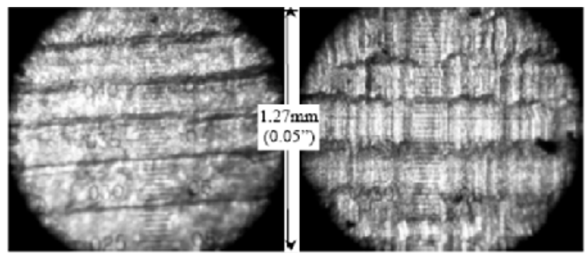
Mode 1 – Gasket Placed in Shear

The second proposed mode of failure would occur when the flange slid across the face of the stationary gasket, causing damage to the sealing surface.



Mode 2 –Gasket Surface Destroyed

A photo micrographic inspection of the failed gasket samples confirmed both of these modes of failure.



The picture on the left shows a gasket firmly clamped by the flanges. This sample had failed when stress fatigue split the inside radius of the Double Jacketed gasket. The picture on the right shows striations as the flange scraped across the surface of the gasket.

These findings were the basis of a seminal paper by David Reeves and Warren Brown entitled "Failure of Heat Exchanger Gaskets due to Differential Radial Expansion of the Mating Flanges".

3. Test Possible Solutions

To confirm that this newly understood phenomenon of differential radial shear was impacting the performance of existing gaskets, it was decided to construct a test fixture to duplicate this occurrence under laboratory conditions. This same fixture could then be used to assess the ability of other gasket types to tolerate radial shear, the relative leakage rate for each gasket, and the amount of relaxation that each gasket would experience when heated. This data was also used to determine the optimal gasket characteristics in order to maintain a seal under these conditions.

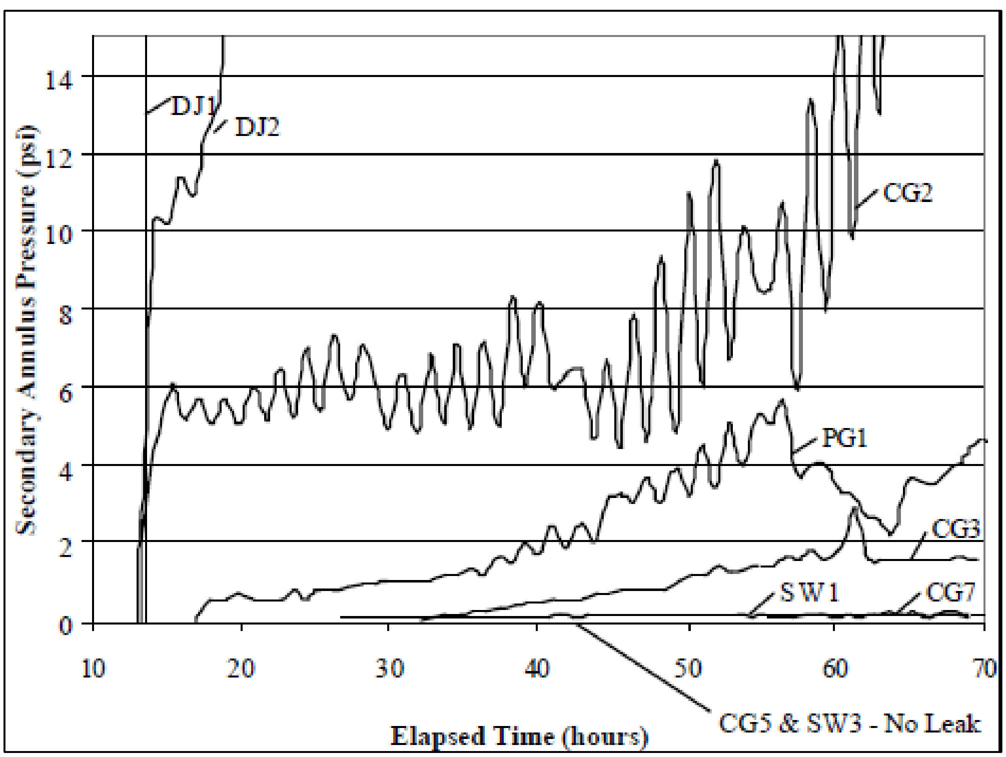
To that end Reeves and Brown designed the Radial Shear Tightness (RAST) test. The fixture was designed to simulate the growth and shrinkage of flanges when exposed to sudden, dramatic temperature changes (see picture below).

In this test, the flanges were held at 600 degrees F., while the tubesheet was rapidly cooled to create 0.020" radial shrinkage. This process was repeated once each hour for 60 hours. The leakage past the gasket – and the amount of relaxation in the gasket – was monitored to assess gasket performance. The results of this testing were published by Dr. Warren Brown in his paper, "The Suitability of Various Gasket Types for Heat Exchanger Service". The chart below graphically compares the results of this test for the various materials tested.

Of immediate interest is the striking failure of the Double Jacketed gaskets (DJ1 and DJ2, below). This failure is seen in the rise in annulus pressure, indicating leakage past the gasket. The two Double Jacketed gaskets were the only ones to suffer a complete failure in the test, which Dr. Brown found particularly interesting, since "the type DJ gasket is probably still the most widely used gasket in heat exchanger joints."

This test confirmed that differential radial expansion was a major cause of failure for Double Jacketed gaskets. However, it also pointed the way forward to alternate materials and construction methods that could result in gaskets that would withstand these scrubbing forces.

The data shows that corrugated gaskets with graphite faces, spiralwounds and Kamprofile gaskets with graphite faces all outperform Double Jacketed gaskets. However Dr. Brown concluded that since there was a great disparity in performance even between gaskets of similar construction, that "it would appear those small variations in gasket construction, such as filler thickness or the number of corrugations, has a very dramatic impact on the gasket performance." Obviously, more testing would be required to optimize the gasket for exchanger service.



The testing needed to optimize the corrugated gasket was conducted in the field at a Southern California refinery. Various tests were designed to determine the optimal:

- Thickness of the graphite faces,
- Density of graphite,
- Grade of graphite,
- Thickness of metal substrate,
- Height of corrugations,
- Pitch of corrugations,
- Method of graphite adhesion.

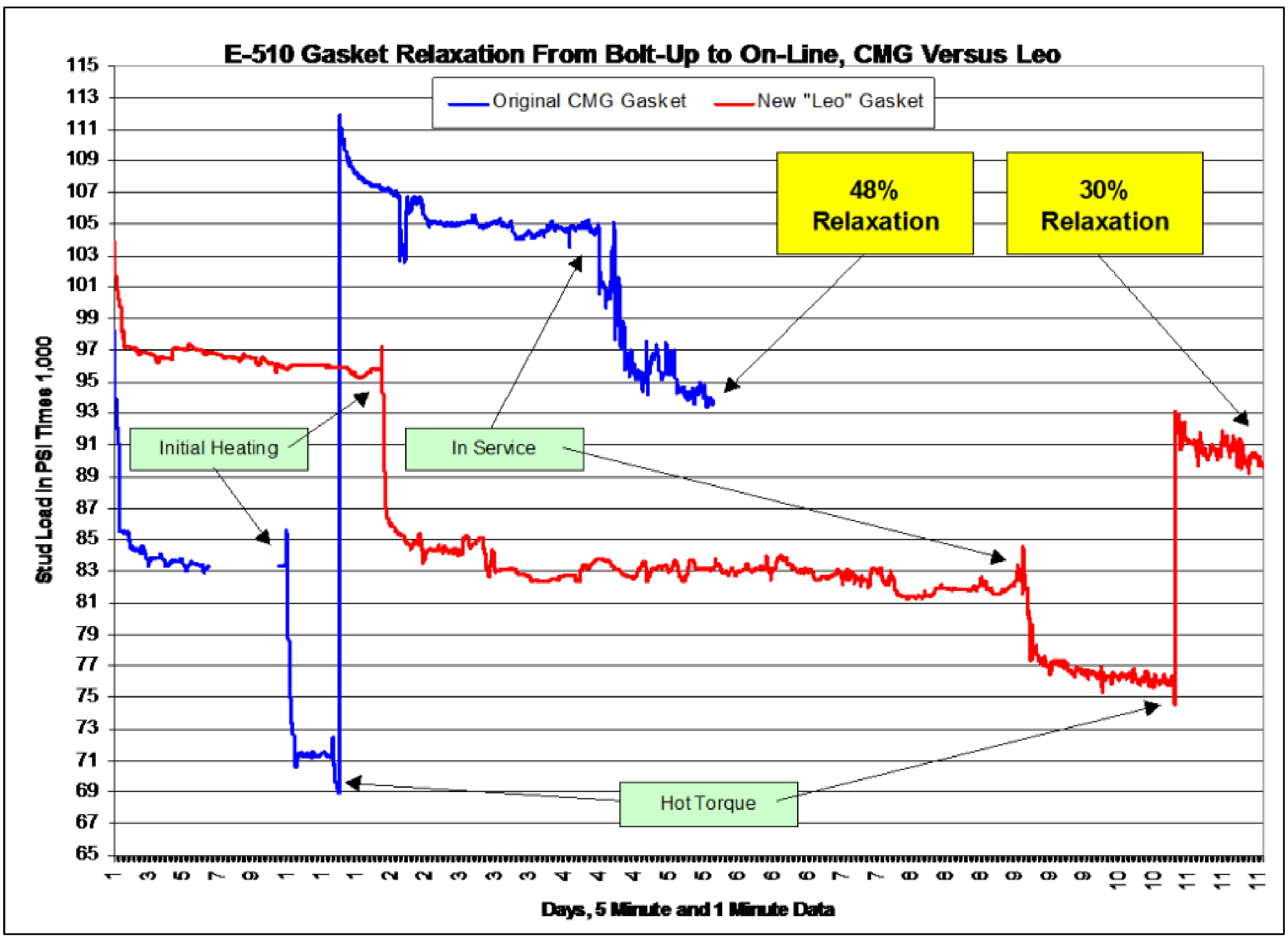
An example of that testing is shown below. In this chart we see the relaxation plot of two different corrugated gaskets that were both tested on the E-510 exchanger. This test examined the effect of graphite thickness on the relaxation of the gasket over time.

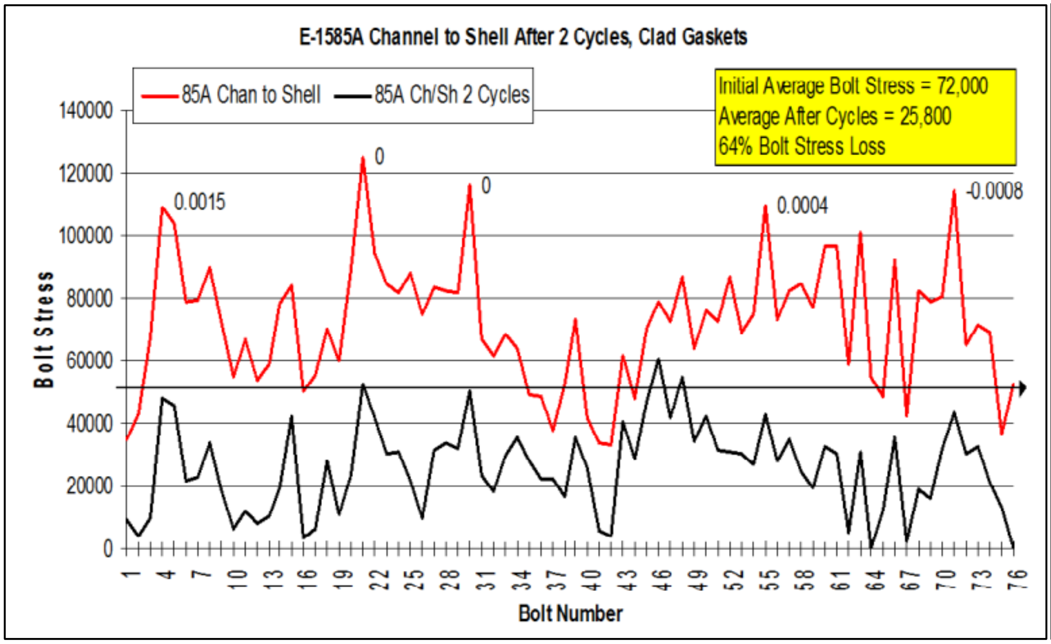
It was earlier stated that the analytical testing of heat exchanger gaskets revealed two root causes of failure. The first, as discussed above, is Differential Radial Expansion. The second root cause – graphically shown in the following chart – is Gasket Relaxation.

That gaskets relax is common knowledge. In fact, gasket manufacturers of sheet material routinely include “Creep Relaxation” in their material data sheets. But since the test only measures short-term relaxation in an unheated joint, and since it applies only to sheet materials, no reliable data has existed to quantify relaxation in heat exchanger gaskets.

The data below shows two important points. First, that even a properly constructed corrugated gasket will relax 30% from the time of initial installation to the time it is in service; and secondly, that a hot torque of the joint can offset this initial relaxation.

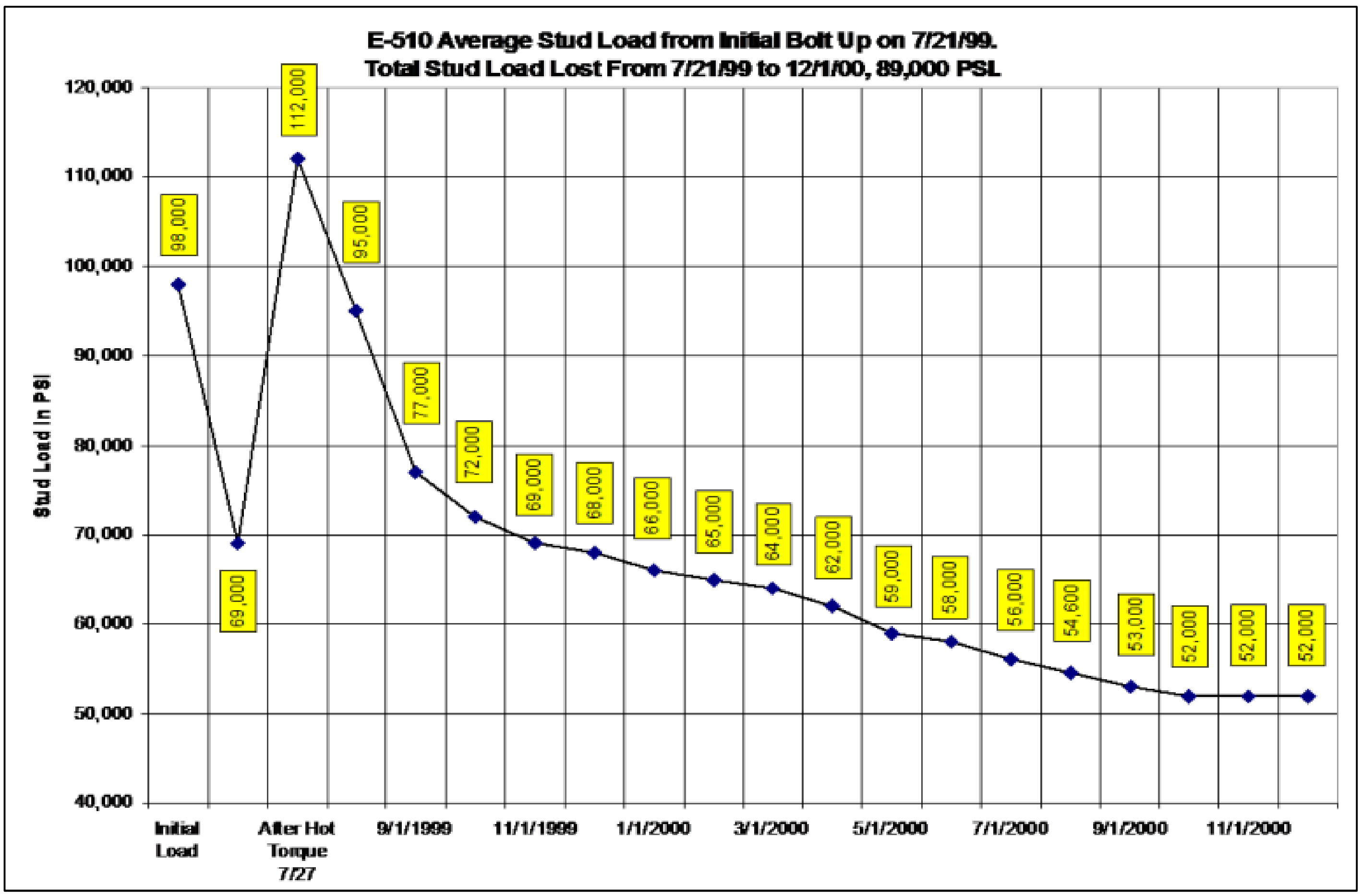
This phenomenon of relaxation is not limited to corrugated gaskets. The chart on at the top of the following page shows the amount of relaxation seen with a Double Jacketed gasket in one exchanger.





The data in red shows the initial stud load on each of the 76 studs – averaging 72,000-psi stud stress. The data in black shows the residual stud stress just two thermal cycles later, when the unit was leaking profusely. The average stud stress had dropped 64% to just 25,800-psi.

Long-term data collection on E-510 revealed that the initial relaxation of 30% - even though offset by retorquing – was just part of the story. The gasket continued to relax at an ever decreasing amount month after month until it reached stability after 15 months, as shown in the following chart.



It is important to point out that the two root causes of heat exchanger gasket failure – Differential Radial Shear and Gasket Relaxation – were resolved in two completely different manners. Differential Radial Shear was nullified by the development of new materials designed to stand up to the forces at work on the gasket. Gasket Relaxation was offset by the development of new installation procedures. These procedures included:

- Setting the stud load to a high, predetermined value to generate a targeted gasket stress,
- Using Moly-based lubricants,
- Using new studs on all heat exchangers,
- Using hardened washers to reduce frictional losses,
- Using clicker torque wrenches (up to 1,000 foot pounds) to achieve a reasonable accuracy,
- Using new, faster tightening patterns to simplify installation, and
- Retightening the joint after start up to offset the initial gasket relaxation.

4. Write Specifications

The above steps – thorough data collection, root cause analysis, rigorous testing of proposed solutions to optimize performance – put this refiner in a position to tell gasket manufacturers exactly what they wanted. Instead of having to select the "best" product from among those offered, they could now dictate the exact properties of the gaskets they knew would work. The resulting specification is unique and far-reaching in scope. It not only defines all the essential parameters of the gaskets, but also lays out specific manufacturing procedures that must be followed, as well as specific QA/QC controls that must be in place to validate the manufacturer's adherence to this specification.

5. Roll out to the Field for Implementation

In some ways, the most difficult part of developing new standards and materials is the implementation of that standard. In addition to writing the gasket specifications, new engineering standards must be written to guide the application of those products in the field. This step requires management buy-in, and must be done with the full authorization necessary to ensure compliance all the way from the top (upper management) down to the maintenance and contracting crews that will do the installation. Failure to get the needed support and authority will assure the failure of the entire program.

Experience in the field has shown that the cornerstone of successful implementation is the selection and empowerment of a Subject Matter Expert (SME) authorized by management to:

- Write (or implement) the new engineering standards,
- Establish training on all levels (Engineering, Operations, Maintenance, and Contracting),
- Establish the required workplace controls and records needed to verify successful implementation.

This last step – the establishment of workplace controls and records – is absolutely essential in order to confirm that the new procedures have been followed when installing the new products.

David Reeves – the co-author of this paper – was the SME charged with implementing this new system at his refinery. Recognizing that the system would not be easily adopted without the proper tools, David developed the following aids.

Flange Closure Design Spreadsheet. This spreadsheet enables the engineering staff to readily make the conversion from the old style of heat exchanger gaskets to the new styles, calculating the appropriate seating stresses, and determining the correct bolt torques to use.

CC–Channel Cover, Ch–Channel, Sh–Shell, SC–Shell Cover, FH–Floating Head, FF–Fin Fan.

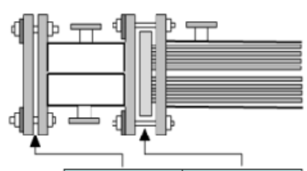
Friction Factors:	0.17 (Custom)
Friction Factor Fin Fan	0.15
Friction Factor Tube & Shell	0.17

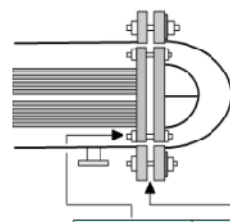
Exch #	Pass-port #	HI #	Connection 1 CC / FF / Ch psi only 2 Ch to TS 3 TS to Sh 4 SC / Sh psi only 5 FH	Enter Bundle Weight	Enter Shell Side Design Pressure (Field Hydro)	Enter Tube Side Design Pressure (Field Hydro)	Enter Number of Studs	Enter the Stud Size	Enter Stud Length	Enter Gasket OD (in)	Enter Gasket ID (in)	Checks Gasket Width. Must be 1/2 min for CMG	Enter Number of Baffles	Enter Baffle Width	Enter Stud Load in 1000 PSI	Gasket Stress at Indicated Pressure	Torque in Ft-Lbs	Enter Gasket Type
2	123		3 TS to Sh	15,000	85	420	76	1		53 1/8	52 1/8	1/2		3/8	86	52,456	675	CGG
3	456	1821	1 CC	30,000	85	420	76	1	13 1/4	53 1/8	52 1/8	1/2	2	3/8	86	22,381	675	CGG
3	456	1821	2 Ch to TS	30,000	85	420	76	1	16 1/4	53 1/8	52 1/8	1/2	2	3/8	86	23,870	675	CGG
3	456	1821	3 TS to Sh	30,000	85	420	76	1		53 1/8	51 5/8	3/4			86	35,027	675	CGG
3	456	1821	4 SC	30,000	85	420	76	1	14	53 1/8	51 5/8	3/4			86	27,903	675	CGG
3	456	1821	5 FH	30,000	85	420	64	1	14.5 B7M	47 1/8	46 1/8	1/2	1	3/8	86	27,500	675	CGG

Exchanger Cards. These cards are output directly from the Flange Design Spreadsheet, and contain all the needed information for the work crew to properly install the gaskets. They also serve as a quality control check sheet, where the workers are required to initial each of the steps in the process, thus insuring that the proper protocols have been followed.

Plant:	(Enter the plant name here)	Comment Box
Exchanger #	3	Test of comments for Ext 3
Date	11/28/2007	
Work Order Number	456	
Bundle Weight (lbs)	30,000	
Channel Hydro (psi)	420	
Shell Hydro (psi)	85	

Exchanger #	3
Channel Hydro (psi)	420
Shell Hydro (psi)	85





	Channel Cover	Channel to Shell
Gasket Type	CGG	CGG - CGG
# of Studs	76	76
Stud Diameter	1	1
Stud Length	13 1/4	16 1/4
Final Torque	675	675

	Floating Head	Shell Cover
Gasket Type	CGG	CGG
# of Studs	64	76
Stud Diameter	1	1
Stud Length	14.5 B7M	14
Final Torque	675	675

Gasket Surfaces Inspected By:		
Gasket Installed By:		
NEW Studs Lubed Both Ends By:		
Hardened Washers Installed By:		
Initial Torquing Done By:		
Hot Torque 250F to 400F Done By:		

Gasket Surfaces Inspected By:		
Gasket Installed By:		
NEW Studs Lubed Both Ends By:		
Hardened Washers Installed By:		
Initial Torquing Done By:		
Hot Torque 250F to 400F Done By:		

When complete, return this tag to: QA/QC or Inspection

Case I - Resolution

The effectiveness of the steps taken to resolve heat exchanger leaks at this major refiner can be readily quantified.

In the initial survey it was determined that nearly 40% of all heat exchangers sealed with traditional materials developed some level of leakage in their 3 to 5-year service cycle. Since switching to the upgraded products and procedures, thousands of gaskets have been installed, giving a great opportunity for comparison. Not one of the exchangers in which these solutions have been implemented has developed any leakage whatever. [The picture below shows Crude Unit exchangers (painted light green) after a 5-year run cycle.]

Case 2 – Valve Packing

1. Define the Problem

As with heat exchangers, it is no secret that valves occasionally leak. This is especially true of gate valves. Sights such as the ones below are not uncommon.

Depending on the criticality of the specific application, any number of "fixes" are utilized, including such creative ones as pictured below:

While such a "fix" may keep product from dripping to the ground, it does nothing to solve the root problem.

2. Collect Data and Identify the Root Causes

The State of California has long placed tight restrictions on the amount of leakage of Volatile Organic Chemicals (VOC's) that can be admitted to the atmosphere through the administration of Air Quality Management Districts (AQMD's). Refineries must regularly sniff leak sources to determine compliance, and must self-report violations to the AQMD, who levies annual fines based upon these reports. Under this system, refineries are highly motivated to continually improve their performance.

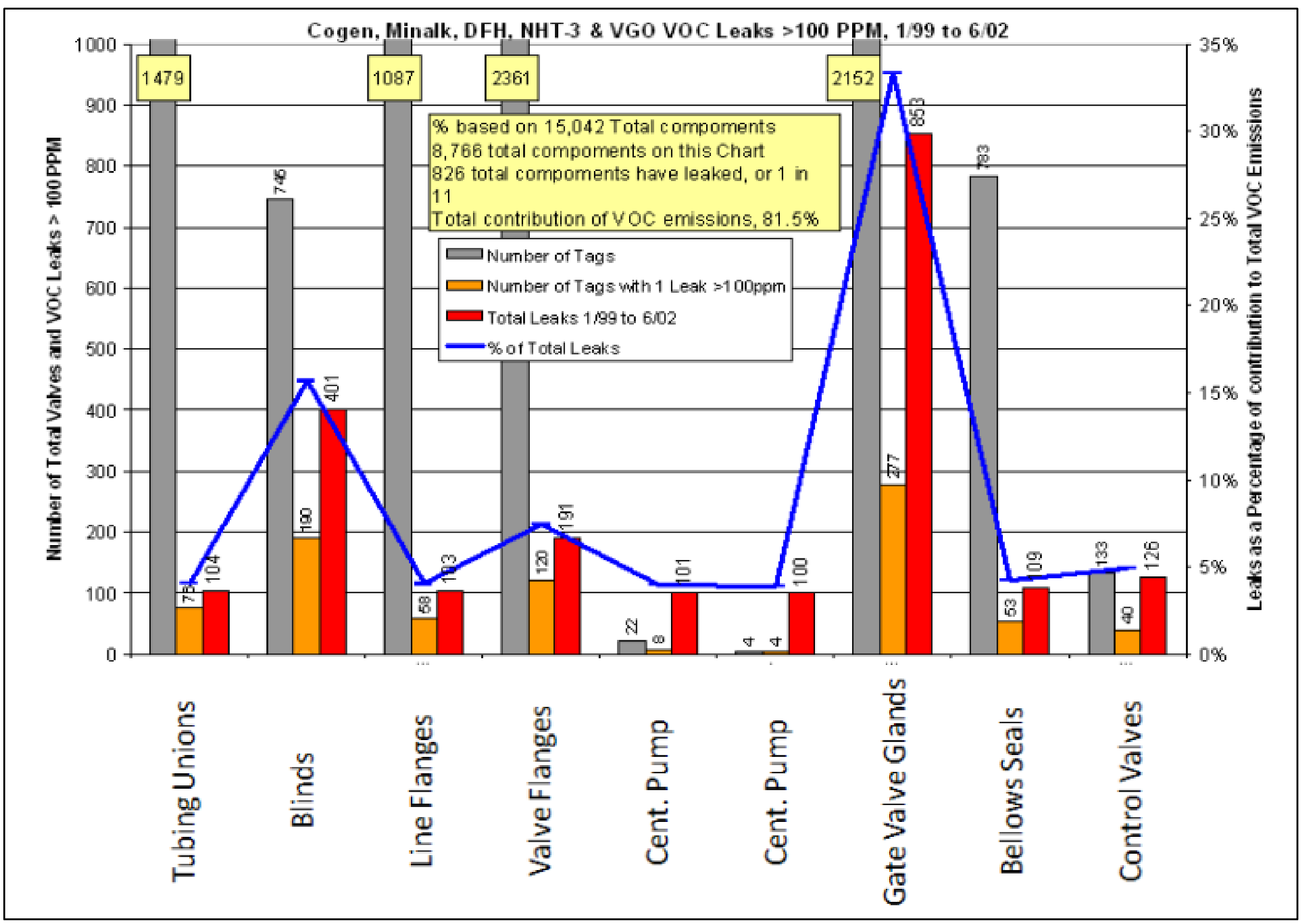
To better define the problem they were facing, the refinery analyzed the data collected for the AQMD to determine which leak sources contributed most to reportable events. As shown in the graph below, fully one third of all reportable events came from gate valves.

Because the allowed leakage levels are so low (500-ppm in Southern California, and only 100-ppm in the Bay Area) the question is not just which packing can best control gross leakage, but which packing can best restrict fugitive emissions of VOC's.

3. Test Possible Solutions

Every major manufacturer of valve packing claims to have the "best" fugitive emission packing. Because of this, end-users are put in the position of picking from among the available choices based mostly on whose data they believe. Only when the chosen product fails to perform in the field as promised, does the end-user discover that the marketing data is often based upon tests that do not represent worst-case field conditions.

To cut through the clamor of competing claims – and to determine just which packing would best meet their actual needs – David Reeves opted to design his own test for valve packing, with conditions that far exceed what most valves will ever see in the field.



The Fugitive Emissions Valve Packing Test:

- Requires 5,000 cycles for satisfactory completion. (A cycle is a full open and close stroke.)
- Includes 10 thermal cycles from 70F to 500F and back to 70F. (One thermal cycle every 500 strokes.)
- Uses Methane at 600F as the test media.
- Uses a Velan 4" gate valve with a rising, rotating stem.
- Requires that the packing be retorqued after the first 30 cycles.
- Allows the packing to be retorqued if emissions surpass 500ppm.
- Terminates the third time methane leakage exceeds 500ppm.

This test – conducted at Yarmouth Research – is not a test that is liked by valve packing manufacturers, who argue that the conditions are unrealistically harsh. 5,000 cycles is extremely high for a 4" Velan valve, and most gate valves will only see a tiny fraction of that number of cycles. The rising, rotating stem is more difficult to seal than a simple rising stem. Furthermore, as if to make it more difficult, the test is conducted with the valve stem in the horizontal plane, instead of vertical – almost forcing the packing into serving as a bushing, supporting the weight of the stem and wheel.

It is this very difficulty that makes this test such a valuable tool for assessing the performance of various packings. If the test were easily passed by a large number of packings, it could only serve to qualify packing for that service. By making the conditions so difficult that none would be likely to pass it, it becomes possible to quantify their performance in relationship with each other.

The results of the test support this assertion. The following pages show the results for several different products. The first (Packing Chart #1) is the OEM-supplied packing – a die-formed set of graphite rings with top and bottom bull rings. As you can see, it did not complete the 5,000 cycles.

The second graph (Packing Chart #2) shows the results for a well-respected spool stock packing (Packing A) that had performed very well under field conditions in eliminating fugitive emissions. This packing, it will be noted, achieved very low emission levels initially, but lacked the resilience needed to provide long-term sealing. Since most gate valves are never operated over 100 times in their entire life, this fundamental weakness in this packing had not manifested in field applications.

The third graph (Packing Chart #3) shows the results of a competitive product (Packing B) that had been on the market for a number of years. Unlike Packing A, it did not perform well in the initial cycles, but had sufficient resilience to eventually "seat in", and gave very low emission readings throughout the latter part of the test.

In an ideal world, a packing would exist that combines the characteristics of both Packing A and Packing B. But subsequent research and testing by various packing manufacturers has shown it to be difficult to meld the suppleness required for initial sealing with the resilience needed for long-term sealing.

The Yarmouth test enabled David to test an alternate hypothesis; namely, might it be possible to combine the Packing A and Packing B materials in a merged set of packing that would seal well at the onset of the test because of the suppleness of Packing A, but would seal well for the long haul because of the toughness and resiliency of Packing B?

This combined set – using one ring of Packing A in the center, with two rings of Packing B on top and bottom – was tested, and the results are shown in the fourth graph (Packing Chart #4). As hypothesized, this packing did achieve the desired results, outperforming all the other OEM packings tested, and all other individual spool stock packings.

4. Write Specifications

Armed with objective, quantifiable data, the refinery was again in the position of defining the solution that they knew would provide the best results. Instead of having to pick between various products offered by packing manufacturers or OEM's, they wrote a new standard based on their long-term interests.

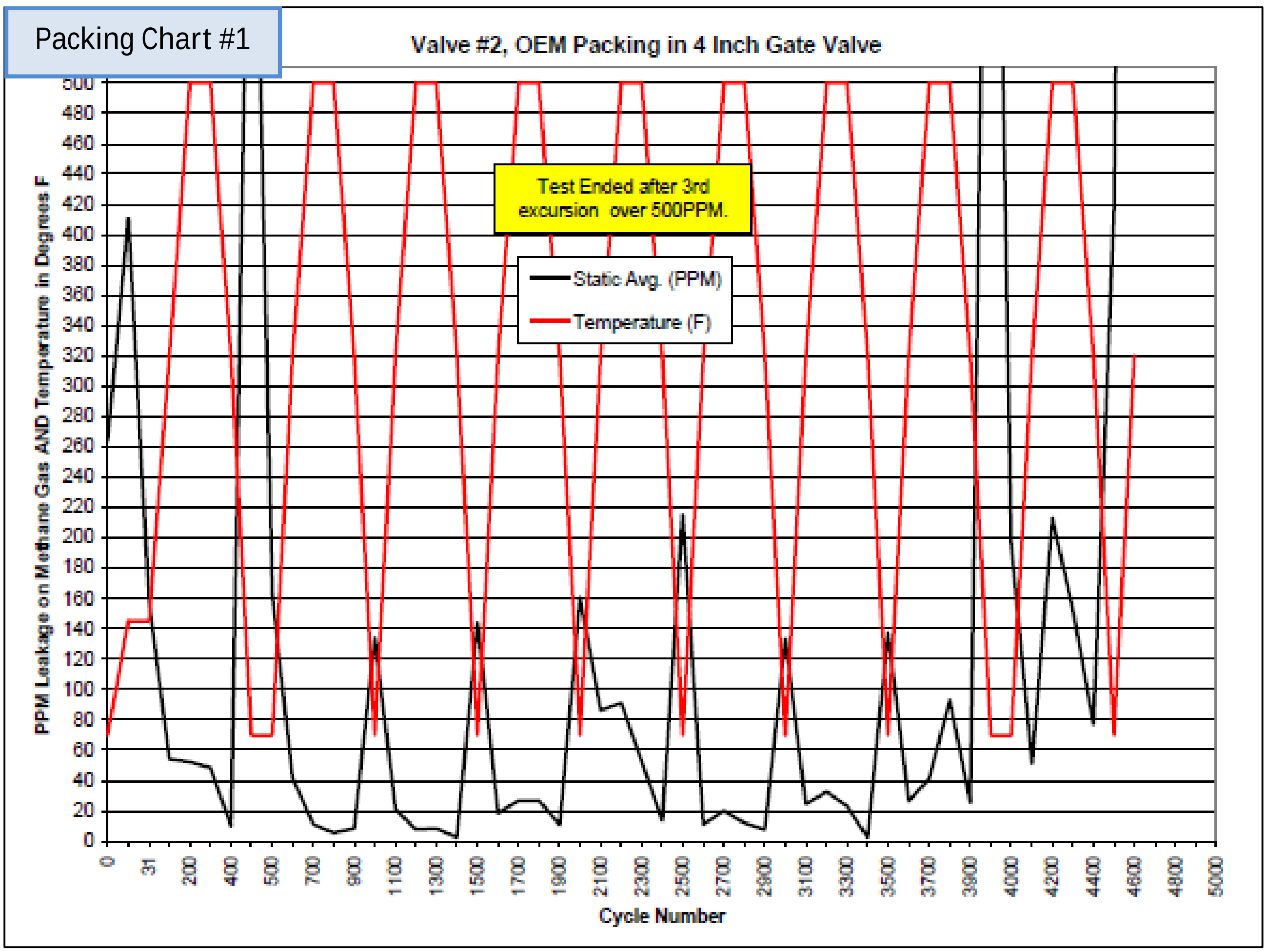
5. Roll out to the Field for Implementation

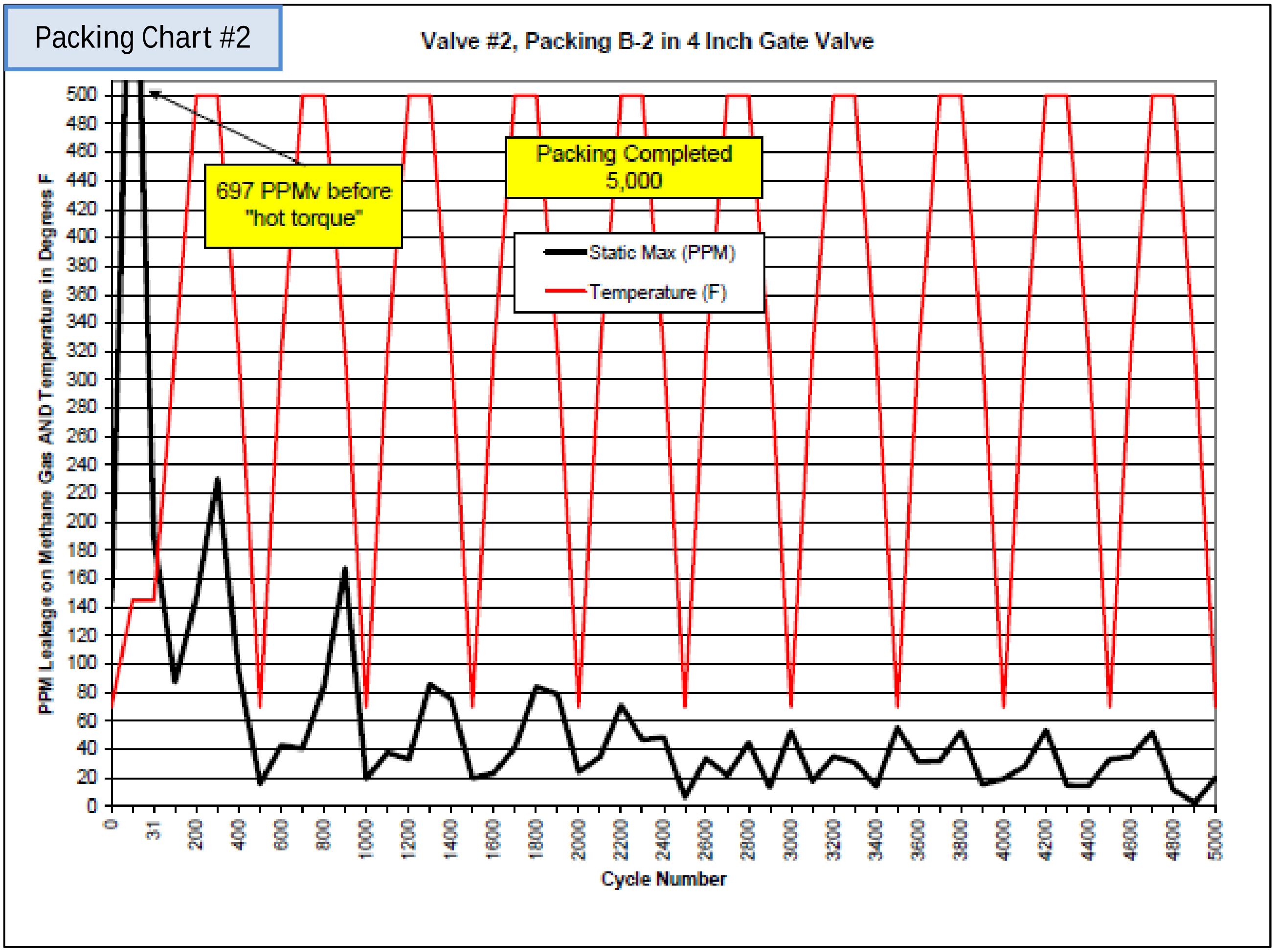
As with the gaskets, field implementation requires far more than just a purchasing specification. Engineering standards and practices must be written, training must be established, and responsibility and accountability must be set forth.

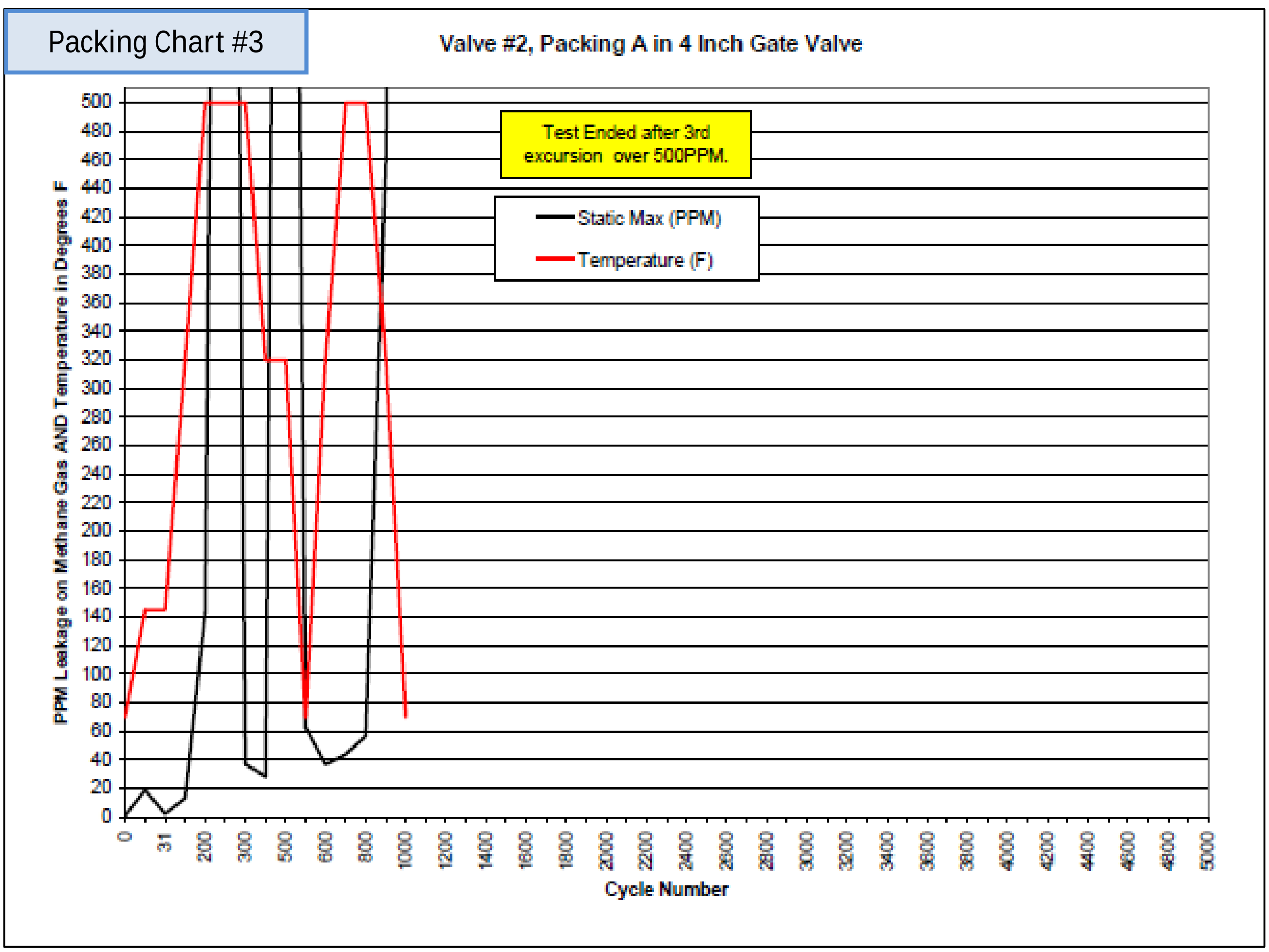
For all these reasons, it is essential that a SME be selected and empowered with the authority to get things done.

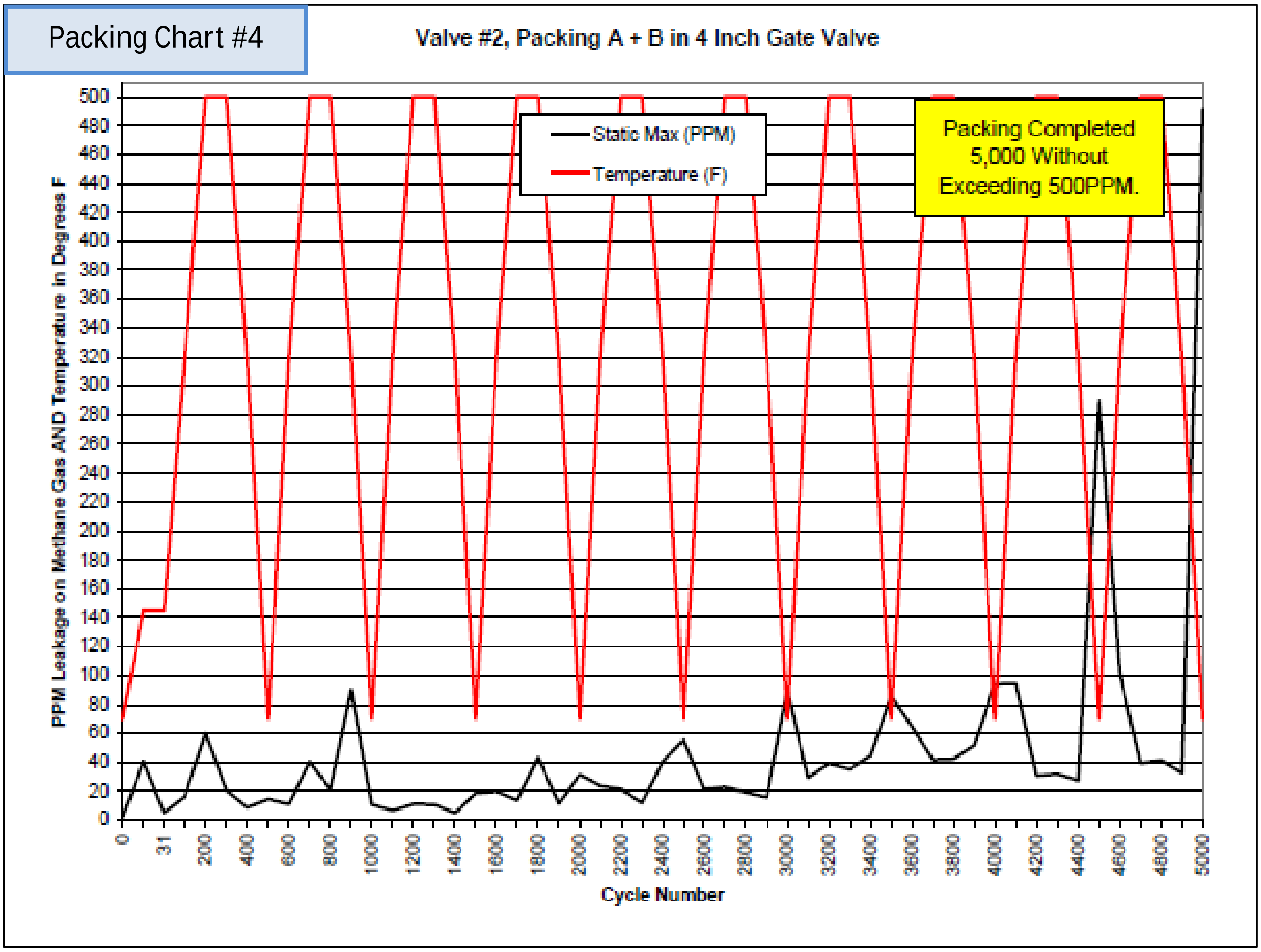
In the case of our subject refinery, comprehensive packing guidelines were developed that have now been implemented throughout North America, as well as at many licensees around the world.

Packing Chart #1




Packing Chart #2
Valve #2, Packing B-2 in 4 Inch Gate Valve
697 PPMv before "hot torque"
Packing Completed 5,000
Static Max (PPM)
Temperature (F)
PPM Leakage on Methane Gas AND Temperature in Degrees F
Cycle Number


Packing Chart #3
Valve #2, Packing A in 4 Inch Gate Valve
Test Ended after 3rd excursion over 500PPM.
Static Max (PPM)
Temperature (F)
PPM Leakage on Methane Gas AND Temperature in Degrees F
Cycle Number



Case 2 - Resolution

In addition to the required self-reporting of leaks, the AQMD conducts random "Blue Sky" audits of refineries in California.

During the May 2007 audit, the AQMD monitored 2,498 valves at the subject refinery. Their testing found only 5 valves (2 of which were control valves) that exceeded the mandated level of 500ppm – a compliance rate of 99.8%!

Summary

One cannot understand leak events in the absence of information. In the first case discussed above, two years extensive studies were carried out on heat exchangers body flanges, which included temperature, on-line stud stress monitoring, and measurement data to understand gasket and bolting interactions. The data clearly showed that much of the "conventional wisdom" that people had followed for years was wrong!

While such a comprehensive investigation is expensive, without the data it generates one is forced to either:

A. Accept as unquestioned truth whatever a sales representative may state. While the trained sales representative can be a valuable resource, he cannot be expected to know the intricacies of your operation.

B. Guess. Of course, guessing is not a substitute for science, and even on a good day will still yield 50% incorrect answers.

Chevron's problem-solving protocol...

1. Define the Problem
2. Collect Data and Identify the Root Cause
3. Test Possible Solutions (Lab and Field)
4. Write Specifications
5. Roll out to the Field for Implementation

... has proven effective in generating radical, field-leading solutions to major, protracted problems. Such an approach will no doubt be efficacious for others also.

> "If you try to gloss over the truth or massage the facts, all you're doing is heightening your chances of arriving at an erroneous conclusion." David Baldacci, Deliver Us From Evil, p. 52, Grand Central Publishing, 2010