# RELIABILITY AND AVAILABILITY OF HIGH POWER PROTON ACCELERATORS*

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**Abstract**

It has become increasingly important to address the issues of operational reliability and availability of an accelerator complex early in its design and construction phases. In this context, reliability addresses the mean time between failures and the failure rate, and availability takes into account the failure rate as well as the length of time required to repair the failure. Methods to reduce failure rates include reduction of the number of components and over-design of certain key components. Reduction of the on-line repair time can be achieved by judiciously designed hardware, quick-service spare systems, and redundancy. In addition, provisions for easy inspection and maintainability are important for both reduction of the failure rate as well as reduction of the time to repair. The radiation safety exposure principle of ALARA (As Low As Reasonably Achievable) is easier to comply with when easy inspection capability and easy maintainability are incorporated into the design. Discussions of past experience in improving accelerator availability, some recent developments, and potential R&D items are presented.

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## Introduction

An accelerator facility requires very high availability in order to carry out its mission effectively, independent of whether it is designed to provide for multi-user research such as synchrotron radiation or particle physics, or whether it is to be used for a single purpose such as an accelerator-driven nuclear energy system (ADS). Availability of a facility is defined as the ratio of the actual run time to the scheduled duration of the run. Accordingly, in order to make the availability high, one must not only reduce the failure rate but also reduce the time required to repair the failures.

For an ADS, short mean time to repair (MTTR) is a very important consideration because of the nature of the ADS. If an ADS is used for generating power, reliability of the power station is a requirement. Secondly, one must consider temperature effects on the ADS's neutron-generating target assembly.

We discuss several concepts associated with availability, followed by some examples from past experience. A brief description of some recent work to improve the availability of an accelerator system as and discussions of potential future R&D work are presented.

### *Reliability*

Reliability is a measure of system failure expressed in terms of probability, failure rate, or mean time between failures (MTBF). The following is a short discussion of the definitions and some examples of the terms associated with reliability considerations.

If a system consists of a large number of components, and if each component is 99% reliable, then the reliability of the entire system approaches zero as the number of components becomes very large since $0.99^N \rightarrow 0$ as N becomes very large.

The probability of a system failure during a period of time, dt, is proportional to dt with a proportionality constant $\lambda$. The probability that the system will still be operating after a time dt is: $\Delta P(t) = 1 - \lambda dt$. Integration of this equation gives:

$$P(t) = e^{-\lambda t} = e^{-t/\tau}$$

$$\tau \equiv 1/\lambda$$

where $\lambda$ is the failure rate, and $\tau$ is the MTBF. These two quantities are inverses of each other. For a system with a large number of subsystems, the MTBF of the system is:

$$1/\tau_{system} = \sum_{i=1}^{N} 1/\tau_i \ .$$

The above equation implies that the shortest MTBF dominates in a multi-component system, and that if the system has N identical subsystems, the MTBF for the system is shortened by a factor of N.

The failure rate, $\lambda$, is not always constant. Rather, it is a time-varying function, $\lambda(t)$. One expects to have frequent failures during the commissioning period of a new system, and to have more frequent failures in older facilities. A typical functional expression of $\lambda(t)$ has the shape of a bathtub, and is called the reliability bathtub curve (RBTC) as shown in Figure 1. Perhaps the most important consideration related to the failure rate is the built-in stress on the system. A highly-stressed system will have a higher failure rate than a less-stressed system. Judging the acceptable degree of stress in design and construction requires good engineering knowledge and extensive experience.

Figure 1(a) shows three bathtub curves as a function of "built-in design stress levels." A highly-stressed design would exhibit a higher failure rate. Three bathtub curves show that regardless of the design stresses, newer and older systems have higher failure rates than systems of moderate age. The high failure rate of new systems is attributed to "infant mortality." The higher failure rate of aging systems needs no explanation. Proper quality control and inspection during construction can alleviate infant mortality problems, and the failure rate of older systems can be controlled by proper preventive maintenance. Figure 1(b) illustrates the effects of quality control and preventive maintenance. A system that is easy to inspect is also much easier to maintain well, thus good maintenance capability requires easy inspectability. Maintenance and inspection issues are discussed in the next section.

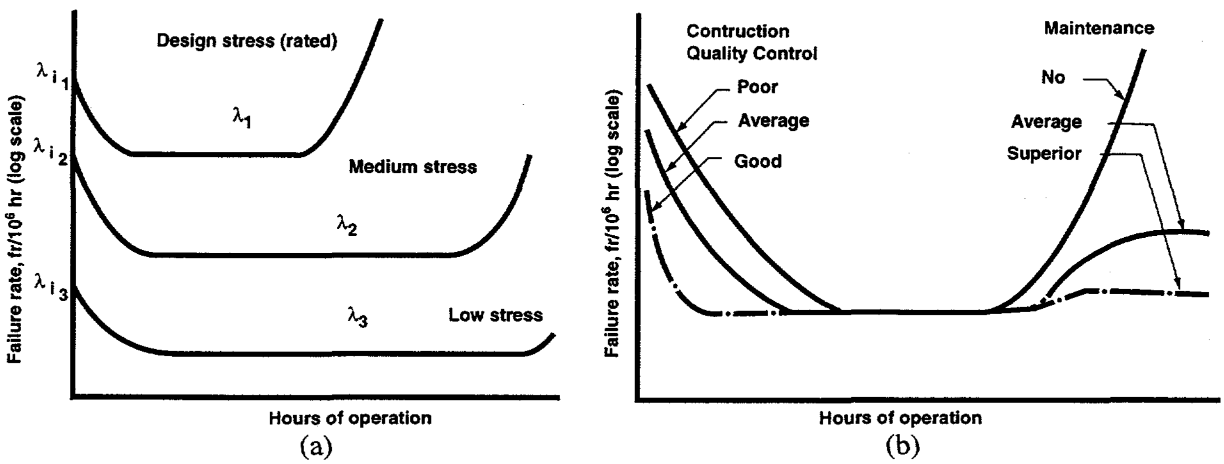



Figure 1: (a) Reliability Bathtub Curves as a function of design stress. (b) Reliability Bathtub Curves as a function of quality control during construction and preventive maintenance.

### *Availability, Maintainability and Inspectability*

In order to have high availability, the MTBF should be made as long as possible while the mean time to repair (MTTR) should be as short as possible. The importance of the MTTR is illustrated by the following examples. Suppose there is a system with an MTBF of one day, and the system is scheduled for a 10-day operational period. Case (1): If the system's MTTR is 10 minutes, then the system would lose 100 minutes out of ten days. Case (2): If the MTTR is one day, then the system would lose five days out of ten due to system repairs.

It is therefore very important to incorporate the capability to do quick and easy repairs or replacements of the hardware that is most likely to have a high failure rate already during the design stage. Redundancy, "hot spares," and "quick disconnects" are some of the options used to shorten the on-line repair time. As noted in the previous section, a superior preventive maintenance plan reduces the failure rate while a well-conceived repair system reduces the time required to repair. The next level of sophistication is designing the capability for easy inspection into the system. Easy inspectability allows both preventive and corrective maintenance to be expedited.

It is possible to expose workers to residual radiation during maintenance and repair activities. The ALARA principle (as low as reasonably achievable) of radiation exposure to workers should be incorporated into the inspection and maintenance plans, and into the equipment designs. Efforts after-the-fact to limit worker exposure to residual radiation may lengthen the repair time and increase costs.

## Some Past Experiences of Accelerator Availability

It is worthwhile to review what we can learn from past experience. Three examples described below are used to illustrate methods by which availability issues are addressed at various facilities.

### *IPNS Experience*

The accelerator system of the Intense Pulsed Neutron Source (IPNS) at Argonne National Laboratory (ANL) consists of a 50-MeV linac and a 500-MeV synchrotron, both operating at 30 Hz for some 17 years. These accelerators were originally built as the injector linac and booster synchrotron for the 12-GeV, Zero Gradient Synchrotron (ZGS) for high-energy physics.

The availability of the IPNS facility has consistently been 95% or better for the past several years as shown in Figure 2 [1]. It has one of the highest availabilities of any accelerator facility of its kind.

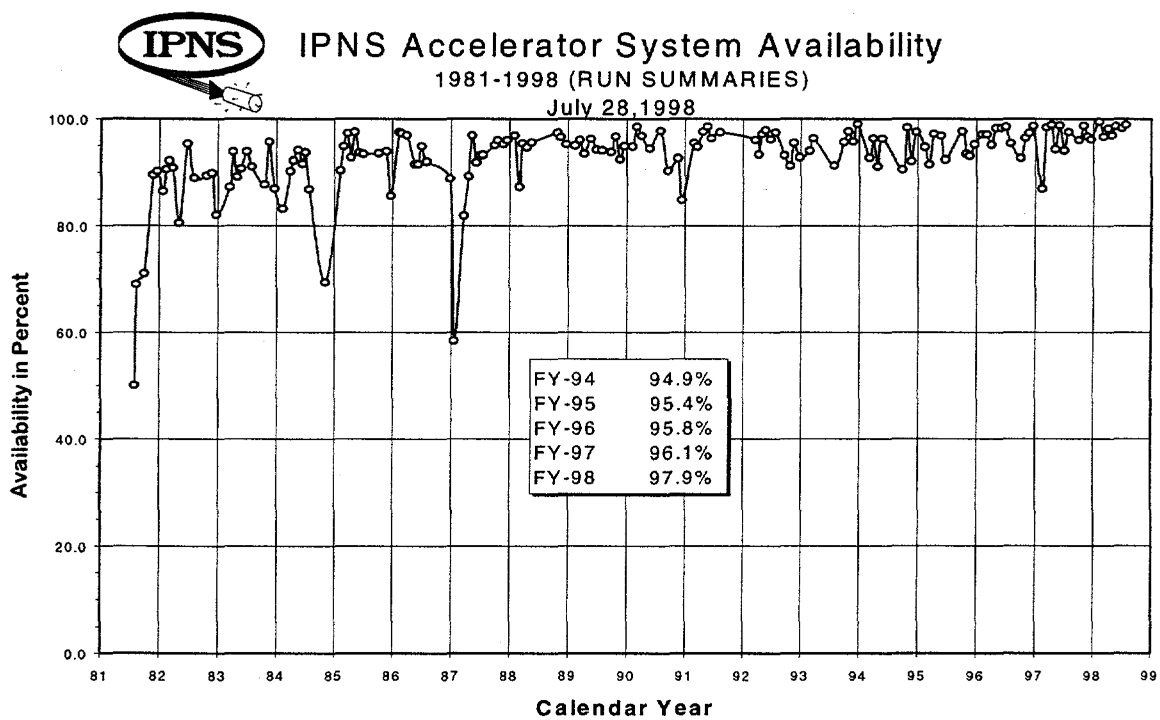



Figure 2: IPNS Accelerator System Availability Since 1981.

The IPNS linac was built in the late 1950s, and was designed to operate at a 0.2-Hz repetition rate. In spite of its age and design parameters, it has been operating at 30 Hz with good efficiency. It may be a highly under-stressed design. On the other hand, the synchrotron was designed for 500-MeV operation at 30 Hz, and was built during the budget-tight waning years of the ZGS program. As it turns out, the design of the synchrotron was an over-stressed design. The machine had a very high initial failure rate and a very low availability when operating at its design energy.

During the transition from the ZGS program to the IPNS program, we made two major remedial actions to reduce built-in system stresses. The first was to re-engineer all pulsed magnets such as kicker magnets and septum magnets. The second was to operate the synchrotron at 450 MeV rather than at 500 MeV, thus reducing stress in the ring magnet and its power supply systems. The lesson is to reduce stresses in the system. The resulting improvement in operation in 1981 is shown in Figure 2.

### *PSR Experience*

The Los Alamos neutron source, based on an 800-MeV linac and a proton storage ring (PSR), was commissioned in late 1980 to operate at a beam power level of 80 kW by delivering an average current of 100 μA for neutron scattering science. The linac was an existing accelerator that was being operated for the medium energy nuclear physics program, and the PSR was specifically designed and built for that facility. From the beginning, the facility suffered from marginally acceptable to low availability and low beam power. Figure 3 [2] shows the past performance of the Los Alamos neutron source. It is important to note that the linac had about 80% availability and the PSR also had about 80% availability. The combination of the two resulted in an overall availability of some 65% for the facility. To alleviate the availability difficulty and to reach the original design beam current, a two-step improvement program is in progress. Performance is expected to improve in the very near future.

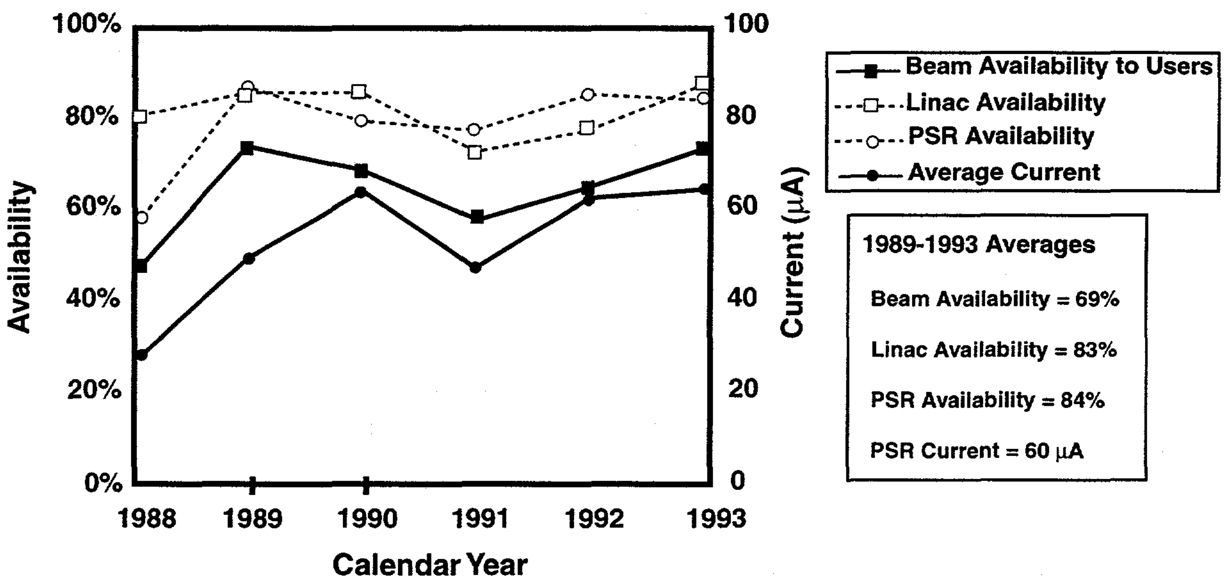
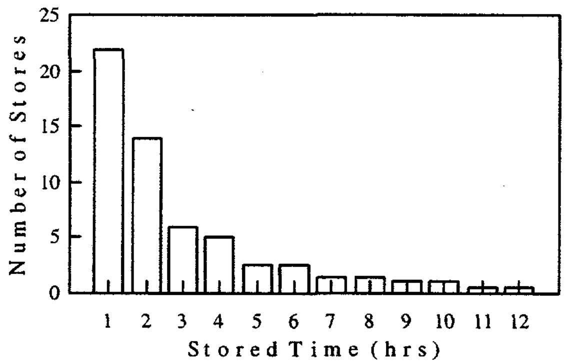



Figure 3: PSR and Linac Availability and Delivered Beam Current.

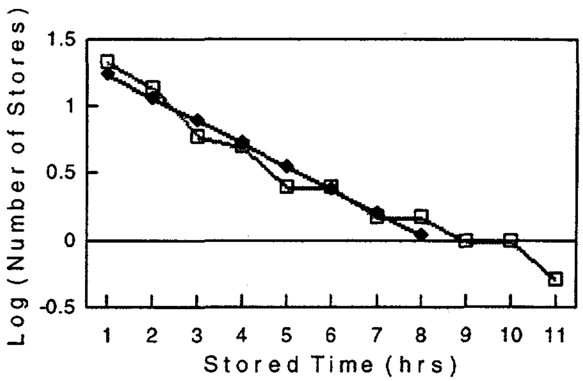
### *APS Experience*

The Advanced Photon Source (APS) is a synchrotron radiation source, not a high-power proton accelerator. However, the APS was designed and constructed for very high availability operation (95% or better) to satisfy user needs. A typical experiment using photons from a synchrotron radiation source may only need a few hours of uninterrupted beam time to collect data from a sample, however the user may have worked many weeks to produce the sample and the sample may be short lived. Accordingly, we decided to design and construct a highly reliable facility. The APS has been operational for the past two years, and has achieved 95% availability.

In a storage ring like the APS, the failure rate is measured by the frequency of beam loss due to a system component trip or malfunction. The time between failures is the stored beam time. As discussed previously, the time between failures should have an exponential distribution $e^{-\lambda t}$. The histogram in Figure 4 (a) is a stored-beam-time distribution in 1996 plotted on a linear scale. Figure 4 (b) shows the same data and a straight line fit to the data on semi-$\log_{10}$ scale. The straight line in the semi-log plot indicates that the time between failure goes as $e^{-\lambda t}$, and the slope of the linear fit can be converted to the mean time between failures. The MTBF given by the fit is 2.5 hours.




(a)




(b)

Figure 4: (a) A histogram of the stored beam time distribution for an early operational period in 1996, plotted on a linear scale. (b) The same distribution plotted on a semi-log scale (curve) and the result of a linear fit to the data on a semi-log plot (straight line). The slope of the straight line is the failure rate. The MTBF from the fit is 2.5 hours.

Figures 5 (a) and (b) show the stored-beam-time distribution from a 1998 run on a linear and on a semi-$\log_{10}$ scale, respectively. The straight line in Figure 5 (b) is the result of a linear fit to the data on a semi-log scale. This shows that the distribution still has an $e^{-\lambda t}$ shape. The mean time between failures is 14.7 hours obtained from the slope of the line. Note that the time between failures has improved substantially. The improvement in the stored beam time or time between failures demonstrates that the failure rate has improved as predicted by the reliability bathtub curve.

In the next section, we describe work we have done during the design and construction of the APS in order to have a highly reliable and available machine.

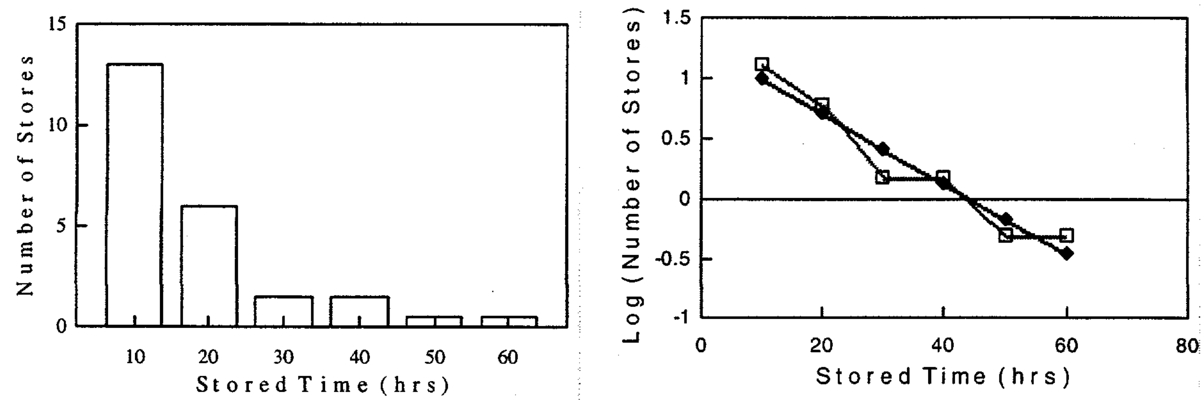
## Recent Work to Improve Availability

To achieve the availability presented in the previous section, several measures were implemented during the design and construction phases of the APS facility. It could be useful to consider some or all of the measures used in the APS design and construction when designing a high-power proton accelerator (HPPA) for high availability. Short descriptions of these measures are presented below.

### *Alleviating Stressed Designs*

The failure rate of a facility depends on the degree of design stresses, as was shown in Figure 1. In an era of tight budgets, designers try to get the most performance for the least cost. The following simple example illustrates the dilemma one can face when making a decision on design stresses. Suppose one designs a system that requires a motor. Calculations show that a 97-horsepower motor would be adequate. The question is whether to specify a 100-, 150- or 200-horsepower motor in the design. Such decisions depend on the experience of the designers and their willingness to take risks.

To make the risk-taking somewhat uniform at the APS, we decided from the beginning that, although the normal operating energy of the storage ring was 7 GeV, all hardware would be designed to operate at 7.7 GeV. This concept of designing for 10% over the operating energy had its origin at the IPNS and ZGS. Both IPNS and ZGS performed much better at 10% below their design energies.




(a) (b)

Figure 5: (a) Stored beam time distribution histogram in linear scale for an operation period in 1998. (b) The same stored beam time distribution in semi-log scale and the result of least square fit to the data. The slope of the straight line is the failure rate, which can be converted to MTBF of 14.7 hours.

***Reduction in the Number of Components***

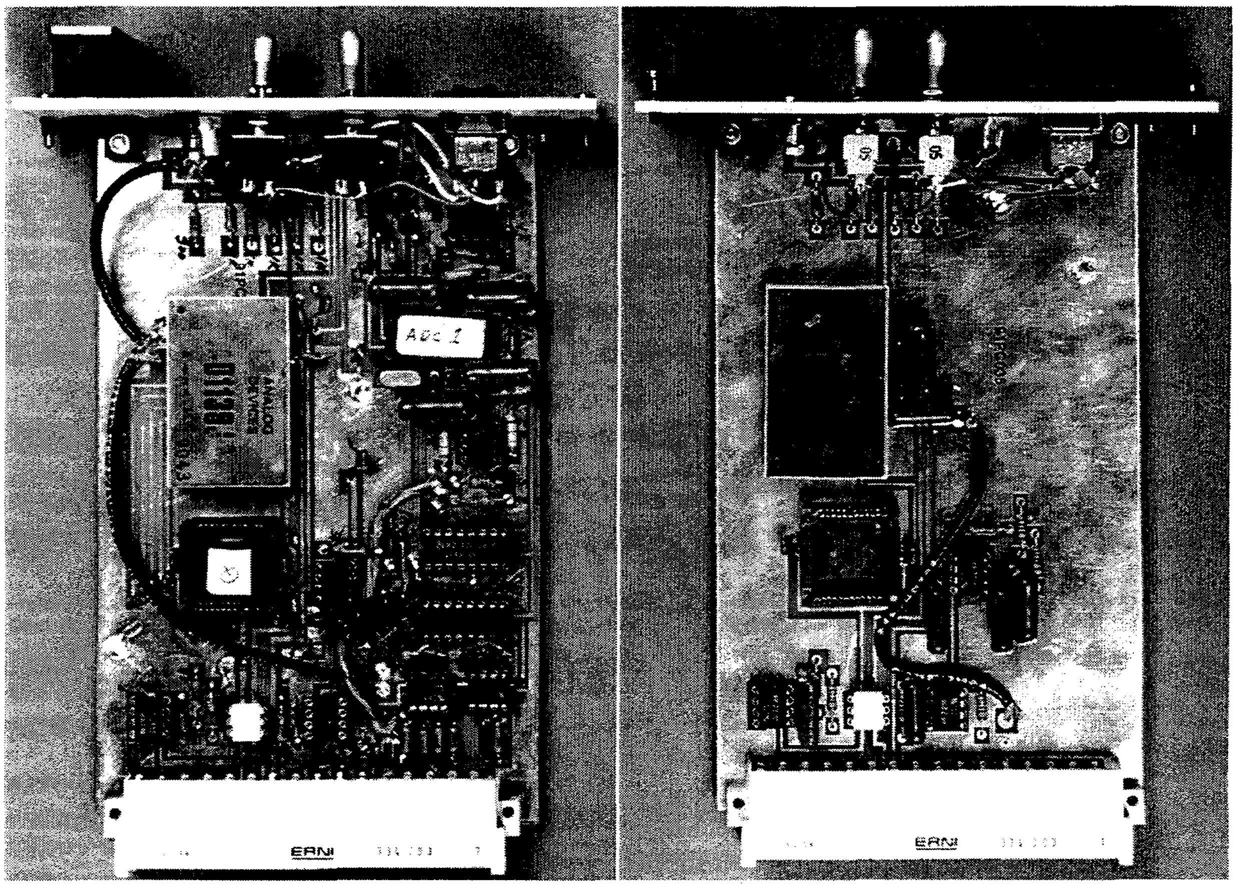
It was noted that $0.99^N \rightarrow 0$ when N becomes very large. Consequently, reduction of the number of components in a system usually increases the system reliability. However in some cases, increasing the number of components may be desirable for scientific reasons. The following discusses the resolution of a conflict during the APS construction between the desire to reduce the number of components for reliability and the need to increase the number of components for scientific reasons.

The APS storage ring has 400 quadrupole magnets. Each magnet is powered by an individual power supply, thus the system has maximum flexibility. Alternatively, since these 400 magnets are in 10 families, the conventional way would have been to use 10 power supplies and energize each family separately. Doing latter would reduce the number of the quadrupole magnet power supplies from 400 to 10, but would eliminate scientifically desirable flexibility.

A design decision made was to have 400 quadrupole supplies but to reduce the number of components within the power supplies themselves. Figure 6(a) shows a picture of the original circuit board of a DAC (digital to analogue converter) and Figure 6(b) shows the improved DAC [3]. Such a reduction in the number of components requires very good engineering judgement. In many cases reduction of components may result in a loss of flexibility. Decisions on how much flexibility one can trade off for improved availability, and how to recover lost flexibility must be made.

*Spare Parts, Redundancy, and Reduction of Time to Repair*

So far we have discussed methods to reduce hardware system failure rates to achieve high system availability. Next we discuss how to reduce the time required to make on-line repairs. "On-line repair" is any remedial action performed on hardware and software that requires shutting down the facility system. "Off-line repair" implies that the malfunctioning hardware or software can be removed from the system and replaced with a spare or a redundant part allowing the system to be brought back into operation while the repair of the malfunctioning subsystem is performed later. In this off-line repair mode, the time-to-repair is the period of time required to replace the component.



(a) (b)

Figure 6: (a) and (b) are initial and reduced-component designs of ADCs in the APS power supplies.

There are many ways to design easy-to-repair systems with built-in redundancy. Such features should be designed into the facility from the beginning, since retrofitting systems at a later date can be very costly. Designing in such capability requires sound engineering judgement, generally based on years of experience in operating accelerators, neutron generating targets, and reactor systems.

It may be worthwhile to note a couple of examples on the topic of spares and redundancy. All high-power accelerators require high-power radio-frequency sources, regardless of accelerator type. A common concern is how to reduce the time required to make repairs if one of many klystrons or associated power supply systems fails. For a circular machine like the APS storage ring, the solution was to have a "hot spare" installed in the ring. Switching from one to another takes about 10 minutes.

A hot spare rf source for a linear accelerator could be very costly because it requires a completely redundant rf system. However, it is possible to operate the linac with the affected section turned off if the system is designed with phase and energy adjustment capabilities. The design of such a re-phasing capability requires good engineering judgement and a thorough study of the beam dynamics to support re-phasing to obtain the same beam power.

### *ALARA Concepts and Reduction of Repair Time*

Many accelerator hardware designs have been optimized to minimize radiation exposure to repair personnel, following the ALARA Principle. The same design concepts can be used to reduce the time required for repair. An example of this is the quick-disconnect mechanism for accelerator vacuum chamber flanges. Under normal circumstances, nuts and bolts are used to connect and disconnect the vacuum chambers. Making and breaking of these connections is time-consuming work that usually can be avoided in high radiation areas if quick-connect systems are used. Repair time can be significantly reduced.

Another example to reduce radiation exposure to the repair personnel is found at the proton beam transport line just before the neutrino target at FNAL. During normal operation, radiation levels in the neutrino target area can be tens of thousands of rads, thus hands-on maintenance is impractical. A solution to this problem was to install the beam line components on a train with well-engineered rails to support the beam line and align it to the target. When a beam line component or diagnostic element in the line malfunctions, the train is pulled out and allowed to cool down prior to repair, and a new train is inserted so that operation can resume. This kind of idea implements the ALARA concept, and also reduces the time required to accomplish on-line repairs.

With regard to the interface between the proton beam line and the target, this writer would like to question the desirability of doing vertical injection of a proton beam onto the target. Is vertical injection necessary? Horizontal injection would allow much better inspectability and maintainability both for the proton transport system and for its interface to the target system.

## Potential R & D Work for High Availability

There are many R & D topics for high availability goals. Some are facility specific and others are generic. We list here some generic topics that could be collaboratively performed.

### *Interface between Target and Proton Beam*

The following topics related to interfacing the target and the beam transport line are of great interest in all high-power proton accelerators:

1) Window between the target and the beam transport line. Window materials and lifetime.
2) Beam transport line geometry as vertical vs. horizontal injection.
3) Quick replacement of transport line elements such as magnets and diagnostic equipment.
4) Self-alignment systems.

*Radiation-Hard Components*

Since the availability of a facility depends on its mean time between failures and its mean time to repair, we must consider potential failure of system due to radiation damage, and the repair process for radiation damaged components. Hardware elements such as magnets, vacuum joints, ceramic chambers or inserts and certain diagnostic equipment are sensitive to radiation damage. There are two key items that should be addressed in this connection. The first is the failure rate vs. dose rate for such equipment. The second is the engineering design of the repair/replacement process to minimize the repair time and radiation exposure to the repair personnel. It may be worthwhile to note that there have been many radiation damage studies by many laboratories around the world for various purposes. The results of past work should be a good starting point for a comprehensive study for future HPPA systems.

## Conclusion

The high power proton accelerators now being proposed and designed would provide unprecedented beam power and neutron yields, opening up a new realm of science and technology. In order to make optimum use of such facilities, facility availability resulting from reliability, repairability, maintainability, and inspectability, must be addressed during the design of the facility.

Past experience has shown that one must avoid designing over-stressed accelerator systems. A case in point is the IPNS synchrotron that has had trouble free operation at 450 MeV although it was designed for 500 MeV operation.

Reliability statistics obey the $e^{-\lambda t}$ rule. Minimizing the number of components in a system helps to reduce its failure rate.

To maximize the availability, both hot and cold spare systems must be addressed during the design. Well-engineered repair processes can incorporate radiation hazard ALARA concepts for the repair personnel at the same time.

Some generic R&D items pertinent to the HPPA are discussed. The R&D could be performed collaboratively.

## Acknowledgement

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