ASME BPVC Fatigue Analysis – Part 5.5: Protection Against Failure from Cyclic Loading

Even with an academic and experimental background in fatigue analysis, it is daunting to provide a hard, no-nonsense life-cycle prediction. It is especially daunting when your fatigue prediction can cost or save your client millions of dollars. As for seeking an easy way out with "fatigue software", it can just mean a black-box solution where one off-loads their reputation and hopes for the best.

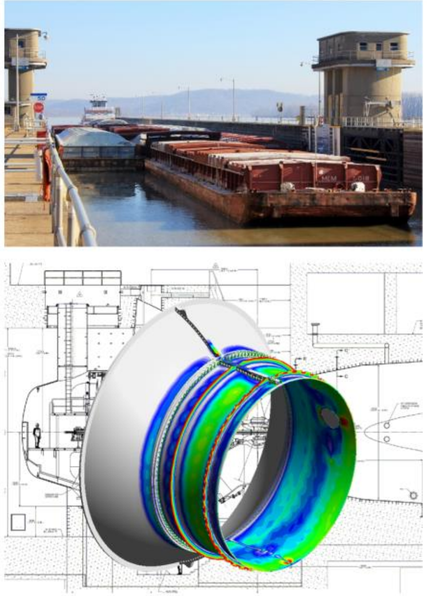
Over the years, we have learned that there are three critical components to a quality fatigue analysis: i.) accurate FEA stress results, ii.) accurate FEA stress results and iii.) accurate FEA stress results. Okay, sad, old, real-estate joke about location, location, and location; but let us just imagine that your stress numbers are good, then what? Fatigue analysis is all about the protection of structures and systems against failure from cyclic loading. This is where the ASME Boiler & Pressure Vessel Code (BPVC) provides a tried and true standard that, if your stress numbers are good, then you can be assured that your fatigue prediction will be conservative.

Besides providing robust fatigue curves, the Code provides explicit guidance on how to treat welds based on type, inspection and surface quality. For example, if the weld is completely un-inspected and un-finished, then it earns a fatigue-strength-reduction factor of 4.0, which means your FEA stress numbers are multiplied by 4.0 prior to the calculation of fatigue cycles per the ASME curve. In contrast, if a full penetration weld is ground to smooth profile and then fully-inspected (volumetric and surface examinations) , then the fatigue-strength-reduction factor is 1.0. The ASME code makes clear that it is not saying that the weld material is as good as the base material, but merely that the ASME fatigue curves are still accurate.

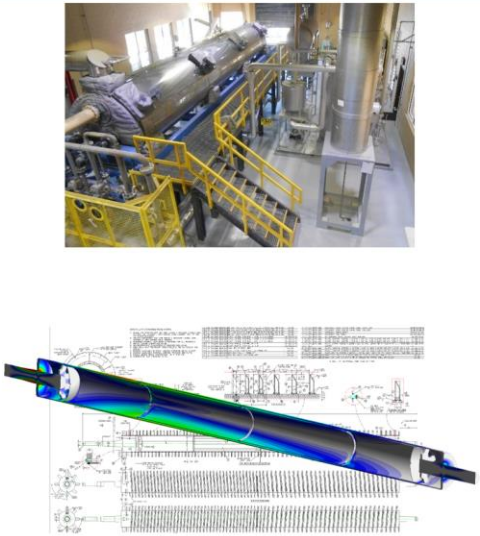
The ASME fatigue method was recently used to confirm cyclic fatigue damage and to guide subsequent design revisions. From an engineer's perspective, it was a very satisfying journey since the Code provided clear guidance on how to treat welded and non-welded sections. The projects have been completed and now we wait to see what happens. Nothing is perfect and one never truly knows with fatigue, but at least following the ASME "Protection Against Failure from Cyclic Loading" we are not flying alone.

ASME Fatigue Code Application – Non-Pressure Vessel Application

Hydroelectric Facilities: Large Rotating Equipment



Twin-Screw Augers: Large Rotating Equipment



ASME Section VIII, Div. 2, Part 5.5.3 Fatigue Assessment

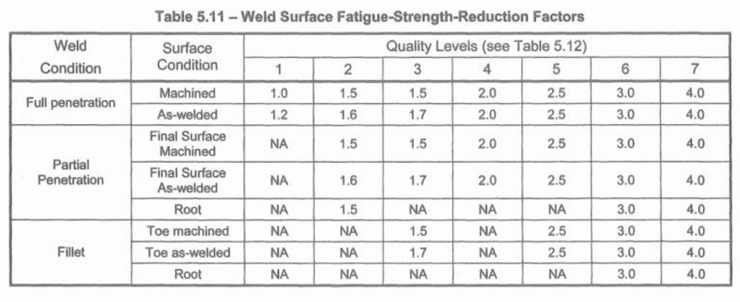


Table 5.11 – Weld Surface Fatigue-Strength-Reduction Factors

Weld Condition	Surface Condition	Quality Levels (see Table 5.12)						
		1	2	3	4	5	6	7
Full penetration	Machined	1.0	1.5	1.5	2.0	2.5	3.0	4.0
	As-welded	1.2	1.6	1.7	2.0	2.5	3.0	4.0
Partial Penetration	Final Surface Machined	NA	1.5	1.5	2.0	2.5	3.0	4.0
	Final Surface As-welded	NA	1.6	1.7	2.0	2.5	3.0	4.0
	Root	NA	1.5	NA	NA	NA	3.0	4.0
Fillet	Toe machined	NA	NA	1.5	NA	2.5	3.0	4.0
	Toe as-welded	NA	NA	1.7	NA	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	3.0	4.0

The ASME BPVC.VIII.2 – Part 5.5 code provides a straight-forward approach for classical fatigue analysis of welded structures.

Fatigue of Welded Structures: Weld Surface Fatigue Reduction Factors

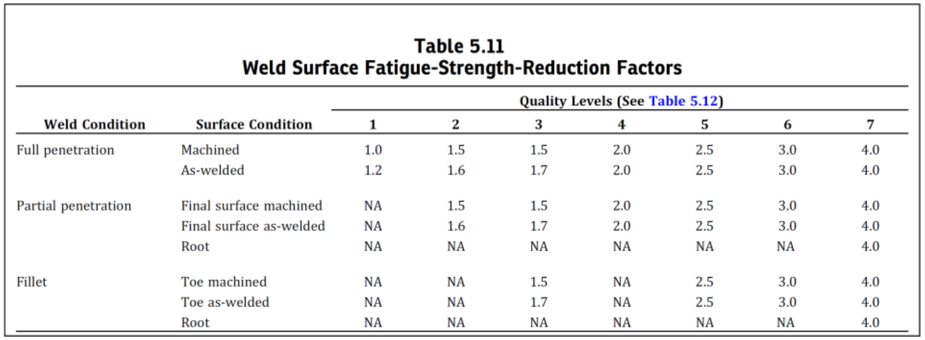


Table 5.11
Weld Surface Fatigue-Strength-Reduction Factors

		Quality Levels (See Table 5.12)						
Weld Condition	**Surface Condition**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Full penetration	Machined	1.0	1.5	1.5	2.0	2.5	3.0	4.0
	As-welded	1.2	1.6	1.7	2.0	2.5	3.0	4.0
Partial penetration	Final surface machined	NA	1.5	1.5	2.0	2.5	3.0	4.0
	Final surface as-welded	NA	1.6	1.7	2.0	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0
Fillet	Toe machined	NA	NA	1.5	NA	2.5	3.0	4.0
	Toe as-welded	NA	NA	1.7	NA	2.5	3.0	4.0
	Root	NA	NA	NA	NA	NA	NA	4.0

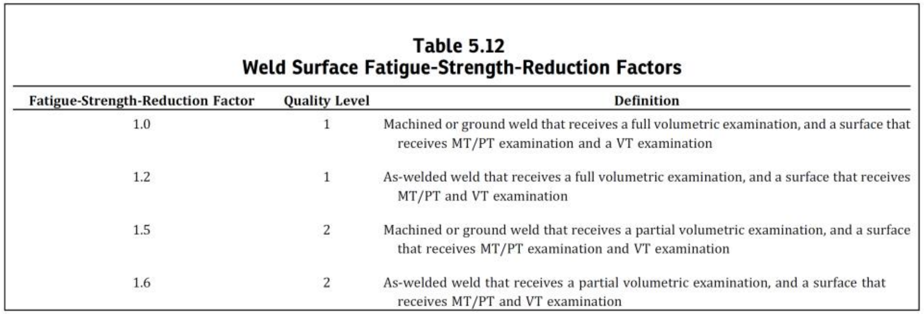


Table 5.12
Weld Surface Fatigue-Strength-Reduction Factors

Fatigue-Strength-Reduction Factor	Quality Level	Definition
1.0	1	Machined or ground weld that receives a full volumetric examination, and a surface that receives MT/PT examination and a VT examination
1.2	1	As-welded weld that receives a full volumetric examination, and a surface that receives MT/PT and VT examination
1.5	2	Machined or ground weld that receives a partial volumetric examination, and a surface that receives MT/PT examination and VT examination
1.6	2	As-welded weld that receives a partial volumetric examination, and a surface that receives MT/PT and VT examination

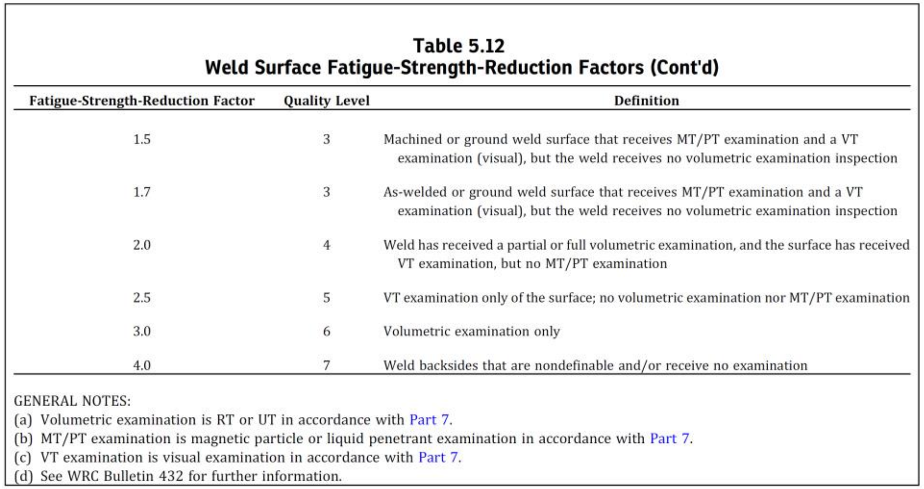


Table 5.12
Weld Surface Fatigue-Strength-Reduction Factors (Cont'd)

Fatigue-Strength-Reduction Factor	Quality Level	Definition
1.5	3	Machined or ground weld surface that receives MT/PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
1.7	3	As-welded or ground weld surface that receives MT/PT examination and a VT examination (visual), but the weld receives no volumetric examination inspection
2.0	4	Weld has received a partial or full volumetric examination, and the surface has received VT examination, but no MT/PT examination
2.5	5	VT examination only of the surface; no volumetric examination nor MT/PT examination
3.0	6	Volumetric examination only
4.0	7	Weld backsides that are nondefinable and/or receive no examination

GENERAL NOTES:
(a) Volumetric examination is RT or UT in accordance with Part 7.
(b) MT/PT examination is magnetic particle or liquid penetrant examination in accordance with Part 7.
(c) VT examination is visual examination in accordance with Part 7.
(d) See WRC Bulletin 432 for further information.

The ASME Section VIII, Division 2 “Design-by-Analysis” code provides an industry accepted criteria for the classification of welds. If the weld is left in its as-welded condition, then the Fatigue-Strength-Reduction Factor is 4.0. From a FEA perspective, this means that the calculated stress numbers are multiplied by 4x and then applied to the ASME fatigue curves. The utility of this approach is that the engineer can provide clear justification for weld quality improvements to obtain lower Fatigue-Strength-Reduction Factors (FSRF).

Weld Quality Levels: As-Welded (4.0) to Machine Profiled, Fully-Inspected (1.0)

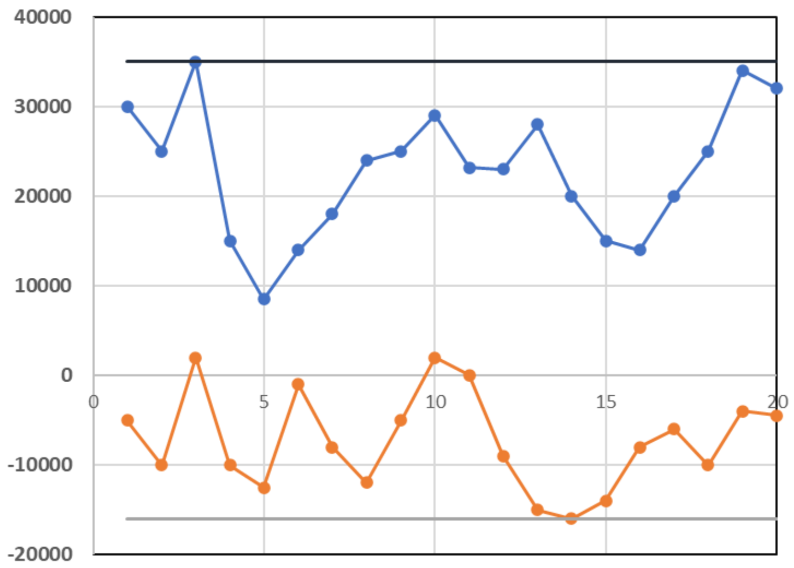
As-Welded Connection	Machine Ground, Tapered and Fully-Inspected

A section of the welded structure is shown above in the as-welded condition and then after weld-preparation. In the as-welded condition with no inspection, the ASME Section 5.5 Protection Against Failure from Cyclic Loading requires a Fatigue-Strength-Reduction Factor of 4x. To obtain a Factor of 1x, our client ground the full penetration weld surface to a smooth continuous profile and then performed a full-inspection per the Code requirements.

Application of ASME Fatigue Code: Effective Total Equivalent Stress Amplitude

Elastic Stress Analysis and Equivalent Stresses

$$\Delta S_{p,k} = \frac{1}{\sqrt{2}}\left[\left(\Delta\sigma_{11,k} - \Delta\sigma_{22,k}\right)^2 + \left(\Delta\sigma_{11,k} - \Delta\sigma_{33,k}\right)^2 + \left(\Delta\sigma_{22,k} - \Delta\sigma_{33,k}\right)^2 + 6\left(\Delta\sigma_{12,k}^2 + \Delta\sigma_{13,k}^2 + \Delta\sigma_{23,k}^2\right)\right]^{0.5}$$



$$S_{alt,k} = \frac{K_f \cdot K_{e,k} \cdot \left(\Delta S_{p,k} - \Delta S_{LT,k}\right) + K_{v,k} \cdot \Delta S_{LT,k}}{2}$$

The calculation of the effective total equivalent stress amplitude appears complex, but it really just boils down to enveloping the maximum and minimum principal stresses in the fatigue load sets. For example, one has 20 load sets and then envelopes the max and min stresses (35,000 – (-16,000)) which yields an effective equivalent stress range of 51,000. To arrive at the ASME fatigue stress one uses equation 5.30, whereas $S_{alt,\ k}$ = {51,000·(Fatigue-Strength-Reduction Factor)}/2. However, it is all about your weld quality and given your weld quality level, one can have an Effective Total Equivalent Stress Amplitude of 25,500 (FSRF = 1) or 102,000 (FSRF = 4).

Application of ASME Fatigue Code: 3-F.1 ASME Smooth Bar Fatigue Curves

Alternative Effective Stress vs Fatigue Cycles (S-N Curve)

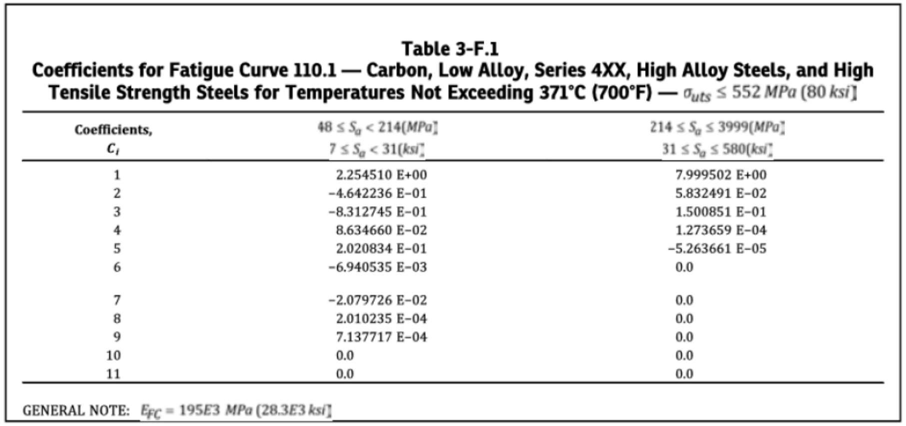
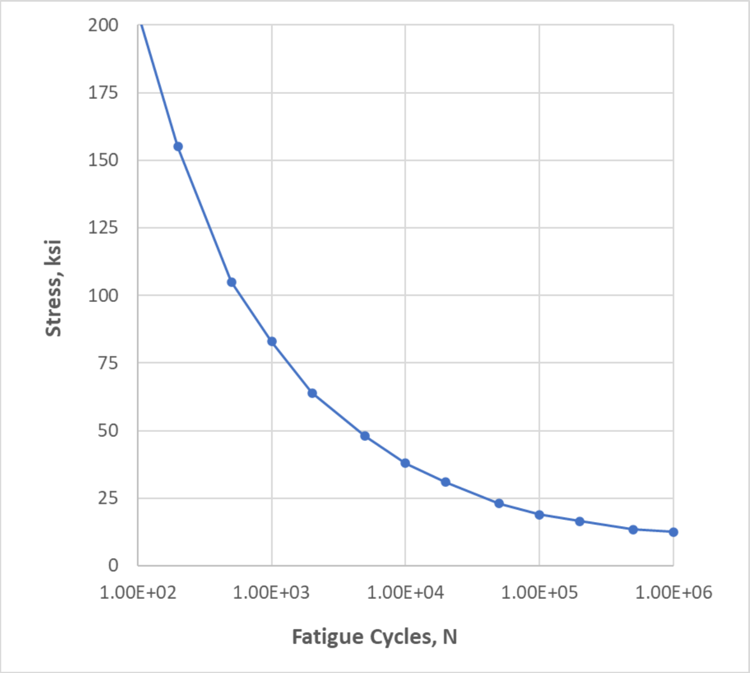


Table 3-F.1
Coefficients for Fatigue Curve 110.1 — Carbon, Low Alloy, Series 4XX, High Alloy Steels, and High Tensile Strength Steels for Temperatures Not Exceeding 371°C (700°F) — $\sigma_{uts} \le 552\ MPa\ (80\ ksi)$

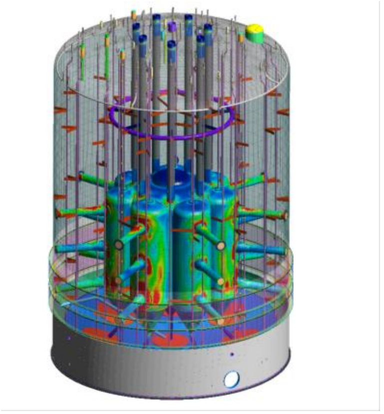
Coefficients, C_i	$48 \le S_a < 214 (MPa)$ $7 \le S_a < 31 (ksi)$	$214 \le S_a \le 3999 (MPa)$ $31 \le S_a \le 580 (ksi)$
1	2.254510 E+00	7.999502 E+00
2	−4.642236 E−01	5.832491 E−02
3	−8.312745 E−01	1.500851 E−01
4	8.634660 E−02	1.273659 E−04
5	2.020834 E−01	−5.263661 E−05
6	−6.940535 E−03	0.0
7	−2.079726 E−02	0.0
8	2.010235 E−04	0.0
9	7.137717 E−04	0.0
10	0.0	0.0
11	0.0	0.0

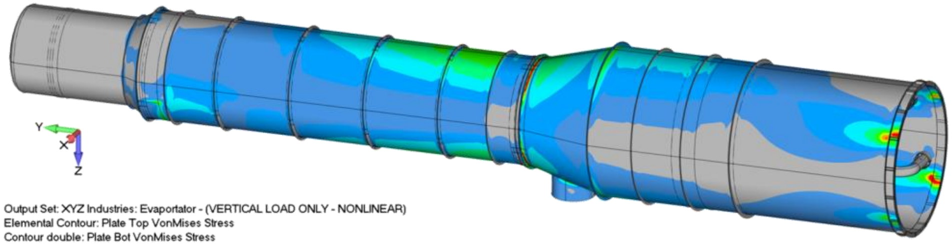
GENERAL NOTE: $E_{FC} = 195E3\ MPa\ (28.3E3\ ksi)$



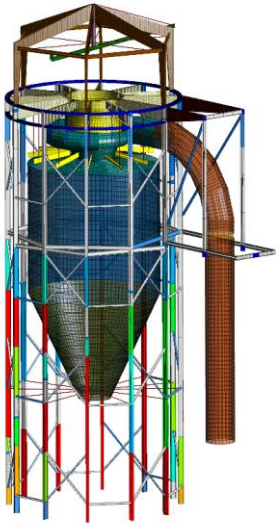
With your weld quality level assessed and an accurate FEA stress number, one can use the ASME fatigue curve to calculate the number of Fatigue Cycles. In our prior example, the fatigue stress could be 25.5 ksi or as high as 102 ksi, depending on the fatigue strength reduction factor. Working with the ASME smooth bar fatigue curves, the number of cycles to failure could be 70,000 or as low as 800. This fundamentally explains the challenge engineers can have with fatigue predictions of welded structures. Please keep in mind that the ASME fatigue curve has been adjusted by 2 or 20, to arrive at a clean curve that accounts for material variability.

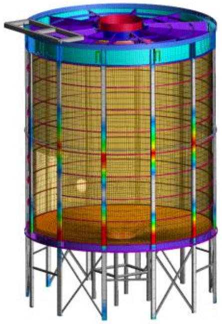
Application of ASME Fatigue Code: More Than Just Boilers and Pressure Vessels

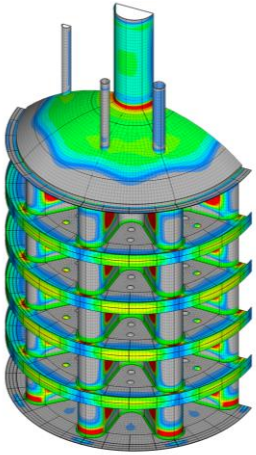


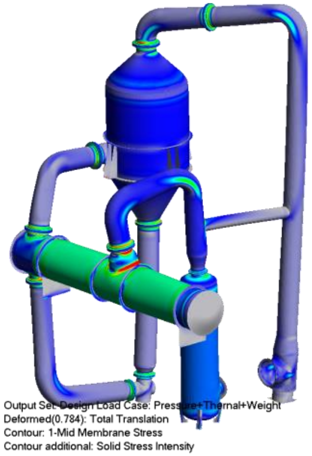


Output Set: XYZ Industries: Evaporator - (VERTICAL LOAD ONLY - NONLINEAR)
Elemental Contour: Plate Top VonMises Stress
Contour double: Plate Bot VonMises Stress

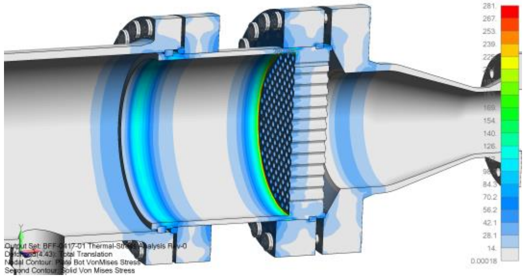








Output Set: Design Load Case: Pressure+Thermal+Weight
Deformed(0.784): Total Translation
Contour: 1-Mid Membrane Stress
Contour additional: Solid Stress Intensity



Output Set: BFF-0417-01 Thermal-Stress Analysis Rev-0
Deformed(4.43): Total Translation
Nodal Contour: Plate Bot VonMises Stress
Second Contour: Solid Von Mises Stress

Our experience with the ASME Section VIII, Division 2 Alternative Rules, or as we like to say “Design-by-Analysis”, allows us to accurately, quickly and safely certify structures and systems for fatigue loading. Our experience has been gained over +20 years of finite element analysis consulting. We are practical, hands-on engineers with a background in manufacturing, experimental mechanics and of course, getting our hands dirty when we are not pounding on the keyboard. If you have any questions or would like to send us a project to analyze, please contact us at www.PredictiveEngineering.com.