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RELIABILITY ENGINEERING FOR FACILITY EFFECTIVENESS*

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Abstract

The problem of optimizing the effectiveness of a large scientific facility is considered in a discussion of the probabilistic, statistical, engineering, and managerial aspects of reliability.

Introduction

The goal of a modern, high-cost scientific endeavor such as an accelerator facility must be to produce results worthwhile to society. The product mix in this case is often discussed in terms of the proper ratio of pure vs. applied research. There is of course an even nearer term result in terms of economic benefit to the area where the project is located.

Progress toward the goal is perhaps summarized by the quality of the results and the cost effectiveness with which they were achieved. The total cost must consider initial and operating costs in terms of capital outlay and also in human and environmental terms. The problem is to maximize the quality and quantity of the results while minimizing the cost.

This is obviously an enormous task, and not one in which I can claim to be an expert. However, it is in this context that some of the more common ideas about reliability fit, and this is the context where some of the extensive multidisciplinary work currently being applied to the understanding and direction of large systems is most meaningfully discussed. So we are going to take a very condensed look at a variety of things which have an impact on facility effectiveness.

The facility systems of major interest here are those with the nature of long-term investment - the accelerator and main beam-lines. The experimental program has somewhat different aspects, particularly in the short-term nature of the individual experiments, and is not considered. Given the physics impetus, the problem of building an effective facility is largely one of engineering and education. The systems must be educated to run well, starting at the beginning, with conception, R & D, design, construction and commissioning. The education of the system continues into the operation, maintenance, support and development over the facility life. Increased emphasis on the desired equipment performance, reliability, availability, maintainability, beam quality, stability and reproducibility in the early stages increases initial cost but hopefully reduces running costs. Education of the people involved, all of them, is a major factor.

Aspects of Reliability[1]

1. Probabilistic - the definition and prediction of reliability characteristics

2. Statistical - data collection and evaluation

3. Engineering - specification, design, development, production, testing, retrofitting or replacing

4. Managerial - decision, responsibility, assignment, communication, training, correlation, consistency, coordination, organization

In order of importance, I would suggest a reverse ordering, with little space between 4. and 3. In order of incidence, in terms of general application of state-of-the-art techniques, 3. first, with 2. and 4. in either order well behind, and 1. well in the rear. Let us look further at each.

Engineering Aspects and Tools

These are the most familiar, numerous and best-developed of our methods. The early stages of each project, system or facility involve specification, design and development. These aspects interact and sometimes considerable time and effort are spent demonstrating practical feasibility. Powerful tools are available. There is not too wide a gap between theory and practice for many problems of interest, and analysis and experimental development work complement each other. Computer codes are used extensively and effectively to study beam dynamics, magnetic element design, accelerating structure design, shielding parameters, circuit design and many other problems. Prototyping is used whenever possible. The test equipment available is usually modern and very good; both analog and digital equipment are used, often together as, for example, in bead-pull measurements of accelerator structure field distributions or magnet field mapping.

In production, the necessity for low-bid procurement can be a problem, or not, often depending on the clarity and reality of the specification, the bid packaging and buyer-seller interaction as much as on the seller's difficulties.

Once the facility is built, "machine development" begins. Unanticipated problems and requirements or interface difficulties are worked out, design flaws are corrected, replacements and retrofits are made. Additions, new requirements, new techniques and equipment come along.

It is usually at the "machine development" stage that reliability gets its big play, being then quite obvious. The whole reliability program then often amounts to reworking chronic subsystems until their problems subside into an acceptable noise level.

A rough cost, from machine commissioning to a later time, of the overall facility reliability at that later time, can be estimated as the operating cost rate times the unplanned downtime, plus the operating cost rate times the machine development time, plus the cost of the development staff and costs for retrofitted or replaced subsystems. Some of these costs may have been identified as deferrals or risks during development, but we often can't claim that. Further cost to achieve a higher degree of effectiveness clearly depends critically at this point on the initial design and development work. While sometimes less visible than initial costs, retrofit costs are often higher than initial cost and reliability goals conceived after construction may be expensive indeed.

On the whole, then, the resources brought to bear on any recognized technical problem or subsystem are powerful and well-used. However, the amount of rework that goes on indicates that improvement is always possible. What are some of the typical difficulties and what might be done?

1. Subsystem development

a. Getting convergence on specifications between physics and engineering viewpoints is often difficult. It is almost impossible to learn enough to have a truly multidisciplinary viewpoint. This suggests that the managerial techniques must bridge the gap.

b. There is a tendency to re-invent the wheel. With modern data-base techniques, outlined below, it is possible that a systematic cataloging of accelerator-related experience could aid the communication of new and old ideas.

c. More attention on the engineering side should be paid in the early stages to anticipating future changes in the physics requirements, anticipation of long-term operating requirements, and critical analysis of the interfaces to adjacent subsystems.

2. System development

a. A conscious, coordinated application of the four reliability aspects should sharpen the direction and quality of the engineering aspect.

b. With the introduction of interactive, large-memory computing systems, further development of the analytical tools is indicated. For example, now separate longitudinal and transverse particle motion codes could be combined into an interactive system model with the potential for phase-space coupling studies. Such modeling of the technical system could be extended to the development of tuning procedures and operator training before the machine is available and during machine development and operation.

From here on, the degree to which application is made at any one facility varies widely.

Statistical Aspects and Tools

Statistics implies documentation, which can become a nightmare. But so can the lack of it. The idea from the overall facility point-of-view is to decide what you need or want, let the documentation support that, and use the best tools available.

The tools now becoming available in this area are computer-based, general, powerful; they are beginning to be applied in many disciplines. You have heard about PERT - do you know about information retrieval systems or data-base techniques? Software systems, now commercially available[2,3] and on-line at some laboratories, can take care of all the grubby details of how information is stored and retrieved, leaving the user free to concentrate on his use of the information. Interactive modes, in combination with graphics, are possible, and communication with the computer is done through an English-like language. The interaction is similar in many respects to what goes on at modern accelerator control room consoles with the machine, except that here the data-base may be anything you choose. Some application has been made at LAMPF,[4] so far at only a low level of sophistication; examples are mentioned below. The potential seems enormous but fraught with difficulties, many connected with the managerial aspects to be covered later.

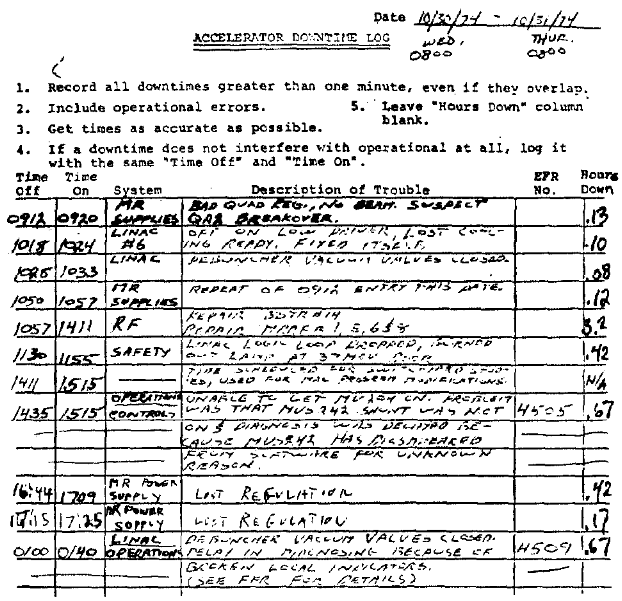
1. System Documentation

a. It is important throughout the life of the facility to document goals, objectives, technical and economic decisions taken, the assignment of resources, the interfaces and how they will be handled. If you can't remember what was decided and why, it's difficult to arrive at an integrated system. This is managerial documentation, usually found in memos or committee minutes. It would seem that this is an area where use of a data-base and system modeling could be used.[5]

b. Equipment data in the form of drawings, procedures, SOP's and manuals are important adjuncts to overall consistency. Facility economics often result in shortcuts in this area. Again, the potential of computer assisted techniques could improve the long-range picture. Some data-base systems have strong capabilities for text handling,[3] or modern record/playback electric typewriter systems can be used to speed the job of editing and updating manuals. The use of computerized drafting,[6] using table digitizers, terminal displays and interactive editing modes, offers tremendous advantages in speed and versatility. Such equipment should allow more time to be spent on better design in the early stages, and later would help make thorough documentation more feasible.

2. Operating Data

a. Types of data collected are numerous. Most facilities use log-books to keep track of operating conditions and problems. See Fig. 1. The computer control system is used in varying degrees for logging and to collect long-term records of equipment stability, beam delivery and parameter settings; exploitation of this potential is gradually increasing. Records of induced radioactivity, energy use, machine effectiveness reports from users, and equipment problems are among those kept. Machine experiment data collection methods are well developed through the use of the computer control system.[7]


Date 10/30/74 – 10/31/74
WED. 0800 THUR. 0800

ACCELERATOR DOWNTIME LOG

1. Record all downtimes greater than one minute, even if they overlap.
2. Include operational errors.
3. Get times as accurate as possible.
4. If a downtime does not interfere with operational at all, log it with the same "Time Off" and "Time On".
5. Leave "Hours Down" column blank.

Time Off	Time On	System	Description of Trouble	EFR No.	Hours Down
0912	0920	MR SUPPLIES	BAD QUAD REG., NO BEAM. SUSPECT QA2 BREAKOVER.		.13
1018	1024	LINAC #6	OFF ON LOW DRIVER, LOST COOLING READY. FIXED ITSELF.		.10
1025	1033	LINAC	DEBUNCHER VACUUM VALVES CLOSED.		.08
1050	1057	MR SUPPLIES	REPEAT OF 0912 ENTRY THIS DATE.		.12
1057	1411	RF	REPAIR [illegible] REPAIR [illegible] 1, 5, 6		3.2
1130	1155	SAFETY	LINAC LOGIC LOOP DROPPED, BURNED OUT LAMP AT 37 MEV [illegible]		.42
1411	1515	—	TIME SCHEDULED FOR [illegible] STUDIES, USED FOR [illegible] PROGRAM MODIFICATIONS.		N/A
1435	1515	OPERATIONS CONTROLS	UNABLE TO GET MU [illegible] ON. PROBLEM WAS THAT MUS 242 SHUNT WAS NOT ON & DIAGNOSIS WAS DELAYED BECAUSE MUS242 HAS DISAPPEARED FROM SOFTWARE FOR UNKNOWN REASON.	4505	.67
16:44	1709	MR POWER SUPPLY	LOST REGULATION		.42
17:15	17:25	MR POWER SUPPLY	LOST REGULATION		.17
0100	0140	LINAC OPERATIONS	DEBUNCHER VACUUM VALVES CLOSED. DELAY IN DIAGNOSING BECAUSE OF BROKEN LOCAL INDICATORS. (SEE EFR FOR DETAILS)	4509	.67

Fig. 1. Example of a printed form log sheet.

b. Equipment data are forwarded to support personnel, sometimes with the aid of computer tools. Often only the most expensive equipment is covered. At LAMPF, all machine equipment has been cataloged and a master data-base set up. Operating problems are reported using a card fill-out system, (Fig. 2), keypunching, and a daily computer report which adds background information to make the report format more convenient to read. (Fig. 3) The reports are also stored in the data-base, and summaries or analyses in various forms are possible, at various levels of aggregation. Figure 4 shows a summary spanning one year for a major system. Similar graphs are generated for functional groupings or individual types of equipment. Some of the reports used, like the graphs of Figure 4, are generated by software which we wrote. However, the main data-base is supported by a very powerful retrieval system which we did not have to write. It allows you, in an English-like language, to phrase questions based on logical combinations of the information stored and interrogate the data-base in an interactive manner through a computer terminal. For example: list all failure report data on klystron amplifiers of a certain vendor, where the date is between November 1 and January 31, the running time meter is greater than 5000 hours, and accelerator downtime was greater than 15 minutes or adjustments were made in place. You can ask for sums, ordering or other functions to be performed with the data as it is retrieved - example: sum the number of failure reports and downtime on a shift basis, to see differences between day, swing and mid-shift operations.

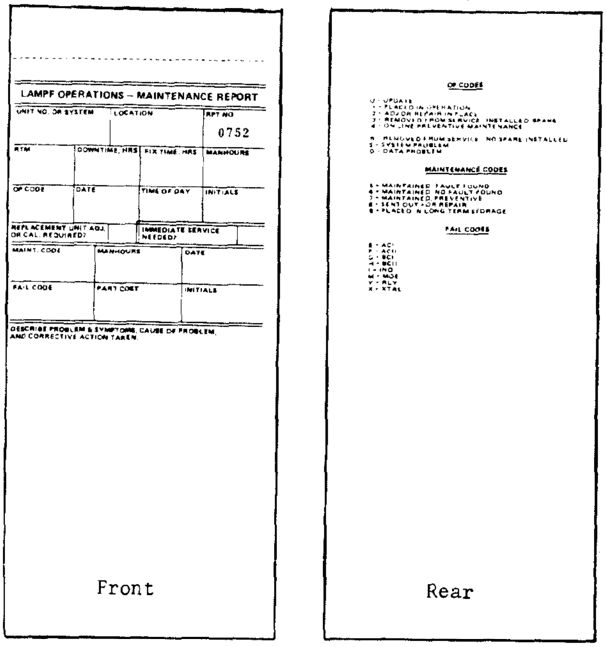
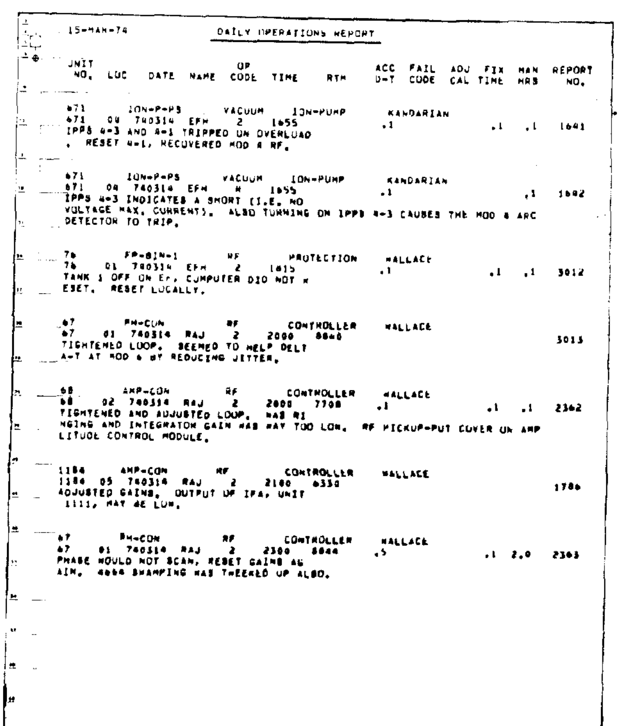


Fig. 2. A card-format equipment report, used with a computer data-base.



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15-MAR-74                    DAILY OPERATIONS REPORT

UNIT                       OP                          ACC  FAIL  ADJ  FIX  MAN  REPORT
 NO.  LOC   DATE   NAME   CODE  TIME     RTM           D-T  CODE  CAL  TIME HRS    NO.

671        ION-P-PS      VACUUM    ION-PUMP         KANDARIAN
671   04  740314  EFH     2     1655                .1                  .1   .1   1641
IPPS 4-3 AND 4-1 TRIPPED ON OVERLOAD
.  RESET 4-1, RECOVERED MOD 4 RF.

671        ION-P-PS      VACUUM    ION-PUMP         KANDARIAN
671   04  740314  EFH     4     1655                .1                       .1   1642
IPPS 4-3 INDICATES A SHORT (I.E. NO
VOLTAGE MAX. CURRENT).  ALSO TURNING ON IPPS 4-3 CAUSES THE MOD 4 ARC
DETECTOR TO TRIP.

76         FP-BIN-1       RF        PROTECTION       WALLACE
76    01  740314  EFH     2     1615                .1                  .1   .1   3012
TANK 1 OFF ON EF, COMPUTER DID NOT R
ESET.  RESET LOCALLY.

67         PH-CON         RF           CONTROLLER    WALLACE
67    01  740314  RAJ     2     2000   8840                                       3013
TIGHTENED LOOP.  SEEMED TO HELP DELT
A-T AT MOD 6 BY REDUCING JITTER.

68         AMP-CON        RF           CONTROLLER    WALLACE
68    02  740314  RAJ     2     2000   7708       .1                  .1   .1   2362
TIGHTENED AND ADJUSTED LOOP.  WAS RI
NGING AND INTEGRATOR GAIN WAS WAY TOO LOW.  RF PICKUP-PUT COVER ON AMP
LITUDE CONTROL MODULE.

1184       AMP-CON        RF           CONTROLLER    WALLACE
1184  05  740314  RAJ     2     2100   6330                                       1786
ADJUSTED GAINS.  OUTPUT OF IPA, UNIT
 1111, MAY BE LOW.

67         PH-CON         RF           CONTROLLER    WALLACE
67    01  740314  RAJ     2     2300   8844       .5                  .1  2.0   2363
PHASE WOULD NOT SCAN, RESET GAINS AG
AIN.  4064 SWAMPING WAS TWEEKED UP ALSO.
```

Fig. 3. Page from daily report, computer generated from cards shown in Fig. 2

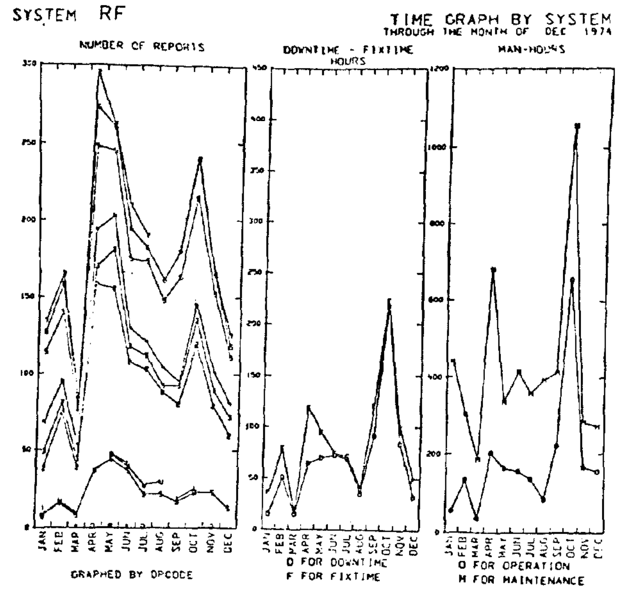
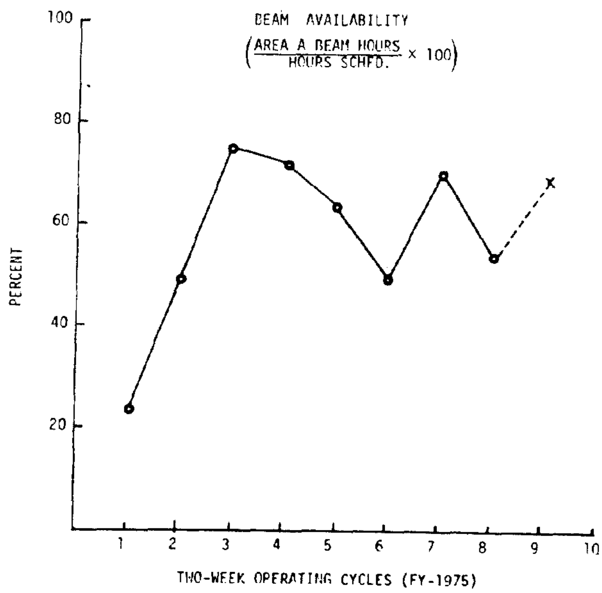


Fig. 4. System summary spanning a year, computer generated from the data-base compiled from reports shown in Figs. 2 and 3.



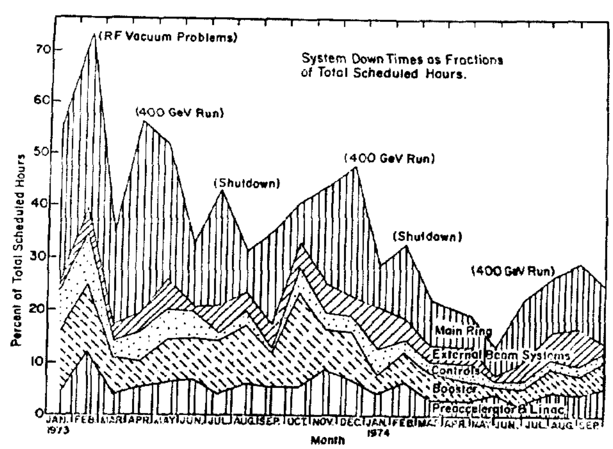


Fig. 5. Two examples of facility-aggregated reliability and availability summaries.

You don't have to know all the questions beforehand - you can type them in and get answers almost as fast as you can think them up.

c. The use of the data generated at most facilities, however, is not usually very extensive, flexible or convenient, because it must be processed by hand. System summaries are usually highly aggregated; for example, total current delivered per month or total downtime per month. Examples are shown in Fig. 5. These summaries are largely prepared for external consumption - they don't lend themselves to internal, dynamic use. They tend to be upper or lower bound estimates, and often are not well calibrated or verified in a statistical sense, yet form a basis for measuring and evaluating facility effectiveness. The data-base systems can help increase the usefulness of operating information.

It is interesting to note the strong tendency toward thinking ratios rather than absolutes, and to consider using this in control system or information display design. A perhaps unfortunate consequence is the tendency to evaluate facility effectiveness on the basis of comparison to the one next door, who is in the same business, may have the same or worse blind spots, and is doing the same thing by comparing himself with you.

3. Scheduling Data

For construction or other once-through activities like a long shutdown, PERT has found a fairly widespread usage. Sometimes the manpower-leveling and costing capabilities of PERT are also used. The tools for effective handling of recursive activities like development, maintenance, and floor management are not so well developed. Research in this area might consider modified use of PERT or other computerized technique, using multidisciplinary input from operations research and other business-oriented disciplines where scheduling is a common problem. One general-purpose reliability-oriented software package[8] is set up to help estimate needed preventive maintenance schedules and personnel levels based on reliability statistics accumulated.

At LAMPF, the equipment pools for experimental physics are controlled using a data-base and some specially written assignment and scheduling algorithms. The data-base contains unit and property numbers, manufacturer, model number and description. The total number, in use or available, and the distribution at any time are kept track of. The activities of the facility user's program is also supported extensively by computer data-bases. The files include members' names, addresses, institutions, citizenship, and experiments on which they are spokesman or participator. The experimental proposals are cataloged by number, with records of spokesman, participants, engineering support assignments, approval status, channel and beam time assignments. Detailed scheduling assignments for the experiment are entered by date, priority and expected shift and micro-amp hours. Actual time is entered as accumulated. All scheduling is presently done by hand. This is an obvious area where computer tool development might be of benefit. All capital equipment in the facility is managed by a data-base. Other applications which have been considered are space allocation and safety-related change orders.

4. Reliability Data

Equipment operating data are not commonly carried through to reliability formulations, mostly because hand methods are too expensive. The computer processed data-base techniques add a new dimension.

Probabilistic Aspects and Tools

This area implies the quantization of the reliability or effectiveness problem. Very little has been done at accelerator facilities along this line. Sometimes the statistics for expensive components such as rf tubes are presented this way.[9] See Fig. 6. Component reliability is a restricted point of view - the interesting aspects come when components are made into systems. There is a vast literature and a wide variety of sophisticated techniques, for example, Monte Carlo methods, queuing theory, optimization and nonlinear programming methods.

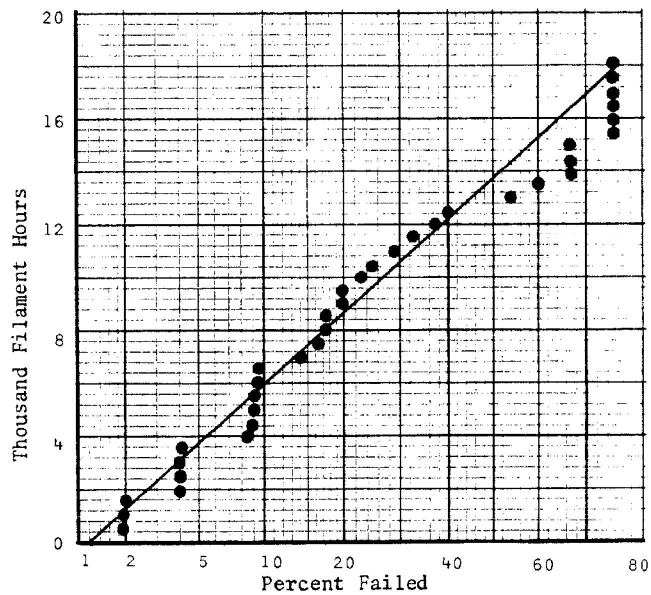


Fig. 6. Cumulative failure distribution of klystron amplifiers, giving a life estimate of 13,700 hours for 50% of the population to fail. Fit to a Weibull distribution $(1-e^{(t/\theta)^b})$ shows $b \cong 2$, as seen at other installations.

Basic reliability is defined as the probability that an "unrepairable" system will perform without failure a specified function under given conditions for a stated length of time. It is influenced by engineering, human factors, age, system structure and environment, and so on. Failure rate functions, probability of failure in any time interval (bath-tub curve), mean-time-to-failure, and other properties emerge.

For repairable systems, concepts like maintainability, availability, mean-time-to-repair and mean-time-between-failure are added. Stability and reproducibility concepts could also be worked into quantified form.

Quantization is a major step. The differences between facilities and the developmental nature of new facilities make it largely impractical to use real data before operation begins. However, a study of the system interactions using assumed data would probably be useful. Once in operation, it would make sense to enlist the aid of previously developed generalized computer tools, such as an information retrieval system plus a reliability oriented package such as cited above. The large development cost for these tools has been absorbed elsewhere, and we could concentrate on application to our type of systems.

Managerial Aspects and Tools

If there is one thing that is perfectly clear, it is that managerial aspects have something to do with the subject of facility effectiveness. Beyond that, nothing is clear, not even the sign! Most reliability work widely skirts this aspect, but a fair amount of day-to-day discussion seems to relate to it. There is no right way; there are perhaps more or less effective ways. The dimensions of the interactions and variables transcend those of most technical problems. There is a great deal of literature and on-going research. If we would grant that improvements in this area would have an impact equal to that of innovations in the other aspects, then the subject is worth an objective look.

The primary managerial roles might be summarized as definition of the goals and objectives, and making a climate which encourages, if not insures, accomplishment.

Managerial techniques are in constant evolution. What actually happens at any one facility boils down to a complicated compromise based on the individual people involved, and all kinds of combinations succeed. There are some general tendencies. For example, there are opposite-pole positions on the value of planning![10] A very common approach to a problem is to find some bright guys and turn them independently loose, assuming that this is the best climate for creativity and that much in the way of documentation would be restrictive. The anti-planners bring arguments in humanistic and behavioral terms, arguing that planning is a negative thing, invading privacy, stifling creativity, creating images of the "technocratic society," and so on. Planners feel that more potential can be realized overall by a coordinated approach. Most accept the difficulty of identifying the right problem, separating a system that one might do something with from its environment, and the need for judgment. There is evidence that planning can aid creativity by freeing up resources and time. It seems clear that merging the many parts of any complex system into an effective whole must benefit from effective coordination.

Some of the characteristics of present (planning type) managerial techniques used at accelerator facilities of acknowledged success around the world might be listed.[11,12,13] This is a somewhat idealized composite.

1. Project setup is done with overall objectives in mind. Boundaries are made clear, as are resources. The tendency is toward self-supporting structure.

2. Project staffing and resources are sufficient. This is an absolute prerequisite if higher order goals, such as reliability, are included. Staff continuity throughout the life cycle of the project is emphasized as much as possible. The fact that as many or more people will be necessary to operate, maintain, and develop the facility as were involved in building it is recognized and planned for.

3. Clear procedures for technical decision-making are set up. Often a committee, or set of committees, led by the top management, form the framework. All aspects of policy, assignment of responsibility, performance specs, budget, time-scale, priorities, work program review, performance aims, technical relations to other divisions, standardization, general direction for theoretical studies and important apparatus, and so on are covered. Written records are kept.

4. Thorough documentation is required.

a. Typically for systems: general specifications; design, budget, and time reviews; progress reports; final report or publication; operations and maintenance manuals.

b. Typically for experimental (development) programs: committee review of experimental proposals, with minutes of meetings; preparation sheets; log book; post-experiment debrief; analysis; report or publication.

c. Typically for facility: written objectives; scheduling aids, sometimes computerized; performance review aids, sometimes computerized; program reviews; progress reports; aggregated summaries; reports and publications.

5. A proper balance is found between operations, support, and development work. Operators and engineers-in-charge of operations shifts often have split job roles with time for participation in machine development, preparation of operating statistics, etc. Maintenance activities are specifically given machine time, and preventive maintenance is actively encouraged.[14] The desired areas for development work are made clear and creativity is supported as much as possible.

Application of these and other managerial approaches is fraught with sociological impact, especially if an innovation or change is made.[15] Please note that the organization chart has not been mentioned. It has its large effect because it is an instrument of management policy.

Computer techniques may be a major aid in the future.[16] It is already common practice, in other fields, to use the computer extensively to perform book-keeping functions and to make many "routine" decisions concerning resource allocations, scheduling, warehousing and inventory, spare parts, transportation, and so on. In other words, the computer helps supervise what a business does. It is already clear that personnel cost displacement is not a good measure of the value of such use of computers - the horizons are opened to doing more and better things, requiring other kinds of people. Future development is pointed toward tactical planning, optimization, and finally to strategic planning.

As one progresses from one end of this spectrum to the other, there is less dependence on internal data and more on external influences. The heuristic nature and difficulty increase. Quickness of response needed from the computer increases up through the tactical phase, and decreases again at the strategic level.

A large amount of experimentation has already been done, but the potential is so far only dimly realized. One recognized difficulty of major proportions is the degree that upper management is not involved in setting the pace for computer use in management functions. Another stems from the near impossibility at this point of deciding a priori what management needs to know. They don't know. In part, it is that it is not easy even to foresee how one could use new information assuming it were really available in a conveniently accessible form. Analysis of information on the basis of job content or organizational relationships is not very useful - a better approach seems to be toward unstructured storage with the capability for free browsing.

Predictions include the extensive development of the theory of large systems, and modeling techniques for simulation of the interrelationships and the effects of decisions. Abstraction techniques will allow study at various levels of aggregation - microscopic or telescopic.

Summary

What I have tried to point out is that reliability is not just probability functions or equipment retrofits. It is an attitude, supported by rapidly developing techniques, toward a broad-scaled striving

for excellence in a facility in both technical and social terms. In that sense, what you might have expected from the title "reliability engineering" turned out to be a subset of "systems engineering."

A great deal of work is going on in these areas, outside the realm of accelerators or physics in general. While very sophisticated techniques are being used, their application is still largely art. Some scientists have suggested that the "scientific approach" is the way to solve large system problems (e.g. the energy problem). The rub comes, of course, when the bridge from things to people is crossed. Suddenly what has been carefully relegated to the environment becomes an integral and perhaps dominating part of the problem. The old philosophy of science is challenged, and must grow.

The problems that spurred the development of the new techniques are huge compared to the problem of an accelerator facility - energy, business, environment, government, military systems. This may mean that it is uneconomical to pursue facility effectiveness as a technically based objective. It may mean there are tools we don't have to pay the development costs for. It may mean that an accelerator project could serve as a fertile demonstration of the effectiveness of new techniques on a reasonable time-scale, perhaps adding credence to application in other areas. The situation is analogous to the application of computer control to accelerators about twelve years ago. Appreciation of the potential of other fields must be gained, and a true commitment to multi-disciplinary endeavor must be made and developed. Some innovative work has been done and will continue in the form of feasibility or background studies. Eventually a facility will incorporate an overall program from the beginning.

It should not be inferred that an enormous overburden of paper is needed, nor that there is any panacea. We should learn new tools and use them the way we do our analytic and computer-control tools in an evolutionary process. In those areas we realize that the tools are an aid and even make solution possible, but that they don't substitute for thought and decision. As in strictly technical matters, the simple solution, so obvious once seen, is often best. One of the best examples I know was a change that made shift-to-shift communication better during operation, and noticeably improved facility effectiveness. The shift schedule of the operations supervisors was simply shifted several hours from that of the operations crew. The result included the benefit that the shift-change hardly has to rely on written information at all.

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