SERI/TP-215-3975
UC Category: 233
DE91002118

# The High Cost of Low Quality in R&D

**Chester V. Wells**

October 1990

Prepared under Task No. 20003001

**Solar Energy Research Institute**
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
**U.S. Department of Energy**
Contract No. DE-AC02-83CH10093

## NOTICE

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A03

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA)*; *Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR)*; and publication NTIS-PR-360 available from NTIS at the above address.

# THE HIGH COST OF LOW QUALITY IN R&D

Chester V. Wells
Staff Engineer

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

## ABSTRACT

The principles of quality assurance and quality control yield high payoffs when applied to research activities. Researchers are usually highly motivated individuals who earnestly desire to produce excellent results. The nature of research and the temperament of researchers are such that considerable freedom and latitude are usually required so that the creative processes are not impeded. There are approaches that can be used in applying quality assurance and control that researchers will accept and use when they see the payoff. Some examples are given, with particular emphasis on quality cost systems applied to measurement processes in R&D.

## INTRODUCTION

We often hear a question stated something like this: "Why is there always time to do a job over again, when there is never time to do it right the first time?" Restating the question in the language more appropriate to the subject at hand, "Why does it appear that there are usually resources and management support available to perform a specific task over again, but rarely are they available to do the task right the first time?" This appears to be as true in the R&D environment as it is anywhere else.

In this paper, I will show that quality assurance and quality control efforts are just as important to technical success and cost control in an R&D environment as in manufacturing facilities. This is particularly true where measurement processes are a vital part of the R&D work.

I have reached this conclusion based on observations from 40 years of experience in the college and university environments (23 years) and at military and government laboratories (17 years), and on information from facilities in addition to those at which I have worked. These experiences include bench-scale basic research, reactor development and research operations, accelerator design and construction, instrumentation development and applications, and metrology.

What is "quality" in an R&D environment? Although often associated with manufactured products and services, these two definitions can be appropriately applied to products from research and development(1): (a) conformance to established requirements (specifications), and (b) meeting customer/user needs.

Problems occur right at the outset of trying to specify and improve quality in the service and R&D environments, because often the requirements and customer/user needs have not been clearly established. Therefore, it is difficult to appraise the quality of the products and services in these work environments. Sometimes, the expected results of a research activity are described only in terms of a "best effort" or level of effort.

I am frequently asked to assist in specifying, selecting, and evaluating instrumentation for experiments. In beginning my process, I need to know the overall accuracy or uncertainty that is to be achieved in the experiment's final results. Yet, all too often, this information has not been written out in a formal manner; so, we must begin there before developing specifications for instrumentation.

Therefore, an early step in characterizing and improving quality in R&D activities is to describe in greater detail the results expected, and to have a formal agreement with the sponsor of the R&D. It's a challenge to describe more completely the expected research results without restricting the initiative of the researchers themselves.

## THE HIGH COST OF LOW QUALITY

A scientist from an accelerator facility was asked if they calibrated the vacuum (ionization) gauge used to measure the pressure in a chamber in the facility. The scientist stated that they did not calibrate the ionization gauge because they did not need to know the absolute value of the pressure in the vacuum system. They would pump the system pressure down to the same indicated pressure each time. When asked what they did when the ionization gauge filament burned out and a new gauge was installed, the scientist replied that they just installed the new gauge and then experimented until they found the optimum operating point on the new gauge. This took from one to three days' time, while the rest of the crew of seven people waited around! Think of how many hours could be saved if this facility would invest a few hundred dollars (at most) to calibrate vacuum gauges, which could be installed and the optimum pressure re-established much more rapidly.

All of us, I'm sure, can recall examples where a conscious decision was made that resulted in significant loss of quality and increase in expense; that is, where high cost resulted from low quality. But we may not be convinced that there are examples of high cost everywhere in our organizations that can be almost totally eliminated, and at a cost that is more than offset by the expenses that have been eliminated.

## PRODUCTS OF RESEARCH AND DEVELOPMENT

Obviously, the products and services of research and development activities are generally quite different from those of a manufacturer. By looking at a few, such as (a) research and engineering data, (b) conceptual products, and (c) technical support products, we can see the challenge of applying quality assurance concepts and techniques to the R&D arena.

---

(1)Numbers in parentheses refer to similarly numbered references at end of paper.

Three management categories that have a significant influence on the quality of research products and the efficiency with which a research organization carries out its work: equipment and facility management, project and program management, and fiscal management. Specifications for the products and services in all these areas are necessary for measuring the quality of the product and even to know if the work has been completed properly.

## IS QUALITY REALLY FREE?

The title of a best-selling book states, "Quality Is Free." How can that be, if there are quality inspectors, quality engineers, quality reports, and other quality control expenses to cover? The cost of these individuals and their activities should be accounted for, obviously. But not so obvious is a whole group of expenses which should be included in the accounting for the real cost of quality:(3)

> "Unfortunately, significant chunks of quality cost are normally overlooked or unrecognized simply because most accounting systems are not designed to identify them....most company top managements are more sensitive to overall cost and schedule than to quality. The inter-relationship of quality, schedule and cost, without attention to the contrary, is likely to be unbalanced in favor of schedule and cost--and often unwittingly at the expense of quality....When the cost of quality rises without constraint, or is tolerated at too high a level, failure to expose the condition will ultimately become a sign of ineffective management--and yet it is entirely possible for this condition to exist without top management's awareness....Each identified quality performance problem carries with it a tangible recovery cost which can be assigned a value. This is the essence of quality cost measurement. In a certain percentage of cases, however, the value of the intangible costs entailed may transcend the pure economics of the situation. For example, what is the cost of missing an important milestone in a schedule? Quality problems are more often at fault here than others. But the most important of all intangible quality costs is the impact of quality problems and schedule delays on the company's performance image in the eyes of its customers--with all its implications for the profit picture and the company's future."

We'll look now at the principles of how quality costs are accounted for and can be applied in the R&D area. This will give us some insight into the real costs that should be properly associated with quality. Then, we'll examine some methods that actually reduce research costs by more than the expenses incurred to track quality costs and implement quality assurance practices.

It may surprise some people that research scientists and development engineers are engaged in significant activities that come under the heading of quality, even if their organizations have no formal quality assurance program. What will surprise the scientists and engineers is what they are incurring in "quality costs," costs which could be greatly reduced by paying careful attention to the principles of quality cost and quality improvement.

Is quality really free? In one sense, no; there are real costs that must be incurred to support a quality product. But to achieve improved quality over what is often obtained will result in actually lower costs for quality if a careful accounting of quality costs is made. In that sense, then, quality is not only free, it pays!

## PRINCIPLES OF QUALITY COSTS AND THEIR APPLICATIONS TO R&D

An ideal quality cost system attempts to measure the difference between the actual cost of performing research and development and what it would cost if everyone performed their functions perfectly.

Applying quality cost techniques to R&D activities will be a new idea to most people in R&D. The reduction of expenses from applying these techniques in a manufacturing plant will lead directly to greater profit for the factory. The results for research managers will be reduced overhead rates, fewer missed milestones, greater confidence in and knowledge of the "quality" of their research products, improved equipment reliability leading to fewer failures and repeated experiments, better acceptance of research results by the sponsoring organization and peers, and even increased award fees paid by the sponsoring federal agencies.

Many of the routine activities that are regular laboratory practice for good researchers are usual components of quality costs. To the quality engineer, these are appropriate expenses to include under quality costs.

The challenge in R&D is to properly distinguish quality costs from research costs, and then appropriately eliminate or reduce the sources of those quality costs with their accompanying delays and frustrations.

Does a "failed" experiment constitute a "quality cost," when the research was to determine whether or not a particular hypothesis was true or false? The researcher must make sure that the failure is not the result of improper technique or failed instruments, but rather proof that the hypothesis is not true.

Both research and development work, by their very natures, require trying various approaches to find one that works and optimizing that approach. We must separate failure because of poor quality (in planning, execution, equipment, measurements, documentation) from failure because of physical principles, limitations of materials, etc. that we could not have known. We must separate quality costs from research costs so that the quality of research can be improved and the cost of that quality can be reduced.

> "Simply stated, quality costs are a measure of costs specifically associated with the achievement or nonachievement of product or service quality--as defined by all product or service requirements established by the company and its contracts with customers and society. Requirements include marketing specifications, end-product and process specifications, purchase orders, engineering drawings, company procedures, operating instructions, professional or industry standards, government regulations and any other document that can affect the definition of product or service. More specifically, quality costs are the total of the costs incurred by a) investing in the *prevention* of nonconformances to requirements; b) *appraising* a product or service for conformance to requirements, and c) *failure* to meet requirements...."(4)

Some brief definitions of the quality cost categories will facilitate our understanding of the subject.(5) Prevention costs: the costs of all activities specifically designed to prevent defects in deliverable products or service. Appraisal costs: The costs associated with measuring, evaluating or auditing products or services to assure conformance with quality standard and performance requirements. Failure costs: The costs required to evaluate and either correct or replace products or services not conforming to requirements or customer/user needs. Internal failure costs: The costs occurring prior to completing or shipping the product or furnishing a service. External failure costs: The costs occurring after shipping the product and during or after furnishing a service.

The primary responsibility of a quality assurance program or quality management system is to assure the acceptability of R&D products and services as delivered to customers and users of those products and services. To make certain that this occurs, particular preventive measures, appraisal activities, and failure corrective actions must take place throughout the research or development program and process.

Prevention costs of quality include all activities incorporated into the basic management system to make it nearly impossible for known and suspected sources of quality failure to occur in the R&D operation and its support. Adapting a common saying to quality costs, *to fail to plan* adequately for prevention costs *is to plan to fail* in the quality of results. Typical or needed prevention activities should include working carefully with the sponsoring organization to obtain and evaluate the quality needs and perceptions (anticipations) which will affect their satisfaction with the R&D products and services to be supplied.

One difficulty in determining specifications is that a great portion of R&D data and results have unknown (as yet unidentified) users and customers. Hold a brain-storming session to suggest potential users and what should be anticipated as their needs. We can do this by envisioning ourselves in the user's situation and stating what we would then expect and need.

The result should be stated in the basic contract with the sponsoring agency and incorporated into the detailed research program descriptions and agreements. Appropriate national and international consensus standards should be referenced in the agreements and utilized in the R&D operations. Agreement should be reached at the outset of a research or development program concerning measurement uncertainty goals in the final R&D results.

Prevention costs include planning, designing research experimental approaches, techniques, and hardware to achieve agreed upon goals. Conduct formal design reviews prior to ordering hardware or beginning experimentation. Include the preparation of an overall quality management plan for the research task. Include costs incurred to make sure that the parts, instruments, or systems to be purchased will conform to requirements necessary to meet experiment goals, such as incoming inspection and environmental tests of measurement and control equipment. Include procedures and development costs for newly required inspection and test equipment. Include the cost of all activities (including design and development costs) which ensure the performance capability of new research techniques and processes, and new or special measurement and control equipment. Other costs appropriate to prevention are data analysis quality assurance and formal training to ensure research quality through error prevention.

In subcontracting research, this can include on-site surveys by a team to evaluate each individual subcontractor's capability to meet all prime contractor's quality requirements. Include a system to evaluate each subcontractor's continuing acceptability for future subcontracted research, based on actual performance to established requirements. Update the system periodically.

Additional activities under the prevention category include the administration of the quality management function, including salaries, expenses, QA program planning, and performance reporting and audits of the QA program itself. Quality education, awareness, and improvement costs would be placed here. All of these activities must be tailored to the specific R&D environment in which it operates, be it bench-scale research, a manufacturer's R&D operation, or a large high-energy physics facility.

Appraisal costs of quality are defined as all costs incurred in the planned conduct of appraisals of research and development products or services to determine compliance to predetermined quality requirements and specifications. These activities are to assure the acceptability of an R&D product (such as a research data report) at each step in the the operation from the start of "production" (routine research activities) to delivery of the final report. This includes qualification and receiving (incoming) inspections and tests of purchased materials and services, together with necessary measurement equipment to perform the appraisals. Appraisal includes data analysis of routine operations and drawing up control charts on samples prepared to monitor process stability and accuracy. Measurement check standards can be used, and the results can be compared with previously agreed upon uncertainty limits for final results. Include costs for maintenance and calibrations, outside tests and certifications, and all review costs for test data prior to releasing the product to the customer. Costs of source inspections and quality control programs (especially of research subcontractors) are also included.

External appraisal costs include field trials of new products or services, life and environmental testing, reliability tests, appraisal efforts planned and conducted on-site for installation and delivery of large systems.

Failure costs in R&D work must be evaluated carefully to separate failures due to inadequate planning or design from routine operational failures. Rigorous uncertainty analysis can give information concerning failure characteristics.

Internal failure costs are those costs required to evaluate, determine, and either correct or replace defective or deficient products or services prior to delivery to the customer, including the associated documentation. They include all unplanned costs that are incurred because of inherent design inadequacies in released documentation for procurement or production operations. They include design corrective action, rework due to design changes, all scrap materials and labor discarded, and unplanned support work because of necessary design and documentation corrections.

Internal failure costs also include costs of rejecting purchased items and materials, including added incoming inspections and evaluation, replacement materials, supplier corrective actions (including for subcontracted research) and rework of supplier rejects. The costs associated with a defective product or service discovered during the normal operations processes of research should also be included.

External failure costs are those incurred for defective (or suspect) products or services after delivery to the customer or when the product or service does not meet customer or user requirements. These costs include investigating and resolving individual customer or user complaints, evaluating and repairing or replacing products not acceptable due to quality problems, and retrofit and recall costs. They also include penalties and liability costs, loss of sales, refunds or rewards, or other actions necessary to retain or restore customer and user goodwill.

## MEASUREMENT UNCERTAINTY CAN REDUCE R&D QUALITY COSTS

Measurement uncertainty analysis (an enhanced form of error analysis) provides a rigorous estimate of the interval (region) about a measurement or experimental result in which the true value(6) for that result is expected to lie. Measurement uncertainty applies statistical techniques to the random (precision or repeatability) component of the uncertainty. Engineering measurements and judgments are employed to describe the systematic (bias) component of uncertainty. The techniques are reasonably well documented (7,8,9,10) and are being applied to a growing group of projects and disciplines.(11,12,13)

The "pretest" analysis described in this uncertainty analysis methodology provides an initial insight and estimate of the uncertainty to be expected in an experiment or measurement result, even before the experiment is run. It can be based on similar measurement experiences, manufacturer's specifications, and seasoned engineering judgment. By performing this pretest analysis in advance of doing the experiment (a "prevention cost"), and comparing the analysis result against the agreed upon uncertainty requirements, the adequacy of the experiment and system design can be evaluated, instrumentation can be chosen, or choices can be modified until acceptable results can be expected.

For example, I performed extensive temperature tests and a simple uncertainty analysis on a multiplexer unit of a data acquisition system(14) used in outdoor testing. One of the project researchers reviewed the report of these tests and found that the noise and instability from that instrument would have masked the measurement results needed from a planned year-long experiment. By changing to another data acquisition system, several hundred thousand dollars in wasted data and analysis was saved, in addition to a year's time.

In another case, it took only two weeks to perform a pretest analysis (a prevention cost) for a two-year experiment to be performed in Hawaii. As a result, instruments were sent back to the manufacturer for modifications to meet the specifications found necessary through the analysis. Otherwise, the experimental results from the two years of work would have fallen significantly short of goals necessary for meaningful results.

An appropriately designed experiment and instrumentation system can provide data, during the actual experiment, that can be analyzed immediately to demonstrate whether the experiment and instrumentation is performing as expected. These would be considered appraisal costs. The experiment can be stopped early if results are suspect, saving time, material, and associated costs.

When the experiment is finally completed, a careful uncertainty analysis can be used to ascertain whether or not the customer's requirements have been met. This can be used to avoid shipping bad data to the customer or having to notify him later that problems were uncovered and a new experiment will be performed, causing the results to be late (internal failure costs).

## ADDITIONAL AREAS FOR QUALITY COST REDUCTIONS

In an R&D environment, more value can be obtained for the dollar spent on research by also reducing overhead costs. This can be accomplished by reducing errors in accounting reports and data entry, improving budgeting software for easier and more effective usage, using higher reliability building systems (air conditioning, power, lab chiller system), and providing faster and more complete response to building and utility problems. Overall R&D costs can be reduced by having quicker turn-around times in placing subcontracts for outside subcontracted research, more responsive laboratory stores operations, and more careful handling in shipping and receiving operations.

## THE LOW COST OF HIGH QUALITY

The foregoing discussion has pointed out some examples of high cost failures in research operations. These are just a few of the many of which I have become aware. The costs that have resulted from these failures will more than pay for the prevention costs, especially those of more effective planning.

The results are higher quality, the first time, and without the delays, frustrations, and higher expense incurred when the work has to be done over again. For example, because an oven temperature controller system was not calibrated (and subsequently found to be defective) before the experiment was begun, a whole experiment was conducted in which materials were exposed to temperatures noticeably higher than planned. When the oven problem was discovered, an additional month's worth of experiments had to be conducted to prove that the higher temperatures had not caused misleading results from the experiment. The cost of the new controller: about $200!

These are expenses of "research": quality expenses that should be acknowledged, tracked and reduced through an effective quality cost and continuous quality improvement program. The cost of such programs will be more than paid for by the savings made.

Should we expect to eliminate all failure costs? The nature of research is that not every failure can be found before an experiment is attempted, but the most easily prevented ones can and should be caught, thereby leading to a much higher success rate. For example, an effective calibration program for general purpose measurement and test equipment finds a high percentage of problems and impending failures, often before the user becomes aware of them. Instead of 50% of all measuring and test equipment still meeting specifications at the time it is recalibrated, the percentages can be brought up to 90% or greater. And the reliability (remaining within specification between calibrations, and freedom from abrupt failure) is vastly improved. This achievement does not stop the problems caused by misuse and abuse, power line surge-related problems, electrostatic discharge from operators, etc.; but it helps eliminate bad data from poor measuring and test equipment management practices.

## CONCLUSIONS

Traditional methods of identifying and tracking quality costs are appropriate for R&D activities. The measurement uncertainty methodology fits exactly with quality cost methods. The insights gained from applying quality cost and uncertainty methods can clearly identify and aid in reducing the high cost of low quality in research and development.

We presented several challenges to face in improving quality in R&D environments. Management support is absolutely necessary for a quality assurance program to succeed, *especially* in the R&D environment. Gaining that management support for a quality assurance program in general, and for a quality cost program in particular, is a challenge. We must learn how to refine specifications for expected results without restricting or dictating to the researchers. Identifying quality and failure costs, and properly delineating these in experiments that yield knowledge in the form of negative results, will be a challenge to both the quality engineer and the scientist.

By eliminating the high cost of low quality, an effective quality cost program can be supported and higher quality research results can be obtained at lower total costs. The response of many people to the idea of quality assurance in an R&D environment is, "We just cannot afford quality assurance," or, "We didn't budget for it." Therein lies a serious misconception: research programs are already paying high costs for lower quality than we are capable of producing. This results from failure costs usually being disguised as experimental costs.

## REFERENCES

1. Principles of Quality Costs; John T. Hagan, Editor; American Society for Quality Control, Milwaukee, Wisconsin, 1986; p. v.

2. Quality Is Free; Philip B. Crosby; McGraw-Hill Book Company, New York, New York 1979.

3. Hagan; p. 3-5.

4. Hagan; p. 3.

5. Hagan; p. 4.

6. Identifying the True Value--The First Step in J. Moffat; Proceedings of the 34th International Instrumentation Symposium, Instrument Society of America, Research Triangle Park, NC.

7. Measurement Uncertainty Handbook, Revised 1980; Robert J. Abernethy; Instrument Society of America, Research Triangle Park, NC, 1980.

8. Measurement Uncertainty: A Standard Methodology; R.B. Abernethy; and R.P. Benedict; ISA Transactions, Vol. 24 (1985), No. 1, pp. 75-79.

9. Part I - Measurement Uncertainty; ANSI/ASME PTC 19.1-1985; The American Society of Mechanical Engineers; New YOrk, New York, 1985.

10. The History and Statistical Development of the New ASME-SAE-AIAA-ISO Measurement Uncertainty Methodology; Robert B. Abernethy; and Barbara Ringhiser; AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, July 8-10, 1985; Monterey, CA.

11. Uncertainty Analysis for Thermopile Pyranometer Calibrations Performed by SERI; Daryl R. Myers; April 1988.

12. Uncertainty Analysis of Photovoltaic Efficiency Measurements; K.A. Emery; C.R. Osterwald; and C.V. Wells; Proceedings of the 19th IEEE PV Specialists Conference 1987, pp. 153-159.

13. A Thorough Approach to Measurement Uncertainty Analysis Applied to Immersed Heat Exchanger Testing; R.B. Farrington; and C.V. Wells; presented at the 1986 ASME Solar Energy Division Conference, Anaheim, CA, 14-17 April 1986; SERI/TR-253-2862, April 1986.

14. Some Significant Results from Testing a Remote Multiplexing Unit (RMU) for Temperature-Induced Errors; Chester V. Wells; SERI/TR-215-3195, June 1989.