WHEN DO PUMP FAILURES PREVENT SYSTEM RE-USE OR LIFETIME EXTENSION?

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Abstract: Re-using or extending the life of existing submarine systems can offer significant economic benefits, but raises obvious questions about reliability. This paper focuses on lasers and explores what lifetime is likely to be achieved and the way in which a system might eventually fail. Where good practice has been employed it seems likely that laser reliability will allow systems to operate beyond 25 years, providing that there are no other blocks, such as lack of operating margin. Thanks to laser redundancy, system failure should be relatively gradual, with several years between the first laser failure and the time when an amplifier-pair fails.

1. INTRODUCTION

Re-using or extending the life of existing submarine systems can offer significant economic benefits, but it raises obvious questions about system lifetime. In particular it's important to ask how rapidly the system will become impractical to operate due to repairs, ageing and component failures.

There are a number of measurements, most importantly system Q, that show how transmission margin is being eroded as the system ages and is repaired. By tracking these it's possible to make an estimation of how much margin remains, although the end of life is not completely predictable, as events leading to repair will generally occur at random times.

There are systems which have been in operation for many years and experienced virtually no signs of ageing and few repairs. In these cases it's likely that at the end of the 25 year nominal life there will be sufficient operating margin to continue operation or for the system to be good for recovery and re-use elsewhere.

Extended operation or re-use, however, would be unattractive if component failures in repeaters were to occur frequently as the system reaches the end of its nominal life. Marine repairs are always expensive and disruptive and it may also prove difficult to get old repeaters repaired or to find replacement units.

A repeater uses a variety of components, but pump lasers are probably the most significant in terms of reliability. Their small dimensions and high power levels mean that carrier density and optical flux are both high and accelerated life-testing shows that they will ultimately fail at some time. Other semiconductor devices (e.g. ICs, diodes and transistors) operate at quite low current densities and passive components should be virtually failure-free unless there is some residual strain or contamination of the packaged component.

So far, most reported repeater problems [1] have indeed involved pump lasers, although most of these are probably due to issues in device production and inadequate protection against current variations, rather than early wear-out failures. Informal comments from operators support the idea that other components have, so far, been very reliable. This is probably because once the repeater has reached the sea-bed it is free from mechanical shocks and vibration, and the temperature will have no significant daily variation. Since these are the effects that cause many failures in the terrestrial world it's unsurprising that carefully constructed cable system components operate underwater with a very low "random" failure rate.

2. WEAR-OUT OF PUMP LASERS

Suppliers have put a lot of effort into developing and testing lasers and there is a lot of published data. Most of the tests estimate lifetime on the basis of temperature-accelerated ageing, where by doing a number of tests at different temperatures one can derive the activation energy associated with the failure process and then apply the Arrhenius law to predict the lifetime at the device's operating temperature. An objection to these tests is that they would not detect a second failure mechanism that was less accelerated by temperature. However, there are now room temperature tests [2] covering up to 17 years, which do not show a second failure mechanism.

From these publications there are some clear trends that should apply to all pumps used in submarine systems.

1. The wear-out is reasonably well modelled by the lognormal distribution. Even when the fit is not very good, it is usually good up to the mean of the distribution, the point at which half the devices have failed [3].

2. The ageing rate is dependent on temperature, increasing according to the Arrhenius law, with activation energies in the range of 0.45-1.1 eV, depending on the device type. The following graph shows the acceleration factor for 0.5 and 1.0 eV.

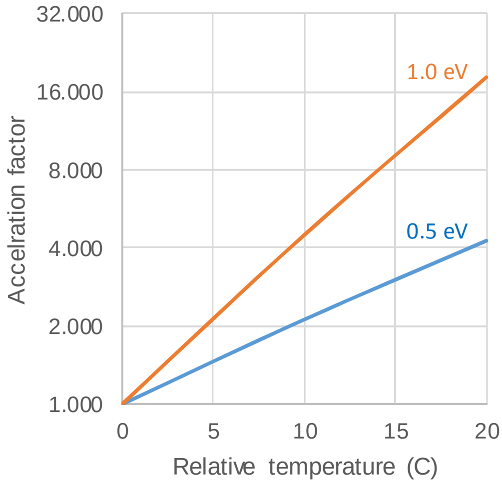

Figure 1: Temperature acceleration

3. It is also quite strongly accelerated by increasing the drive current. One paper [3] suggests that wear-out increases with the current raised the n'th power, where n is 4 to 6.

The following graph shows three example of lognormal curves for 40, 50 and 60 year mean life (the time at which 50% of the components would have failed) and 0.4 standard deviation – larger values of standard deviation cause earlier onset of failures for the same mean value.

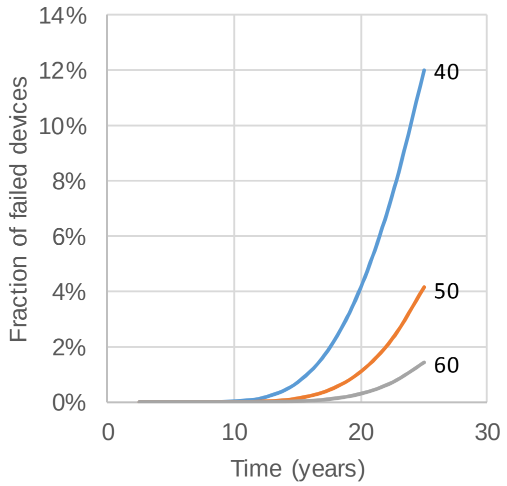

Figure 2 – Lognormal curves

The graph illustrates a key problem in determining lifetime from field failures. During the first years the curves are identical in predicting almost zero failures, so one cannot say which one best represents the devices in the system. However, even a single failure should be very unlikely and several failures during early life suggest strongly that the devices are failing faster than expected.

A further complication is that the operating temperature of devices is usually not well known, yet it has a significant impact on the rate at which ageing occurs, as shown in the following graph.

1480 nm lasers typically have activation energies of ~0.5 eV, while for 980 nm devices a figure of ~1.0 eV is applicable. In deep water the sea temperature is ~2C, while in shallow water the temperature could easily be 10-20C higher, thus accelerating ageing by a significant factor, particularly for 1480 nm devices.

3. HOW WILL SYSTEMS FAIL?

Predicting the end of life would be easy if one had precise values for the mean and standard deviation of the lasers used in a given system. For a variety of commercial and legal reasons – and the time since the initial procurement – it's usually very hard to obtain these. A further complication is not knowing precisely what the device temperature will be in a repeater.

Nonetheless, it may be possible to put a bound on the lifetime, by using the fact that good systems appear to have very few failures to date – this comes from informal comments from operators. One system, which has around 2,000 pumps in total has been operating for over 15 years without any pump failures. The following graph shows the cumulative probability of getting this behavior for a range of mean lifetime and standard deviation values.

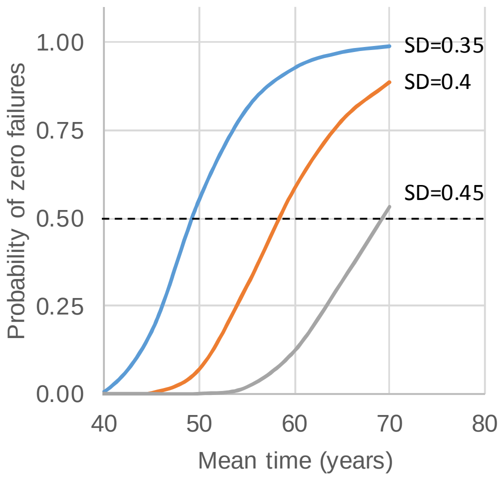

Figure 3: Lifetime of "good" pumps

The 50% probability value represents the lifetime that is most probable, or looked at another way, one is 50% confident that the lifetime is not less than that value.

The calculation is a little simplistic, as it assumes that all the lasers experience the same operating conditions. On a long system most of the repeaters are in deep water at ~2C, but a few are likely to be in shallower, warmer water and these will age more rapidly. For 1480 nm devices the acceleration will be a factor of around 4x for a temperature increase of just 10C (see Figure 1). If the deep water lifetime were 60 years then the shallow water devices would have a mean life of only 15 years, which makes the failure probability 50%. With even a very few repeaters in warmer water a few failures at 15 years would be inevitable. This suggests that the lifetime in deep water must be somewhat greater than 60 years. 980 nm lasers have a lower activation energy and are less affected by temperature.

Some suppliers have selected lower current lasers for use in warm repeaters, reasoning that this will reduce the ageing rate. On this basis the acceleration factor between cool and warm repeaters would be less than 4x, but the warm lasers will still be likely to fail much sooner than the cold ones. This strategy may also be open to an operator in the case of systems where the repeater power can be reduced – even a small reduction in output will extend the laser lifetime significantly.

Given the design objective to meet a 25 year lifetime with few failures and the general experience that correctly manufactured systems have, so far, had very few pump failures, it's interesting to perform some "what-if?" analysis. For simplicity let's assume the system has just two types of repeaters, cool and warm, with a lifetime difference of 3x. Each amplifier pair has 4x 1480 nm pump lasers and failure occurs when 3 or 4 failed – 3 failures would be a power drop of >6 dB, which might in fact be tolerable, but the intention is to be pessimistic.

First consider a system with 500 amplifier-pairs, of which just 4 are in warm water.

Condition	Mean	SD	Lasers
Warm	28 years	0.4	16
Cool	84 years	0.4	1984

The number of laser failures is calculated separately for warm and cool and the likely number of laser amplifier-pair failures is estimated by calculating the probability of 3-4 failures in any given 4 lasers and multiplying by the number of amplifier-pairs. The values of mean and standard deviation have been chosen to produce 1 failure in 2000 lasers at 15 years.

The following graph shows the results, but it must be remembered that the lines represent the likely occurrence of failures, not a precise prediction – there will be some statistical scatter around the trend-lines on the graph.

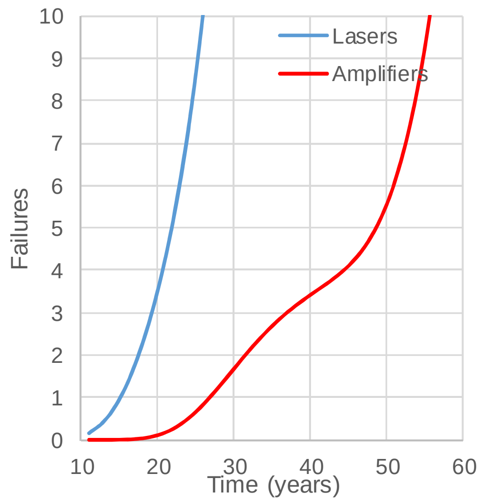

Figure 4: Failures for 500 amplifier-pairs 4x 1480 nm lasers/amplifier-pair

As expected, the onset of laser failure starts at around 15 years, but thanks to redundancy, amplifier-pairs don't fail until after 25 years. The first failures will mostly be in the warm repeaters, after which the failures slow down; they then become more significant as the cool repeaters start to experience laser failures.

Consider now a system with 100 amplifier-pairs, of which just 2 are in warm water.

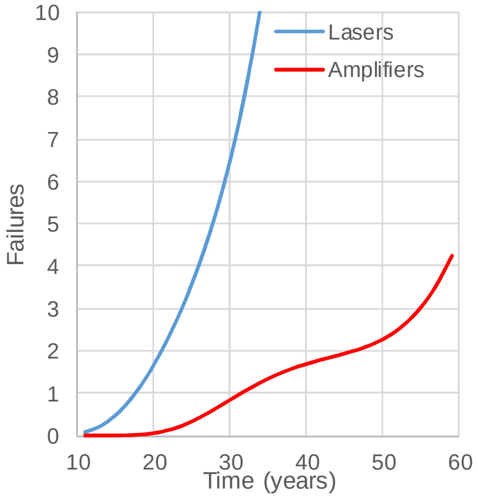

Figure 5: Failures for 100 amplifier-pairs 4x 1480 nm lasers/amplifier-pair

The trend is similar, but amplifier-pair failure occurs somewhat later, as would be expected.

The results in Figure 4 show that this model fits both the reported case and also the essential requirement that large systems should survive 25 years with few amplifier failures. Changing the mean and standard deviation within reasonable limits, while still predicting almost no early failures doesn't change the shape of the graph very much. A concern might be that even if the supplier generally meets the specification, what happens if a small batch of bad devices are used. Taking the example of a system with 100 amplifier pairs and assuming that just 16 lasers have a lifetime of 21 years rather than 28 puts the first laser failure at 13 years rather than 15. The first amplifier failure would be at 23 years.

980 nm lasers have a lower activation energy, making the difference between cool and warm repeaters less. The following graph shows a difference in cool and warm lasers of only 2x; all other parameters are the same

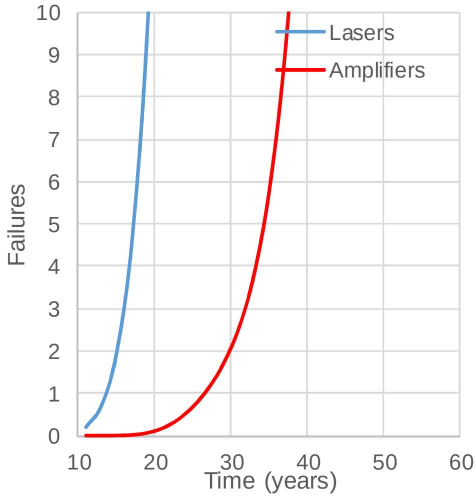

Figure 6: Failures for 500 amplifier-pairs 4x 980 nm lasers/amplifier-pair

This has the effect of almost completely removing the two distinct ageing phases observed previously.

A lot of effort has gone into improving the reliability of 980 nm and 1480 nm lasers [4] and more recent systems typically use just two 980 nm lasers per amplifier-pair, reflecting a greater confidence in the lifetime of more recent devices. Because such systems have fewer years of data available they have not been examined in detail in this paper. However, the trends will be similar: very few failures in early life, with laser redundancy making the time between the first laser failure and the first amplifier failure several years.

4. SUMMARY / DISCUSSION

There is insufficient time/data to say much about recent submarine systems, but for older systems experience suggests that lasers either:

1. exhibit almost no failures before the expected wear-out phase, OR
2. show problems much earlier.

The scenarios considered in this paper

cover the first case and have aimed to be somewhat pessimistic. Nonetheless, they suggest that systems with laser redundancy could well last 30 years – maybe more – providing that other problem do not prevent operation. (It's important to remember that the graphs show trends and that actual failures will show some statistical scatter.)

The effect of laser redundancy is that several lasers can fail before it's likely that there is an amplifier-pair that no longer functions, so tracking and analysing laser failures can provide an early warning of system wear-out. Q should also be tracked, since laser failures will reduce Q. In systems in systems which have used up the power budget repair and ageing allocation this might reduce the overall margin to zero before amplifier failure causes problems.

Because shallow water repeaters are generally warmer than those in deep water, long systems with 1480 nm lasers may well exhibit two phases of wear-out – this could also apply to 980 nm lasers if the temperature profile has large differences.

When analysing a system it's important to know the system temperature profile, the laser type and the laser redundancy – 2 or 4 devices per amplifier-pair.

Once the main wear-out phase is reached there will be an increasing need to repair/replace repeaters. How long the system can be kept in operation will depend on the number of spare repeaters available, or the ability to replace failed repeaters. The long outage during replacement operations will also need to be considered.

An owner considering extending the operating life of the system should have access to a lot of information and may well be able to construct a more detailed model and thus make a well informed decision regarding likely failure. A potential buyer of a system (who might wish to redeploy it for example) is usually much less well informed. Here it is useful to ask whether the current failure rates are consistent with a lifetime that makes a purchase a good decision.

Since most systems considered for re-use will be purchased well before 25 years, the expected failure rate should be close to zero and even a single laser failure should be regarded as suspicious. However, a failure in a warm repeater might be entirely acceptable if the plan were to redeploy only part of the recovered system and there were sufficient cool repeaters.

It is, of course, poor statistics to draw conclusions from a single failure and for life extension one can afford to monitor the initial laser failures and attempt to fit a trend-line, which will then allow estimation of likely amplifier problems. For a prudent purchase decision, however, even a single failure should be a warning sign, suggesting further investigation and/or thought.

5. REFERENCES

[1] Mark Andre, "How about technical skills within the submarine industry?" SubOptic 2013, p2.

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[3] J Van de Casteele et. al., "High reliability level on single-mode 980-1060 nm lasers for telecom and industrial applications" Photonics West 2008.

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