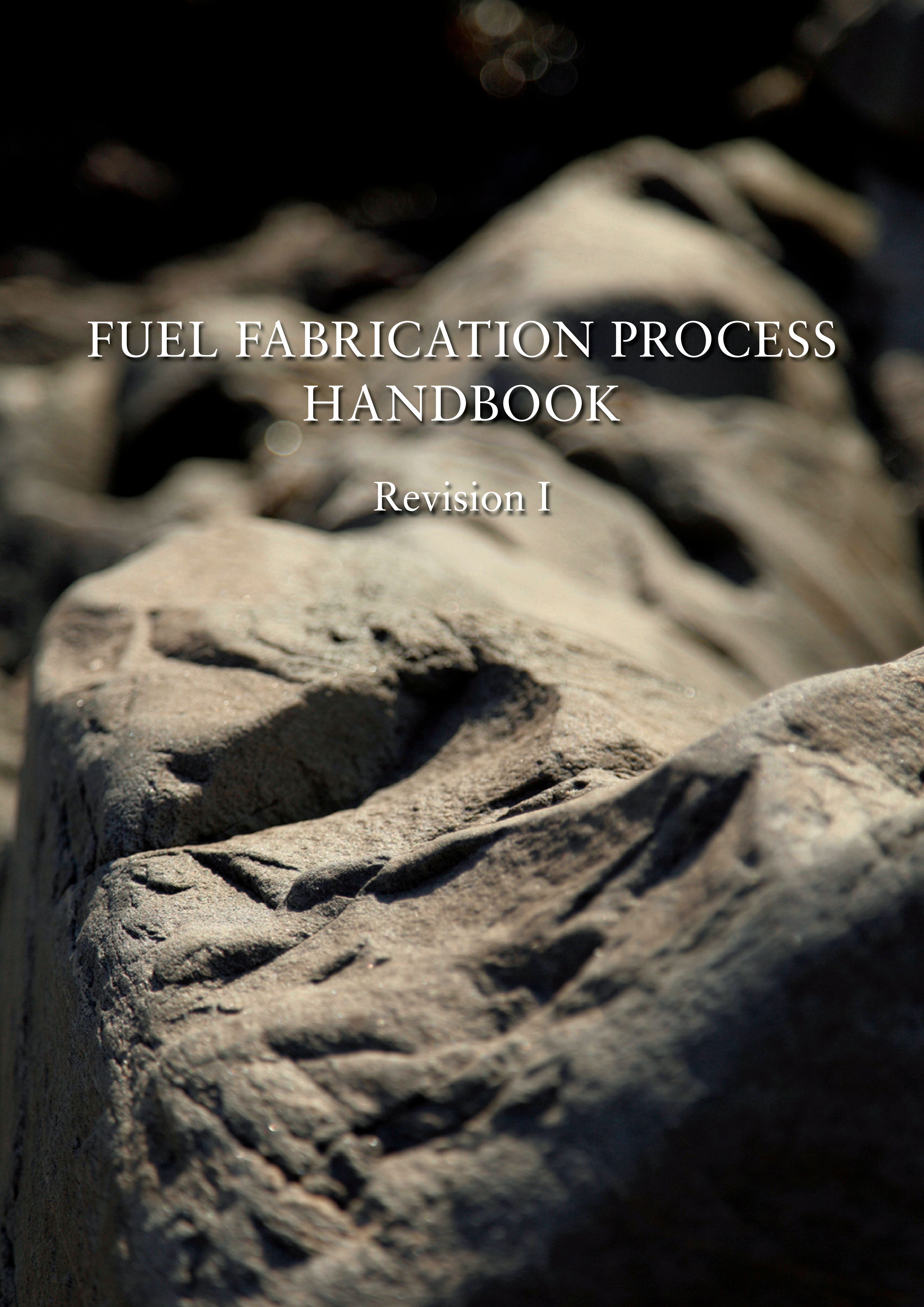

FUEL FABRICATION PROCESS HANDBOOK

Revision I

Fuel Fabrication Process Handbook

Revision I

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Ecolabelled printed matter, 441 799

Contents

1 Introduction (Peter Rudling)

1.1 Objectives of handbook

Many of the nuclear fuel fabrication steps have a significant effect on fuel performance; therefore, the audits of the fuel fabrication process are an important step to assure that the fuel will perform as designed, including the margins to regulatory limits and failure.

The Fuel Fabrication Process Handbook focuses on a "Process Audit" of BWR and PWR fuel fabrication, the audit of the fabrication process parameters most important for reliable fuel performance. Of the various audit types, this is the most difficult to implement successfully, as an auditor will require the appropriate combination of fabrication process and fuel performance knowledge, a background this Fuel Fabrication Process Handbook intends to supplement.

This Fuel Fabrication Process Handbook provides the "what, why and how" to look at in an audit by:

- Listing the generic fabrication process steps for all components and their assembly (what to look for)
- Identifying important audit points and the attendant potential effect of deviations on performance (why to look)
- Assess the fabrication and QC process control at critical points (how to look)

The Fuel Fabrication Process Handbook also provides guidance for setting up and carrying out an effective audit and very importantly, how to handle deviations found by either the vendor or the utility auditors.

1.2 Nuclear fuel cycle

The nuclear fuel cycle refers to all of the activities related to the use of fissile materials as the main fuel in fission reactors.

The nuclear fuel activities start with the extraction of uranium from the ore and terminate with the disposal of radioactive wastes generated during the routine operation of a reactor, Figure 1-1.

The first step is the mining of uranium ore and refining in a mill to produce U_3O_8, yellow cake. At this stage, the yellow cake has the isotopic composition of natural uranium, which is:

^{238}U—99.28wt%

^{235}U—0.711wt%

^{234}U—0.006wt%

Most power reactors are designed to use uranium fuel enriched in ^{235}U. The enrichment method used most today is by the centrifuge processes, which employ UF_6 as a starting material. The gaseous diffusion plants have been phased out. Thus, the U_3O_8 needs to be converted into UF_6 by a chemical process, see section 6 for more details. On the other hand, the CANDU (CANada Deuterium Uranium) pressurized heavy water reactor does not require enrichment of the natural uranium due to the use of heavy water (D_2O) as moderator instead of H_2O in LWRs.

For Light Water Reactors, LWRs, the enriched fuel contains from 2 to up to slightly lower than 5% ^{235}U. What is left behind at the other end of the enrichment operation is depleted uranium, containing between 0.2 and 0.3% ^{235}U, called uranium tails. A considerable amount of energy is needed for the enrichment process. The price of enrichment is expressed in terms of the work necessary to achieve a certain level of enrichment, Separative Work Unit (SWU). The separative work required for enrichment corresponds to about one-third of the average fuel cycle cost.

The enriched uranium is subsequently sent to the fuel fabrication plant where the UF_6 is converted to UO_2 and made into the fuel assemblies. The fuel leaving the fabrication plant is only mildly radioactive.

The fabricated fuel is then placed in the reactor core to start producing energy. LWR power reactors are refuelled at intervals of 12 to 24 months. During refuelling only a fraction of the fuel is removed and replaced with fresh fuel. The number of fuel assemblies that are treated as a group (placed and removed from the core at the same time) is called a *batch*. The energy generated by the nuclear fuel is expressed by the term *burnup*, given in units of MWD/MT (megawatt days thermal per metric ton of uranium fuel).

The fuel that is removed from the core, referred to as spent fuel, is normally stored on site under water in a deep spent fuel pool. It is highly radioactive and eventually has to be removed from the storage pool and disposed of in the "once through" fuel cycle shown in Figure 1-2. The disposal method depends on the regulatory requirements for the fuel in the specific country where the irradiation has taken place. Reprocessed fuel (MOX) is currently only used in France, Switzerland and Japan and has been used in Germany. A number of other countries are preparing to use MOX fuel from either reprocessed power reactor fuel or from weapons-grade plutonium. All other countries are using and planning for the "once through cycle".

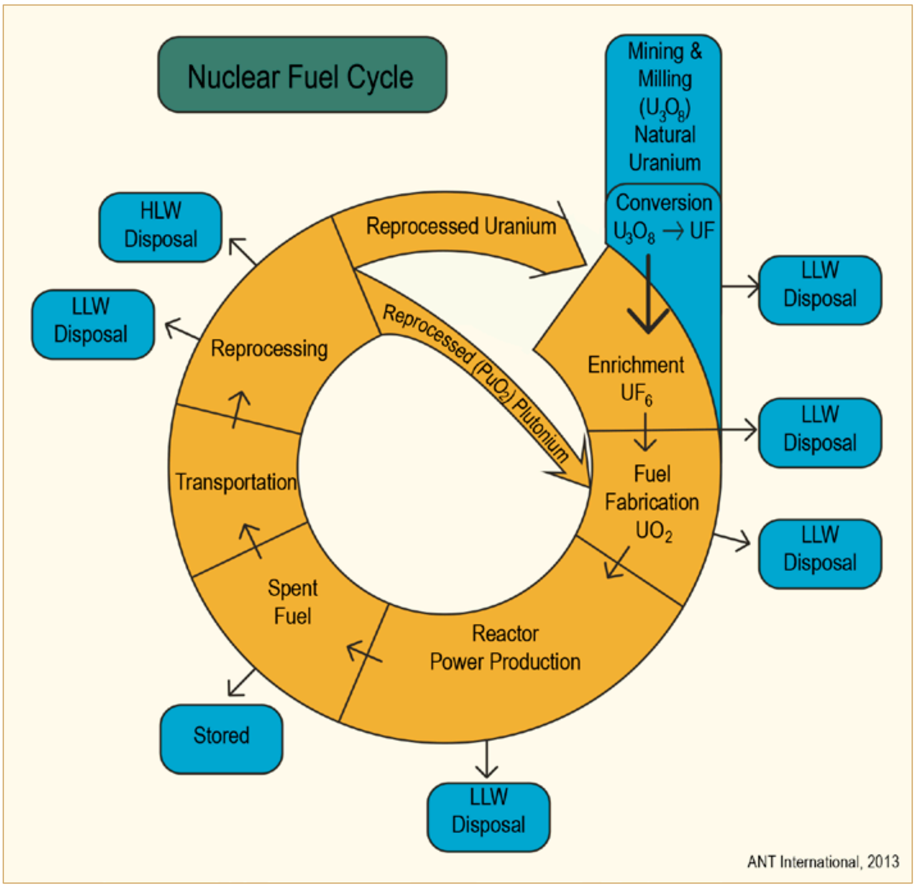

Figure 1-1: I figure showing all the nuclear fuel activities, after [Cochran & Tsoulfanadis, 1999].

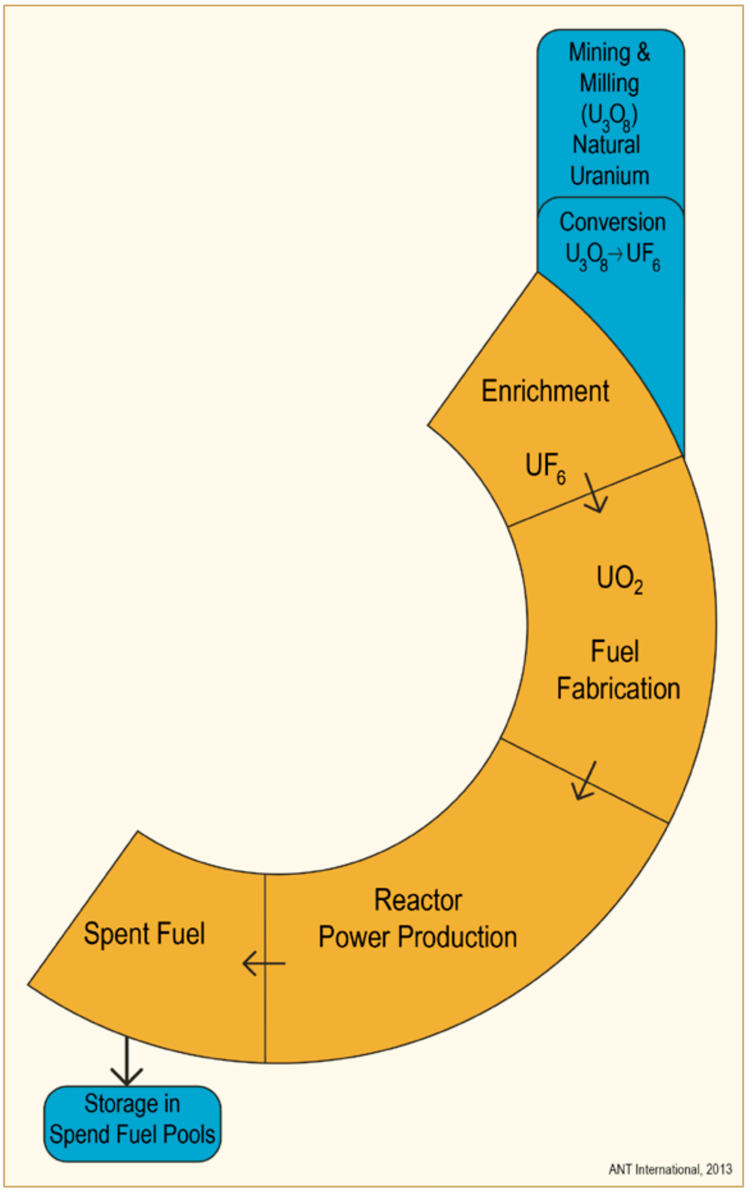

Figure 1-2: The once-through cycle nuclear fuel activities [Cochran & Tsoulfanadis, 1999].

1.3 The fuel fabricators who's who

The original number of fuel suppliers has been reduced by a series of corporate mergers and is currently dominated by a few large fuel manufacturers such as AREVA, GNF, TVEL and Westinghouse Electric. As shown in Table 1-1 to Table 1-3, however, a number of other organizations are actively supplying water reactor fuel. This table also indicates that there exists a large overcapacity to produce nuclear fuel today.

The ownerships and organisation structure has undergone large changes for AREVA, GNF, and Westinghouse, see Figure 1-3 to Figure 1-4.

2 Structure and components of the fuel assembly (Peter Rudling)

2.1 Introduction

There is a wide variety of different types of fuel assemblies for Light Water Reactors, LWRs. The fuel rod array for BWRs was initially 6x6 or 7x7 but there has been a trend over the years to increase the number of Fuel Assembly, FA, rods and today most FA designs are either of 9x9 or 10X10 square configuration design. The development of 11x11 BWR designs is currently underway. The driving force for this trend was to reduce the Linear Heat Generation Rate, LHGR, which resulted in a number of fuel performance benefits such as lower Fission Gas Release, FGR, and increased Pellet Cladding Interaction, PCI, margins. However, to increase utility competitiveness, the LHGRs of 9x9 and 10x10 FA has successively been increased, and peak LHGRs are today almost comparable to that of the 7x7 and 8x8 older designs.

Also for PWRs there has been a trend to greater subdivision of fuel rods; e.g., from Westinghouse 15x15 to 17x17 design. To accomplish this, however, one had to go to a new reactor design. This since the PWRs do not have the same flexibility with core internals and control rods as is the case for BWRs. Figure 2-1 shows the current PWR fuel rod array designs.

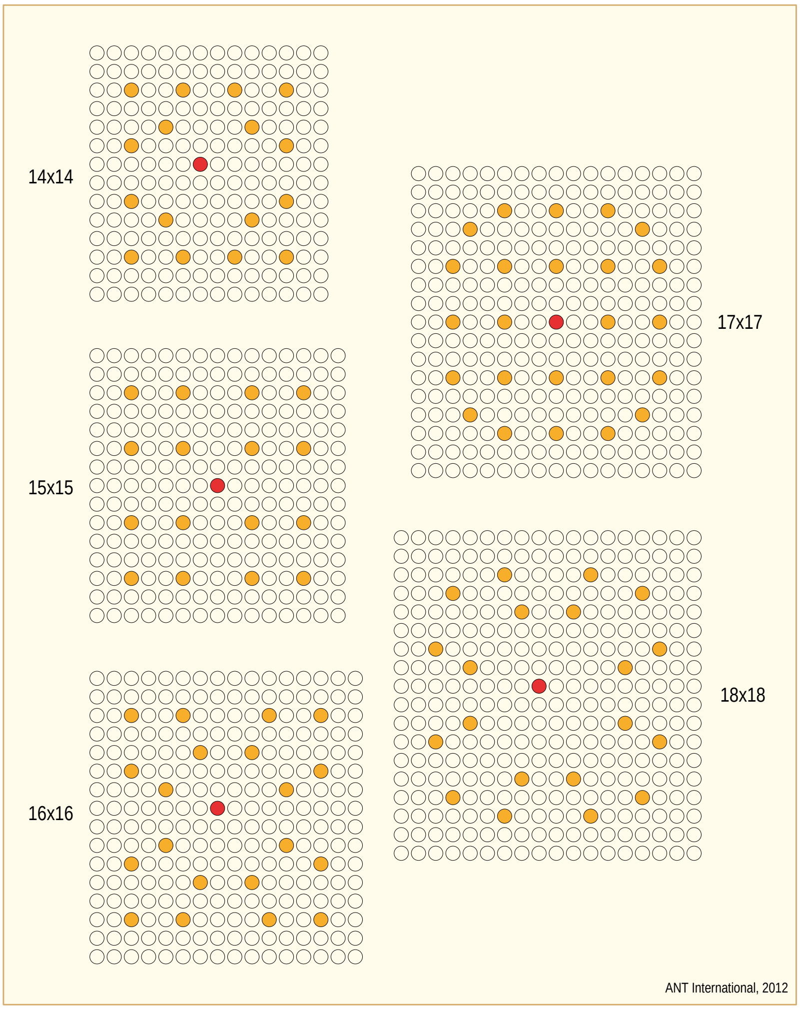

Figure 2-1: Layouts of different PWR fuel assembly design, Rods marked with yellow colour are guide tubes into which the control rod cluster is inserted. The position marked by a red filled circle is the instrument tube position.

In most PWRs, the assemblies are positioned in the core by bottom and top fittings, and the lateral clearances are restricted by the assembly-to-assembly contacts at the spacer-grid levels. Furthermore, the control rods consist of Rod Cluster Control assemblies, RCCAs, the poison part of which moves into guide thimbles (or guide tubes). These guide thimbles are an integral part of the assembly structure.

In all BWRs the assemblies are enclosed in "fuel channels" surrounding the assemblies and between which the blades of the control rods moves.

Irrespective of the many possible different shapes, sizes and configurations, the common FA design requirements are:

- maintain proper positioning of the fuel rods under normal operating conditions and in design basis accidents (e.g. seismic effects, LOCA, RIA)
- permit handling capability before and after irradiation.

Figure 2-2 and Figure 2-3 show a typical BWR and PWR FA, respectively. Also, the different fuel assembly components are shown and the material selections for these components are provided. The reason for the difference in structural material selection is that in general the most inexpensive material is chosen for a specific component that yields the lowest cost to produce the component while ensuring adequate performance during normal operation and accidents.

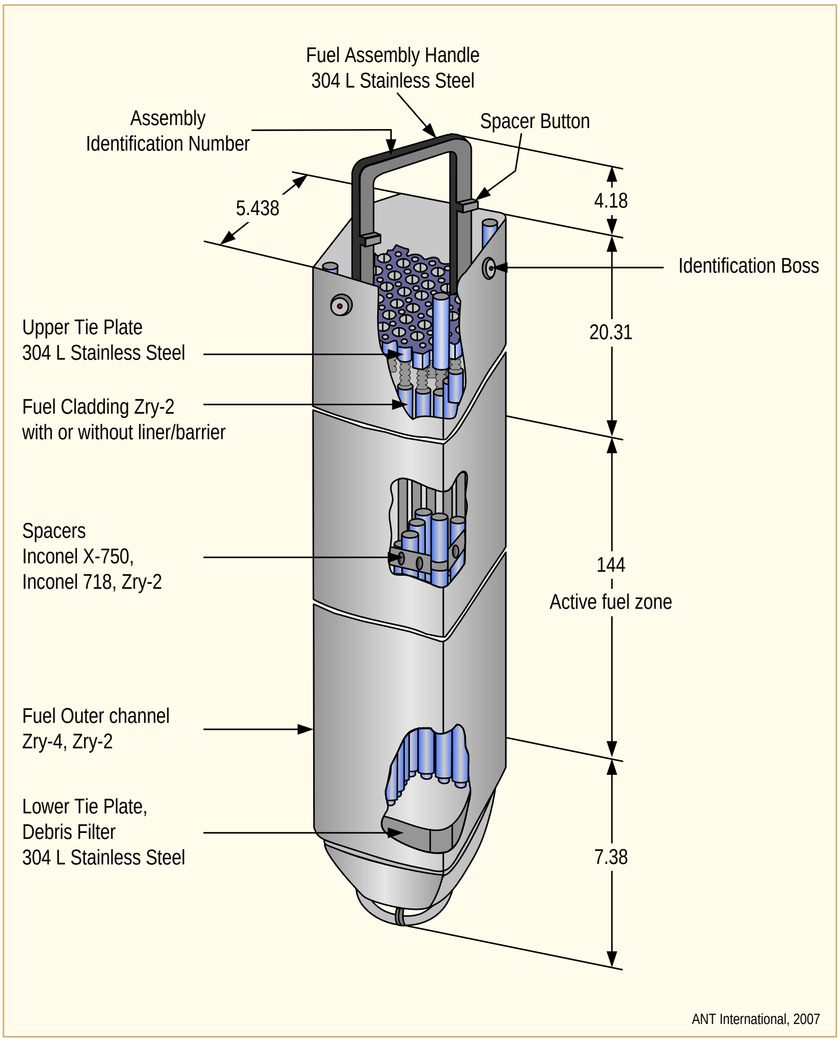

Figure 2-2: Typical BWR FA in inches.

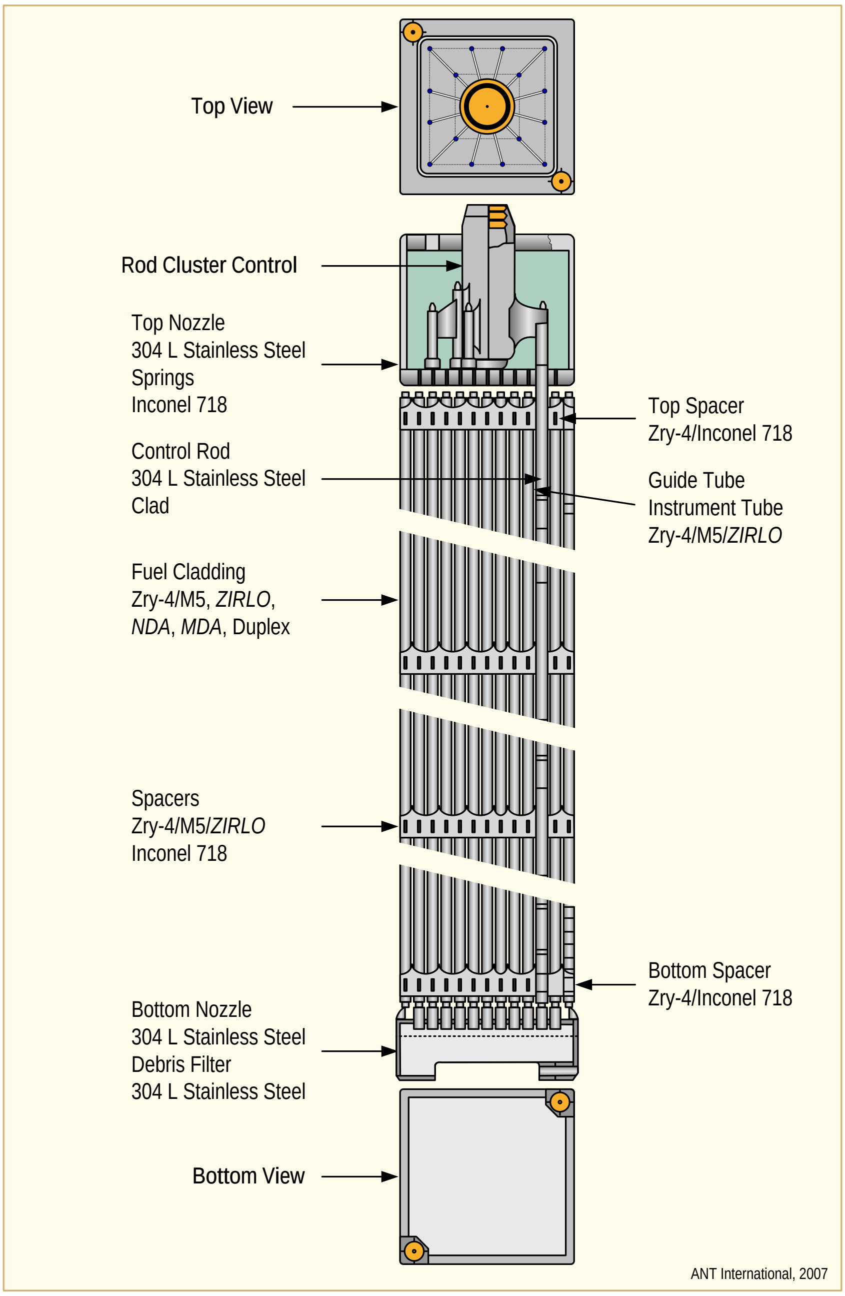

Figure 2-3: Typical PWR FA.

3 Utility audit procedures (Alfred Strasser)

3.1 Overall objectives

The broad objectives of nuclear fuel QA and its related audits are to:

- achieve the design performance levels and projected fuel cycle costs through the reliable and safe utilization of the fuel,
- protect the health and safety of the public.

The achievement of reliable performance and low fuel cycle costs is dependent on good technical design and fabricated quality of the fuel, a responsibility of the fuel vendor, and good reactor operating practices, a responsibility of the utility. The protection of the public is based on the policies, regulations and criteria of government agencies and must be met by both vendors and utilities. However, the requirements for economic fuel performance are more stringent than those for safe fuel performance; most fuel failures do not have significant influence on the operation of the external reactor systems and therefore do not affect the general safety of the plant. While the government provides good safety limits, the vendors and the utilities must implement more exacting QA procedures to meet their economic goals.

The cost savings accrued from improved reliability must be balanced against the cost of the QA system. Determination of the cost/benefit of increased QA levels is one of the most difficult aspects of establishing a detailed QA system since at some point the increased levels and increased cost of the QA system will bring diminishing economic returns in terms of performance reliability.

In order to ensure that the audit itself is cost effective, the audit time must be used to concentrate on areas that are most closely related to potential performance problems. The purpose of this Handbook is precisely to identify and prioritize the QA of fabrication steps that are most important and cost effective for reliable performance; however, one should be aware that details of some of these may vary from design to design and from one fabrication process to another. Since the ability to identify the relationship between fabrication problems and the design and performance of the fuel are critical, the scope and schedule of the audits should be established by, and the audits made by personnel familiar with these areas of technology.

The audit of all the Priority 1 audit items listed in this Handbook is not possible during a single campaign. Choices of the areas must be made based on the state of the art of the vendors' design, fabrication, QC and performance of the fuel to be audited. These choices will vary from design to design and from vendor to vendor as a function of time and a detailed choice of items applicable to every occasion cannot be made. However, a generic list that would serve as the basis for the detailed choices can be provided. The list given below is the most condensed and perhaps the best generic answer in this Handbook to the question "what should I audit?":

- Items with a history of fabrication problems that can be identified by recent high rejection rates,
- Items with a history of in-reactor performance problems,
- Operator sensitive processes in fabrication or inspection of components,
- Parameters sensitive to small changes,
- Areas of design uncertainty,
- Changes in processing or QC since the processes were qualified,
- New fabrication and inspection techniques,

- New design features with limited prior in-reactor experience,
- Results of statistical process quality control of sensitive processes and their trends,
- Sampling plans and their statistical bases,
- Review the vendors' QA audit reports to identify problems and the state of their remedies.

The above list will be re-emphasized throughout this Handbook.

This Section will summarize the mechanics, or methods, of making the audits and will focus on areas that have the most sensitive relationship to reliability. Good communications and relationship with the vendor are necessary to accomplish this and this topic is discussed as well. Adherence to these methods is basic in order to accomplish the most effective audit in the minimum amount of time.

Included in the Section are:

- description of various types of audits,
- the planning, scheduling and structure of an audit,
- the audit mechanics, or what to do during the audit,
- handling of deviations,
- post-audit follow-up,
- audit of subcontractors.

3.2 Audit types

Several, different types of audits are made at vendor facilities and the may be classified as follows:

- Quality System Audit
- Process Audit
- Fabrication Audit
- Product Audit
- Design Audit
- Environmental Audit

While these may be somewhat arbitrary classifications, they are useful in that they focus on different areas and can use audit personnel with different backgrounds and qualifications.

Quality System Audit

A Quality System Audit is a detailed evaluation of an existing QA program for its conformance to company policies, standards, regulatory requirements and contract commitments. Nuclear quality system audits are based on criteria originally established in the US Code of Federal Regulations, 10CFR50, Appendix B and the many standards developed subsequently based essentially on this document. The standards are discussed in Section 4.

These audits are used to determine whether the vendor is meeting its QA obligations according to the applicable standards and whether the vendor management controls are sufficient to ensure that the product will meet the requirements of the contract.

Process Audit

The Process Audit is a review and evaluation of the:

- fabrication processes,
- process controls,
- inspection and test plans,
- inspection procedures.

The actual procedures and documentation to control these items are audited to determine whether they are adequate to assure reliable performance of the components at the specified performance conditions.

The basis of the documentation should be the original qualification of the process step and its subsequent modifications. The qualification test and its related audit are described in Section 3. The audit of the process qualification is the most effective first step in a Process Audit, followed by a step-by-step review of the process as it is actually carried out. The process as it is performed in the plant and the related documentation are then reviewed for adequacy. The auditor clearly needs to be knowledgeable in the technology of the process he or she is auditing in order to do a satisfactory job.

Ideally, such an audit is made prior to the production of the utility client's fuel, so that any modification or improvements may be implemented during the utility's fuel production campaign.

The Process Audit has been called other names such as "Technical Audit", "Engineering Audit" and the US Navy has called it a "Procedure Audit".

Fabrication Audit

A Fabrication Audit verifies that the vendor is operating according to his written procedures and applicable standards. This type of audit verifies that the process, the procedures and the inspections are performed to the requirements defined in written procedures, work instructions and process specifications. In addition the audit includes the review of the training and qualification of personnel, of the purchasing documentation for materials and services of subcontractors and the subcontractor audits and other items outlined in the QA Plan of the vendor.

The vendors' statistical process control charts (SPC) will indicate the quality status of the process and these, together with the vendors' evaluation and actions based on the data, are audited as part of the Fabrication Audit.

Product Audit

A Product Audit is the examination, inspection or test of a product by the utility auditor, or witnessing these as they are carried out by a qualified vendor inspector. Still another good option is the re-inspection and re-test of a product, which has already been accepted by the vendor using the same test procedures, methods and equipment. The audit of the QC inspection records and comparison to specifications falls within the scope of the Product Audit. The audit will measure the level of product conformance to specified standards of workmanship, performance and quality and will be an indicator of quality going to the customer.

4 Quality assurance systems and standards (Alfred Strasser, Graham Walker and Kenny Epperson)

4.1 Introduction

The safe, reliable and cost-effective application of nuclear power depends to a considerable degree on the quality assurance (QA) and quality control (QC) systems that are implemented for fuel and other components. QA is a management system ensuring that all important activities are accomplished in a planned, systematic and controlled manner to assure the satisfactory performance of components. QC controls and measures the characteristics of a process, a piece of equipment and a component to endure that they meet the established requirements. One of the functions of QA is to assure that the QC process is functioning satisfactorily.

The objective of this section is to provide a broad overview of the QA system and the most important, current, applicable standards. An audit of the vendor's QA system is a special audit type, as discussed in Section 12, and the details of such an audit are not part of the scope of this Handbook. Some of the most important issues, however, are pointed out in the general system description that follows.

Each vendor and qualified subcontractor must have a QA Manual that describes the company's QA system.

The manual may be in two parts. The first part could be very general, restricted to principles of operation and intended to satisfy regulators and reviewers interested in assuring that basic requirements are met. The second part is likely to be very detailed, describing how the QA activities are implemented and providing guidance to company personnel associated with QA activities. The first part is generally available on a non-proprietary basis; however, the second part will probably describe proprietary operational procedures and have a restricted distribution. Each utility auditor should be familiar with both QA system descriptions even if he or she are not involved in a specific QA System Audit; understanding the vendor's QA system will greatly assist in an effective audit. Obtaining both QA manual types from the vendor and maintaining them at the utility's offices is recommended to facilitate the auditors' familiarization with the systems prior to their audits.

4.2 Basic system requirements

4.2.1 History

The "parent" of all basic QA requirements in the nuclear field was established by the US Government's Code of Federal Regulations (CFR) Title 10, Chapter 1. These documents set forth the rules and regulations that govern the actions of the NRC and the applicable licensees. The CFR requirements are general and the detailed regulations and standards are evolved from these. The most relevant regulations to the fuel fabrication processes described in this Handbook are contained in Appendix B to 10CFR50, "Quality Assurance Criteria for Nuclear Power Plants and Fuel Processing Plants", issued in 1970. These criteria, in turn, were originally developed, prior to this time, by the US naval propulsion program under Admiral Rickover.

Appendix B has become the basic "constitution" of QA, as its 18 criteria cover all of the QA requirements. Like other types of "constitutions", this one outlines the general principles and actions required of a QA system and are open to very broad interpretation. More detailed guidance was needed and this task was assumed by various standards organizations. The 18 criteria have been adopted in most countries, in one form or another, by their regulatory bodies, as well as their standards organizations. The 18 criteria are discussed in Section 11.2.2, and points that have a particularly important bearing on the audits recommended by this Handbook are identified.

In the US, the task of providing detailed guidance was assumed by the American National Standards Institute (ANSI) and the American Society of Mechanical Engineers (ASME) and for some issues by the NRC's Regulatory Guides. The initial ANSI Standard N45.2 was the equivalent of Appendix B and its series of detailed standards were numbered N45.2 with additional numerical digits. The NRC staff reviewed each ANSI standard and subsequent to its issuance issued a parallel Regulatory Guide, which either endorsed or modified the ANSI standard. Subsequently a joint standard was issued with the ASME, NQA-1, in 1979, which had essentially the same structure as its predecessor. The latest version of this standard was issued in the year 2000.

The international community developed its series of standards with the International Organization for Standardization (ISO) starting in the 1980-ies and these are also based on the criteria outlined in 10CFR50, Appendix B. The ISO technical committees have memberships from the countries interested in the special topics covered by each standard. Both governmental and non-governmental organizations take part in developing the standards. Publication of a standard requires approval by a minimum of 75% of the members. The ISO 9000 series of standards are the applicable to fuel fabrication. The recent issues also combined the standards with ANSI and the American Society for Quality (ASQ) and their latest publications are from the year 2000. These standards are discussed in Section 11.3.

4.2.2 Appendix B, the Constitution

Organization

The responsibility for establishing and implementing a QA Program must be established and described. Of particular importance is the independence of the personnel that attain and verify quality. Auditors should confirm that the QA organization reports directly and independently to the manager of the plant and has direct access to the president of the company. QA should be independent of QC.

QA Program

Each vendor is required to have a documented QA Program Plan that provides (a) control over identified activities affecting quality and safety, including organization, (b) recognition of the need for special skills, (c) training of personnel that perform those activities, (d) management review of the status and adequacy of the QA Program. As noted in Section 11.1, the utility should have copies of the QA Program Plan in its offices in order to facilitate the auditors' familiarization with each vendor's program.

Design Control

This applies to a Design Review and Audit and is not within the scope of this Handbook.

Procurement Document and Control

Applicable quality requirements, including a documented QA Program that meets applicable standards, must be included or referenced in the Procurement Documents issued to subcontractors.

Instructions, Procedures and Drawings

Documents must be prepared for all activities that affect quality and preparation of these documents must include appropriate quantitative and qualitative criteria for attaining the desired quality and for satisfactory accomplishment of the activities described.

Document Control

A control system must assure that all quality related documents are issued only after review for adequacy and approval by authorized personnel. Changes to the documents require the same degree of control as the original documents and must be distributed to the locations where the related work is being performed. Auditors should review the documentation of critical operations to assure that the drawings, specifications operator instructions, operator qualifications and QC plan are all the latest, compatible versions with the work being performed.

Control of Purchased Material, Equipment and Services

Measures must be established to assure that purchased materials, equipment and/or services conform to the requirements of the purchase documents, including all quality requirements including the QA Program plan. It requires the vendor (the purchaser) to evaluate the subcontractors and suppliers and acquire documentary evidence that the procurement requirements are being met. Utility auditors should assure that the vendors have documented evidence of such evaluations and audits and in selected cases the utility auditors should evaluate the subcontractors independently.

Identification and Control of Material Parts and Components

The identification of parts, components and assemblies must be maintained either directly on the item (bar codes or other) or on records that provide traceability to the item. These measures are designed to prevent the use of incorrect or defective material, parts or components during fabrication and also provide traceability if subsequent problems occur either prior to, during or subsequent to their service.

Control of Special Processes

Certain special processes, such as welding, require the preparation and maintenance of qualified procedures for process control and the use of qualified personnel to operate them. Personnel need to be requalified periodically. Changes in qualified processes may have to be requalified and the personnel reinstructed at a minimum.

Inspection

Inspection of activities affecting quality must be performed by individuals independent of those that performed the activities, to verify conformance to documented requirements.

Test Control

The establishment of a program is required to assure that all testing is identified and performed in accordance with written procedures. The procedures are to include the test requirements, acceptance criteria, test conditions and that adequate instrumentation is used in the tests. Results of the tests have to be documented and evaluated for satisfaction of test requirements. Audits of critical test procedures, such as cladding non-destructive testing, should be included in each audit visit.

5 Qualification programs (Alfred Strasser)

5.1 Introduction

The objective of this Section is to describe the concept of qualification programs for fuel fabrication, the need for qualifications and their relationship to fuel quality and performance and to provide a guide to their audit. The descriptions given here are generically applicable and specific applicable details are given in the process descriptions.

The purpose of a qualification program is to define the bounding parameters for a process that, if observed, will turn out a product that meets the specifications within a certain statistical reliability. A fabrication or inspection process is qualified by a short, statistically designed production campaign, within and extending beyond the proposed process limits. The product is then inspected thoroughly to determine whether it meets the specified product quality throughout the ranges evaluated in the qualification program. Subsequent changes to the process may need to be requalified.

The qualification programs can be sorted by several types of activities:

- Qualification of fuel *fabrication process* steps,
- Qualification of *inspection methods*,
- Qualification of *personnel* responsible for processing and inspection,
- Qualification of fabrication subcontractors and material suppliers.

The importance of adequate qualifications cannot be overemphasized. *Processing* outside the qualified bounds involves activity that has not been demonstrated to give the desired results and, depending on the stability of the process, can lead to the production of a deviate product In turn, the inspection and test plan, the accept/reject criteria and the associated confidence levels for fuel quality are based on a combination of design requirements and the statistical distribution of product characteristics observed in qualification tests. If these change by processing outside the qualified range, the potential of accepting deviate products increases.

Similarly, if an *inspection* technique cannot produce results within the required accuracy, or is operated outside of its qualified methodology, the results could be unreliable and accept deviate material. Unqualified *operators* can commit a large variety of mostly untraceable set of errors that can produce deviate material as well.

Subcontractors for fuel assembly components must abide by the same qualification processes as noted above to provide products that consistently meet specifications and performance requirements. *Suppliers of materials* that can range from providing gadolinia powders to etching solutions and grinding belts or wheels have to be qualified to provide products that are compatible with the vendors' qualified process.

In the event the vendor makes a change in the process, for reasons that usually include improvements to quality or reduction of cost, the vendor makes a decision whether the change is sufficiently significant to require requalification of the process, or whether it is small enough to obviate the need of requalification.

Such decisions need to be audited to assure they are based on adequately low risk to produce undetected deviate fuel and assurance that fuel performance will not be degraded. *To do this, the auditor must monitor all changes to processing, process control and inspection techniques by questioning the vendor to provide and discuss written notices that document the changes, called "change notices" by a variety of names, at each audit.*

The quality of the fuel assembly and its components cannot be assured unless they were produced by qualified processes. It is imperative, for this reason, that the qualification programs be audited at least once and that any changes in processing, inspection and personnel be monitored, to assure that the original qualification still applies or alternately, to decide that a revised qualification may be needed.

Details and examples of each qualification type and guides for their audit are included in the subsequent sections.

5.2 Process qualification

5.3 Extent of Qualification

The ***current process*** used by the vendor and its subcontractors should have qualification test records for all critical steps in the process. These are noted subsequently in the Handbook as part of the individual descriptions of the process steps. The qualification procedures for the current process are the same as those described below for a new process.

The extent and depth of the qualification test needed in case the current process is modified will depend on the extent of the process modifications. The changes can range from an entirely new process for the component to slight changes in the processing procedure as discussed below.

New Process

A new process could be represented by the fabrication of sintered pellets from a new UO_2 powder source, that is, powder made by a new chemical process, or cladding tubing made from a new alloy. For a new process the vendor will do extensive preliminary development work to define the processing parameters that will make a satisfactory product prior to running an "official" qualification test. At the conclusion of the development the vendor will have a reasonable knowledge of the bounding, acceptable process parameters. The review of the development work is worthwhile for an auditor in order to gain better knowledge of the parameters that have a sensitive relationship to quality.

The qualification test should involve a statistically significant amount of product, that is, an amount that would provide a valid, statistical distribution of the properties to be measured. The vendor should provide a justification for his selection of the quantity of product in the test and the sampling plan applied in order to establish the statistical distribution of the various properties measured.

The test procedure should define:

- Parameters and combination of parameters to be varied and the extent to which they will be varied,
- Parameters to be tested beyond the qualified range,
- Parameters that will be measured during qualification only, but will not be part of process control or final QC during subsequent production.

All of the process and process control parameters intended to be used should be included for the entire new procedure. As an example, for a pellet production process from a new powder this should include, at a minimum, all the parameters listed in Section 6.2 and 6.3. Examples of parameters that are likely to be varied are amount of scrap recycle, milling times and particle size distribution, amounts of binder or lubricant, pressing forces, green density, sintering times and temperatures and so on. Microprobe analyses of Pu distribution in the MOX pellets or Gd distribution in BA pellets are examples of parameters evaluated at the qualification stage only. Other, more accessible examination methods are normally validated by such specialized measurements and then used to assure the process continues to produce the intended characteristics.

The qualification of a new cladding alloy is a much more extensive project and could take years of development prior to final qualification. As one can observe in recent ZIRLO and M5 developments, these are not over even after the first "qualification". In this case the qualification should start with alloy melting and proceed all the way through final tube production. Each process step presents a major qualification effort with numerous parameters to be varied, starting with ingot melting, a process that controls the alloy content homogeneity. Parameters that affect this include the ingot size, molten pool size, residence time, amperage, voltage, ingot diameter, and others discussed in Section 7.2.4. Final tubing has to go through extensive evaluation beyond the inspection and sampling plan expected for subsequent production control; as an example, texture measurements and 100% ID inspection would be additional parameters that are evaluated at the qualification stage only.

Modified Process

The modification of a single process step or group of process steps are the most frequent cases requiring requalification. Types of modifications and typical examples are:

- Changes in equipment - introduction of a new fuel powder blender, a new welding setup, a new sintering furnace,
- Changes in processing parameters - to accommodate blending powders with new, larger enrichment differentials, welding a new weld joint design, changing the sintered density specification, changes in zirconium alloy heat treatment conditions,
- Changes in processing steps - elimination of a pellet drying step, addition or elimination of a zirconium alloy heat treatment or tube reduction step, changes in the sequence of zirconium alloy etching and pickling steps,

The criteria for planning and implementing the qualification test are identical to those described for the New Process. The preparatory work prior to the qualification test will be significantly less if any. The maintenance or improvement of properties significant to reliable fuel performance should be given high priority as a result of these changes; they are discussed under the appropriate process descriptions for each component and assembly.

Qualification of existing processes and process changes at subcontractors can be equally critical to fuel performance as the qualifications at the fuel vendor. There can be a tendency to neglect these even by the fuel vendor. As an example a particularly critical operation is the qualification of the β quenching step at the tube shell stage of zirconium alloy cladding production. The time-temperature history of the tube shell should be and is traditionally monitored by thermocouples embedded in a tube shell at several positions extending radially from the surface into the centre or ID of the tube shell at several radii along the axis of the tube shell. These should provide a record that all sections of the tube shell were heated into the β range and quenched at the required rate into the α region. Complete metallography of all cross sections should confirm the appropriate structures. Changes in the tube shell configuration, alloying content, equipment and process parameter changes should trigger requalification considerations of the process. Additional details are discussed in Sections 7.3 and 7.4.

6 Pellet and fuel pellet fabrication (Alfred Strasser)

6.1 Raw materials

6.1.1 Introduction

The initial fuel fabrication step that can have an effect on fuel performance is the production of the starting material provided to the fuel fabrication vendor, enriched UF_6 in the case of uranium (U) and $Pu(NO_3)_2$ in the case of plutonium (Pu). The important performance related quality requirements of these materials are the enrichments and isotopic compositions and are discussed in Section 6.2.

The processes from the U ore to the materials provided to the fuel fabricator will not have a direct effect on fuel performance, but have important commercial aspects that deserve audits. They are summarized briefly here.

The general process outline from conversion to loading of the fuel rods is given on Figure 6-1. Detailed outlines are on Figure 6-3 and Figure 6-4. Adjacent to each process step is a reference to a Section number in the report that:

- Describes the process
- Lists the recommended audits at that point and their priorities with Priority 1 as the highest one.
- Indicates the potential effect of a deviation on fuel performance.

6.1.2 Uranium

6.1.2.1 Process

The majority of the uranium comes from ores mined in Canada, Australia, Kazakhstan and South Africa. The uranium is in the form of oxides combined with other minerals that vary depending on the source of the ore. The processes to prepare pure oxides for subsequent conversion to natural UF_6 vary depending on the other minerals that the uranium is associated with. In general the processes involve acid leaching of the ore, followed by purification of the uranium solutions and their conversion to uranium oxides. The oxides are generally a mixture ranging from UO_2 to U_3O_8 but are marketed as "equivalent U_3O_8" to the utilities that buy the uranium. The "yellowcake", as it is called, is then either purified and converted to UO_2 or UO_3 or shipped to another vendor for conversion to the hexafluoride, UF_6.

For heavy-water reactors (CANDU), the conversion of U_3O_8 to UF_6 is optional. The uranium can be purified and converted directly to UO_2 or UO_3 for subsequent fabrication of naturally-enriched UO_2 fuel pellets. Such conversions are performed in Argentina, China, India and Romania.

For LWRs, the oxides from the processed ore can be reduced in hydrogen to UO_2 and then reacted with anhydrous HF to form UF_4 and subsequently with gaseous F to form UF_6. Vendors that perform this conversion on a commercial scale are located in Canada, China, France, Germany, the Russian Federation, US and UK.

The UF_6 containing natural uranium is then shipped to one of the enrichment plants located in the US, UK, France, Holland, Germany, Japan or Russia that produce the enriched UF_6 by either the diffusion or the centrifuge process. [12] The enriched UF_6 produced is then shipped to the fuel fabrication vendors for processing into fuel pellets.

6.1.2.2 Audits

As noted above, audits at this stage of the production process are of commercial interest rather than related to fuel performance. Of primary importance is the assurance that the quantity of uranium contracted for is actually delivered and that the impurity level of the natural UF_6 delivered to the enrichment plant meets the specifications. Enriched UF_6 delivered to the fuel fabricator would be rejected or require acceptance of a deviation if it were off-specification.

The uranium content of the ore as well as the UF_6 is determined by the weight and analyses of the materials. A principal issue in this area is the homogeneity of the sample with respect to both enrichment and chemical composition. Homogeneity is typically achieved by heating the UF_6 container to convert its contents to the liquid state and allowing sufficient time for convective currents to produce a homogenous mixture. Enrichment homogeneity is easily achieved. Impurity homogeneity can be more difficult in cases where insolubles are present due to the residue (heels) from prior use of the UF_6 container. The following items should be audited:

- Homogenization and sampling procedures.
- Weight measurements.
- Calibration of the balance or weight measurement system.
- Correction for tare weights of the containers.
- Analytical determination of the U content; in the case of the ore one should recognize that it is a mixture of U oxides reported as U_3O_8 equivalent and that corrections should be made for impurities and moisture in particular.
- Enrichment and impurity analyses.

6.1.3 Plutonium

6.1.3.1 Process

Pu is recovered by the dissolution of irradiated fuel at the reprocessing plant where the Pu is then separated from U and from fission products. The PuO_2 powder is produced by either peroxide or oxalate precipitation from a nitrate solution; although various co-precipitation processes with uranium exist as well, they have not been used commercially. Similarly the U that still contains some ^{235}U is separated and reused as reprocessed uranium or REPU. The powders are shipped to the fuel fabricator for processing into pellets.

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[12] The China National Nuclear Company (CNNC) also operates an enrichment facility, but is not currently a factor in the western supply chain.

6.1.3.2 Audits

As in the case of the U audits, the following items should be audited:

- Homogenization and powder sampling methods.
- Weight measurements,
- Calibration of the weight measurement system,
- Correction for container tare weight,
- The Pu and/or the U contents and isotopic compositions of the oxides should be determined to assure that the amount of fuel contracted for is in fact being returned. The contract should state the amount of fuel loss permitted in the reprocessing operation. Since some of the Pu and U transformation products have high radioactivity levels, these should not be in excess of those provided to the reprocessing plants, since higher amounts could require increased radiation controls and increased costs in addition to affecting the nuclear design. Section 6.5 provides additional discussion on this topic.
- Impurity analyses.

6.2 Powder production

6.2.1 UF_6-UO_2 conversion

6.2.1.1 Process

The conversion of UF_6 to UO_2 powder can be accomplished by several routes classified into "wet" and "dry" routes. Essentially all the vendors used wet processes during the early stages of the nuclear industry, but almost all have changed to dry processes at this time. The advantages of the dry processes are that the radioactive liquid wastes are minimized and the overall costs are lower than the wet processes.

The wet processes convert the UF_6 by vaporization and water addition to form a solution from which one process precipitates Ammonium Diuranate (ADU) by the addition of ammonium hydroxide and the other process precipitates Ammonium Uranyl Carbonate (AUC) by the addition of ammonia and carbon dioxide. These compounds are then dissociated and oxidized to form uranium oxides, then reduced to form UO_2 powder.

The dry conversion processes are similar to each other in principle, but the details of each vendor's process are different. The UF_6 is reacted directly with steam in a high temperature furnace to produce uranium oxides and HF. The oxides are then reduced to UO_2 with hydrogen. A schematic of Westinghouse's Integrated Dry Route (IDR) process is shown in Figure 6-2. The dry conversion processes of AREVA and GNF are similar to the IDR process in terms of unit operations and flow, but different slightly with respect to equipment and operation.

6.2.1.2 Audits

The performance related audits start with this operation and the most important ones relate to the assurance that the specified enrichment and isotope composition is provided within an acceptable variance. The same recommendation applies to the chemical impurity limits in the material.

7 Zirconium Alloy Component Fabrication (Peter Rudling)

7.1 Introduction

The fabrication methods and parameters have a significant effect on the properties and microstructure of the Zr alloys, and these in turn on the performance of the Zr components in the reactor. The effect of the major fabrication steps on the properties, the effect of the properties on performance and the effect of the reactor environment on performance are shown on Figure 7-1. The Figure can be interpreted as follows, for example: The melting operation determines the Chemical Composition and Homogeneity of the alloy in the large ingot, properties that do not change in subsequent fabrication steps. The Chemical Composition affects every property of the alloy, while Homogeneity affects the Corrosion resistance and Ductility of the alloy. These in turn are affected by most of the environmental parameters during their exposure.

The relationship of the critical parameters of each fabrication step to performance are discussed in the appropriate Section for each step, indicated by the Section number on the Figure. Additional details and background can be found in the extensive ANT International Special Topical Reports (STRs) referenced in each Section as well as in the overall report by [Rudling et al, 2009].

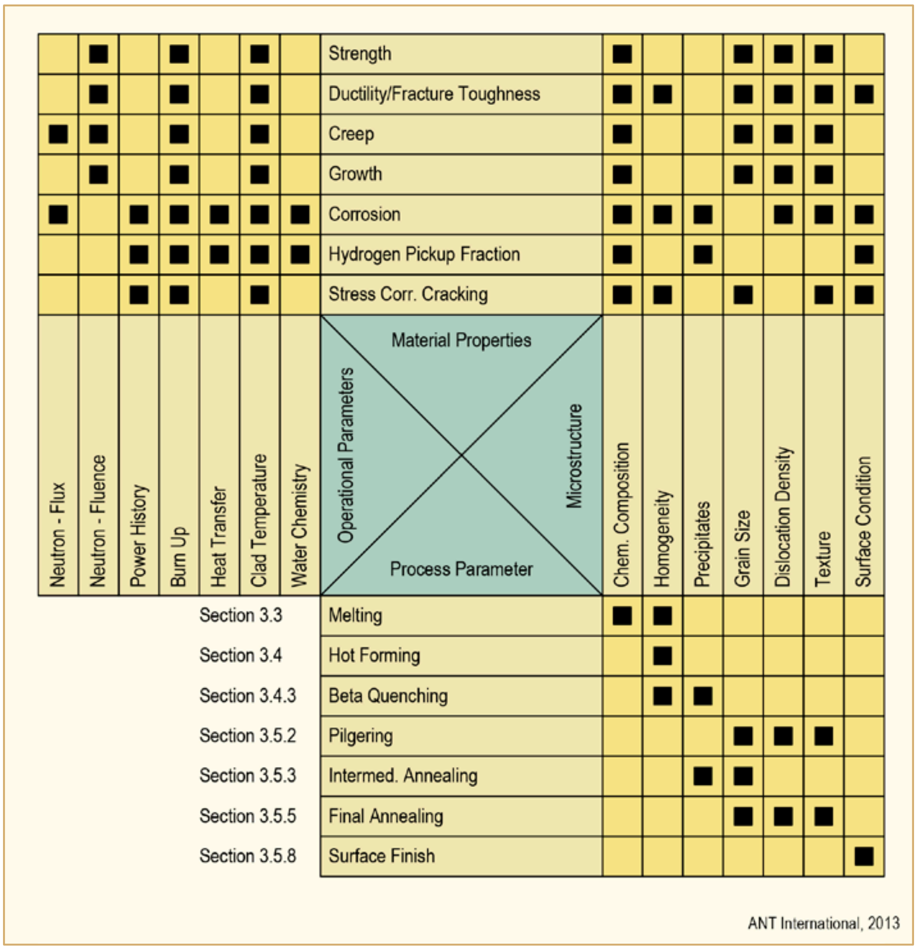

Figure 7-1: The relation between material properties, operation parameters, material characteristics and manufacturing processes. Hydrogen pickup fraction is a measure of the fraction of the hydrogen produced in the corrosion reaction between zirconium alloy and water which is pickup up by the zirconium alloy material. The section number relates to sections in this report where more information is given for each manufacturing step. The figure is a revision of the one used by [Strasser et al, 1994].

This section describes the Zr alloy manufacturing process and impact of the process and chemistry effects microstructure. An overview of the microstructure effects on in-reactor performance is also provided here. The interested reader of the microstructure effects on performance is referred to the ZIRconium Alloy Technology (ZIRAT)/Information on ZircoNium Alloys (IZNA) which ANT International publish every year (see our web-site www.antinternational.com for more information).

Figure 7-2 gives an overview of the manufacturing of Zr round, tubes and flat products from Zr sand. The various manufacturing steps are discussed in the following subsections.

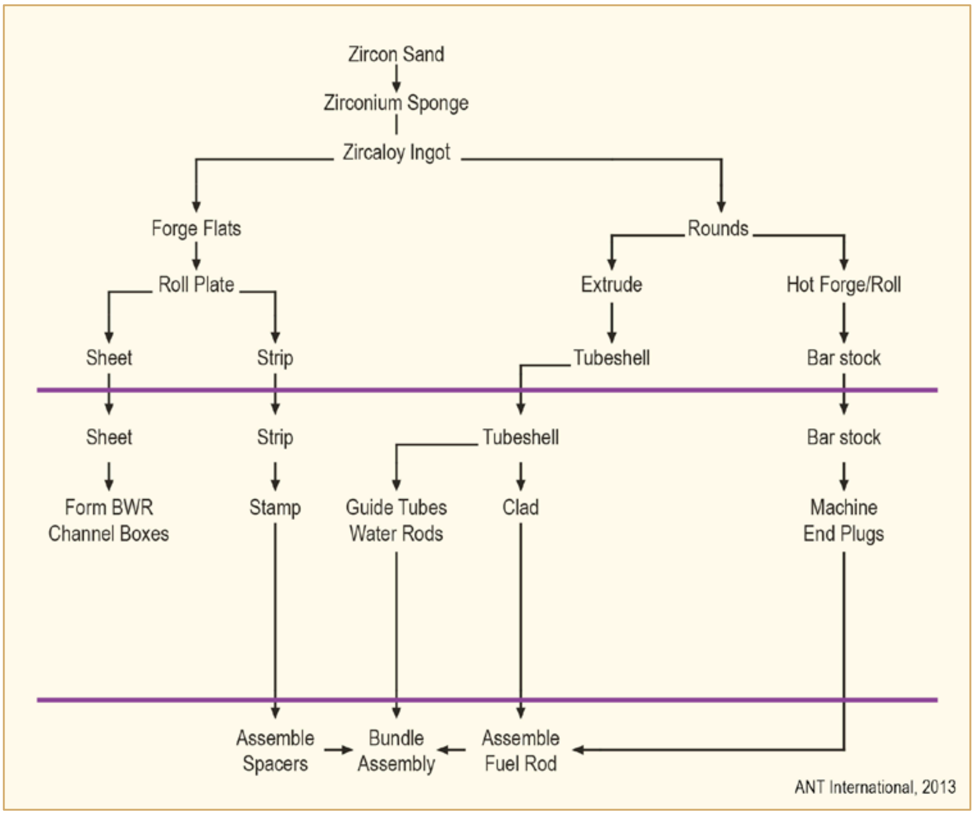

Figure 7-2: Zircaloy Production Outline.

Zr-sponge is being manufactured by Companie Europen Ziconium Ugine Sandvik, CEZUS, in France (within the AREVA corporation), ATI Wah Chang, (independent), Western Zirconium, WZ (within the Westinghouse corporation) in USA, see Table 7-1. WZ also delivers tube shells, sheet, strip and bar stock to Global Nuclear Fuels, GNF. Some limited amounts of Zr-sponge are in addition being produced in India and Argentina. All the zirconium used in WWER fuel elements is produced in a plant at Glazov in the Russian Federation. This plant is unique in the world since they do not use the Kroll process but an electrolytic process to produce the Zr raw material.

CEZUS also manufacture strip/sheet and tubes for AREVA, see Table 7-2. AREVA cladding is also being produced at a facility in Duisburg, Germany.

AB Sandvik Steel, ABSS, in Sweden and Sandvik Special Metal, SSM, in USA are independent manufacturers (i.e. not tied to a specific fuel vendor) and produces tubes from tube shells or TREX purchased from either CEZUS or ATI Wah Chang.

Carpenter in USA manufactures fuel outer channels for mostly AREVA.

Table 7-1: Zr metal production, after [NEI, 2012].

Product	Location	Company	Capacity per year (tons)	Process used
Zr Sponge from Zircon sands	Jarrie, France	AREVA NP[1)]	2200	Chlorination – Kroll process
Zr sponge, Crystal bar from Zircon sands	Hyderabad, India	DAE	210	Not available
Zr metal	Palayakayal	DAE		Under construction
Zr sponge, Crystal bar from Zircon sand	Albany, Oregon, USA	Oremet-Wah Chang (OWC)[2)]	2000	Kroll process
Zr-metal from Zircon sand	Ogden, Utah, USA	Western Zirconium Div., W	3 000 000	Kroll process
Zr sponge, Crystal bar from Zircon sand	Glazov, Russia	TVEL	Not available	Electrolytic process[3)]
Zr sponge	Pilcaniyeu, Argentina	National Aeronautics and Space Administration (NASA)	Not available	Kroll process
Zr sponge, Crystal bar from Zircon sand	Ezeiza (ZMP), Argentina	NASA	Not available	Not available

[1)] Previously CEZUS

[2)] Previously Teledyne Wah Chang [3)] Changing to Kroll process

ANT International, 2014

8 Fuel rod assembly (Alfred Strasser)

8.1 Fuel Rod Components

The assembled fuel rod is shown in Figure 8-1 and consists of the fuel pellet column seal welded in the cladding by end plugs, held in place by a spring or spring-like retainer in the upper plenum space and filled with pressurized helium. The components of the fuel rod are summarized below.

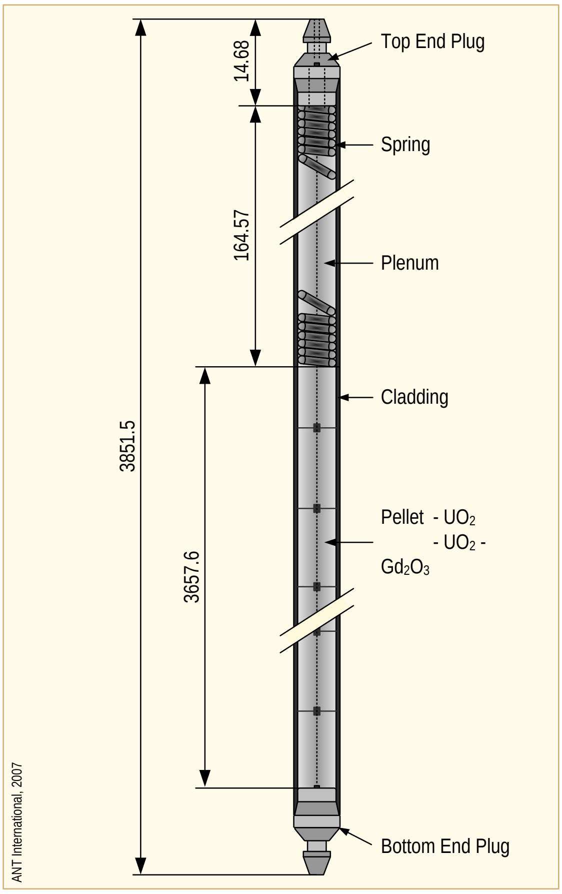

Figure 8-1: Typical PWR Fuel Rod. (Dimensions in mm for AFA 2G Rod of Framatome).

The *zirconium alloy cladding* is provided by the tubing vendor, usually in finished, cleaned, cut to length form and with appropriately machined tube ends. PWR alloys in most common current use are ZIRLO, M5, Duplex Zircaloy-4 and Zircaloy-4. The Zircaloy-4 type cladding is expected to be completely replaced by advanced alloys. BWR alloys in use are Zircaloy-2 and its variants. The majority of the BWR cladding tubes have a soft, thin zirconium liner to minimize the effects of PCMI and PCI on clad integrity. The liners contain small amounts of alloying elements (Sn and/or Fe) to improve the oxidation resistance of the liner in case of a failure and the potential, subsequent degradation of the cladding. Their fabrication and QA are described in Section 7.

The *fuel and burnable absorber pellet columns* come from the fuel pellet fabrication operation described in Section 4. This includes UO_2, burnable absorbers (BAs) such as Gd, ZrB_2, or Er in combination with UO_2, or MOX fuel. Note that burnable absorbers such as gadolinia are typically located in absorber rods rather than being mixed with UO_2 and PuO_2 powders in MOX fuel pellets.

The *top and bottom end plugs* are usually (but not always) made of the same zirconium alloy as the cladding. Their fabrication and QA are described in Section 7.

The *plenum spring* is made of either steel or nickel alloys and is generally made by a subcontractor and delivered in final form to the fuel vendor to the vendor's specifications. The age hardenable nickel alloy (Inconel) springs are solution treated and aged.

Helium gas used for filling and pressurizing the fuel rods comes from a gas supply vendor either in pressurized bottles or in liquid form to "standard" specifications approved by the vendor.

8.2 Assembly Procedure

The fuel rod is assembled as shown in the flow chart on Figure 8-2 and described in subsequent sections.

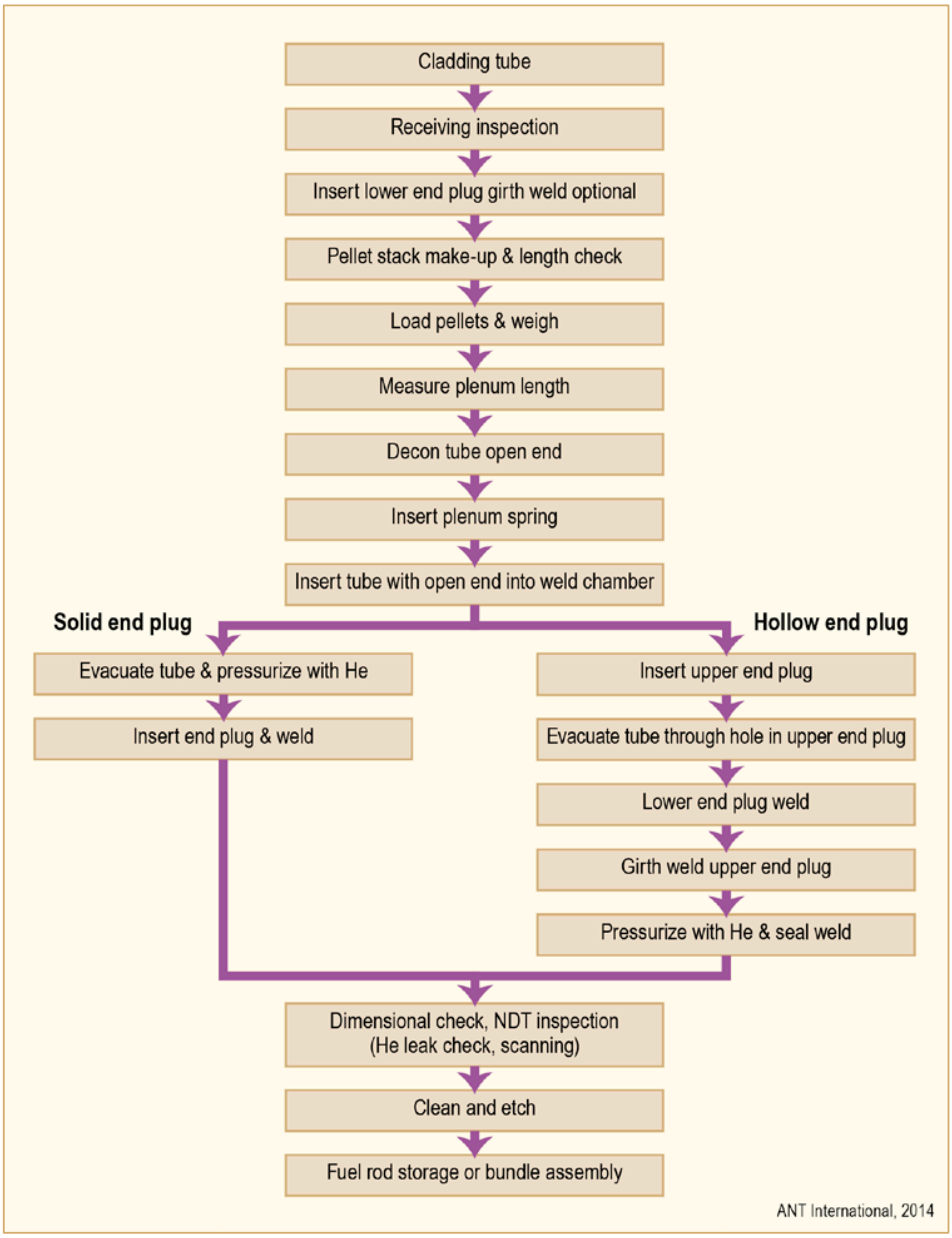

Figure 8-2: Fuel Rod Assembly Process.

The process generally consists of welding the bottom end plug to the cladding, pushing or vibratorially feeding the fuel pellet column into the cladding, adding the plenum spring, pressurizing the fuel rod with helium and welding the top end plug. Variations in the details of the process vary from vendor to vendor as discussed subsequently. The references to Section Numbers on the flow chart refer to the Sections that describe the process details and the audit priorities.

8.3 Welding

8.3.1 Process

Two or three different welds are made in the fuel rod fabrication process by potentially four different welding methods: tungsten inert gas (TIG), laser (L), magnetic force (MF) and resistance (R) welding. The different welds and the methods that have been used to make them are:

- Bottom and top end plugs: TIG, L, MF, R,
- Seal weld: TIG, L.

The TIG weld fuses the weld joint by an electric arc generated between the tip of a tungsten electrode and the weld joint The L welds are made by a highly amplified and focused light beam. The MF welds are made by passing a current through the weld joint via the cladding and the end plug, while the weld area is held under pressure by a magnetic force. The combination of resistance heat and pressure fuses the joint. Resistance welds are made in a similar manner without the use of the magnetic force.

The majority of the TIG welding processes have been replaced by magnetic force or resistance welding.

The bottom and top end plugs are welded to the cladding by a circumferential weld seam. The seal weld closes a small hole in the top end plug used on designs that pressurize the fuel rod in two steps: top end plug weld followed by pressurization through the hole that is subsequently sealed by welding. The alternate process pressurizes the fuel rod, then inserts and welds the top end plug in one step using a pressurized weld chamber.

Cleaning of the weld joints prior to welding is critical in order to remove any impurities, such as UO_2 at the top end plug that could affect weld quality.

The welding atmosphere purity is critical since the hot or molten zirconium alloy will absorb oxygen and nitrogen rapidly. The weld quality of Nb alloys (M5, E110) is particularly sensitive to nitrogen pickup. The atmosphere in the weld chamber should be monitored for qualified limits on nitrogen, oxygen and moisture; in case of a vacuum, a maximum pressure limit should be observed. The TIG welding process uses small additions of argon gas to help start the arc in the helium atmosphere. Since excessive low thermal conductivity argon can degrade the high thermal conductivity of the helium atmosphere in the fuel rod, the potential of excess argon dilution must be controlled. Note that the addition of argon to promote welding is not equivalent to the contamination of the helium filler gas by air. The primary constituents of air (nitrogen and oxygen) react with or are absorbed by the fuel and cladding during operation so that they cease to be a factor in heat transfer early in the life of a fuel rod. Any argon added to the filler gas remains throughout life and degrades conductivity by the same mechanism as released fission gas and can adversely affect fuel operation.

All welding processes are automated, electronically controlled with electronic readouts and often-automated in-process inspection. The electronic controls should be set within predetermined process parameters limits. The controls and any related software should be audited to ensure that the settings represent actual conditions. Typically the controls are for voltage, amperage, time at power, weld joint or arc rotation speed and other parameters that control the welding process. The spacing between the electrodes (tungsten electrode, electron gun, laser) and the weld joint may be manually controlled.

9 Spacer grid assembly (Alfred Strasser)

9.1 Spacer types and their components

9.1.1 Introduction

The spacer grids are precision made products that serve multiple functions in addition to spacing the fuel rods as the name indicates.

The spacer structure has a significant influence on the hydraulic flow and the efficiency with which the coolant performs its function. The flow holes in the grid straps, the mixing vane geometry and distribution, the spacer strip thickness, the envelope design and the spacer height influence the pressure drop across the spacer, the flow patterns, the turbulence and thereby the departure from nucleate boiling (DNB) and critical heat flux (CHF) limits. In PWRs the core flow patterns are affected in part by the spacer design as well. The DNB and CHF limits can be improved by modifications in the spacer dimensions and configuration.

The spacer structure has a significant effect on the pressure drop across the core and in PWRs the pressure drop distribution within the core, on mechanical vibration, assembly lift-off as well as heat transfer, especially in cores with a mixture of different spacer designs. The combined effects of flow patterns and heat transfer will have an effect on CRUD deposition as well.

The mechanical function of the spacer springs is to limit the axial and radial movement of the fuel rods as well as their vibration. The mechanical design material and heat treatment of the springs will affect this function.

The bottom spacers can act as debris catchers and some designs are intended to serve that function either instead of or in addition to a debris catcher in the lower tie plate or nozzle.

Fuel performance can be improved by changes in spacer design, without changes in the remainder of the fuel assembly and for that reason changes in spacer design can be more frequent than changes in the remainder of the assembly. This can result in a variety of spacer designs operating simultaneously within a core.

Small variations in dimensions and shapes within an existing design or small changes from one design to another can have a significant effect on the spacer performance and for that reason the dimensional inspection and any changes from the qualified, specified spacer must be reviewed thoroughly by thermal-hydraulic, nuclear and mechanical specialists to take all effects into account.

In general, the spacers consist of:

- Grid straps welded in an egg-crate format or ferrules (short tube sections) welded within a square outer strap configuration,
- Springs either punched out of the grid straps or inserted and fastened in the strap structure,
- Holes punched into the grid straps and outer straps to reduce neutron absorption and promote flow,
- A means of attachment to an assembly structural member to restrain the spacers from axial movement.

Typical spacers are shown in the Figures for various vendors' designs in Section 2.

9.1.2 BWRs

The spacers for BWR fuel assemblies can be either bimetallic or, now more commonly, a single, high-strength alloy. The bimetallic types consist of a Zircaloy-2 structure with Inconel -alloy springs. The alloy used for the springs has been Inconel X-750 or Inconel 718 most of the time. The original design for all vendors' bimetallic spacers was an egg-crate strip type until the former GE (now GNF) and the former Siemens-KWU (then Framatome and more recently called AREVA) changed to a ferrule design that consists of an array of Zircaloy-2 tube sections. The ferrule design improved the margin to critical power (CPR) and reduced the pressure drop across the spacer. The former ANF (now also AREVA) maintained the egg-crate design and improved the CPR margin by the addition of mixing vanes and other mechanical modifications that improved the hydraulics.

The advanced GNF and Framatome/AREVA designs now offer spacers constructed entirely of nickel alloys for their advanced 10x10 or 11x11 fuel rod array designs. An all Inconel spacer has been used throughout the evolution of the former ABB Atom (now Westinghouse Electric Sweden). The design of the structure, made of stamped strips and integral springs, is shown in Figure 2-20. Alloy X-750 is used in the age hardened condition.

The advantages of the all-Inconel design are higher corrosion resistance without hydrogen embrittlement, higher strength that leads to thinner sections and lower pressure drop. The disadvantages are higher neutron capture cross-sections and a slight increase in system activity from Ni and Co and more opportunity for shadow corrosion of the zirconium alloy cladding.

9.1.3 PWRs

The vendors for western PWR fuel designs used high strength Ni alloy spacers for all their initial designs with the exception of former Combustion Engineering (currently Westinghouse) that started out with all-Zircaloy-4 spacers and ANF (now AREVA) that used bimetallic spacers. Most vendors are currently using either bimetallic or all-ZIRLO or M5 spacers. (Figure 2-7, Figure 2-11 and Figure 2-27) The springs are stamped out of the Zr alloy strips. In addition there are "hard stops" stamped into the strips that keep the fuel rod centred within the cell. The Russian VVERs used stainless steel spacers and are in the process of changing to a Zr alloy.

The Inconel spacers are still in use for the bottom and top spacers of the assemblies. Their higher neutron absorption does not affect the enrichment requirements significantly in these low flux locations. The bottom spacer is exposed to the greatest amount of vibration from coolant flow and in order to maintain a high spring force throughout life a higher strength alloy than a Zr alloy is needed. The choice of a Zr alloy or a high strength nickel alloy (Inconel) for the top spacer is dependent on the hydraulic environment at that location and is a reactor dependant decision by the vendor, a choice best evaluated in a design review. The alloys used for these high strength spacers include age hardenable Inconel X-750, 718 and solution treated Inconel 625.

9.2 Fabrication process

9.2.1 Process

9.2.1.1 Stamping

The flow sheet for the spacer fabrication process is on Figure 9-1.

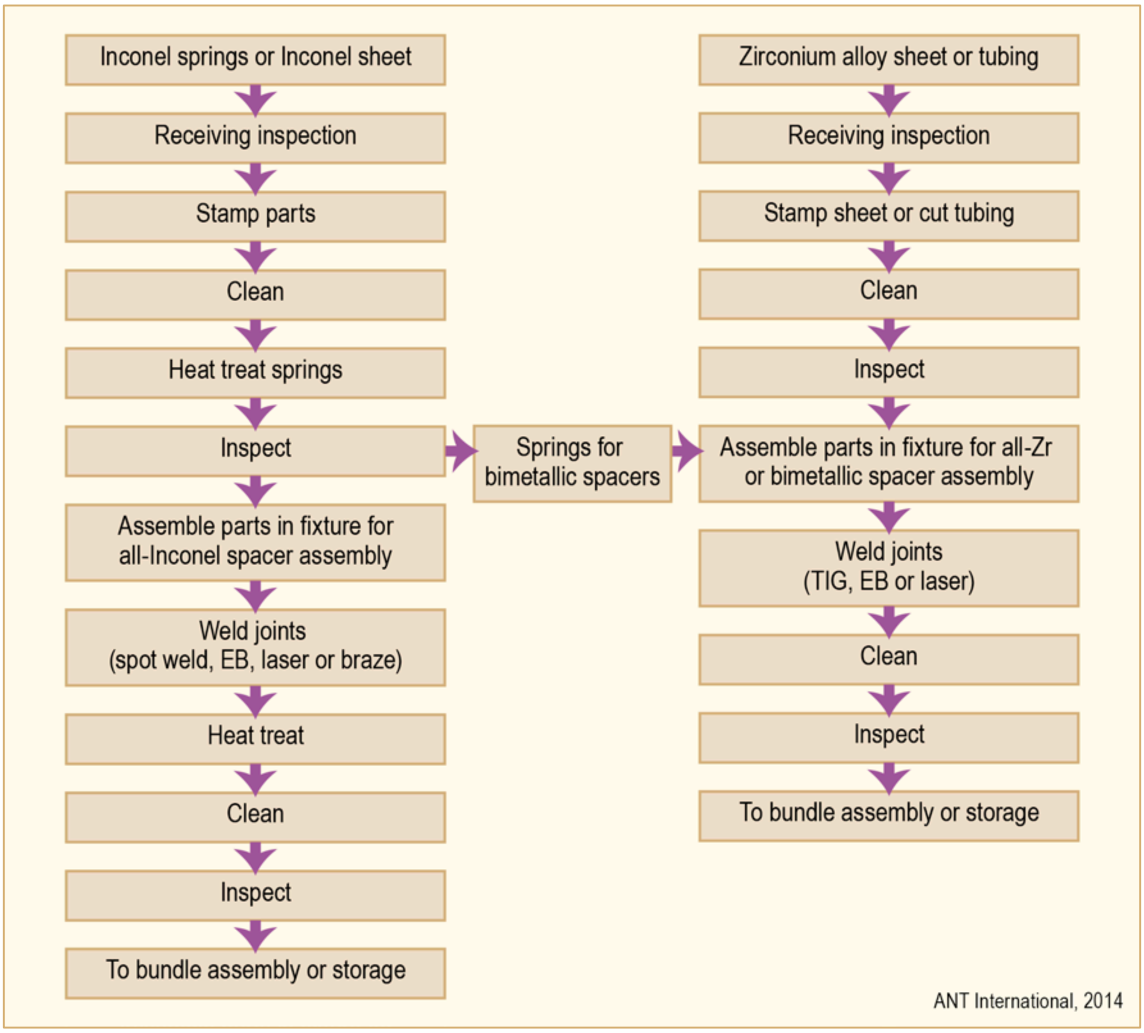

Figure 9-1: Spacer fabrication process outline.

The zirconium alloy strip or tubing (for BWR ferrule spacers) is supplied by the basic zirconium alloy producers and their fabrication process is described in Section 7. The nickel alloy strip is also provided by a primary metal fabricator and produced by a series of hot and cold rolling steps. Both materials are provided in the fully annealed condition in order to accommodate the significant local deformations that can occur during the stamping process. Formability tests, such as a cupping test, and bend tests are made to assure the strip meets acceptance criteria. These are in addition to the standard chemical, metallurgical and mechanical properties the strip has to meet.

The alloy strips are stamped to form the required shapes for hard stops, flow holes or channels, mixing vanes and integral fins for the designs that use them. Outer straps are bent as required. The stamping is done either by the vendor or by a subcontractor with dies that the vendor usually owns. The process uses either a continuously rotating die or a reciprocating stamping press. The die design and maintenance are critical for producing spacer strip with consistent, high precision dimensional control. Die wear can modify dimensions that may not be detected by sampling control. Periodic die inspection and maintenance are essential. Pressing pressures and speed are important parameters as well for control of quality.

10 End fitting fabrication and assembly (Alfred Strasser)

10.1 End fitting types and their components

10.1.1 Introduction

The fuel assembly end fittings are generally called “tie plates” in BWRs and “nozzles” in PWRs. They are located at the top and bottom of each fuel assembly and perform several major functions:

- They form the interface with the reactor core plates or other components,
- Together with fuelled tie rods, water rods, inner channels in BWRs and guide tubes in PWRs they are an essential component of the fuel rod support structure,
- They are a significant factor in determining the pressure drop across the core,
- They determine the hold-down forces for the assemblies,
- Debris filters are included in some lower end fitting designs.

The design of the BWR and PWR end fittings are significantly different from each other. The fuel assemblies have to be compatible with the different reactor core designs of the different NSSS types. Additional reactor and vendor design specific differences exist for the same NSSS among both the BWR and PWR fuel designs. The BWR designs have greater flexibility for design differences since the fuel assemblies are contained in a channel that can have its own end fitting designs. The PWR fuel assemblies’ end fittings must stay compatible with the NSSS core internal designs and components. The major differences between the end fitting designs are noted in this Handbook.

10.1.2 BWRs

The lower and upper tie plates form a part of the fuel assembly structure that holds the fuel rods in place. In one design the channel box is lowered over the fuel assembly and rests on the upper tie plate. Originally all vendors’ BWR fuel assemblies were of this type, sometimes called the “integral nozzle” design. In this design the *lower tie plate* has a nozzle that fits on a core component, such as the lower core plate, and directs coolant flow into the assembly. In some assembly designs, the small gap between the lower tie plate and the channel is closed off with thin stainless steel or high nickel alloy leaf springs attached to the tie plate to prevent coolant from flowing through this gap. In other assembly designs, the gap width is constrained to limit the bypass flow and the channels are designed to minimize increases in the gap due to channel creep. The upper tie plate has a lifting bale to allow the assembly to be moved with the reactor fuel grapple. The various vendor’s designs are shown in Section 2: Figure 2-12 to Figure 2-14 (AREVA), Figure 2-19 to Figure 2-20 (Westinghouse), Figure 2-23 to Figure 2-25 (GNF) and Figure 2-34 (NFI).

In the alternative, “bundle-in-basket”, design the nozzle is attached to the fuel channel instead of being part of the lower tie plate and the fuel assembly is lowered into the channel. The lower tie plate or assembly end fitting in this case is essentially a perforated square plate that rests on the nozzle. Leaf springs to prevent coolant bypass out of the assembly are not needed in this design. Figure 2-20 shows a design of this type (Westinghouse-SVEA).

Debris filters can be incorporated in the lower tie plates or nozzles of both design types and differ from vendor to vendor.

The nozzle is a several inches long, square stainless steel channel that is tapered at the bottom. A round opening at the bottom of the nozzle interfaces with the fuel assembly supports in the core. This component, usually a casting, supports up to four fuel assemblies and also guides the reactor control rods.

The *upper tie plate* consists of a grid plate and an attached lifting bale to allow the assembly to be moved in and out of the reactor core and the spent fuel pool. The “integral nozzle” design also incorporates a means to fasten the upper tie plate to the assembly proper, that is, the fuel rods and the spacers. The upper tie plate has corner posts that, along with the lifting bale, guide the channel over the fuel assembly. The channel is fastened to the corner posts with clips and bolts. The fuel assembly is normally handled with the channel in place and this protects fuel rods and spacers against side impact and damage.

Regardless of assembly design, the lifting bale is placed diagonally across the upper tie plate and incorporates an orientation knob or pointer to indicate the wide-wide corner of the assembly. All designs include an easily removable upper tie plate to facilitate access to the fuel rods for post irradiation measurements or repairs. A unique assembly number is engraved or etched on the top of the bale so that it can be read from the fuel loading bridge.

The upper tie plate of the “bundle-in-a-basket” is designed to permit lowering the fuel assembly into the channel. The end fitting of this design has leaf springs attached to the sides of the tie plate grid to guide and to keep the assembly centred in the channel and to keep the assembly from vibrating. The Westinghouse-Atom design has four mini-bundles of either 4x4 or 5x5 array that are attached to the upper tie plate and are lowered into the channel as a single unit.

10.1.3 PWRs

The lower and upper nozzles of the PWR assemblies in combination with the control rod guide tubes and spacers form the structure, or “skeleton” that holds the fuel rods in place. As in the case of the BWRs, their design varies to fit the different reactor designs and within that restriction their design also varies from vendor to vendor.

The *lower nozzle* consists of a strong horizontal grid plate to support the fuel rods and has legs on the bottom of the four corners of the grid plate to rest the fuel assembly on the lower core plate. The control rod guide tubes are fastened mechanically to this grid. In order to locate the fuel assembly in an exact position on the core plate, there are typically two locating pins on the feet of the nozzle, or as in the design for Siemens NSSS, by a large diameter ring on the bottom of the nozzle. Debris filters have been designed to be part of the lower nozzle or alternatively part of the bottom grid spacer.

The lower nozzle forms the entrance of the coolant through the grid plate and into the fuel assembly. The design of the nozzle has a significant effect on the pressure drop and coolant flow through the core.

The *upper nozzle* consists of a variety of stainless steel structures combined with a variety of hold-down spring designs and their attachments. The upper end of the guide tubes are fastened to the upper nozzle to permit passage of the control rods through the nozzle in order to enter the fuel assembly. Most vendors now use guide tube fastening devices that can be unlocked to allow remote removal of the upper nozzle and access to the irradiated fuel rods for examination or repair.

A unique assembly number is engraved on the top and usually on one side of the upper tie plate. An orientation hole is typically drilled in one corner of the upper tie plate so that it is clearly visible from the top.

The main functions of the upper nozzles are to provide:

- A means to lift the assembly for insertion and removal from the core, spent fuel pool or other movements of the assembly,

- To provide the necessary hold-down force and prevent the assembly from lifting off of the lower core plate due to the large upward coolant forces,
- To take up the differential thermal and irradiation growth expansion between the core plates and the fuel assembly via the hold-down springs.

The various vendors' nozzle designs for PWR fuel assemblies are shown in Section 2: Figure 2-4, Figure 2-7, Figure 2-9, Figure 2-10 AREVA), Figure 2-16 (Westinghouse), Figure 2-27 (ENUSA), Figure 2-28, Figure 2-35 (NFI), Figure 2-36 and Figure 2-37.

Most of the BWR nozzles are made of machined precision castings and some from wrought stainless steel components. Most PWR nozzles are made of wrought stainless steel parts or from precision castings. Wrought plate and/or precision castings are obtained from subcontractors. Complex assemblies may be made of welded wrought or cast components. Machining and/or welding are usually done at the fuel vendor.

The springs and some of their attachments are made of high strength nickel alloys and are either leaf or coiled springs obtained from subcontractors. Additional attachments and fixtures are usually made of machined stainless steel parts.

The fabrication methods of the end fittings and their components are described in the Sections that follow.

10.2 Tie plates and nozzles

10.2.1 Castings and BWR Tie plate Assembly

The BWR and PWR stainless steel end fittings can both be made by precision casting. One such process, the lost wax process, is shown for BWR tie plates on Figure 10-1, but is applicable to PWR nozzles as well.

11 Fuel bundle assembly (Alfred Strasser)

11.1 Assembly types and their components

11.1.1 Introduction

The BWR and PWR fuel bundle assemblies are similar in concept, in that an array of fuel rods is held in place by spacers and a structure that consist of upper and lower BWR tie plates or PWR nozzles at each end and a variety of structural member types that hold these upper and lower components together. In detail, however, each vendor's design is different. The BWRs have the largest variety of bundle designs because each bundle is located in an individual flow channel isolated mechanically and hydraulically from the neighbouring bundle by the channel. In addition the control assemblies are outside the bundles and are independent of the fuel design. As a result the designers have significant latitude in modifying the designs to provide improved performance fuel and still be compatible --- within limits of course --- with the balance of the fuel designs in the core. The PWR fuel bundles are mechanically and hydraulically in close contact with each other and must retain a higher degree of compatibility. The designs must also maintain a fixed control rod pattern within the fuel bundle. These features limit the extent of their design flexibility.

The fuel bundle designs of the various vendors as of 2014 are described in Section 2 and will be referred to throughout this Section.

11.1.2 BWRs

The BWR fuel designs are integral with the channels that enclose the fuel rod bundle assemblies. The channels are square zirconium alloy boxes that contain the coolant flow into the rod bundles. Their fabrication is described in Section 12.

BWR assembly designs have two different approaches for connecting the channels to the rod bundles. In one design the channel is lowered over the fuel assembly, rests on and is attached to the upper tie plate. In this design the lower tie plate has a nozzle that fits on a core component and that directs the coolant flow into the assembly. Thin leaf spring baffles on the lower tie plate or other design features limit the flow of coolant between the channel and the tie plate. Figure 2-2, in Section 2 represent such designs and are provided by GNF (GE series) and AREVA-Siemens (ATRIUM series).

In the other design the nozzle that directs coolant flow into the assembly is attached to the bottom of the channel and the fuel assembly is lowered into the channel. The lower tie plate or assembly end fitting in this case is essentially a square plate that rests on the nozzle. Leaf springs to prevent coolant diversion out of the assembly near the bottom tie plate are not needed in this design. "Bundle-in-basket" is the name used occasionally for this design and these types are provided by AREVA and Westinghouse Electric Sweden (SVEA series). The latter is shown in Figure 2-20, Section 2, a unique design that has four individual fuel rod bundles placed in the channel separated by a cross that is an integral part of the channel, as described in Section 12.

Additional design differences exist within each of these BWR assembly design types. The GNF rod assemblies have water filled zirconium alloy tubes ("water rods") and fuelled tie rods. The tie rods are attached mechanically to the upper and lower tie plates and that form the mechanical structure of the assembly. The spacers are captured axially by fittings on one of the water rods. The AREVA ATRIUM series has a central, square zirconium alloy water rod, which is called a channel, and its ends are attached to the upper and lower tie plates. The spacers are attached to the central channel by mechanical fastening devices. The fuel rods in both designs can have hold-down springs between the top of the fuel rod and the upper tie plate.

The bundle-in-basket design by AREVA (Framatome-Siemens/KWU), except for its different lower tie plate design, is similar to that of the ATRIUM series. The Westinghouse SVEA design is completely different and has four separate fuel bundles sitting in the configuration provided by the external channel and internal water cross.

The number of fuel rods per assembly has increased over the years from 6x6 or 7x7 arrays to 10x10 arrays to improve fuel utilization and efficiency, and the thermal performance of the assemblies. Each vendor's assembly type has gone through this evolution, made possible by the isolation of the assemblies in channels. Mixed cores of different arrays are feasible if nuclear and hydraulic compatibilities are respected.

The bottom end plugs of the fuel rods are located in holes machined in the lower ties plates in most designs. All designs have both full length and part-length rods. The part length rods do not extend to the top tie plates and are intended to provide more water moderator and lower pressure drop at the top of the core for improved nuclear and thermal-hydraulic properties. The part length rods are mechanically attached to the lower tie plate to maintain their axial position; e.g., threaded end plugs and tie plate holes.

The fuel rods have many different composition levels of fuel enrichment zones. Fuel rods with burnable absorbers have several composition levels of absorbers. It is not uncommon to have ten or more different fuel rod designs in a single assembly. It is very important that a fuel rod of a given design be located in its designed position in the assembly.

11.1.3 PWRs

The generic PWR assembly designs of various vendors are similar to each other for reasons discussed in the Introduction. The structure, or "skeleton", of each assembly consists of zirconium alloy guide tubes for the insertion of control rod assemblies and are attached mechanically to the upper and lower nozzles. The spacers are attached mechanically or by welding to the guide tubes. The fuel rods sit on the bottom nozzle, although some designs have used off-the-bottom designs.

The differences in design are in the components themselves, as described in previous Sections, and the methods by which they are attached to each other. Most of these vary from vendor to vendor.

11.2 Assembly process

11.2.1 BWRs

The assembly process of the fuel rod bundles is outlined in Figure 11-1. Varying degrees of process automation have been implemented at all of the vendors.

12 BWR channel assembly (Peter Rudling and Alfred Strasser)

12.1 Introduction

The in-reactor performance of the fuel bundle assembly and the channel assembly are interactive. This means that the mechanical, thermal-hydraulic and nuclear design and performance of each assembly will affect the performance of the other one. The fabrication QA audits of the channels, therefore, have an importance that is similar to that of the fuel bundles.

The channels are square zirconium alloy boxes that envelop the fuel bundles and have attachments that connect to the upper and lower tie plates in a variety of ways. There are three different, general types of channel designs and they are vendor specific:

- Outer channel boxes for all designs,
- Inner channel boxes (rectangular water rods) for AREVA ATRIUM designs,
- Water cross assemblies for Westinghouse Electric Sweden SVEA designs.

The function of the outer channel boxes is to contain the coolant flow in all BWR fuel bundle designs. The GNF and AREVA ATRIUM designs have gone through a number of modifications that started from the original uniform wall thickness box made of Zircaloy-4 as shown in Figure 2-2. The current designs have a reduced wall thickness on the box faces and the original wall thickness at the corners. Wall thickness is reduced on the faces to increase the amount of water moderator and decrease enrichment requirements. Face thickness at the channel bottom and corner thickness along the fuel channel length is maintained to resist bulging due to the pressure difference between inside and outside of the channel, as shown in Figure 12-1. Zircaloy-4 was used originally for all channels and continued to be used in some designs; e.g., Japanese BWRs. Some vendors have switched to Zircaloy-2 for improved corrosion resistance. Zircaloy-4 is becoming more common, however, because of lower hydrogen pickup at high burnups and the resulting beneficial effects on channel bow due to shadow corrosion. Other Zr-alloys designed to minimize hydrogen pickup, irradiation growth or both pickup and growth are currently undergoing irradiation as lead-use channels.

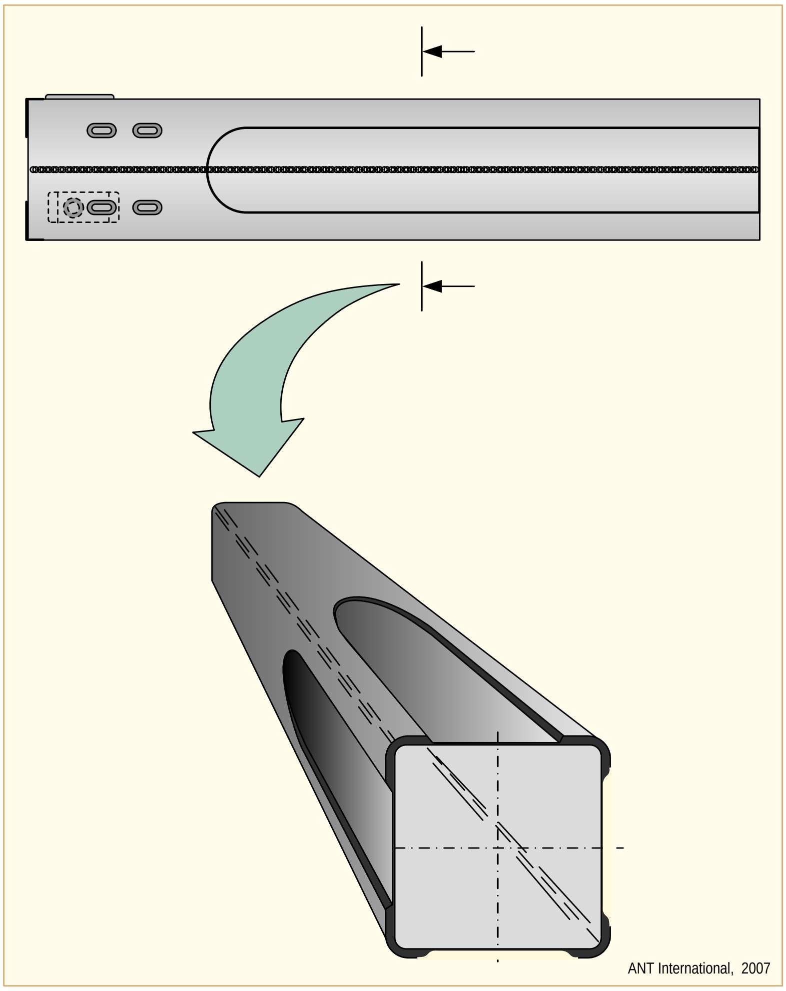

Figure 12-1: Typical Variable Wall Channel Box.

The inner channel box of the AREVA ATRIUM designs introduces unvoided water moderator into the centre of the assembly to increase reactivity and reduce enrichment requirements and in that respect is similar to the water rods of the GNF design. The uniform wall thickness box is made of Zircaloy-4 or -2. The design is shown on Figure 2-2 and Figure 2-13.

The water cross of the Westinghouse SVEA designs serves a similar function by containing unvoided water moderator in its hollow interior that extends the width and length of the fuel assembly. The tips of the water cross are attached to an outer channel. The assembly is made of Zircaloy-4 and shown on Figure 2-19 and Figure 2-20.

All of the sheet materials for the channel boxes, sometimes called “channel blanks”, are made by the primary zirconium alloy producers as described in Section 7. The boxes are formed and finished by a variety of vendors as discussed for each design. As noted earlier, they can be shipped separately from the fuel bundles and assembled with the fuel at the reactor site or installed at the fuel fabrication plant and transported to the reactor site with the fuel.

12.2 Outer and inner channel fabrication

12.2.1 Fabricators

Uniform texture throughout the channel walls is extremely important to avoid differential irradiation induced growth and bowing of the channels. Differential growth induced bowing was noted some time ago and traced to channels fabricated from two different sheets, made by the "same" fabrication process, but differing slightly in texture. The uniform texture is now achieved by two different basic fabrication processes to form the box shape. One process (two-sheet) involves cutting a single sheet into two pieces which are then oriented in the same direction, bent into two U-shaped sections and connected by two weld seams on opposing faces. The second process (single-sheet) involves forming a single sheet into a box and joining the mating edges with a single weld. The single-sheet process also includes a "dummy" weld bead on the face adjacent to the actual seam weld.

13 Statistical quality control (Graham Walker)

13.1 Introduction

Variability in fabrication processes and variability in the properties of the material being processed result in variations of the properties of the final product. In order to assure that the product meets the desired specifications, the statistical nature of the process and of the material properties must be known and if necessary, controlled. This requires the statistical analyses of the variations during the process qualification phase of the production, which determines the process parameter limits that will produce a product in specifications within certain confidence limits. The subsequent production is statistically monitored to assure that the process stays within the qualified process parameters. These actions are the responsibility of the fuel vendor. The responsibility that they are implemented is the responsibilities of the QA organizations of both the vendor and the utility client. This Section is intended to provide background and guidance on auditing the statistical processes, their application and evaluation of their results. The corrective actions will depend on the specific items and problems that are involved.

The primary application of such Statistical Process and Product Control in nuclear fuel fabrication is in three areas. The first, acceptance sampling (AS) for QC inspection is applied for the inspection of parameters that cannot be subjected to 100% inspection due either to technical or economic reasons. Hence, a statistical number of samples are taken in a sampling plan that is based on the statistical data distribution of the parameter being tested and the confidence level desired for the rejection of non-conforming items. The second, statistical process control (SPC), monitors the production process with statistical charts to determine whether the process stays within the limits defined by the process qualification test. In the event it tends to drift off or exceed the limits, the cause must be identified and corrected. The third, measurement system analysis (MSA), qualifies the statistically based precision, accuracy and linearity of the measuring system by the repeated analyses of certified standards of various values by the same and different operators. The measurements systems, qualification is valid for a specified length of time and must then be repeated.

Quality control therefore exists to ensure that a product or service has been, or is being, produced within specifications, where the limits of a specification or tolerance are often taken to be the $\pm 3\sigma$ (three sigma) limits associated with a particular product characteristic. This would imply that 99.73% of the product will lie within these limits. In the first case, where the product has already been produced the process is called Acceptance Sampling (AS), while in the second case, where the product is being produced the process is called Statistical Process Control (SPC). The applicable statistical methodology, examples and list of related audits follow.

13.2 Data presentation

13.2.1 Data presentation introduction

Raw data presented merely as a set of numbers communicates very little information; therefore several graphical methods have been developed to allow salient features and characteristics of the data to be represented visually. In the area of quality control there are two common ways by which data is displayed graphically; the simple histogram, and the scatter graph which allows basic trends to be identified.

13.2.2 Histogram

A histogram is a chart that shows how data is distributed and is also known as a frequency distribution. It shows how many items are associated with a specific category, where the categories could be non-rankable such as types of tools used while performing an assembly operation (e.g. wrench, screwdriver, hammer, vise grips, etc.) or rankable such as diameter ranges (e.g. 1.90 to 1.99 in, 2.00 to 2.09 in, 2.10 to 2.19 in, etc.). In either case the data is discrete, forming identifiable and countable groups. An example of a histogram would be the number of rods that fall within a specific diameter range (Figure 13-1), or the presentation of the probability distribution associated with a data set (Section 13.9).

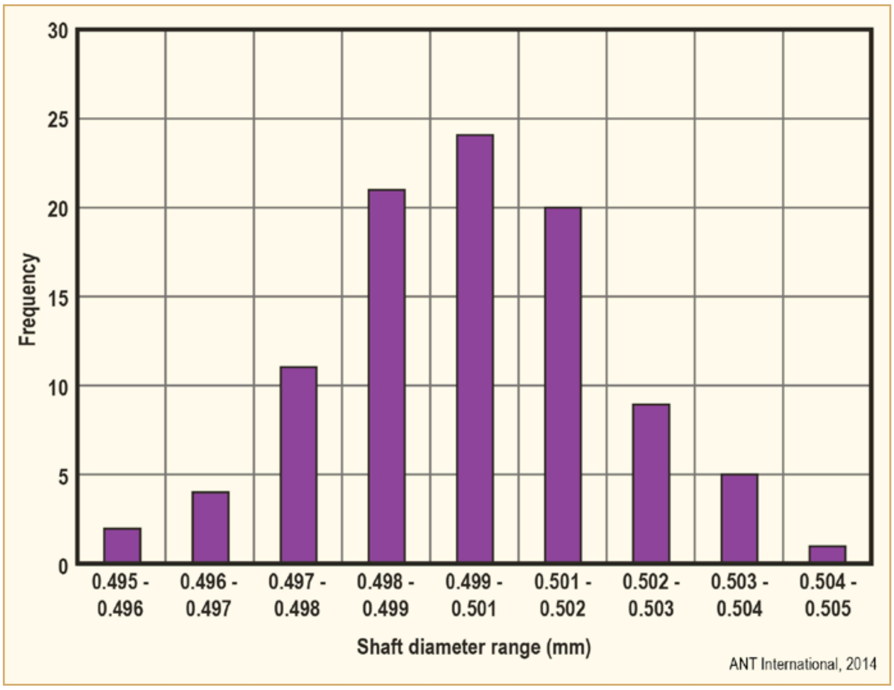

Figure 13-1: Example of a Histogram.

13.2.3 Scatter graph

A scatter graph allows relationships between variables and test results to be discerned. This is done by plotting the variable using the abscissa (the x-axis) and the result using the ordinate (the y-axis) and plotting each point with individual markers. In most cases the abscissa data is rankable but need not be. Also, sometimes the variable may have multiple results and the subsequent graph will then consist of multiple lines of points, thereby showing the degree to which results are scattered. An example of a simple scatter graph would be a material's hardness at different locations along its length (Figure 13-2).

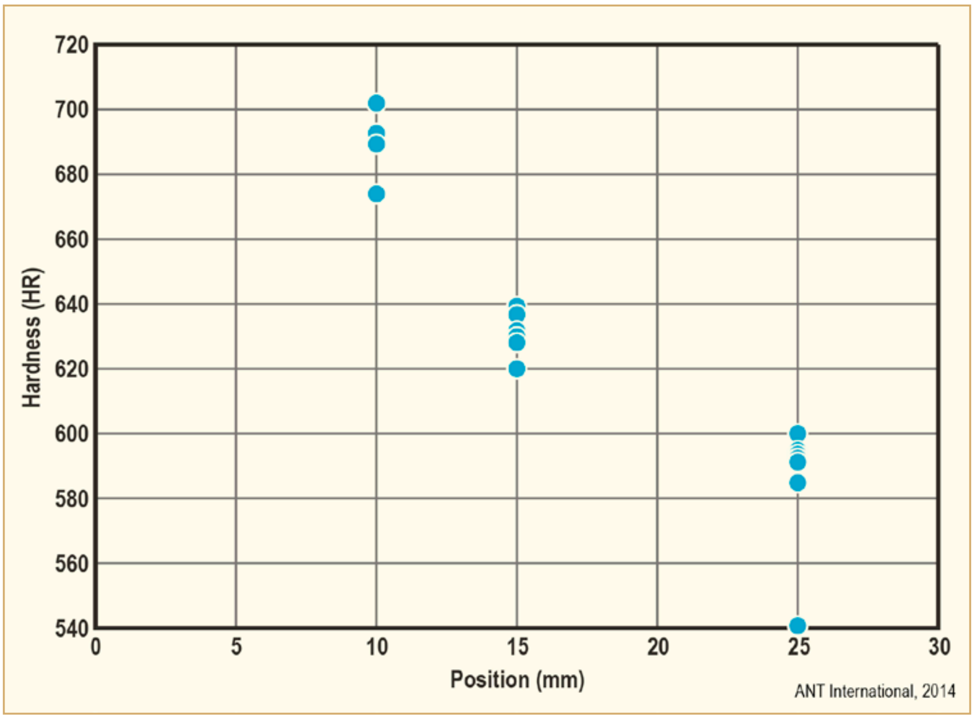

Figure 13-2: Example of a scatter graph.

In the special case, where the abscissa is time and only one point is plotted for each time, the data is referred to as being a time series, and the associated graph is called a time series plot. An example of this would be a Shewart chart (Figure 13-10) [Wadsworth et al, 2001a].

13.3 Acceptance sampling

13.3.1 Acceptance sampling overview

Nuclear fuel assembly components are 100% QC inspected, to a large extent, by non-destructive methods. However, some attributes must be inspected by sampling a large lot of material for either technical or economic reasons, and the data are then used to represent the quality of the entire lot. The validity of the decision depends on the selection of the appropriate sampling plan, which in turn depends on the data distribution and lot size being sampled and the confidence level desired in the results. The original sampling plan should be based on the qualification run of the process and the data distribution of that lot. Qualification runs usually use a higher inspection sampling size for this reason.

The data distribution is generally “normal” and the vendor’s sampling plans are based on such a distribution. However, it may be “skewed” requiring a different sampling plan to achieve the same confidence level. As an example, the low density level of fuel pellets and the high end of their moisture content are important to evaluate correctly to prevent unexpected moisture content to hydride the cladding. Such skewed data sets can often be described using either a lognormal or Weibull distribution (Figure 13-3) [Wadsworth et al, 2001b]. Auditing the vendor’s bases for the sampling plan and the statistical nature of the data distribution are the key items in this phase of the audit. Testing for the degree to which a data set is normal is discussed in Section 13.7.4.5; however, a discussion of the techniques used to develop a sampling plan for non-normal data is beyond the scope of this chapter but are discussed in the a number of technical papers: [Krishnamoorthy & Mathew, 2003] for lognormal distribution cases, [Takagi, 1972] for Weibull distribution cases, and [Suresh & Ramanathan, 1997] for symmetrical non-normal distributions.

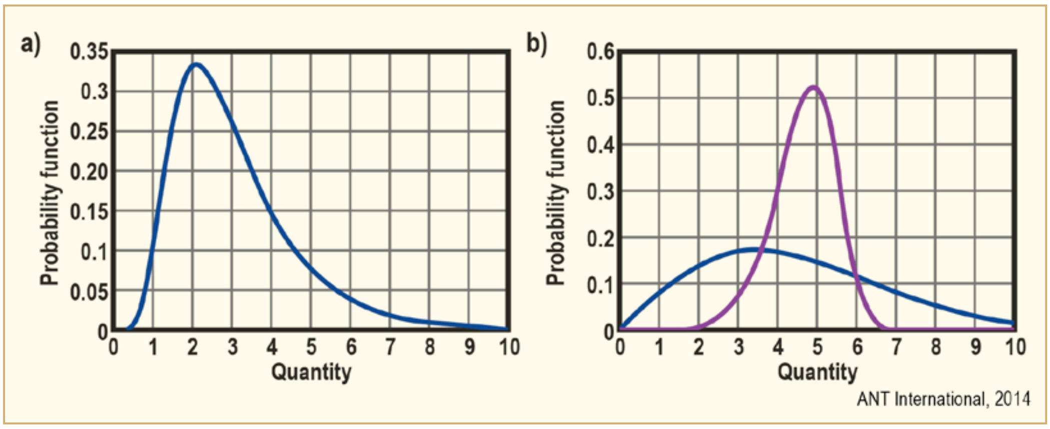

Figure 13-3: Examples of a) lognormal and b) Weibull distributions [Wadsworth et al, 2001b].

There are many situations where 100% inspection cannot be done for either economic, safety, or practical reasons (e.g. destructive testing). Also, 100% inspection does not guarantee that non-conforming product will not be accepted, since errors occur in the inspection process itself. Consequently, most inspection employs acceptance sampling where the decision to accept or reject a batch is based on the statistical analysis of the characteristics of a multi data value sample. However, it should be noted that if a statistical approach is used, there is a possibility of making a wrong decision about the quality of the product (e.g. a batch of product that does not meet specifications could be identified as being an acceptable batch). Unfortunately, this is *always* the case, but a well-designed QC system will minimize these possibilities at an optimal cost.

Acceptance sampling can be done using either quantities that are discrete (i.e. attributes) or have an infinite resolution (i.e. variables). Attributes are quantities that have specific set names (e.g. red, green, yellow, etc.) and in most cases are one of two options (e.g. go or no-go, accept or reject, etc.) and are analysed using a binomial distribution assumption, while variable are quantities that have numerical values that can have any number of significant figures (e.g. 37.152904 kg) and are analysed using a normal distribution assumption.

In the attribute case the sampling is easier to perform and can encompass multiple product characteristics at one time, however large samples are required since only a crude good/bad designation is used to characterize the quality of an item. Variable acceptance sampling uses higher quality information and therefore requires smaller samples, however the sampling protocol is more complex and only one product feature can be tested at one time.

Standards exist that detail how an acceptance sampling scheme can be performed, but these may not address all of the statistical requirements needed to achieve the quality desired, since they focus primarily on an Acceptable Quality Level (AQL) and not on a Rejectable Quality Level (RQL). However, significant statistical knowledge is needed to create a customized acceptance sampling protocol. In either case any acceptance sampling protocol is a trade-off between the efficiency of the procedure and its complexity.

Whether a standard or custom scheme is used, acceptance sampling relies on the fact that a specific sample characteristic (e.g. sample mean) for all samples of a given size from a particular population will have a predictable probability distribution (i.e. a probability density function). Consequently, since all important parameters associated with a product will have a desired value and associated tolerance, it is possible to calculate the probability that a sample drawn from a batch of the product will have a particular mean value for the parameter in question. In other words, it is possible to determine the probability of a particular sample coming from a batch that has certain desired characteristics (i.e. mean and tolerance), or from a batch that has certain undesirable characteristics.

14 Software quality assurance process (Kenny Epperson)

14.1 Introduction

14.1.1 Objectives

The objective of this Section is to describe a method utilities can use for auditing the software that controls automated processes used in nuclear fuel fabrication. Automated systems are implemented to improve reliability and speed up production. A key assumption is the process is set up correctly and repeated exactly the same way every time. The component that makes this happen is the software. Just like using out of spec materials or an inadequate procedure, untested or uncontrolled software can lead to a flawed product. The purpose of a software control program is to verify quality work in the development, use, and maintenance of software. The increased use of automated fabrication processes makes the audit of the software a priority.

The following discussion describes the details of software development, application, and quality control as well as listing specific audits recommended for each level of operation. In addition, Section 14.4 outlines an example approach to a software field audit of an automated fabrication step.

14.1.2 Scope

The word software is a general term that refers to a set of computer instructions used to do a task. The same term is used whether the task is a simple, single step operation on one machine or an immense sequence of complex and interdependent tasks on many machines. Software is also an integral part of every process used in day to day operation of businesses. While the term itself is very general, the quality standards by which each specific software application can be audited are consistent.

The method described is based on the general principals of software control. For software application to the fuel fabrication process, there are two main areas considered:

- **Fabrication Process Control –** software that controls and/or monitors specific fabrication steps. Typical examples are:
  - UF_6 vaporization and conversion process
  - Pellet pressing/sintering operations
  - Pellet inspection and measurement systems
  - Pellet storage and retrieval
  - Fuel rod loading station
  - Rod Welding stations
  - Fuel rod inspections (Leak test, UT, Gamma, etc.)
  - Laser welders for grid construction
  - Visual inspection of grid cells
  - Fuel assembly envelope inspection

- **Product Configuration Control –** software that controls the documentation of the delivered product. Typical examples are:
  - Definition of the Bill of Material for a fuel region
  - Creation of the DOE/NRC 741 forms, and QA Product Certification
  - Chemistry records database

Control of software should also extend to all types of devices, including Programmable Logic Controllers or PLCs. PLCs are digital computers used for automation of electro-mechanical processes, such as control of machinery on factory assembly lines. Unlike general purpose computers, the PLC is designed for multiple inputs/outputs and is resistant to the conditions (heat, electrical noise, vibration, and extreme temperatures) present on a factory floor. A PLC monitors output results based on input conditions within a set time period, otherwise unintended operation can occur. Before the use of PLCs, control, sequencing, and safety interlock logic for manufacturing was performed by relays, cam timers, drum sequencers, and dedicated closed-loop controllers.

Modern PLCs can be programmed in a variety of ways, from relay-derived ladder logic to languages such as adapted dialects of BASIC and C or even higher level programming languages. PLCs are typically programmed using software on personal computers via a cable or network connection. The programming software allows entry to and editing of the PLC logic. Generally the programming software provides functions for debugging and troubleshooting the PLC software. The functions include highlighting portions of the logic to show status during operation or simulations. The software control process presented in this section should be applied to PLCs since the process is generic to all software types, the PLC uses software to perform its intended function, and PLCs are an integral component in many manufacturing control and verification processes.

14.1.3 Definitions

Several terms used in this discussion are defined below. The definitions are not intended to be comprehensive, but to ensure the concepts are clearly understood in the context of this section. The terms used by the vendor can vary, but the evidence of a controlled process should be present. The defined terms are:

Acceptance Testing - The set of test conditions or parameters used to verify software is performing the intended functions described in the *Specifications*.

Certification - The process for documenting that the *Acceptance Testing* and *Validation and Verification* elements of software control have been performed satisfactorily. Once software has completed the Certification process, it can be implemented as *Production Software*.

Configuration Control **–** The overall process used to control software including development of new software, certification for production use, control of certified software to ensure the proper and consistent application, and modification of production software. Reporting and error correction of *Production Software* is assumed to be managed by the vendor's existing corrective action program.

Production Software **–** Software that has completed the *Certification* process and is in use performing the functions for which it was designed. Production Software is controlled to ensure traceability of the operating version to the *Certification* documentation.

Specifications - Written instructions describing the purpose, design, and functions of the software.

Validation and Verification - Tests, inspections, or other technical or quality activities performed by someone other than the software developer to ensure the quality, reliability, and functionality of the software meet the *Specifications*.

Also, please note the terms code and software are used interchangeably in this Section.

14.1.4 Overview

As described previously, while each specific application of software can be unique, some aspects of software control are common. These common items include:

- Software is uniquely identified by name and version.
- The certified software has access controls to ensure common use and to provide safeguards to ensure integrity.
- Documentation and files including source code, compilation directives, inputs and outputs of test cases, and user manuals are stored as lifetime records.
- Certified software can only be modified by a controlled process according to established specifications and/or procedures.
- All software modifications are documented and a history of changes retained.

The vendor should have a process or program that controls each of these areas in some fashion. The higher tier documents or procedures that the vendor maintains related to software quality include:

- Company Quality manual.
- Corrective Action program.
- Software Quality plan or procedure, including:
  - Software Development plan or procedure.
  - Software Configuration Control plan or procedure.
- Vendor's internal audit results of the Software Quality plan

These documents should be reviewed for adequacy one time for each vendor or subcontractor. Subsequent audits would then focus on a review of any program changes.

The process defined here is based on the fundamental steps of the typical life cycle for software, shown in Figure 14-1. The software life cycle starts with a specification and ends with retirement. The figure shows this as a linear process for convenience, but there are loops or iterations between steps in real life application. For logistical purposes, the format of the remainder of this section is divided into two main areas, software development (focusing on new software) and production software control (existing software in use in processes). The major steps and some key items in each area are depicted in Figure 14-1 in tan (software development) or green (production software) boxes.

14.1.5 Audits

The following items should be audited with Priority 1:

- Review of the vendor's Quality Manual for items addressing software acquisition and control.
- Review of the vendor's Corrective Action program to verify software error reporting is addressed.

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