Characterization, Inspection and Quality Control of Zirconium Alloy Cladding Tubes and Other Components for Fuel Assemblies

Workshop on Modeling and Quality Control for Advanced and Innovative Fuel Technologies

Lecture given
at International Centre of Theoretical Physics
in Trieste on November 23, 2005

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CONTENT

Quality Assurance

General

Total Quality Management

Process Development

International Standards

		Classical Quality Assurance	**Process Oriented Quality Assurance**	**Total Quality Management**
Quality Strategy	Main objective	Detection and removal of quality deficiencies	Prevention of quality deficiencies (market monitoring, product and process planning) as well as control during fabrication	Prevention of quality deficiencies
	Typical timing	Post-line control after completion of fabrication step	Initially during planning, especially during fabrication (Online-control with feed-back to process), and after completion of fabrication step	During planning, fabrication and life time of a product
	Characteristics of quality strategy	Reactive, product oriented	Active, process and product oriented	Active integrative emphasis on system-thinking
Realization	Employees involved	Quality inspection	All employees in development and fabrication, in particular head of QA	All company employees, in particular management
	Volume and use of Q-data	Evaluation of only few data which are generally subject to multiple use	Evaluation of accumulating quality data for different purposes: process planning process control quality audits, etc.	
	Typical way of data acquisition	Manually	Computer aided CAQ by "island solutions"	Fully computer supported CAM as CIM module
	Complexity of applied procedures	Simple algorithms, graphical tools (e.g. histograms)	Sophisticated algorithms to process Q-data become applicable. Also application of advanced graphical tools (e.g. Boxplots)	
	Typical statistical tools	Sampling plan	Test plans for quality planning. Quality control cards for process control	Test plans for quality planning. Quality control cards for process control and service control

Qualitätsregelkarten
(Quality Control Charts)

H.J. Mittag, C. Hanser Verlag
München/Wien, 1993

Steps of Development in Quality Assurance

Two Basic Ideas for Modern Quality Management*:
Total Quality Management

Process Orientation

- control and instantly correct the processes that are crucial for the fabrication quality,
- with an active attitude toward foresighted prevention, i.e
- any problem must be detected and corrected before it may occur.

Continuous Improvement

- constant effort to improve all steps of fabrication , i.e. manufacturing and testing,
- deviations from target values must be reduced constantly;
- it is not sufficient to meet the specification, process variation must stay as clear off as possible in between lower and upper control limit (LCL, UCL) as defined by statistical process control;
- quality data have to be collected, analyzed and assessed frequently and regularly.

Those activities essentially imply a continuous feed back from the customer how the delivered products perform in service.

This feed back has to be sought and understood (!) actively by the supplier.

*)For more details see:

H. G. Weidinger, "Modern Requirements to Quality Assurance and Control in Nuclear Fuel Fabrication", IAEA Regional Training Course on 'WWER Fuel Design, Performance and Back End' in Bratislava, Slovakia, 21 June-2 July 1999.

Realization of Total Quality Management

Example Framatome Approach

1. Organizational:

The responsibility to make the adequate quality was appointed to the manufacturing units.

Independent QA/QC continued to exist with surveillance tests

Decentralized continuous process control – and improvement – was implemented.

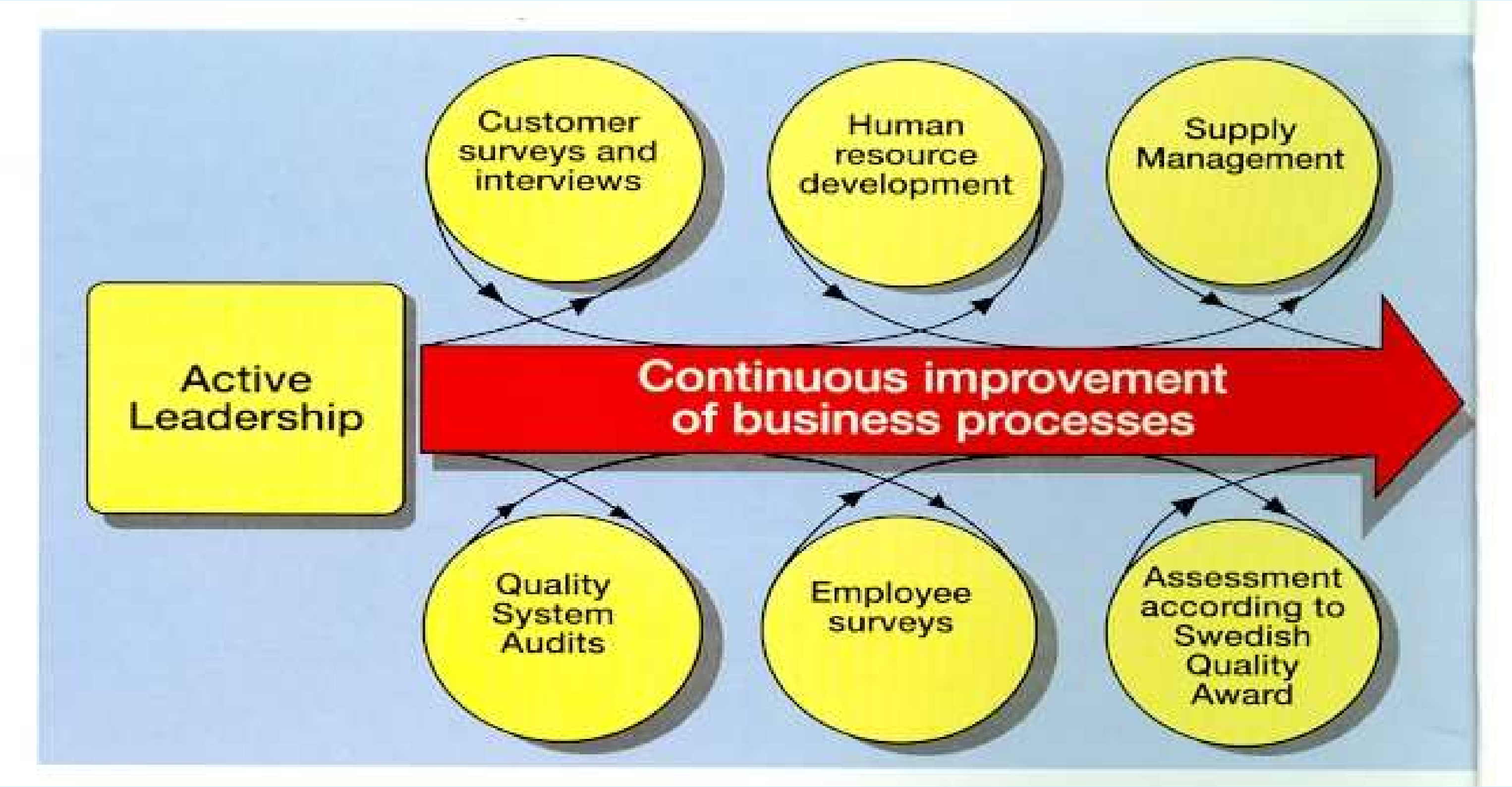
2. Technical:

Highly automated fabrication processes were introduced step by step.

Online data acquisition and evaluation was established with those modern processes to continuously provide the necessary data for manufacturing as well as QA/QC.

R. Viard et.al., "Progress in Manufacturing, Process Control and Associated Criteria",
Proc. Conf. KTG, Subgroup Fuel Elements, Karlsruhe/Germany (1995), pp. 45-56

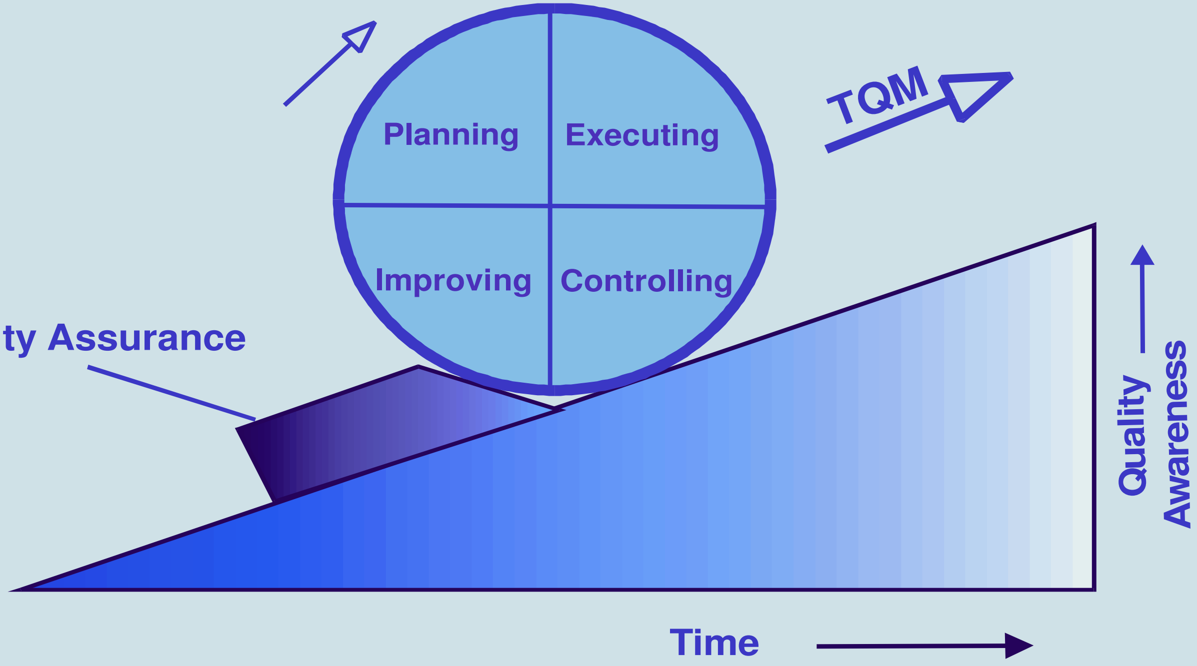
Realization of Total Quality Management, TQM;
Example ABB Approach:
Includes All Areas of Company's Business Activities



Total Quality Approch at ABB Atom Nuclear Fuel Division

A. Micko and E. Halldén, Proc. Conf. KTK Subgroup
"Fuel element", Karlsruhe/Germany (1995) pp. 111 - 117

Relation between Quality Assurance, Total Quality Management, and (Customer´s) Quality Awareness



Qualitätssicherung in der Systemintegration,
in ‘Schlüselfaktor Qualität’

Acc. U.Richert in Dietzel/Seitschek, Mansche Verlags- und
Universitäts-Buchhandlung, Vienna 1992

Process Development for Quality Management

Three main stages for process development have been identified*:

- process and product design (off line)
- manufacturing (on line)
- final inspection, packaging and distribution (off line)

Specific tools are necessary for each of these three stages:

- Improvement Tools for the "Design of Experiments" (DOE) in stage1
- Monitoring tools for the "Statistic Process Control" (SPC) in stage 2
- Controlling tools for the "Statistical Quality Control" (SQC) in stage 3

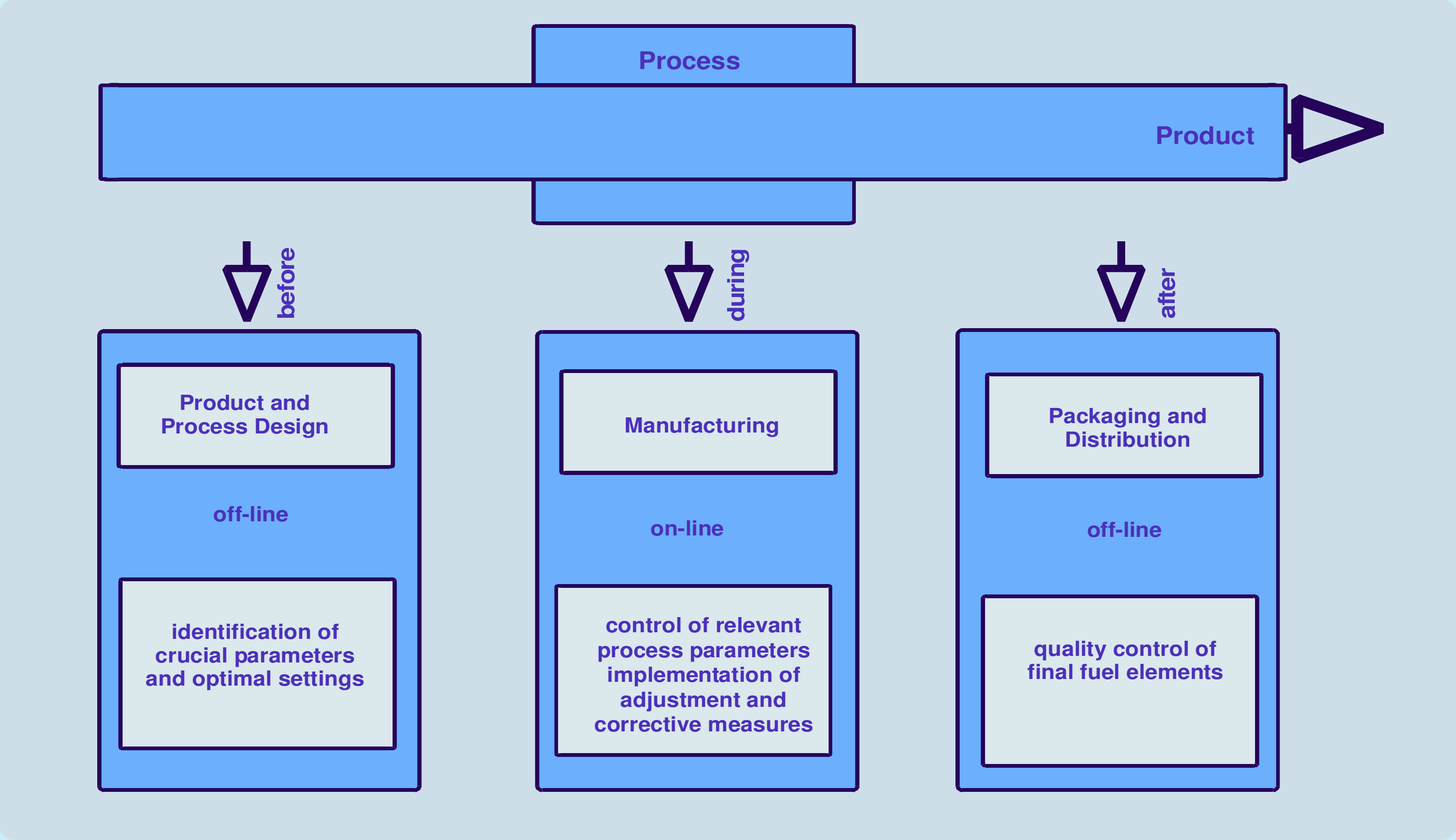
****) Literature***

K. Ishikawa, “Guide to Quality Control”, Asian Productivity Organization, Unipub NY 1985.

H.M. Wadworths et.al., “Modern Method for Quality Control and Quality Improvement”, John Wiley&Sons, NY (1986)

G.E.P. Box et.al., “Quality Practices in Japan”, Quality Progress (1988) 37

The Three Stages of Quality Management in Modern Fuel Production



Process

Product

before

during

after

Product and Process Design

off-line

identification of crucial parameters and optimal settings

Manufacturing

on-line

control of relevant process parameters implementation of adjustment and corrective measures

Packaging and Distribution

off-line

quality control of final fuel elements

Quality management and Quality Assurance
in the Manufacture of Nuclear Fuel Eements

Acc K. Baur and Y.-L. Grize, Kerntechnik 63 (1998) 3, pp. 92 - 97

Quality Tools for Process Development

Overview

Product and Process design, Improvement Tools :“before “

- Quality Function Deployment QFD
- Ishikawa Diagram
- Pareto Diagram
- Failure Mode and Effect Analysis
- Factorial Design Techniques
- Taguchi Method

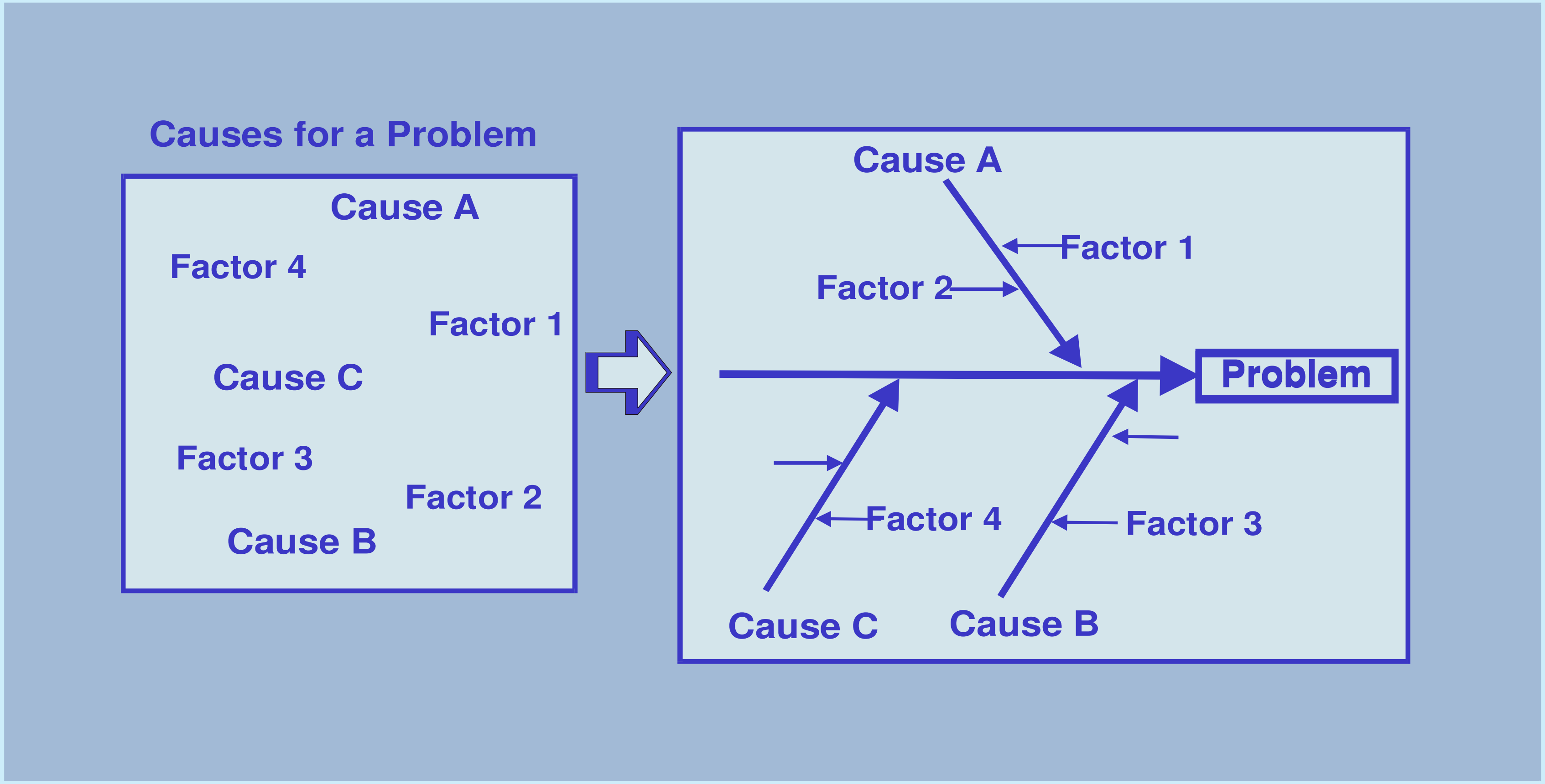
Manufacturing, Monitoring Tools, SPC: “during”

- Box-Plots
- Process-Control-Charts
  - Shewhart Charts (“without memory”)
  - CUSUM Charts (“with memory”)

Final Inspection, Packaging etc. Controlling Tools ,SQC: “after”

- Sampling Plans,
- Process Capability

Quality Tools for "Design of Experiments" (DOE)
Example



Causes for a Problem

Cause A

Factor 4

Factor 1

Cause C

Factor 3

Factor 2

Cause B

Cause A

Factor 1

Factor 2

Problem

Factor 4

Factor 3

Cause C

Cause B

Techniken zur statistischen Qualitätskontrolle
bei der Herstellung von Brennelementen
(Techniques for Statistical Quality Control of Fuel Elements)

Y.-L Grize and . Schmidli Handbuch (Guide Lines)
PreussenElektra, Hannover/Germany (1997)

Design of an Ishikawa Diagram

QA/QC Standards

US-NRC Code of Federal Regulations 10 CFR 50, App. B

The ‚parent‘ of all all basic QA requirements in the nuclear field.
"Quality Assurance Criteria for Nuclear Power Plants and Fuel Processing Plants", issued in 1970, was the basic 'constitution' of QA for many years –
and is still part of most of the commercial purchasing contracts in international nuclear fuel business.

QA/QC Standards

IAEA Quality Assurance Standards

The International Atomic Energy Agency released the “Quality Assurance Standards 50-C-QA” in 1978(1978).

These IAEA standards mainly were safety related and therefore already a 1st revision was released as“Safety Series No. 50-C-QA (Rev. 1)”.

This one was replaced by “Safety Series No. 50-C/SG-Q”, issued in 1996.

A revised version with the same Safety Series No. 50-C/SG-Q was issued in 2001
with the title “Quality Assurance for Safety in Nuclear Power Plants and other Nuclear Installations, Code and Safety Guides Q1-Q14”.

QA/QC Standards

Quality Management Standards in the ISO 9000 Family - I

The “ISO 9000 family” became famous with its "quality management".

Its aims to fulfil:

- the customer's quality requirements, and
- applicable regulatory requirements, while aiming to
- enhance customer satisfaction, and
- achieve continual improvement of its performance in pursuit of these objectives.

There are two key issues of Total Quality Management, i.e.

- ➢ Continuous Improvement,

But now in combination with

- ➢ Customer Satisfaction

And what is called shortly “ISO 9000” is a group of five elaborations from ISO 9000 to ISO 9004, covering

- Guidelines,
- Standards,
- Definitions, and
- Quality management prototypes

QA/QC Standards

Quality Management Standards in the ISO 9000 Family – II

The first versions of ISO 9000 were released in 1994, updated versions exist up to releases in 2000.

In 2003 the tenth – and most recent - edition of the

ISO Standards Compendium ISO 9000 - Quality management

includes the 11 International Standards currently making up the ISO 9000 family, which is developed and maintained by ISO technical committee ISO/TC 176.

Eight quality management principles should considered first:

Principle 1: Customer focus
Principle 2: Leadership
Principle 3: Involvement of people
Principle 4: Process approach
Principle 5: System approach to management
Principle 6: Continual improvement
Principle 7: Factual approach to decision making
Principle 8: Mutually beneficial supplier relationships

Zr-Products Characterization

Specifications

Performance Characterization

Zr-Products Specifications
General

Specifications are *commercial* documents

describing – as a compromise between supplier and customer –

product properties and their determination in a way

that the product properties can be checked for acceptance by the customer.

They can never describe the “real life” performance of the product^.

In particular, for products to be used in a nuclear reactor they can not describe any “in-pile” behavior.

Nevertheless Zr-product specifications have been and always will be part of the purchasing contract for supplying (and accepting) nuclear fuel fuel.

They also play an important role in any licensing procedure for nuclear fuel.

However, they only make sense in the context of the operation experience with the respective Zr-product.

Zr-Products Specifications of Fuel Rod Cladding Tubes I

The function of fuel rod cladding tubes is

- to separate reliably the fuel (-pellets) from the coolant to avoid any mechanical or chemical interaction, and
- to retain all radioactive substances, in particular fission products) within the fuel rod

The specification of fuel rod cladding tubes

- describes their purpose and function within the fuel rod and fuel assembly,
- defines manufacturing and testing procedures, as important for their function, and
- limits for their dimensions and material properties,
- properties of the pre-material as far important for the properties of the cladding tubes.

Zr-Products Specifications of
Fuel Rod Cladding Tubes II

Typically the following requirements are specified:

- qualification of the manufacturer by the purchaser (a/o fuel designer),
- a manufacturing and examination sequence plan, accepted by the purchaser (a/o fuel designer),
- description of all sensitive fabrication and test procedures and the frequency of their application, to be accepted by the purchaser (a/o fuel designer),
- traceability of the final cladding tubes to the used pre-material and main fabrication steps,
- pre-material chemical composition,
- final dimensions and their tolerances according to provided design drawings,
- tube imperfections tested by ultra-sonic technique,
- tube surface quality according to specified tests.
- final material properties as:
  - mechanical properties (short term tensile and circumferential mechanic tube properties and at room and elevated temperature),
  - elevated creep properties according to specified laboratory tests ,
  - laboratory tested corrosion properties according to specified laboratory tests,
  - micro-structure properties like grain size and texture,

The figures for dimensions, material properties etc. depend on the specific design.

Fuel Rod Cladding Tubes
Test Techniques

Testing techniques for cladding tubes (and other Zr-products) have to be in agreement with national and international testing standards.

ASTM testing standards for are used in many specifications for nuclear Zr-products.

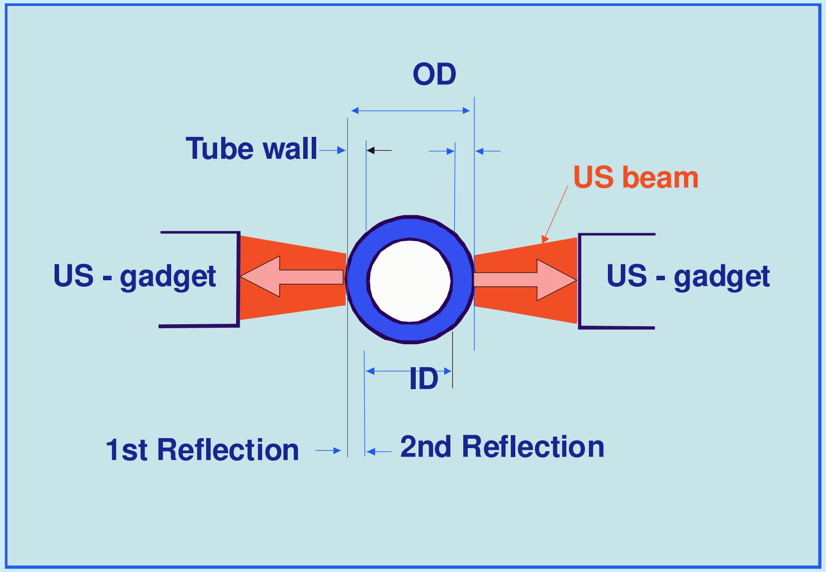
However, most designers of nuclear fuel ask for additional tests or at last for additional requirements, due to their specific experience.

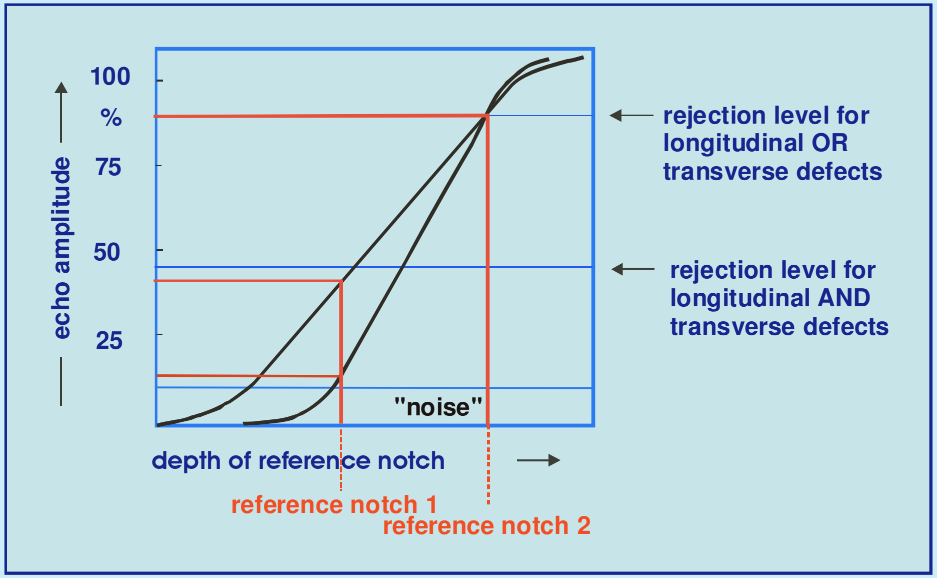
Those additional test are, for example:

- specific tube burst tests to determine the circumferential elongation (ductility) of cladding tubes.
- special corrosion tests with improved simulation of the chemical and thermal conditions in the reactor,
- specific examination of the microstructure, like the texture.

Additional requirements for example, are sometimes requested for the ultrasonic testing on imperfections in cladding tubes

Ultrasonic Tube Tests





G. Dreßler und H. G. Weidinger, IAEA STI/PUB/435, Vienna (1976)

Principle of Ultrasonic test of Zr-Alloy Tube

US-echo-amplitude as a function of the reference notch depth from US equipment having different characteristics (curve A and and B)

Attention:

- ➢ calibration of the UT equipment with two reference notches is very important!
- ➢ the shape of the reference notch and the shape of the US-beam influence the result!
- ➢ every tube producer has to set up a broad evidence of typical imperfections by destructive examination (”defect atlas”)

Zr-Products Specifications
Other Components

Other components in a LWR fuel assembly made of Zr-material today are:

For BWR fuel assemblies:

- the main body of spacer grids (normally springs made of Inconel material are added), fabricated from sheet material
- water-channels or –rods (to improve the moderation in the FA), fabricated from sheet material or tubes (similar as cladding tubes), respectively,
- FA channels, fabricated from sheet material.

For PWR fuel assemblies:

the main body of spacer grids (sometimes springs made of Inconel material are added), fabricated from sheet material

the guide tubes (for the control rods), fabricated tubes (similar as cladding tubes).

The specifications for these products, taking into account their specific functions, are basically set up the same way as for cladding tubes.

Zr-Products
Performance Characterization

Zr-product specifications do not describe any properties directly reflecting the in-pile behavior of those products.

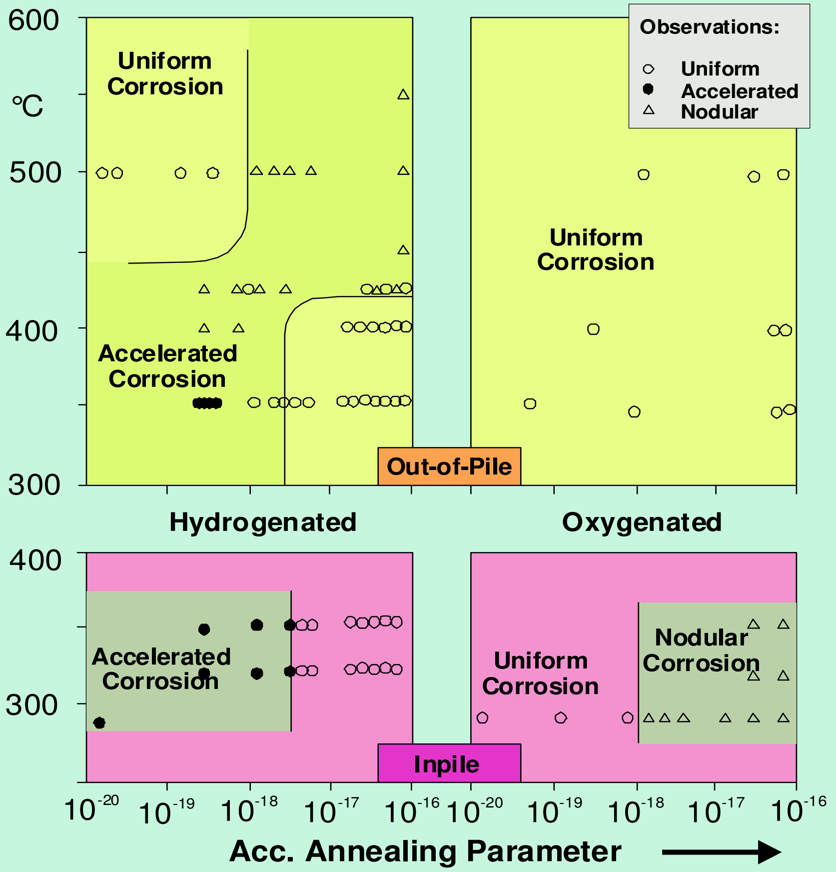
In some cases it is known that laboratory test information is qualitatively different from the respective in-pile behavior.

This holds in particular for the ASTM corrosion tests.

Also laboratory tests that provide rather close simulation of the chemical and thermal conditions in the reactor can not always reliably forecast the in-pile corrosion behavior (see next foil).

Nevertheless these laboratory tests and make sense and are necessary to ensure that a modified Zr-product stays within the range of the existing experience.

SIMULATION OF IN REACTOR CORROSION
CORRELATION WITH OUT-OF PILE RESULTS



F. Garzarolli, E. Steinberg, H.G. Weidinger ASTM STP 1023 (1989) 202

Comparison
In-Pile : Out-of Pile
Results:

Areas of Nodular,
Regular Uniform and
Accelerated Uniform
Corrosion of Zircaloy-4
in BWR - PWR Environment

Zr-Products
Performance Characterization II

A very long and broad experience with the in-pile behavior of Zr-products is necessary to

- develop correlations between
  - the fabrication processes' characteristics and the product properties on the one side, and
  - the in-reactor performance on the other hand.

- define and specify adequate fabrication process parameters and product properties
  - on the basis of the in-pile behavior of Zr-products.

A systematic approach for an adequate – multidimensional – analysis has been proposed.

BEHAVIOR OF ZR-MATERIAL UNDER NORMAL OPERATION

GENERAL 1

The behavior of cladding tubes made of zirconium alloys, either in western pressurized water reactors (PWR) as well as eastern pressurized water reactors (WWER), in boiling water reactors (BWR), and other water-cooled reactors (for example the Canadian CANDU-type or the Russian RBMK), is essentially determined by:

- ☑ Corrosion in the coolant
- ☑ Hydrogen uptake, essentially as a result of corrosion
- ☑ Irradiation induced growth
- ☑ Irradiation induced and thermally activated creep

Water chemistry inside the coolant, the temperature and irradiation conditions determine the corrosion behavior and the hydrogen uptake. These conditions are distinctly different in a PWR as opposed to a BWR. The material composition and the manufacturing conditions must therefore be adjusted thoroughly to the reactor type and its operation conditions in order to achieve an optimization of corrosion.

BEHAVIOR OF ZR-MATERIAL UNDER NORMAL OPERATION

GENERAL 2

The dimensional behavior of fuel components, which is determined mainly by growth and creep is essentially influenced by irradiation conditions and temperature, as well as by the internal stresses in fuel components made of zirconium alloys. These conditions also differentiate among the various reactor types, although not quite to the extent as operation conditions (coolant chemistry) with regard to corrosion.

Whereas many steps of manufacturing history are important for the optimization of corrosion characteristics, the optimization of dimensional behavior solely requires the correct adjustment of the final manufacturing steps, especially the final deforming and annealing parameters.

Altogether, the optimization of manufacturing zirconium materials and the subsequent production of the fuel components is a very complex task which demands highly empirical experience.
The most important correlation which are to be considered can be learned from a multi-matrix.

More detailed data on the behavior during normal operation can be obtained through an overview on the relevant issues.

LWR Performance Oriented Evaluation of Zr-Material Fabrication Processes and Products
General

Performance Criteria
Operation Parameters
Material Properties
Process Parameters

	NEUTRON - FLUX	NEUTRON - FLUENCE	POWER HISTORY	BURN - UP	HEAT TRANSFER	CLAD TEMPERATURE	WATER CHEMISTRY	
STRENGTH		■		■		■		
DUCTILITY		■		■		■		
CREEP	■	■		■		■		
GROWTH		■		■		■		
CORROSION	■		■	■	■	■	■	
HYDROGEN UP-TAKE			■	■	■	■	■	
STRESS CORR. CRACKING		■	■	■				
LOCA				?		■		

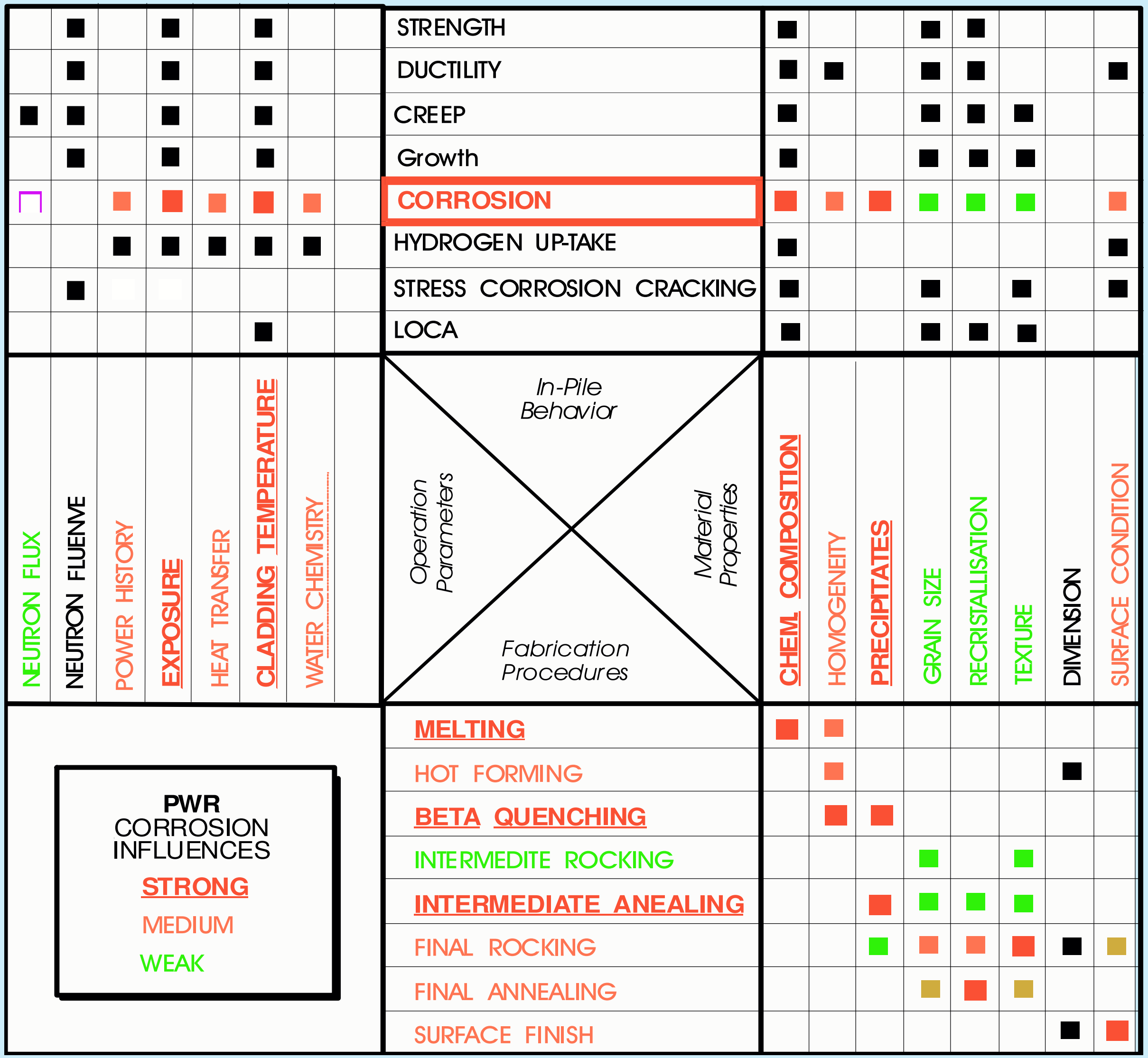
	Chem. Composition	Homogeneity	Precipitates	Grain Size	Recrystalization	Texture	Dimension	Surface Condition
STRENGTH	■			■	■			
DUCTILITY	■	■		■	■			■
CREEP	■			■	■	■		
GROWTH	■			■	■	■		
CORROSION	■	■	■	■	■	■		■
HYDROGEN UP-TAKE	■							■
STRESS CORR. CRACKING	■			■				■
LOCA	■			■	■	■		

	Chem. Composition	Homogeneity	Precipitates	Grain Size	Recrystalization	Texture	Dimension	Surface Condition
MELTING	■	■						
HOT FORMING		■	■					
BETA QUENCHING		■	■					
INTERMED. ROCKING				■		■		
INTERMED. ANNEALING			■	■	■	■		
FINAL ROCKING				■	■	■	■	■
FINAL ANNEALING			■	■	■	■		
Surface Finish							■	■

Hans G. Weidinger, Nürnberg/Germany

Performance Oriented Evaluation of Zr-Material Fabrication Processes and Products

Example PWR-Corrosion



NEUTRON FLUX	NEUTRON FLUENVE	POWER HISTORY	**EXPOSURE**	HEAT TRANSFER	**CLADDING TEMPERATURE**	WATER CHEMISTRY			**CHEM. COMPOSITION**	HOMOGENEITY	**PRECIPITATES**	GRAIN SIZE	RECRISTALLISATION	TEXTURE	DIMENSION	SURFACE CONDITION
	■		■		■			STRENGTH	■			■	■			
	■		■		■			DUCTILITY	■	■		■	■			■
■	■		■		■			CREEP	■			■	■	■		
	■		■		■			Growth	■			■	■	■		
⊓		🟧	🟥	🟧	🟥	🟧		**CORROSION**	🟥	🟧	🟥	🟩	🟩	🟩		🟧
		■	■	■	■	■		HYDROGEN UP-TAKE	■							■
	■							STRESS CORROSION CRACKING	■			■		■		■
					■			LOCA	■			■	■	■		

	CHEM. COMPOSITION	HOMOGENEITY	**PRECIPITATES**	GRAIN SIZE	RECRISTALLISATION	TEXTURE	DIMENSION	SURFACE CONDITION
MELTING	🟥	🟧						
HOT FORMING		🟧					■	
BETA QUENCHING		🟥	🟥					
INTERMEDITE ROCKING				🟩		🟩		
INTERMEDIATE ANEALING			🟥	🟩	🟩	🟩		
FINAL ROCKING			🟩	🟧	🟧	🟥	■	🟨
FINAL ANNEALING				🟨	🟥	🟨		
SURFACE FINISH							■	🟥

PWR
CORROSION
INFLUENCES

STRONG 🟥
MEDIUM 🟧
WEAK 🟩

Zr-Products Quality Verification

Process Control

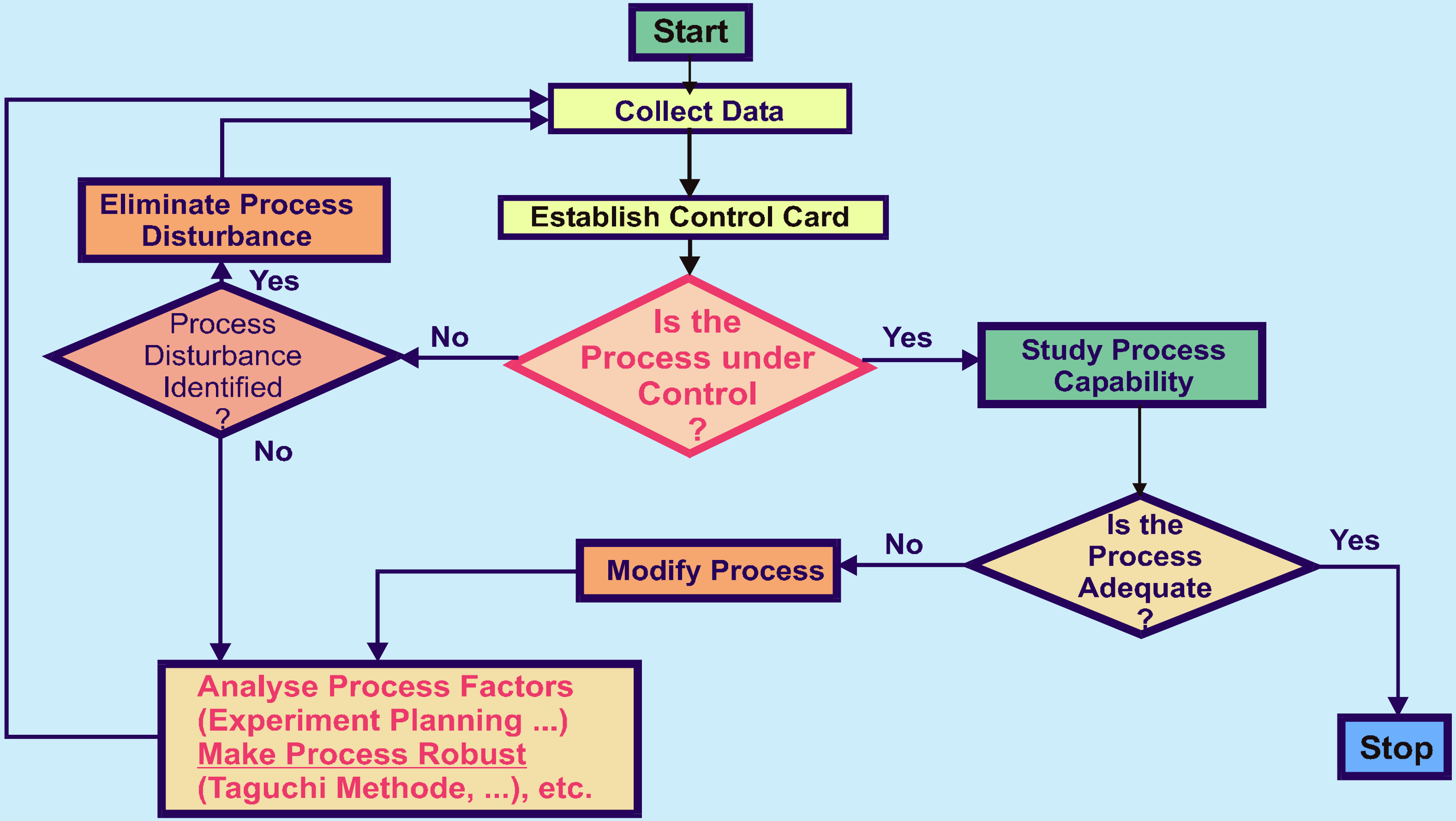
Process Assessment

Product Control

Measuring Equipment Assessment

Process Control

Approaches to Modern Quality Management



Start

Collect Data

Establish Control Card

Is the Process under Control ?

Yes

Study Process Capability

Is the Process Adequate ?

Yes

Stop

No

Modify Process

No

Process Disturbance Identified ?

Yes

Eliminate Process Disturbance

No

Analyse Process Factors (Experiment Planning ...)
Make Process Robust (Taguchi Methode, ...), etc.

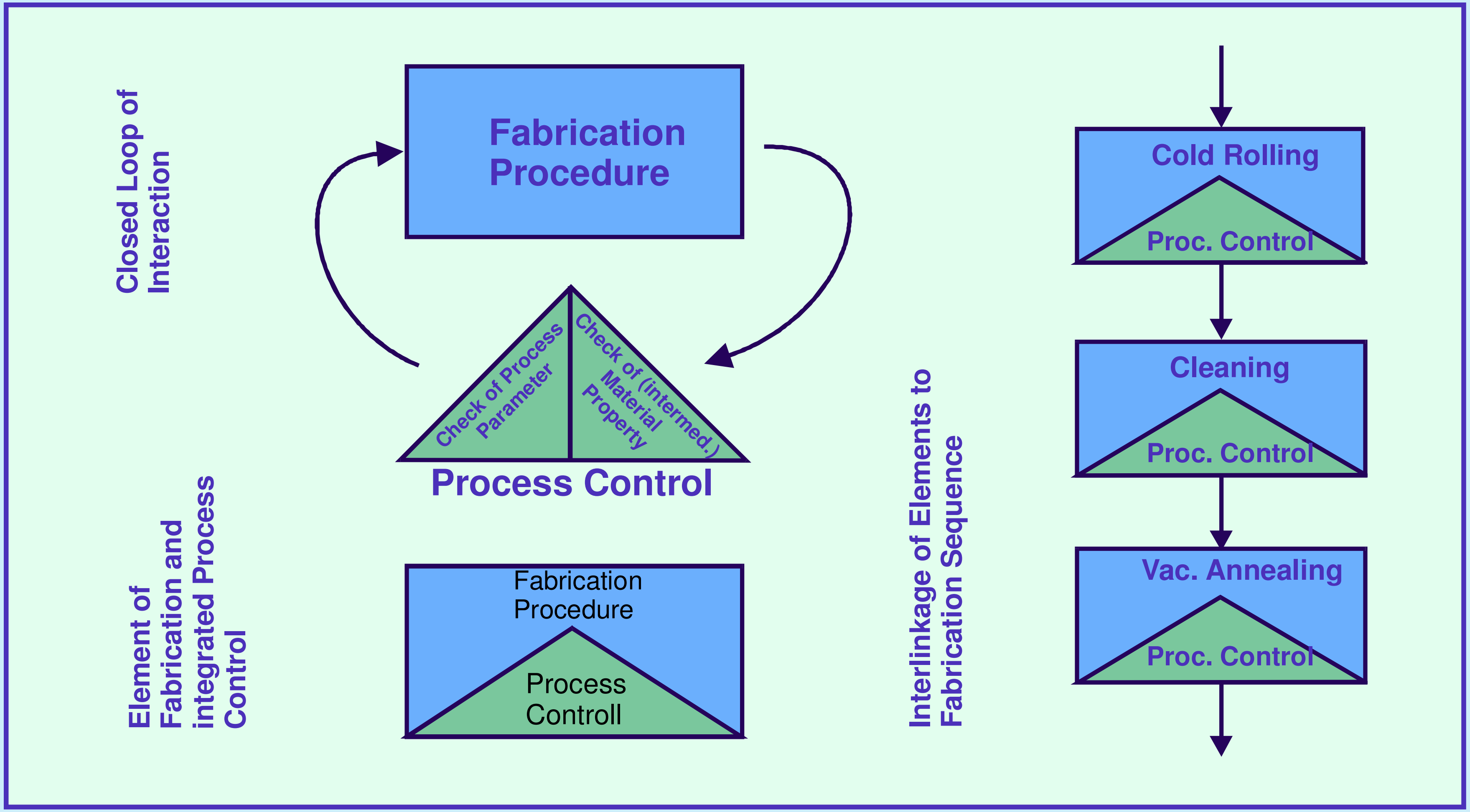
Strategy to Improve Fabrication Processes

Y.L. Grize, CIBA Techn. Report Nr. 9304 (1993)

Performance Related Process Aanalysis and Assessment Example

Process Step	Process Target	Critical Process Parameter	Critical Material Properties	Consequences On Final Product
Scrap-Recycling	Re-Use of Scrap	Removal of Foreign Particles, Cleaning Processes	Foreign Particles Cleanliness Scrap, Reliability of Chem. Composition	Chemical Composition, Corrosion Mechanical Properties
Alloying	Chemical Composition of Alloy	Calculation and Addition of Alloying Elements in Accordance with Scrap Composition	(Tolerances of) Chemical Composition	Short Term and Creep Strength , Corrosion
Electrode Preparation	Combination of Sponge, Scrap and Alloying Elements	Mixing and Pressing of "Briquets"; Melting of Electrode(Vacuum!)	Contamination (From Electrode or Foreign Material)	Purity and Homogeneity, **Corrosion**
Melting	Chemically Homogeneous Alloy	Height and Centrality of Melting Pool, Power Characteristic of Melting Process, Vacuum Quality	Chemical Purity (Chlorine!) , Chemical Homogeneity, Gas Contents	Chemical Purity (Cl!), Homogeneity of Alloying Elements (Sn, Fe, Cr, etc.) **Corrosion**

Process Control
Feed Back



Closed Loop of Interaction

Fabrication Procedure

Check of Process Parameter

Check of (intermed.) Material Property

Process Control

Element of Fabrication and integrated Process Control

Fabrication Procedure

Process Controll

Interlinkage of Elements to Fabrication Sequence

Cold Rolling

Proc. Control

Cleaning

Proc. Control

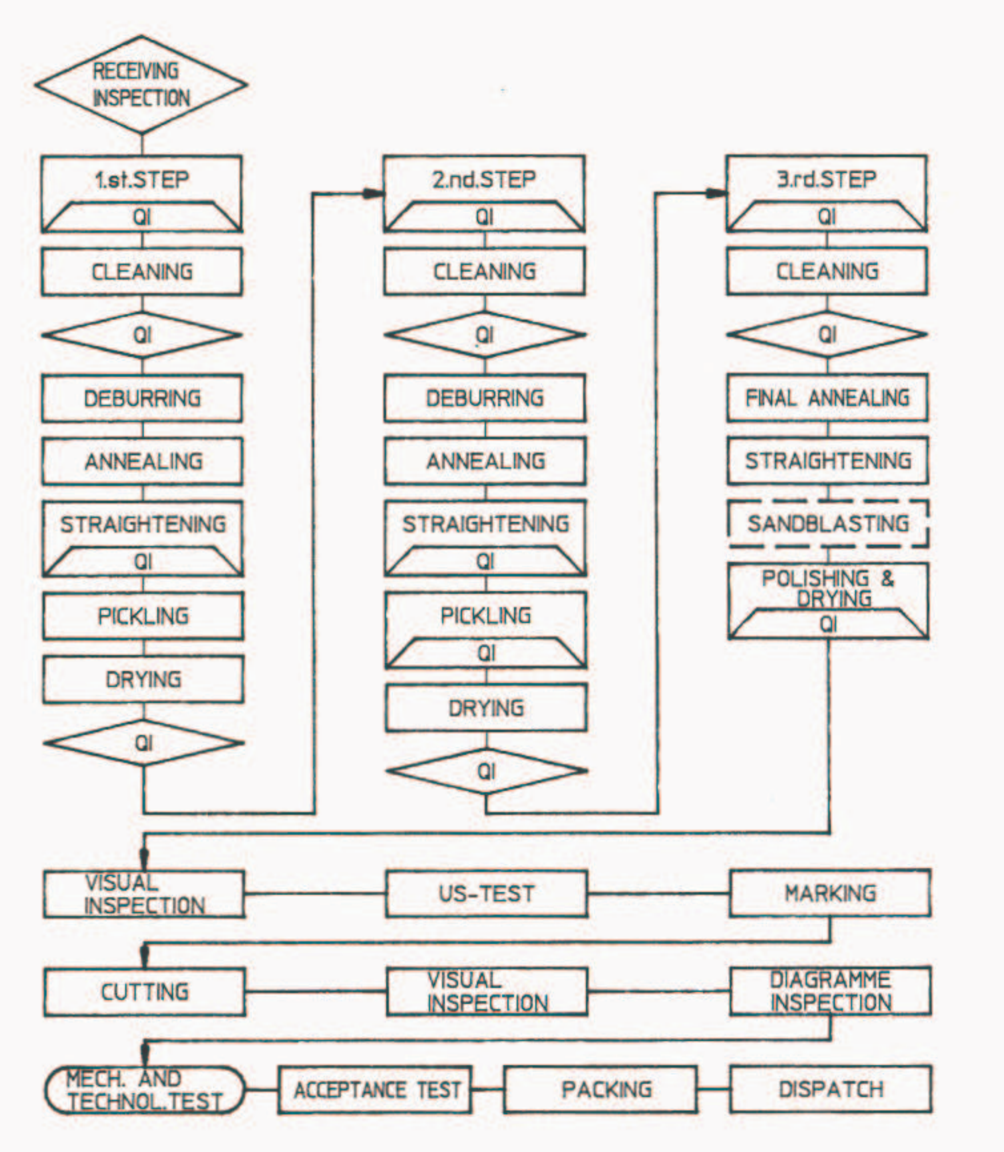
Vac. Annealing

Proc. Control

Interaction of Fabrication and Integrated Process Control and Example for Fabrication Sequence with Interlinked Fabrication Elements

H.G. Weidinger and K.H. Kunz, IAEA SR-102/53 Karlsruhe KFK 3777 (1984) 365

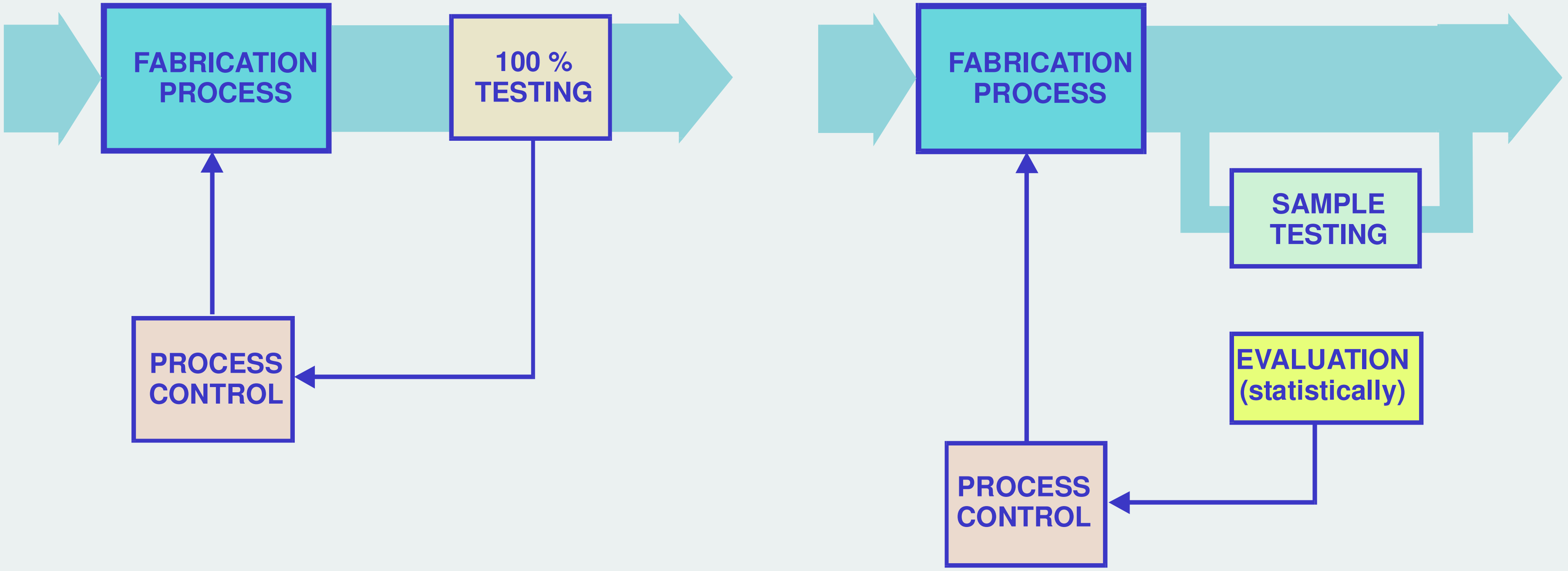
Process Control by Product Control Feed Back



Example of process flow and QC
at cladding tube production

D. Knödler et al. Kerntechnik 50 (1987), No. 4. P.245 - 265

Process Control by
Product Control Feed Back



FABRICATION PROCESS

100 % TESTING

PROCESS CONTROL

FABRICATION PROCESS

SAMPLE TESTING

EVALUATION (statistically)

PROCESS CONTROL

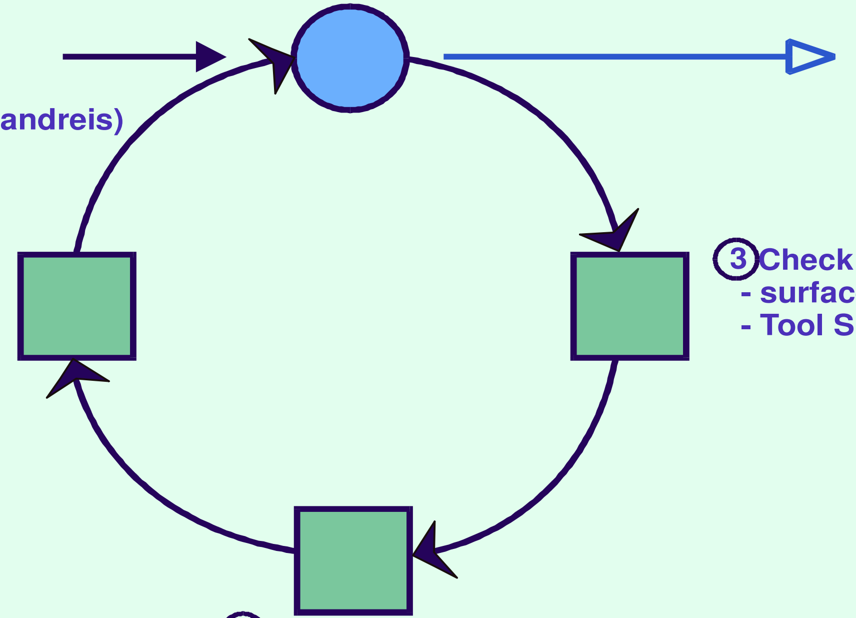
CONTINEOUS PROCESS CONTROL

STATISTICAL PROCESS CONTROL

Qualitätssicherung, Statistische Methoden, **W. Timischl, Carl Hanser Verlag, München-Wien (1995), p. 177**

Fabrication as Part of a Control Circuit

Process Control
Cladding Tube Cold Rolling



① **TARGET**

Process:
Surface and Geometry of
Rolling Tools (Dies and Mandreis)

Product:
Warning Limits and Limit
for Action for Roughness

② **Performance of**
Cold Rolling Step

Information for
next Step:
- Roughness within
Warning Limits or
- Rework of surface

③ **Check actual**
- surface Roughness
- Tool Surface and Geometry

④ **Compare measured Roughness**
with warning Limit

⑤ **Corrective Actions:**
- Rework of Tools
- Change of Cold
Rolling Parameters
(f.i. feed)

Process Control During Cold Rolling on Surface Roughness

H.G. Weidinger and K.H. Kunz, IAEA SR-102/53, Karlsruhe KFK 3777 (1984) 365

Cladding Tube Process Control
Example

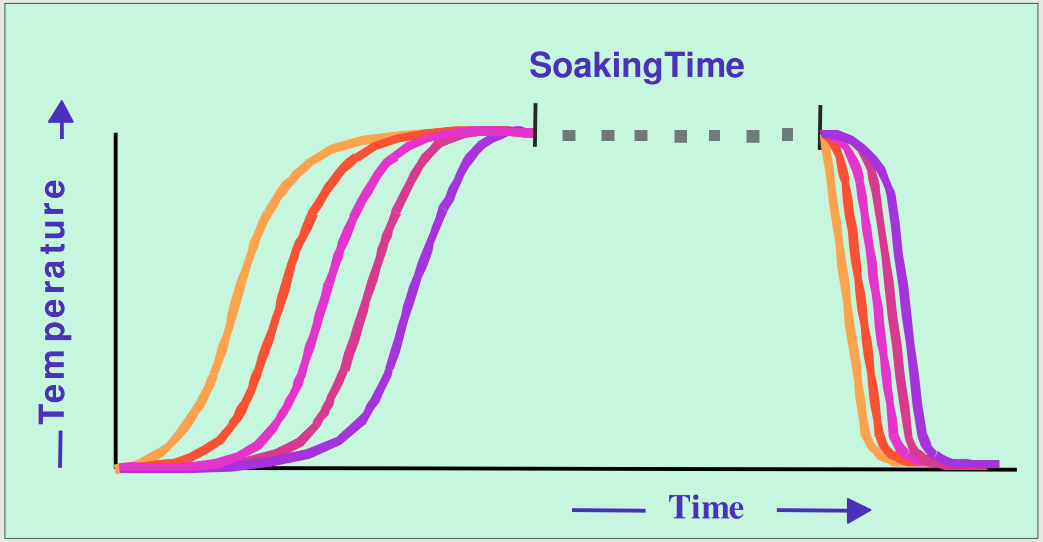
Procedure	Check of Process		Check Intermed. Product	
	Process Parameters	Test Method	Product Property	Test Method
Cold Rolling	Tool Geometry Feed Speed of Lift Lubrication	Specific Measuring Equipment Inspection	Dimension Surface Inspection	Micrometer Inspection Pulse Echo UT
Cleaning	Bath Composition Temperature Pressure	Chem. Analysis Themocouples & spec. Gadgets + Recording	Cleanliness	Wiping Test Visual Inspection
Vacuum Annealing	Temperature Time Vacuum	Thermo-couples & spec. Gadgets + Recording	Surface Mechanical Properties (Final Anneal only)	Inspection Tensile Test Burst Test Structure & Texture

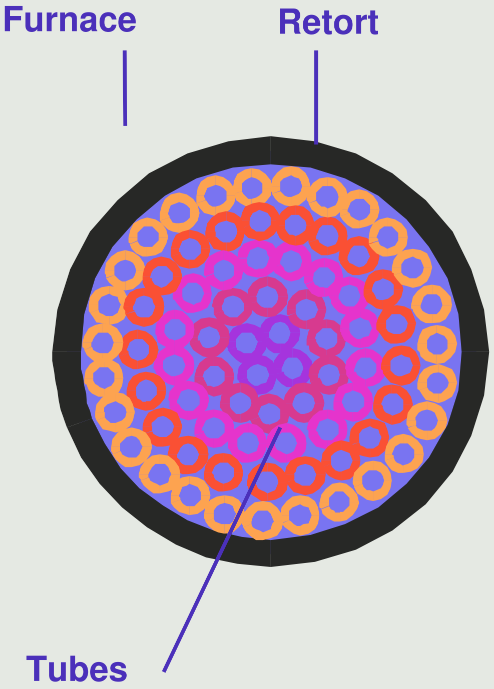
Process Control at Cold Rolling, Cleaning and Vacuum Annealing

H.G. Weidinger and K.H. Kunz, IAEA SR-102/53, Karlsruhe KFK 3777 (1984) 365

Optimizing Tube Annealing

TECHNOLOGICAL BACKGROUND
FOR ADEQUATE VACCUUM ANNEALING

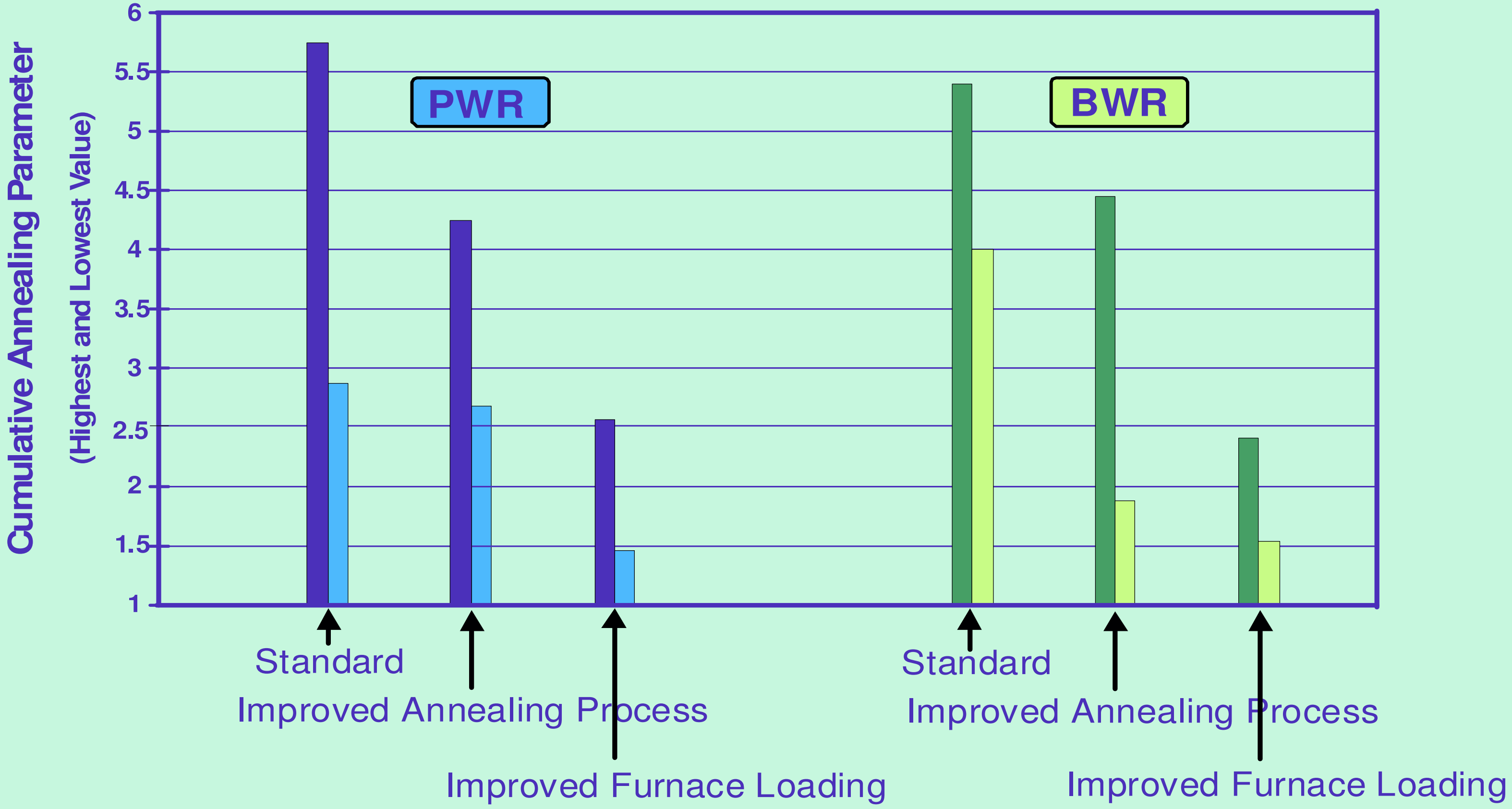




Schematic Depiction of The Local Difference in Temperature
vs. Time History During Vacuum Annealing of Zircaloy Tubes

H.G.Weidinger

Process Improvement Example



Acc. C. M. Eucken and J. P. Tosdale, EPRI PWR Corrosion Workshop, Washington D.C. (1993)

Annealing Parameter before and after Improvement of Processes

Process Assessment

Two Basic Objectives
of Process Oriented Quality Strategy

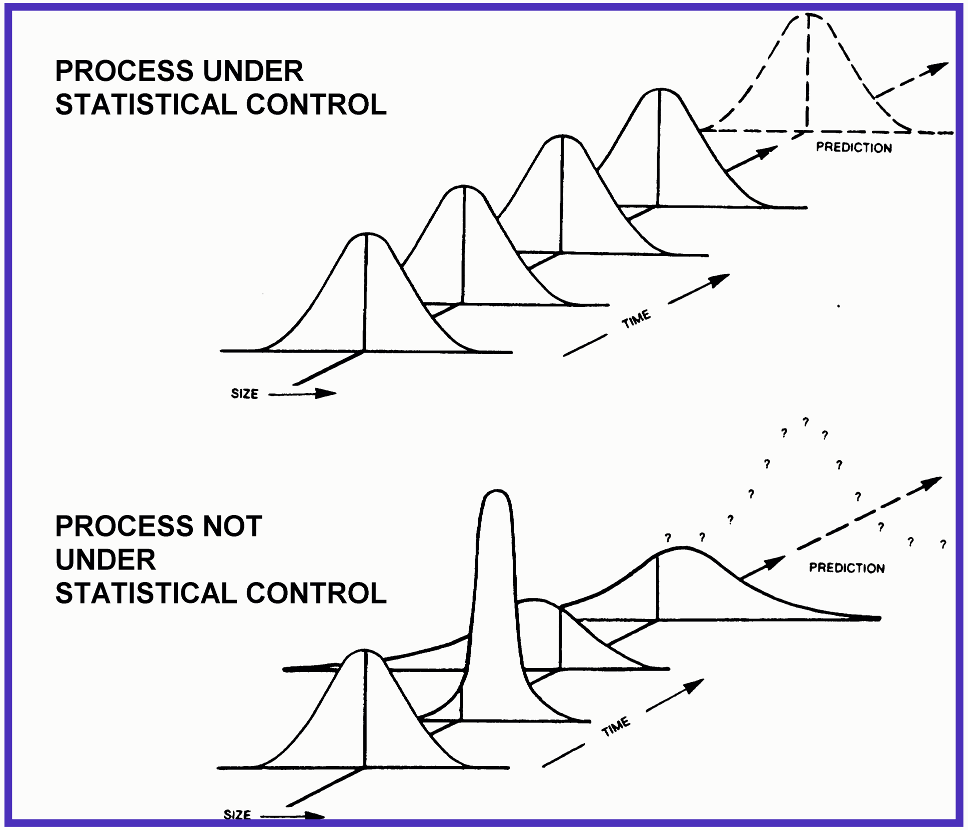
- ☼ assure that the applied processes are STABLE,
  i.e. controlled within a normal stochastic scattering;

- ☼ assure that the applied processes are CAPABLE
  of staying within the tolerance limits of the respective quality characteristics.

A process may be stable but does not stay within the QC limits.

Also, a process – for some time – may stay within those QC limits but is not stable.
Such a process may run out of control and then also out of the limits specified.

Each process shows variations, however ...”



Y.L. Grize Ciba-Geigy Tech. Report No. 9304

Control of Process Variability

The Basic Characteristics of Quality Control Charts (QCC)

A QCC is a graphical evaluation of the time history of a quality characteristic, i.e. as a function of the (random) sample number or of time respectively. Commonly a constant number of random samples is taken from the process in equal time intervals.

Shewhart Chart:

Observed or measured values are plotted

- directly, as observed measured, or
- as densified values, e.g. as mean values, standard deviations etc.

This type of chart does not add up time effects (chart “without memory”)

Typically such a chart shows

- a central line, i.e. the nominal value, and
- an upper and lower control limit (UCL, LCL)

For a normal distribution control limits of directly plotted values are defined as

x ± 3 ♦

leading to a probability of 0.3 % that any single value is out of those limits (6-Sigma criterion).

In case of plotting mean values ☒ the control limits within a 6-Sigma criterion are given as

$$\bar{x} \pm 3 \frac{\bar{\sigma}}{\sqrt{m}}$$

The Basic Characteristics of Quality Control Charts (QCC) Ct'd

CUSUM Chart:

(Cumulative Sum Chart)

In this case the test variable is a function of the actual plus previous sampling results.
Therefore this is called a "chart with memory
If n measurements are performed, the cumulative sums Z_1, Z_2, ... Z_n are defined as

$$Z_i = (x_1 - \mu) + (x_2 - \mu) + \ldots + (x_i - \mu),\ i = 1, 2, \ldots N$$

with µ as nominal or expected value.

Z_i is plotted versus the time steps i.

The special advantage of this way of plotting is that small process shifts can be shown as drastic trend changes.

Other Types of Charts

MOSUM Chart: Moving Sum Chart,
EWMA Chart: Experimentally Weighted Moving Average Chart

Quality Control Cards (QCC)

(Acc. Shewhart)

TARGETS

Distinguish between, normal (unavoidable) random deviations (disturbances) from systematic deviations within a fabrication process.

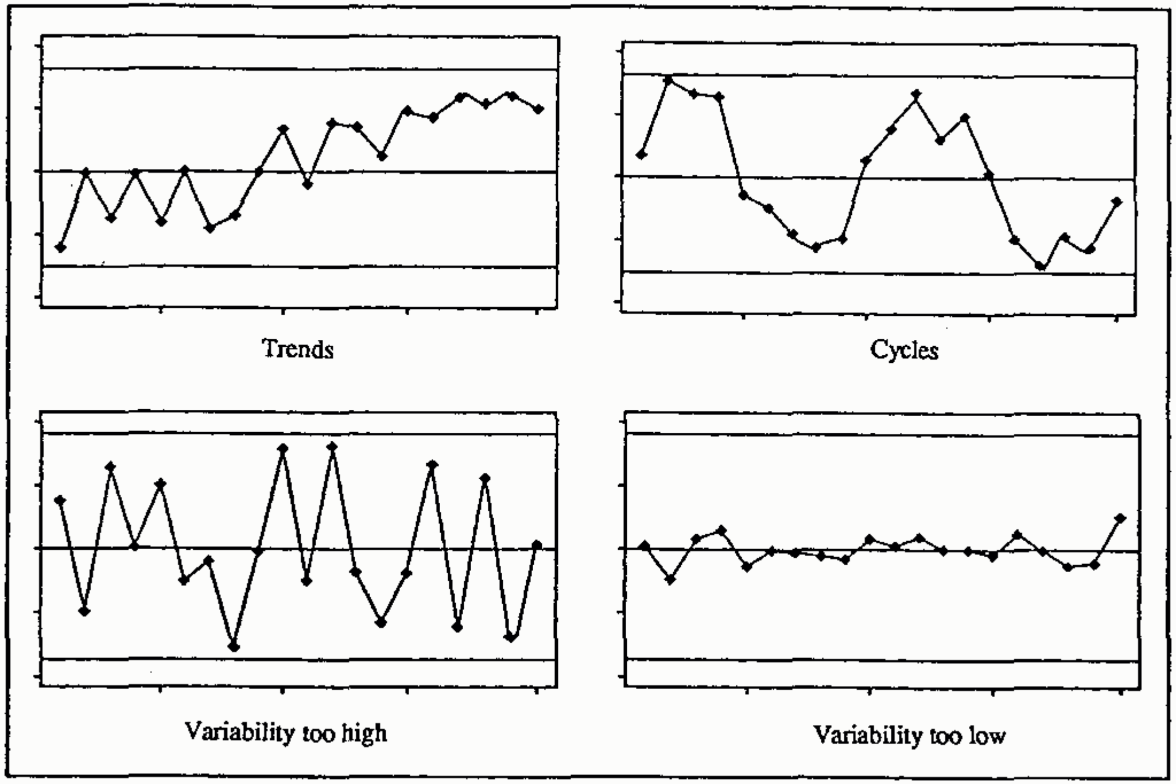
Assess if a fabrication process is under control: i.e. if the process is stable (undisturbed, or, with other words, if the process is “under statistical control”.

APPLICATION

On counting and measuring test procedures.

METHOD

- Collect a set of (random) sample values of the process relevant property
- List and plot these values vs. Flow of process flow timing
- Identify type and parameters of value distribution, e.g. normal distribution, mean value, standard deviation, etc.
- Determine Upper and Lower Control Limit UCL for the process relevant property values (depending on type and parameters of distribution)
- Assess process stability, trends etc.



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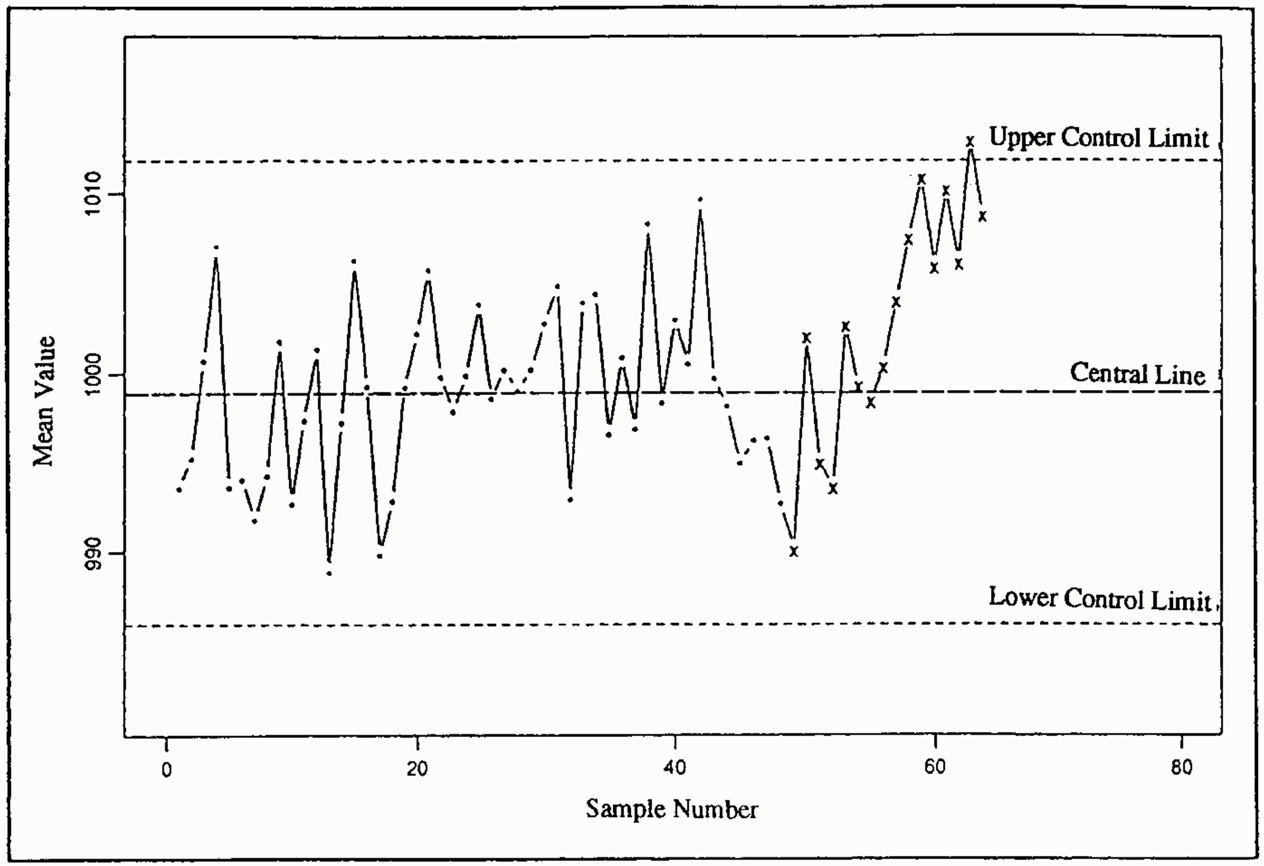
Example for evaluation of trends, cycles, variability too high and too low with $\overline{X}$-process control charts acc. Shewhart



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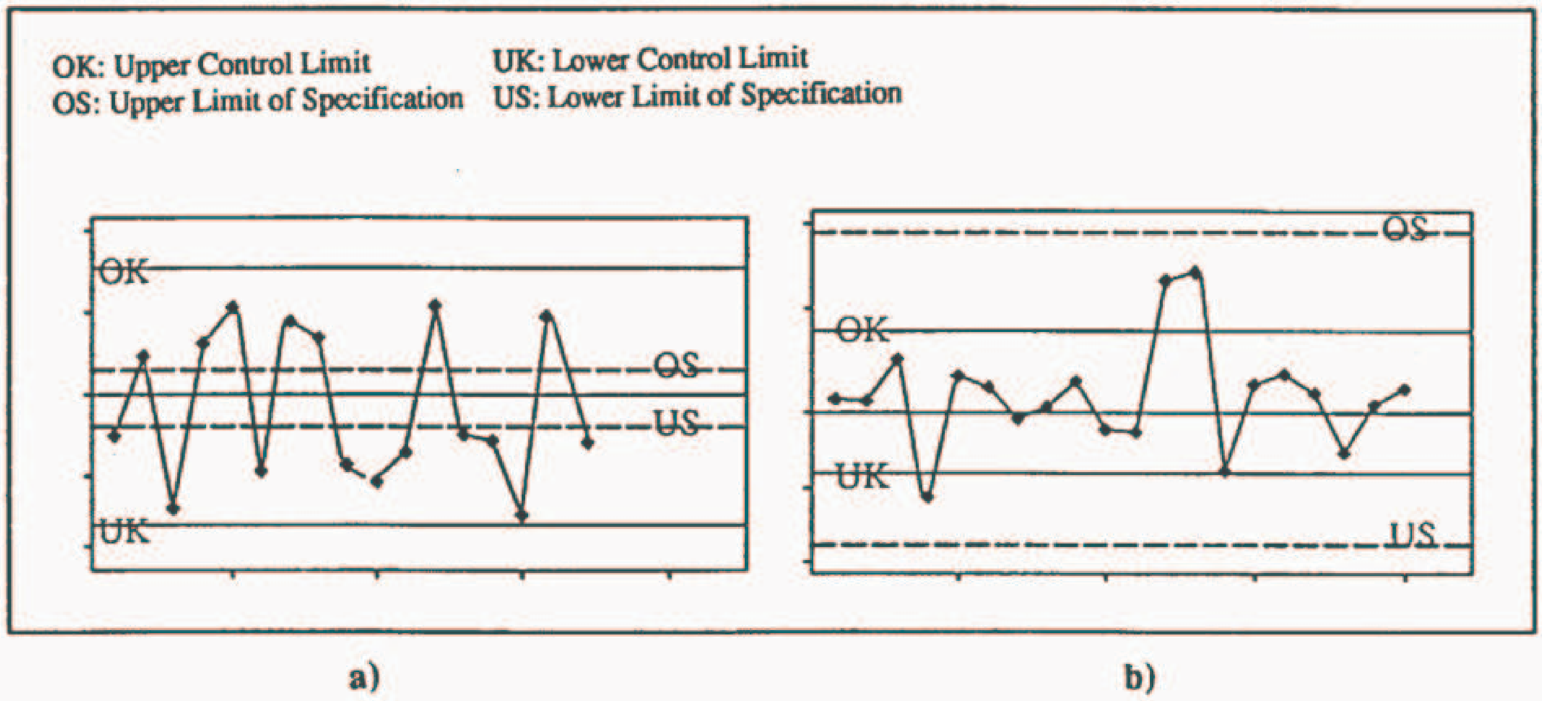
General Example for $\overline{X}$- Process Control Chart



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Examples for

a) **Process Is under statistical control, yet all points are out of specification**
b) **Process is not under statistical control, but all points are within specification**

Process Capability

The Basic Target of Quality Control Charts (QCC)

- Evaluate if a process is under statistical control, i.e. the process is stable

The primary purpose of a QCC is to monitor quality characteristics of a process running during production to detect undesirable developments as soon as possible.

Those developments may be trends, cycles, undesirable variability in the process.

The primary cause of QCC is NOT to control if the product of the monitored process stays within the specification limits.

This is done by process capability evaluations.

Process Capability Indices

Basic Idea:

How well does a stable (= statistically controlled) process fulfill the specification?

Cp-Index

$$Cp = \frac{\text{Width of Specification}}{\text{Width of Process}} = \frac{USL - LSL}{6\sigma}$$

USL = upper specification limit

LSL = lower specification limit

This Cp index does not answer the question if the process is “centered”. This is done by

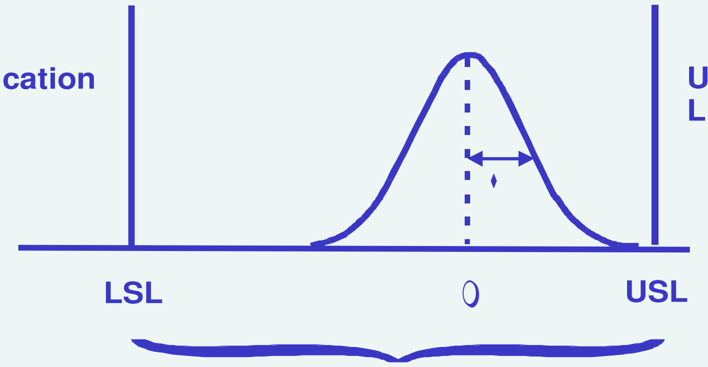
Cpk-Index

$$Cpk = \text{Min}\left(\frac{USL - \mu}{3\sigma} , \frac{\mu - LSL}{3\sigma} \right)$$

with 3σ = 1/2 process width

Process Variability Described by Normal Distribution

Lower Specification Limit (LSL)



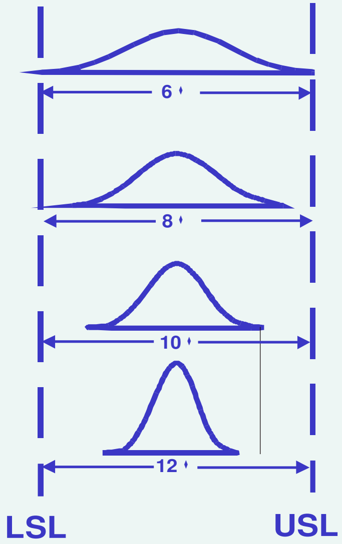
Upper Specification Limit (USL)

Given Specification Interval

"Techniken zur statistischen Qualitätskontrolle
bei der Herstellung von Brennelementen"
(Techniques for Statistical Quality Control during
Fabrication of Fuel Assemblies)

Y. L. Grize and H. Schmidli, Handbook
PREUSSENELEKTRA, Hannover/Germany (1997)

Comparison of Specification Width with Process Variation



c_p	Process width in % of specification width	Number of values out of specification
1.0	100	2700 ppm
1.33	75	63 ppm
1.67	60	0.6 ppm
2.0	50	< 0.01ppm

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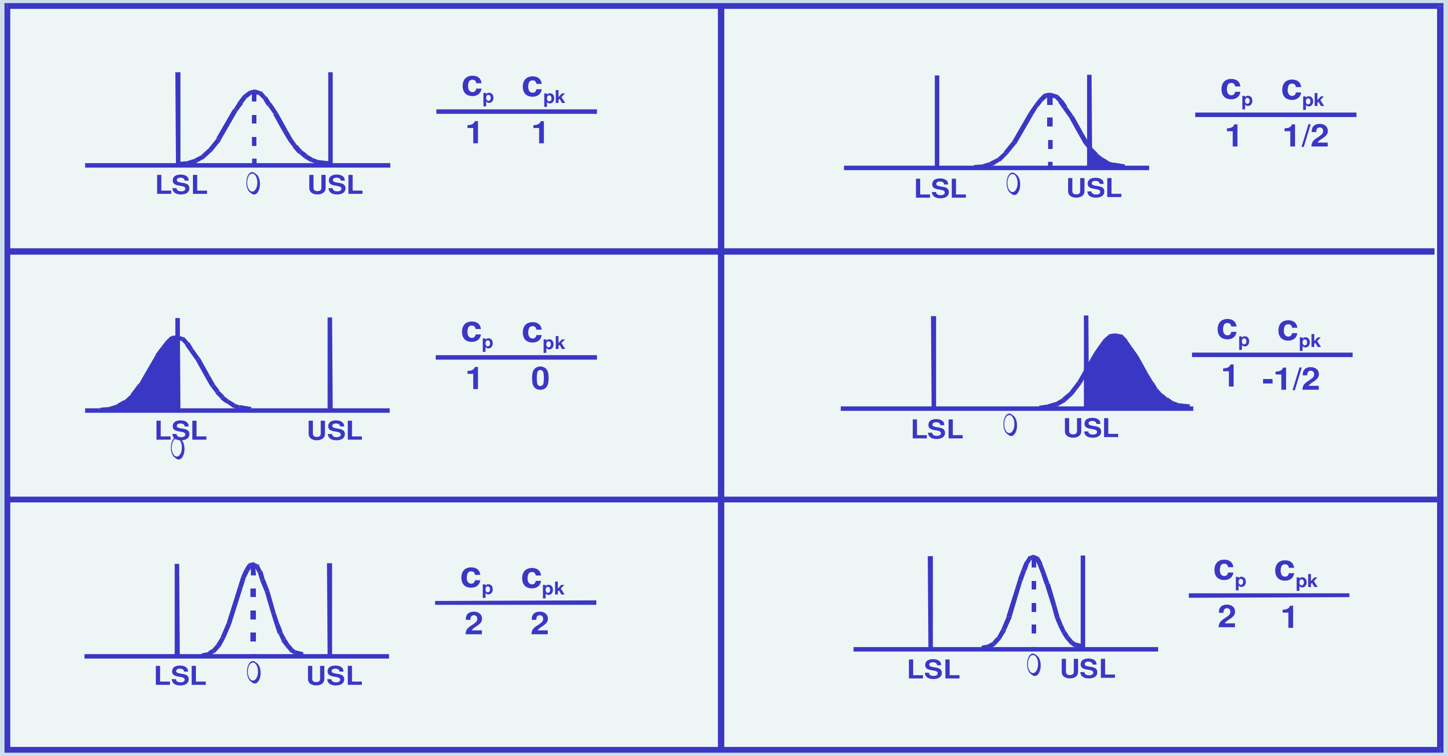
PREUSSENELEKTRA, Hannover/Germany (1997)

Process Capability c_p for Various Process Variations



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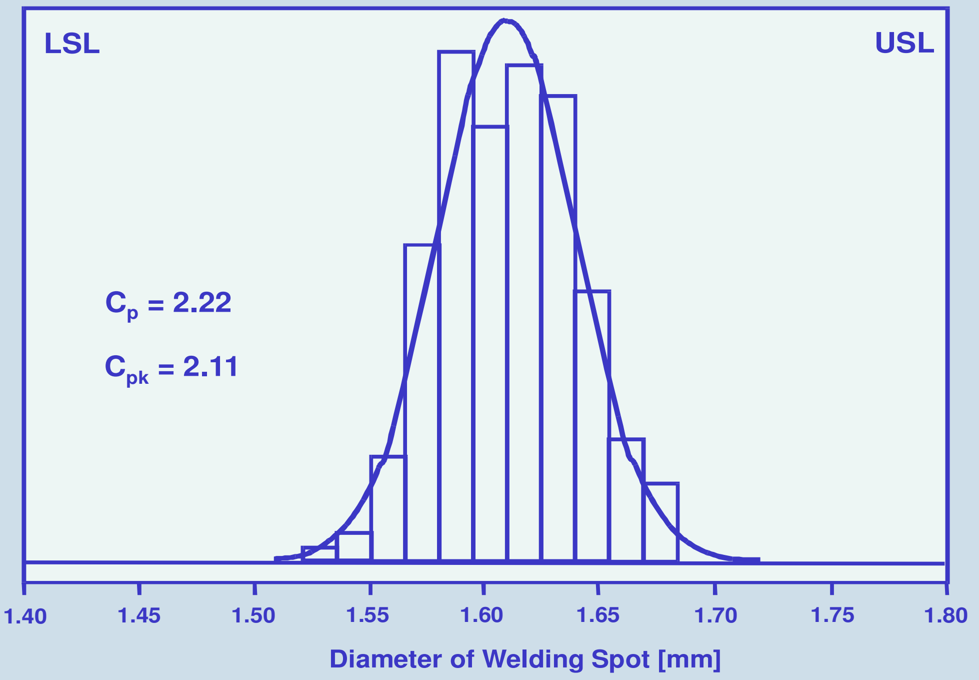
PREUSSENELEKTRA, Hannover/Germany (1997)

Process Capability c_p and c_{pk} for Various Processes with Normal Distribution



Specification: LSL = 1,40 mm, USL = 1,80 mm

Measurement of 189 spacer grids results in

μ = 1,61 mm
σ = 0,03 mm

with the 6σ criterion the process capability indices are

$$Cp = \frac{1.80 - 1.0}{6 \times 0.3} = 2.22$$

$$Cpk = \mathrm{Min}\left(\frac{1.80 - 1.61}{3 \times 0.03} , \frac{1.61 - 1.40}{3 \times 0.03} \right) = 2.11$$

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Y. L. Grize and H. Schmidli, Handbook
PREUSSENELEKTRA, Hannover/Germany (1997)

Example: Process Capability of Spacer Grid Welding

Product Control

Two Basic Causes
for Deviation of Quality Characteristics

<u>Common Causes = Systematic Disturbances</u>,

to be identified case by case (e.g. quality of pre-material, conditions of equipment, training of workers, etc.).

They can be reasonably controlled.

Those controllable factors are the real objective of QC

<u>Special Causes = Stochastic Disturbances</u>.

They are out of a reasonable deterministic control.

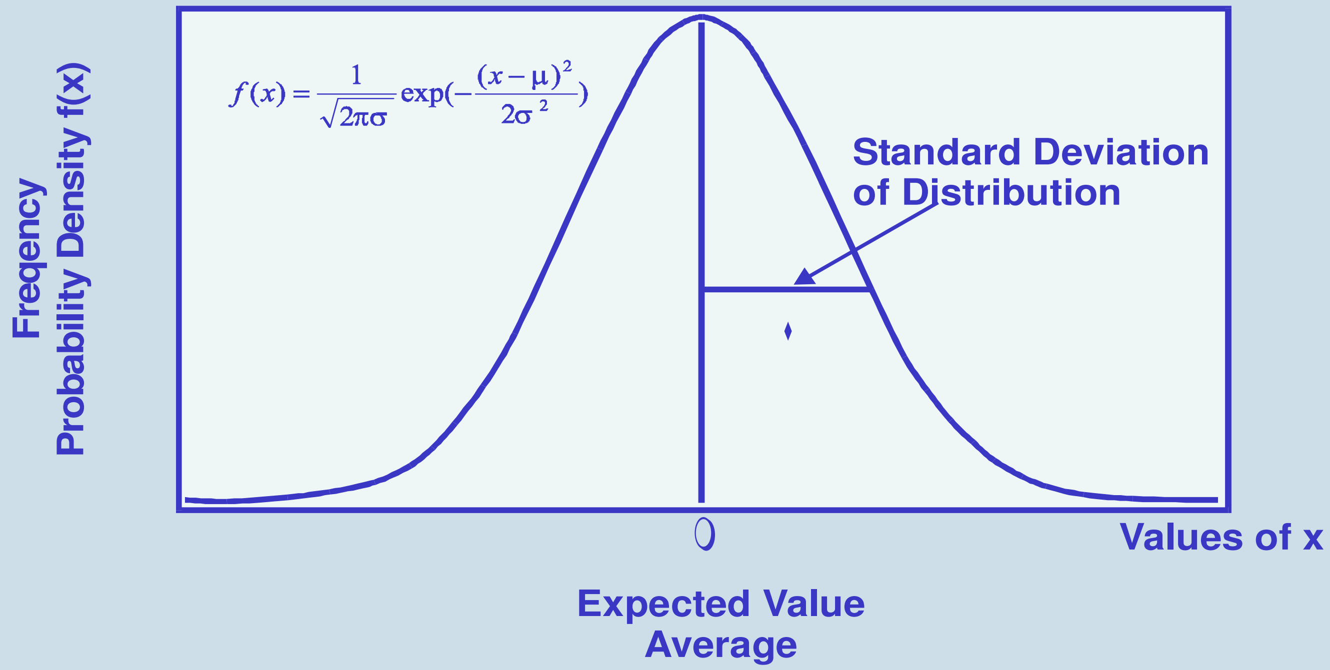
They result in typical statistical distribution of process or product parameter.

In many cases a so-called “normal” (Gaussian) distribution is found.

However, very important:

there are also <u>other types of statistical distribution</u>, e.g.

- a “log-normal”, or a
- “Weibull”-distribution



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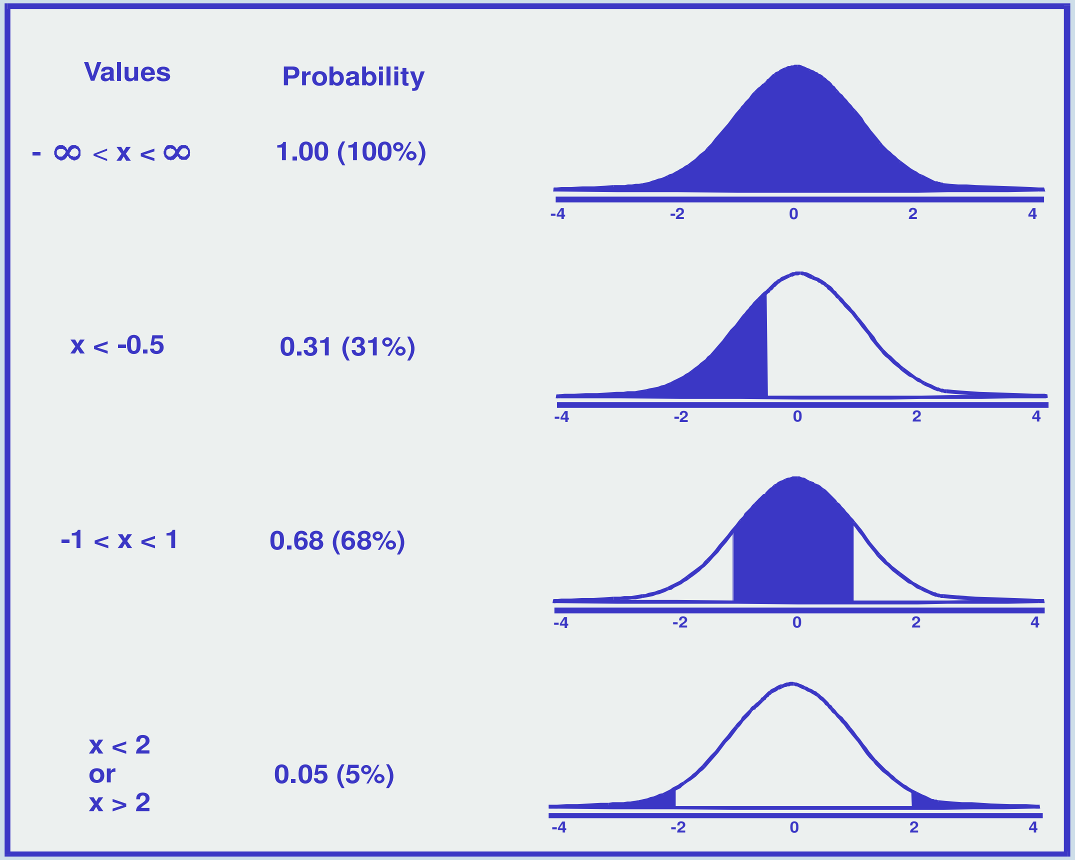
PREUSSENELEKTRA, Hannover/Germany (1997)

Normal Distribution of Quality Characteristics: Probability Density, Expected Value (Average), Standard Deviation

3. Statistical Distribution of Quality Characteristics



Values	Probability
$-\infty < x < \infty$	1.00 (100%)
$x < -0.5$	0.31 (31%)
$-1 < x < 1$	0.68 (68%)
$x < 2$ or $x > 2$	0.05 (5%)

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PREUSSENELEKTRA, Hannover/Germany (1997)

Probabilities in Normal Distribution

RANGE	PROBABALITY
0 📫 ♦ to 0 🖃 ♦	~68% or ~2/3
0 📫 📄♦ to 0 🖃 📄♦	~95%
0 📫 🗏♦ to 0 🖃 🗏♦	~99,7%

Qualitätssicherung - Statistische Methoden
(Quality Assurance - Statistical Methods)

W. Timisch, Carl Hanser Verlag
München Wie (1995), p. 91

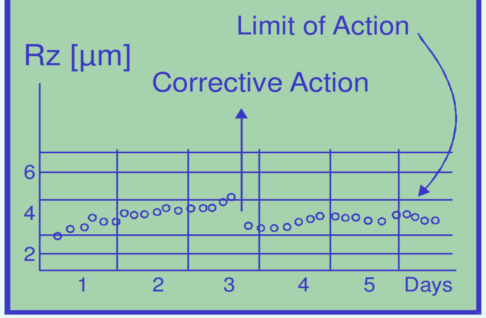
Table I Ranges and Probabilities for Measured Values in a Normal Distribution

Pilger Mill Nr.
Day, Month, Year
Shift Nr.
Ingot Nr.
Order Nr.

Time	Rz[µm]	Ra[µm]	Comment
—	5	0,7	Specif.
—	4,3	0,6	Warnig Unit
—	4,5	0,64	Unit for Action
6^{00}	4,1	0,4	O.K.
6^{30}	4,0	0,4	O.K.
7^{00}	4,4	0,45	W.L.!
7^{30}	4,6	0,5	L.A.!
etc.	....	....	....

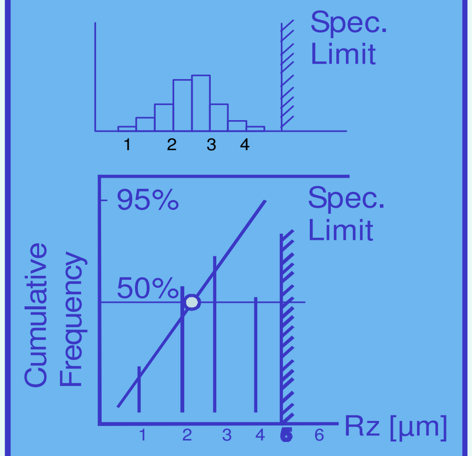
Test Record per shift

Pilger Mill Nr.
Week, Year
Ingot Nr.
Order Nr.



Weekly Data Survey per Rolling Mill

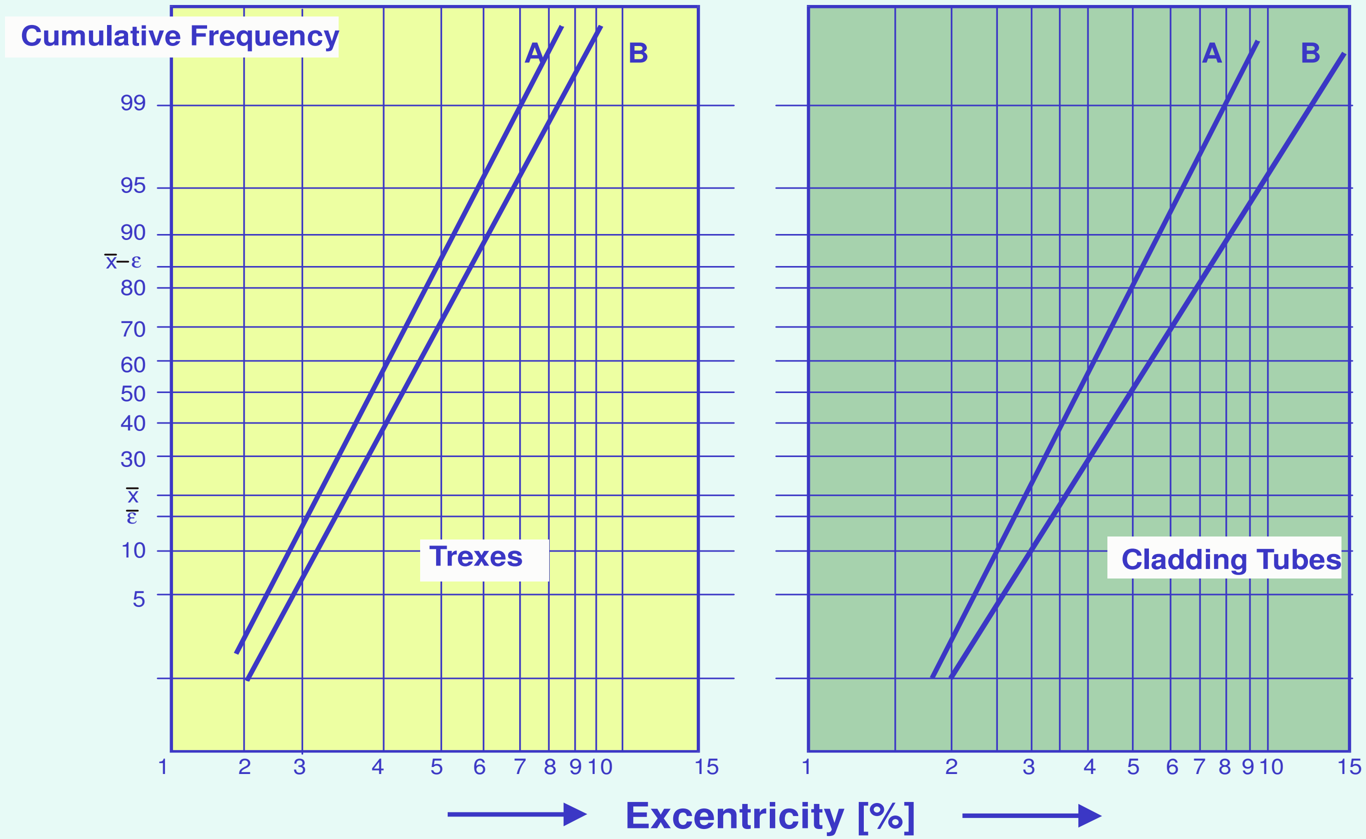
Ingot Nr. Order Nr.



Statistical Distribution per Ingot

H.G. Weidinger and K.H. Kunz, IAEA SR-102/53
Karlsruhe KFK 3777 (1984) 365

Evaluation and Documentation of Surface Roughness Values from Process Control during Cold Rolling



H.G. Weidinger and K.H. Kunz, IAEA SR-102/53
Karlsruhe KFK 3777 (1984) 365

Influence of Trex Eccentricity on Eccentricity of Cladding Tubes, Comparing Statistical Evaluations for two Projects: A and B

Measuring Equipment Assessment

Two Major Causes Influence the Measurement Capability:

- ☼ The (standard deviation) of the measuring instrument is too large in comparison to the (standard) deviation of the process (or product)
- ☼ The instrument generates data that shift the process location m systematically to too high or too low values

Definitions to Assess the Quality of Measurements:

"CORRECTNESS" assesses the influence of systematic failures.
A measure for correctnes is the distance between the measured average value and the true value of a property.

"PRECISION" assesses the influence of stochastic failures.
A measure for for precision for example is the (standard) deviation of the measured values.

"EXACTNESS" is the sum of
Correctness + Precision