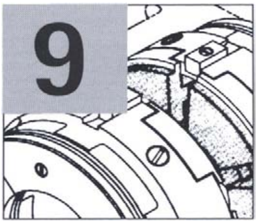


9 Preparing a site reliability optimization plan

- Introduction
- Identifying opportunities for optimization
- Determine the root cause of each identified opportunity
- Establish steps to prevent re-occurrence of problems
- Setting up an effective multi disciplined site reliability initiative
- Obtain and maintain management support
- How to maintain continuous improvement of the established program
- Appendix
  - Questionnaires
  - Design Audit Example 1 Rotor axial (thrust) forces tutorial
  - Design Audit Example 2 Lube system design tutorial
  - Management awareness workshop agenda example

Introduction

Regardless of the level of a site reliability optimization program, it can be improved. My personal experience is that:

- Bad actors* are defined but not permanently solved
- The majority of maintenance activities still are reactive – 'Firefighting'
- Preventative maintenance (time based) activities are excessive
- Predictive maintenance (condition based) activities still are minimal
- Some action plans for bad actor resolution have been defined but are not implemented
- Lessons learned, from bad actors, have not become best practices for machinery upgrades and/or new equipment purchases.
- The reliability effort is maintenance based and does not incorporate other site disciplines.

  *A bad actor is defined as any machine or stationary item that experiences one or more ESD's per year (un-scheduled shutdowns or failures). Note that while this book is devoted to rotating equipment, the principles discussed in this chapter are equally applicable to all the equipment in any plant.

Why are these characteristics prevalent in most plants? My opinion is that the plant management has not been convinced of the opportunities available to save considerable operating costs and increase profit by reducing downtime related to reliability issues and excessive maintenance time. Plant management must be shown results and the associated savings to endorse any plan for reliability optimization. Often, a 'salesman' that has the ear of management is required. I have found that this person is usually a trusted, senior operator or a process engineer. And considering that most reliability efforts are maintenance based, this salesman is nowhere to be found.

This chapter will therefore cover all the steps, in clear concise terms from identifying the problems and turning them into opportunities, thru the development of a reliability program and the continuous improvement of that effort to make it an established world class site reliability optimization program.

Identifying opportunities for optimization

Begin by using all available site information and process this information to determine the 'targets' that present the greatest opportunity for increased profit. The site reliability audit form contained in Chapter 8, and its associated availability worksheets are a guideline and starting point for obtaining the input information. Once this information is obtained the MTBF or failure rate, MTTR, availability and cost of un-reliability for the most costly 'bad actors' on site can be identified as opportunities for optimization. The 'targets' should also consider the time and cost of the resolution effort. These issues are noted in Figure 9.1 below.

Target opportunity guidelines

Select the bad actors with:

- The lowest MTBF
- The highest cost on un-availability

That are:

- The easiest to resolve
- For the lowest cost to resolve

Figure 9.1 Target opportunity guidelines

I have found that once the input information is obtained (Chapter 8 Audit form or other means), further questionnaires issued separately to Maintenance, Operations and Engineering provide additional valuable information to define key issues concerning the culture of the plant and possible root causes based on the procedures used. These questionnaires are contained in the back of this chapter. Separate questionnaires are supplied for Maintenance and Maintenance Engineering and Operations and Process Engineering. This information can be either emailed to the appropriate people or used as a checklist if questions are asked personally.

I have used these forms successfully prior to visiting a plant and usually have cycled the questionnaires 2 or 3 times to enable me to obtain as much information as possible prior to entering the plant and to prepare a site audit agenda that optimizes the effectiveness of the time on site and minimizes the time necessary for interviews. Figure 9.2 presents the form of a typical site audit agenda we have used.

Site audit agenda – example

Day 1 – am	■ Assemble audit team – introduction ■ Review completed audit questionnaires ■ Confirm schedule for each day of audit
pm	■ Visit first process unit ■ Daily review of results
Day 2 – am	■ Review day 1 activity report ■ Define remaining activity for first process unit
pm	■ Visit site for remaining first process unit activity ■ Daily review of results
Day 3 – etc.	■ Same activity as day 2 for each process unit
Last day – am	■ Management presentation

- Present
  - Audit procedure
  - Observations
  - Recommendations
- Emphasize that intent is to 'test' all observations and recommendations prior to final report

Figure 9.2 Site audit agenda – example

The audit agenda will also define the makeup of the individuals that need to participate. It is advisable to assemble a site audit team of experienced personnel prior to the visit. This action will also aid in having the required information assembled or even sent to the auditor prior to the site visit since the assigned team members can perform this task. Figure 9.3 presents the disciplines typically assembled for an effective site audit team.

Suggested site audit team make-up

One experienced member should be on the team from each of the following disciplines:

- Operations
- Maintenance
- Process engineering
- Reliability engineering
- Maintenance engineering
- Instrumentation and control

Figure 9.3 Suggested site audit team make-up

At the conclusion of the site audit and/or completion of the questionnaires, all the required input information will be available to identify the site opportunities for reliability optimization. An example of a proposed site opportunity list is shown in Figure 9.4.

Site reliability optimization opportunity list example

- Site awareness training
- The 5 most costly bad actors
- Increase PDM activities in 2 plant areas
- Minimize plant PM activities in 2 areas
- Optimization of spare part storage and retrieval

Figure 9.4 Site reliability optimization opportunity list example

Note that this opportunity list not only includes bad actors but site procedure change opportunities such as increased PDM, reduced PM and spare part procedures. When preparing this list be sure to benchmark all recommendations compared to other plants in your company or the industry. Be honest, the lower the ranking of your unit, the better the opportunity for improvement – if you don't lose your job in the process!!

In my experience, I have led many a group on a successful benchmarking trip that has resulted in not only valuable information for us but also the visited plant and has often resulted in the establishment of a valuable user network. Figure 9.5 presents an example of benchmarking recommendations.

Benchmark all opportunities

Opportunity	Benchmark	
Awareness training	The company Houston	plant
Increase PDM	Shell ______________	plant
Form seal taskforce	Exxonmobil ___________	plant

Figure 9.5 Benchmark all opportunities

It is very important to have benchmarks to demonstrate to management the need for improvement and/or that the proposed recommendation has been successfully implemented in an effective life cycle cost manner at other industry locations. It is most effective if benchmarks can be used from similar plant processes in the same geographical region. Figure 9.6 demonstrates the effectiveness of this approach.

Benchmarking guidelines

Effective references (benchmarking) of successful problem resolution have the following characteristics:

- Taken from similar process units
- Taken from your company if possible
- In the same country
- Visit approved, with final agenda, 2 weeks prior (usually with reciprocal visit arranged)

Figure 9.6 Benchmarking guidelines

Be sure to list the incurred cost of un-availability for each major bad actor as well as procedure improvement recommendations. Refer back to Chapter 8 for calculation of the cost of un-availability and note that the most important part of this calculation is the cost of incurred process unit downtime or rate reduction. This is the 'hammer' that will 'nail' the recommendation. Refer to Figure 9.7 regarding a suggested management presentation format.

Obtain and maintain management support by ...

1. Clearly stating impact of problem on plant profit (cost of unavailability)
2. Prepare a brief statement of:
   - Problem
   - Impact on plant
   - Reliability improvement plan
3. Be confident!
4. Be professional!
5. Be autonomous (do not expect management to do your job!)
6. Provide timely updates

Figure 9.7 Obtain and maintain management support by ...

Also do not forget to 'walk before your run'. Do not attempt to incorporate every opportunity into the program at this point, you want to prove the profitability of the program first, there will be plenty of time to add items. Choose the 'big bang for the buck' targets (lowest cost for the highest return) first.

Following a successful management presentation, you should have the required management support budget and necessary resources to proceed to the next step of the program. See the management support pyramid in Figure 9.8.

The most difficult task

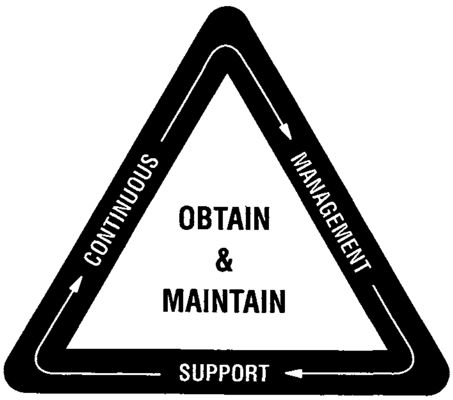


Figure 9.8 The most difficult task

A detailed report of the audit is both expected and required to serve as a checklist for the program status and success. It is very important to list all salient points pertaining to observations and recommendations in the management power point presentation (PPT) prior to leaving the site so that the validity of all facts can be confirmed and so that there will be 'no surprises' in the final report. Figure 9.9 presents a typical management outline format for your use in preparing a management 'asset opportunity improvement' presentation.

Presentation outline

- Study objective and methodology
- Presentation objective
- Study observations
- Study recommendations

Figure 9.9. Presentation outline

To complete this section, I have noted the following salient points that I have experienced during the audits that I have performed over the years:

- The most frequent machinery bad actor types are: pumps, general purpose turbines and auxiliary systems.
- The most frequent application areas for bad actors are: pumps in light and heavy hydrocarbon service, general purpose turbines in low pressure steam applications, transient events on lube/seal oil systems and dirt entrainment in dry gas seal systems.
- The most frequent component problems: pump seals and bearings, general purpose turbine carbon ring seals and governor linkages, dry gas seals (face seal blockage and secondary seal hang up) and auxiliary system oil systems components – control valves and small turbine linkages.
- The standard industry approach concerning bad actors is to group only according to equipment type and not to group according to application and components. Grouping according to application and components allows greater focus to determine the specific root causes.
- My experience with the bad actor approach and its subsequent root cause analysis procedure is that the problems are solved only for the short term and not for the long term and repeat over time.

- 80% or greater of the actual root causes of failure lie in the effects of the process or support systems on the equipment components.
- Management does not totally commit to the implementation of the proposed action plan.
- Continuation of a successful program must consider upper management change and the need to demonstrate credibility to each new regime.

Determine the root cause of each identified opportunity

Once the targets are identified, use the RCA procedure in Chapter 5 to determine the root cause of each identified opportunity. Do not forget to examine all 5 of the failure classifications when looking for causes and root causes. Start with the technical issues but remember that the actual root cause of many of the technical issues may in fact be an inadequate site procedure or lack of one! An example would be the continuous mechanical seal failures for a light hydrocarbon application. Refer to Figure 9.10.

Procedural root cause example

- Determined root cause = low seal chamber pressure causing premature vaporization across seal faces resulting in 5 or more failures per year
- Actual root cause = lack of an established site seal system condition monitoring program (refer to material in Chapter 4 for parameters to monitor)

Figure 9.10 Procedural root cause example

Once the target opportunity root cause is identified be sure to develop an easy to implement, cost effective action plan. Make sure that the solution is quick to implement and low cost. Refer to Figure 9.11 for the action plan generated for the *example* in Figure 9.10.

Mechanical seal problem resolution action plan

- Drill and tap affected pump seal chamber for installation of a pressure gauge
- Use available pressure gauges in the site warehouse
- Establish an operation procedure to monitor pressure gauges and define acceptable limits.
- Conduct mini-info awareness sessions to obtain implementation and ownership among operators

Figure 9.11 Mechanical seal problem resolution action plan

Many times the defined root causes point to a failure classification that requires contractor, vendor or consultant input. In these cases, a question list should be constructed and sent to the appropriate party well in advance of any discussion or meeting. An example of a vendor information request form is shown in Figure 9.12. Note that this form could also serve as a meeting agenda if required.

General purpose steam turbines reliability improvement issues

Turbine plant item numbers

____

____

Turbine vendor serial numbers

____

____

I Reliability improvement issues

1. Installation of independent electronic over-speed devices
   We wish to install electronic over-speed devices on the above noted turbines. Please advise the following:
   a. Modifications required for each turbine
   b. If the present mechanical over-speed device can be disabled by tightening the adjustment screw. We want to eliminate the mechanical device, but we do not wish to rebalance the rotor. Therefore, we would prefer securing the present over-speed device (over-speed bolt).

2. Installation of a vacuum device in the steam leak off ports to positively prevent steam leakage from entering the bearing housing.

   We wish to modify the following turbine item numbers: ______, ______

   The item numbers are turbine serial numbers: ______, ______

   ______________, and ______________

   Please provide the following information:

   a. Approximate steam and air leakage for each end seal.

   b. A proposal for steam eductors. The steam conditions available are:

      P__________

      T =__________

   c. The approximate steam flow required for each eductor.

Figure 9.12 General purpose steam turbines reliability improvement issues

Following an initial discussion with the vendor, a design audit may be required to determine the actual root cause. We have included two examples in this chapter of audit formats required to resolve long term, costly field reliability issues – balance drum and lube oil system audit in the back of this chapter. Additional information regarding design audits is contained in Chapter 10.

If the defined root cause is a procedure issue, contact with the vendor and/or the process licensor may be required. Figure 9.13 presents an example of such a case.

Compressor liquid bushing seal repeated failure RCA example

- Defined root cause – gas pressure applied to the compressor before the liquid seal system was put into operation causing debris to enter and plug the small clearance (0.002-0.004) between the inner seal bushing and shaft sleeve.
- Action – review of instruction book and confirmation discussion with vendor to revise site operating procedure and training with operations to absolutely assure that the seal oil system is always put into operation before gas is introduced into the compressor case.

Figure 9.13 Compressor liquid bushing seal repeated failure RCA example

In Figure 9.14, I have presented a typical design audit meeting agenda to resolve a long term compressor seal oil system problem. Always remember to be sure to send agendas well in advance to allow the vendor sufficient time for preparing the required material.

Design audit agenda

Lube/seal oil system

1. Introductions
2. Purpose of meeting
   2.1 Review study results, past modifications/failures and recommendations to assist client in resolving seal oil delta pressure trips on the subject compressor.
      2.1.1 Supply client with recommendations, modifications required and cost and delivery.
3. Results of studies performed in the field
   3.1 Client field reliability study
   3.2 Vendor engineering study
4. Review seal design and requirements
   4.1 Review seal components and function
      4.1.1 Upgrades?
      4.1.2 Modifications?
5. Review seal oil system component design
   5.1 Sizing of components (pumps, coolers, filters, reservoir, etc)
   5.2 Review valve selection and sizing (including Cv)
   5.3 Review control system
      5.3.1 Upgrades?
      5.3.2 Modifications?
6. Review comments to seal oil system component sizing study
   6.1 List recommendations
      6.1.1 Feasibility and reliability issues
7. Review final recommendations and feasibility
   7.1 Assign tasks and schedules
   7.2 Create final timeline up to delivery of parts and installation
8. Conclusion

Figure 9.14 Design audit agenda

In conclusion, be sure to minute all meetings and/or conference calls in detail and to define action and the responsible personnel. Guidelines are presented in Figure 9.15.

Always record all details

- Accurate, approved minutes
- List all major details in simple, concise terms
- Define each reason for proposed action
- Define required date and responsible individual
- Follow-up until all action items are completed

Figure 9.15 Always record all details

Establish steps to prevent re-occurrence of problems

I cannot tell you how many times I have solved the same problem ... in the same plant. Does this scenario sound familiar? Why is it the rule rather than the exception? In my opinion it has to do with the state of asset function awareness on site. Wherever I have worked, the state of the awareness of the design function of the installed assets can be improved. True, all plants have experienced engineering, operations and maintenance personnel. However, they rarely have had the opportunity to be directly involved with the design of installed equipment. I have found that most plant personnel crave for this knowledge regardless of their experience level. Once the experienced people on site become more aware of asset function, they naturally acquire a spirit of ownership in terms of condition monitoring and problem analysis. This leads directly to a site culture change and the beginning of a predictive maintenance approach. I have encouraged our clients to adopt the philosophy shown in Figure 9.16.

Reliability is everyone's responsibility

Regardless of position or discipline!!!

Figure 9.16 Reliability is everyone's responsibility

How can component function awareness be acquired? Is an outside consultant required? There are many alternatives depending on your company culture, budget and staffing. I have found that the most effective approach is to initially use a corporate specialist, supported by the corporate training department or an experienced outside consulting firm (If your 'corporate approach' is no longer in place) to present the training to site experienced, interpersonal communicators who in turn will train the remaining staff. Some approaches are presented in Figure 9.17.

Awareness improvement on site

- Mini-information sessions presented by site personnel
- Newsletters and/or emails relating the cause and solution of site reliability issues
- Asset function training presented by in-house specialists
- Asset function training presented by corporate specialists
- Asset function training presented by vendor specialists
- Asset function training presented by outside consultants

Figure 9.17 Awareness improvement on site

What should the objective of the training, regardless of the approach be? The objective is to explain what the function of a specific asset and its major components are and how they accomplish the stated function. The presentation should be brief and specific with a specific site example or two noted. And the training should include a group visit to the actual asset requiring the group to perform an exercise to assure implementation of the principle. Figure 9.18 presents these important facts.

Suggested format of site awareness training
'Talk – Walk – Talk'

- Include all disciplines (operations, maintenance & engineering) in the training group
- Define asset and major component functions
- Use actual site drawings and documents
- Define how the functions are performed
- List the parameters to be monitored
- Visit the asset and perform group condition monitoring exercises
- Return to the classroom, discuss results and formulate action plans

Figure 9.18 Suggested format of site awareness training

An important consideration is to be sure to integrate the training group using all affected site disciplines. I have found that this approach definitely improves site overall awareness and a spirit of teamwork that significantly reduces 'finger pointing'.

Before leaving the subject of site awareness training, one additional question has to be asked ... Who receives the training? Answer ... Everyone!!!

A 'top down' approach is required. If the personnel responsible to approve action plans are not aware of the consequences, in terms of lost profit, of not approving recommended action, the plan will never be implemented! I have taken the approach to separate management training from the other site training and usually use a corporate specialist or outside consultant company for this purpose.

It is suggested that consideration also be given to retain the same individual or company to provide the first session of component function awareness training to site senior people who are respected on site for their experience and ability to effectively communicate. I call these people the 'believeables'. An agenda for a 2 day management awareness workshop is presented in the back of this chapter.

Once site awareness is on the rise, it will be time to start to 'condition everyone' literally!!! The next step is to introduce the concept of CCM (Component Condition Monitoring) presented in Chapter 4. As you will remember, CCM requires that each of the 5 major components in any type of rotating equipment be monitored using all of the required parameters for each component. Figure 9.19 presents the five (5) major components in each piece of rotating equipment.

The five major rotating equipment components

- Rotor
- Journal bearing
- Thrust bearing
- Seals
- Auxiliary systems

Figure 9.19 The five major rotating equipment components

While this book is written with rotating equipment in mind, the principles presented can also be applied to stationary equipment.

How can CCM become part of the plant culture? I suggest that an example of CCM be included either in a mini information session or that a 'Talk – Walk – Talk' session be presented as detailed in Figure 9.18.

Try to minimize the length of the training sessions especially if your plant has not done this in the past. But be sure to start implementing the principle as soon as possible and include maintenance and operations in the program. In newer plants, it is easy to incorporate CCM into an Excel Format that can provide trends of all desired parameters using the site process information system (PHD, PI, ASPEN etc.). Figure 9.20 presents an example of the parameters to monitor for a bearing.

Condition monitoring parameters and their alarm limits

Journal bearing (anti-friction)

Parameter	Limits
1. Bearing housing vibration (peak)	.4 inch/sec (10 mm/sec)
2. Bearing housing temperature	185°F (85°C)
3. Lube oil viscosity	off spec 50%
4. Lube oil particle size	■ Non metallic = 25 microns
5. Lube oil water content	■ Metallic – any magnetic particle in the sump below 200 PPM

Figure 9.20 Condition monitoring parameters and their alarm limits

Remember that CCM is the basis of predictive maintenance (PDM) but this concept must be practiced site wide and requires implementation, practice and acceptance by all site disciplines.

A good example of 'conditioning everyone' into a new site culture is the refinery that had persistent reliability issues in a certain area of the plant. Using awareness training of operations, maintenance and engineering by dedicated site personnel, the concept of the equipment reliability operating envelope (EROE) was implemented. This approach uses the CCM for a Rotor, see Figure 9.21 below, to determine the operating point of each pump.

Pump performance monitoring 'the rotor'

1. Use calibrated instruments
2. Measure:
   - P_1
   - P_2
   - Flow
   - Specific gravity
3. Calculate:

   Head produced $\dfrac{FT\text{-}LB_F}{LBM} = \dfrac{\Delta P \times 2.311}{S.G.}$
4. Determine flow rate from either:
   - Flow meter
   - Control valve
   - Motor amps
   - Steam turbine throttle valve position
5. Plot the operating point on the pump shop test curve to assure the operating point is in the equipment reliability operating envelope (EROE)*
6. Take appropriate action if required

*EROE is typically -50% to +10% in flow of the pump best efficiency point (BEP)

Figure 9.21 Pump performance monitoring 'the rotor'

This approach was used since all of the affected pumps suffered from the effects of the process causing the pump to operate outside the heart of the pump curve, see Figure 9.22, thus being the root cause of all the damage suffered by these pumps (repeated bearing, seal and wear ring failure).

Operations saw the value of this approach and immediately implemented a program using local monitoring to maintain the operating point in the heart of the curve and remove these pumps from the 'bad actor' list ... for now! The challenge will be to see if this program can be maintained!

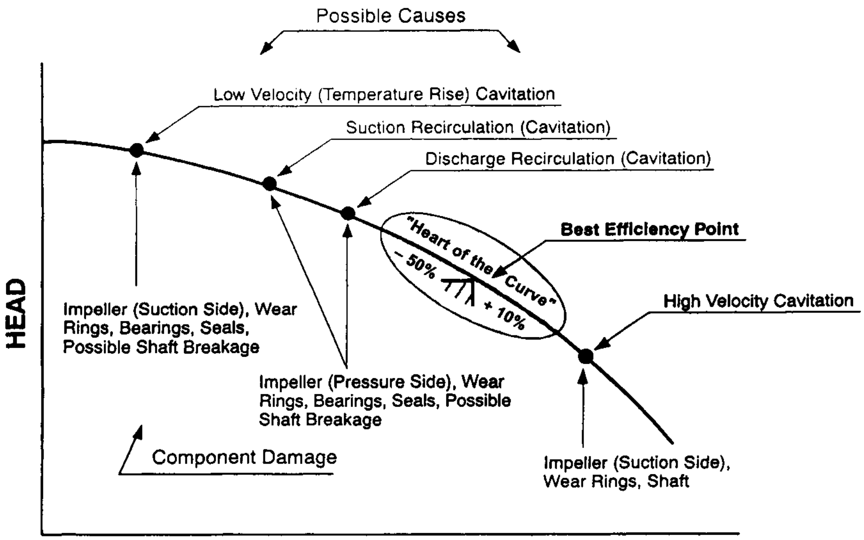


Figure 9.22 Centrifugal pump component damage and causes as a function of operating point

Along these same lines, I was recently involved with a new oil field project where all critical pumps were designed with pressure and flow transmitters to automatically assure that pumps were controlled to stay in the heart of the curve. In the control room, the 'Live' operating point was displayed on the shop test pump differential head vs. flow curve to allow operations to see if the pump was operating in the 'Heart of the Curve' and if the pump performance had deteriorated (if the operating point was not on the shop test, new condition, curve).

Once the concept of PDM starts to take hold, it is time to begin to whittle away the expensive and extensive PM (preventive maintenance – time based) list! Optimize your existing PM program based on the results of the PDM program. Figure 9.23 presents these facts.

Optimizing PM based on PDM results

- Use CCM monitoring parameters to determine condition of components prior to and after the established PM interval
- Extend the interval based on a constant (no significant change) trend of the affected parameter
- An example is extending the established 26 week pump oil change interval to an interval of 39 weeks, and eventually 52 weeks, based on using the CCM principle of monitoring bearing parameters (see Figure 9.20)

Figure 9.23 Optimizing PM based on PDM results

Finally, remember that any significant site culture change will mean extra work initially and perhaps involve additional personnel. Do not fall into the trap that I have and be sure to focus on a few 'big bang for the buck' (targets that are costly, high exposure ones) to prove the viability of the program to management and therefore assure improvement and continuation of the program. Also do not forget the most important part ... 'Reliability is everyone's responsibility' and be sure to include multi-disciplines in the effort. And consider helping the future engineers of your country and use students (Interns, Co-op's ... whatever you call them). It is truly amazing that young, dedicated, bright students cannot obtain needed training during their engineering studies. The important points to consider are noted in Figure 9.24.

Easing the transition

- Select the targets that can show immediate cost savings
- Do not overload the staff
- Assure that the effort includes all site disciplines
- Use engineering students to assist where possible
- Report results effectively to management

Figure 9.24 Easing the transition

Do not forget that continued improvement of the knowledge base of asset component function is essential to the success of the program. Refer to the principles presented in Chapter 7 for guidance and get the message across to all site participants.

Setting up an effective multi disciplined site reliability initiative

In my experience, I have worked with many site reliability efforts, different names, different cultures and different levels of experience. In the early days of my experience with these efforts (1970's and 1980's) there was but one constant ... all efforts were strictly maintenance based. Oh, yes, there was another constant ... identified opportunities for reliability improvement were not implemented.

The efforts also usually had a name and some of those were: the reliability group, the vibration monitoring group, the failure analysis unit, the failure analysis and PM group etc., etc. Regardless of the name, the effort was aimed at improving site reliability of all equipment, not only rotating equipment, and definitely achieved results but they were usually short term and problems re-occurred. Over the years, as is natural, the effectiveness of the program in a certain plant varied as personnel entered and left the group. Those who left, usually did so for higher pay and those that entered did so for increased experience.

Review of the historical efforts of these groups also had an interesting similarity. This was that every group or plant effort usually had identified the root cause of a particular problem but was unable to gather sufficient continued management support to implement the identified action plan. As a corporate consultant for a major oil and chemical company and later as an independent consultant, I would be asked to review various site reliability problems and recommend a cost effective action plan. In the majority of the cases, my end result was very close to what had been recommended prior to my study. However the difference was that my action plan was usually accepted and worked (just as the site group's plan would have also been successful!). This is not very encouraging to someone who works long hours, is 'on call' and has to attend to reactive maintenance issues at the usual times ... weekends!!! Incidentally, have you ever noticed that equipment usually decides to 'pack it in' on the weekend everywhere in the world (Thursday, Friday in the Middle East, Saturday, Sunday in the West, etc.).

I asked myself, why this was the case? After observing the characteristics noted above for a number of years, my opinion is that the efforts lacked an effective sales program. As a result, since the middle 1990's, I have been recommending that all site reliability efforts are integrated and definitely include an operations representative who can be a process engineer or senior operator or both. The reasons are because all site equipment reliability depends upon the process requirements and that, let's face it, the plant is run by operations and if there is an element of operations in the reliability group who agrees with the group's recommendation; acceptance and implementation have a much better chance. Because ... there is now a salesman in the reliability group!

Naturally the approach will be different in each plant and there are as many possible variations as there are plants. Figure 9.25 presents some of the possible structures of a site reliability initiative.

Site reliability initiative guidelines

- Specific, multi-discipline experienced reliability group
- A site culture change that makes reliability everyone's responsibility
- Operation, process and instrument reliability group members are on a one year rotation assignment

Figure 9.25 Site reliability initiative guidelines

Rotation of the operations, process and perhaps instrumentation members of the reliability group has shown to be a very good idea since returning members of the group to their own disciplines will naturally spread the word regarding function awareness and the importance of the program. It amounts to automatic function awareness training! Selection of the members of the group on rotation should be made carefully. I have found that these people should be the 'believable people' (experienced personnel who have the respect of their co-workers).

Remember again that regardless of make-up, the initiative must be multi-disciplined. The advantages of this arrangement are many. The major ones are presented in Figure 9.26.

Multi-disciplined reliability group advantages

- Valuable process information input
- Process and operation members are salesmen
- Significantly greater degree of function awareness of site equipment among all site disciplines
- Higher degree of ownership among all site disciplines
- Less finger pointing when problems occur

Figure 9.26 Multi-disciplined reliability group advantages

It is interesting to note that I have always observed that smaller remote plants (Artic region, New Zealand, Southern Chile and Platforms) have consistently out performed larger units in terms of action plan implementation. In these locations, they have to work together! And when they do, since everyone learns something regarding other discipline responsibilities and work scope, the results and acceptance of action plans flows smoothly.

Once the decision is taken to include operations and maintenance groups in the reliability program, consideration should be given to establishing 'ownership' in these groups in regards to the program. I have found that awareness training combined with simple 'tools' to inspire implementation of CCM and PDM help immensely. Figure 9.27 offers some suggested 'tools'.

Tools of the program

Suggested items to assist in CCM and PDM by operations and maintenance

- Laser temperature monitor
- Vibration pen
- Digital data logger to dump local information into DCS
- Strobe - for monitoring pump flinger ring operation and coupling condition
- A piece of $^3/_4$" pipe - for listening

Figure 9.27 Tools of the program

Once the participants are selected and work descriptions are defined and assignments made, a proven method of documenting all results for measurement of improvement and management support must be established. Guidelines for reports are presented in Figure 9.28.

Reliability report guidelines

- MTBF, MTTR and bad actor trends
- Cost savings from elimination of bad actors
- Cost to correct bad actors
- Net savings
- Benchmark recommendations
- Continuous improvement recommendations concerning reduction of PM and required turnaround work

Figure 9.28 Reliability report guidelines

Obtain and maintain management support

As noted in Figure 9.28, show net savings to the plant and believe me, you will obtain and maintain management support. However, you must show continuous savings and improvement. The reliability effort that only issues interesting newsletters won't be around too long. Management is interested in hearing the advice presented in Figure 9.29.

What plant management wants

- What was the problem?
- Is it permanently solved?
- How do you know it is solved? (use benchmark)
- How much did it cost to fix?
- What were our annual losses prior to the fix?
- How much did we save?

Figure 9.29 What plant management wants

Be sure to always provide proof (a benchmark) that the implemented solution has been applied elsewhere and has worked. Be prepared to back up the contention with written support and even a site visit to the benchmark facility. Do not forget to prepare a written agenda and forward it to the facility to be visited well in advance. Never expose yourself to loss of creditability with your management or another facility. You may work there someday!

As the program grows with success, use its cost saving results to justify sufficient resources of material, group state of the art training and manpower. Once success is realized, management will be quick to press for more savings. They must be made aware that the success to date was the result of the workload, manpower and experience level of the group. As work increases, the work to manpower and experience ratios must remain constant and new methods must be introduced to the group to increase effectiveness. The final section of this chapter presents guidelines for continuous improvement of this effort.

How to maintain continuous improvement of the established program

As I have previously stated, I have seen many an effective program fade with time. In order to sustain and improve an effective program, management support must be maintained, regardless of the business climate or management style. Some of the observed reasons for failure of reliability efforts are presented in Figure 9.30.

Why effective reliability programs do not continue

- Lack of management support due to:
  - Poor reports
  - Poor net saving results
  - Failure to benchmark recommendations
  - Lack of group experience
  - Change of business climate (poor corporate results)
  - Management change and not identifying with the new management team

Figure 9.30 Why effective reliability programs do not continue

Continued management support is earned and will yield results that will allow the reliability effort to prosper. Some of the advantages gained from a successful program, continuously supported by management, that will improve the program and maintain its reputation are shown in Figure 9.31.

Rewards for an effective reliability effort

- The percentage of proposed action plans approaches 100%
- Approval for procurement of additional 'reliability tools'
- Approval for site specific awareness training
- Approval for yearly vendor continuous improvement meetings
- Approval for attendance at industry seminars
- Approval for participation in user groups
- Approval for independent audits performed for difficult reliability issues

Figure 9.31 Rewards for an effective reliability effort

Details concerning each of the items in Figure 9.31 are presented below:

The percentage of proposed action plan implementation approaches 100%

This is the main objective of any reliability effort and it will yield many additional opportunities for personal professional growth, plant reputation for reliability and excellence and most importantly, program creditability. But it must be maintained and to be maintained, the group must truly grow in terms of tools, techniques and vendor communication.

Approval for procurement of additional 'reliability tools'

The effectiveness of all reliability efforts are based on the program's ability to obtain state of the art hardware and software. Given today's rapid rate of change, requests must be approved promptly by management. Be sure to keep track of the money saved by the program and use this figure when requesting additional reliability tools. Also do not forget to list the potential additional savings that the new equipment can produce.

Approval for site specific awareness training of all groups

Even if management support is obtained for site and off site training, it may not be approved if the requests are cycled through the human resources department. It must be appreciated that this department, like all other groups on site, have their budgets and culture. I have continuously witnessed proven valuable training workshops rejected by the HR department on the basis of cost and I have also observed that towards the end of the budget year that training is often selected for no apparent reason – other than the budget must be used or it won't be available next year. My recommendations for the improved acceptance of training programs are noted in Figure 9.32.

How to obtain training approval

- Justify on the basis of potential savings
- Benchmark people who have taken the program
- Recommend to your immediate supervisor
- Pass the name of the plant manager and your immediate supervisor to the organization that will conduct the training
- Work towards a joint effort between HR and the client (group that will be trained) in coordinating training

Figure 9.32 How to obtain training approval

You really cannot blame the human resources department if a proper objective for approving training is not given to them. Recommend to top plant management that training decisions be a joint effort of the concerned department (maintenance, technical, operations etc. and the human resources department).

Approval for yearly vendor continuous improvement meetings

It is truly amazing to me how, after the equipment is started, ties are severed with the equipment supplier. Perhaps, it is because of fear of high prices for spare parts or warranty rejection. However considering the exposure to revenue and profit losses that the end user faces, especially today with the size of process unit growing larger and larger, strong consideration should be given to increased vendor – end user communication after the order. The guidelines for vendor/end user communication guidelines are shown in Figure 9.33.

Vendor/end user communication guidelines

- Consider 'e based' vendor communication systems
- List problems, questions and suggestions and inform vendor
- Assure that all vendor updates are read and considered
- Hold a yearly vendor continuous improvement meeting, at the vendor's offices as a minimum
- Always provide detailed agendas for any vendor meetings well in advance.

Figure 9.33 Vendor/end user communication guidelines

Approval for attendance at industry seminars

Industry seminars are excellent opportunities for technology transfer if ... you are sent to the seminar and if management allows implementation of the tremendous amount of new knowledge you will bring back to the plant. However, if management has already bought in to your program, you can be sure that these principles will be implemented.

Approval for participation in user groups

User groups seem to be on the decline. Perhaps our friends in the legal profession have had something to do with that! It is true that many user groups have members that are potential competitors and may have issues. However, the Gas Turbine Users Association (GTUA) and the Texas A&M Turbomachinery Symposium are but two examples where competitors rub elbows and even present together! Inform management of the benefits of participation in user groups ... in terms of potential increased profit!

Approval for independent audits performed for difficult reliability issues

A final benefit of obtaining creditability of your reliability program is to be able to call in external help for a true 'global based audit' when required to solve long term, costly reliability issues. If you have not truly established the creditability of your program with management, this action will be impossible.

In summary, the objective of this chapter was to present practical guidelines for establishing, maintaining and continually improving a world class site reliability effort. Remember that success is dynamic. Change and modifications to the program are always necessary but they will require continued management support no matter who the manager is!

Appendix:

Questionnaires

Rotating equipment continuous improvement study engineering/ maintenance input data questionnaire

I. General

1. Please provide organization charts for maintenance and engineering groups.
2. Please provide start-up date for each process unit and approximate dates of T & I's (turnarounds) since start-up.
3. Please provide approximate T & I's (turnaround) downtime periods (projected and actual) for last two (2) T & I's.
4. List, if possible, reasons for extension of projected T & I's (turnaround) downtime period.
5. Do maintenance personnel become involved with determination of root cause problems? Yes ____ No ____
6. Since start-up of each process unit, have there been changes concerning the maintenance performed on-site? Yes ____ No ____ (Please list for each area)
7. Please describe specific maintenance practices for rotating equipment performed:

   On-site *Off-site*

   *Please note location
8. Please list approximate cost of maintenance labor.
9. Please describe alignment method for:
   - Critical equipment
   - General purpose equipment.
10. Please describe any centrifugal compressor fouling problems and methods used to prevent fouling and to clean compressors.
11. Please describe transient vibration data obtained during start-up of critical equipment (bode, cascade, polar).

12. Please describe if the following at speed data is obtained for critical unspared equipment:
    A. Unfiltered vibration
    B. Radial bearing vibration orbits
    C. Radial shaft position
    D. Bearing pad temperatures
    E. Axial position
    F. Thrust pad temperatures
    G. Centrifugal compressor balance line ΔP
13. Please describe what items are checked during bearing replacement.
14. Please describe what items are checked during pump mechanical seal replacement.
15. Have there been any instances of critical equipment coupling failure? If so, please describe specifics (use separate page).
16. Please briefly describe problems with mechanical/hydraulic governor systems (TG-10, 13, 17) for general purpose turbines.
17 Please briefly describe problems with critical steam turbine governor systems (PGPL or electro-hydraulic).
18. How often are turbine overspeed trips checked?
19. Please describe any problems with critical steam turbine trip solenoids.
20. Please describe any problems with oil contamination (water) for single stage (general purpose) steam turbines.
21. Please describe types of mechanical seal quench systems and seal jacket cooling systems used for bottoms, HGO and LGO pumps (provide P & ID if possible).
22. Please provide reports for bad actor reliability problems. (Major compressor trains, caustic pump mechanical seal problems, bad actor mechanical seals)
23. Please list what information you could obtain regarding process and operation that would enable you to perform your job better.
24. Please provide example of a typical failure analysis report.
25. Please provide present PM (preventive maintenance) schedule for:
    - Single stage process pump
    - Motor (greased anti friction bearings)
    - Motor (sleeve bearings)
    - Centrifugal compressor train
    - Reciprocating compressor unit

II. Specific questions for each area

Note: Please copy this form and distribute to the appropriate personnel in each designated area of the audit.

1. Condition monitoring data

A. Method (i.e. manual vs. 'data trap' vs. D.C.S.)

Example	Method	Years used
	Manual logs	

B. Condition monitoring parameters. (Note) Please answer if the following parameters are condition monitored (Note 1)

1.	Centrifugal compressor performance parameters (P_1, T_1, P_2, T_2 flow, speed, gas analysis)		Yes	No
2.	Pump performance parameters (P_1, P_2, S.G., flow speed)		Yes	No
3.	Compresor seal fluid (gas or oil) supply flows (or valve position if oil system)	(Gas)	Yes	No
		(Oil)	Yes	No
4.	Centrifugal pump seal stuffing box pressures and temperatures		Yes	No
5.	Centrifugal compressor balance line ΔP		Yes	No
6.	Reciprocating compressor performance		Yes	No
7.	Reciprocating compressor crankcase vibration and rod drop		Yes	No
8.	Reciprocating compressor jacket water temperature		Yes	No
9.	Reciprocating compressor packing leakage		Yes	No
10.	Reciprocating compressor lubrication (packing, cylinder) usage		Yes	No
11.	Centrifugal compressor seal oil trap leakage		Yes	No
12.	Centrifugal compressor seal oil reservoir flash point		Yes	No
13.	Steam turbine performance		Yes	No
14.	Steam turbine seal leakage		Yes	No
15.	Steam turbine T & T valve exercising		Yes	No
16.	Prove on line the ability of the auxiliary oil pumps to start without unit trip			

Note 1. All questions in item B pertain only to equipment in each process unit

of the audit. It is suggested that copies of this form be distributed to personnel in each area concerned with the audit.

Note 2. In the space provided between items state item numbers of units where the answer is 'yes'.

Note 3. It is assumed all centrifugal compressor units are vibration and bearing temperature condition monitored. Please advise if this is not the case.

2. Preventive maintenance data

Refer to Note 1 in item 1 above.

A. Please answer if the following items are changed on a preventive (time interval) basis. If the answer is yes, please state the time between replacement (Δ Time)

	ΔTime		
1. Compressor rotors	____	Yes	No
2. Compressor bearing and turbine	____	Yes	No
3. Compressor seals	____	Yes	No
4. Compressor labyrinths	____	Yes	No
5. Steam turbine rotor (spared turbines)	____	Yes	No
6. Steam turbine rotor (unspared turbines)	____	Yes	No
7. Pump bearings	____	Yes	No
8. Pump seals	____	Yes	No
9. Pump wear rings	____	Yes	No
10. Electrical switches	____	Yes	No
11. Accumulator bladders	____	Yes	No
12. Control valve diaphragms	____	Yes	No
13. Oil filter cartridges	____	Yes	No

B. Please answer if the following items are cleaned on a preventive basis.

1. Oil reservoirs	____	Yes	No
2. Cooler tubes	____	Yes	No
3. Control valve pulsation dampeners (snubbers)	____	Yes	No
4. Seal oil drain types	____	Yes	No
5. Seal oil degassing tanks	____	Yes	No
6. Reciprocating compressor lubricators	____	Yes	No

3. Turnaround activities

Please list turnaround activities for each critical (unspared) rotating equipment unit (this includes driver, driven, transmission devices and auxiliary systems) on the following form

Area **Train** ____________

Type and items no.	T & I dates	Major item replaced (note 1)	Reason (note 2)	Part cost	Labor time (hours)	Did activity extend T & I (note 3)

Note 1. Major items: rotors, internals, coupling, bearings, seals, control valves
Note 2. Use following code
P.M. = preventive maintenance
P.D.M. = predictive maintenance indicated imminent failure
F.P. = failed part
Note 3. If activity extended T & I, indicate how many days.

4. Critical equipment forced outages

Please complete the following form for forced outages of major unspared equipment.

Equip. type & item no.	Date of event	Reason for outage	Parts affected	Process unit outage hours	Time to repair (hours)	Cost of parts	Suspected causes	Corrective action

5. Please list the field monitoring performed by operations and note if it is MRC (control room) and/or local.

Type	Parameters measured	Control room	Local
Pumps			
Steam turbines			
Compressors			
Lube/seal systems			

Rotating equipment continuous improvement study operations engineering and operations input data questionnaire

I. General

1. Please provide technical organization chart for:
   - Operations
   - Operations engineering
2. Please provide approximate daily revenue loss (local currency) for all the major process units in the plant.
3. Please provide information concerning control room modernization (DCS) type, date, etc.
4. Please list the field monitoring performed by operations and note if it is MRC (control room) and/or local.

Type	Parameters measured	Control room	Local
Pumps			
Steam turbines			
Compressors			
Lube/seal systems			

5. Do operations engineers and operations personnel become involved with root cause determination of rotating equipment problems?
6. Please describe any centrifugal compressor fouling problems.
   - Methods used to prevent
   - Cleaning methods

7. Please list what information you could obtain regarding rotating equipment, that would enable you to perform your job better.

8. Please advise if and when all site major centrifugal compressors (list each compressor) are checked for performance (head and efficiency).

II. Specific questions for each area

Note: Please copy this form and distribute it to the appropriate personnel in each designated area of the audit

1. Rotating equipment process and operation questions

   Please complete the following questions for each critical (unspared) equipment item in your area. Make additional copies of this form as required.

   1. Centrifugal compressor process conditions

      A. Does compressor surge on start-up?
         - Molecular weight, gas temperature charges

      B. Does compressor surge during normal operations?

      C. Any problems with moisture in the process?

      D. Has performance (flow) been decreasing with time or has turbine speed been increasing with time?

      E. Compressor suction strainer problems?

   2. Steam conditions for critical steam turbines

      A. Present normal steam conditions and flow rates.

      B. Does 'off design operation occur' (low inlet pressure or temperature or high exhaust pressure?

      C. Any slugs of moisture go through the turbine?

      D. Any fouling of turbine?

      E. Trend of first stage pressure vs time.

      F. Any steam strainer problems?

   3. Alarms or trips

      A. Vibration

      B. Bearing temperature

      C. Thrust bearing position

      D. Overspeed

      E. High separator liquid level

F. Low seal oil Press

G. Auxiliary pump running

H. High oil temperature

I. High oil filter differential

4. Seal oil drainers and degassing tank

    A. Do drainers ever need to be removed from service or bypassed?

    B. Any change in drainer flow with change in operation conditions?

    C. Any problems with degassing tank?

5. Steam turbine operation (critical/unspared)

    A. Any vibration problems during start-up?

    B. Any problems with steam seal system?

    C. Any problems with main condenser system?

    D. Any governor control problems?

    E. Can you manually exercise trip and throttle valve? If so, how often?

    F. Any problems with turning gear?

    G. Any problems with turbine tripping off the line or not tripping when signal is given?

6. Operation problems

    A. Is seal oil system for compressors put into operation before process gas is put into the case?

    B. Please describe any compressor operation problems.

7. Lube, control and seal oil problems

    A. Oil reservoir

        1. Oil sample results

        2. Low level alarms

    B. Pumps

        1. Cavitation noise

        2. Vibration

        3. Bearing or seal problems

        4. Turbine control problems
            - Speed decrease
            - Governor instability (hunting)

C. Trip or transfer of lube or seal oil pumps

1. Can main pump be tripped and auxiliary pump start without tripping unit?
2. Is this ever attempted during operations?
3. What checks are performed during operation that auxiliary pump will start without tripping unit?

D. Relief valves

1. Popping
2. Not closing
3. Improper setting

E. Transfer valves

1. Any plug or handle problems?

F. Coolers

1. Any problems with maintaining required oil supply temperature?

G. Filters

1. Have filter cartridges ever been damaged during filter changeover?
2. How often are filters changed?

H. Valve and controllers

1. Any valve or controller instability?
   - On start-up
   - During normal operation
   - During pump changeover
   - When both lube or seal pumps are operating

8. Pump problems – 'process bad actors'

A. Please indicate pumps experiencing repeated seal replacements (more than 1 per year)

B. Please indicate pumps experiencing repeated bearing replacements (more than 1 per year)

C. Please indicate pumps that require internal inspection and/or replacement bearings, rings, internals, etc.

D. Please list any other pump problems.

9. Critical equipment forced outages

   Please complete the following form for forced outages of major unspared equipment.

OEU/Operations critical equipment forced outages

Equip. type and item no.	Date of event	Reason for outage	Parts affected	Process unit outage hours	Time to repair (hours)	Cost of parts	Suspected causes	Corrective action

Design Audit Example 1
Rotor axial (thrust) forces tutorial

In every rotating machine utilizing reaction type blading, a significant thrust is developed across the rotor by the action of the impellers or blades. Also in the case of equipment incorporating higher than atmospheric suction pressure, a thrust force is exerted in the axial direction as a result of the pressure differential between the pressure in the case and atmospheric pressure.

In this section we will cover a specific rotor thrust example and calculate thrust balance for a specific case. We will see the necessity in some applications of employing an axial force balance device known as a balance drum. In many instances, the absence of this device will result in excessive axial (thrust) bearing loadings. For the case of a machine with a balance device, the maintenance of the clearances on this device are of utmost importance. In many older designs the clearances are maintained by a fixed close clearance bushing made out of Babbitt which has a melting temperature of approximately 350°F, depending on the pressure differential across the balance drum. If the temperature in this region should exceed this value, the effectiveness of the balance drum would suddenly be lost and catastrophic failures can occur inside the machine. Understanding the function of this device and the potential high axial forces involved in its absence is a very important aspect of condition monitoring of turbo-compressors.

We will also examine various machine configurations including natural balanced (opposed) thrust and see how thrust values change even in the case of a balanced machine as a function of machine flow rate.

Finally, we will examine thrust system condition monitoring and discuss some of the confusion that results with monitoring these machines.

The hydrodynamic thrust bearing

A typical hydrodynamic double acting thrust bearing is pictured in Figure 9.34.

The thrust bearing assembly consists of a thrust collar mounted on the rotor and two sets of thrust pads (usually identical in capacity) supported by a base ring (Michell type).

The Kingsbury type includes a set of leveling plates between each set of pads and the base ring. This design is shown in Figure 9.35.

Both the Michell and Kingsbury types are used. Figure 9.36 provides a

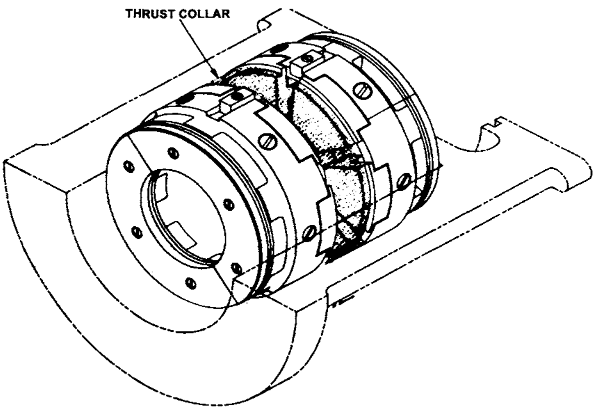


Figure 9.34 Double acting self equalizing thrust bearing assembly (thrust collar removed) (Courtesy of Elliott Company)

Figure 9.35 Small Kingsbury six-shoe two-direction thrust bearing. Left-hand group assembled, except for one shoe and 'upper' leveling plate. Right-hand group disassembled. (Courtesy of Kingsbury, Inc)

view of the leveling plates providing the self-equalizing feature in the Kingsbury design. The self-equalizing feature allows the thrust pads to lie in a plane parallel to the thrust collar.

Regardless of the design features, the functions of all thrust bearings are:

- To continuously support all axial loads
- To maintain the axial position of the rotor

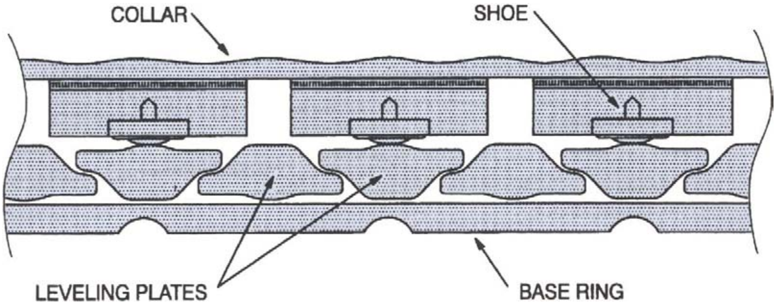


Figure 9.36 Self-equalizing tilt-pad thrust bearing (View - looking down on assembly) (Courtesy of Kingsbury, Inc)

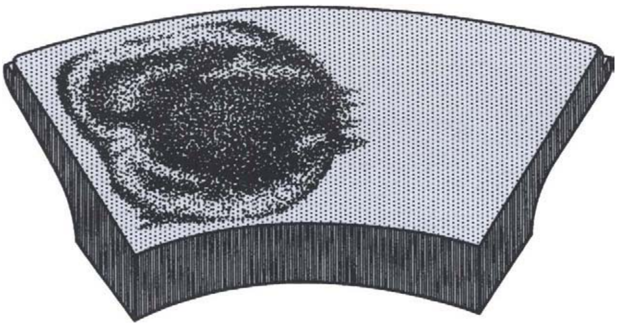


Figure 9.37 Evidence of overload on a tilt-pad self-equalizing thrust bearing pad (Courtesy of Kingsbury Corp)

The first function is accomplished by designing the thrust bearing to provide sufficient thrust area to absorb all thrust loads without exceeding the support film (oil) pressure limit (approximately 500 psi).

Figure 9.37 shows what occurs when the support film pressure limit is exceeded.

The oil film breaks down, thus allowing contact between the steel thrust collar and soft thrust bearing pad overlay (Babbitt). Once this thin layer (1/16") is worn away, steel to steel contact occurs resulting in significant turbo-compressor damage.

Thrust pad temperature sensors, located directly behind the Babbitt at the pad maximum load point protect the compressor by tripping the unit before steel to steel contact can occur.

Figure 9.38 presents different Kingsbury bearing size rated capacities as a function of speed.

Figure 9.39 shows how thrust pad temperature and thrust load are related for a given thrust bearing size and shaft speed. Note that the

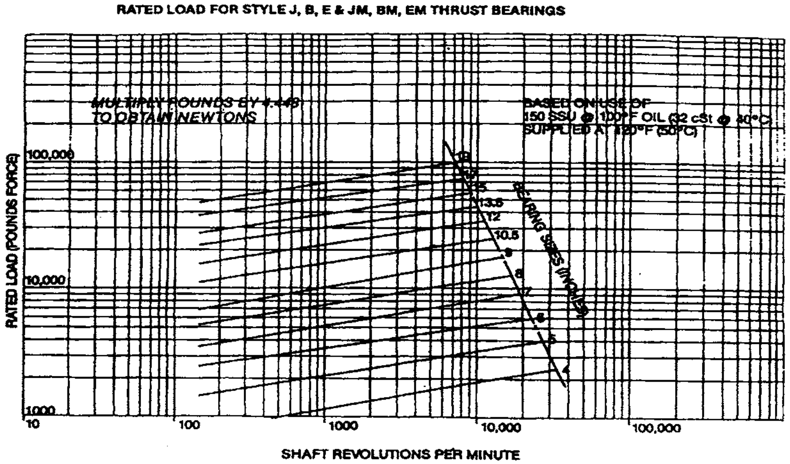


Figure 9.38 Thrust bearing rated load vs. speed (Courtesy of Kingsbury, Inc)

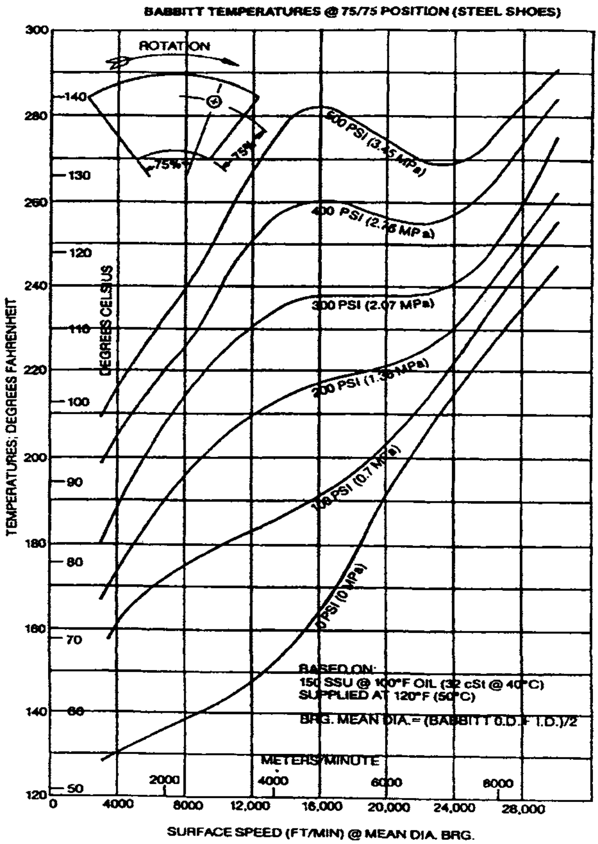


Figure 9.39 Relationship between thrust pad temperature and thrust load (Courtesy of Kingsbury, Inc.)

greater the thrust load (P.S.I.), the smaller the oil film and the greater the effect of oil viscosity on oil flow and heat removal. Based on a maximum load of 500 psi, it can be seen from Figure 9.39 that a turbo-compressor thrust bearing pad temperature trip setting should be between 260° and 270°F.

Other than to support the rotor in an axial direction, the other function of the thrust bearing is to continuously maintain the axial position of the rotor. This is accomplished by locating stainless steel shims between the thrust bearing assembly and compressor axial bearing support plates. The most common thrust assembly clearance with the thrust shims installed is 0.011 – 0.014. These values vary with thrust bearing size. The vendor instruction book must be consulted to determine the proper clearance.

The following procedure is used to assure that the rotor is properly positioned in the axial direction.

1. With thrust shims removed, record total end float by pushing rotor axially in both directions (typically .250" – .500").
2. Position rotor as stated in instruction book.
3. Install minimum number of stainless steel thrust shims to limit end float to specified value.*

*An excessive number of thrust shims act as a spring resulting in a greater than specified axial clearance during full thrust load conditions.

Proper running position of the rotor is critical to obtaining optimum efficiency and presenting axial rubs during transient and upset conditions (start-up, surge, etc.)

Impeller thrust forces

Every reaction type compressor blade set or impeller produces an axial force towards the suction of the blade or impeller. Refer to Figure 9.40.

Note that the pressure behind the impeller is essentially constant (50 psi), but the pressure on the front side of impeller varies (from 50 psi to 40 psi) because of the pressure drop across the eye labyrinth. Every impeller in a multistage compressor will produce a specific value of axial force towards its suction at a specific flow rate, speed and gas composition. A change in any or all of these parameters will produce a corresponding change in impeller thrust.

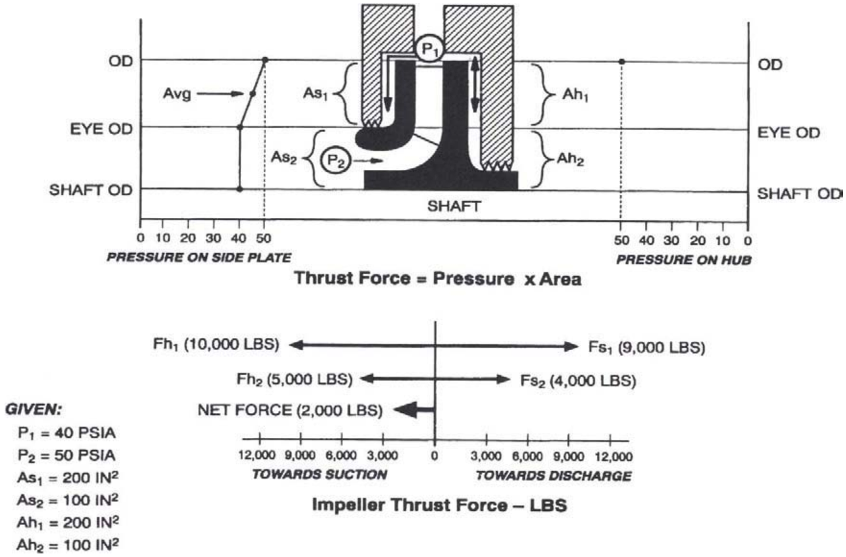


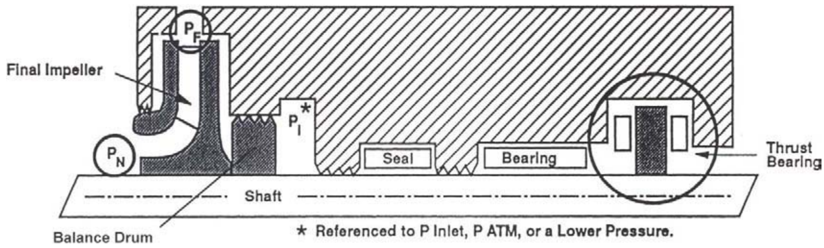
Figure 9.40 Impeller thrust force

Rotor thrust balance

Figure 9.41 shows how a balance drum or opposed impeller design reduces thrust force.

The total impeller force is the sum of the forces from the individual impellers. If the suction side of the impellers is opposed, as noted in Figure 9.41, the thrust force will be significantly reduced and can approach 0. If the suction side of all impellers are the same (in series), the total impeller thrust force can be very high and may exceed the thrust bearing rating. If this is the case, a balance drum must be mounted on the rotor as shown in Figure 9.41. The balance drum face area is varied such that the opposing force generated by the balance drum reduces the thrust bearing load to an acceptable value. The opposing thrust force results from the differential between compressor discharge pressure (P_F) and compressor suction pressure (P_1) since the area behind the balance drum is usually referenced to the suction of the compressor. This is accomplished by a pipe that connects this chamber to the compressor suction. This line is typically called the 'balance line'.

It is very important to note that a balance drum is used only where the thrust bearing does not have sufficient capacity to absorb the total compressor axial load. And the effectiveness of the balance drum depends directly on the balance drum seal. Fail the seal, (open clearance significantly) and thrust bearing failure can result.



Total Impeller Thrust (LB) = Σ Individual Impeller Thrust
Balance Drum Thrust (LB) = (P_F - P_I) x (Balance Drum Area)
Thrust Bearing Load (LB) = Total Impeller Thrust – Balance Drum Thrust

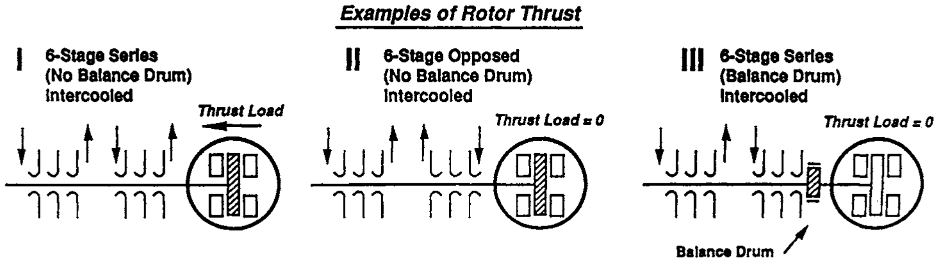


Figure 9.41 Rotor thrust force

A common misunderstanding associated with balance drum systems is that a balance drum always reduces the rotor thrust to zero. Refer to Figure 9.42 and observe that this statement may or may not be true depending on the thrust balance system design. And even if it is, the thrust is zero only at one set of operating conditions.

Figure 9.42 shows a rotor system designed four (4) different ways. Note how the thrust **always** changes with the flow rate regardless of the design. Another misconception regarding thrust balance systems is the normal or 'active' direction of thrust. In many cases, the active thrust is assumed to always be towards the suction of the compressor. Observing Figure 9.42, it is obvious that the 'active' direction can change when the turbo-compressor has a balance drum or is an opposed design. It is recommended that the use of active thrust be avoided where possible and that axial displacement monitors be labeled to allow determination of the thrust direction at all times.

Please refer to Figure 9.43 which shows a typical thrust displacement monitor.

These monitors detect thrust position by targeting the shaft end, thrust collar or other collar on the rotor. Usually two or three probes (multiple voting arrangement) are provided to eliminate unnecessary compressor trips. The output of the probes is noted on the monitor as

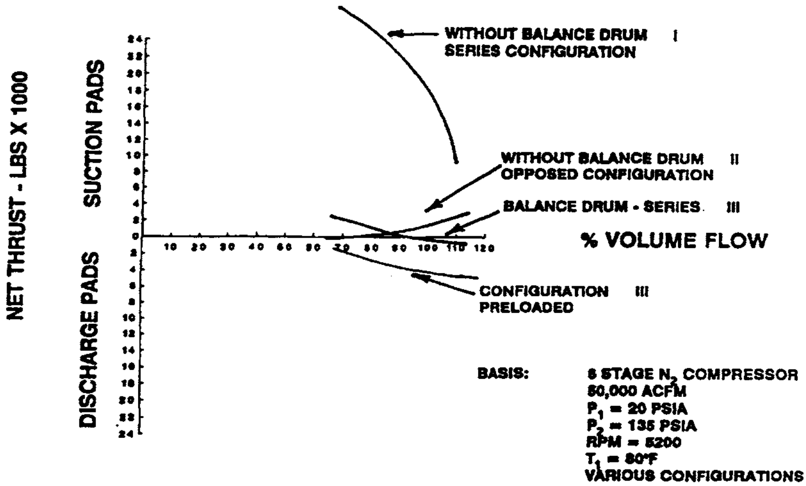


Figure 9.42 Net thrust load vs. % flow

either + (normal) or – (counter). However, this information gives no direct indication of the axial direction of the thrust collar. The following procedure is recommended:

1. With compressor shutdown, push rotor towards the suction and note direction of displacement indicator.
2. Label indicator to show direction towards suction of compressor.

Knowing the actual direction of the thrust can be very useful during troubleshooting exercises in determining the root cause of thrust position changes.

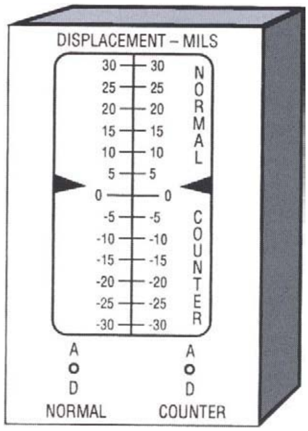


Figure 9.43 Axial thrust monitor

Thrust condition monitoring

Failure of a thrust bearing can cause long term and possibly catastrophic damage to a turbo-compressor. Condition monitoring and trending of critical thrust bearing parameters will optimize turbo-compressor reliability.

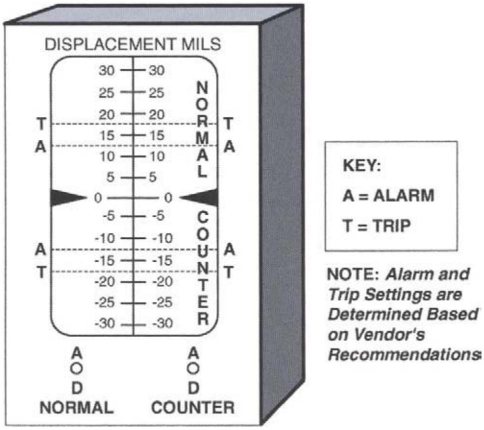


Figure 9.44 Axial displacement condition monitoring

The critical thrust bearing condition monitoring parameters are:

- Rotor position
- Thrust pad temperature
- Balance line ΔP

Rotor position is the most common thrust bearing condition parameter and provides useful information regarding the direction of thrust. It also provides an indication of thrust load but does not confirm that thrust load is high. Refer to Figure 9.44.

All axial displacement monitors have pre-set (adjustable) values for alarm and trip in both thrust directions. Typically, the established procedure is to record the thrust clearance (shims installed) during shutdown and set the alarm and trip settings as follows:

$$\text{Alarm} = \frac{\text{clearance}}{2} + 10 \text{ mils (each direction)}$$

$$\text{Trip} = \text{alarm setting} + 5 \text{ mils (each direction)}$$

The above procedure assumes the rotor is in the mid or zero position of the thrust clearance. An alternative method is to hand push the rotor to the assumed active position and add appropriate values for alarm and trip.

The writer personally recommends the first method since an active direction of thrust does not have to be assumed.

As noted, axial displacement monitors only indicate the quantity of thrust load. False indication of alarm or even trip settings can come from:

- Compression of thrust bearing components
- Thermal expansion of probe adaptors or bearing brackets
- Loose probes

It is strongly recommended that any alarm or trip displacement value be confirmed by thrust pad temperature if possible prior to taking action. Please refer back to Figure 9.39 and note that the thrust pad temperature in the case of thrust pad overload is approximately 250°F. If an axial displacement alarm or trip signal is activated observe the corresponding thrust pad temperature. If it is below 220°F, take the following action:

- Observe thrust pads. If no evidence of high load is observed (pad and back of pad) confirm calibration of thrust monitor and change settings if necessary.

The last condition monitoring parameter for the thrust system is balance line pressure drop. An increase of balance line ΔP will indicate increased balance drum seal leakage and will result in higher thrust bearing load. Noting the baseline ΔP of the balance line and trending this parameter will provide valuable information as to the root cause of a thrust bearing failure. In many field case histories, the end user made many thrust bearing replacements until an excessive balance drum clearance was discovered as the root cause of the thrust bearing failure. It is a good practice to always check the balance line ΔP after reported machine surge. Surging will cause high internal gas temperatures which can damage the balance drum seal.

This completes the section on thrust forces. An example of a balance drum calculation is given below.

Balance drum audit exercise

Title: Determining the thrust load of a three (3) stage compressor and the effect of different balance drum diameters.

Required:

I. Calculate rotor thrust for example assuming no balance drum.

II. Calculate rotor thrust assuming balance drum is installed on rotor.

Task 1 Given:

- Rotor and compressor internals shown in Figure 9.45

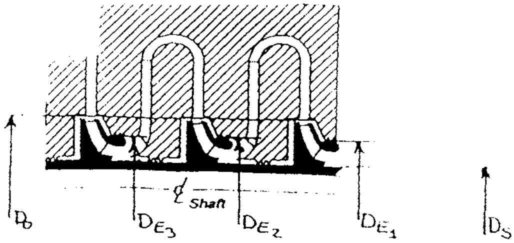


Figure 9.45

- D_0 of each impeller = 40in. diameter
- D_E of each impeller as follows:
  D_{E1} = 20 in. diameter
  D_{E2} = 18 in. diameter
  D_{E3} = 16 in. diameter
- D_S of shaft = 8 in. diameter

Task 1 Find: Rotor thrust for the following data.

Stage	1		2		3	
	P_1	P_2	P_1	P_2	P_1	P_2
56,000 acfm	20	27	27	38	38	50
51,000 acfm	20	30	30	43	43	57
42,000 acfm	20	33	33	47	47	62

Note: all pressures in psia

Task 1 Procedure:

1 Relationship:
Individual impeller thrust:

$$F_{T_N} = [P_{2_N} - P_{1_N}] \bullet [(\pi/4) \bullet [(D^2_{E_N} - D^2_S)]$$

Where: F = Impeller thrust force (lb)
N = Impeller stage
D_E = Impeller eye diameter (inches)
D_S= shaft diameter inches

Stage 1 $F_{T_1} = [P_{2_1} - P_{1_1}] \bullet \pi/4 \bullet [(D^2_{E_1} - D^2_S)]$

$2639_1 = [(30) - (20)] \bullet \pi/4 \bullet [(20)^2 - (8)^2]$

Stage 2 $2654_2 = [(43) - (30)] \bullet \pi/4 \bullet [(18)^2 - (8)^2]$

Stage 3 $2111_3 = [(57) - (43)] \bullet \pi/4 \bullet [(16)^2 - (8)^2]$

Note: obtain values of P_{2_N}, P_{1_N} from stage calculations.

2 Relationship:
Total impeller thrust

$$F_{TOTAL} = \sum_1^N F_{T_N}$$
$$= F_{T_1} + F_{T_2} + F_{T_3}$$

Where + = thrust towards impeller suction

Where – = thrust towards impeller discharge

$7404 \text{ LB} = 2639_1 + 2654_2 + 2111_3$

Note: This relationship assumes that impeller discharge pressure is equal on the hub (backside) and eye (front side) of each impeller. Due to disc friction (windage) and impeller seal leakage this is not exactly the case. Therefore, the actual impeller thrust towards the suction of each impeller is slightly greater.

Task 2 Find: Rotor thrust for 51,000 acfm flow and P_{2_N}, P_{1_N} values in Task 1 assuming an 18" balance drum is installed on rotor.

Plot results on curve on Figure 9.47.

Task 2 Given:

- Rotor and compressor internals shown below.

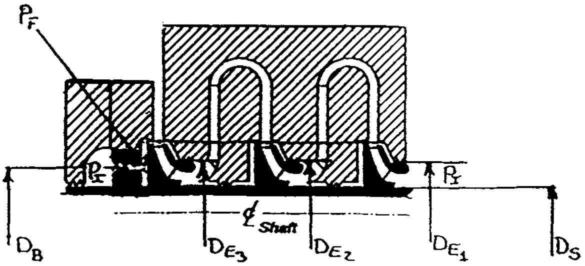


Figure 9.46

- D_0 of each impeller = 40in. diameter

  Where: D_B = Balance drum = 18"

Task 2 Procedure:

1 Relationship:
$F_{BAL\ DRUM} = (P_F - P_S) \bullet (A_{BAL\ DRUM})$

$7555 \text{ LB} = [(57) - (20)] \bullet [\pi/4 ((18)^2 - (8)^2)]$

Where: P_F = Final compressor discharge pressure
P_S = Compressor suction pressure
$A_{BAL\ DRUM} = \pi/4\ (D^2_{BD} - D^2_S)$

2 Relationship:

$F_{\text{THRUST BEARING}} = F_{\text{IMPELLERS}} - F_{\text{BALANCE DRUM}}$

151 (lb) = 7404 (lb) −7555 (lb)

Plot values on curve on Figure 9.47.

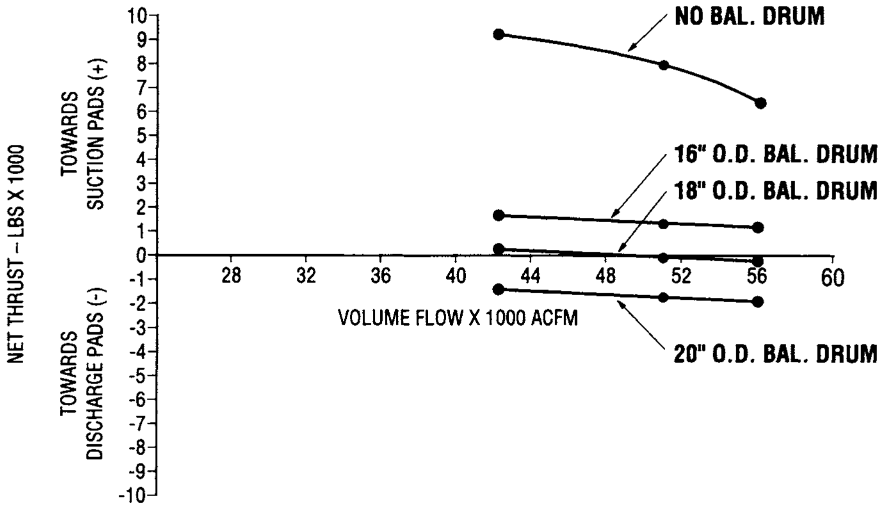


Figure 9.47 Compressor Thrust vs. inlet flow for no balance drum and various balance drum diameters

Design Audit Example 2
Lube system design tutorial

The lube system design audit objective is to confirm the scope of supply, component design and correct manufacture of the specified system. Two factors that play a great part in attaining a reliable auxiliary system are communication and revenue. Frequently auxiliary systems are subcontracted by the original equipment manufacturer to a speciality auxiliary system facility. The communication between original equipment manufacturer (OEM) and sub-vendor is not always efficient. After receipt of an order to manufacture an auxiliary system, confirmation of scope of supply should be obtained with the end manufacturer of the system present.

The other factor involved concerns the cost of the critical equipment and the price charged for that equipment. In the real world of competition, original equipment vendors many times sell the equipment for less than originally anticipated. Therefore, costs are high and profit decreases. In an effort to minimize cost, sub-systems can suffer in terms of design and quality. OEMs will competitively select sub-vendors for auxiliary systems. Care must be taken to assure the selected sub-vendor is an experienced, quality shop.

This section then will deal with the major areas of system design, the component sizing audit, system manufacturing and factory testing.

Design audit agenda

In this section, we will be dealing with the specific areas important to the confirmation of auxiliary system design and manufacture. To assure maximum effectiveness of these reviews, it is recommended that a prior agenda, mutually agreed upon between OEM and user, be generated and supplied to both parties well in advance of any meetings. In addition to detailing subjects of the discussion, the agenda should also define the attendees of the meeting. A well defined meeting is still ineffective if the participants are not familiar with the subject or have a minimum amount of experience.

Confirmation of scope

For the reasons mentioned above, scope review approximately one to two months after auxiliary system order placement is recommended. The major areas of scope review are:

A. Schematic review

B. Data sheet review

C. Exceptions to specification

Schematic (P & ID) review

The original system schematic (P & ID) (console and unit) as contained in the equipment specification should be reviewed at this point to confirm all system logic and instrumentation is as specified. That is, the schematic should be reviewed in the framework of P&ID (process and instrument diagram). All comments should be noted and the system schematics corrected.

Data sheet review

The system data sheet should be thoroughly reviewed and be complete at this point to include specific component details and desired manufacturers of major components. This review goes both ways. That is, vendor required information and user information must be detailed and correct on the data sheets. Frequently utility information and site information is not complete. This absence can only lead to reliability and communication problems in the field. As with any meeting, detailed minutes should be kept and every effort be expended to resolve all open items prior to conclusion of meeting. Postponing decisions only creates inefficiencies.

Exceptions to specifications

All vendor exceptions to specifications must be reviewed and either be accepted or rejected. The final, mutually agreed to list of vendor exceptions should become part of the job specification.

Component sizing audit

A typical component sizing audit form is included in the back of this section. We will now review the major areas of this audit form and comment relative to the specific items.

System requirements

The first subject of discussion concerns confirmation of auxiliary system flow rates, pressures and heat loads required. This information determines the size of all major system components. It must be correct and not subject to modification during the design process of the equipment. The component sizing agenda should emphasize the need

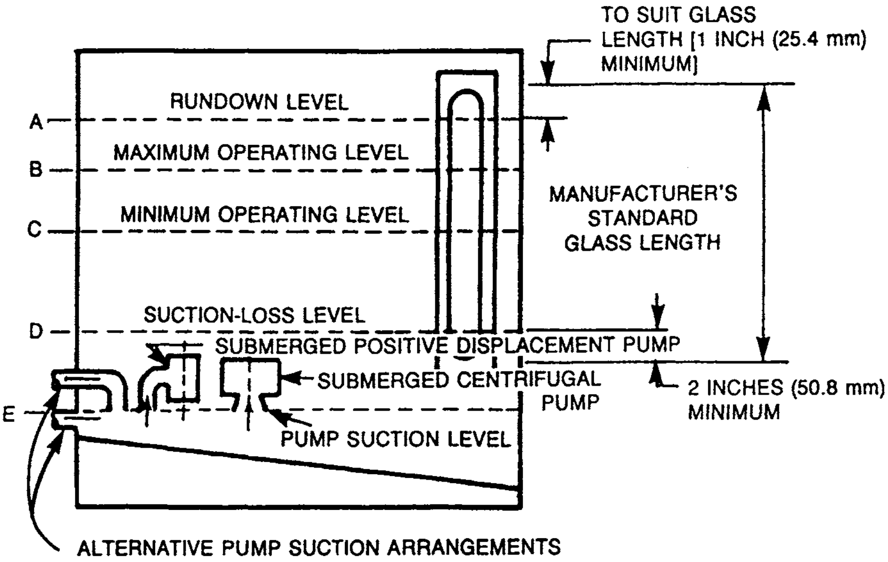


Figure 9.48 An auxiliary system reservoir

to have all required information furnished and confirmed by each critical equipment vendor. Attention is drawn to comparing values noted. If significant discrepancies appear, question them! Remember all critical equipment components are equivalent orifices and at a specified pressure will only pass a given flow. If the component oil flow specified is greater than the amount the components will actually pass, the excess oil will be bypassed back to the oil reservoir and could create overheating problems in the system. Conversely, if too low a value of component oil flow is specified, a system may continuously operate with both main and stand-by pump in operation since the capacity of the main pump will have been sized too small for the system.

Reservoir sizing, construction, and sub-component details

Refer to Figure 9.48 which is a schematic representation of an auxiliary system reservoir. Reservoir size and levels as noted in Figure 9.48 must be determined at this time. Size will be a function of system flow which previously will have been defined.

The height of the reservoir should be such that in its final field location, it will provide adequate gravity return from the main equipment.

The construction of the reservoir should be checked at this time. The original equipment vendor should have a reservoir drawing that details the reservoir internals available for review. Attention is drawn to the requirement that auxiliary return fluid should not be allowed to free fall to the surface of the liquid. All returns should be through stilling tubes or sloped troughs. It is also wise to confirm that internal design is proven and that the manufacturer has successfully designed similar reservoirs in the past. Accessibility for cleaning should be confirmed and the location of return connections and pump supply nozzles should be such that maximum residence time of system fluid is assured. Material of construction should be confirmed at this point and all details of the following reservoir sub-components reviewed:

A. Reservoir heater sizing calculations

B. Level control alarm

C. Connection locations and size

D. Additional instrumentation

Pump and driver sizing

Pump performance

Regardless of the types of pumps used, centrifugal or positive displacement, the performance curves should be reviewed at this point.

A. *Positive Displacement* – Positive displacement pumps, furnished without external timing gears, are mechanically sensitive to fluid viscosity. The performance curve should be checked at all operating points to confirm that adequate rotor separation is present at low fluid viscosities. If an operating point is at the end or within 20% of a pressure vs. flow curve at a low operating viscosity (50–60 SSU), the pump vendor should be contacted to confirm a correct selection has been made. Refer to Figure 9.49 for an example of this case.

B. *Centrifugal pumps* – Since centrifugal pump performance must be corrected for viscous fluid operation, pump sizing must confirm that the actual operating points are not close to the operating extremities of the corrected curve. That is, any operating point should not be less than 20% of pump best efficiency point nor be more than 110% of best efficiency point of the operating curve corrected for viscosity. Refer to Figure 9.50 for an example. Operation outside the stated boundaries, in addition to causing high revenue costs due to lower efficiency, can jeopardize the reliable operation of the pump.

Pump mechanical requirements

Pump data sheets must be checked at this point to confirm that proper pump case material design, bearings, seals and pump flushing arrangements are provided as specified. In addition, it is recommended that all pumps be factory tested prior to the auxiliary system test to confirm acceptable operation.

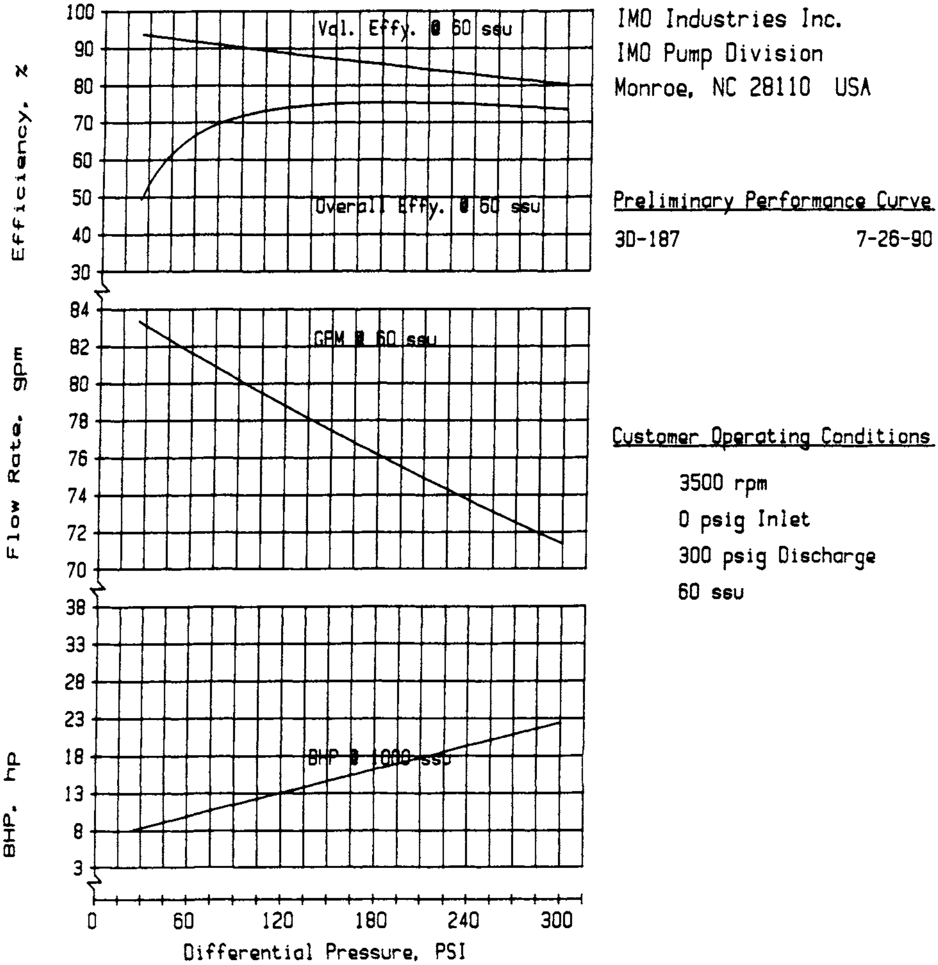


Figure 9.49 Screw pump performance (Courtesy of IMO Industries)

Pump unit couplings

Couplings should be selected for the maximum driver horsepower and include a sizing safety factor (usually 20–25%) above the maximum driver horsepower rating. Spacer couplings are recommended in order to provide ease of maintenance and minimize the necessity to remove a pump or driver while the critical equipment unit is operating. The type of coupling selected should be of high quality and reliability and provide a minimum of three years continuous operation. While either batch lube gear type couplings or dry flexible element types can be used, the latter types are preferred for their low maintenance requirements. Coupling material should be steel as opposed to cast iron

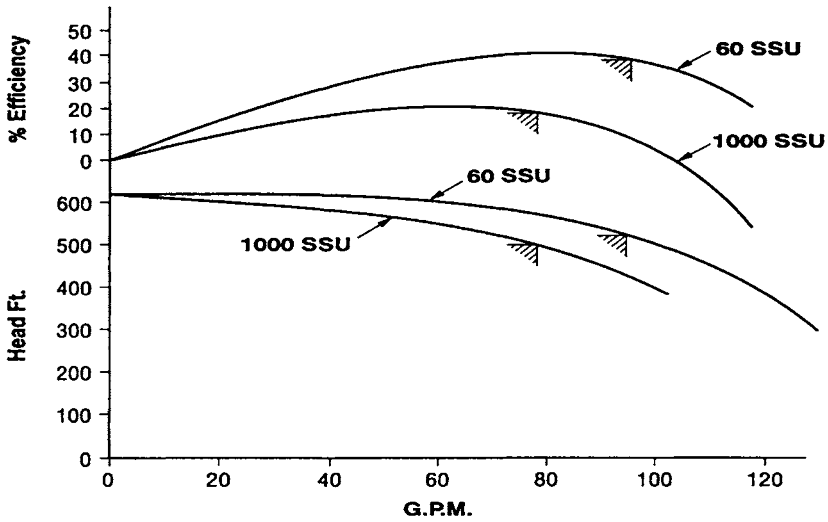


Figure 9.50 The effect of oil viscosity on centrifugal pump performance

to prevent breakage during removal or during extreme temperature changes (as during a fire). Flexible elements should be stainless steel.

The coupling shaft fit configuration and amount of shrink fit should be checked to confirm correct values.

Driver sizing

Driver sizing must be confirmed to assure adequate delivered horsepower during all operating conditions. Utility conditions to the drivers should be rechecked at this point to assure that values are as stated on data sheets. As an example, steam turbine data (inlet pressure and temperature and exhaust temperature) should be checked so that all conditions as stated will exist on site. Similarly, minimum starting voltage for motor drivers should be confirmed. Lower minimum starting voltage values than stated on data sheets will cause stand-by pump start time to be less than anticipated, shorten motor life, and could result in serious transient auxiliary pump start problems that could cause critical equipment shutdown.

Driver sizing must be confirmed with specification requirements such that driver horsepower equals pump horsepower times a specified service factor. Selection charts for expansion turbines should be checked and confirmation that proper standard size electrical drivers have been selected should be checked. In applications where viscous fluids are used, pump calculations for horsepower corrections at maximum fluid viscosity must be confirmed. Attention is drawn to realistic sizing of pumps and drivers concerning viscosity. If minimum site ambient is below 40°F for example, and a properly sized reservoir heater is furnished, there will not be a requirement for high viscosity operation if it is accepted that reservoir heater will bring the auxiliary fluid to a minimum pump starting temperature prior to pump operation. A permissive temperature switch could be installed to preclude the possibility of equipment start prior to acceptable temperature conditions.

Driver mechanical requirements

Data sheets for both main and auxiliary drivers should be checked to confirm proper mechanical design.

Motor drivers should be designed as specified with attention being paid to bearing design and motor housing design. Many smaller auxiliary systems have utilized aluminum frame motors in the past. Due to the high coefficient of thermal expansion of aluminum (double that of steel), these motors are subject to significant alignment changes with operating temperatures and could cause coupling misalignment problems.

Expansion turbine mechanical review should include governor system confirmation and safety system confirmation. Some safety valves furnished with small expansion turbines are not designed for positive shut off. This can result in operation of the turbine at lower speed once the equipment has been tripped. Most steam turbines presently operating in auxiliary systems, do not have speed indicators. To assure correct operating speed a stroboscope or hand-held tachometer, both of which can give inaccurate readings, are used. Particularly in the case of dynamic pumps, turbine speed setting is important to assure proper flow to the system. Therefore, any new installation incorporating expansion turbines should be equipped with speed indication.

Relief valve selection

Relief valve selection should be confirmed to qualify proper size, minimum accumulation (the pressure required over the valve setting to provide full flow) and chatter free operation. Relief valves should be located as close as possible to the pump discharge line to minimize the possibility of air entrainment in the line to the relief valve which can result in a delayed pump flow to the unit. This would be the case if the RV's were mounted on the reservoir a significant distance from the pump discharge line.

Control valve selection

Control valve data sheets for each control valve in the system should be available for review. Information furnished on control valve data sheets should be complete in terms of valve sizing, actuator selection and valve controller (if furnished).

Valve C_V – All operating valve coefficients (C_V's) should be stated on the control valve data sheet. That is, the normal C_V, maximum C_V and minimum C_V. These values should be compared with the selected valve internals to assure that all operating conditions fall within 10% to 90% of the maximum valve coefficient. Failure to confirm this can lead to valve instabilities. When reviewing valve coefficients, the system design must be reviewed (system schematic) since certain changes in the system could render the valve unstable.

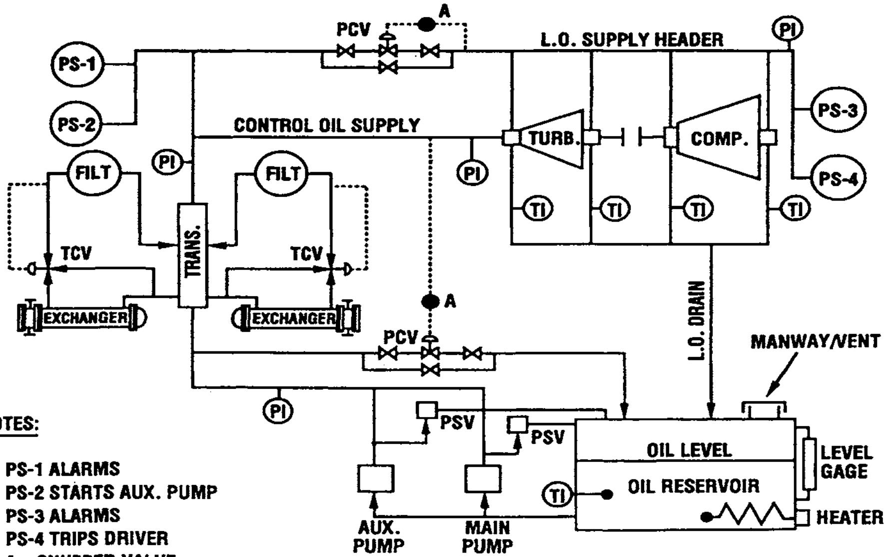
Bypass valve

For this application, the valve back pressure is atmospheric and the control valve differential depends on the condition of the auxiliary system cleanliness and any additional control valve setting (refer to the typical system schematic Figure 9.51).

C_v Minimum – The minimum valve coefficient in this application would be with a dirty filter (filer ΔP) and one pump operating.

C_v Maximum Normal – The normal valve coefficient in this application occurs with a clean system (minimum filter ΔP) and one pump operating.

C_v Maximum – The maximum valve coefficient would be with the main and auxiliary pumps operating and the minimum pressure drop across



NOTES:

1. PS-1 ALARMS
2. PS-2 STARTS AUX. PUMP
3. PS-3 ALARMS
4. PS-4 TRIPS DRIVER
5. A = SNUBBER VALVE

Figure 9.51 Typical lube oil supply system (Courtesy of ME Crane Consultant)

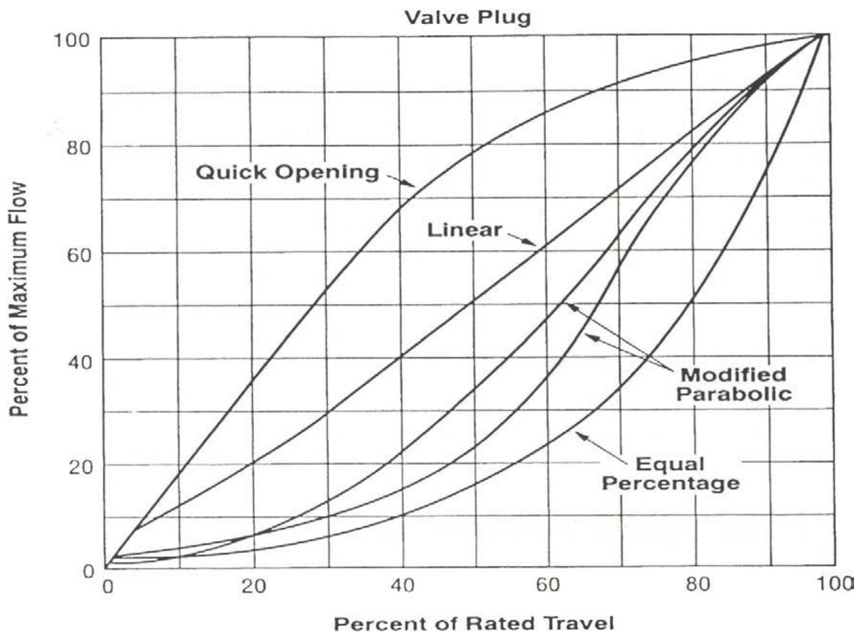


Figure 9.52 Control valve flow characteristics (Courtesy of Fisher Controls, Inc.)

the valve (clean filter). The maximum flow for this condition would be the normal bypass flow of the main pump plus the total flow of the auxiliary pump.

Attention is drawn to determining the characteristic of the valve curve for this application. The normal operating point would be approximately the minimum C_V therefore, a valve characteristic that results in a fairly significant (15–25%) valve travel for this small C_V would be desired (quick opening). Two pump operation (maximum C_V) is an abnormal case. Therefore the valve should be designed merely to pass this flow (refer to Figure 9.52) at 90% of the valve catalogue C_V.

Pressure reducing valve

In a centrifugal pump application, pressure reducing valves would experience minimum, normal and maximum C_V's similar to bypass valves with the exception that downstream valve pressure will change with increasing flow.

When pressure reducing valves are used to reduce pressure levels (control oil pressure to lube oil pressure, seal oil pressure to lube oil pressure, etc.) the valve C_V should be selected for all possible operating cases as mentioned above for bypass valves. Care should be taken to assure *all possible operating cases* are considered.

Temperature control valves

The temperature control valve C_v will remain relatively constant under all auxiliary system conditions. In the case of a two way valve however, the valve must be sufficiently sized such that the full flow pressure drop across the valve is less than the clean pressure drop across the cooler in parallel with this valve.

Differential pressure control valves and level control valves are sized and examined in the same manner as described above for bypass and pressure reducing valves. Viscosity corrections are required for all control valve sizing when operating viscosities exceed 50 Sabolt Universal Seconds (50 SSU). Significant size increases are required for high viscosity operation approaching 1,000 SSU on the order of 1½ to 2 times the selected valve coefficient without viscosity considerations.

Control valve sensing line snubber devices (dampers)

If these devices are furnished, a review of device design and confirmation of proper installation should be confirmed. Such devices provide unrestricted flow in one direction and restricted flow in another direction. The total auxiliary system operation must be reviewed in this light to confirm proper installation and orientation.

Supply pipe velocity checks

The pump header, interconnecting console pipe, and piping to the unit should all be checked for proper fluid velocity. Typical velocity values in auxiliary system supply pipes are on the order of four to six feet per second velocity. Velocity is derived from the following equation for incompressible flow.

Q ft/min = AXV

where: A = Internal pipe area (ft^2)
V = Fluid velocity (ft/sec)

Charts for standard pipe sizes and schedules are available to determine velocities (see Figure 9.53). Note that schedule 80 is usually used for carbon steel pipe below 2". Schedule 40 is used above 2". For stainless steel pipe, schedules 10 and 20 are used respectively.

Typical drain line velocities are ½ to ¼ feet per second. Attention is drawn to properly sizing drain pipes for installations where critical equipment is significantly elevated above reservoir. All drain pipes should be sized with adequate area to preclude excessive air being entrained with the oil to promote drainage back to the reservoir. An additional consideration for supply headers at the unit is that supply headers are frequently sized for one standard pipe dimension. In the

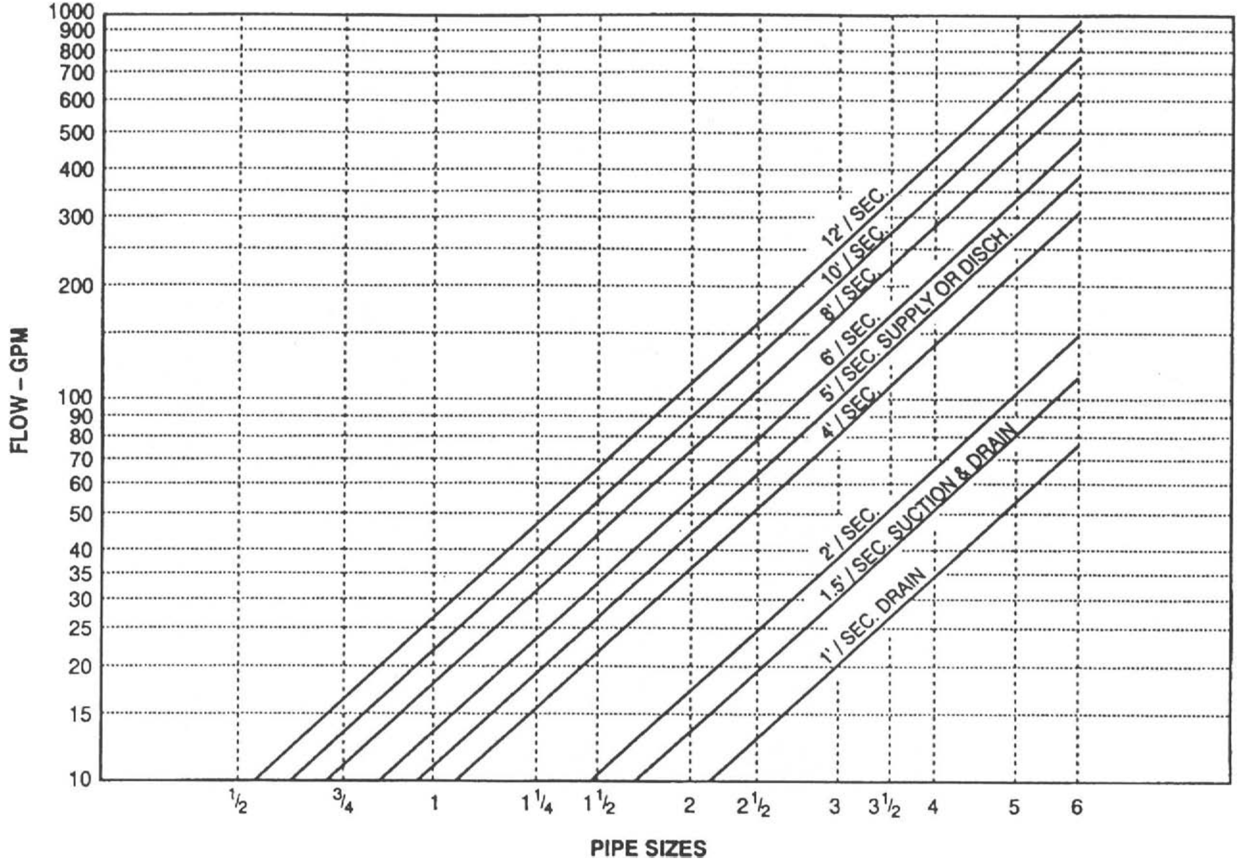


Figure 9.53 Typical pipe sizing chart

case of large critical equipment units (two or three bodies and driver), the amount of oil from the entrance to the header to the last component decreases significantly. In an effort to minimize pipe size, many vendors size headers small. Therefore, pressure drop in the header is excessive and requires a higher supply header pressure than anticipated in the unit design. Improper sizing of critical equipment supply headers could cause excessive flow across equivalent orifices (bearings) thereby requiring all flow of the main pump and necessitating the operation of the auxiliary pump.

Transfer valve sizing

Transfer valve configuration and materials of construction should be confirmed at this point. Transfer valve design should be checked to confirm tight shutoff.

Cooler sizing

The cooler data sheet should be reviewed to confirm correct duty, confirmation of correct of cooling media details, fouling factors and materials of construction.

Filter sizing

Filter information should be reviewed to confirm correct filter sizing for the normal and the maximum viscosity case (in the case of viscous fluids). Additionally, maximum filter collapse pressure, internal filter cartridge design and cartridge sealing design should also be reviewed at this time.

Instrumentation

All instrumentation should be reviewed to confirm proper selection, materials of construction and proposed installation locations. All instrumentation loops should be reviewed to assure that critical instrumentation can be calibrated and maintained while unit is in operation.

Console layout and component arrangement

Having confirmed the acceptable component sizing and selection, the console layout and arrangement of components must be reviewed. Methods of this review incorporate either the review of outline drawings of the proposed arrangement or CAD 3D drawings, a model review or a CAD 3D drawing review. Many vendors and users have found that models aid greatly in understanding and reviewing maintenance accessibility and layout considerations.

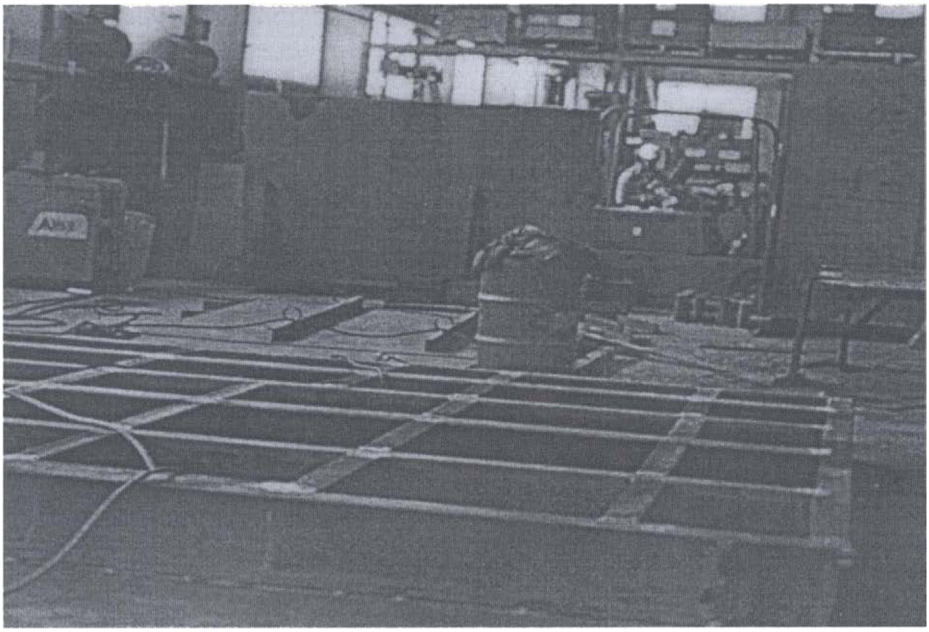


Figure 9.54 Console baseplate construction (Courtesy of Fluid Systems)

Console construction

Auxiliary equipment consoles or modules house most of the components present in the auxiliary systems. Their construction should be reviewed to assure proper stiffness and facilities for installation on site. Many horizontal consoles are constructed in a flexible manner that can result in bending or excessive pipe strains introduced into components during shipment and at installation. It is suggested that full length cross members be positioned as a minimum under pumps, coolers and filters on the equipment baseplate (see Figure 9.54). If the baseplate is to be grouted in the field, grout and vent holes should be specified and reviewed for accessibility to pore grout when equipment is installed on the baseplate.

Maintenance accessibility

Since equipment must be maintained and calibrated while the auxiliary system is in operation, it is important to provide ample personnel space such that equipment can be maintained safely and reliably without damage to surrounding components. A rule of thumb is to provide approximately one meter of space around components for accessibility. Note that this is with the utility lines installed. The review of equipment on a model CAD 3D drawing or an outline should be made considering installation of all utility lines that will be installed in the field.

On-line testing and calibration accessibility

Considering that many components (pumps, drivers, coolers, filters, control valves, instrumentation) will be tested and calibrated with equipment in operation, accessibility for this operation must be considered.

In addition to reviewing the vendor manufactured skids, the placement of all skids in the field must be reviewed for accessibility. Consideration of the skid arrangement only to be complicated by installation against a column or wall in the field will not obtain the objectives of total accessibility.

Utility supply arrangement

Care should be given to the routing of all utility (conduits, steam lines, water lines) supply lines in order to maximize accessibility to the critical equipment auxiliary systems.

Considerations for component disassembly

All components must be able to be dissembled quickly, easily and safely while the unit is operating in the field. To meet this requirement, sufficient space around the auxiliary console must be available for such exercises as cooler bundle removal, filter cartridge removal and auxiliary or main driver removal. In addition, consoles are frequently installed in congested areas and lifting arrangements should be reviewed beforehand to confirm components can be removed in a safe and easy manner.

This completes comments concerning the component sizing audit. All changes made during this meeting should be documented and followed up to guarantee that final component design and arrangements are as specified and agreed to in this meeting.

Auxiliary system component sizing audit form

Applicable specifications

Critical equipment description

Schematic drawing numbers

Data sheet

I. System requirements

A. Oil requirements

APPARATUS		FLOW RATE				GAGE PRESSURE (At Equipment)		ΔP (At Equipment)		HEAT LOAD	
		GPM	L/min.	GPM	L/min.	PSI	bar	PSI	bar	BTU/HR	kw
COMPRESSOR	THRUST BEARING										
	SUCTION END JOURNAL										
S.O.	DISCHARGE END JOURNAL										
COMPRESSOR SEALS (TOTAL)	NORMAL										
	MINIMUM										
	MAXIMUM										
Leakage ____ GPD (___ L/day)											
COMPRESSOR	THRUST BEARING										
	SUCTION END JOURNAL										
S.O.	DISCHARGE END JOURNAL										
COMPRESSOR SEALS (TOTAL)	NORMAL										
	MINIMUM										
	MAXIMUM										
Leakage ____ GPD (___ L/day)											
GEAR											
S.O.											
TURBINE	THRUST BEARING										
	STEAM END JOURNAL										
S.O./P.R.	EXHAUST END JOURNAL										
GOVERNOR											
SERVO MOTOR	NORMAL										
SERVO MOTOR	MAXIMUM										
TRIP & THROTTLE VALVE											
TURNING GEAR											
MOTOR	OUTBOARD END BEARING										
S.O.	COUPLING END BEARING										
NON RETURN VALVE											
CONTINUOUS LUBE COUPLINGS(S) TOTAL											
TOTALS											

Figure 9.55 Auxiliary system component sizing audit form

I.B. System requirements

1. Total pump flow = ________ x equipment flow (I_a)
   (Positive displacement pump) = ________

   Total pump flow = ________ (total flow in I_a)
   (Centrifugal pump)

2. Bypass flow (positive displacement pump) = (1) – I_a total flow

   = ________ – ________

   = ________________

3. Total head load (from I_a) = ____________ BTU/HR

4. Pump discharge pressure

Viscosity (SSU)	60	1000
A. Lube oil pressure (at equipment)	______	______
B. Elevation ΔP	______	______
C. Pipe ΔP	______	______
D. Valve ΔP	______	______
E. Cooler ΔP	______	______
F. Filter (clean) ΔP	______	______
G. Miscellaneous ΔP	______	______

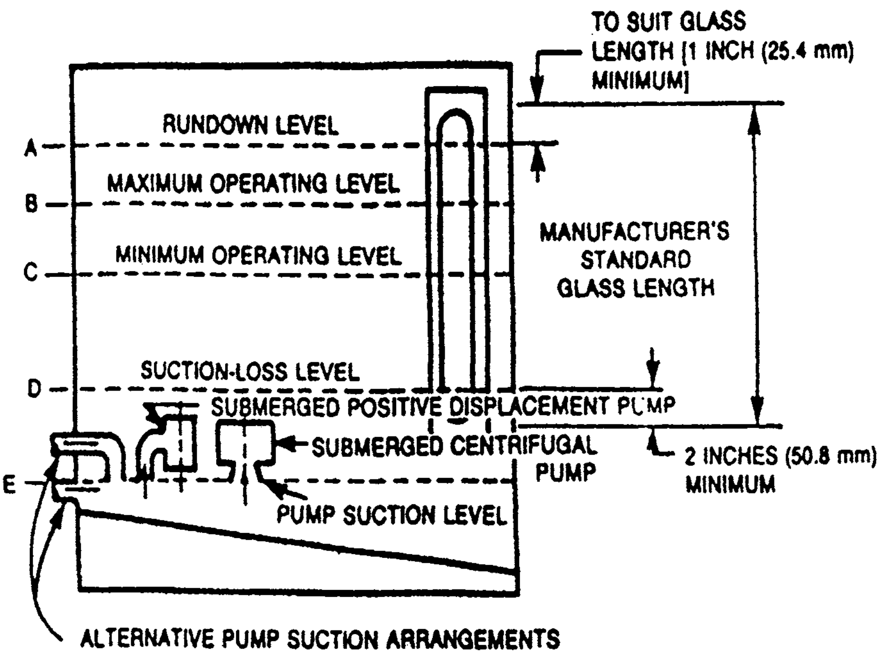


Figure 9.56 Reservoir levels and oil level glass details

Pump discharge press (Add A through G)	______PSI	______PSI

Note: If system is combined with seal and/or control oil, add highest value to determine pump discharge pressure.

II Component requirements

Confirm sizing as started below and check data sheet and specific requirements for each component.

A. Pump selection

	Positive displacement main/auxiliary	Centrifugal main/auxiliary
1. Pump type	______	______
2. Make	______	______
3. Model	______	______
4. *Speed	______	______
5. Disch. Press @ 60 SSU (rated)	______	______
6. Disch. Press @ Max SSU	______	______
7. Rated flow @ 60 SSU	______	______
8. Flow @ Max SSU	______	______
9. Flow @ relief valve pres (positive displacement pump only)	______	______
10. Rated BHP	______	______
11. Max. BHP (@ R.V. and max. viscosity)	______	______
12. NPSH available	______	______
13. NPSH required	______	______
14. Suction lift (if pumps are mounted above fluid level)	______	______

*If steam turbine driver is used, it is recommended that speed should be 2 pole (3600/3000 RPM) motor speed to minimize steam rate.

B. Coupling selection

	Main	Auxiliary
1. Pump	______	______
2. Coupling model	______	______
3. Size	______	______
4. Driver max. HP	______	______
5. HP/100 RPM	______	______
6. Coupling HP/100 RPM	______	______

Note: Confirm appropriate coupling service factor is used. Rotary (P.D.) pumps require a higher service factor.

C. Driver selection

		Main	Auxiliary
1.	Service	______	______
2.	Type	______	______
3.	Speed	______	______
4.	Pump max. HP	______	______
5.	Driver rated HP (= 1.1 x pump max. HP)	______	______
6.	Driver normal HP (@60 SSU)	______	______
7.	Turbine steam rate (max/rated)	______	______
8.	Steam quantity @ minimum steam energy condition LB/HR	______	______
*9.	Driver starting time 0 RPM-rated speed	______	______

Note: Confirm sufficient steam is available at minimum energy conditions.

*Calculated for minimum energy conditions (minimum steam energy or motor minimum starting voltage) and pump rated conditions. If greater than three (3) seconds, accumulator(s) should be used.

D. Relief valve selection (Positive displacement pumps only)

1. Pump max. discharge pressure at max. viscosity = __________
2. Relief valve pressure = 1.1 x D1 or 25 PSI. greater, whichever is higher

   Relief valve type (modulating preferred) = __________

   Model = __________

   Set pressure = __________

   Overpressure (pressure to pass full flow) = __________

   Normal leakage (valve closed) = __________

E. Reservoir sizing (based on rectangular tank) per API 614

1. Normal flow (GPM) = __________
2. Retention time (minutes) = __________

   2A Capacity = (1) x (2)

   Confirm size

3. Reservoir length and width (inches) = ________ , ________
4. Capacity/inch of height $= \dfrac{(3)}{231 \text{ in.}^3\text{/gal}}$

   = ______ gal/inch

5. Level E (pump suction level) = ________ in. above grade
6. Level D (suction loss level) = (5) + level required to maintain prime

   = ________

7. Level C = (6) + 5 (minutes) x(1)

   Note: 5 minutes = working time

   Working capacity (volume between levels C & D) *or* level C =

   $$\frac{8\text{ (min)} \times (1)}{(4)} + \text{tank bottom height above grade}$$

   Note: 8 minutes = retention time

   Retention capacity = volume between bottom of tank and level C.

8. Level B = Highest level of oil during operation (approximately 1 minute retention time)
9. Level A = Highest level oil can reach
   = Level B + capacity contained in all components that drain back to the reservoir ÷ (4)

   Note: This quantity should also include allowance for interconnecting piping and any overhead tanks.

10. Minimum reservoir free surface area:

    = 0.25 $ft.^2$/gpm of normal flow

    = 0.25 x (1)
    = ________ ft^2

    Confirm reservoir internals, material, etc. meet data sheet and specifications required. Review reservoir internal drawing.

F. Reservoir heating requirements

Type: Electric Steam

Requirements

Time to head oil from _______ °F to _______ °F = _______ hours

1. Calculated heat load = ________ BTU's
   (minus reservoir heat loss)

2. Heater size BTU/HR = $\frac{\text{(F1)}}{\text{Total time allowed (hours)}}$

3. Electric heater max. watt density = _______

   Note: Confirm if heaters can be removed without draining reservoir.

G. Supply pipe velocity

Maximum velocity 4–6 ft/sec.

Maximum console supply pipe velocity = ______________ft/sec.

Maximum unit supply pipe velocity = ______________ft/sec.

H. Control valve sizing

H1. Bypass (back pressure) valve

1.1	Type: self acting, pneumatic or electric controller		__________
1.2	Make		__________
1.3	Model		__________
1.4	Action – Direct or Reverse		__________
1.5	Valve plug type		__________
1.6	Failure mode		__________
1.7	Actuator size		__________
1.8	Actuator force available/force required		__________
1.9	Maximum valve C_V	=	__________
1.10	Operating C_V min. (one pump dirty system)	=	__________
1.11	Operating C_V max. (two pumps clean system)	=	__________

Note: Operating C_V's should be between 10% – 90% of valve max. C_V.

Sensing line pulsation snubber required? If so, confirm proper orientation. Confirm fast response is to *open or close* valve.

H2. Transfer valve (s)

2.1 Make ____________

2.2 Model ____________

2.3 Size ____________

2.4 Plus type – taper, straight, globe ____________

2.5 Lifting jack required? ____________

2.6 Tight shut-off required? ____________

2.7 Max ΔP on changeover ____________

H3. Temperature control valve(s)

3.1 Make ____________

3.2 Model ____________

3.3 Size ____________

3.4 Normal flow ____________

3.5 Temperature range ____________

3.6 Valve max operating C_V ____________
(if 2-way valve, C_V must be based on clean cooler)

3.7 Valve maximum C_V ____________

Note: Butterfly type valve often used for 2-way applications.

H4. Pressure reducing valve

4.1 Type: self acting, pneumatic or electric ____________

4.2 Make ____________

4.3 Model ____________

4.4 Action-direct or reverse ____________

4.5 Valve plug type ____________

4.6 Failure mode ____________

4.7 Actuator size ____________

4.8 Actuator force ____________

4.9 Maximum valve C_V = ____________

4.10 Normal valve operating C_V = ____________
(unit at operating speed)

4.11 Minimum valve operating C_V = ____________
(unit at rest – oil system on)

I. Cooler sizing

Type	Shell and tube	Air (fin fan)
1. Twin or single	________	________
2. Make	________	________
3. Model	________	________
4. Size	________	________
5. Heat load btu/hr	________	________
6. Oil side ΔP clean (psi)	________	________
7. Fouling factor (total)	________	________
8. Oil flow (gpm)	________	________
9. Water quantity (gpm)	________	

J. Filter sizing

1. Make	________		
2. Model	________		
3. Type – surface	________	depth	________
4. Normal flow (gpm)	________		
5. Max. flow (gpm)	________		
6. Filtration (microns)	________		
7. Clear filter ΔP max.	________		
8. Cartridge material	________		
9. Type end seals	________		
10. Cartridge-single or multiple	________		
11. Cartridge center tube material	________		
12. ΔP at max. viscosity	________		
13. Collapse pressure	________		
14. Number of cartridges	________		
15. Gpm per cartridge	________		

K. Switches or transmitters

Confirm proper range, type, materials and maximum deadband (change in actuation point) of each switch. Confirm proper selection of transmitters.

L. Gauges

Confirm proper range, type, material of each pressure, differential pressure, temperature and level gauges.

M. Accumulator sizing

1. Type: bladder _______ or direct acting _______
2. System flow (gpm) = _______
3. System transient time (sec.) = _______
4. Capacity of fluid required = $\dfrac{(2) \times (3)}{60}$ = _______ Gallons
5. System pressure below which accumulator begins to drain (PSIA) = _______
6. Precharge pressure (PSIA) _______
7. Proposed accumulator internal volume (approximately 90% of normal size) = _______
8. Actual fluid capacity per accumulator = _______

   $$(7) \times \left[1 - \left(\frac{(6)}{(5)}\right)\right] = \_\_\_\_\_\_\_$$
9. Precharge type: manual, self contained, automatic _______

N. Additional tank sizing and construction confirmation

Overhead rundown (lube)

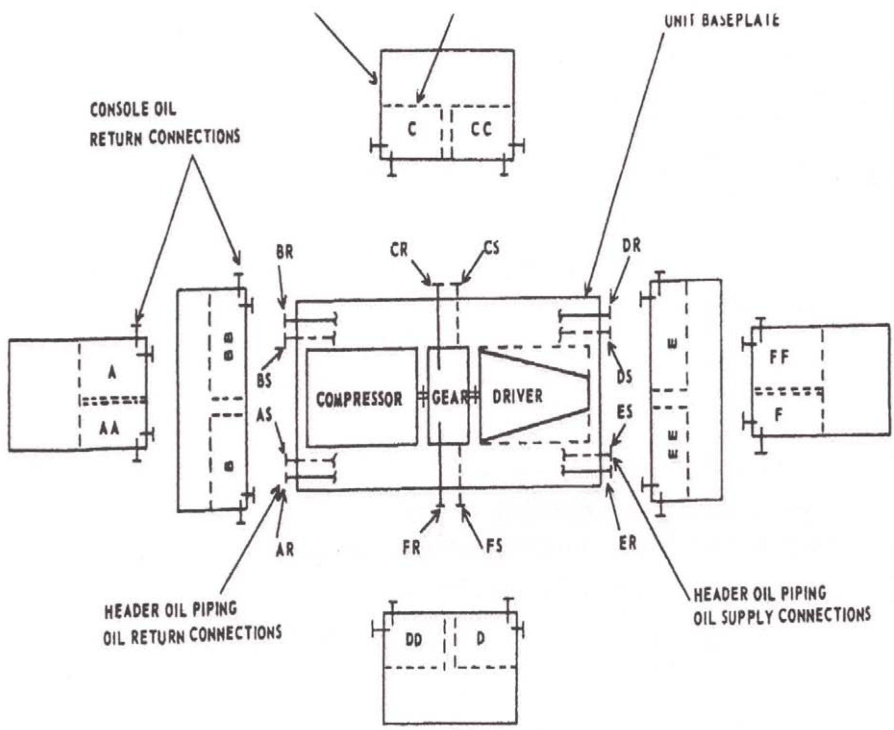
Overhead (seal)

Degassing tank(s)

These tanks should be checked against specifications data sheets for proper capacity, construction and ancillaries.

O. Piping, vessel, flange and component material

Refer to Figure 9.57 and finalize all connection locations.



AQ. Standard console location relative to unit (identify by letter)

Normal arrangements	☐A	☐B	☐C	☐D	☐E	☐F
Inverted arrangements	☐AA	☐BB	☐CC	☐DD	☐EE	☐FF
Header oil piping supply oil conn.	☐AS	☐BS	☐CS	☐DS	☐ES	☐FS
Header oil piping oil return conn.	☐AR	☐BR	☐CR	☐DR	☐ER	☐FR
Conns. to terminate at	☐ Edge of unit baseplate*	☐______________				

Figure 9.57 Connection orientation drawing (Courtesy of Elliott Company)

Management awareness workshop agenda example

Day 1

Session	Topic
1	Workshop introduction and overview ■ Objectives ■ Schedule ■ Agenda review ■ The benefits of improved reliability to machinists and operators ■ How machinists and operators can contribute to improved reliability ■ Important concepts (reliability, MTBF, machinery environment, bad actors)

2, 3, 4, 5, 6, 7	The root causes of machinery failures (the 5 why's)
	■ Introduction
	■ Process condition changes
	  ● Pumps
	  ● Steam turbines
	  ● Auxiliary system problems
	■ Installation errors
	■ Design problems
	■ Operating procedures
	  ● Pumps
	  ● Steam turbines
	■ Component wearout
	■ Auxiliary system problems

8	How to prevent machinery failures ■ Component function awareness ■ Component condition monitoring ■ Predictive maintenance techniques ■ Reliability is everyone's responsibility

Day 2

9, 10	Component condition monitoring and predictive maintenance
	■ The major components in any machine
	■ Rotor condition monitoring
	  ● Pumps
	  ● Steam turbines
	■ Journal bearing condition monitoring
	■ Thrust bearing condition monitoring
	■ Seal condition monitoring
	  ● Pumps
	  ● Steam turbines

11, 12	Steam turbine reliability factors (effective warm-up, cool down procedures) ■ Procedures ■ Monitoring
13, 14	Centrifugal pump reliability factors (hydraulic disturbances – cavitation, re-circulation) ■ Causes ■ Determination of root cause ■ Prevention
15, 16	Workshop summary ■ How 'learned principles' can be implemented ■ Action plan by attendees