32. Extreme Value Statistics for Predicting Pitting Damage – A Tour

Overview

In this tour we will show examples of applications of Extreme Value Statistics for predicting pitting damage. Specifically, we will show how to predict

- The depth of the deepest pit in the engineering structure or laboratory systems as a function of time and the surface area of the system;
- Probability of failure for a given penetration depth and the area of the system as a function of observation time.
- Probability of failure for a given observation time and the area of the system as a function of penetration depth.
- Probability of failure for a given penetration depth and observation time as a function of the area of the system.

At this point you should be very familiar with entering data into OLI Studio. Also, you need to know the foundation of Extreme Value Statistics (Aziz, 1956, Kowaka et al. 1994, Laycock et al. 1990, Engelhardt and Macdonald, 2004).

Example 1: Corrosion of aluminum alloy in tap water

In this example, we will consider the classical data for pitting corrosion (Aziz, 1956). In this paper, we can find particularly the experimental data for the maximum pit depths developed on Alcan 2S-O coupons with area s ≈ 129 cm^2 immersed in Kingston tape water at 25 ^{0}C (see **Table 32-1**).

Table 32-1 *Maximum pit depth (in μm) developed on Alcan 2S-O coupons with immersed in Kingston tape water for different observation time*

Coupon #	One Week	One Month	Three Months	Six Month	One Year
1	180	460	480	620	640
2	266	500	578	620	680
3	290	510	610	620	700
4	306	580	610	680	760
5	334	580	610	680	800
6	340	640	660	720	810
7	340	654	690	740	820
8	410	680	718	740	840
9	410	692	760	760	840
10	545	692	798	760	900

Double-Click the Add Standard EVS Calculation icon

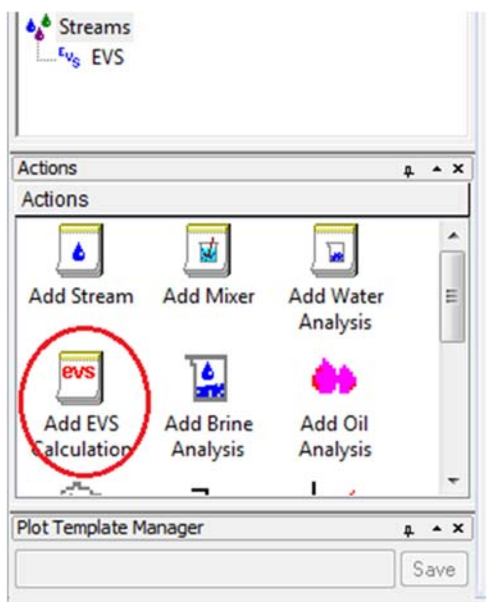

Figure 32-1 Starting EVS

Click on **Definition** tab and start by inputting experimental data.

Because all samples have the same area s = 129 cm^2 we input this value into **Default Value Area**. Other possible unit for area is m^2. The default value of pit depth is chosen to be in µm. Other possible units are Å, mm, ft, m, ft.

Because, in the first step, we will predict propagation of pitting damage in the same system (for the same coupons) we choose S = s = 0.0129 m^2.

The definition grid of the system should look like Figure 32-2.

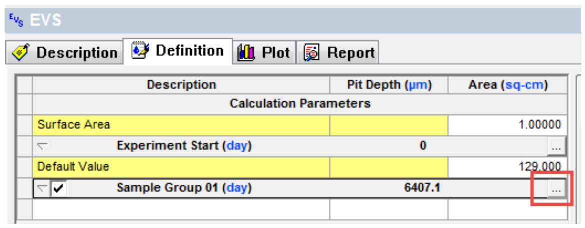

Figure 32-2: The system definition.

There are experimental data for 5 different times (5 groups). Click on the button inside the red oval (see Figure 32-2) and type time 7 days in empty space below Elapsed (Figure 32-3).

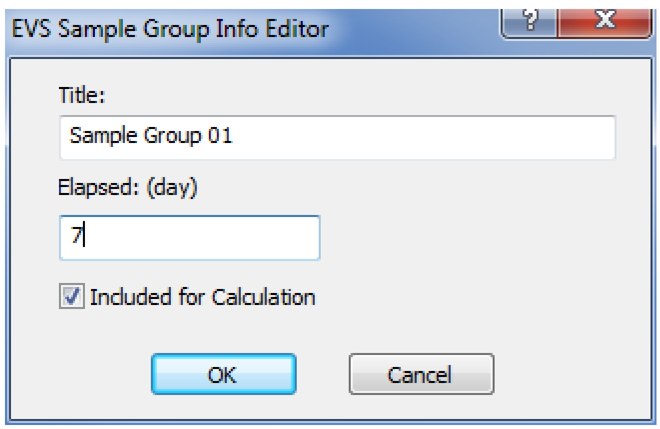

Figure 32-3: Drop down-table for adding groups.

Insert data from the second column in **Table 32-1** into the Sample Group 01. Group 01 is representing 1 week.

After that, click on **Add Group** button (inside green oval), and in blank space type elapsed time = 30 days and insert all data from the third column for Sample Group 02. After inserting the data from Table 1 (from columns 1 and 3) the definition grid for EVS calculations should look like Figure 32-4.

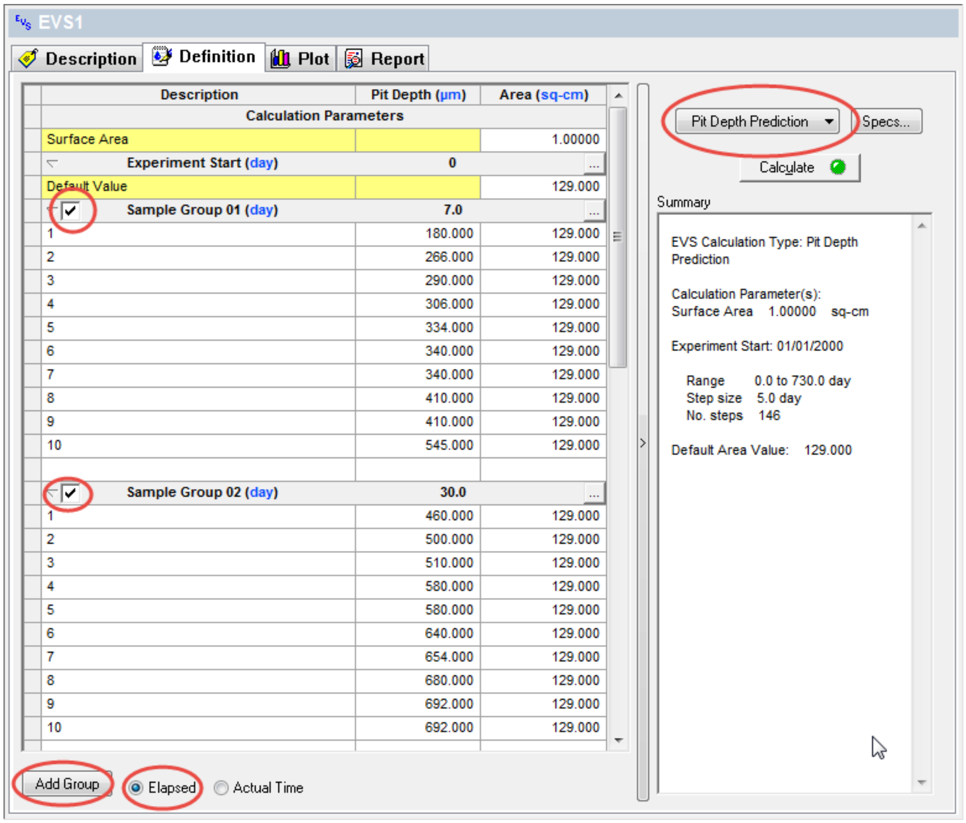

Figure 32-4: Specifying experimental data for depths of deepest pits (not completed)

Note the following:

- Here for the description of different experiments we simply used the number of the corresponding row in Table 1. However this description can be done in an arbitrary form.
- For each group, the order of samples relative depth can be arbitrary (not necessary in ascending order as in Table 1 or Figure 32-4).
- If coupons have different areas each area must be specified in the column **Area**.
- Radio button **Elapsed** (red ellipse in Figure 32-4) means the time after corrosion attack is used in calculations and namely this time is used usually in scientific publication. However it is possible to use also Actual Time of the experiments.

Enter the remaining data from Table 32-1 as new groups (columns 4 & 5), make sure the "Include boxes" are unchecked.

Description	Pit Depth (μm)	Area (sq-cm)
Calculation Parameters		
Surface Area		1.00000
Experiment Start (day)	**0**	...
Default Value		0.129000
Sample Group 01 (day)	**7.0**	...
1	180.000	0.129000
2	266.000	0.129000
3	290.000	0.129000
4	306.000	0.129000
5	334.000	0.129000
6	340.000	0.129000
7	340.000	0.129000
8	410.000	0.129000
9	410.000	0.129000
10	545.000	0.129000
Sample Group 02 (day)	**30.0**	...
1	460.000	0.129000
2	500.000	0.129000
3	510.000	0.129000
	580.000	0.129000
	580.000	0.129000
	640.000	0.129000
7	654.000	0.129000
8	680.000	0.129000
9	692.000	0.129000
10	692.000	0.129000
Sample Group 03 (day)	**90.0**	...
1	480.000	0.129000
2	578.000	0.129000
3	610.000	0.129000
4	610.000	0.129000
5	610.000	0.129000
6	660.000	0.129000
7	690.000	0.129000
8	718.000	0.129000
9	760.000	0.129000
10	798.000	0.129000
Sample Group 04 (day)	**180.0**	...
1	620.000	0.129000

Group 03 was entered but by un-checking the box we are not considering it in the calculation.

Figure 32-5 Adding more data, un-checking groups not to be considered in the calculation

Setting up the calculation (Pit depth prediction)

We will simulate the results of Aziz's experiments assuming that only data for short-time experiments (for 1 week and 1 month) are available. To include these data into calculations we must mark the boxes (black ovals in Figure 32-4). It can be done also by using the drop-down menu for adding groups (see Figure 32-4). All others group (Groups 03 – 05) must not be marked.

Since we will predict corrosion on the samples with the same area, **the value of 129 cm²** must be inserted into the property window Surface **Area**.

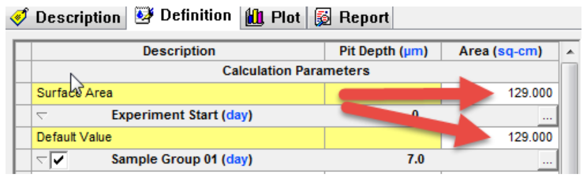

Figure 32-6 Setting Surface Area

In the drop-down menu for the Type of calculations (inside the blue oval) we choose **Pit Depth Prediction**. Now, click on the **Specs…** button.

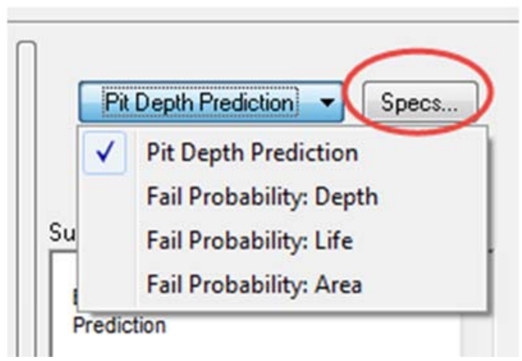

Figure 32-7 Selecting the type of calculation

The Survey Range category allows you to specify the range for the pit depth prediction survey. The default range is from 0 to 365 days that corresponds the available experimental data (Groups 01-05).

Then click **Calculate** button.

Analyzing the results

When the calculations are finished, click on the **Plot** tab.

You will see a plot of the predicted mean value of the depth of the deepest pit, x_m and the plots of values $x_m - \sigma$ and $x_m + \sigma$, where σ is the standard deviation of x_m.

It is important to note that only data for short term experiments (for 1 week and 1 month) denoted by black circles are included in calculations. Other data, denoted by red diamonds are shown only for demonstrating the accuracy of prediction. Of course, these additional data may be included in calculations by marking the corresponding boxes.

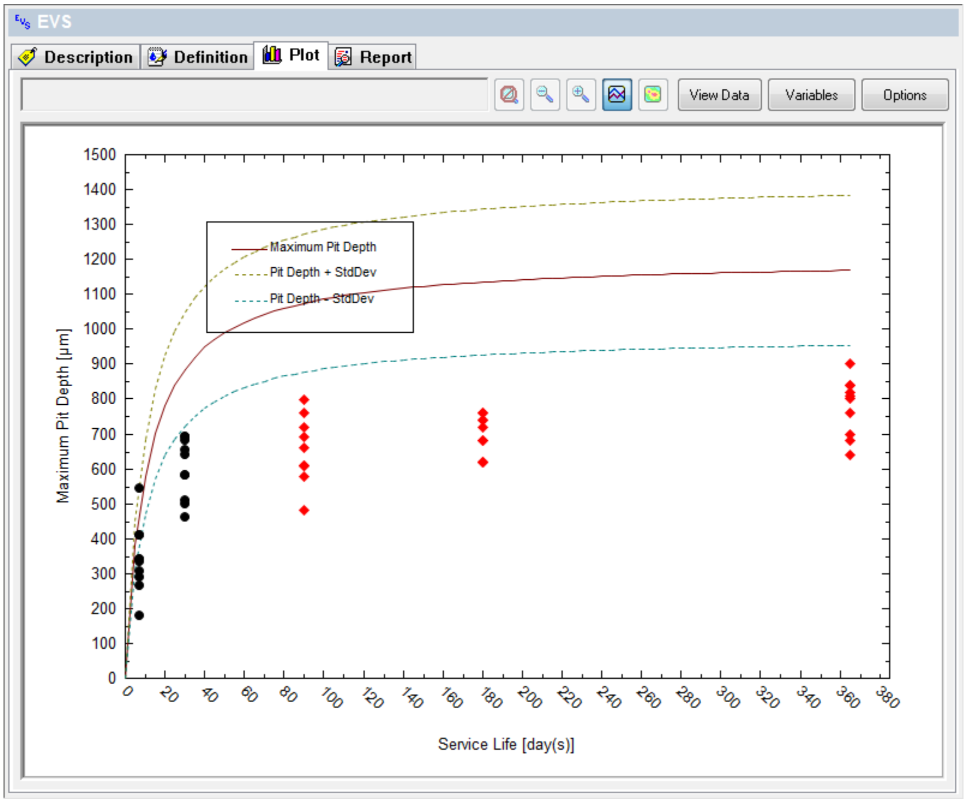

Figure 32-7: Predicted depth of the deepest pit. The experimental data for t = 1 week and 1 month are included into consideration. S = 129 cm².

Of course, the accuracy of prediction increases when additional group of experiments are included into consideration. Click back on the **Definition** tab.

Include (check) 90 days so that you now have 7 days (1 week), 30 days (1 month) and 90 days (3 months).

Click **Calculate**

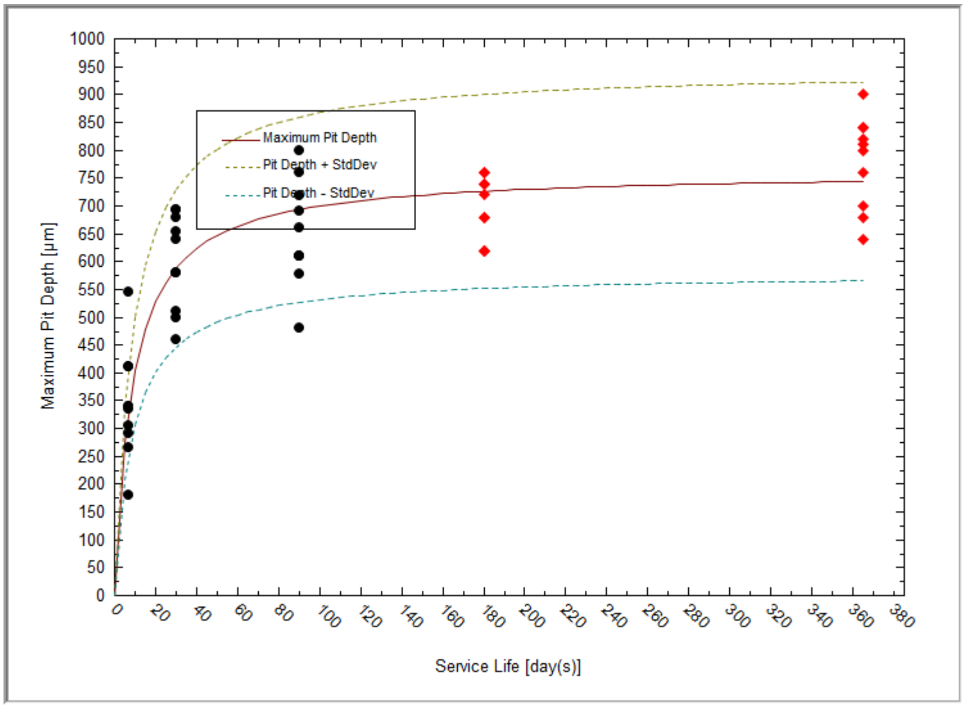

Figure 32-8:Predicted depth of the deepest pit. The experimental data for t = 1 week, 1 month, and 3 months are included into consideration. S = 129 cm^2.

For predicting depth of the deepest pit in the system with a substantially larger area (say, 10 m^2) for the period of observation time of 2 years we have to input S = 10 (m^2) into **Surface Area** window and to specify the range [0, 2] (years) for observation time by clicking on **Specs…** button.

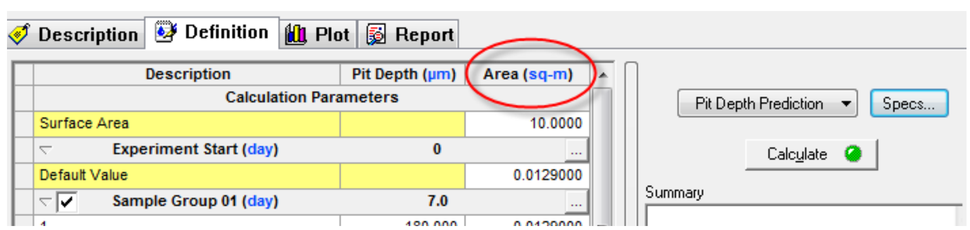

Figure 32-9 Changing the surface area, note the unit change from sq-cm to sq-m

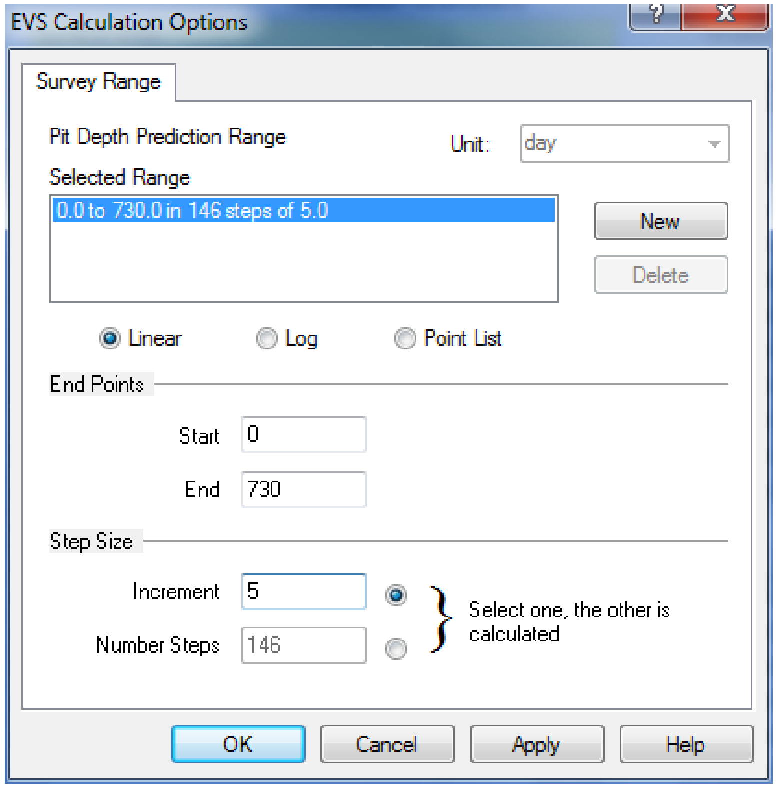

Figure 32-10 Changing the end time to 2 years (730 days)

The results of calculations are shown below.

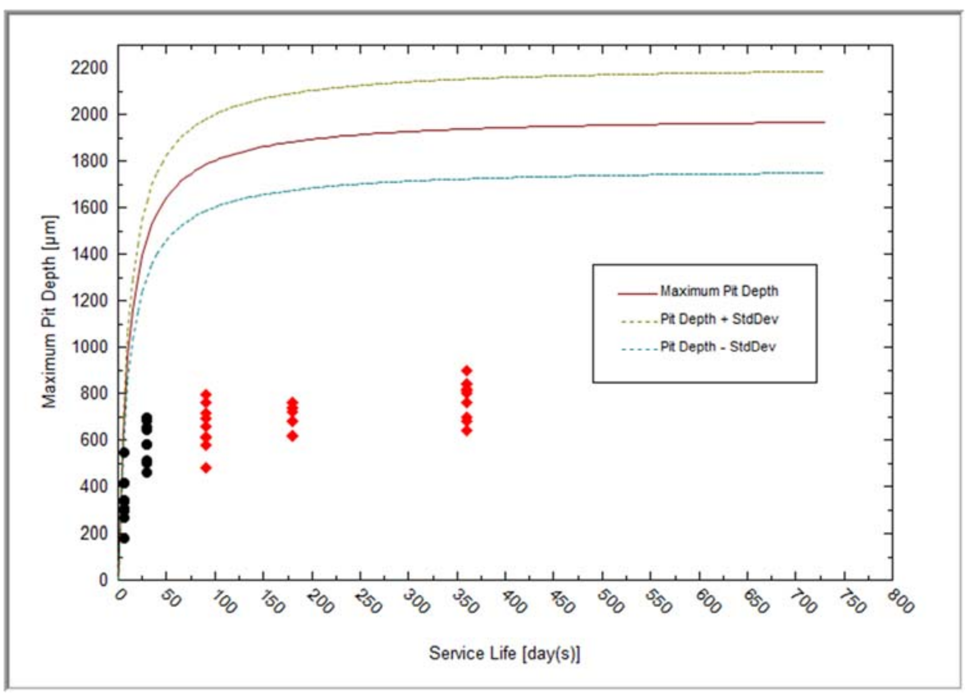

Figure 32-11: Predicted depth of the deepest pit. S = 10 m².

Setting up the calculations for engineering tasks

Here for the given system we consider some important engineering tasks.

First task:

Which thickness, d, does an the aluminum pipe with the area of S (say, 1 m^2) have to have in order to ensure acceptable performance (probability of failure, P_f , say, $P_f <$ 5%) at design service life, t_s , (say, 5 years)?

In order to do so we have to choose in drop-down menu **Fail Probability: Depth**, and insert into the window **Surface Area,** S = 1 (m^2) and insert into the window **Service Life**, t = 5 (years).

The definition grid for calculating the acceptable pipe wall width should look like Figure 32-18

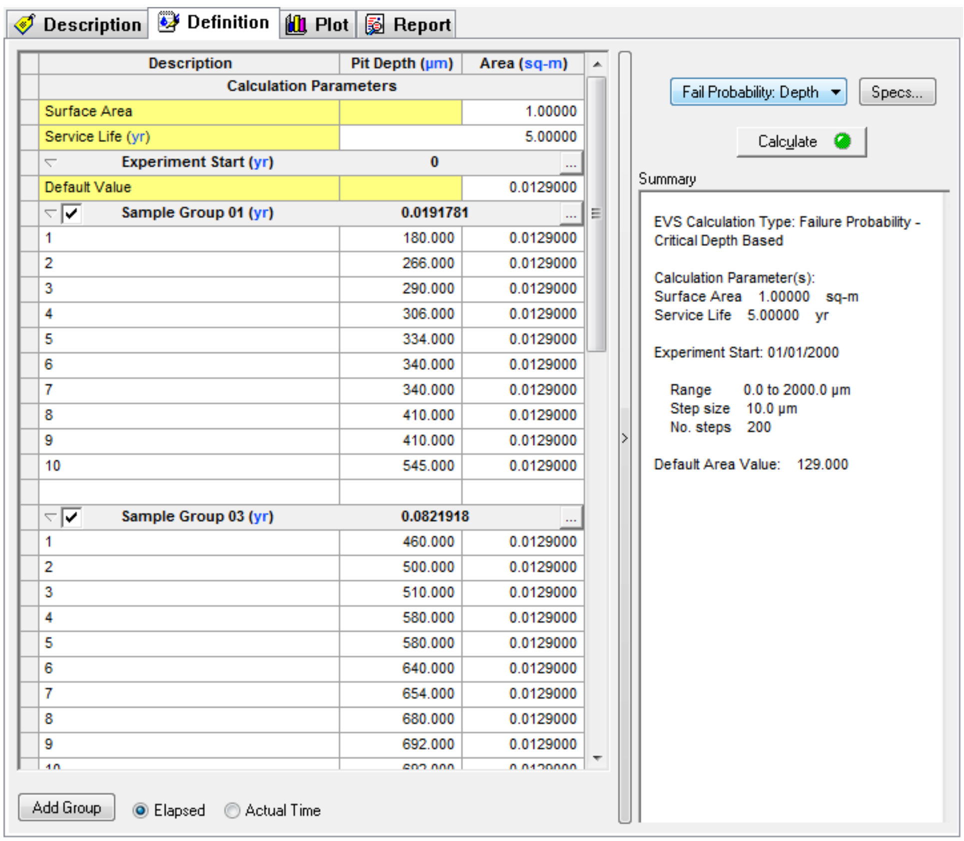

Figure 32-12: Specifying data for calculating probability of failure as a function of the width of the wall at given observation time and area of the pipe.

Then click **Calculate** button.

When the calculations are finished, click on the **Plot** tab. You will see a plot of predicted probability of failure

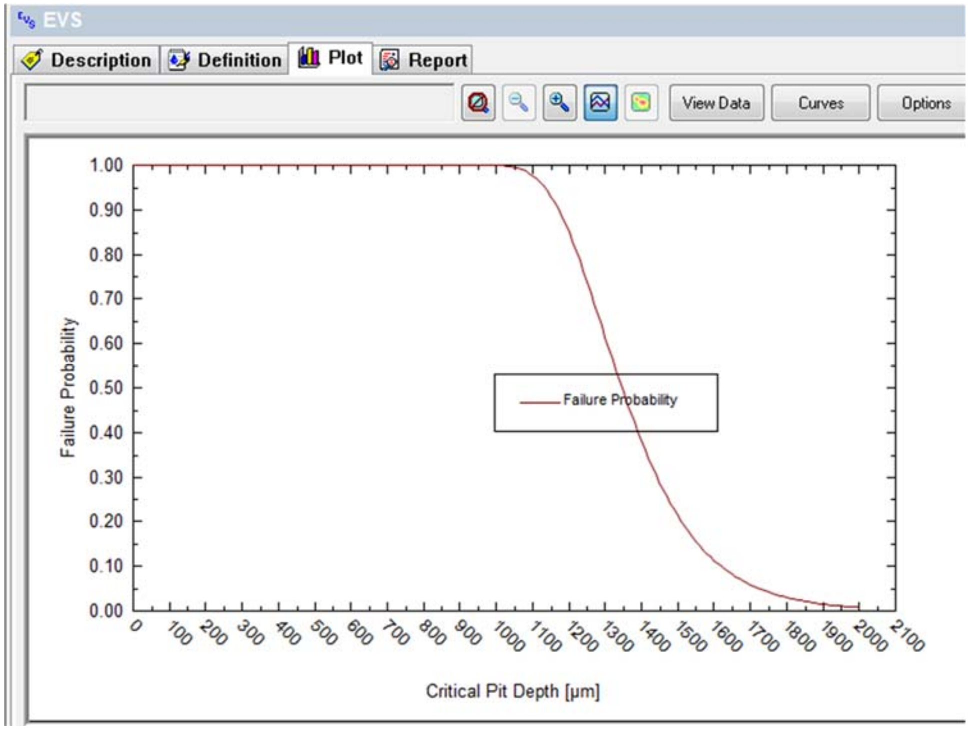

Figure 32-13: Probability of failure as a function of the width of the wall at given observation time and area of the pipe.

Click on the tab Report. From the Table: "**Calculation Results**" you can conclude that acceptable performance is reached at d > 1950 μm.

Second Task:

What service life, t, will have the aluminum pipe with the width, d, (say, 2300 μm), with area S (say, 10 m^2) in order to ensure acceptable performance (probability of failure, P_f , say P_f< 5 %).

In order to do so we have to choose in drop-down menu **Fail Probability: Life**, and insert into the window **Surface Area,** S = 10 (m^2) and insert into the window **Critical Pit Depth**, d = 2300 (μm).

We also wish to cover a sufficient period of time for the simulation. Click the **Specs…**button and change the range to 3 years in 0.2 year increments.

Also we need to deselect Groups 04 and 05 so un-check the appropriate group boxes.

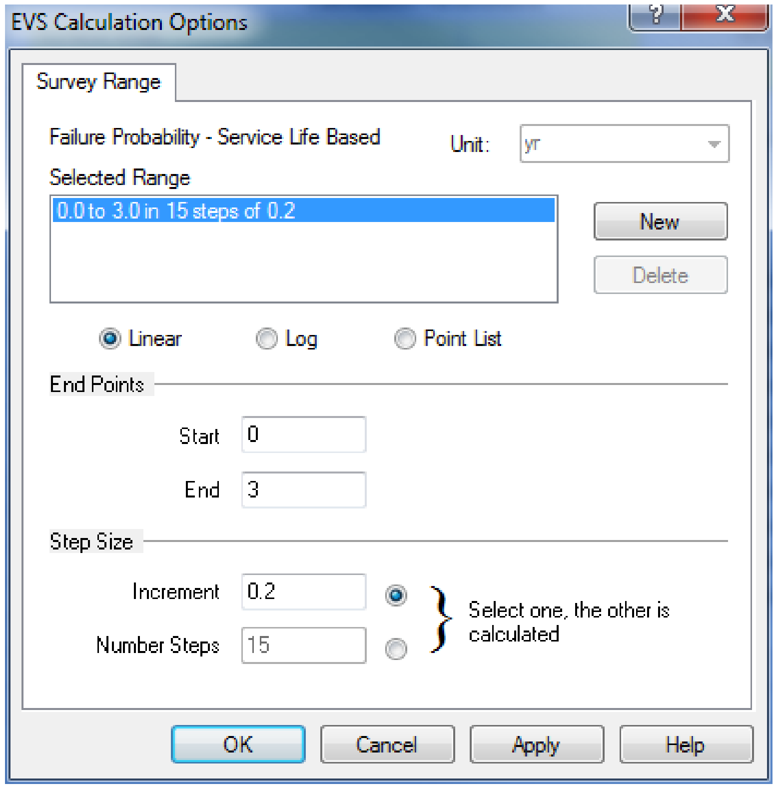

Figure 32-14 Changing the time to 3 years. Note the change in units from days to years

Click **OK**

The definition grid for calculating the acceptable pipe wall width should look similar to Figure 32-15

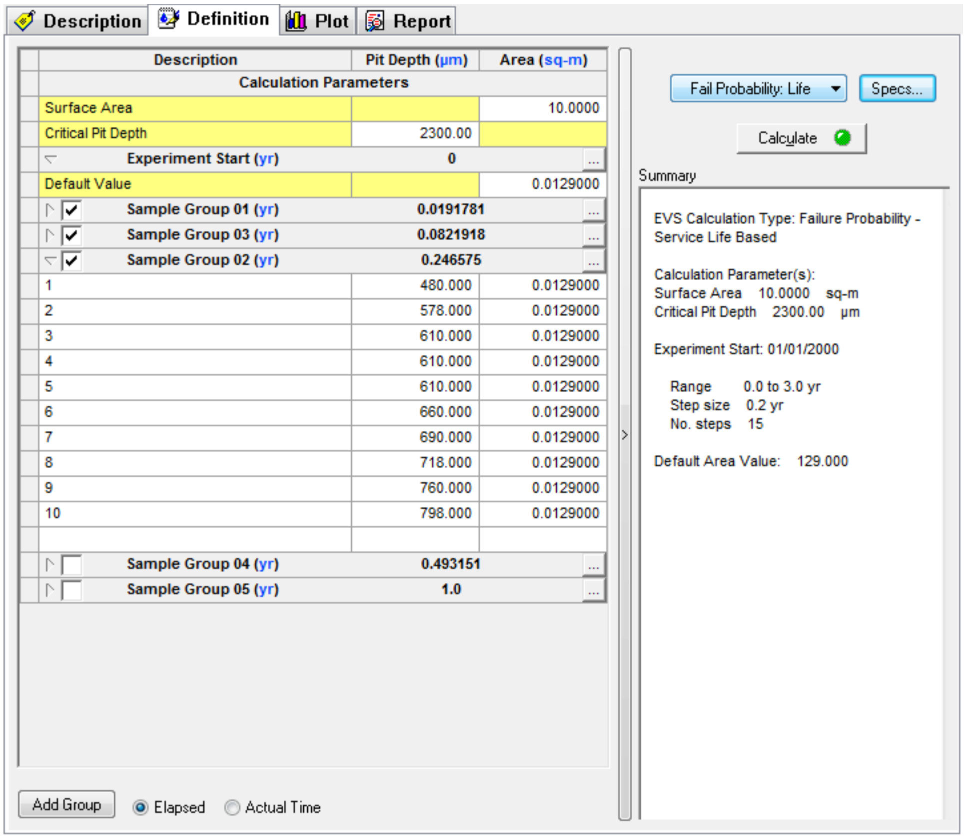

Figure 32-15: Specifying data for calculating probability of failure as a function of the width of the wall at given observation time and area of the pipe.

Then click **Calculate** button.

When the calculation is finished, click on the **Plot** tab. You will see a plot of predicted probability of failure (Figure 32-16). (You may need to change the axis ranges via the **Options Button**)

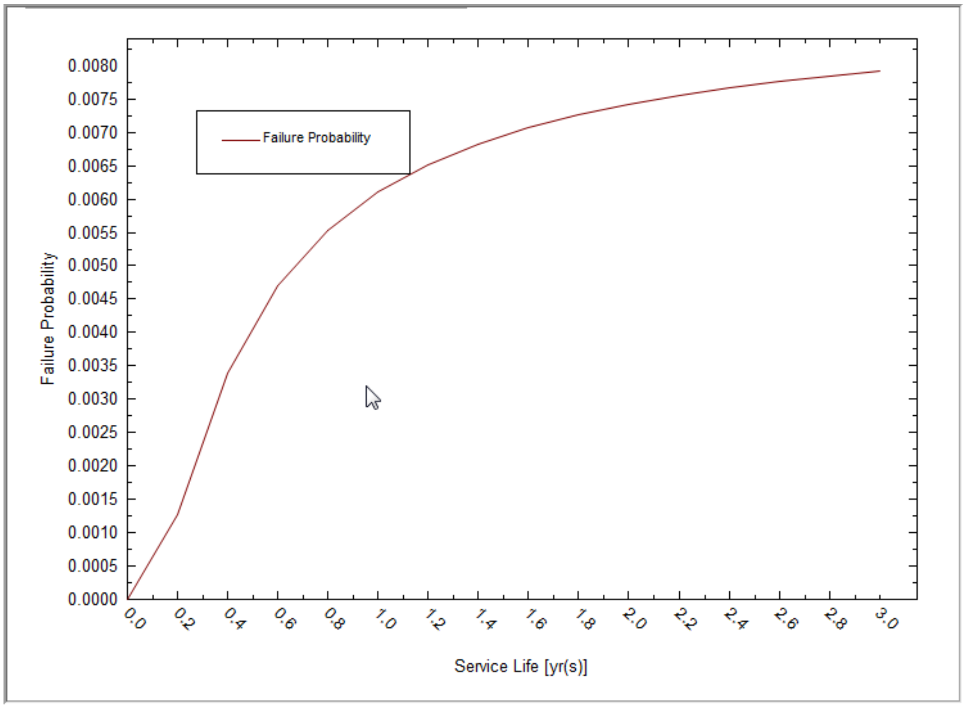

Figure 32-16: Probability of failure as a function of service life for a given width of the wall and given area of the pipe.

Click on the tab Report. From the Table: "**Calculation Results**" you can conclude that acceptable performance is reached at t < 657 days.

Third Task:

What area, S, can have the aluminum pipe with the width, d, (say, 2000 µm), and service life, t, (say, 5 years) in order to ensure acceptable performance (probability of failure, P_f , say, $P_f < 5$ %).

In order to do so we have to choose in the drop-down menu **Fail Probability: Area**, and insert into the cell ***Critical Pit Depth*** the value 2000 (µm) and into cell ***Service Life***, 5 (years).

We need to set the range for the area from 0 to 100 sq-m in 0.1 sq-m increments. Click the **Specs…** button.

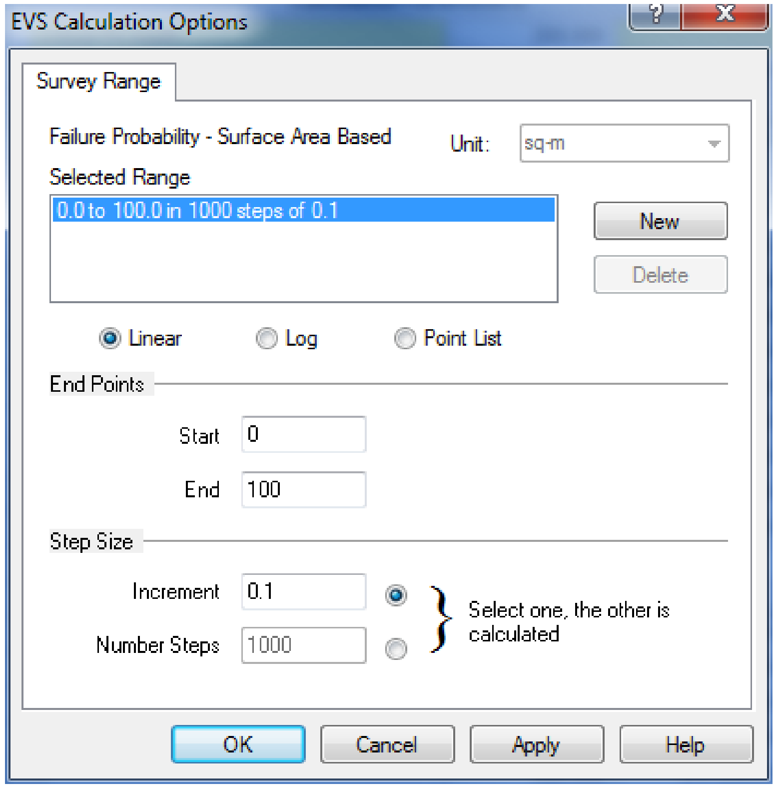

Figure 32-17 Setting the area range for Failure Probability

The definition grid for calculating the acceptable pipe wall width should look similar to Figure 32-18.

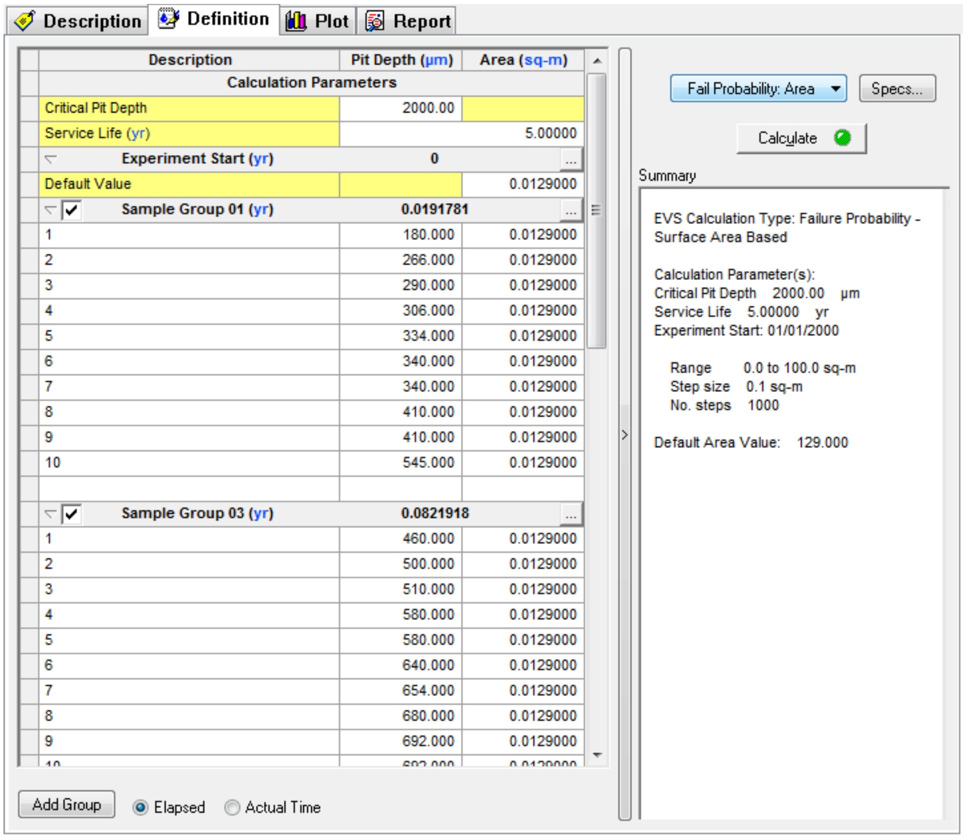

Figure 32-18: Specifying data for calculating probability of failure as a function of area of the pipe at given width o f the wall and given service life.

For this simulation we will only be using Group 01 and Group 02. Un-check the remaining groups.

Then click **Calculate** button.

When the calculation is finished, click on the **Plot** tab. You will see a plot of predicted probability of failure (Figure 32-19).

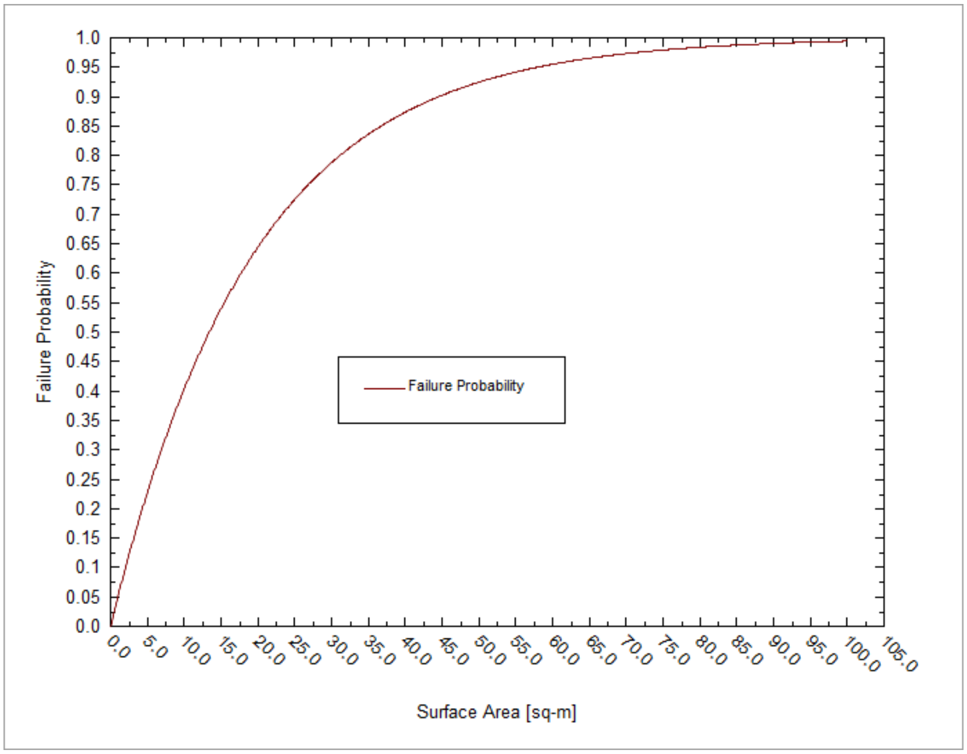

Figure 32-19: Probability of failure as a function of the area of the pipe at given width of the wall and given service life.

Click on the tab Report. From the Table: "**Calculation Results**" you can conclude that acceptable performance is reached at S < 14000 cm^2 = 1.4 m^2.

Example 2: Corrosion in Pipelines.

By using this example we would like to demonstrate that in some cases reliable prediction of corrosion damage can be done by using a very limited number of experimental points.

In Figure 32-21 you can see the results of direct measurements of the depth of the deepest pits in the pipeline between Samara and Moscow [Zikerman, 1972]. The data has been inserted, by the way, as was described in Example 1.

Table 32-2 *Pit depths(mm) for pipeline between Samara and Moscow*

	Group 1	**Group 2**	**Group 3**	**Group 4**	**Group 5**	**Group 6**	**Group 7**	**Group 8**
Sample	**1440 hrs**	**5040 hrs**	**5760 hrs**	**8959 hrs**	**12624 hrs**	**17688 hrs**	**28032 hrs**	**28272 hrs**
1	0.1			1.4	1.7	1.9		2.1
2		0.49		1.95	2.1	2.08		2.25
3	0.3	1.6		1.8				
4	0.4			1.6	1.65	1.88		
5	0.9		1.57	2.1	2.21	2.4	2.4	
6	0.3		1.2	1.4	1.4	1.55	1.71	

We would like to simulate for 30,000 hours so we need to change the **Specs…**button.

Start 0.0 hrs

End 30000 hrs

Increment 2000 hrs

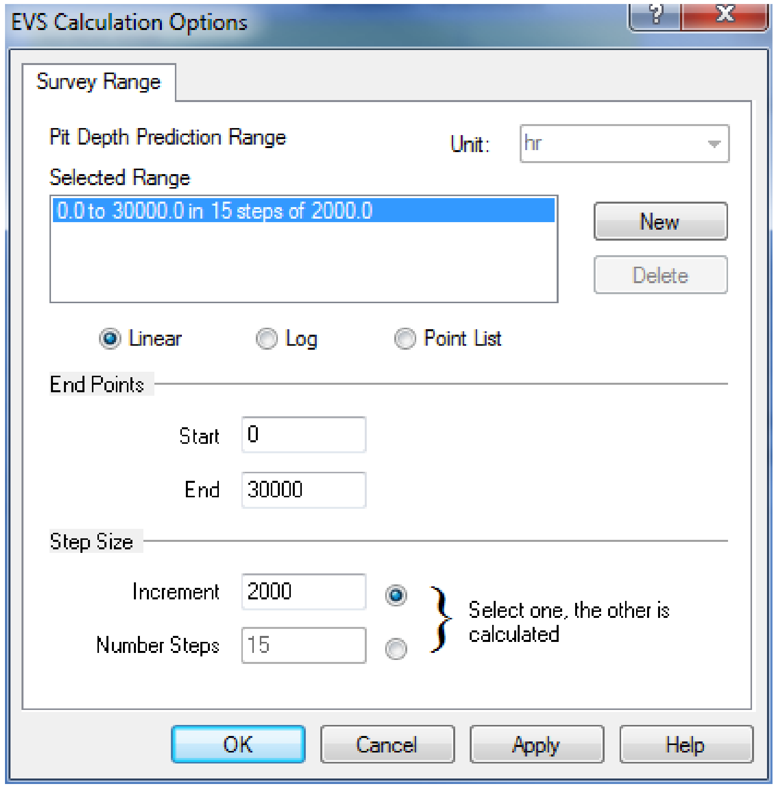

Figure 32-20 Setting the range to 30,000 hours, Note the units for time

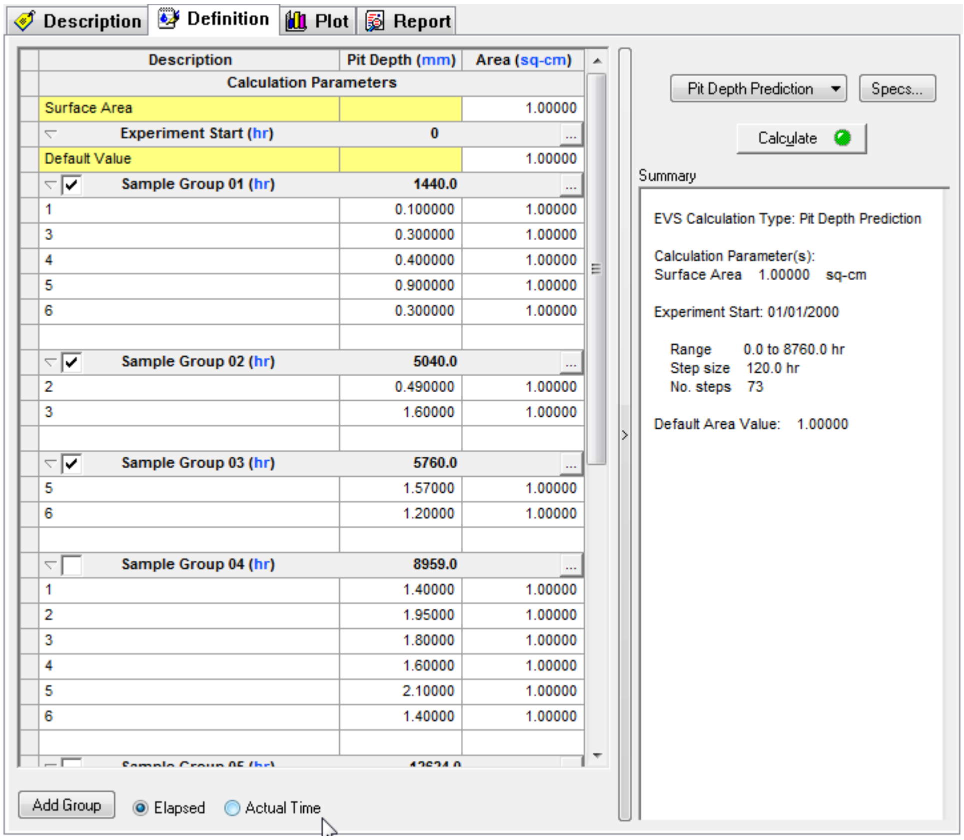

Figure 32-21: Specifying experimental data for depths of deepest pits for corrosion in pipelines. Only 3 observation times are used

Because the area of the pipelines metal was not changed with time the information about this area is not needed for extrapolation of corrosion damage in time. That is why all data for Area in Figure 32-21 are arbitrary.

Check only Groups 1 through 3 are used.

Click the **Calculate button.**

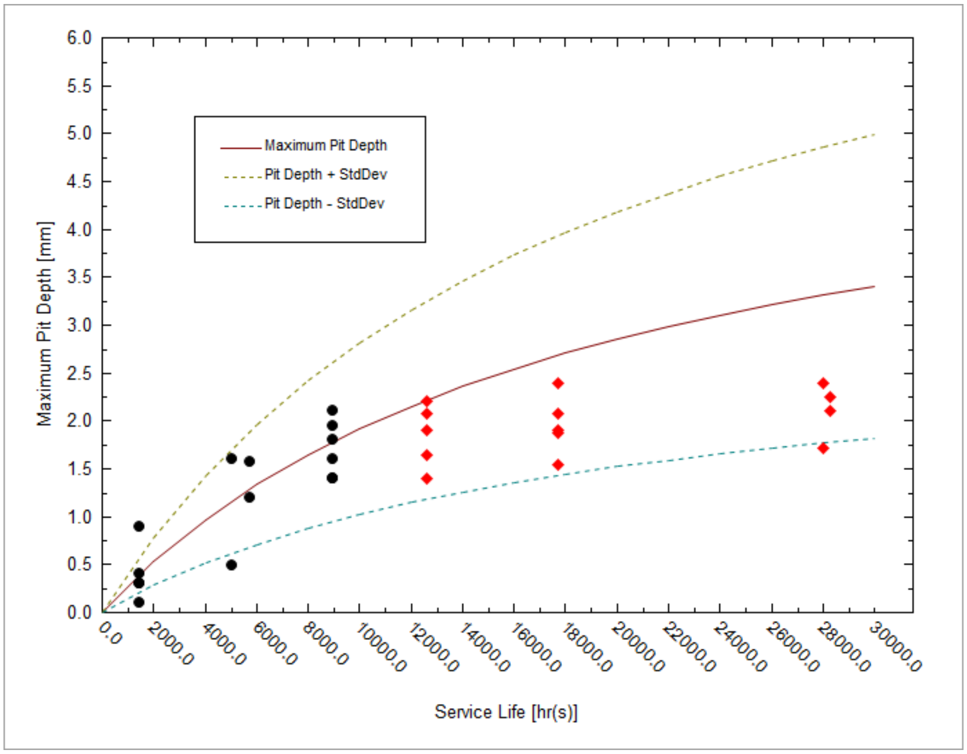

Figure 32-22: Predicted depth of the deepest pit with calibration on three observation times.

Click on the **<u>Definition</u>** tab and **Check** Groups 1 through 5.

Recalculate the diagram.

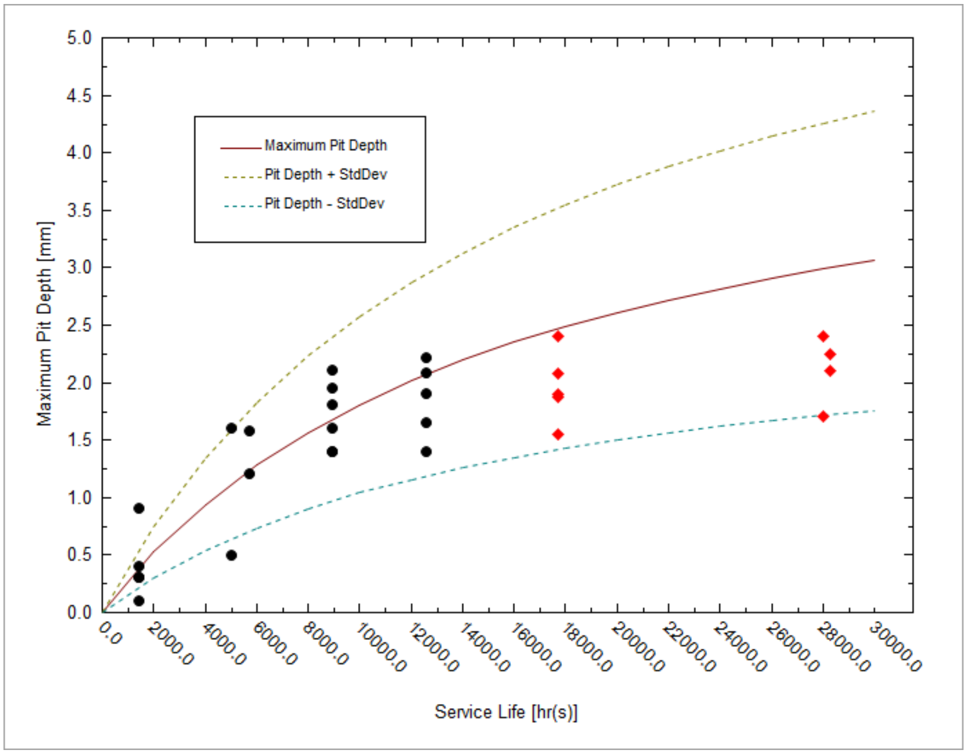

Figure 32-23: Predicted depth of the deepest pit with calibration on five observation times.

Figure 32-22 and Figure 32-23 show how the predicted results improved with increasing number of subsequent inspections. As previously, only points in black were used for predicting propagation of corrosion damage and other data, denoted by red diamonds, are shown only for demonstrating the accuracy of prediction

The predictions can be substantially improved if they were obtained on the same part of the pipe where conditions are approximately the same (see Figure 32-25and Figure 32-26).

Table 32-3Pit depth from measurements a single location.

Time (hours)	Pit depth (mm)
1440	0.9
5040	
5760	1.57
8959	2.1
12624	
17688	2.21
28032	2.4
28272	

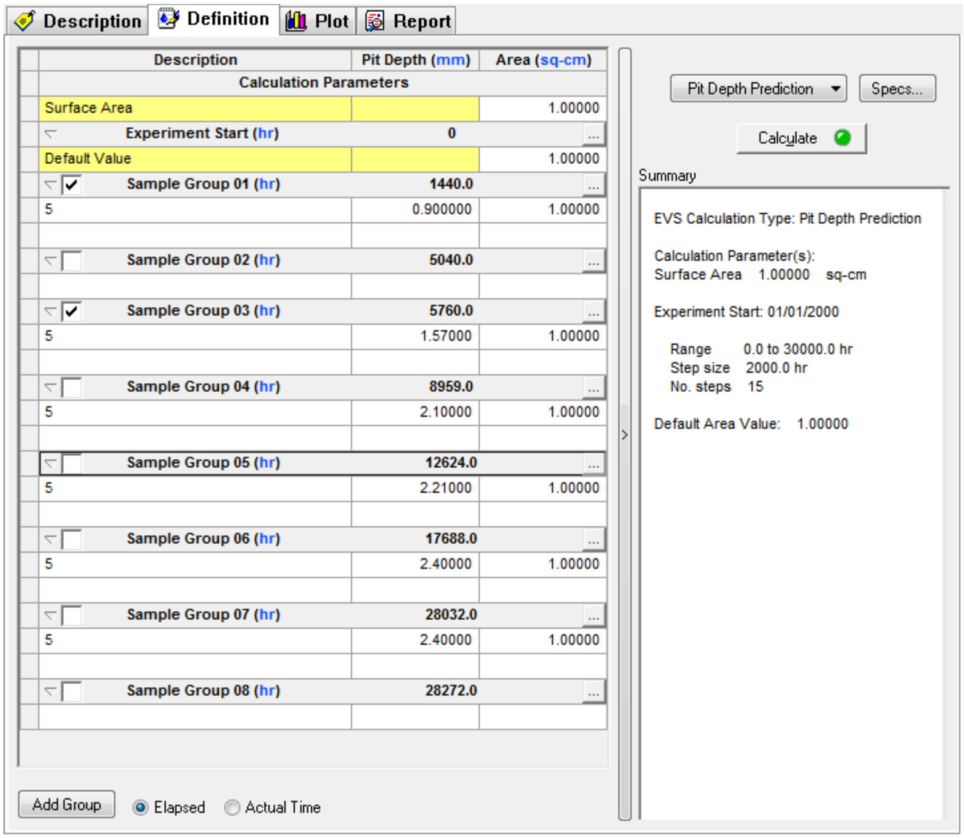

Figure 32-24: Specifying experimental data for depths of deepest pits for corrosion in pipeline. Experimental data are taken from one location on the pipe.

Only Groups 1 and 3 were used in the calculation.

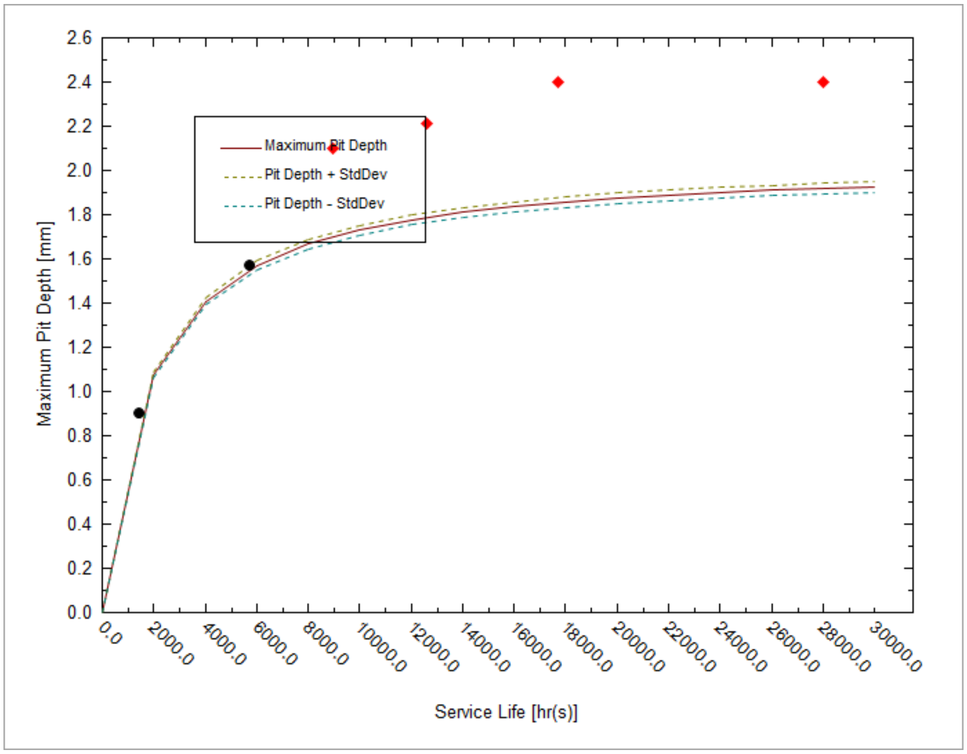

Figure 32-25: Predicted depth of the deepest pit with calibration on two observation times. Data are taken from one location on the pipe.

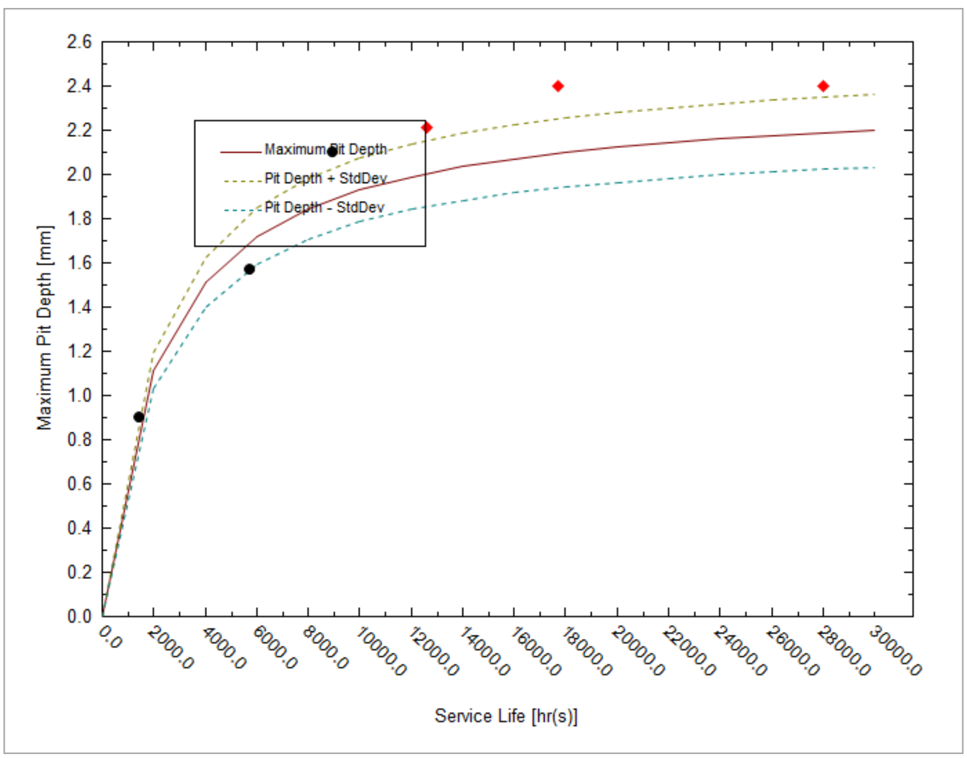

Figure 32-26: Predicted depth of the deepest pit with calibration on three observation times (groups 1,3 and 4). Data are taken from one location on the pipe.

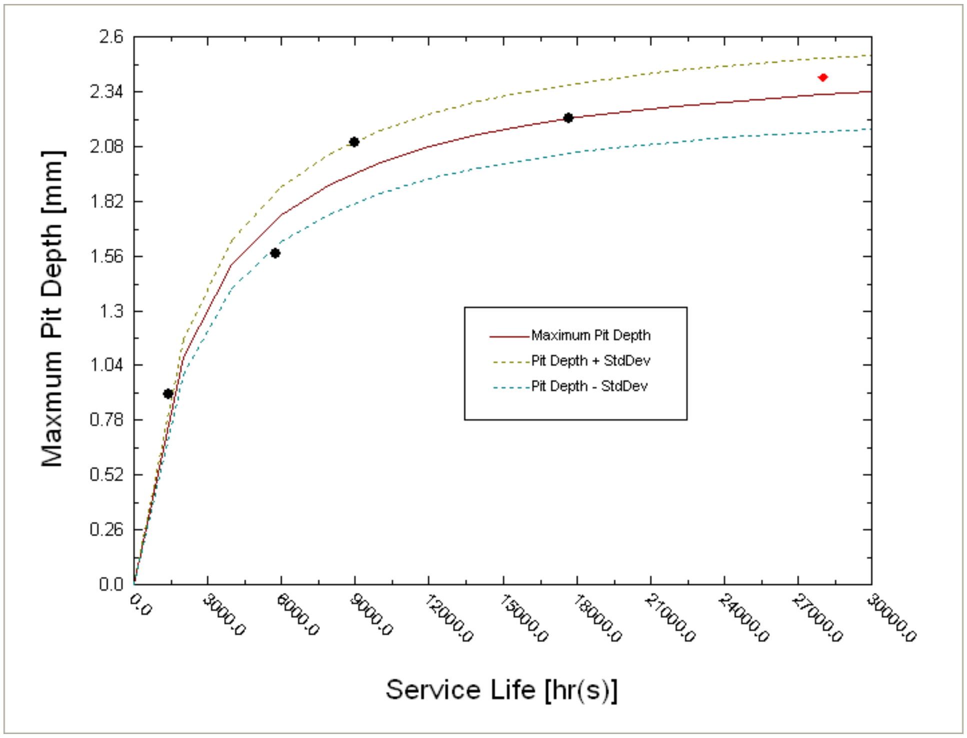

Figure 32-27: Predicted depth of the deepest pit with calibration on four observation times(groups 1, 3, 4, and 6). Data are taken from one location on the pipe.

Example 3: Possible Case of Insufficient Data

In some cases the data that provided by the user may be insufficient for reliable prediction of corrosion damage. Thus Figure 15-20 shows a part of experimental data that can be found in the paper (Laycock et al. 1990) for depths of the deepest pits that were measured on 316L coupons (2x2x1/2 in. thick) in a 10% ferric chloride solution at 50 ^{0}C. The full set of data from this paper is seen in Figure 32-28, which shows the predicted maximum pit depth for this system by using measurements at first three observation times.

Table 32-4 Pit depth data for 25.8 sq-cm, depth in micrometers

Sample	Grp 1	Grp 2	Grp3	Grp 4	Grp 5	Grp 6	Grp 7	Grp 8	Grp 9
	40.5 hrs	144.17 hrs	215.33 hrs	292.5 hrs	331.0 hrs	378.5 hrs	453.25 hrs	477.0 hrs	528.0 hrs
1	775	1326	1036	912	1361	1613	2101	1722	1714
2		1176	1199	1173	1534	1641	2024	1798	1767
3								1496	1775

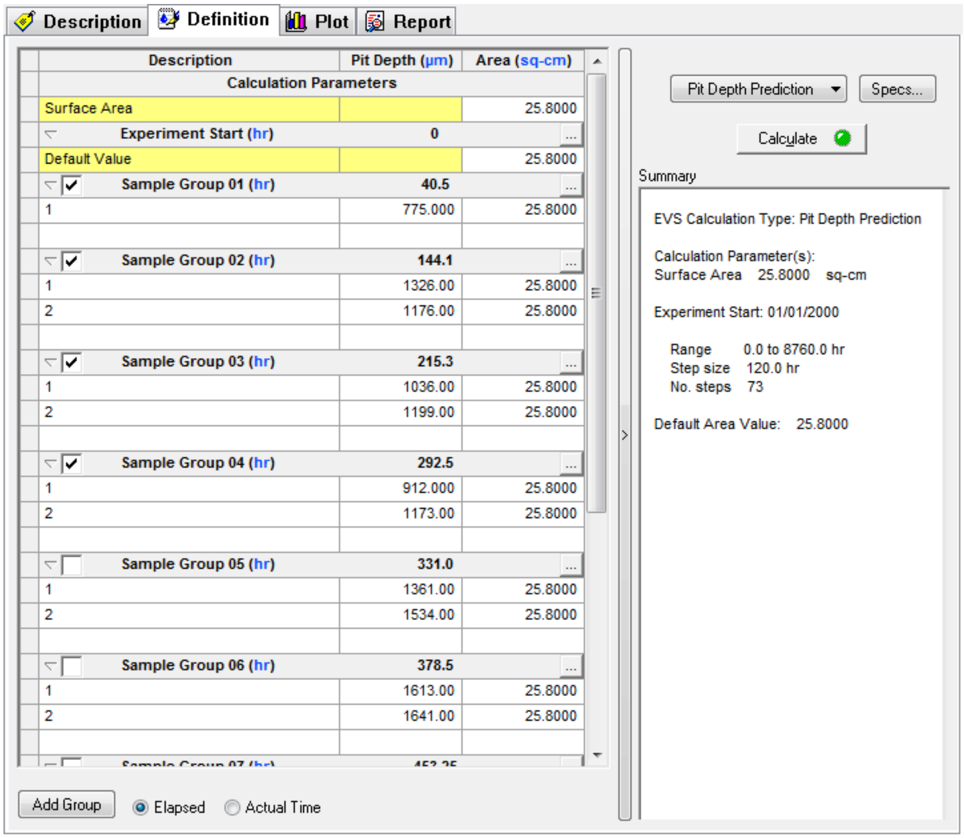

Figure 32-28: Specifying experimental data for depths of deepest pits for corrosion of 316L coupons in 10% ferric chloride solution.

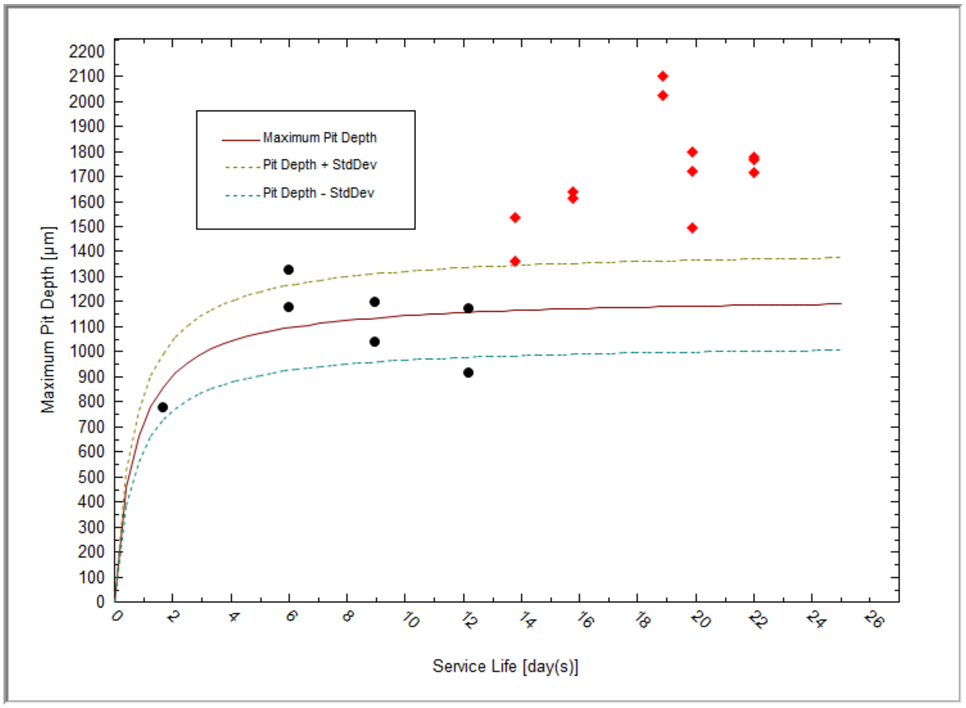

Figure 32-29: Predicted depth of the deepest pit on the stainless steel with calibration on the first four observation times (groups 1 through 4)

We see that in this case the prediction cannot be considered satisfactory. The reason is that for the second, third and fourth observation times the observed mean value of deepest pit decreases. Obviously such behavior of maximum pit depth has no physical foundation. Generally speaking such situation is the results of an insufficient numbers of experiments (used coupons) for given observation times. Accordingly, we can expect that after increasing the number of used coupons the situation can improve.

All of this does not mean that a full set of already available data cannot be used for predicting propagation of corrosion damage. Thus Figure 32-30 shows that the results of approximation of the full set of available experimental data from (Laycock et al. 1990) can be reasonably approximated by using EVS approach.

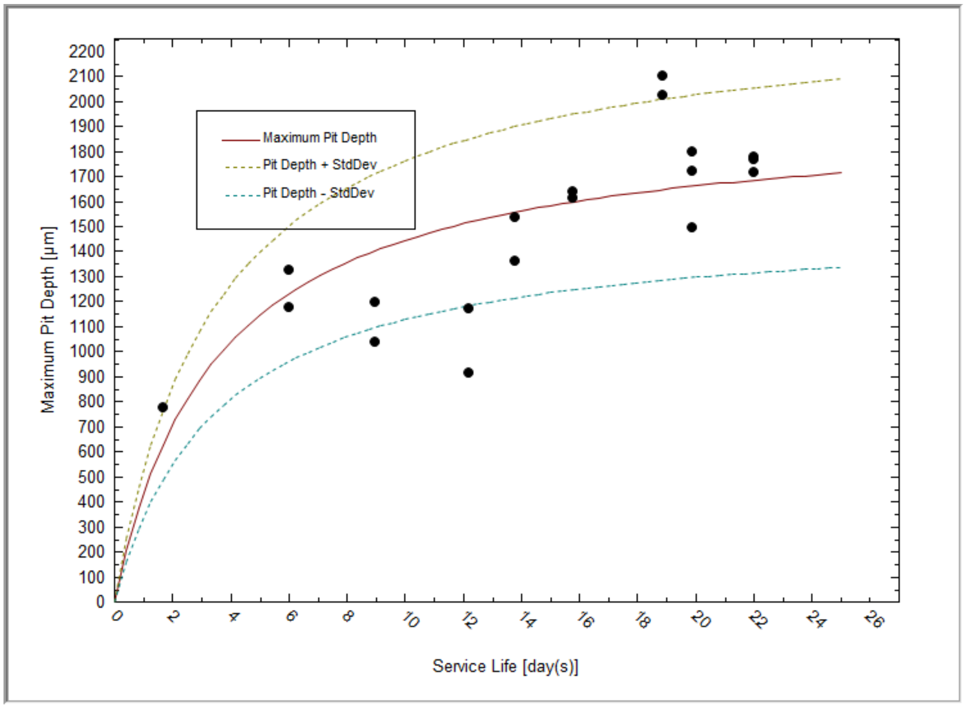

Figure 32-30: Predicted depth of the deepest pit on the stainless steel with calibration on full set of available data.

It means that sometimes the insufficient number of coupons (measurements at given observation times) can be compensated by increasing numbers of observation at different times.

You can download all the examples for this chapter from the OLI Wiki Page or from the support site