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QUALITY AND RELIABILITY ASPECTS IN NUCLEAR POWER REACTOR FUEL ENGINEERING

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IAEA NUCLEAR ENERGY SERIES No. NF-G-2.1

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FOREWORD

One of the IAEA’s statutory objectives is to “seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world.” One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish “standards of safety for protection of health and minimization of danger to life and property”. The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

This publication covers major technical, safety and organizational aspects of fuel quality and reliability assurance for both light and heavy water cooled power reactors, including: pressurized water reactors, Russian water cooled water moderated power reactors, boiling water reactors and pressurized heavy water reactors. These reactors are operated in 31 States and comprise more than 90% of their reactor fleet.

To decrease costs and to increase competitiveness, nuclear utilities use more challenging operational conditions, longer fuel cycles and higher burnups, which require modifications in fuel designs and materials. Different aspects of quality assurance and quality control, as well as analysis of fuel performance have been considered in a number of IAEA publications. This publication is prepared on the basis of three consultants meetings and a technical meeting jointly organized by the Division of Nuclear Fuel Cycle and Waste Technology, the Division of Nuclear Power and the Division of Nuclear Installation Safety. It provides a concise but comprehensive overview of the interconnected issues of fabrication, design and operation in fuel quality and reliability assurance. It tackles technical, safety and organizational aspects, and includes state of the art developments and good practices of coordinated work of fuel designers, fuel vendors and reactor operators.

Appreciation is expressed to all the organizations and experts that contributed to this publication. The IAEA is particularly grateful to P. Rudling (Sweden) for his assistance as the scientific editor and the chairman of all preparatory meetings. The IAEA officer responsible for this publication was V. Inozemtsev of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

The more sophisticated technologies become, the more important are quality and reliability aspects for guaranteeing the properties and operational characteristics of the technology. This is particularly true for industries such as nuclear power, which are potentially dangerous for people and the environment due to the use of radioactive materials and highly concentrated energy density.

When applied to nuclear fuel engineering, quality assurance and quality control (QA/QC) and reliability requirements are completely interconnected. Sometimes, however, the terms are preferably used separately by fuel producers (stress on 'quality') and fuel operators (stress on 'reliability'). Thus, depending on the context, one of the terms will usually be used in this publication with the other kept in mind. The QA/QC procedures and instructions are a part of the overall integrated management system (IMS) for an organization. The requirements for the IMS are also discussed in this publication.

Nuclear power belongs to a highly competitive power industry that aspires for better commercial nuclear power plant performance within defined safety margins. Nuclear power development reflects the evolving compromise between technoeconomic incentives and safety requirements. Hence, both technical and safety aspects are to be considered together with managerial approaches aimed at effective practical implementation of these alternate motivations.

A nuclear reactor is generally characterized by very challenging operational environments, with the most extreme conditions in the reactor core, where high temperatures, corrosive media and mechanical stresses are combined with intensive radiation load on fuel elements, fuel assemblies and reactor internals. All of these operational aspects can lead to the degradation of material properties and ultimately to failures of fuel and other reactor internals. The cost of such failures is high and their consequences can be extremely severe. Therefore, very careful attention is given to the proper selection, development, design, manufacturing, testing and operation of fuels and in-core components of nuclear reactors.

Whereas separate technical, safety and managerial aspects of fuel engineering and performance are examined in numerous publications, there is a deficiency of holistic guidance over the range of interconnected issues of fuel quality and reliability.

1.2. OBJECTIVE

This publication describes how to achieve nuclear fuel cycle objectives specifically in the case of nuclear fuel engineering and performance (see Refs [1, 2]). It mainly focuses on the technological aspects of fuel quality and reliability, but also provides necessary information about corresponding areas of nuclear safety and management.

Different fuel designers, vendors and utilities have their own QA/QC procedures and safety regulations. However, under the present globalization of fuel markets and the growing concerns about the assurance of nuclear safety and fuel supply, the issues of harmonization of national practices and the sharing of best experiences are receiving special attention. This publication is intended to contribute to tackling these issues. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.3. SCOPE AND STRUCTURE

This publication covers major technical, safety and organizational aspects of fuel quality and reliability assurance for all types of water cooled reactors:

— Pressurized water reactor (PWR);
— Russian water cooled water moderated power reactor (Voda Voda Energo Reactor, VVER);
— Boiling water reactor (BWR);
— Pressurized heavy water reactor (PHWR).

Section 2 discusses fuel designs for different reactor types, providing a general outline of fuel assembly designs and the materials used. Section 3 refers to the complexity of critical fuel components, explaining fuel behaviour under normal reactor operations and accidents. Section 4 describes the importance of design criteria adequacy of the fuel and control assembly throughout the design life, during normal operation and accident conditions. Section 5 provides a brief overview of the manufacturing processes of the fuel assembly and its components and the processes that are crucial. Section 6 explains the relation between IMSs, quality management systems (QMSs) and QA/QC aspects, and examines and emphasizes the aspects of quality management of fuel manufacturing. Section 7 further elaborates Section 6 in the wider sense of reliability, explaining means to achieve trouble free fuel performance, with some examples of good practices presented in Sections 8 and 9.

1.4. USERS

This publication addresses decision makers and senior managers involved in the organization of fuel related activities at different national or company levels, as well as specialists in R&D institutions, fuel vendor organizations, nuclear utilities and safety regulatory authorities interested in particular aspects of fuel quality and reliability assurance.

The information provided in this publication is intended to apply to both States with established nuclear power industries and States embarking on, or planning, nuclear power programmes. Sections of this publication will be of interest for particular States, depending on their involvement with the development, production and management of fuel. Furthermore, the contents will be useful to all users, providing an overview of subjects related to nuclear power reactor fuel.

2. FUEL DESIGNS FOR DIFFERENT REACTOR TYPES

2.1. GENERAL DESCRIPTION OF FUEL ASSEMBLY DESIGNS

2.1.1. PWRs and BWRs

There is a wide variety of different types of fuel assemblies for water cooled reactors (see Refs [3−5]). Updates on water cooled reactor fuel assembly design are periodically published in Nuclear Engineering International [6]. According to Ref. [3]:

> "The fuel rod array for BWRs was initially 7 × 7 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 9 × 9 or 10 × 10 square configuration designs. 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 9 × 9 and 10 × 10 FA has successively been increased, and peak LHGRs are today almost comparable to that of the 7 × 7 and 8 × 8 older designs.

“Also for PWR there has been a trend to greater subdivision of fuel rods, e.g. from Westinghouse 15 × 15 to 17 × 17 design, however to accomplish this 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 do BWRs.

“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 move.

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

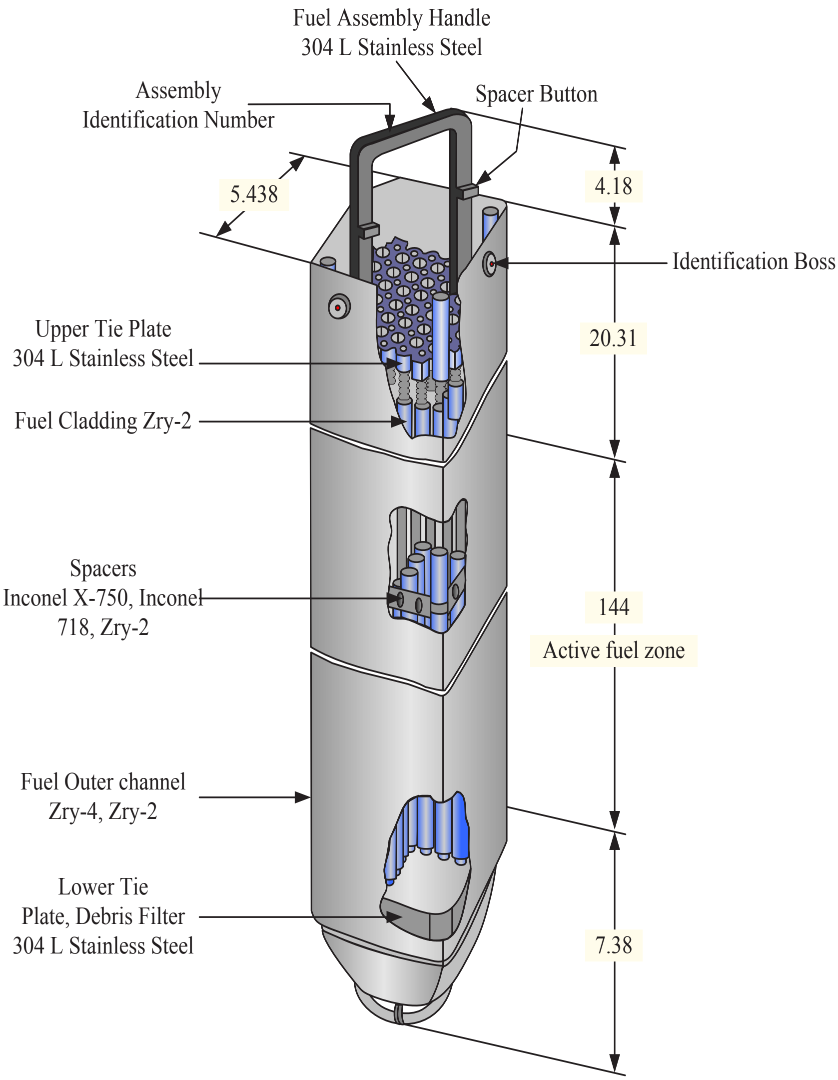
— maintain proper positioning of the fuel rods under normal operating conditions and in design basis accidents (e.g. seismic effects, LOCA [loss of coolant accident], RIA [reactivity initiated accident]);
— permit handling capability before and after irradiation.”[1]

Figures 1 and 2 show typical BWR and PWR fuel assemblies, respectively. In addition, 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 the most inexpensive material is generally chosen for a specific component that yields the lowest cost to produce the component, while ensuring adequate performance during normal operation and accidents [6].

2.1.2. PHWR general outline of fuel assembly design

The fuel assembly (bundle) in PHWR is a cluster of elements. In most current PHWR designs, the number of fuel elements is 37. Figure 3 shows a fuel bundle from a Canadian deuterium–uranium (CANDU) reactor. The fuel elements are joined together by welding to end plates at both ends. The 37 elements

[1] Handling and storage systems should ensure integrity and required properties of fresh and spent fuel (see Ref. [7]).



Dimensions in inches.

FIG. 1. Typical BWR fuel assembly (reproduced from Ref. [3] with permission courtesy of ANT International).

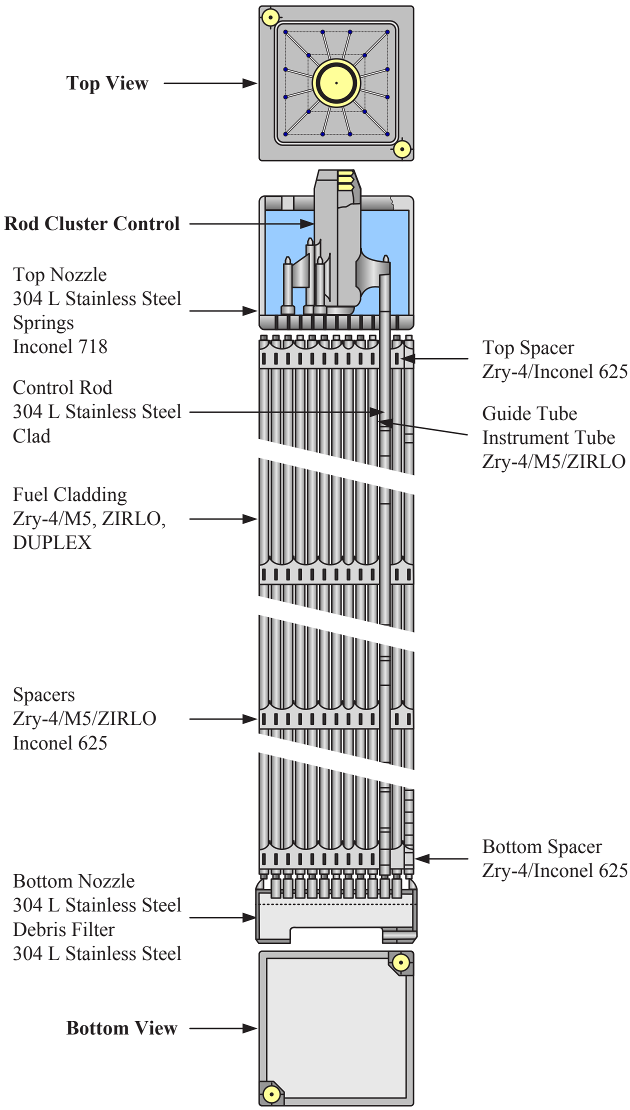


FIG. 2. Typical PWR fuel assembly (reproduced from Ref. [3] with permission courtesy of ANT International).

in the fuel bundle are arranged in concentric rings of 6, 12 and 18 elements with a central element. Each element consists of a stack of sintered natural uranium dioxide (UO_2) pellets in a thin zircaloy-4 sheath with end plugs welded at both the ends. The inside surface of the sheath is coated with a thin layer of graphite.

Note: Length = 0.5 m, diameter = 10 cm and weight = 24 kg.

FIG. 3. A 37 element CANDU fuel bundle (courtesy of Atomic Energy of Canada Limited).

The important components of the fuel bundle are the fuel elements and the end plates. The fuel elements consist of:

— Pellets;
— Tube sheath;
— Graphite coating;
— End plugs;
— Appendages (spacers and bearing pads).

With regard to the end plates, the fuel element consisting of stacked pellets is welded by resistance welding at the ends. The fuel pellets are sintered to high density (typically 10.6 g/cm^3) and have length to diameter (L/D) ratios of 1.0–1.25, with dishes at both ends. The zircaloy-4 sheath is designed to collapse onto the UO_2 pellets during reactor operation for increased heat transfer. The fuel pellets contained in the sheath are hermetically sealed at the ends by welding on end plugs made of zircaloy-4. These end plugs are conical in shape and are welded to the end plate. The elements are prevented from directly coming in contact with neighbouring elements by providing interelement spacing through split spacers which are made of zircaloy-4. These spacers are attached to the outside surface of the sheath. The spacers are attached to each of the neighbouring element such that the two spacers are in contact with each other in an opposite skewed angle position. This arrangement reduces the tendency of elements to become interlocked. Bearing pads are attached to the elements of the outer ring of the bundle at three axial planes at the middle and near the bundle ends. These bearing pads are made up of zircaloy-4 and have a curvature matching the inside surface of pressure tube. The end plates are made up of zircaloy-4 material. All the elements are welded to the end plate at each end to form a fuel bundle assembly. The end plates have a web structure to allow the coolant to flow through the open cross-sectional area of the end plate.

The fuel bundle is designed to withstand the exposure in the reactor to high pressure, temperature, irradiation, corrosion and hydriding. The bundle is designed to contain the radioactive fission products during nuclear fission. The fuel bundle is designed to take into account the effects of irradiation and loads due to temperature, pressure, coolant flow and the fuel handling system. The concept of design acceptance criteria has been explored in recent advanced PHWR fuel design [8].

The are some additional important design requirements for the components and the fuel assembly. In the pellet, the critical design features include:

— Density;
— Pellet L/D ratio;
— Purity (in terms of equivalent boron content);
— Oxygen/uranium ratio;
— Dish at the ends;
— Surface finish.

For the sheath design, the critical design features include:

— Thickness for collapsibility under external coolant pressure;
— Diametral clearance with the pellets;
— Mechanical properties;
— Corrosion and hydriding properties.

The fuel element integrity is an important parameter, and hence so is the leak rate of prefilled helium gas in the element.

2.1.3. VVERs

According to Ref. [9]:

"In the early VVER-440 reactors (440 MWe), the fuel assemblies were hexagonal arrays of 126 fuel rods. The rods were clad with E110 (Zr1Nb) tubes. The assemblies contained 10 or 11 stainless steel grid spacers and were enclosed in an E125 (Zr2.5Nb) hexagonal wrapper (which performs the same function as a BWR channel) [see Fig. 4 and Ref. 10].

"In some early VVER-440 fuel assemblies that were tested in reactors such as the MR or MIR, boron was added to the E125 wrappers for reactivity control. In commercial power reactors, boric acid is usually added to the coolant for reactivity control along with movable control assemblies.

"The fuel is uranium-enriched up to 4.95% and is arranged in a hexagonal grid. Fuel pellets can have a central coaxial hole."

The VVER-1000 reactor core is designed for heat generation and transfer from the fuel rods' surface to the coolant during the design lifetime, without exceeding the permitted fuel rod failure limits. The VVER-1000 reactor core consist of 163 fuel assemblies, incorporating the control protection system absorber rods or synonym — the RCCA, positioned in accordance with the core cartogram [9].

The core is assembled according to the fuel assembly loading cartogram (pattern). The fuel assemblies are spaced in plane by fixing the fuel assembly end fittings in the protective tube unit and in the core barrel bottom inside the reactor internals. Fuel assembly rising is prevented and vibration is reduced by means of elastic compression of spring loaded fuel assembly top nozzles by the reactor cover via the protective tube unit.

The VVER-1000 fuel assembly consists of the following components:

— Skeleton;
— Fuel/gadolinium rod bundle;
— Top nozzle;
— Bottom nozzle.

The general views of two base designs of the VVER-1000 fuel assembly are illustrated in Fig. 5 [11, 12].

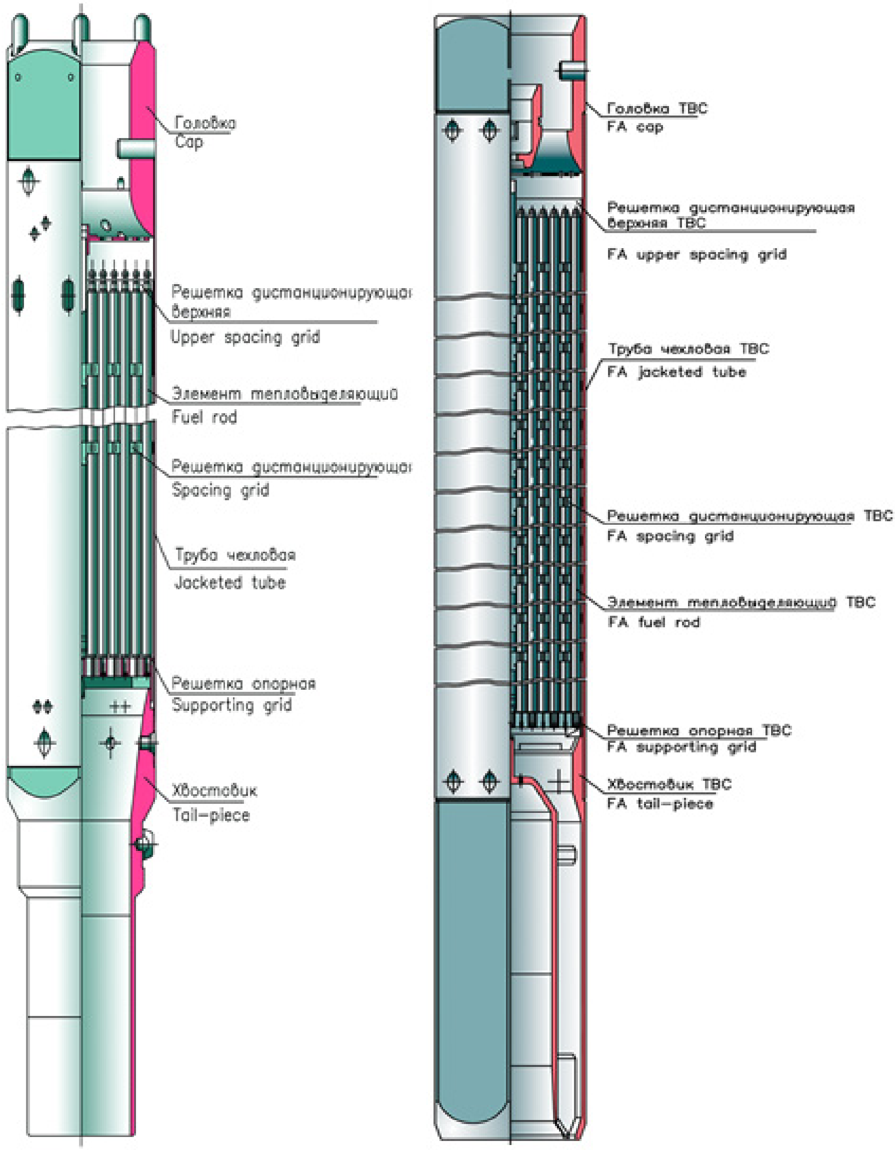
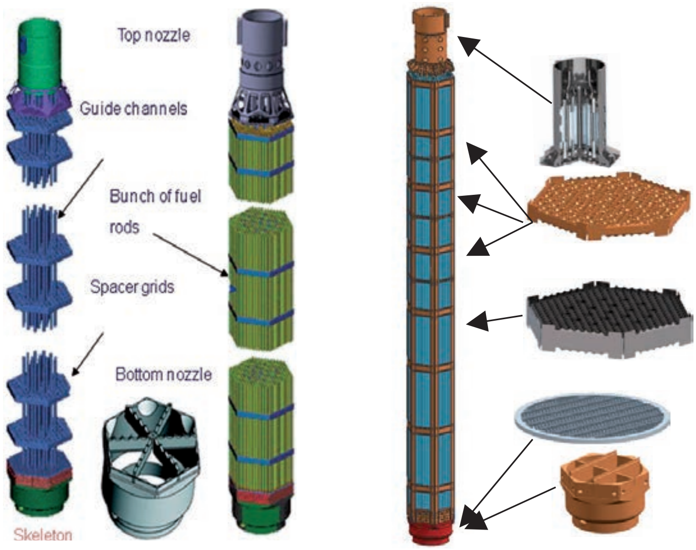


FIG. 4. VVER-440 fuel assembly and working cassette (courtesy of TVEL).



TVS-2M TVSA

FIG. 5. Two base designs of the VVER-1000 fuel assembly (courtesy of TVEL).

2.2. MATERIALS USED IN FUEL ASSEMBLIES

According to Ref. [3]:

“The materials used for the FA components are Zr alloys, Inconel (precipitation hardened Inconel X-750, Inconel 718 and solution treated Inconel 625) and stainless steel (SS 304L). A low cobalt content is desired to keep the radiological exposure of workers (man-rem) low in the stainless steel and nickel-base alloys. However, only Zr alloys have low thermal neutron cross section. Thus, for components in the core mostly Zr alloys are used since the high thermal neutron flux would otherwise result in large loss in reactivity if other materials such as stainless steels and/or nickel-base alloys were used. Spring materials need to be made of materials with low stress relaxation rates, such as e.g. Inconel X-750 or Inconel 718. These Ni base alloys are generally heat treated to reach an optimum precipitation hardening. To lower the parasitic neutron absorption for grids/spacers, the strips are made of Zry-2 and -4, while the spring itself is made of either Inconel X-750 or Inconel 718 to ensure adequate fuel rod support during its entire irradiation. In some fuel designs also the top and bottom PWR grid is entirely made of Inconel X-750 or Inconel 718. This is possible since the neutron flux is much lower at the top and bottom part of the core resulting in a very small loss of thermal neutrons due to parasitic material absorption. The low neutron flux at the top and bottom part of the core is also the reason why the much cheaper material SS 304 L can be used instead of e.g. Zr alloys for components at these elevations. In newer BWR designs the spacers are made entirely of Inconel X-750, using the minimum thicknesses possible."

Table 1 presents chemical composition of stainless steel and nickel base alloys used in light water reactor (LWR) fuel assemblies.

TABLE 1. CHEMICAL COMPOSITION OF VARIOUS STAINLESS STEEL AND NICKEL BASE ALLOYS

Material	Concentration (wt%)								
	Fe	Ni	Cr	Mn	Si	Mo	Ti	Nb	Al
AISI 304	Bal.	10	19	≤2	≤0.75	n.a.[a]	n.a.[a]	n.a.[a]	n.a.[a]
DIN 1.4541	Bal.	11	18	≤2	≤0.75	n.a.[a]	0.4	n.a.[a]	n.a.[a]
Inconel X-750	7	Bal.	15	≤1	≤1	n.a.[a]	2.6	1	0.7
Inconel 718	17	Bal.	19	0.5	0.75	3	0.7	5	0.6
Inconel 625	12.5	Bal.	22	0.3	0.1	8.8	0.3	3.9	0.2

Source: Data from table 2-1 of Ref. [3].

[a] n.a.: not applicable.

The main zirconium alloys are currently used on commercial scale as structural components in the cores of LWRs include:

(a) Zircaloy-4 (PWR cladding and structural materials, BWR channels) and zircaloy-2 (BWR cladding and channels);
(b) Binary Zr-1Nb alloys: E110 (VVER and RBMK (a Russian graphite moderated light water cooled reactor) cladding and fuel assembly structural material) and M5-PWR cladding and fuel assembly structural material);

(c) Binary Zr-2.5Nb alloy (pressure tubes for PHWRs and RBMKs);
(d) Multicomponent zirconium alloys with additions of iron, niobium and tin (E635 for VVERs and RBMKs and ZIRLO for PWRs).

Chemical composition of these alloys is presented in Table 2. This table characterizes so called preferable alloy composition which is within the limits specified by patents or American Society for Testing and Materials (ASTM) standards. It might be seen from comparison of data given in Table 2 and ASTM B-353 Standard (first version is dated 1990, last version is 2007 [13]) describing chemical composition of zircaloy-2 and zircaloy-4 alloys (see Table 3). Data on zirconium alloy cladding tubes are presented in the ASTM-811 Standard [14].

TABLE 2. CHEMICAL COMPOSITION OF COMMERCIAL ZIRCONIUM ALLOYS

Alloy	Concentration (wt%)					
	Sn	Fe	Ni	Nb	Cr	O
Zircaloy-2	1.2–1.7	0.07–0.20	0.03–0.08	n.a.[a]	0.05–0.15	0.09–0.16
Zircaloy-4	1.2–1.7	0.18–0.24	n.a.[a]	n.a.[a]	0.07–0.13	0.09–0.16
E110	n.a.[a]	n.a.[a]	n.a.[a]	0.9–1.1	n.a.[a]	0.06
M5	n.a.[a]	n.a.[a]	n.a.[a]	0.9–1.2	n.a.[a]	0.125
E125	n.a.[a]	n.a.[a]	n.a.[a]	2.4–2.7	n.a.[a]	0.05
Zr-2.5Nb	n.a.[a]	n.a.[a]	n.a.[a]	2.4–2.8	n.a.[a]	0.125
E635	1.1–1.3	0.3–0.45	n.a.[a]	0.69–1.10	n.a.[a]	0.08
ZIRLO	1.0–1.1	0.09–0.10	n.a.[a]	1.0–1.2	n.a.[a]	0.125

[a] n.a.: not applicable.

The composition and structure of these alloys are subject to constant modification because of changing requirements for materials intended for increasingly onerous in-pile conditions of operation.

TABLE 3. COMPOSITION RANGE OF STANDARD ZIRCONIUM ALLOYS, ASTM STANDARD B353-07

ASTM Ref.	Common name	Concentration (wt%)					
		Sn	Fe	Cr	Ni	Nb	O
R60802	Zircaloy-2	1.20–1.70	0.07–0.20	0.05–0.15	0.03–0.08	n.a.[a]	TBS[b]
R60804	Zircaloy-4	1.20–1.70	0.18–0.24	0.07–0.13	n.a.[a]	n.a.[a]	TBS[b]
R60901	Zr-2.5Nb	n.a.[a]	n.a.[a]	n.a.[a]	n.a.[a]	2.40–2.80	0.09–0.15
R60904	Zr-2.5Nb	n.a.[a]	n.a.[a]	n.a.[a]	n.a.[a]	2.50–2.80	TBS[b]

[a] n.a.: not applicable.
[b] TBS: to be specified in the purchase order.

Zircaloy-2, zircaloy-4 and E110 alloys have been the main materials for fuel claddings and other fuel assembly structural components for many years. They were subject to continuous modernization and finally partial replacement by more radiation/corrosion resistant alloys (e.g. E635 in the Russian Federation, M5 in France and ZIRLO in the United States of America.

3. FUEL BEHAVIOUR UNDER NORMAL REACTOR OPERATIONS AND ACCIDENTS

According to Ref. [15]:

"The performance of the critical fuel components is the result of a complex interaction of a large number of variables that challenge the evaluation of the mechanisms in progress and the prediction of their behaviour at extended and more severe conditions. The technologies involved include just about every aspect of materials science imaginable: properties of materials, metallurgy, structural mechanics, coolant chemistry, physical chemistry, and their basic mechanisms just to mention a few examples. In addition, exposure to radiation changes all of the physical properties and processes: the properties of the structural materials and of the coolant change, transformations in structure and composition occur in all the materials ..., and these processes occur in a non-homogeneous and non-equilibrium manner throughout the core.

"A study of the materials' performance is difficult even outside the reactor's radiation field and provides limited data. Test reactors offer a good tool for evaluating a limited number of variables and mechanisms and have provided some valuable data, however, the operation and use of these reactors is expensive. The final performance evaluation is in the power reactor itself since it provides all the variables of importance; however, the lack of instrumentation, the inability to control testing time, as well as the difficulty of separating variables makes interpretation of ongoing processes difficult. The final evaluation of new materials and fuels for high burnups progresses necessarily through the stages mentioned: ex-reactor testing, test reactor evaluation of samples, power reactor evaluation of samples or full fuel assemblies.

> "The degree of success achieved in fuel performance to date has been remarkable considering the lengthy evaluation process required and the tough conditions the fuel assembly is exposed to in service."

During normal operation the following material/component properties have a major impact on fuel performance and may limit the discharged burnup[2] (see Refs [4, 16–32]):

— Corrosion of zirconium alloy cladding and the water chemistry parameters that enhance corrosion [14];
— Dimensional changes of zirconium alloy components [14];
— Stresses that challenge zirconium alloy ductility and the effect of hydrogen pickup and redistribution as it affects ductility [14];
— Fuel rod internal pressure [14];
— PCI and pellet cladding mechanical interactions (PCMI) [14];
— Grid to rod fretting (GTRF) (in PHWR fuel bundles spacer pad wear);
— Fuel rod collapse.

The list has not changed significantly over the last few decades. The only items above that have posed limits to extending burnups have been corrosion and dimensional changes in both BWRs and PWRs and PCI in BWRs and PHWRs [14], more details are provided in Refs [30–32]. Improved materials and operating procedures have been able to exceed all of these limits and have not reached new limits within current operating strategies.

Poor fuel performance may result in fuel failures (see Table 4).

Other material performance problems have occurred in reactors such as:

— Manufacturing defects (e.g. the internal hydriding of fuel rods due to moisture in the pellets);
— Debris and baffle jetting fretting defects;
— Degradation of failed fuel.

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[2] The product of irradiation time (in days) and power generated by the fuel (in MW).

TABLE 4. FUEL PERFORMACE ISSUES IN BWR, PWR, VVER AND PHWR DURING NORMAL OPERATION AND ANTICIPATED OPERATIONAL OCCURRENCE

Performance issue	Short description	Reason for issue
Manufacturing defects	Non-through-wall cracks in the fuel cladding developed during the cladding manufacturing process may propagate through the whole cladding thickness during a power ramp by a PCMI mechanism.	Manufacturing
	Defects in bottom and/or top end plug welds.	
	Primary hydriding due to moisture in fuel pellets and or contamination of clad inner surface by moister or organics.	
	Too large gap between the fuel rod and the spacer grid supports leading to excessive vibrations in the PWR fuel resulting in grid–rod fretting failures.	
	Defected pellets (chipped or pellet missing surface) may result in PCI failures.	
Excessive corrosion	Accelerated corrosion resulting in cladding perforation. This corrosion acceleration can be generated by water chemistry impact such as CRUD deposition or thermohydraulic impact leading to DNB, which may be related to excessive fuel rod or fuel assembly bowing.	Design/manufacturing/customer (e.g. related to water chemistry transient)
Excessive spacer growth	There is one reported case in a BWR when excessive spacer growth made it impossible to withdraw the fuel assembly from the fuel outer channel.	Design

TABLE 4. FUEL PERFORMACE ISSUES IN BWR, PWR, VVER AND PHWR DURING NORMAL OPERATION AND ANTICIPATED OPERATIONAL OCCURRENCE (cont.)

Performance issue	Short description	Reason for issue
Fuel assembly bowing	Fuel assembly bowing is due to excessive fuel assembly holding down forces that may be due to excessive guide tube growth by hydriding (from the hydrogen released through the corrosion reaction between the coolant and the zirconium clad material) and irradiation growth. Fuel assembly bowing may result in difficulties to insert the control rods (a safety issue) and/or decreased thermal margins (LOCA and DNB). Excessive bowing may also result in grid–grid fretting and grid damage as well as difficulties in fuel assembly handling during the outage.	Design
Fuel channel bowing (BWRs)	Fuel channel bowing may result in difficulties to insert the control rods (safety issue) and/or to smaller thermal margins (LOCA and dry-out/DNB). In 1988, four fuel rods failed in the Oskarshamn 2 reactor. The local power is too high for the coolant flow, causing the cladding to be overheated. The overheating causes (local) corrosion penetration of the cladding.	Design/customer (due to new core loading schemes)
PCI	PCI iodine assisted SCC phenomenon that may result in fuel failures during rapid power increases in a fuel rod. This failure mechanism is occurring much more frequent in BWRs but has also occurred in PWRs and HWRs. There are three components that need to occur simultaneously to induce PCI: (1) Tensile stresses — induced by the power ramp; (2) Access to freshly released iodine — occurs during the power ramp; (3) A sensitised material — zircaloy is normally sensitive enough for iodine SCC even in unirradiated state.	Manufacturing (defected pellets), design, customer (e.g. usage of computer codes underestimating the power ramp increase)

TABLE 4. FUEL PERFORMACE ISSUES IN BWR, PWR, VVER AND PHWR DURING NORMAL OPERATION AND ANTICIPATED OPERATIONAL OCCURRENCE (cont.)

Performance issue	Short description	Reason for issue
Cladding collapse	This failure mechanism occurred in earlier days due to pellet densification. This failure mode has today been eliminated by fuel design changes and improved manufacturing control.	Design and manufacturing
Fretting	This failure mode has occurred owing to: (1) Debris fretting. (2) GTRF — excessive vibrations in the PWR fuel rod causing fuel failures. This situation may occur due to different pressure drops in adjacent fuel assemblies, causing cross-flow. Grid–rod fretting may also occur due to a poor grid design or manufacturing process. (3) Baffle jetting failures — related to unexpectedly high coolant cross-flows close to baffle joints.	Debris fretting — customer GTRF — design, manufacturing Utility (mixed cores) Baffle jetting — utility

Note: BWR — boiling water reactor; CRUD — chalk river unidentified deposits; DNB — departure from nucleate boiling; GTRF — grid to rod fretting; HWR — heavy water reactor; LOCA — loss of coolant accident; PCI — pellet cladding interaction; PCMI — pellet cladding mechanical interaction; PWR — pressurized water reactor; SCC — stress corrosion cracking.

Source: Refs [16, 31, 32].

During accident conditions (RIA and/or LOCA) the following material/component property has a major impact on fuel performance (e.g. see Refs [16, 17, 33]):

(a) Embrittlement of the zirconium alloy cladding which partly depends on:
   — Hydrogen pickup (i.e. total amount of hydrogen) in the cladding occurring during normal operation before the hypothetical LOCA and/or RIA event;
   — Hydride orientation in the cladding before the RIA event;
   — Pellet to cladding gap size prior to the RIA transient. This gap size depends, for example, on the pellet swelling rate and the fuel clad creepdown rate. The gap size will impact the clad stresses during the RIA transient. The degree of cladding embrittlement and pellet to cladding gap size (before the RIA transient) is partly related to fuel design.

During normal operation, irradiation of nickel base alloys (e.g. used in spacers/grids) will result in irradiation induced microstructural changes, which in turn may result in stress corrosion cracking (SCC) provided that the stresses in the material are large enough (e.g. see Ref. [34]). The tendency for SCC may be related to both design and manufacturing [4, 16].

4. FUEL AND CONTROL ASSEMBLY DESIGN CRITERIA DURING NORMAL OPERATION AND ACCIDENT CONDITIONS

For fuel behaviour, some acceptance criteria are assessed in safety analyses; others may be the subject of specific design calculations. These acceptance criteria focused on fuel behaviour can be summarized as follows:

— For anticipated transients, the probability of failure of the fuel cladding, resulting from a heat transfer crisis or from some other cause, needs to be insignificant.
— For design basis accidents, the fuel damage needs to be limited for each type of accident to ensure a coolable geometry. Energetic dispersal of fuel needs to be prevented in RIAs.

Fuel assembly design criteria provide assurance that the nuclear fuel will perform satisfactorily in the core of a reactor throughout the design lifetime. The design criteria represent standards to which they are designed and provide assurance of the adequacy of the design throughout the design life. Fuel vendors use design calculations, testing and performance data to demonstrate compliance with these criteria.

The purpose of this section is to present design criteria for the fuel rod and for the fuel assembly structure for normal operation, anticipated operational occurrences (AOOs) and postulated accidents for which reactor shutdown and emergency core cooling need to be verified [5, 35–41].

The primary function of the components, the design requirements and the design criteria for the fuel rod and for the fuel assembly structure are also presented.

4.1. FUEL ROD

4.1.1. Function of the fuel rod

The primary function of the fuel rod is to generate and transfer heat to the reactor coolant. In the process of generating this heat via fission reactions, both radioactive and stable fission products are produced in the fuel. A second function of the fuel rod is to contain these fission products within the fuel rod so that the reactor coolant does not become contaminated.

To meet these goals, the structural integrity of the fuel rod needs to be ensured for normal operation and AOOs. Fuel cooling needs to remain possible during and after bounding class IV events (i.e. RIA and LOCA).

4.1.2. Fuel rod design requirements

The detailed fuel rod design establishes such parameters as pellet diameter and density, pellet to cladding diametral gap, plenum size and rod pressurization level. The design process needs to consider the effects of the variations and fluctuations in core and local power and in reactor coolant temperature, pressure and flow which occur during normal operation and AOOs. The design also considers effects and physical properties of fuel rod components which vary with burnup.

The integrity of the fuel rod during normal operation and AOOs is ensured by designing to prevent excessive gas pressure, excessive fuel temperatures and excessive stresses and strains in the cladding. This is achieved by designing the fuel rods so that the specific design criteria are satisfied.

4.1.3. Fuel rod design criteria for normal operation and AOOs

To ensure reliable operation, the following criteria need to be satisfied for normal operation and AOOs. The fuel rod design is judged to have met those criteria when it is demonstrated that the performance of a fuel region is within the limits specified by each criterion for all normal operation and AOOs. This is generally accomplished by demonstrating that the fuel rod performance with appropriate allowance for uncertainties is within the limits specified by each criterion.

4.1.3.1. Fuel rod internal pressure

To prevent unstable thermal behaviour and to maintain the integrity of the cladding, outward circumferential creep, which may cause an increase in the pellet to cladding gap, needs to be prevented.

This can be accomplished by demonstrating — when internal rod pressure exceeds the system pressure — which the internal pressure due to the fission gas release and initial pressurization needs to be less than the value which would lead to an increase or a re-opening of the pellet to cladding diametral gap by cladding tensile creep.

4.1.3.2. Cladding stress and strain

The licensing basis for fuel rod cladding is that the fuel system will not be damaged due to excessive cladding strain. In order to meet this basis, a design limit is established for cladding strain during steady state operation and AOOs. This limit depends on the cladding material: for example, M5 claddings can accept a higher deformation than zircaloy-4 claddings.

During a transient event, the cladding is not to exceed the PCI technological limit of the fuel rod. This criterion intends to avoid fuel rod PCI cladding failure due to local power increases at a rapid rate such that cladding creep cannot accommodate the pellet thermal expansion. This limit depends on cladding and fuel materials. For example, AREVA, a French equipment manufacturer, defined some technological limits — based on mechanical parameters — by analysing ramp tests results with its fuel rod performance codes and assessing the risk of failure due to PCI for normal operations and AOOs with the same codes.

4.1.3.3. Cladding corrosion

Cladding corrosion reduces cladding thickness and results in less cladding load carrying capacity. Limitation on the cladding oxide layer is needed to avoid being in accelerated oxidation conditions which could lead to cladding failure and in conditions where the cladding mechanical properties are degraded. An appropriate oxidation limit protects also the cladding against excessive hydriding.

4.1.3.4. Fuel temperature

In order to avoid fuel rod failure due to overheating for normal operations and AOOs, the maximum temperature of the pellets needs to remain less than the fuel melting point. The aim of this criterion is to prevent fuel melt conditions, which could cause volume variation due to phase change, resulting in severe duty on the cladding.

4.1.4. Fuel rod design criteria for postulated accidents

For postulated accidents in which severe fuel damage might occur, core coolability and the capability to insert control blades (BWR) or RCCAs (PWR) are essential. This analysis is usually not part of the standard thermomechanical analysis but is part of the plant safety analysis.

4.1.4.1. Violent expulsion of fuel

In a severe RIA, such as a control rod ejection accident, large and rapid deposition of energy in the fuel occurs. This could result in melting, fragmentation and dispersal of fuel. The mechanical action associated with fuel dispersal might be sufficient to destroy the fuel cladding and rod bundle geometry and to provide significant pulses in the primary system. Design criteria are defined to exclude cladding or assembly destruction.

4.1.4.2. Cladding embrittlement

The most severe occurrence of possible cladding fragmentation due to cladding oxidation during a postulated accident is the result of a LOCA. In order to mitigate the effect of cladding oxidation during a LOCA, limiting criteria of 1204°C on peak cladding temperature and of 17% on maximum cladding oxidation are used [36].

4.1.4.3. Fuel ballooning

Zircaloy cladding will burst under certain combinations of temperature, heating rate and differential pressure conditions that occur during a LOCA. Cladding swelling and burst strain can then result in flow blockage. There is no explicit limit on the deformation. However, the LOCA analysis needs to consider the cladding swelling and burst strain impacts on the flow.

4.1.4.4. LOCA hydrogen release

A criterion is in effect to limit the total hydrogen production by oxidation of the zircaloy cladding during LOCA. This assures containment integrity (possible explosive gas mixture) rather than protecting against cladding embrittlement. For PWRs and VVERs, the LOCA limit on the amount of hydrogen generated from the chemical reaction between the zirconium based cladding and water/steam is generally 1% of the hypothetical amount that would be generated if all the cladding were to react [36]. Released hydrogen caused the explosions at the Fukushima nuclear power plant.

4.2. FUEL ASSEMBLY STRUCTURE

4.2.1. Function of the fuel assembly components

4.2.1.1. Spacer grid

The purpose of PWR spacer grids is to provide the support and to maintain separation of the fuel rods, and to provide support for an instrument tube (if any) and means for connection of structural guide tubes.

The purpose of BWR spacers is to provide lateral support and spacing of the fuel rods and the means for connection of the water channel.

The purpose of VVER honeycomb spacer grids is to provide the support and to maintain separation of the fuel rods, and to provide support for a central instrument tube (if any) and means for connection of structural guide tubes. The cells are interconnected and the peripheral cells are connected with the hoop by spot welding. The grid cells are pressed of a thin walled tube. They are hexagonal with three bulges positioned at 120° intervals and are meant for the fuel rod spacing.

4.2.1.2. PWR fuel assembly load bearing structure: Guide tube, and bottom and top nozzles

The load bearing structure of a PWR fuel assembly consists of the top nozzle and hold down system, the guide tubes and the bottom nozzle.

The hold down spring system counteracts hydraulic up-flow forces during operation.

The guide tubes are the major supporting structure of the fuel assembly skeleton. It also provides the channels for the neutron absorber rods of the control assembly. The design of the guide tube is to allow insertion of the control rod during a scram and to accommodate the flow of the coolant during normal operation.

The mechanical function of the bottom nozzle is to accommodate the vertical load transmitted by the guide tubes that apply to the structure, to limit axial movement of rods downward.

4.2.1.3. BWR fuel assembly load bearing structure: Water channel, water rods, and upper and lower tie plates

The load bearing structure of a BWR fuel assembly consists of the upper tie plate with the handle, the water channel (AREVA and Westinghouse), water rods (Global Nuclear Fuel, GNF) and the lower tie plate.

The water channel and rods are designed to keep non-boiling water within the fuel bundle over its entire height, hold the spacers both laterally and axially, and form a support structure joining the upper and lower tie plate together. It transfers the weight of the fuel rods, which stand on the lower tie plate, to the handle of the upper tie plate.

The mechanical function of the lower tie plate is to accommodate the vertical load transmitted by the guide tubes that apply to the structure, to limit axial movement of rods downward.

4.2.1.4. Fuel channel (BWR only)

The BWR fuel channel is a square duct with rounded corners and open at both ends. It encloses the sides of each fuel assembly for the main purpose of providing a flow boundary between the active coolant flow and the core bypass flow. The fuel channel also lends considerable stiffness to the channelled fuel assembly, and it provides a bearing surface for the guidance of the control blade during movement.

4.2.1.5. VVER-1000 fuel assembly load bearing structure: Guide tube, and bottom and top nozzles

The load bearing structure of a VVER-1000 fuel assembly consists of the skeleton, top nozzle and bottom nozzle. The skeleton is assembled of 18 guide thimbles, spacer grids welded to them (TVS-2M) or to corners (TVSA), the lateral in-core instrumentation device (ICID) tube, the central tube and the lower support lattice.

The top nozzle has the following main functions:

- To ensure the dismountable connection with the fuel rod bundle;
- To ensure the required compression of the fuel assembly in the reactor core;
- To ensure constant matching of the fuel assembly and the seat of the protective tube unit as well as to match the RCCA channels located in the fuel assembly and in the guide thimbles of the reactor protective tube unit;
- To interact with the grippers of the handling equipment;
- To protect the upper end faces of fuel rods against mechanical damages during reloading.

The guide tubes are the major supporting structure of the fuel assembly skeleton. It also provides the channels for the neutron absorber rods of the control assembly. The design of the guide tube allows insertion of the control rod during a scram and accommodates the flow of the coolant during normal operation.

The lower support lattice is made of a plate with openings meant for fixing fuel rods, guide thimbles, ICID tube and central tube and through grooves for the coolant flowing to the inter-rod volume of the bundle.

The bottom nozzle ensures the matching of the lower part of the fuel assembly with the core barrel supports and serves the guide for the coolant supply to the fuel rod bundle. The bottom nozzle is connected with the lower support lattice by means of six corner pieces. It excludes the possibility of their mutual displacement or their vertical axes deformation to reduce the initial bending of the fuel assembly during its insertion into the core barrel.

4.2.2. Fuel assembly structure design requirement

The fuel assembly design process needs to consider the effects of the variations and fluctuations in reactor coolant temperature, pressure and flow which occur during normal operation and AOOs. Moreover, the vibration loadings on the rods exerted by the coolant, due to the turbulent nature of the flow and the horizontal components of the fluid velocities, need to be considered. The design also takes into consideration the effects and physical properties of fuel rod components which vary with time resident in the core.

The integrity of the fuel assembly during normal operation and AOOs is ensured by designing to provide assurance that the fuel assembly should not fall as a result of normal operation and AOOs, prevent assembly lift-off, keep the fuel assembly geometric compatibility and prevent excessive stresses and deformations of the components and fuel rod failures due to fretting wear.

Core cooling and the capability to insert control blades (BWR) or RCCAs (PWR and VVER) need to remain possible during and after bounding class IV events (i.e. the safe shutdown earthquake (SSE) and LOCA). This is achieved by designing the fuel assembly so that the specific design criteria are satisfied.

4.2.3. PWR/VVER/BWR fuel assembly structure design criteria

Fuel system criteria are established to assure that fuel system dimensions remain within operational tolerances. The criteria apply for normal operation, AOOs and in-plant handling and shipping. In addition, they provide assurance that fuel system damage never prevents control rod insertion when it is required and that fuel cool ability is always maintained.

The structure design criteria for authorized operation consider in particular the following topics:

- Hold down capability (no lift-off) compromise to prevent assembly bow;
- Geometric compatibility;
- Hydraulic and neutronic compatibility;
- Strength, buckling and fatigue requirements;
- Hydrogen content;
- Vibration induced fretting of the fuel rods in the spacer grids;
- Fuel assembly handling.

4.2.3.1. Hold down capability (PWR/VVER)

The guidelines to prevent assembly lift-off are that the worst case hydraulic loads that occur during normal operation and AOOs should not exceed the hold down capability of the fuel assembly.

In normal operation, the combined action of flow forces and buoyancy resisted by fuel assembly weight and hold down spring force should not lead to fuel assembly lift-off for both cold and hot conditions. For accident conditions, the normal hydraulic loads plus accident loads should not cause the yielding of the hold down springs.

4.2.3.2. Assembly lift-off (BWR)

The guidelines to prevent assembly lift-off are that the worst case hydraulic loads that occur during normal operation and AOOs should not exceed the hold down capability of the fuel assembly.

Licensing criteria require that the assembly not levitate from hydraulic or accident loads. Therefore, the submerged fuel assembly weight for normal operation, including the channel, needs to be greater than the hydraulic loads. The criterion covers both cold and hot conditions and uses the maximum specified flow limits for the reactor. For accident conditions, the normal hydraulic loads plus accident loads should not cause the assembly to become disengaged from the fuel support. This assures that control blade insertion is not impaired.

4.2.3.3. Geometric compatibility

The faster irradiation induced fuel rod growth and the larger thermal expansion at operating temperature of the fuel rods compared to the guide tubes leads to a decreasing total gap between the fuel rods and the top and bottom end pieces of the fuel assembly. Simultaneously closed upper and lower gaps, however, would result in excessive axial loads on the fuel rods carrying the risk of rod bow, which in turn implies non-admissible disturbances of the coolant flow path. Therefore, gap closure needs to be avoided during the complete residence time of the fuel assembly.

The gap between the top end piece of the fuel assembly and the upper core plate decreases due to the irradiation induced guide tube growth. A continued guide tube growth after complete gap closure, however, would cause excessive axial loads on the fuel assembly — in particular the guide tubes. Therefore, the gap should remain open during the entire residence time of the fuel assembly.

During and after postulated accidents (SSE and LOCA), deflection of components should not interfere with reactor shutdown or emergency cooling of the fuel rods.

4.2.3.4. Hydraulic and neutronic compatibility

The hydraulic flow resistance of the reload fuel assembly is to be sufficiently similar to existing fuel in the reactor such that the impact on total core flow and flow distribution among assemblies in the core is acceptable. The component hydraulic resistances in the reactor core are determined by a combination of both analytical techniques and experimental data.

The nuclear design analyses are subdivided into two parts: a nuclear fuel assembly design analysis and a core design analysis. The fuel bundle nuclear design analysis is assembly specific and changes only as features affecting the nuclear characteristics of the fuel change (e.g. rod enrichments and burnable absorber content, among other things).

The neutronic design characteristics are selected such that fuel design limits are not exceeded during normal operation or AOOs and that the effects of postulated accidents will not cause significant damage to the fuel assembly system or impair the capability to cool the core.

The fuel bundle nuclear design analysis is performed to assure that the new fuel assembly or design features meet the nuclear design criteria established for the fuel and core.

4.2.3.5. Strength, buckling and fatigue (PWR/VVER)

The structural integrity of the fuel assemblies is assured by setting design limits on stresses and deformations due to operational and accident loads. The primary external loads on the fuel assembly — flow force and buoyancy force of the coolant, fuel assembly weight, hold down force, flow limiter spring force or impact spring force at control assembly drop — and the reaction forces lead to internal loads on the different fuel assembly components. These internal loads should not exceed certain limit values in order to exclude non-admissible plastic deformations (control rod drop and core cooling needs to remain possible during and after SSE and LOCA), rupture, fatigue or buckling of the affected components.

4.2.3.6. Stresses of the structural parts (BWR)

The structural integrity of the fuel assemblies is assured by setting design limits on stresses and deformations due to various handling, operational and accident loads. These limits are applied to the design and evaluation of upper and lower tie plates, grid spacers, water channel, fuel assembly cage and spring, where applicable. Integrity of the fuel channel is also verified by limiting the stresses and deformations.

The primary external loads on the fuel assembly — flow force and buoyancy force of the coolant, fuel assembly weight, compression springs force and leaf spring force — differential thermal expansion between the water channel and the fuel rods, and the difference in pressure variation inside and outside the water channel lead to internal loads on the different fuel assembly components. These internal loads should not exceed certain limit values in order to exclude non-admissible plastic deformations of the affected components.

4.2.3.7. Hydrogen content

The hydrogen generated by the corrosion reaction of zircaloy components is partly absorbed by these components. The hydrogen in the zircaloy material leads to an increase in the strength (yield and tensile strength) and a reduction of the ductility of the material. Therefore the mean hydrogen content across the thickness of the wall of structural zircaloy components needs to be limited to values ensuring that the specified design loads do not impair the integrity of the components and the strength of the assembly structure.

4.2.3.8. Fuel rod support: Fretting wear (PWR/VVER)

The design basis for fretting wear is that the fuel rod failures due to fretting should not occur. Since significant amounts of fretting wear can eventually lead to fuel rod failure, the grid spacer assemblies are designed to minimize such wear.

Fuel rod vibrations in the spacer grids are excited by turbulent or quasi-periodic coolant flows. The fuel rod support conditions in the spacer grids — in particular the spacer spring forces and the interference conditions between the springs and the fuel rod cladding tubes — are affected by several interacting parameters as, for example, irradiation induced spring relaxation and creep of the cladding tubes. Their assessment needs to rule out fretting damage of the fuel rods in the spacer grids and spacer spring cracking during the entire residence time of the fuel assembly.

This assessment can be done by out of reactor flow tests on fuel assemblies to verify their fretting performance. For example, AREVA performs fretting tests to verify consistent fretting performance for new spacer designs and examination of a large number of irradiated rods has substantiated the appropriateness of the loop tests.

4.2.3.9. Spacer grid springs: Fretting wear (BWR)

Fuel rods and water channel are positioned clearance free in the spacers by springs. The bearing conditions change during operation due to spring relaxation, elastic deformation and creep of fuel rods and water channel, and due to spacer growth.

Limited fretting damage of the fuel rods in the spacer grids needs to be demonstrated during the whole lifetime of the fuel element. This assessment can be done by out of reactor flow tests on fuel assemblies to verify their fretting performance. In addition, the support of the spacer grids on the water channel by the springs needs to be verified.

4.2.3.10. Transport: Fuel assembly handling (PWR/VVER)

The assembly design needs to withstand all normal axial loads from shipping and fuel handling operations without permanent deformation [7]. Either stress analysis methods or testing to demonstrate compliance with the licensing basis and criteria can be used.

The rod plenum spring also has design criteria associated with handling requirements. The inertial forces acting during transport parallel to the fuel assembly axis should not displace the fuel pellets against the pre-tensioned fuel rod plenum spring in order to prevent separations of the fuel pellet stack.

4.2.3.11. Handling (BWR)

The assembly design needs to withstand all normal axial loads from shipping and fuel handling operations without permanent deformation. Either stress analysis methods or testing to demonstrate compliance with the licensing basis and criteria can be used.

The load on the fuel channel should remain below the limiting loads to avoid plastic failure of the fuel channel or of the screw connection between the fuel channel and transition piece.

The rod plenum spring also has design criteria associated with handling requirements. The inertial forces acting during transport parallel to the fuel assembly axis should not displace the fuel pellets against the pre-tensioned fuel rod plenum spring in order to prevent separations of the fuel pellet stack.

4.2.4. RCCA design criteria

RCCA design criteria provide assurance that the RCCA will perform satisfactorily in the core of a PWR throughout its design lifetime [35–38, 42]. The design criteria represent standards to which the RCCAs are designed and provide assurance of the adequacy of the design throughout their design lifetime. Fuel vendors use design calculations, testing and performance data to demonstrate compliance with these criteria.

The purpose of this section is to present design criteria for the RCCA for normal operation and AOOs. The following subsections presents the primary function of the components, the loadings, the design requirements and eventually the design criteria for the RCCA.

4.2.4.1. Function of the RCCA

The functions associated with the RCCA are:

(a) To provide reactivity control in the core by the insertion and withdrawal of the absorber rods. This is to compensate for core reactivity changes during operation associated with changes in power, coolant temperature and dissolved poison concentration.
(b) To provide reactivity control for the normal shutdown of the core by the insertion of the absorber rods into the fuel assemblies using the control rod drive mechanisms (CRDMs).
(c) To provide reactivity control for the rapid shutdown of the core by 'tripping' the RCCAs (in a trip situation, the RCCAs are released from the CRDMs and drop rapidly due to gravity into the fuel assemblies). The RCCA insertion time during a trip needs to be within the time limits established by the overall core safety analysis.
(d) To support and position the absorber rods in the proper array for insertion into the fuel assembly guide thimbles, and to mate with the guide tubes and guide cards in the upper internals (control rod guide assembly) to enable the operational functions of reactivity control and shutdown to be accomplished.
(e) To absorb the kinetic energy of the RCCA and control rod drive after the rapid insertion of the RCCAs and to prevent impact damage to the fuel assemblies.
(f) To mate with the drive couplings in the reactor upper internals assembly so that axial positioning can be accomplished using the CRDMs.
(g) A fuel assembly is usually handled together with its RCCA. Therefore, the RCCA needs to be designed to avoid interference with the assembly handling tool. It also needs to be compatible with the RCCA handling tools.

4.2.4.2. Loadings

The set of loadings experienced by the RCCA includes:

- RCCA spider loads during stepping;
- RCCA drops;
- Absorber rod loadings;
- Stepping frequency;
- Heating of absorber rod materials;
- Operating temperature;
- Fluence on the RCCA components.

4.2.4.3. Design requirements

The RCCA design process needs to consider the effects of the variations and fluctuations in reactor coolant temperature, pressure and flow which occur during normal operation and AOOs. The integrity of the RCCA during normal operation and AOOs is ensured by designing to keep the RCCA geometric compatibility and to prevent excessive stresses and deformations of the components. This is achieved by designing the RCCA so that the specific design criteria are satisfied.

The detailed absorber rod design establishes such parameters as absorber diameter and density, cladding to absorber diametric gap, plenum size and gas filling. The design process needs to consider the effects of the variations of power, coolant temperature, pressure and flow which occur during normal operation and AOOs. The design also considers effects and physical properties of absorber which vary with burnup.

The integrity of the absorber rod during normal operation and AOOs is ensured by designing to prevent excessive absorber rod swelling, excessive absorber temperatures and excessive stresses in the cladding. This is achieved by designing the absorber rod so that the specific design criteria are satisfied.

4.2.4.4. Design criteria

RCCA criteria are established to assure that dimensions remain within operational tolerances. The criteria apply for normal operation, for AOOs and in-plant handling and shipping.

The design criteria for authorized operation consider in particular the following topics:

— Geometric compatibility;
— Strength and fatigue requirements;
— RCCA handling;
— Absorber rod geometric compatibility.

(a) Criteria, codes and standards

The stress criteria generally conform to the American Society of Mechanical Engineers (ASME), French RCC-C code or Finnish YVL code. In the absence of precise ASME or RCC-C or YVL rules for formulation of a criterion, the used code or standard is stated.

(b) Stress limits for other than threaded structural fasteners

These limits concern RCCA structural members:

— Spider, except for its spring;
— Absorber rod cladding.

It also concerns the following connecting features:

— Vane weld and braze joints;
— Grooves in the spider hub;
— End plug to absorber rod welds joints.

(c) Stress limits for threaded connections

These limits concern the absorber rod to spider screwed system.

(d) Stress limits for springs

For the springs, a mechanical strength criterion is applied.

(e) Cladding tube non-collapse criterion

The cladding tube is loaded by the reactor coolant pressure. To retain tube elastic stability, the latter needs to be verified to remain under the critical collapse pressure corresponding to overstepping of the material yield strength in the case of initial tube ovality.

(f) Absorber temperature

In order to avoid issues due to overheating for normal operations and AOOs, the maximum temperature of the absorber needs to remain lower than its melting point.

(g) Absorber rod geometric compatibility

The absorber thermal creep and swelling under neutron flux can lead to an increase in absorber diameter and for RCCAs under important cumulative neutron flux to an increase of cladding diameter. A code calculation allows determining the recommended period for first RCCA inspection, if any.

(h) Strength and fatigue

The structural integrity of the RCCA is assured by setting design limits on stresses and deformations due to operational and accident loads. The primary external loads on the RCCA (flow force and buoyancy force of the coolant, RCCA weight, step by step motion or impact on the fuel assembly top nozzle tie plate at RCCA drop) and the reaction forces lead to internal loads on the different RCCA components. These internal loads should not exceed design limit values in order to exclude non-admissible plastic deformations, rupture or fatigue of the affected components.

(i) Transport: RCCA handling

The RCCA design needs to withstand all normal axial and transverse loads from shipping and handling operations without permanent deformation. Either stress analysis methods or testing to demonstrate compliance with the licensing basis and criteria can be used.

5. MANUFACTURING OUTLINE OF FUEL COMPONENTS AND ASSEMBLY

The following subsections provide a brief overview of the manufacturing processes of the fuel assembly and its components, and the processes that are crucial for the in-pile performance are identified. The fuel manufacturing process also has a significant effect on the safety of nuclear fuel cycle facilities that need to be considered, especially with regard to criticality issues [43–45]. Basic information on fuel powder/pellet fabrication technologies is presented in Refs [46, 47]. Advances in the fuel pellet manufacturing processes were reviewed at the IAEA Technical Meetings on Advanced Fuel Pellet Materials and Fuel Rod Design for Water Cooled Reactors in 2003 and 2009 (see Refs [48, 49]). In general, this publication continues QA/QC aspects of reactor fuel fabrication and utilization considered in Refs [50, 51].

Section 5.1 describes the powder and pellet manufacturing, while Section 5.2 provides an overview of the zirconium alloy manufacturing of zirconium source material, tubes and flat products. Sections 5.3–5.5 provide information about fuel assembly component and PWR/BWR/VVER/PHWR assembly manufacturing. Section 5.6 describes the manufacture process of control rods.

5.1. POWDER AND PELLET MANUFACTURING

For manufacturing nuclear fuel pellets, the enriched uranium hexafluoride (UF_6) needs to be converted to UO_2 powder. There are essentially two types of conversion procedures: wet and dry [46, 47].

There are two wet conversion procedures: the ammonium uranyl carbonate (AUC) procedure and the ammonium diuranate (ADU) procedure. The procedures are named after their main intermediate compounds. Wet conversion procedures are characterized by the intermediate compound being obtained by precipitation and separation from uranium solutions. Subsequently, the intermediate compound is converted to UO_2 powder by heat treatment.

Dry conversion procedures are, for example, the integrated dry route procedure and the AREVA Dry Conversion procedure. These procedures directly convert UF_6 to uranyl fluoride (UO_2F_2) and, subsequently, with hydrogen to UO_2.

The most important powder and pellet manufacturing steps to manufacture good quality pellets are as follows (see Refs [46–49] for more details):

(a) Blending is the first of a series of critical fabrication steps that will affect pellet quality, specifically their homogeneity and consistent quality.
(b) Process parameters that influence green pellet quality include:
  — Pressing and production rate to permit uniform powder feed and ejection of air from powders;
  — Pressure;
  — Die design, surface finish and condition (i.e. wear);
  — Lubrication of the die surfaces, or addition of lubricant to the powder at blending step;
  — Pellet *L*/*D* ratio.
(c) Process parameters that influence the characteristics and quality of the sintered pellets are:
  — Quality of the green pellets as noted above;
  — Temperature and time at sintering temperature;
  — Sintering atmosphere composition and flow rate;
  — Total load and arrangement of the pellet load in the furnace.

5.1.1. Ammonium diuranate procedure

Powder manufacturing is described in Refs [47, 52, 53]. The complete flow sheet for the powder and pellet manufacture using the ADU route is given in Fig. 6. During the manufacturing of the powder the precipitation time, calcination and reduction temperature have a major influence on the powder characteristics.

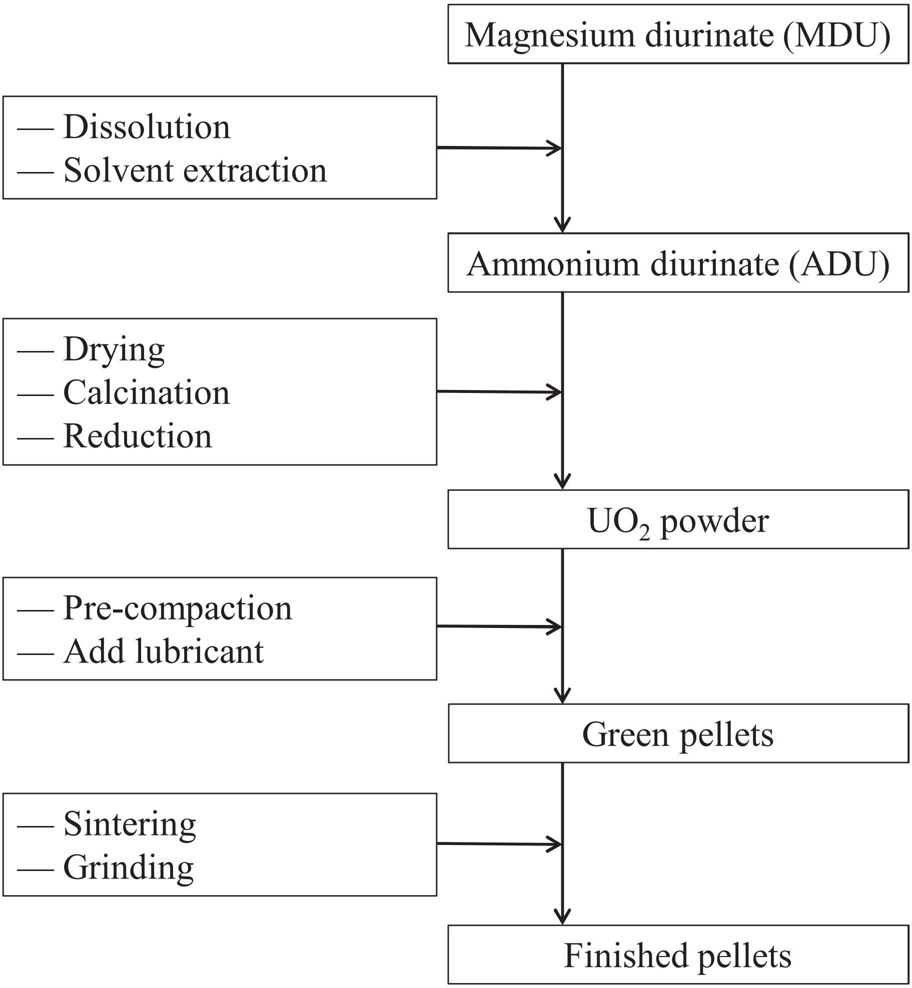


FIG. 6. Flow sheet for the UO_2 powder manufacture using the ADU route.

The pellet manufacturing is done in three different steps (see Refs [54, 55] for more details):

(a) Pre-compaction: The fine powder obtained by processing has very poor flowability and cannot be compacted to uniform density. The powder is firstly pre-compacted and granulated to flowable granules. Before the final compaction an add-mix lubricant is added in the granulated powder. The uniformity in the distribution of the lubricant is important, and mechanization in addition of lubricant is desired.

(b) Final compaction: For final compaction, hydraulic or mechanical presses are used. For having uniform density, double end compaction is favourable. The green pellets have density in the range of 5.5–6.0 g/cm^2. The green pellets made are loaded in the molybdenum boats. Regular inspection of the toolings during production is important for getting consistent quality of pellets. Their integrity is checked by using an acetone dip test during regular intervals of production.

(c) Sintering: The green pellets are loaded in a continuous sintering furnace and sintered at 1700°C in reducing atmosphere (cracked ammonia or hydrogen). The powder characteristics influence the density achieved during sintering. The moisture content of the cracked gas (measured in terms of dew point) is an important parameter. These pellets are then ground to a cylindrical shape using centreless grinding. The sintered and ground pellets are inspected for defects and measured for density and chemical purity. The sintered and ground pellets are stacked to the fixed lengths in trays. These stacked pellets are then ready for loading into the tubes.

The corresponding ADU manufacturing process used in the Russian Federation is shown in Fig. 7, while the pellet manufacturing process for VVER fuel is shown in Fig. 8.

5.1.2. Ammonium uranyl carbonate procedure

The AUC procedure was developed in Germany and used in the Hanau UO_2 plant. It was also used by Westinghouse in Sweden (where it is still being used) and in Brazil for the production of UO_2 for sintering (see Refs [47, 55] for more details). The first steps are the same as in the ADU procedure:

(a) The enriched UF_6 is supplied in a high pressure steel cylinder with UF_6 being a solid.

(b) The steel cylinder is heated, and the UF_6 is vaporized. The UF_6 gas is fed to a precipitation vessel where it reacts with water, ammonia (NH_3) and carbon dioxide (CO_2) in two steps:

$$UF_6 + 2H_2O + 4NH_3 \rightarrow UO_2F_2 + 4NH_4F \qquad (1)$$

(c) Which is then directly followed by the forming of $(NH_4)_4UO_2(CO_3)_3$ (i.e. AUC):

$$UO_2F_2 + 3H_2O + 3CO_2 + 6NH_3 \rightarrow (NH_4)_4UO_2(CO_3)_3 + 2NH_4F \qquad (2)$$

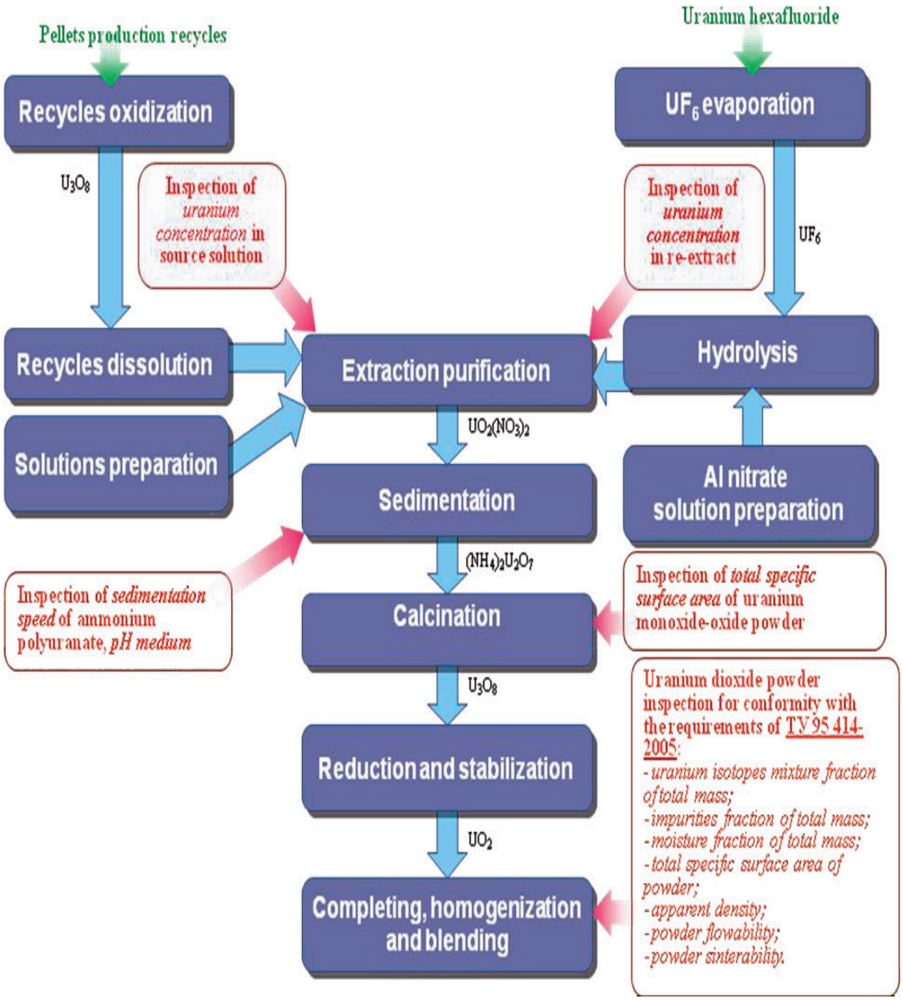


FIG. 7. Basic flow chart of powder production by ADU method (Russian Federation) (courtesy of TVEL).

(d) The AUC obtained as a crystallized compound is fed into a rotary filter, where it is washed and dried.

(e) The AUC is heat treated in a fluidized bed furnace where it decomposes followed by a reduction to UO_2 using steam and hydrogen, including a pyrohydrolysis step:

$$(NH_4)_4UO_2(CO_3)_3 + H_2 \rightarrow UO_2 + 4NH_3 + 3CO_2 + 3H_2O \qquad (3)$$

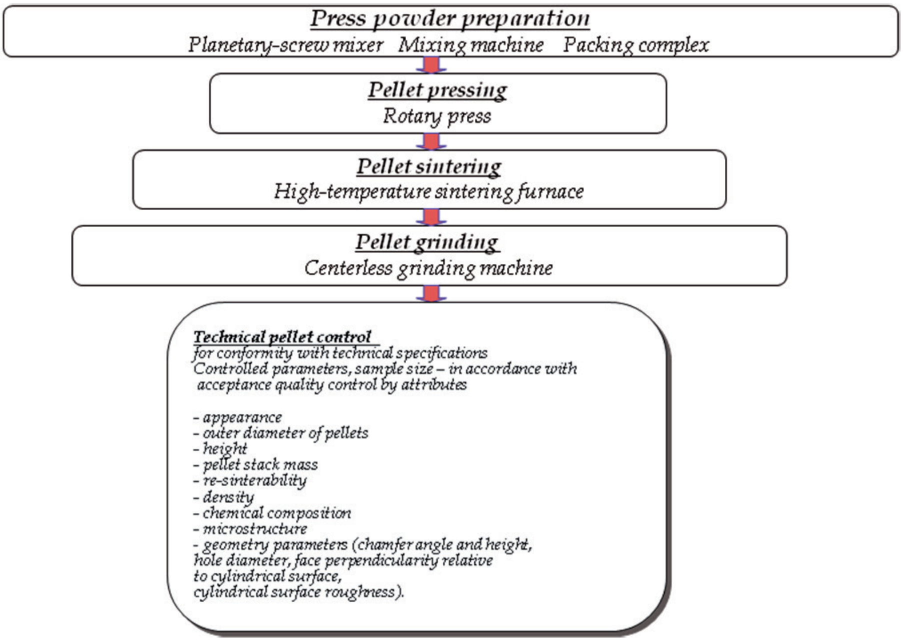


FIG. 8. Fabrication of nuclear ceramic pellets of standard sizes (courtesy of TVEL).

(f) The UO_2 powder obtained by the AUC procedure has good free flowing properties. Further processing does not need granulating, compacting and milling. Furthermore, there is no need for additives.

5.1.3. Dry route

5.1.3.1. Conversion

The conversion process is outlined in Fig. 9. The UF_6 comes from enrichment plants in standardized cylinders. The UF_6 material is solid at ambient temperature and becomes gaseous around 70°C. The cylinder is placed in an autoclave (step 1, Fig. 9) to be heated to a temperature of around 100°C (step 2). Then the UF_6 flow is sent to the conversion reactor (step 3) through gaseous UF_6 pipes. The temperature of the pipes transferring UF_6 needs to be accurately monitored to prevent cold points and plugging occurrence of tube by UF_6 re-condensation.

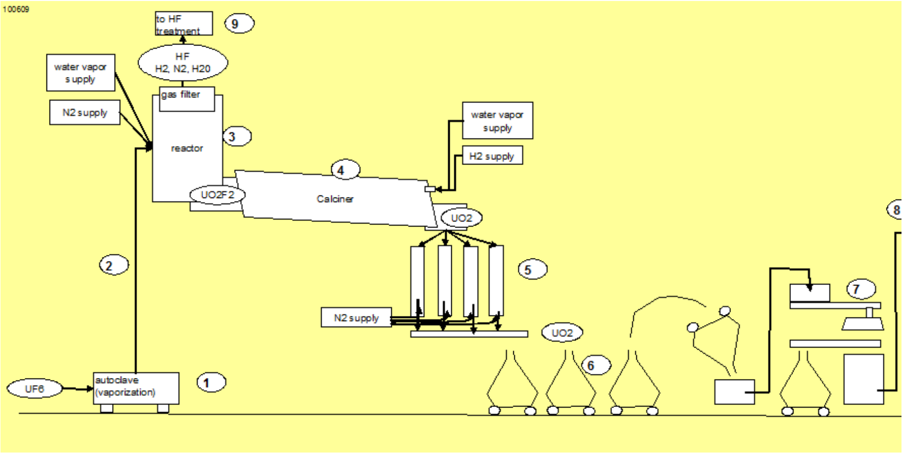


FIG. 9. Conversion: $UF_6 \rightarrow UO_2$ powder (courtesy of AREVA NP).

In the hydrolysis reactor, the UF_6 gaseous jet is mixed with a jet of overheated water vapour. The following exothermic reaction takes place:

$$UF_6 + 2H_2O \rightarrow UO_2F_2 + 4HF \quad (4)$$

(a) UO_2F_2 is a solid powder and hydrogen fluoride (HF) is gaseous.
(b) UO_2F_2 tends to fall down to the bottom by gravity and HF goes up to the top of the reactor.
(c) At the top of the reactor, there is a set of sintered filters to stop and contain in the reactor UO_2F_2 particles which may be driven in suspension in the escaping HF gas flow.
(d) These filters tend to be progressively plugged by trapped UO_2F_2 particles. Nitrogen counter pressure pulses are periodically applied through the filters to remove UO_2F_2 dust accumulated and stuck on the filter surface.
(e) UO_2F_2 also sticks on the walls of the reactor. Mechanical impactors hit the walls of the reactor to remove stuck powder.

The UO_2F_2 powder is moved through the rotary calciner (step 4); during this travel, powder is swept by a counter gas flow which is a mixture of hydrogen and superheated water vapour. Through the following reaction chain the UO_2F_2 powder is progressively transformed into UO_2 powder:

$$3UO_2F_2 + 3H_2O \rightarrow U_3O_8 + 6HF + \tfrac{1}{2}O_2 \text{ (defluoration)} \quad (5)$$

$$U_3O_8 + 2H_2 \rightarrow 3UO_2 + 2H_2O \text{ (reduction)} \quad (6)$$

$$\tfrac{1}{2}O_2 + H_2 \rightarrow H_2O \quad (7)$$

These reactions are endothermic and different controlled electrical heaters placed along the length of the calciner tube provide the appropriate temperature profile. Hot UO_2 powder is unloaded in cooling hoppers where nitrogen gas flow is injected (step 5).

The content of the cooling hopper can be unloaded into powder storage containers (step 6). A final treatment of the powder is performed (step 7) before its delivery to the pellet shop.

The UO_2 powder is sent to the neighbouring pellet shop by pneumatic transfer or placed in intermediate storage containers if powder is to be sent to another plant (step 8). Gaseous HF is sent to an HF treatment station (step 9), where the following complementary operations are performed:

(a) Gaseous HF passes through a condenser and then the most part of HF is diluted in a liquid solution. This HF solution is free of uranium, since at the reactor exit there are filters to stop UO_2F_2 particles.
(b) The absence of uranium materials is confirmed by a mass spectrometry measurement on periodic solution samples and after this positive check, the HF solution can be discharged as a non-contaminated waste.
(c) The gaseous phase at the exit of the condenser still contains some traces of HF. Two successive washing columns operate and remove at the residual HF contained in the gas flow before its final release to the atmosphere.

5.1.3.2. Pellet manufacturing

The pellet manufacturing process is outlined in Fig. 10 and described in Refs [45, 54, 55] and in the following. Step 10 in the process is the constitution and the homogenization of the blend as follows:

— Powder from conversion shop is unloaded into the blender.
— Lubricant, to facilitate subsequent pressing steps, and pore former are added.
— Powder has a very high level of sinterability. Pore former addition will enable the shift to the sintered pellet density range required by the designer.
— At the entrance of the pellet line, uranium scraps generated at the back end of the line (grinder scrap, visual aspect inspection) are introduced.

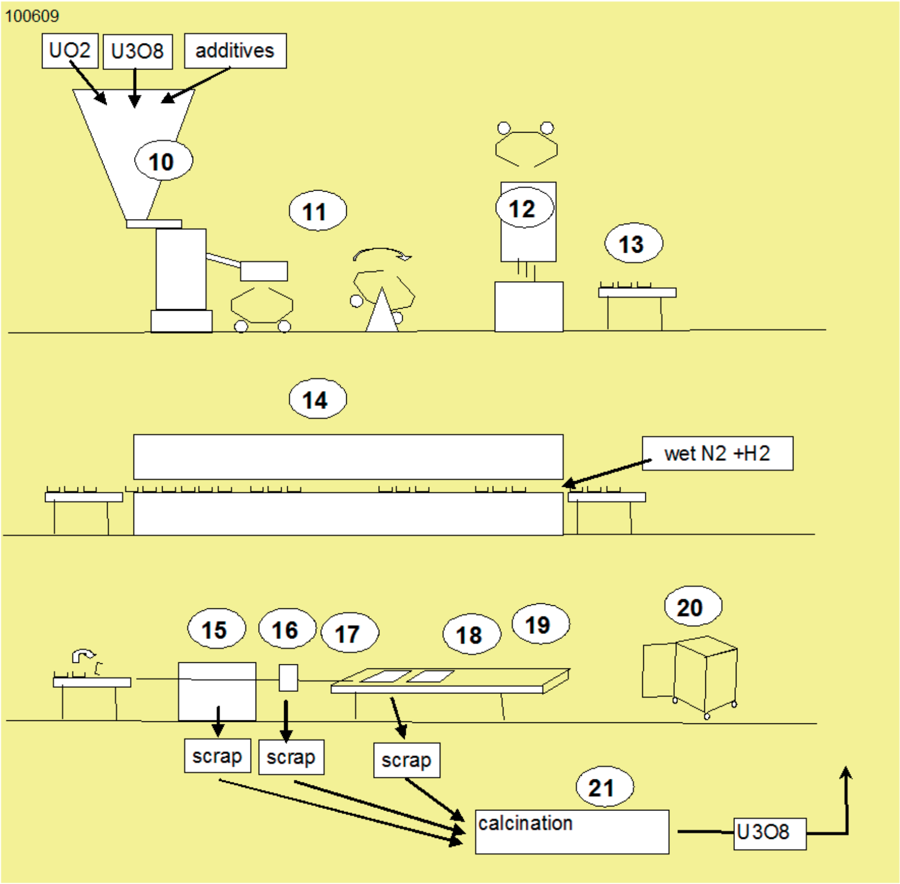


FIG. 10. Pellet: UO_2 powder → UO_2 pellet (courtesy of AREVA NP).

- These scraps have been transformed into triuranium octaoxide (U_3O_8) by calcination.
- The blending batch is homogenized.

Step 11 is the preparation of granulates:

- Big pellets are pressed to form pre-compacts.
- The pre-compacts are broken by a granulator to produce granulates.
- Rough granulates are rounded by rotations of the granulate container.
- Lubricant is added again at this spheroidization step.
- At the end of this step, lubricated spherical granulates are obtained which have a higher density and higher flow ability than the initial powder.

In step 12, granulates are pressed to form pellets. Pressed pellets are automatically loaded into sintering boxes made of molybdenum (step 13). The pellet boxes are forwarded through the sintering furnace tunnel and sintering is performed in a wet mixture of $H_2 + N_2$ (step 14).

At the beginning of the travel, there is the preheating zone. The temperature level in the preheating zone produces vaporization and evaporation of organic additives (lubricant, pore former) introduced at the initial step. At the middle of the sintering furnace, pellets are exposed at high temperature. Then pellets get the entire main features required (e.g. density, oxygen/uranium ratio, pore spectrum and grain size).

During the sintering process, densification is not uniform along the pellet height, which gives the pellet a non-cylindrical profile. A grinding operation is applied to return the pellet to an accurate cylindrical shape (step 15).

There is a strong requirement to have the pellet diameter within a tight range, so a 100% automatic measurement of the pellet diameter is applied and any pellet is rejected when its diameter does not meet the required range (step 16). At the output of the grinder the accepted pellets are placed on flat trays (step 17). Pellets are 100% inspected and pellets showing visual features (e.g. cracks and chips) exceeding the acceptance level is rejected (step 18).

In step 19, random pellet samples are selected for the following purposes:

— Non-destructive testing (NDT) is performed to check the density and diameter conformity;
— Destructive tests are performed to check conformity features like chemical content, impurity content.

Trays of accepted pellets are stored in closed pellet cabinets (step 20).

The main sources of pellet scraps are scraps generated by the grinder when adjusting the pellet diameter and pellets rejected at the ultimate step of visual inspection. The scraps are calcined to produce U_3O_8 (step 21) and enter the recycling loop in the manufacturing process (step 22).

5.2. ZIRCONIUM MANUFACTURING

Zirconium alloys are used as much as possible in the fuel assembly as structural materials owing to their following properties:

— Low thermal neutron cross-section;
— Adequate mechanical properties;

— Adequate corrosion properties;
— Adequate high temperature oxidation properties.

Since pure zirconium has poor (at best unpredictable) water/steam corrosion resistance, it needs to be alloyed. Figure 11 summarizes the structure of the industry.

The performance of the zirconium alloy and components of this alloy is dependent on the environment (e.g. temperature, coolant chemistry and neutron flux) and alloy microstructure which in turn depends on alloy chemistry and the thermomechanical process. Thus, the manufacturing of the zirconium alloy material has a crucial impact on the in-reactor performance of the material.

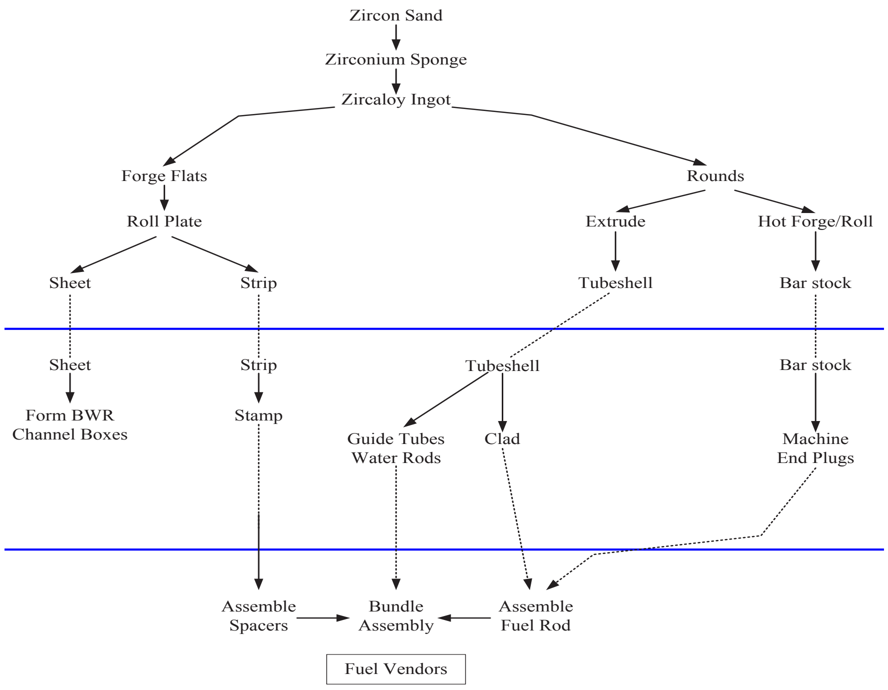


FIG. 11. Zircaloy production outline (reproduced from Ref. [4] with permission courtesy of ANT International).

The most important zirconium alloy manufacturing steps to manufacture good zirconium alloy materials used for fuel zirconium components are as follows (see Refs [4, 47] for more information):

(a) Process parameters that influence the characteristics and quality of the ingot:
  (i) Quality of the raw material;
  (ii) Molten pool diameter and depth that is a function of amperage and speed of melting;
  (iii) Number of remelts of the ingot;
  (iv) Sequence of order of cut up cylindrical pieces from ingot from previous melting;
  (v) Electrode welding and copper mold atmosphere composition.
(b) Process parameters that influence the characteristics and quality of the final zirconium alloy tube, bar, sheet and strip (the most critical parameters in beta quenching) are:
  (i) Heat up rate;
  (ii) Time at temperature to achieve uniform temperature distribution;
  (iii) Cool down process and quenching rate.
(c) Process parameters that influence tube hollow quality include:
  (i) Quality of dies and mandrel;
  (ii) Type of lubricant and its cleanliness;
  (iii) Degree of reduction as a function of tube wall thickness/diameter.
(d) Process parameters that influence the characteristics and quality of the recrystallized tube hollow include:
  (i) Temperature and time at heat treatment temperature;
  (ii) Heat treatment atmosphere composition;
  (iii) Total load and arrangement of tube hollows in the furnace;
  (iv) Temperature uniformity in furnace with production load.

5.2.1. Zirconium source material

According to Ref. [56] (original emphasis):

"Nearly all the zirconium metal is extracted from zircon sand, Zr-Hf SiO_4, occurring in beach sand all over the world. The zirconium to hafnium ratio in zircon is about 50/1 but since Hf has a very large thermal neutron cross section, it is crucial that as much Hf as possible is separated from zirconium during the manufacturing process.

"*The alloy homogeneity and chemical impurity concentrations of the final products is mainly established in the very first steps, starting from the zirconium sand, i.e. hafnium separation, ZrO_2 reduction, scrap recycling and ingot melting. Only the gas contents can be influenced also in later processes.*"

There are essentially three different processes to produce zirconium metal:

(1) Kroll process (physical and chemical process);
(2) Van Arkel process;
(3) Electrolytic process.

5.2.2. Zirconium sponge

5.2.2.1. Physical process

To manufacture zirconium based alloys, one needs to master key metallurgical and technological processes from the zirconium sand of a beach to the final in-reactor product. The phase transformations, strong anisotropy and pyrophoricity of zirconium need to be taken into account in implementing the manufacturing processes.

The first step in the process is to produce zirconium sponge made of pure zirconium to fulfil the neutron transparency requirement (see Fig. 12). The purity is increased successively with the key processes being the hafnium/zirconium separation, the Kroll reduction process and the vacuum distillation process. The sensitive product properties are the silicon and hafnium contents for the chlorination and separation processes and the chlorine and magnesium contents for the reduction and distillation processes.

5.2.2.2. Chemical process

The zirconium sponge is manufactured in two steps, first production of hafnium free zirconium oxide (ZrO_2) (see Fig. 13) and second manufacturing of zirconium sponge by the Kroll process (see Fig. 14). Regarding the first step, purification and separation impurities in zircon to obtain the hafnium free zirconium is done by fusion with sodium hydroxide (NaOH) and removal of sodium silicate after leaching with water followed by solvent extraction route using tributyl phosphate (TBP) [57]. The basic outline for the solvent extraction route is given in Fig. 13. The separation of hafnium by solvent extraction is a critical process.

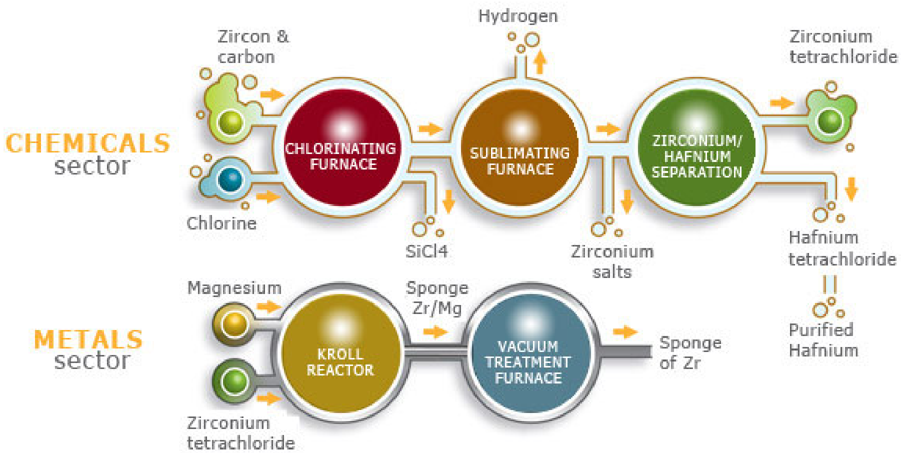


FIG. 12. Zirconium sponge manufacturing by the physical process at the Jarrie plant (courtesy of AREVA NP).

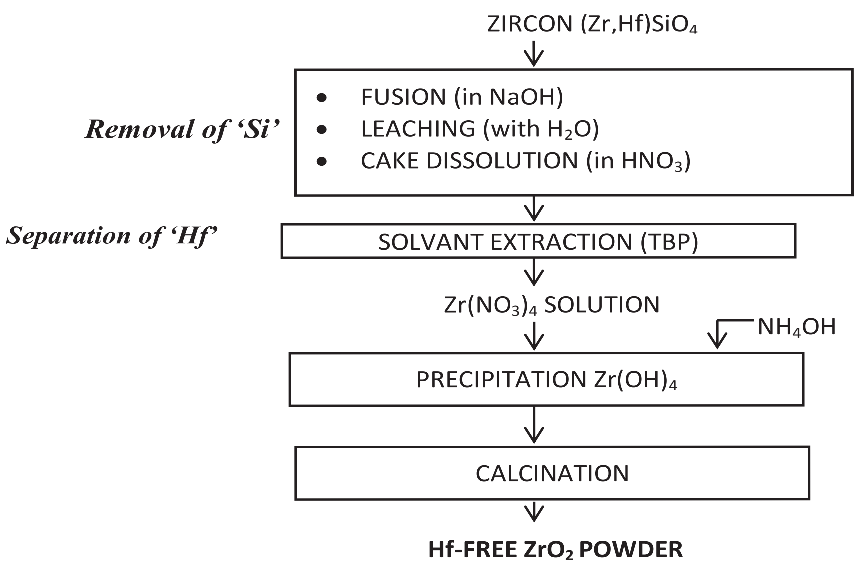


FIG. 13. Flow sheet for hafnium free ZrO_2 production using the TBP process.

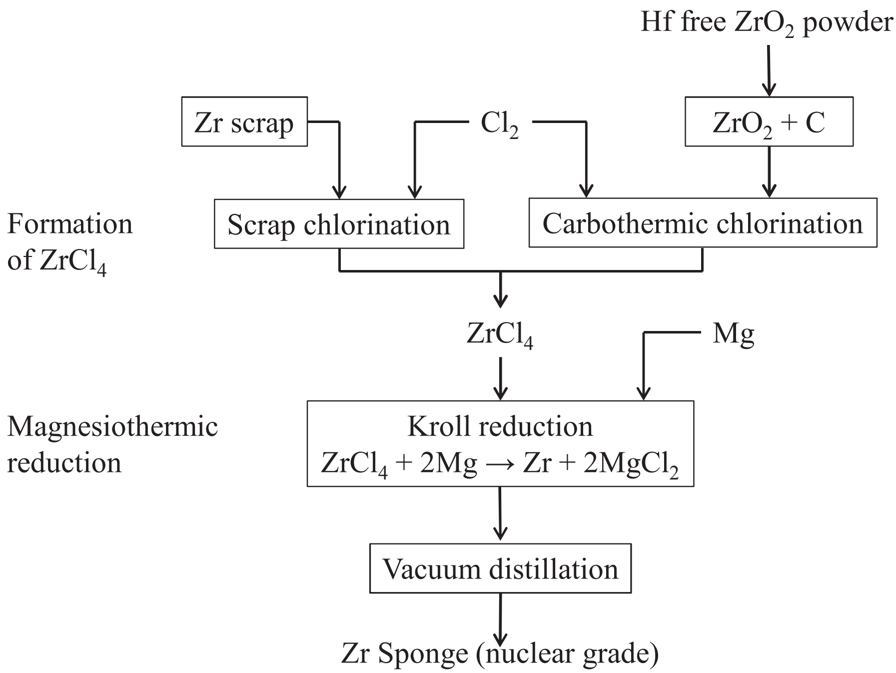


FIG. 14. Flow sheet for zirconium metal (sponge) production using the Kroll process.

In the case of the Kroll process, the high purity zirconium metal is made by reduction of zirconium tetrachloride ($ZrCl_4$) (obtained from the ZrO_2) by magnesium [58, 59]. By using the raw cake obtained after the reduction, high purity zirconium metal sponge is made by vacuum distillation. The process flow sheet is given in Fig. 14. To obtain the high purity sponge, vacuum distillation for removal of the residual impurities is critical.

5.2.2.3. Electrolytic process

Industrial production of reactor purity malleable zirconium in the Russian Federation is performed via fluoride–chloride fusion electrolytic reduction in impermeable reduction cells. See Fig. 15 for the process flow sheet.

As a result of impermeable cells reduction, zirconium powder with an oxygen reading of 0.04–0.08% is produced. It serves as a basis for E110, E125 and E635 alloys. Metallic zirconium for E110 and E635 alloys production is usually produced by electrolytic and iodide (produced by the Van Arkel process) zirconium melting.

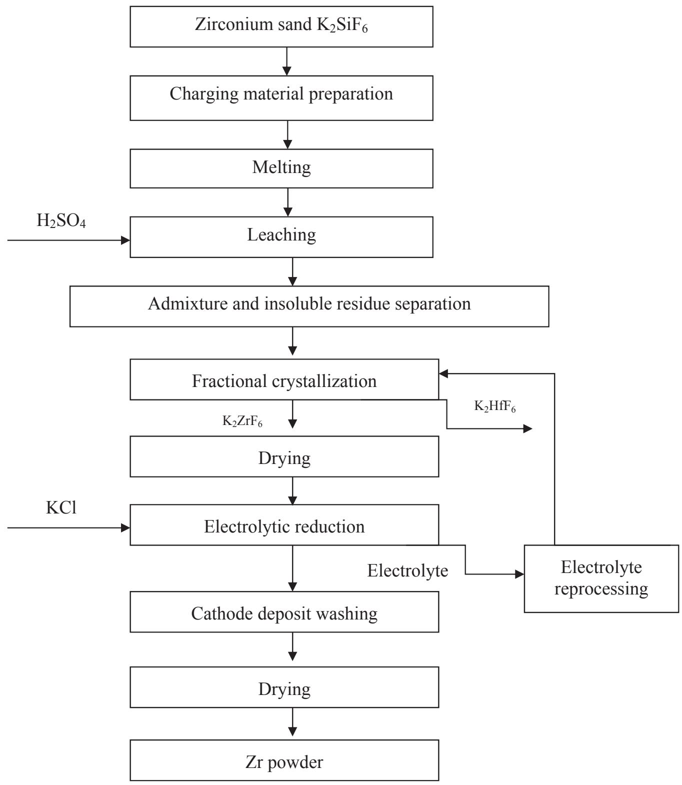


FIG. 15. Flow sheet for zirconium metal production using electrolytic process.

5.2.2.4. Crystal bar process

At present, chloric technology is used to produce zirconium sponge of reactor purity (see Fig. 16). Chlorination in fusion is used in the Russian Federation. Salt refining in the salts fusion is then performed to remove simple admixtures (e.g. aluminium, chromium, iron, nitrogen and titanium) from $ZrCl_4$.

5.2.3. Tubes, bars and flat products

An overview of the round and flat product manufacturing is provided in Fig. 17. The first step prior to manufacture tubes, bars or flat product is the melting and hot deformation operations. The key processes are scrap recycling, melting and hot deformation.

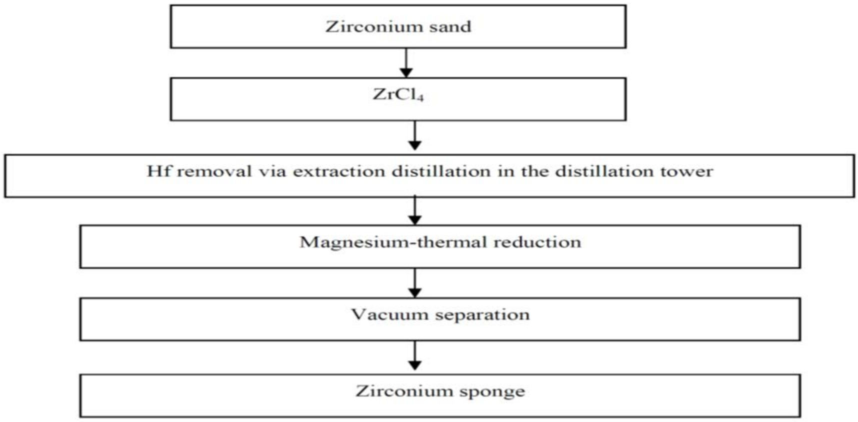
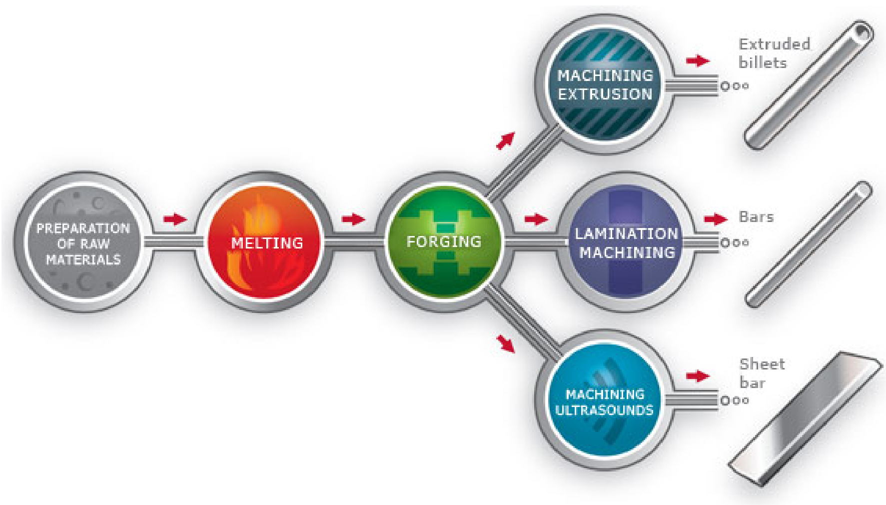


FIG. 16. Flow sheet for zirconium metal production using the crystal bar process.



Note: Ugine specializes in vacuum arc melting and hot forging of zirconium, using the sponge from Jarrie and recycled scraps. It then supplies these semi-finished products to other facilities to be processed into tubing, slab and strip.

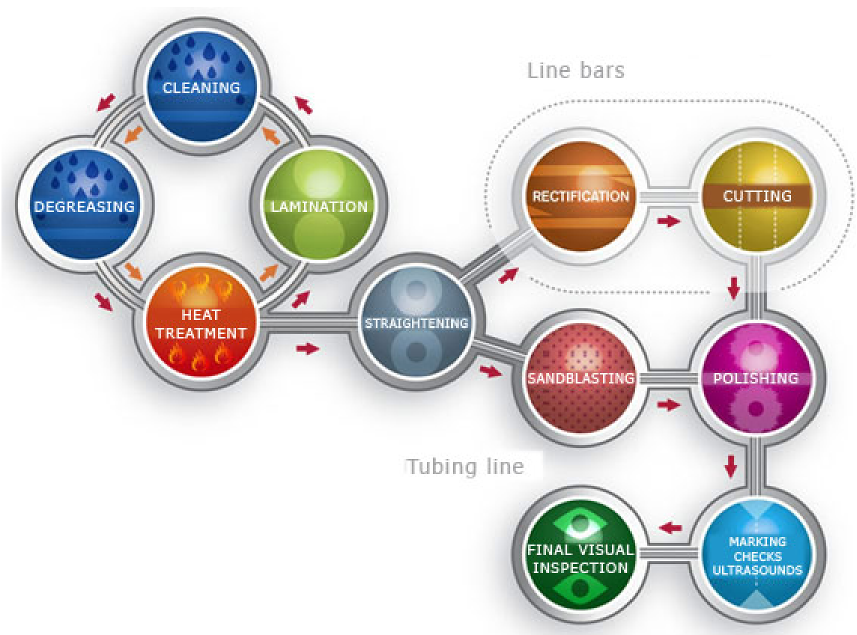
FIG. 17. Overview of round and flat zirconium product manufacturing at the CEZUS Ugine site (courtesy of AREVA NP).

The sensitive product properties are:

(a) For scrap recycling, a product free of contaminants and foreign materials.
(b) For melting, the chemical composition homogeneity across the ingot.
(c) For hot deformation, by forging and then hot rolling for flat product or bars and extrusion for hollow tubes the dimension reduction and the metallurgical homogeneity, without internal defects, with an adequate metallurgical structure and good corrosion resistance.
(d) For zircaloy, a beta quenching operation is crucial to ensure a good corrosion resistance of the material.

5.2.3.1. Tube manufacturing

An overview of the round product manufacturing is provided in Fig. 18. The soundness of the tube is the key, since the cladding is the first barrier against the fission product dissemination in the core. The key processes are cold mechanical deformation, thermal treatment and surface conditioning.



Note: The Paimboeuf plant receives tube blanks from Montreuil-Juigné site.

FIG. 18. Overview of round product manufacturing: cladding tubes, guide tubes and rod cap bars at the Paimboeuf plant (courtesy of AREVA NP).

The sensitive product properties are the final dimensions specified by the designer, the metallurgical texture and micro structure of the tube for the in reactor fuel performance to control, creep, growth, PCI and corrosion resistance.

5.2.3.2. Bar manufacturing

Bar stock used to manufacture end plugs for fuel rods is manufactured from forged bars either by swaging and grinding or by pilgering and polishing up to the final dimensions. The main steps can be seen in Fig. 17.

The key processes are mechanical deformation and thermal treatment. The sensitive product properties of the end plug of the fuel rod are corrosion resistance, soundness to prevent any leakage and mechanical properties for rod insertion into, or extraction out, of the skeleton of the fuel assembly.

5.2.3.3. Flat product manufacturing

An overview of the flat product manufacturing is provided in Fig. 19. The key processes are mechanical deformation, thermal treatment and surface conditioning.

The sensitive product properties are the metallurgical structure, texture, mechanical characteristics, and final dimensions specified by the designer. One important property of the flat product is a predictable geometric stability under irradiation, control by texture and structure.

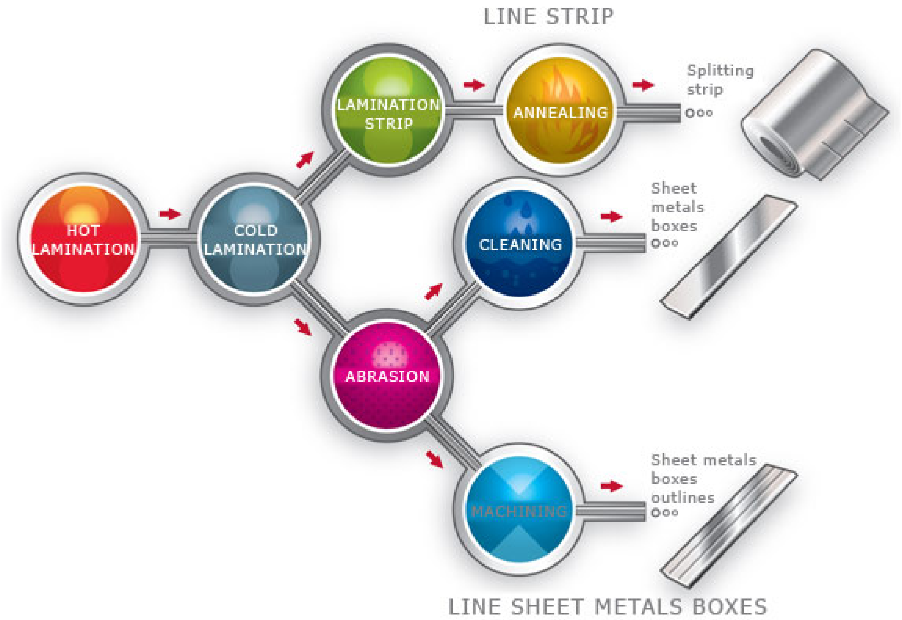
5.3. FUEL ASSEMBLY COMPONENT AND ASSEMBLY MANUFACTURING (PWR AND BWR)

Figure 20 gives an overview of the complete manufacturing process of a fuel assembly. The different manufacturing steps are described more in the following subsections.

5.3.1. Fuel rod manufacturing

The fuel rod manufacturing is outlined in Fig. 21 (steps 23–35). Tubes are unpacked from transportation boxes and installed at the entrance of the rod line (step 23). The tubes are received from external suppliers in ready to use state conditions.

Bottom plug welding is performed in step 24, and different processes may be used to connect the lug, such as tungsten inert gas (TIG), laser or resistance welding processes.



Note: Zirconium billets supplied by the Ugine site are the main raw material for the Rugles facility. The billets (i.e. rectangular bars) are pilgered into sheets and strips using hot and cold processes.

FIG. 19. Overview of flat product manufacturing (strips and sheets) at the CEZUS Rugles plant (courtesy of AREVA NP).

The next step in the process, step 25, is a non-destructive inspection to check the conformity of the welding operation with process and product requirements. The method of inspection depends on the welding process used: for TIG and laser welding processes, X ray is used to detect volumetric defects, which may be generated during welding. In the case of resistance welding process, there is an upset creation: the quality of weld is rather checked by a measurement of the upset dimensional profile and control and on-line check of the welding parameters.

Step 26 consists of a destructive inspection of the weld:

— Weld samples are generated periodically.
— Different destructive tests (e.g. strength tests, metallographic examinations and corrosion tests) are performed on periodic samples to check that the welding process is kept under control.

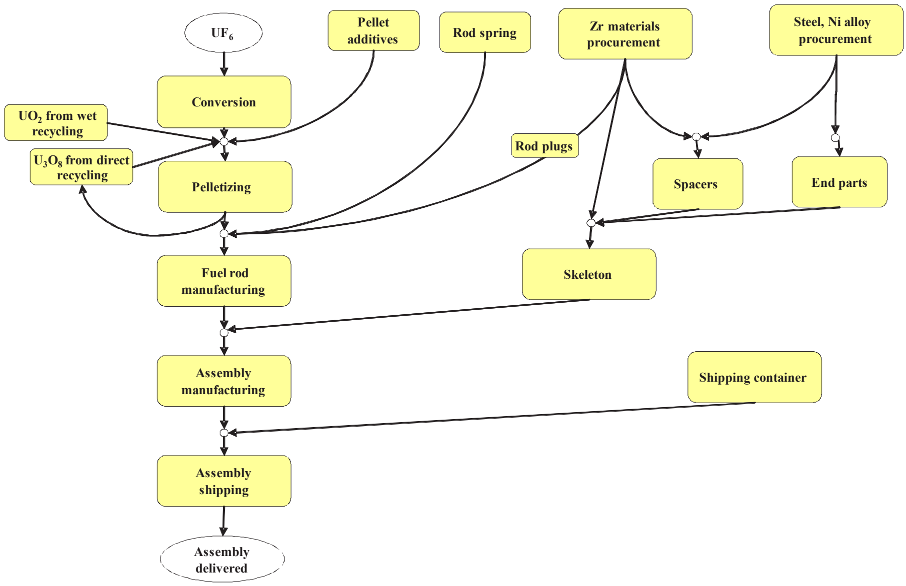


FIG. 20. Summary of the successive manufacturing steps (courtesy of AREVA NP).

In step 27, the pellets are loaded into the tubes in the following sequence:

(a) Successive segments of pellet are introduced at the still open end of the tube by moving them towards the bottom end of the tube until pellet stack completion the plenum length is checked, and the volume used to house the spring as well as the fission gas at the top of the rod is also checked. Pellets are added or removed as much as necessary to adjust the plenum to the specified length.

(b) Tube end face is cleaned before welding the top end plug. The concerned end face of the tube is swept carefully to be sure to remove any surface pollution (e.g. UO_2) which might have been deposed during pellet insertion and may influence the welding process.

The fuel rod spring is installed in step 28. The rod is then pressurized and the welding of the top end plug is performed. The welding process looks like the process already applied at the bottom level, but the inert atmosphere in the welding chamber is helium. The helium imposed pressure has the value of rod pressure required by the designer. At the end of step 29, the fuel rod is completed.

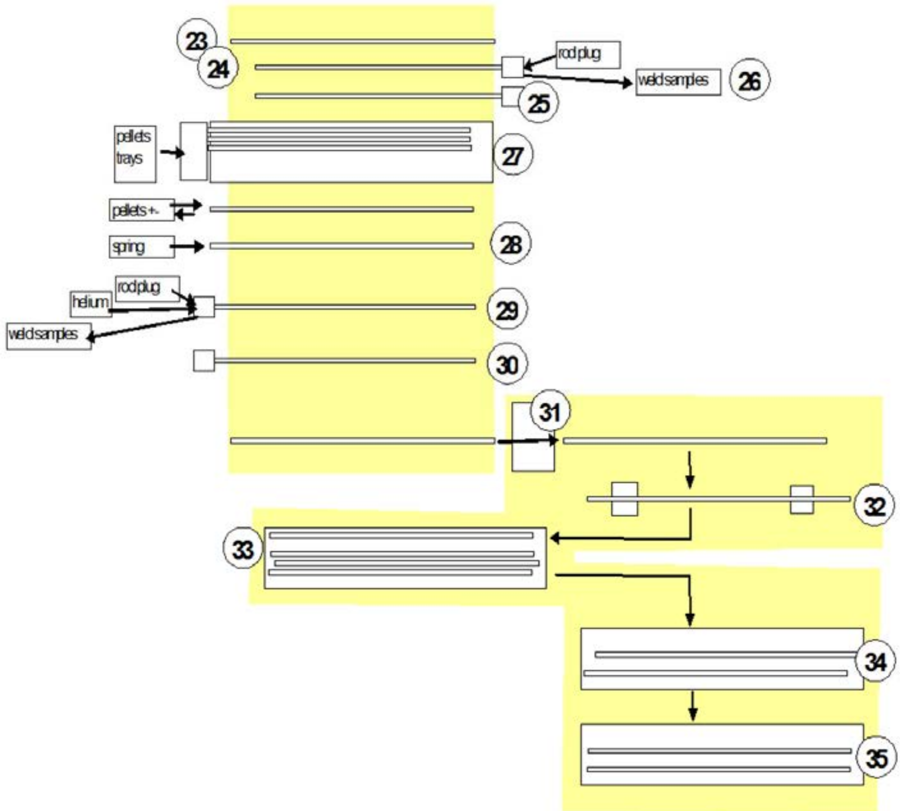


FIG. 21. Fuel rod manufacturing steps: tube → rod (courtesy of AREVA NP).

During step 30, the same method of inspection (e.g. involving non-destructive and destructive testing) as already explained for the bottom end plug weld is performed for the top end plug weld. A non-destructive and automatic examination of the fuel rod content is performed at the step 31 with:

(a) A gamma scanning test with a californium source emitting a neutron flux. When a neutron hits an atom of ^{235}U, there is fission and afterwards gamma emission. A gamma counter records the gamma flux during all the travel of the rod through the inspection device (the gamma emission rate is proportional to the ^{235}U content). Since the rod is moving through the scanner at a very constant speed, the resulting record will be a curve giving the evolution of ^{235}U linear content along the pellet fuel stack. So a gamma scan record will enable to detect deviations in the fuel stack constitution, such as presence of pellet of different enrichment, existence of gap between pellets, pellet with abnormal diameter, density or enrichment.

(b) A densitometry measurement with an X ray picture of the rod is performed.

In step 32, the rod weight is determined to check the correct ^{235}U quantity loaded in the fuel rod through the following previous points of conformity: pellet ^{235}U content, pellet diameter and pellet stack length. An additional weight measurement may be performed on completed rod.

A rod leak test is done in step 33 in a vacuum cell. Since the rod is pressurized by helium, in the case of a leakage, helium will be released and detected by the helium sensors placed in the vacuum cell.

As final fuel rod inspection (step 34), an ultimate attentive visual examination is performed on the completed rod. Completed rods are stored temporarily until they will be requested to constitute assemblies.

In step 35, repairing loop sequences are used to enable the rod to be reworked in the following two deviation situations:

(a) When a weld is not acceptable, the plug involved is mechanically removed, the tube end face is re-prepared, and a new plug is welded.

(b) When a failure in the pellet stack constitution is detected by the gamma scanner or the densitometry, the rod may be fully repair: the pellets may be unloaded. After inspection they may be reused to load further rods.

The changes regarding the manufacturing process of guide tubes for PWRs, compared to the cladding tube manufacturing, regards the way to produce the dashpot at the bottom of the guide tube. This can be made as an example by swaging, but another manufacturing process can be made to improve the stiffness of the guide tube by keeping the same external diameter for the thick zone, the transition zone and finally the thin zone (guide tube MONOBLOC [60]). In that case the changes are:

(a) The pilgering operation which is more complex since the thick and thin parts of the tube (the dashpot at the bottom of the tube) need to be made on the same equipment using an appropriate mandrel with a specific motion.

(b) After silicon carbide blasting, polishing and NDT, a drilling operation is performed before the final inspection.

5.3.2. Top and bottom end pieces manufacturing

The end pieces are the mechanical interface of the nuclear reactor to the bundle of fuel rods. The materials currently used are stainless steel for structural elements, nickel based alloys for components such as spring and screws. Different processes may be operated to obtain the elementary subcomponents. The fastening processes used include:

— Classical machining;
— Electrical discharge machining to drill accurately some particular holes;
— Water jet or cutting;
— Forging;
— Stamping;
— Electron beam welding;
— TIG welding;
— High temperature vacuum brazing.

Final annealing heat treatments are applied to harden the components made out of nickel based alloys (e.g. springs and screws).

Different techniques are used to perform the finishing operation:

— Deburring;
— Electropolishing;
— Sand blasting;
— Automatic cleaning;
— Pickling;
— Engraving on the end part of the assembly an identification number (used when the assembly will be operated in the nuclear plant).

5.3.3. Guide tube manufacturing

The guide tube manufacturing is outlined in the lower part of Fig. 18 and described more in Ref. [60]. Automatic 3-D inspection equipment is used to check in detail the parts dimensions beside gauges for functional testing.

5.3.4. Spacer and mixing grid manufacturing

According to Ref. [3]:

> “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 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,
- Flow holes punched into the grid straps and outer straps,
- A means of attachment to an assembly structural member to restrain the spacers from axial movement."

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.

The texture orientation of the zirconium alloys needs to be taken into account when stamping the zirconium alloy strips. The texture orientation influences the irradiation induced growth which should be in the assembly axial direction; alternately the spacers will grow radially and interfere with the channel wall in BWRs and the neighbouring assemblies in PWRs at high burnup. In order to obtain the correct texture orientation, the spacer strips need to be cut from the sheet transverse to the rolling direction. This will provide an orientation with the minimum number of basal poles, 10%, in the assembly axial direction and 33% in the transverse direction, and will direct the growth in the axial direction and no growth in the radial direction.

The nickel alloy springs for bimetallic spacers are also stamped from strip in most instances. The same criteria for good control apply. The springs are heat treated prior to assembly with the zirconium alloy spacers. The spring alloys used, alloy X-750 or 718, are both age hardening and the heat treatment will consist of solution treatment and aging as discussed subsequently for Inconel spacers.

A cleaning cycle is applied to all materials after stamping and prior to assembly. Detailed dimensional inspection of the strip is necessary prior to assembly to assure that the configurations meet specifications.

The quality control inspection of the spacer components occurs during various stages of the process as noted in the process description: the spacer sheet material and tubing are inspected for dimensional, chemistry and metallurgical characteristics on receipt. The stamped parts are inspected for conformance to dimensional specifications prior to welding.

The inspection of the fully fabricated spacers is primarily dimensional with exception of the spring force test. A mechanical crush test and any seismic tests required for licensing are made as part of the qualification programme. Specific inspections of production spacers are to include:

— Spacer envelope dimensions, squareness and perpendicularity;
— Proper orientation of strips and cells;
— Cell size;
— Spring force;
— Visual inspection of weld joints.

The dimensional and spring force measurements should include 100% of the cells. The measurements are automated and the audits of the standards and software are important (see Refs [3, 4, 47] for more information.

5.3.5. BWR fuel channel manufacturing

According to Ref. [3]:

> “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 for Framatome ATRIUM designs,
> — Water cross assemblies for Westinghouse–Atom SVEA designs.
>
> “The function of the outer channel boxes is to contain the coolant flow in all BWR fuel bundle designs. The GNF and Framatome 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 [Fig. 1]. The current designs have a reduced wall thickness on the box faces to increase the amount of water moderator and decrease enrichment requirements and the original wall thickness are maintained at the corners where strength to resist bulging is required, as shown in [Fig. 22]. Zircaloy-4 was used originally for all channels. Some vendors have switched to Zircaloy-2 for improved corrosion resistance.

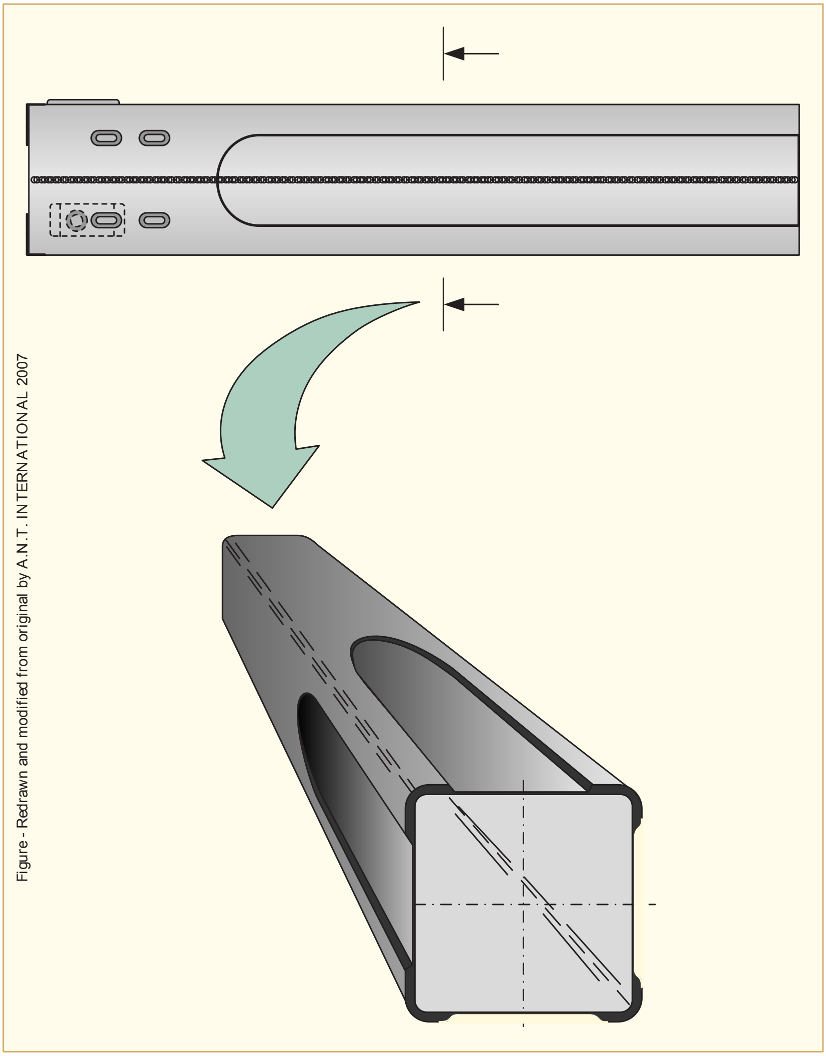


FIG. 22. Typical variable wall channel box (reproduced from Ref. [4] with permission courtesy of ANT International).

“The inner channel box serves the function for introducing unvoided water moderator into the center 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.

“All of the sheet materials for the channel boxes, sometimes called ‘channel blanks’, are made by the primary zirconium alloy producers ... . The boxes are formed and finished by a variety of vendors as discussed for each design. They are shipped separately from the fuel bundles and assembled with the fuel at the reactor site.

“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: two U bend sheets welded together, but cut from the same sheet and oriented in the same direction or one sheet formed into a square with one seal weld.”

5.3.5.1. Forming and welding: Two sheet method

The sheet received from the metal supplier has the dimensions for one complete channel and is pre-machined for the design wall contours of the four sides. The sheet is slit in its centre and each side is formed into a U shape by a brake press, the bottom of the U being one box side and each leg a half box side. The welds seams are in the centre of the box faces.

The texture orientation of the sheet is important and similar to that for zirconium alloy spacers. Irradiation growth is to be in the channel axial direction, and this is accomplished by orienting the rolling direction that the sheet was exposed to in the channel axial direction. This will orient 10% of the basal poles in the axial direction and orient the growth in that direction. The vendor doing the machining has the responsibility for the proper texture orientation and it is the responsibility of the fuel and box vendors to assure that this is done.

The sheet is cleaned and the edges are prepared for welding. The two axial seams are TIG welded in a flushed helium atmosphere. Visual inspection of the weld to assure acceptable oxidation levels is important at this stage. The seam leveling of the weld follows.

The inner channel for the Framatome ATRIUM assemblies is fabricated by a similar method. One difference is that the seams are laser welded.

5.3.5.2. Forming and welding: One sheet method

The pre-machined sheet's axial channel edges are prepared for welding and a dummy TIG weld is made in the centre of the sheet in the channel axial direction to be symmetric with the actual seal weld to be made after forming the sheet into a tube. The function of the dummy weld is to provide a symmetric metallurgical structure in the channel in order to promote symmetric properties and dimensional changes during its service.

The texture orientation requirements are the same as for the two sheet method.

The sheet is first cold roll formed into a tube and TIG welded along its axis. TIG welding is on the open plant floor, but protected from air ingress by the helium cover gas from the torch. Visual examination of the weld to assure acceptable levels of oxidation is important. Weld inspection by ultrasonic testing (UT), radiography or dye penetrant may be made at this point. Seam leveling of the weld and a stress relief heat treatment follow. Sizing of the tube for dimensional control is done next by drawing it through a die.

Forming a square channel from the tube is done by a 'Turk's Head Mill', which draws a square mandrel through the tube. A cleaning cycle follows.

5.3.5.3. Thermal sizing and final assembly

Final sizing for both the one and two sheet processes is by heating the channel on a stainless steel mandrel to temperatures just below 600°C in an inert atmosphere or vacuum. The mandrel expands more than the zirconium alloy and deforms the channel to the desired final dimensions. The thermal treatment serves as the final anneal and stress relief as well.

5.3.5.4. Final quality control

Final channel dimensional inspection is by automated systems and will include some or all of the following over the length of the channel:

— Wall thickness;
— Internal dimensions;
— Transverse flatness and squareness;
— Bow, twist, straightness and envelope dimensions.

Length inspection may be automated or manual. A residual stress test should be included at this or some other point in the process. A bow orientation hole is made on the top end to facilitate plant operators to orient the channel with the bow away from the control rods (see Ref. [47] for more information).

5.3.6. Skeleton manufacturing for PWR and BWR

The skeleton is the structure sustaining and positioning the bundle of fuel rods according to the regular pattern. There are two product lines:

(1) For PWRs: On the skeleton bench the spacers and the guide tubes are installed. Then the spacer and mixing grids are connected with the guide tubes by a resistance weld process to assure a defined spacing of the spacer and mixing grids and to achieve the mechanical robustness of the skeleton. Connecting devices, which define the interface of the skeleton to the end pieces, such as nuts and sleeves, are connected to the guide tubes be processes like swaging or resistance welding.
(2) For BWRs: The load carrying structure is a central square tube where stops are welded on to limit the movement of the spacer grids in the AREVA design. In the case of W and GNF designs, the load bearing structure is the centre water cross and water rods, respectively. The mechanical interface is provided by connecting features which are part end plugs, which are connected to the central square tube by welding. For BWR skeletons, a detailed dimensional inspection, using optical coordinate measurement equipment and gauges are used.

For both type of skeletons different zirconium alloys are used.

All welding processes in use to manufacture the skeleton are qualified to assure that product requirements are fulfilled and monitored by regular in-process samples and parameter control and visual examination.

5.3.7. BWR and PWR assembly manufacturing

5.3.7.1. Fuel rod loading

In the assembly present designs, the fuel rod is maintained only by friction at the different spacer levels. This design feature lets the rod to slide through the spacers when, during reactor operation, the fuel rod growth tends to be larger than that of the skeleton. This design feature will be also used when manufacturing the assembly.

To assure a proper positioning of the rods systems are in use to track where which rod is loaded to the bundle by push or pull, should be done at a defined and qualified speed and force, qualification being extremely important. Qualification should among others look at the rods (scratches, straightness and on the damage of spacers after unloading of rods). This is especially important when there are different enrichments used in the assembly.

5.3.7.2. Assembly handling system completion

When all the rods have been loaded into the skeleton, the assembly manufacturing is completed by the installation of the end parts. All screws and nuts are to be tightened only with newtonmeter. The bench clamping the assembly is moved from the horizontal position to the vertical position. The assembly is gripped by a handling system and can be moved to the different further stations.

5.3.7.3. Assembly cleaning

Blowing or washing using demineralized water removes most of the small fines generated during the assembling process.

5.3.7.4. Assembly dimensional inspection

The PWR assembly is placed on inspection equipment where the following dimensional features, which are of importance for the assembly in-reactor performance, are checked:

— Verticality of the assembly;
— Straightness of the assembly;
— Straightness of the fuel rods as installed in the assembly (regularity of the flow channels between fuel rods).

The BWR assembly is checked for straightness of the fuels rod by checking the water gap between the rods by measurement or by gauging. Dimensional tests to verify the shape of the assembly are done at skeleton stage.

5.3.7.5. Control rod insertion checking (PWR only)

A functional representative test is performed to verify on every assembly that the control elements can be moved freely into the guide tubes.

5.3.7.6. Assembly final visual inspection

An ultimate attentive examination by an operator is the last step before the final release of the assembly. Final inspection includes the following, among others things:

— End plug welds;
— Rod position;
— Appearance of spacers and vanes;
— Debris;
— Discolourations and contaminations;
— General geometrical appearance.

5.3.7.7. BWR fuel channelling

For BWR fuel, so called fuel channels are part of the configuration which is in use at the nuclear power station. Depending on the customer this assembling step is done at the fuel manufacturers' site or at the nuclear power station.

5.3.7.8. Assembly temporary storage

After they have been released, the assemblies are transferred to an area of temporary storage, with possible different storage solutions like storage racks or under floor storage. In all cases, the assemblies are handled and stored in vertical conditions.

5.3.7.9. Container for assembly shipping

The container to ship the assembly can receive two assemblies (e.g. PWR ANF-18 and BWR ANF-10 shipping containers). To install an assembly in the container, the sequence is the following:

(1) The container fixture receiving the assembly is placed in vertical position.
(2) The assembly to be shipped is gripped by the hoist, moved to the container fixture.
(3) After it has been accurately positioned along the container fixture, the assembly is clamped on the fixture.
(4) Then the hoist is ungripped and the container fixture can be lowered in horizontal position.

(5) After two assemblies have been installed, the container is closed.
(6) Preparation of assembly shipping.
(7) Acceleration sensors, possible adapters and required fixation systems in place.

The loaded containers are handled with appropriate systems (e.g. hoist and crane) to be installed on road, trailers and railway trucks.

5.4. FUEL ASSEMBLY COMPONENT AND SKELETON AND ASSEMBLY MANUFACTURING (VVER)

An overview of the VVER fuel assembly manufacturing and its components are shown in Figs 23–25.

The following subsections describe the manufacturing of the VVER fuel assembly and its components.

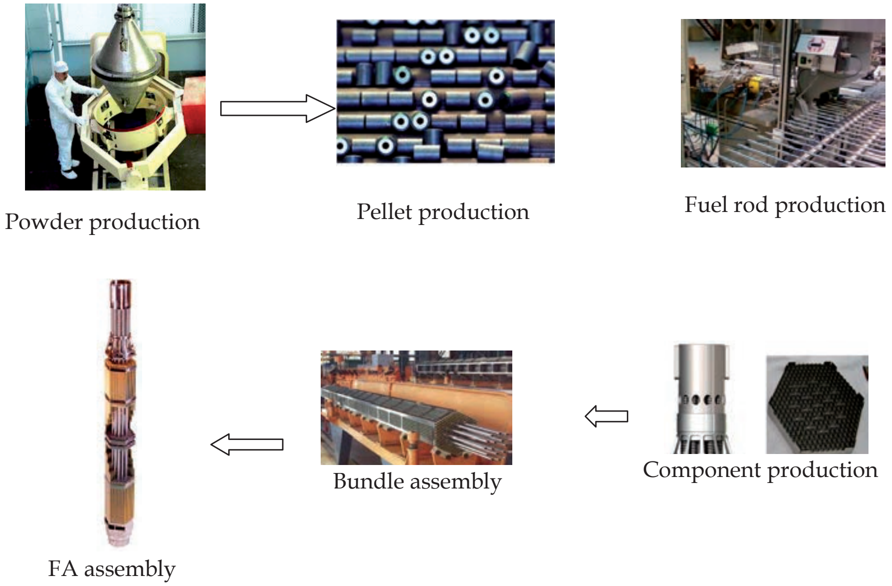
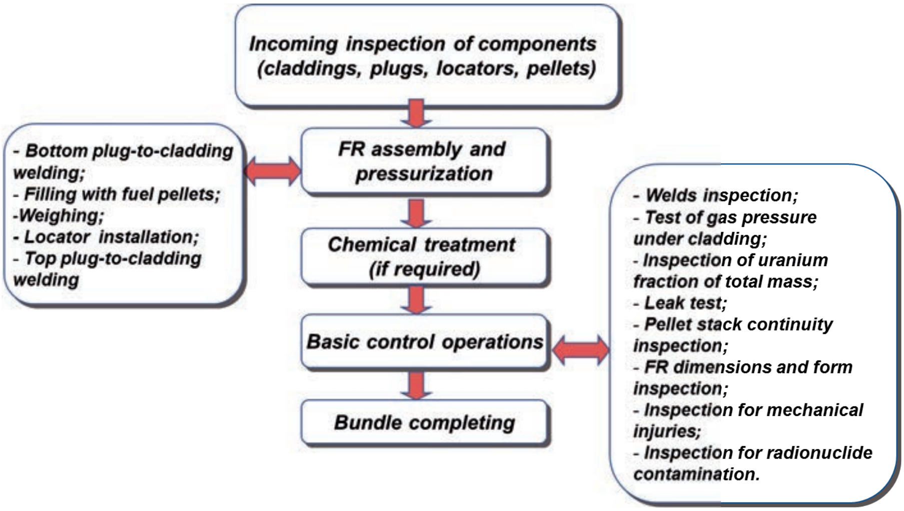
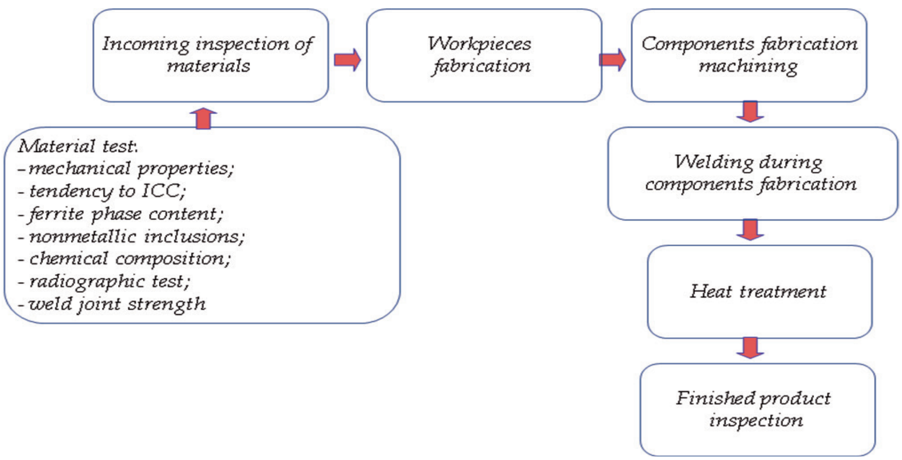


FIG. 23. Complete cycle of VVER fuel assembly fabrication (courtesy of TVEL).



Note: FR — fuel rod.

FIG. 24. VVER fuel rod fabrication (courtesy of TVEL).



Note: ICC — intercrystalline corrosion.

FIG. 25. VVER fuel component fabrication (courtesy of TVEL).

5.4.1. End parts manufacturing

Materials used currently are stainless steel for structural elements, Inconel materials for components such as springs and screws. Different processes may be operated to obtain the elementary subcomponents:

— Classical machining;
— Electrical discharge machining to drill accurately some particular holes;
— Water jet cutting.

Electron beam welding, TIG welding and brazing are the fastening processes used to assemble subcomponents.

Final annealing heat treatments are applied to harden the Inconel components (e.g. springs and screws).

Different techniques are used to perform the finishing operation:

— Deburring;
— Electropolishing;
— Sand blasting;
— Automatic washing;
— Engraving on the end part of the assembly identification number (used when the assembly will operate in the nuclear plant).

Automatic Tri-Dim inspection equipment is used to check in detail the parts dimensions.

5.4.2. Spacer manufacturing

The main materials used are a zirconium alloy for straps which are assembled in a square array and constitute the structural frame of the spacer. Small Inconel springs are installed and locked in every cell to provide the fuel rod with a friction sustaining force. The successive steps of the spacer manufacturing sequence are the following:

(1) Strap and spring stamping are done by subcontractors.
(2) Strap and spring cleaning.
(3) Inconel spring installation and welding operation to lock it on the zirconium strap.
(4) Spacer mounting.
(5) Spacer welding: electron beam or laser welding processes are used.

(6) Spacer automatic dimensional inspection.
(7) Spacer visual aspect inspection.

VVER-1000 spacer grids use hexagonal cells which are pressed of a thin wallet zirconium alloy E110 tube. Each cell has three bulging positioned at 120° meant for the fuel rod spacing. The cell bulging profile and its elastic and plastic properties ensure a play free fuel rod insertion into spacer grid. Spacer grid hoop parts are interlapped using butt resistance welding (see Fig. 26).

5.4.3. Skeleton manufacturing

The skeleton is the structure sustaining and positioning the bundle of fuel rods according to the regular pattern. On the skeleton bench, the spacers and guide tubes are installed (see Fig. 27). The spacers and guide tubes are then fastened by a resistance weld process.

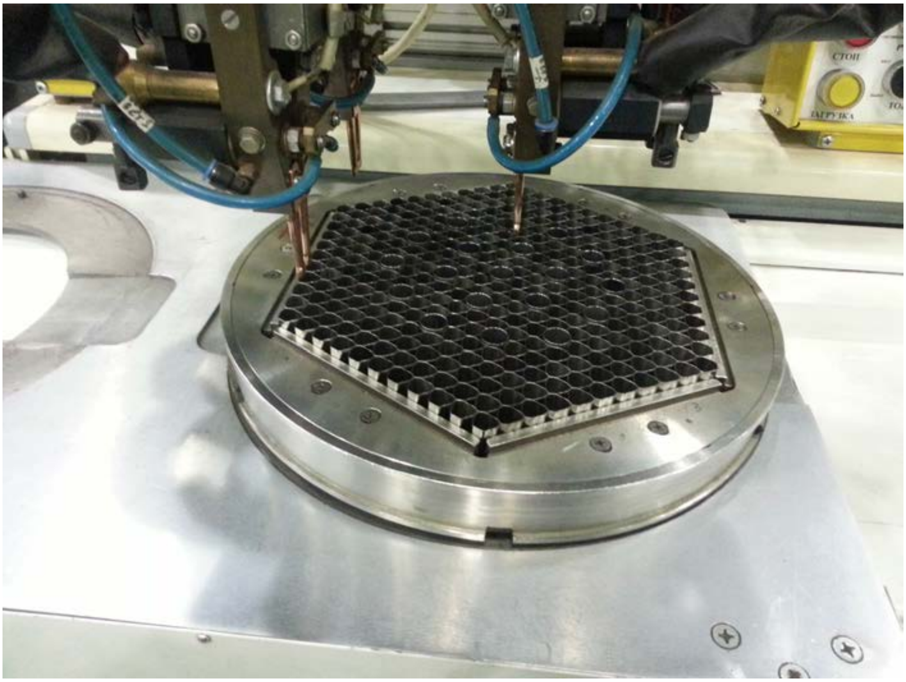


FIG. 26. Spacer grid butt resistance welding (courtesy of TVEL).

FIG. 27. Assembly manufacturing (courtesy of TVEL).

5.4.4. Fuel rod loading

In the present design of the assembly, the fuel rod is maintained only by friction at the different spacer levels. This design feature lets the rod to slide through the spacers when during reactor operation the fuel rod growth tends to be more important than this of the skeleton. This design feature will be also used when manufacturing the assembly. The skeleton is clamped in horizontal position on the assembly bench. The rods to be inserted are placed in the alignment of the assembly to be loaded.

A puller system grips the rods and inserts them into the assembly. To move the rod, the puller needs to apply a significant drag force to balance the opposite friction forces generated at the different spacer levels. Fabrication of VVER fuel assemblies uses a pushing instead pulling system — with respect of fixing the bottom end at the lower support lattice.

5.4.5. Completed assembly handling hoist system

When all the rods have been loaded into the skeleton, the assembly manufacturing is completed by the installation of the both end parts. The bench clamping the assembly is then moved from the horizontal position to the vertical position. The assembly is then gripped by a hoist system and can be moved to the different further stations (see Fig. 28).

5.4.6. Assembly blowing

Because the insertion of the rod has been performed by forcing a friction of the rod into the spacer, the rod tubes are a bit scratched and some small debris are released. A blowing step enables removal of most of the debris generated.

FIG. 28. Assembly hoist system (courtesy of TVEL).

5.4.7. Inspections

5.4.7.1. Assembly dimensional inspection

The assembly is placed on an inspection bench, where the following dimensional features are checked, which are of importance for the assembly in-reactor performance:

— Verticality of the assembly;
— Straightness of the assembly;
— Straightness of the fuel rods as installed in the assembly (regularity of the flow channels between fuel rods).

5.4.7.2. Control rod insertion checking

This is a functional representative test to verify on every assembly that the control elements can be moved freely into the guide tubes.

5.4.7.3. Assembly final visual inspection

An ultimate attentive examination by an operator is the last step before the final release of the assembly.

5.4.8. Assembly temporary storage

After they have been released, the assemblies are transferred to an area of temporary storage in the storage racks the assembly is installed vertically.

5.4.9. Assembly shipping

5.4.9.1. Container for assembly shipping

Container TK-5 (different modification) to ship the assembly has the following features:

(a) A container can receive two assemblies.
(b) To install an assembly in container the sequence is the following:
  (i) The container is placed in a vertical position.
  (ii) Container cover is removed. The assembly to be shipped is packaged in a protective plastic cover and placed inside a hexagonal wooden lining.

(iii) Then cover the pipe container is set in place and the operation is repeated with the second assembly.
(iv) After two assemblies have been installed, the container is placed in a horizontal position.

5.4.9.2. Preparation of assembly shipping

The loaded containers are handled with appropriate systems (hoist and crane) to be installed on road trailers, railways, trucks or cargo planes. Acceleration when moving should not exceed 4g.

5.5. PHWR ASSEMBLY MANUFACTURING

Figure 29 presents flow sheet of PHWR fuel assembly manufacturing [54]. Zircaloy tubes received from the zirconium fabrication plants are machined to the required length and profiled for welding. The spacers are punched from sheet and the end plugs are machined from rods. The profile of the tube ends before welding is critical. The empty fuel tubes in the fuel bundle are denoted as central, inner and outer elements depending on their final placement/position in the fuel bundle. Zircaloy components like spacer and bearing pads are washed and degreased before welding operations. Spacer pads and bearing pads are attached on to the thin zircaloy fuel tubes by resistance welding or beryllium brazing. These appendages are attached at specified positions.

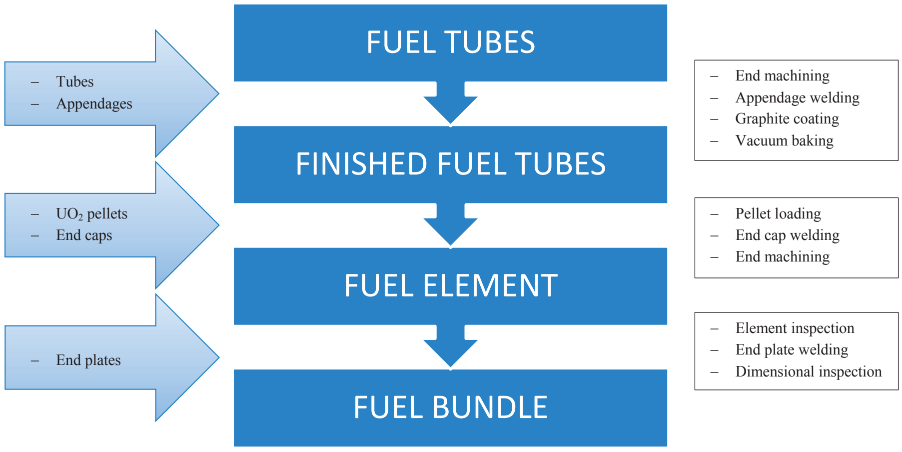


FIG. 29. Flow sheet PHWR fuel assembly manufacturing at the Nuclear Fuel Complex.

A special operation graphite coating of inner surface of fuel tube followed by vacuum baking is carried out for PHWR fuel to mitigate pellet cladding mechanical and chemical interaction. Zircaloy fuel tubes loaded with UO_2 pellets are encapsulated with two zircaloy end plugs on both ends using a resistance butt welding process. The fuel elements are purged with helium gas to achieve the cover gas requirement in the fuel element and also provide an inert atmosphere during the welding operation. High current at low voltage is passed through this joint which results in heat generation depending on the contact resistance. This heat brings the material to a plastic state and metallurgical joining is achieved. After end welding, the fuel elements are machined at the ends to remove the weld flash and to achieve the required end profile and length.

Fuel elements are joined to the end plate using a resistance welding method in an argon atmosphere. Both top and bottom end plates have 'webs' and 'perforations'. Fuel elements are welded to the end plate on the web portion and the perforations allow the coolant to flow through the fuel assembly.

More details can be found in Refs [54, 58, 59]. The quality control of PHWR fuel, including fuel tubes, UO_2 powder, pellets, components, rods and fuel bundle assembly, is presented in Section 6.5.6.

5.6. CONTROL ROD MANUFACTURING

5.6.1. PWR RCCA manufacturing process

The equipment involved and the general features of the RCCA manufacturing process (from raw materials to RCCA shipped to the customer) are described here.

Figure 30 provides an overview of the RCCA manufacturing process.

(a) Manufacturing control rods and RCCA constitutes additional and similar activities for shops experienced with manufacture fuel rods or assembly machined end parts.
(b) Note that the operating sequence, the processes, the technical competencies requested are similar when comparing fuel rod manufacturing with control rod manufacturing or comparing assembly end parts manufacturing with spider manufacturing.
(c) The main difference comes from the fact that manufacturing control rods concerns much smaller quantities of products.

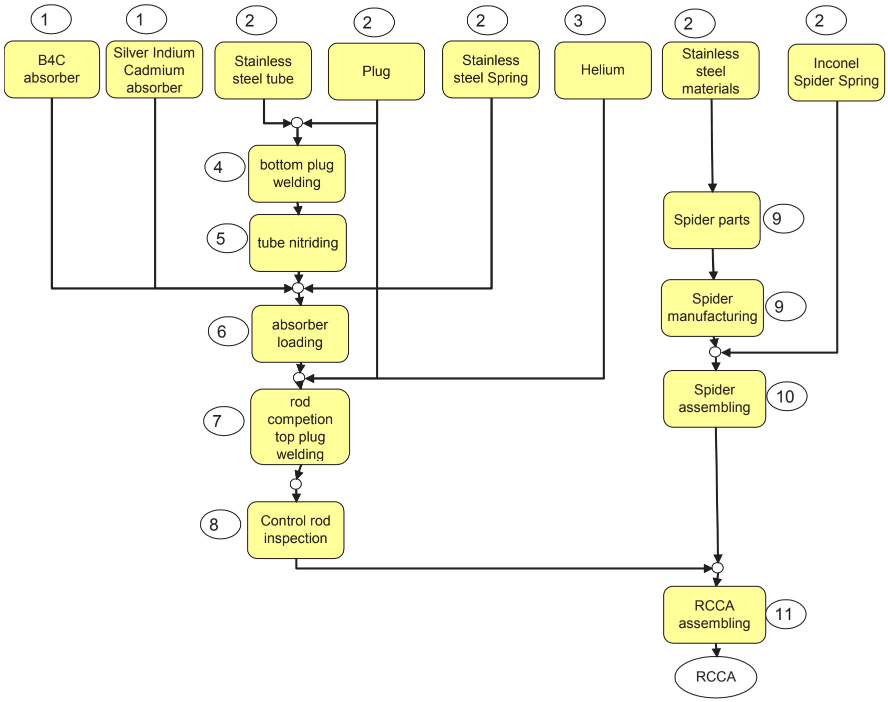


FIG. 30. Overview of the RCCA manufacturing process (courtesy of AREVA NP).

For a 900 MW(e) reactor containing around 160 assemblies, about 40 new assemblies are reloaded every year. This reactor operates with about 50 RCCA, which are supposed to last more than ten years.

As shown in Fig. 30, the following manufacturing steps are carried out:

(1) Procurement of absorber materials:
- (a) Two types of absorber are used:
  - — Boron carbide (B_4C) sintered pellets;
  - — Silver–indium–cadmium bar.
- (b) The main steps to manufacture B_4C pellets are:
  - — B_4C powder procurement;
  - — Blending preparation (including addition of lubricant);
  - — Pellet pressing;
  - — Pellet sintering;
  - — Final diameter of pellet obtained by a grinding operation.

(c) The main steps to manufacture a silver–indium–cadmium bar are:
   - Manufacturing through multiple melting of an initial ingot having a diameter of around 100 mm;
   - Ingot outer diameter (OD) finishing by turning operation;
   - Extrusion operation to reduce the diameter of the absorber bar to the required final value;
   - End cutting operation to get the final length of the absorber bar.

(2) Procurement of different metallic components: tube, plug, screw, rod spring, spider raw materials, spider spring:

(a) Stainless steel cladding tube manufacturing sequence:
   - Starting from a bigger hollow shell, successive cold extrusion passes in presence of an inner mandrel are performed to obtain the final tube cross-section dimensions. After every extrusion pass tubes appropriate annealing thermal heat treatments under hydrogen are performed. The manufacturing sequence includes appropriate steps to degrease, clean, polish and finish the inner and outer surfaces of the tube as required.
   - Samples are collected and tested to check the following tube properties: alloy chemical content, tube tensile final properties, intergranular corrosion resistance, grain size features and alloy microstructure features.
   - The following conformity direct inspections are performed on every tube made: an UT automatic inspection checks the tube inner soundness, outer and inner diameter (ID) measurement, and visual inspection of the tube surface.

(3) Helium filling the control rod:

(a) Helium of high purity needs to be procured.

(b) This material will be used as welding inert protective gas and fill the control rod.

(c) Start of the rod manufacturing sequence: bottom plug welding.

(d) Different processes may be considered to connect the plug: currently, TIG is used.

(e) Welding is performed under (helium) inert atmosphere.

(f) After the welding operation, there is an X ray inspection to check the conformity of the welding operation.

(g) Weld samples are performed periodically: different destructive tests (e.g. metallographic examinations and corrosion tests) are performed on these periodic samples to check that the welding process is kept under control.

(h) Hardening of the tube outer surface by nitrogen diffusion process.

(i) The tube with the first weld is placed in a closed vessel.
(j) A certain level of vacuum is created inside the vessel.
(k) A potential difference is applied between the reactor walls and the work pieces.
(l) Controlled electrical heaters generate a thermal cycle.
(m) During this cycle a mixture of gas including H_2, N_2 and methane is introduced in the vessel.
(n) By electric discharge in the rarefied atmosphere containing nitrogen and hydrogen, active nitrogen ions are formed (by dissociation of the gas mixture).
(o) Nitrogen is implanted at the surface of the work pieces by ion bombardment, and then diffuses into the material under the effect of the temperature at which the work pieces are maintained.
(p) The thermal cycle parameters are adjusted to get a final diffusion of nitrogen over a given distance.
(q) Over this depth the clad materials becomes very hard resistant to mechanical friction wear.
(r) For all the tubes of every batch, the nitrided depth is checked over the entire length by an eddy current automatic inspection.

(4) Installation of the absorber into the tube:
   (a) Absorber (silver–indium–cadmium bar or B_4C pellet) is introduced at the still open end of the tube and manually pushed towards the bottom end of the tube.

(5) Completion of the control rod — spring installation, helium filling and top plug welding:
   (a) The top plug welding process looks like the process already described at the bottom plug level.
   (b) Most of air contained in the rod is removed (pumped) before helium pressure is applied to fill the rod with a high proportion of helium.
   (c) When helium pressure is stabilized, the fuel rod can be closed (seal welding is performed).

(6) Control rod conformity checking:
   (a) An X ray picture of the rod is performed. A picture analysis enables to check the following points of conformity: integrity of the end plug weld, correct length of the spring plenum, correct installation of the spring, correct installation of the absorber stack in the rod.
   (b) Rod leak test: The rod is placed in a vacuum cell: since the rod is filled by helium, in case of leaking weld, helium will be released and will be detected by the helium sensors placed in the vacuum cell.

(7) Spider parts preparation and spider manufacturing:
   (a) The spider is the intermediate part sustaining all the control rods when they are more or less inserted and moved in the guide tubes of the assembly during reactor operations.
   (b) The spider has a very complex final geometry. There are tight requirements on some dimensional features that strongly impact the geometrical compatibility with the mechanical parts located in the upper internals to guide or drive the RCCA.
   (c) Two solutions exist to manufacture a spider.
   (d) The individual elements (hub, vanes and finger) are machined separately by conventional machining techniques and afterwards a brazing step enables the spider to be assembled.
   (e) The complex contour of the spider can be obtained roughly by electric discharge machine, complementary electropolishing enable the surface final features to be obtained.
(8) Spider assembling operation — spider spring installation:
   (a) The spider manufacturing sequence is completed by the installation of the compression spring made of nickel based alloys. This spring is acting when the control rods are dropped in emergency conditions. The spring will moderate the impact force when the RCCA will hit the assembly at end of the drop travel.
(9) RCCA completion — attachment of control rods to the spider:
   (a) The control rods are attached to the spider by a screw system and secured by a welding step.

5.6.2. VVER RCCA manufacturing process

The RCCAs for reactors VVER-1000 include 18 absorbing rods (see Fig. 31). They are unified and can operate both in the mode of automatic control and in the mode of emergency protection. In total, there are 61 RCCAs in the commercial reactor VVER-1000. Of which, six absorber rods work in the automatic control mode and 55 in the emergency protection mode [61]. The absorbing rods move inside the fuel assembly guide tubes.

During operation, the cluster assemblies working in the emergency protection mode are in the position when the lower ends of absorbing rods are approximately 10–150 mm above the core upper edge. During reactor shutdown, they drop by gravity at a rate of about 1 m/s. The RCCA drop should not exceed 4 s.

During operation in the automatic control mode the absorbing rods are inserted into the core for the depth of 300–700 mm only by their lower ends.

FIG. 31. RCCA of reactor VVER-1000 (courtesy of TVEL).

The structure of rod type absorbing element represents itself a cladding filled with the absorbing material and sealed with the end pieces of steel SS 0X18H10T by welding. The absorbing rod cladding is made of SS 0X18H10T tubes. The absorbing material is B_4C powder, with a natural content of isotope ^{10}B. The height of the absorber stack is 3700 mm. Above the absorber stack, there is a gas collector filled with helium at atmospheric pressure. The overall length of absorbing element is 4240 mm (see Fig. 32).

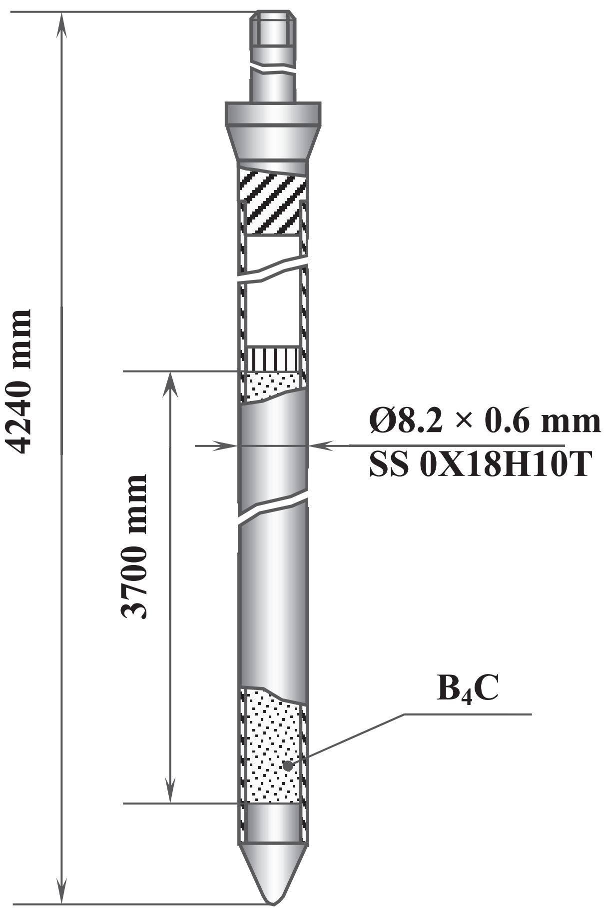


FIG. 32. Absorbing rod for VVER-1000 RCCA based on B_4C (courtesy of TVEL).

The specified service life of absorbing rod based on B_4C is two years in the automatic control mode or five years in the emergency protection mode.

When assembling, the following is controlled: absorbing rod surface condition, linearity, rods being fastened strictly perpendicularly to the head surface, as well as the assembled RCCA being able to enter the fuel assembly guide tubes under their own weight (the effort is controlled by weighing the 'weight loss' when installing the RCCA into the fuel assembly guide tubes).

The structure of rod type element with a composite absorber represents itself a cladding filled with the absorbing material and sealed with the end pieces of alloy 42XHM by welding. The absorbing rod cladding is made of alloy 42XHM tubes, which has an enhanced radiation resistance. The absorbing material

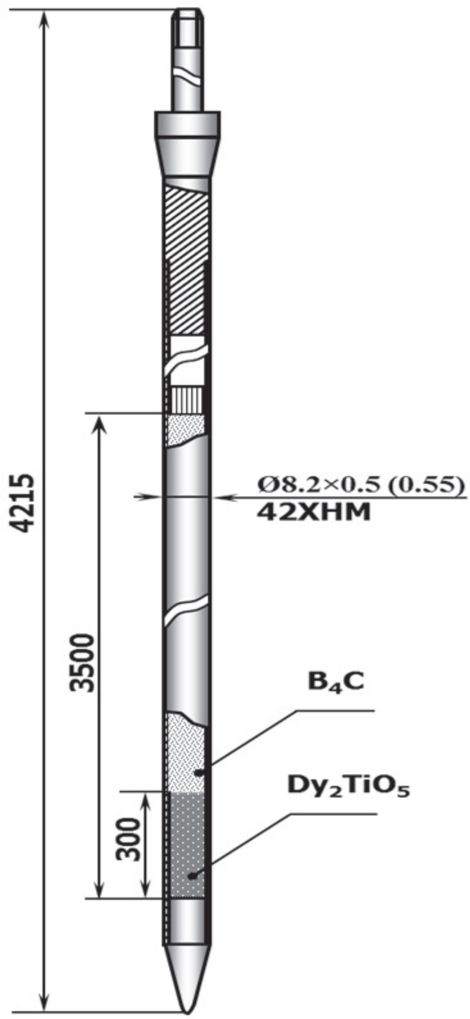


FIG. 33. Absorbing rod for VVER-1000 RCCA with a composite absorber (courtesy of TVEL).

is compound from two parts (see Fig. 33). The bottom part is an n–γ absorber (dysprosium titanate, 300 mm) because of its lower radiation swelling and gas release. The top part (3200 mm) is B_4C powder, with a natural content of isotope ^{10}B. The total height of the absorber stack is 3500 mm. Above the absorber stack, there is a gas collector filled with helium at atmospheric pressure. The overall length of absorbing element is 4215 mm. To increase the total weight of the absorbing rod up to 18 kg, a piece of steel 08 × 18H10T in the top part of the tubs is inserted.

The specified service life of absorbing rod based on B_4C is two years in the automatic control mode or five years in the emergency protection mode.

The specified service life of compound absorbing rod based on B_4C and dysprosium titanate is ten years. Three of these ten years, RCCAs can operate in the automatic control mode. The other seven years (RCCAs) can work in the emergency protection mode.

6. QUALITY MANAGEMENT OF FUEL MANUFACTURING

Traditionally, the hierarchy of a company can be divided into three levels [62]:

— Strategic level;
— Management level;
— Operational level.

At the strategic level, the direction is fixed with respect to leadership, quality and customer satisfaction, people and teamwork, and improvement and innovation [63]. The policy statements and the organization structure of an organization are the strategic part of a management system.

Furthermore, the management system defines the tasks and responsibilities and processes and procedures to ensure that an organization can fulfil all tasks required to achieve its objectives in a coherent manner to manage the organization. It also constitutes the link to the operational level, where the specific quality related activities are performed and recorded by the QA/QC procedures and instructions of the management system.

Ideally, an integrated management system (IMS) consists of a set of interrelated elements that bring together, in a coherent manner, all the requirements for managing an organization or activity. It describes the processes, procedures, instructions and planned and systematic actions necessary to provide adequate confidence that all these requirements are satisfied. It ensures that health, environmental, security and economic requirements are not considered separately from safety requirements, to preclude their possible negative impact on safety [64].

Quality management standards of the ISO 9000 series [65, 66] — in contrast to those of the IAEA's integrated approach [64] — do not require an integration as described above and, as a consequence, the different elements of a quality management system (QMS) are often operated more or less independently from the others, which should be avoided in all nuclear facilities and activities.

6.1. FROM TRADITIONAL QUALITY ASSURANCE AND QUALITY CONTROL TO INTEGRATED MANAGEMENT SYSTEMS

The technological innovations have radically altered the relationship between systems and humans and therefore the way to manage the whole organization.[3] The issues related with complex activities and multiple objectives involve people operating at different levels in the organization. The operating processes are modified by the introduction of new management practices and new requirements. The daily practices and the results achieved by the organization, the organizational culture and the management processes are deeply interrelated. The way to manage the organization has had to evolve accordingly to accommodate these changes and to ensure that the employees understand what needs to be done to meet all requirements. The model illustrated in Fig. 34 presents the evolution over the last decades regarding the approaches applied by organizations in order to achieve good safety standards and performance.

The reality is undoubtedly more detailed and complex. Many initiatives have often been introduced in parallel and new initiatives have coexisted with former initiatives. The important message that the model delivers is that the activity of managing an organization and surviving has been evolving to continually strive for higher levels of performance and safety and that this trend is ongoing. The model marks only the following key management approaches:

(a) Quality control sorted the conforming products from the non-conforming at the end of the process. It mostly consisted of some type of inspection or measurement for acceptance or rejection.
(b) Quality assurance took measures to systematically prevent non-conformances by using established procedures and documentation to demonstrate that quality was implemented throughout the production process. The quality assurance approach has also evolved from a compliance approach to one of a more performance based focus.

Quality management introduced the consideration of everyone involved within the process and the concept of internal customer and supplier. This was a relevant development bringing attention to organization being essentially about

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[3] The introductory part to Section 6.1 is adapted from Ref. [62].

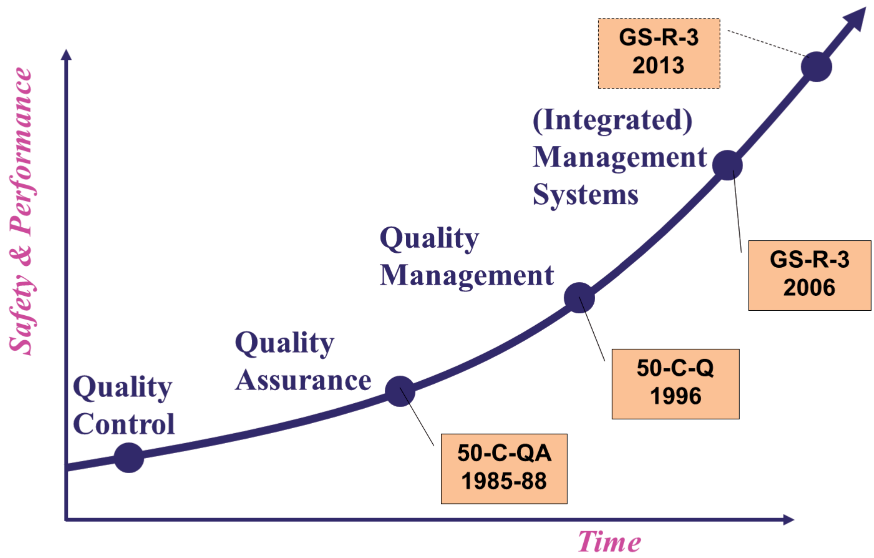

FIG. 34. Evolvement of quality control into IMSs.

people and recognition of the organizational culture issue. Business excellence models appeared during the development of quality management.

Integration of a management system was the development, where the organizations became increasingly aware that other stakeholders, apart from just their customers and employees, had to be addressed while conducting their business. Organizations put increasing attention on issues such as the safety, health, quality, environment, finance, security, human resources, cultural aspects, and aimed to manage the totality by using an IMS aimed at meeting the totality of their objectives. Integrating the management system leads to a coherent, harmonious and optimal way of delivering the vision of top management and the goals and objectives of the organization and minimized the possibility to compromise safety.

The QA/QC procedures and instructions ensure that all important activities with respect to meeting the requirements for the product are still an important part of an IMS.

The model also suggests that an IMS is not the final solution in the evolution. The continuing path and need for higher levels of performance and safety will further evolve. It is therefore important to remain flexible in order to be able to dynamically adjust to the increasing changing and challenging demands. An idealized end point could be envisaged. With full recognition that the human being is the ultimate source of quality and safety. This ideal end point might then be described in a single and short statement: “Do the things right the first time, and apply continual improvement afterwards”.

6.1.1. Integrated management system standards

There has been an evolution in the international consensus on management systems for nuclear facilities and activities, including fuel fabrication. This has been brought about by a number of factors:

(a) Incorporation of feedback from operating experience;
(b) Responses to operating environment challenges and pressures such as globalization of the nuclear industry and the need for harmonized standards;
(c) Recognition of the importance of, among other issues, leadership, organizational culture, particularly the promotion and support of a strong safety culture, meeting the needs of interested parties without compromising safety, managing information and knowledge as a resource, managing organizational change, process management and self-assessment;
(d) The results of research on the impact of management systems on organizational performance;
(e) Observed benefits of management systems;
(f) General improvements in the state of the art.

IAEA Safety Standards Series No. GS-R-3, The Management System for Facilities and Activities [64], defines the requirements for establishing, implementing, assessing and continually improving a management system that integrates safety, health, environmental, security, quality and economic elements with a focus on enhancing safety. In the development of this requirement, the codes and developments within the International Organization for Standardization (ISO) ISO 9001:2008 [66], ISO 9004:2009 [67] and ISO 14001:2004 [68] publications were considered and the specific nuclear and radiation protection safety aspect was included. These considerations ease the integration of these standards in a management system that meets GS-R-3 requirements or have the ability to meet the requirements of these standards and those of GS-R-3 simultaneously (see also the comparisons in Ref. [69]).

GS-R-3 [64] describes the planned and systematic actions necessary to provide adequate confidence that all these requirements can be satisfied, and supports the enhancement and improvement of organizational and safety culture. The IAEA has developed several guidance documents for the implementation of the management system requirements of GS-R-3 [64]. This guidance includes IAEA Safety Standards Series No. GS-G-3.1, Application of the Management

System for Facilities and Activities [70], which provides generic guidance for meeting the requirements in GS-R-3 [64] to be applied by fuel assembly manufacturers. In addition, guidance relating to specific thematic areas, facilities and activities are provided in other published safety standards, such as:

— GS-G-3.2: The Management System for Technical Services in Radiation Safety [71];
— GS-G-3.3: The Management System for the Processing, Handling and Storage of Radioactive Waste [72];
— GS-G-3.4: The Management System for the Disposal of Radioactive Waste [73];
— GS-G-3.5: The Management System for Nuclear Installations [74];
— TS-G-1.3: Radiation Protection Programmes for the Transport of Radioactive Material [75].

GS-R-3 [64] and its supporting guidance replace and supersede the previous IAEA quality assurance standard and associate guides, Safety Series No. 50-C/SG-Q, Quality Assurance for Safety in Nuclear Power Plants and other Nuclear Installations: Code and Safety Guides Q1–Q14[4].

GS-R-3 [64] clarifies and expands the requirements in Safety Series No. 50-C/SG-Q, but also incorporates the principles and concepts of appendix B to 10 CFR 50, Quality Assurance Criteria for Nuclear Power Plants and Fuel Reprocessing Plants [76], and American National Standards Institute (ANSI), American Society for Quality and ISO standards which are described in Section 6.2.2. GS-R-3 [64] also widens the scope of application of the IAEA requirements for management systems. As can be inferred from the list of GS-R-3 supporting guides given above, this applies to organizations directly responsible for:

— Nuclear facilities;
— Activities using sources of ionizing radiation;
— Radioactive waste management;
— Transport of radioactive material;
— Radiation protection activities;
— Any other practices or circumstances in which people may be exposed to radiation from naturally occurring or artificial sources;
— Regulation of such facilities and activities.

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance for Safety in Nuclear Power Plants and other Nuclear Installations: Code and Safety Guides Q1–Q14, Safety Series No. 50-C/SG-Q, IAEA, Vienna (1996).

Consequently, the nuclear facilities or activities to which GS-R-3 [64] applies include those engaged in fuel fabrication.

Organizations manufacturing, supplying, handling or using fuel can enjoy the benefits that come with establishing management systems. Fuel quality and reliability can be enhanced by adoption of integrated, process based, management systems that meet the requirements of GS-R-3 [64]. These organizations can adopt such management systems on their own accord, or, what is more often the case, the requirement for such a management system may be imposed, directly or through contracts with licensees, by a regulatory body adopting and adapting the requirements in GS-R-3 [64] for use in its regulatory framework. The requirements in GS-R-3 [64] are divided into a number of areas, which are briefly outlined in the following sections.

6.1.2. General requirements

There is a requirement to establish, implement, assess and continually improve a management system that integrates in a coherent manner all the requirements for managing an organization, while keeping safety paramount. The organization is required to demonstrate fulfilment of these requirements. The management system is required to be aligned with the goals of the organization. The management system is required to be used to promote and support a strong safety culture.

A graded approach that takes into consideration significance, complexity, risks and consequences of product failure or incorrect use is to be used to apply the requirements of the management system.

The management system is required to be documented. This documentation will include organizational policies, a description of management system, the organizational structure, roles and responsibilities, authority, interfaces and processes. The management system document is required to be understandable to its users and to reflect the characteristics and activities of the organization and the complexity of its processes.

6.1.3. Responsibilities of management

Senior management is ultimately responsible for the management system. Senior management is required to appoint an individual reporting directly to it with the responsibility for coordinating the development of the management system, reporting on its performance and resolving conflicts. Overall responsibility for the management system cannot be delegated to external parties or organizations.

Senior management is required to show active commitment to the management system by providing resources for its proper establishment and functioning, by establishing the mission, values, behavioural expectations, goals, strategies, policies and plans of the organization and leading by example.

Senior management is required to consider the expectations, needs and satisfaction of interested parties, but without compromising safety.

6.1.4. Management of resources

Senior management is required to determine and provide the resources necessary to carry out the activities of the organization and to put in place a management system. This is not limited to human, financial and infrastructure or working environment resource management, but includes managing information and knowledge as a resource.

Senior management is required to determine competence requirements, provide training and evaluate its effectiveness. Senior management needs to ensure individuals are competent to perform assigned work.

6.1.5. Management of processes

The organization is required to identify, develop, implement and continually improve the processes, and their interactions or interfaces, needed to achieve its goals and meet its requirements. Each process is required to identify and address process requirements, such as applicable regulatory, statutory, legal, safety, health, environmental, security, quality and economic requirements, process risks and actions to mitigate them. The process inputs, flows and outputs are to be identified and measurement criteria established.

Each process is required to have an individual responsible for documenting the process, making sure that it functions properly, monitoring and reporting its performance, promoting its improvement, and managing changes to it. Processes are required to be performed under controlled conditions, evaluated for effectiveness, with overall responsibility for any outsourced processes retained by the organization.

The organization is required to specify processes for inspection, testing, verification and validation, with clearly defined acceptance criteria and responsibilities for carrying out such activities. The organization is required to put in place certain generic processes that are common to all organizations, such as processes for:

- Document control;
- Control of products;

— Control of records;
— Purchasing;
— Communication;
— Managing organizational change.

6.1.6. Measurement, assessment and improvement

The organization is required to monitor and measure the effectiveness of its management system and to identify opportunities for improvement. All levels of management are required to carry out self-assessments to evaluate the performance of work and the improvement of safety culture. The assessments need to be complemented by independent assessments by an organizational unit charged with this task or by other independent parties external to the area or work being assessed.

Senior management is required to review the results of assessments, make and record decisions and take the follow-up action deemed appropriate. The management system is required to be reviewed at planned intervals to check its effectiveness or fitness for purpose, to identify opportunities for improvement, to make the necessary adjustments to the management system or to the policies, goals, strategies, plans, objectives and processes of the organization.

The organization is required to manage non-conformances, corrective and preventive actions, including determining the causes of non-conformances, the disposition of non-conforming productions or processes, and taking remedial action to avoid recurrences. Opportunities for improvement are required to be identified and appropriate action taken, with adequate resources provided for the completion and evaluation of the effectiveness of such action.

6.2. MANAGEMENT SYSTEMS AND SAFETY CULTURE

When developing the new set of IAEA safety standards for management systems, it was recognized at an early stage that the aspect of culture needed to be included in an integrated approach to management systems.[5] With an integrated approach, the aspects of the management system that define processes and practices need to be combined with people's values, attitudes and behaviours in order for the organization to reach fully its goals and objectives.

[5] Section 6.2 is adapted from Ref. [62].

Today, nuclear organizations are also facing many new challenges that require the ability continually to change and to improve in order to survive in a more competitive environment. There are numerous examples of how organizations have failed to improve organizational effectiveness through new management strategies due to the fact that the change and improvement efforts did not consider the impacts of the organizational culture. The management system will both influence and be influenced by the overall culture of the organization.

In order to achieve desired outcomes, it is necessary to consider the formal processes and strategies of the organization and at the same time recognize that they have been produced based on the thinking prevalent in the organizational culture. The way in which the management system is implemented will in turn have an impact on the values, attitudes and behaviours of the members of the organization (i.e. the organization's culture).

For a nuclear organization, an integrated approach to the achievement of all the goals of the organization should be addressed in a way that ensures that safety is not compromised. Therefore, the management system should provide structure and direction to the organization in a way that promotes and enables the development of a strong safety culture together with the achievement of high levels of safety performance.

In GS-R-3, the generic requirements are formulated as follows [64]:

> "The management system shall be used to promote and support a strong safety culture by:
>
> — Ensuring a common understanding of the key aspects of safety culture within the organization;
> — Providing the means by which the organization supports individuals and teams in carrying out their tasks safely and successfully, taking into account the interaction between individuals, technology and the organization;
> — Reinforcing a learning and questioning attitude at all levels of the organization;
> — Providing the means by which the organization continually seeks to develop and improve its safety culture."

6.2.1. Organization, safety and quality culture

After the accident at the Chernobyl nuclear power plant in 1986, the term 'safety culture' was introduced to the nuclear community for the first time. While intended to describe how the thinking and behaviour of people in the organization with regard to safety contributed to the accident, it also created a need to further define and describe what was really meant by this concept. A further clarification of the concept came in the report by the International Nuclear Safety Advisory Group to the IAEA [77, 78], which maintained that the establishment of a safety culture within an organization is one of the fundamental management principles necessary for the safe operation of a nuclear facility. The definition they presented recognized that safety culture is both structural and attitudinal in nature and relates to the organization and its style, as well as to attitudes, behaviours and the commitment of individuals at all levels in the organization.

Since the introduction of the concept of safety culture, the IAEA has broadened its perspective further with attention focused on obtaining a deeper understanding of the actual concept of culture and particularly organizational culture.

The latest developments have been the integrated approach to management systems where the organizational culture and safety culture is seen as crucial elements of the successful implementation of this system and the attainment of all the goals and particularly the safety goals of the organization. There are many ways in which the culture of an organization has been described. A common phrase used is “it’s the way we do things around here”, which provides unwritten and often unspoken guidelines for how to get along in the organization — a sense of identity to employees. It reflects what is valued, the dominant managerial and leadership styles, the language, the procedures and routines, and the definitions of success.

Another way to understand culture is to realize that it exists at several ‘levels’ and that we need to endeavour to understand the different levels, but especially the deeper levels. A three level model, consisting of ‘artefacts’, ‘espoused values’ and ‘basic assumptions’ has been proposed when studying organizational culture [79], which can be applied to safety culture as well. These levels of culture go from the very visible to the tacit and invisible.

Examples of visible safety culture artefacts are the documented management system with safety policy statements and clear definition of responsibilities and the behaviour of managers. The guiding principles at the espoused level are those values stated by management such as “safety is top priority”. Key basic assumptions for safety culture is, for example, how the relationship between safety and production is seen — whether they go hand in hand or is safety considered a cost; and whether people consider the hazards in a way that they believe they are vulnerable to an unexpected event, that “it can happen here”. These basic assumptions will ultimately determine how people will think and act in relation to safety issues.

Safety culture, including the quality culture is the basis of a QMS that the organization need put in place as a nuclear fuel manufacturer. Culture (from the Latin *cultura*, from *colere*, ‘to cultivate’) has numerous meanings, however, in the combination ‘organizational culture’, it means the attitudes, values, goals and practices with respect to culture that can be found within the staff and that characterize an institution, organization or group.

Most important for the development of a high safety culture within an organization is the requirement that there be only one set of attitudes, values, goals and practices which is adopted vertically and horizontally by the entire staff of an organization. If there are different safety cultures in different departments or if the safety culture of management is different from that of the workers, then internal frictional losses will almost inevitably occur and essentially diminish the performance of the organization.

Quality may be defined as ‘degree of fitness for purpose’, and in order to understand the term quality, it is therefore important to know the underlying purpose. For example, the overall purpose of an organization is to generate a maximum of long term profit, where the ‘long term’ aspect is of decisive significance because a strategy aiming at increasing the short term profit may prove to be disastrous on a long term basis. The purpose of a fuel assembly is to produce, without problems, a certain amount of energy during a specified time and perform after it has been removed from the reactor core, in accordance with given specifications.

The entire staff need to understand that the organization’s aim can be achieved best, if all those involved cooperate.

(a) It needs to be clear that any occurring problem is to be regarded as a system weakness to be identified and removed instead of holding the culprit to account.
(b) Corporate feeling is to be fostered within an organization of high safety culture. It should be clear to everybody that a high quality of fuel can only be achieved by the entire team and not by any single staff member or a single dedicated team.

6.2.2. Other standards related to fuel fabrication

Historically, the need and development of management systems in nuclear industry was initiated by the formulation of requirements for nuclear facilities and activities in 10 CFR 1 [80]. Based on these general requirements, detailed regulations and standards were developed for different types of facilities and activities. For fuel fabrication activities or processes, the most relevant requirements are contained in appendix B to 10 CFR 50 [76].

In order to prove that the safety requirements could be met by the management of nuclear facilities, corresponding standards became necessary. The ANSI and the ASME therefore developed standards (codes and guidance) for meeting the 18 quality criteria specified in appendix B to 10 CFR 50 [76]. These standards initially comprised the ANSI Standard N45.2 series of detailed standards, which were reviewed and, where deemed appropriate, endorsed or modified by United States Nuclear Regulatory Commission (NRC) staff, through the issuance of a corresponding regulatory guidance.

Eventually, the ANSI and the ASME issued a joint standard, ASME NQA-1 covering the 18 quality criteria in 10 CFR 50 appendix B, the latest version of which is ASME NQA-1-2012 [81]. These standards provide detailed guidelines for quality assurance programmes including the necessary activities during "siting, designing, procuring, fabricating, constructing, handling, shipping, receiving, storing, cleaning, erecting, installing, inspecting, testing, operating, maintaining, repairing, refueling, modifying, and decommissioning" [81] nuclear facilities in accordance with the regulatory criteria, but these standards do not represent standards for establishing a comprehensive management system.

Beside these nuclear specific quality assurance standards, organizations involved in fuel fabrication or implicated in fuel quality use generic quality management standards such as the ISO 9000 and ISO 14000 series of standards, the latest versions of which are:

— ISO 9000:2005, which describes the fundamental principles and the vocabulary used in ISO quality management standards [65];
— ISO 9001:2008, which establishes requirements for QMSs [66];
— ISO 9004:2009, which provides guidance on managing for the sustained success of an organization [67];
— ISO 14001:2004, which establishes requirements for environmental management systems [68].

Organizations implicated in fuel quality often also may have occupational health and safety management systems based on the British Standards Institution occupational health and safety standard OHSAS 18001:2007 [82] or other national standards. There are some more national management systems for special purposes, for example the European Union Eco-Management and Audit Scheme (EMAS) [83].

6.3. SPECIFIC MANAGEMENT SYSTEM ASPECTS FOR FUEL FABRICATION

6.3.1. Management of procurement and outsourcing

There are two issues to be considered in nuclear fuel procurement: quality of the supplied fuel; and long term, economical and stable procurement. The latter issue is met by long term supply contracts with major suppliers setting value on diversification of suppliers and supply areas. Furthermore, by participation in mining projects and maintaining a sufficient level of inventory, the procurement management should guarantee the required fuel for the next several years.

The contract between fuel supplier and utility covers, besides the fuel assemblies such items as design, submittal of design information for the licensing, manufacturing, transport and quality management throughout the implementation of the contract responsibilities. The scope might also include supply of natural uranium, conversion and enrichment services. Moreover, due to the importance of the fuel for the radiation safety and due to the high economic value of the fuel, it is vital that the adequacy of the design and manufacturing is demonstrated by the fuel supplier to the utility and the safety regulators before the fuel manufacturing starts.

Before the fuel assemblies may be used in the customer's nuclear reactor, they need to be licensed by the regulatory authority of the customer's State, taking into consideration that there are different licensing requirements in different States. Licensing covers the design of the fuel and the manufacturing.

6.3.2. Licensing aspects

6.3.2.1. Licensing of fuel design

The information for licensing of the fuel design requires the following documents:

(1) Design basis [35, 39, 40]:
- — Design criteria (design limits);
- — Reasons for criteria (failure mechanisms);
- — Justifications for the criteria (analytical and experimental evidence that criteria are adequate);
- — Design conditions.

(2) Design verification [41, 82, 84, 85]:
- Description of the verification methodology (analytical and experimental methods);
- Summary of the results of the verification work demonstrating that the design basis requirements have been met and reference to relevant topical reports for detailed information;
- Topical reports referenced in the design verification summary.

6.3.2.2. Licensing of manufacturing

Licensing of the manufacturing of the materials, components and complete fuel assemblies needs to be performed in accordance with written documents, such as:

- Specifications;
- Drawings;
- Manufacturing;
- Inspection plans.

As to the required quality, the supplier and utility cooperate in manufacturing surveillances, in fuel assembly design and engineering verification and in verifying that design requirements are adequately translated into the manufacturing documents.

The scope of the vendor in the context of the nuclear fuel fabrication depends on the specific requirement. When the fuel or services are purchased, emphasis needs to be placed on developing the capability for qualification of suppliers, auditing, and inspection and confirmation upon receipt. In the case where the technology for fuel manufacture or for services is purchased, greater emphasis will be placed on project management, manpower training, management development and procedure/equipment qualification.

There are other typical activities which are the result of the cooperation between the supplier and utility in the course of the procurement process. Before manufacturing reload quantities, the fuel type needs to be licensed in the customer's State. The licensing consists typically of the design basis and design verification as described above.

During the manufacturing, the customer conducts surveillance of the manufacturing in the manufacturing plant. Final acceptance of the fuel typically takes place at the site after the receipt inspection. In addition to the delivery of the fuel assemblies themselves, at each stage of the fuel supply the supplier should submit certain documents to the customer for their acceptance and further for the approval of the safety authority.

6.3.3. Customer surveillance of the fuel assembly supplier

Nuclear fuel is a critical component involved in the safety of the core and its reliability is essential for an efficient operation of reactors. Consequently, a customer is responsible for ensuring that all safety requirements are fulfilled in accordance with the legal requirements of the State where the products are delivered, and that the reliability and quality of the products meet these expectations.

To ensure secure and appropriate behaviour of the fuel, a customer needs to define and perform an independent surveillance of the fuel supplier's activities. This surveillance cannot interfere with the supplier's controls and internal decision process in order not to jeopardize the supplier's responsibility. This surveillance should be as cooperative and didactic as possible. Customer surveillance covers all activities from the design to the delivery of the product, including manufacturing, with an appropriate level of implication coherent with the customer's responsibilities. The surveillance on fuel manufacturing conducted by Électricité de France (EDF) is described in Section 8.2.

Common possible tools to perform the surveillance of the supplier include:

(a) Documents (i.e. qualification and fabrication documentation) review and approval before they can be considered usable by the supplier;
(b) Cross-checking of data or information given by the supplier by means of contradictory controls which can be product examination, design or manufacturing document analysis, or numerical analysis calculation;
(c) Monitoring of ongoing manufacturing processes in the workshop performed by a customer representative;
(d) Audits of the quality system;
(e) Technical inspections focused on topics important for safety or quality (welding process, gamma scanning control, design code and test facilities).

Customer surveillance is described in documents taken into account by the QMS of the supplier. In particular, these documents provide all the supplier's obligations necessary to enable the customer's surveillance and ensure that all the legal safety requirements are met. The results of customer surveillance are recorded in an appropriate way so that they can be inspected if necessary by the regulator or any person designated by the final user, or if they are needed by the customer's quality system.

Customer surveillance for manufacturing needs verifications performed in the supplier's and subsuppliers' factories based on a sampling approach. The list of subcontractors under customer surveillance is decided in accordance with legal requirements and with expected final product quality, considering the risks associated with the subcontractors' activities.

Based on the evaluation of the manufacturing process risks that the customer intends to mitigate, the following aspects are to be treated:

— Manufacturing documents of the supplier whose conformity to legal, quality or contractual requirements are reviewed (drawings, specifications, manufacturing quality plans, qualification programmes and reports, technical notes, non-conformance treatment reports, design or safety calculation notes);
— Activities involved in a manufacturing process related to product characteristics important for the fuel assembly safety and reliability on which surveillance is defined (including the appropriate level of surveillance concerning qualifications).

Customer surveillance describes management of non-conformances and deviations to ensure that the suppliers provide an adequate level of information to enable the fuel assembly user to handle a potential issue in a safe manner and that the legal requirements concerning information supplied to the regulators are achieved. In any case, the supplier can support utility's surveillance by the following actions:

(1) Compiling and providing the customer with an up to date manufacturing schedule of all manufacturing stages. This is important for the customer to be able to time its surveillance visits on the manufacturing stages of interest.
(2) Providing an easy access to all manufacturing facilities and manufacturing documents therein for the customer's manufacturing surveillance, even at short notice.
(3) Making sure that the customer's requirements on the manufacturing of the fuel assemblies and their components are correctly understood and taken into account in the documentation at the manufacturing plants.
(4) Making the practical arrangements for the customer's visits to the subsupplier's plant.
(5) Accompanying and supporting the customer during the manufacturing surveillance visits.

6.3.4. Management of human resources

Whether or not the quality of nuclear fuel is satisfactory depends heavily on the interplay of man and machine on the one hand and the cooperation of the entire staff on the other. In fact, the high quality of the products is not obtained by dedicated individuals or special teams (which focus on quality) but by all the people in the organization, whatever their missions or responsibilities are. Each of them needs to have a clear understanding of the importance of his or her contribution and the underlying purpose that needs to be met.

Human performance and behaviour are keys to reach and maintain a high level of quality. Good performance necessitates highly qualified and trained personnel. However, perhaps even more important is motivation and dedication of the employees. Unfortunately, many surveys have shown that a large number of avoidable and costly failures and mistakes in fuel production occur because of inattentiveness and carelessness which indicates poor motivation of certain employees. Does et al. [63] identify the corresponding task of management:

> "The role of management is not so much motivating the employees as removing causes, circumstances, etc. which lead to de-motivation. We must assume that the employee is always prepared to do his best, and that the role of management is to take away any barriers which obstruct this. Working together as a team is essential hereby."

6.3.4.1. Training and education

Each employee needs to be trained for each work station and at the end to be qualified before being able to handle his or her workplace solely. The training needs to contain theoretical and practical parts. The organization needs to ensure that the people maintain their qualification at each relevant work place.

Nuclear processes require a high level of knowledge and expertise. The ability to manage experts in each relevant domain in the organization (e.g. welding and sintering) is a key success factor for high fuel quality, which can be achieved only by cooperation of all involved departments and individuals. This assumes leadership and the generation of a global mindset based on the joint aims and embracing the entire supply chain.

6.3.4.2. Maintenance and human factors

The key role of the management is to be able to involve all the employees, and the subcontractors, in that global mindset. For that, three points are to be highlighted:

(1) The governance and the organization of the company need to guarantee an operational mastering of the production and need to anticipate and provide guidelines for the future.
(2) A quality culture needs to be implemented and maintained by the organization.
(3) The strategy and the objectives of the company need to be shared and communicated to the shop floor. Each person will be able to identify his or her concrete contribution in the global objectives.

The motivation of the employees is the most important warrantor for high quality in a company. Therefore, the QMS should provide the necessary means for generating and especially maintaining the motivation of the staff.

(a) In case of a nuclear fuel producer, each employee should be instructed about the entire fuel cycle, the significance and also the dangers and problems of nuclear power and the purpose and relevance of his or her tasks. Such an instruction fosters a communal spirit among the employees and a better understanding of the jobs to perform by providing overview and insight. If understanding is not achieved then there will be in general no willingness to activate all capabilities.
(b) The management should leave the initiative to the personnel and thereby transfer some responsibility. Bearing responsibility will ensure that the initiative and enthusiasm of the employees will be preserved, which also need to be supported by making available the necessary resources and by showing interest in the performed job.
(c) Often, competition within an organization is used as a tool for improving quality. This assumes that good quality is the result of a single individual which is wrong. Good quality is the result of the entire staff of a company. Cooperation of employees within an organization should therefore be cultivated.
(d) Any quality improvement assumes a change in the system. Therefore, the employees on all levels should be advised to ask questions about why something is done as it is done.
(e) Any occurring error should not be used to look for and hold the culprit to account, but to identify the corresponding system weakness and to remove it. Monitoring constitutes a means for identifying weak points of the system and not for detecting the misconduct of an employee.

According to many questionnaires, a majority of the employees in all branches of industry work to rule, many have inwardly quit their job and only very few are (still) motivated. Since this also holds for ISO 9000 certified companies, it follows that fulfillment of the requirements of the ISO 9000 series is not sufficient with respect to the human factor.

6.3.4.3. Control and human factors

Because of the importance of the human factor, it is reasonable to locate the control of the human factor at the management level. Controlling the human factor necessitates control plans similar as in the case of production processes where the relevant quality characteristics are continuously monitored.

Just as the machine state or process is monitored, the motivation of the employees should be continually monitored. Any deviation from the desired performance indicates that some countermeasures need to be performed.

It should be noted that the specific activities in nuclear fuel quality control are interrelated. The need for highly qualified and trained personnel in the quality control is well justified, and it is extremely important that these people are motivated and dedicated to their task. They also need to be experienced with regard to the process steps they are watching and the control methods they are applying.

6.3.5. Continual improvement strategies

Continual improvement aims to enhance the effective application of the system, including processes for continual improvement of the system and the assurance of conformity to customer and applicable statutory and regulatory requirements.

A continual improvement strategy needs to be distinguished from so called one shot or "just do it" improvement actions, which may be performed, if the management has a clear view on what should be implemented. The respective knowledge may be based on experience that is shared between sites or organizations and may prove to be very useful to determine the reference which will be implemented.

In contrast, a quality improvement strategy is based on principles and is continually applied to identify possibilities for improvement. One of the most successful continual improvement strategies is the Toyota production system, which is based on permanent effort to identify and remove the production of waste, where waste is defined as everything that decreases the efficiency and thus increases the cost. Waste may be due to overproduction, poor quality, too long operating time, raw material, machine resources and human resources, among other things. There are various search methods known, for example, the value stream mapping or the 5S method.[6]

Starting in November 2005, the Electric Power Research Institute (EPRI) and the Institute of Nuclear Power Operations (INPO), with assistance from Nuclear Energy Institute (NEI) teamed with utilities and fuel vendors from the United States of America and other States to develop guidelines for improving the fuel performance by reducing the number of cladding failures, called the Zero by 10 (or fuel integrity) initiative [86–89]. INPO Report 07-004, Guidelines for Achieving Excellence in Nuclear Fuel Performance [90], was published on 28 June 2007 and Revision 1 in March 2009 (see Appendix 8.1). The guidelines addressed each of the known failure mechanisms: PWR corrosion and crud, BWR corrosion and crud, GTRF and PCI. A fifth guideline was published on fuel surveillance and inspection practices [87, 88]. All five guidelines were published in 2008 and fully implemented by utilities in 2009. The industry guideline for foreign material exclusion has also been updated to include additional practices of direct benefit for fuel reliability.

Besides these two conventional strategies, the recently published first volume of the Nuclear Fuel Quality Management Handbook [47] outlines an innovative improvement strategy that is based on stochastic models of all relevant processes. A stochastic model not only allows reliable and accurate predictions about the performance of the process or product to be made, but it also enables the detection of weak points within the processes. This knowledge can be exploited to develop and implement improvements. Each implemented improvement needs to be verified and yields a new stochastic model which again can be the starting point of some improvement actions.

Once a weak point (known as 'muda') in the Toyota approach has been identified, continual improvement means, among other things, that a systematic approach is used which includes the plan, do, check, act (PDCA) steps:

— Plan their activities;
— Execute the plans;
— Monitor and measure the effectiveness of the activities;
— Evaluate the feedback;
— Implement adequate improvements.

[6] 5S means a sequence of activities in Japanese: seiri, seiton, seiso, seiketsu and shitsuke meaning tidiness, orderliness, cleanliness, standardization and discipline.

A key to building up the customer's confidence that the quality targets have been met and will be met in the future is an open communication between the customer and the supplier on the implementation and on the results of measures for continual improvement. The organization is required to monitor and measure the effectiveness of its QMS and to identify opportunities for improvement.

All levels of management are required to carry out self-assessments to evaluate the performance of work and the improvement of safety culture. The assessments need to be complemented by independent assessments by an organizational unit charged with this task or by other independent parties external to the area or work being assessed. Senior management is required to review the results of assessments, make and record decisions and take the follow-up action deemed appropriate.

The QMS is required to be reviewed at planned intervals to check its effectiveness or fitness for purpose, identify opportunities for improvement, and make the necessary adjustments to the management system or to the policies, goals, strategies, plans, objectives and processes of the organization.

The organization is required to manage non-conformances, corrective and preventive actions, including determining the causes of non-conformances, the disposition of non-conforming productions or processes, and taking remedial action to avoid recurrences. Opportunities for improvement are required to be identified and appropriate action taken, with adequate resources provided for the completion and evaluation of the effectiveness of such action.

6.3.6. Governance and organization

The governance and the organization of the company need to be clearly defined on several points:

(a) All the activities of the company need to be described by processes which clearly underline the added value of each contributor in the final result.

(b) The responsibilities need to be clearly defined for each process. In particular, the human organization needs to define clearly the decision making process which is used in the case of an event. In particular, the organization needs to ensure, in accordance with State regulations, that each product is controlled in an independent manner by the production team to avoid any conflict on the quality of the product. Quality teams need to be empowered by the organization to be able to stop production if necessary.

(c) The governance of the company needs to make sure that the decision making process is organized at the right level, that the information flow, bottom up and top down, is accurate.

(d) Processes, organization and governance need to be adapted as needed to the situation, the customers' requirements and the business priorities.

The QMS needs to be built in order to learn from the experiences: incident collection and product non-conformances. Preventive actions based on risk analysis are performed to maintain high quality. Each event needs to be analysed in order to identify weak points in the systems and to put in place actions to prevent reoccurrence of the event. Risk analysis is performed on a regular basis in all the domains. The aim of this analysis is to prevent incidents with defence in depth actions and security of supply for customers.

6.3.7. Strategies and objectives

Conventionally strategy and objectives are determined on the basis of the results of periodical reviews, involving all the contributors of the company. At this stage:

- The status of the company needs to be shared, underlining the successes and the weaknesses of the quality system in the previous period, summarizing the customers and regulatory expectations, and taking into account the stakeholders expectations.
- Based on that statement, guidelines need to be fixed and improvements need to be targeted.
- At the end, concrete SMART (specific, measurable, attainable, realistic and timely) objectives need to be established, fixing measurable goals, assigning an owner or the person responsible for achieving the objective, and the means for doing so.

The management needs to communicate the objectives to all the employees and to review periodically the status of the objectives and needs to adjust targets and means as needed. This step ensures at the end that all the people of the company are aligned on concrete and consistent objectives to attain product quality and to satisfy customers and other stakeholders.

Another innovative approach is to develop stochastic models for each individual process as well as for the system performance which include — in contrast to conventional approaches — the entire uncertainty involved. Based on these models, strategies and objectives can be determined which directly serve the overall purpose of the organization.

6.4. QUALITY ASSURANCE SYSTEM

The quality assurance system is part of the overall IMS. The IMS defines the tasks, responsibilities and the structure on the management level (i.e. manages the organization's processes to meet customers' expectation and regulatory requirements and achieve continual process improvements). The quality assurance system, on the other hand, presents detailed instructions and checklists for the actions performed on the operational level to maintain the desired quality for manufacture and supply of the fuel. Thus, the IMS provides the means that the task defined on the management level is adequately planned and correctly performed and assessed.

Quality assurance could be defined as all those planned or systematic actions necessary to provide confidence that safety or all requirements of a product or service will be fulfilled [91]. Fuel manufacturers and suppliers require quality assurance as a management tool within their organization, both to coordinate all quality efforts and to assess and ensure that the fuel supplied will meet all specifications. In other words, a quality assurance system assures that the customer's satisfaction is met by securing the high fuel quality delivered to the customer.

A quality assurance system consists of several related activities:

- Process qualification;
- Product qualification;
- Maintenance;
- Quality control;
- Quality assessment;
- Quality documentation.

In nuclear fuel manufacturing, the two parties, supplier and utility, cooperate in the field of quality assurance and have a certain assignment of tasks. For example, the utilities check the relevant processes and verify that design requirements are adequately translated into the manufacturing documents.

The scope of the vendor in the context of the nuclear fuel fabrication depends on the specific requirement. When the fuel or services are purchased, emphasis needs to be placed on developing the capability for qualification of suppliers, auditing, and inspection and check upon receipt. In the case where the technology for fuel manufacture or for services is purchased, greater emphasis will be placed on project management, manpower training, management development and procedure/equipment qualification. A list of requirements having the form of a software guide is given Ref. [92].

Product and process qualification are described in Sections 6.4.1 and 6.4.2, respectively, while software quality assurance is provided in Section 8.5.

6.4.1. Product qualification

Any product development process is a structured decision making process often based on go/no-go funding decisions. Generally, it starts with investigating the technological feasibility. The second step consists of a technological evaluation and an early product evaluation, which leads to the actual product qualification, which includes the manufacturability, functionality, reliability and application of the product.

Fuel qualification needs accurate and reliable analysis of the nuclear fuel composition, the identification and quantification of trace impurities, and microstructural characterization are essential for solving fuel manufacturers' problems. Analytical methodologies need to be provided to enable the validation of nuclear fuels and the study of parameters that are essential for the safe handling of the fuel before, during and after burning in power reactors of various types.

Product qualification ends with the setting of requirements and specifications that need to be taken into account when the manufacturing process is designed, developed and qualified. The final product needs to undergo a final qualification before the process and product are qualified. Once this has been performed, the regular production of the fuel can be initiated.

6.4.2. Process qualification

Process qualification means to prove that the process meets the requirements with respect to the required product design. A process meets the requirement if the probability of producing a non-conforming product is sufficiently small. A process qualification requires that the parameter limitations in the design are correctly accounted for in manufacturing documents, since the product needs to be produced within these limits.

Manufacturing tolerances and uncertainties need to be considered as well. The restrictions due to a particular design need to be imposed on the qualified manufacturing process or the process needs to be requalified.

The management system, and hence also the quality assurance system, should guarantee long term safety and profitability. It follows that not only the safety relevant processes should be qualified but any process, since there is no process which is not economically relevant. The difference is that there are generally no strict regulatory criteria for processes which are not safety relevant. In any case, qualification should result in a quantified model of the process performance which allows the assessment of its suitability.

An important feature of the process qualification is analysing the inherent process variability. There are two possibilities to assess process variability: a conventional and an innovative one.

(1) The traditional possibility was introduced by W.A. Shewhart in the 1920s [93, 94]. He distinguished between two types of causes of variability, or as it is often called variation: the common, or random causes of variation; and the assignable causes of variation. Common causes of variation are based on randomness and cannot be removed economically, and this type of variation is therefore considered to be unavoidable. The second type of variation that can be observed involves variations where the causes generally affect negatively the mean variation and can be precisely identified and eliminated. Examples of this type of variation include poor quality in raw material, an employee who needs more training or a machine in need of repair.
(2) A new possibility was introduced in the Nuclear Fuel Quality Management Handbook [47], according to which the variability is not classified but characterized by a stochastic model which not only reflects any occurred assignable cause, but represents a complete picture of process variability. The model may be used as a reliable basis for making decisions aiming at reducing the overall variability.

The activity of establishing a new process can be termed as process selection qualification (e.g. see Ref. [95]). This is the first step before the process is selected and used for regular production. Owing to a break in the process (such as maintenance or modifications), the already established process also needs to be qualified. For the process selection qualification, the process of manufacturing is to be designed so that it is capable of meeting the required characteristics of the product with satisfactorily narrow variations.

For checking the process capability, simply establishing control charts to monitor whether a process is in control is not sufficient. To produce an acceptable product, the process needs to be capable and in control before production begins. Traditionally, process capability is measured by the process capability index. For process qualification of an already established process, detailed examination and qualification of the following elements need to be conducted individually:

— Input material to be processed;
— Equipment to be used for processing;
— Procedure to be used for processing;
— Personnel involved directly in the processing.

The following special (i.e. safety relevant) processes — those which cannot be verified later in the fabrication sequence — were qualified for use during the advanced CANDU reactor mixed oxide (MOX) fuel fabrication campaign:

- — Low enriched uranium powder blending;
- — MOX powder blending;
- — Sintering of MOX fuel pellets;
- — Welding of fuel elements;
- — Welding of MOX fuel bundles.

The proceeding of these qualifications is illustrated by the examples of the sinter process of MOX fuel pellets and the MOX powder blending process. Note that the main aim of these qualification processes is to demonstrate that the corresponding specifications are met.

The densification of MOX fuel pellets depends on the operating parameters of the sintering process as well as the initial density (green density) of the pellets, which in turn depends on the operating parameters of the final press. Appropriate parameters for the final pressing and sintering processes of MOX fuel pellets were determined prior to the qualification process. Using these parameter values and based on the results from the scoping tests, a qualification test was performed. For this qualification test, ten sintered pellets per tray (there are 80 pellets total on a tray) were selected diagonally across the tray for inspection by immersion density. Figure 35 depicts a typical density distribution of the sintered pellets along the diagonal sample, for each sintering furnace tray.

Merging the results obtained from the ten trays yields an average sintered density of 10.45 g/cm^3 with a standard deviation of 0.06 g/cm^3 meeting the density specification (average density $\geq$ 10.45 g/cm^3).

Proceeding like this does not meet the requirement to consider appropriately the uncertainty generated by randomness because the two values 10.45 g/cm^3 and 0.06 g/cm^3 are the result of a random process, and any repetition of the qualification process could result in rather different values. Considering uncertainty means to take the observed values (10.45 g/cm^3, 0.06 g/cm^3) and determine all those values of the expectation μ and the standard deviation σ which are consistent with them. In the above example with a sample size $n = 80$ (10 samples of size 8) and a confidence level of $\beta = 0.95$, the following sets of consistent values would appear:

- — $10.43 \leq \mu \leq 10.47$;
- — $0.05 \leq \sigma \leq 0.07$.

These values can be used for developing a set of probability distributions which cover the true but unknown probability distribution and hence the entire existing uncertainty. Such a model reveals possible weak points of a process and may therefore not only be used for the purpose of qualification but also to devise a quality improvement plan. Figure 35 reveals another issue that should carefully be considered. The differences of the probability distributions for the different trays on the one hand and the localizations of the samples indicate possible differences in the underlying probability distributions which might be again a hint for possible improvements.

The grain size distribution of the sintered pellets is checked by ceramography while autoradiography is used to determine plutonium rich areas in the MOX powder blending process. Standard ceramography and alpha autoradiography analyses were performed every six batches of sintered pellets to determine plutonium rich area and grain size distribution. Figure 36 depicts a typical ceramographic image of an etched MOX pellet.

The average grain size was determined to be 8 μm and the standard deviation 0.5 μm in this sample. Similar as in the case of the density, the observed empirical values should be used for developing a stochastic model which covers the entire existing uncertainty.

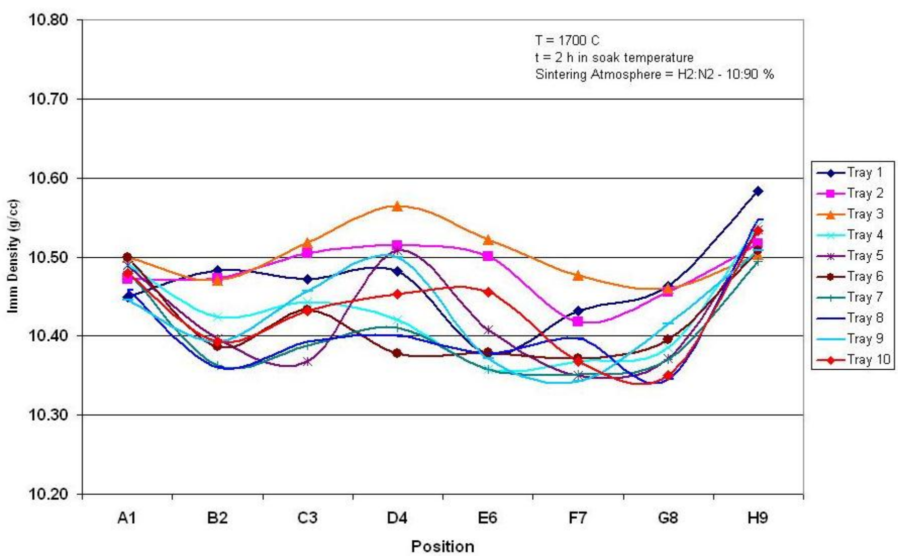

FIG. 35. Sintered densities of the qualification batch.

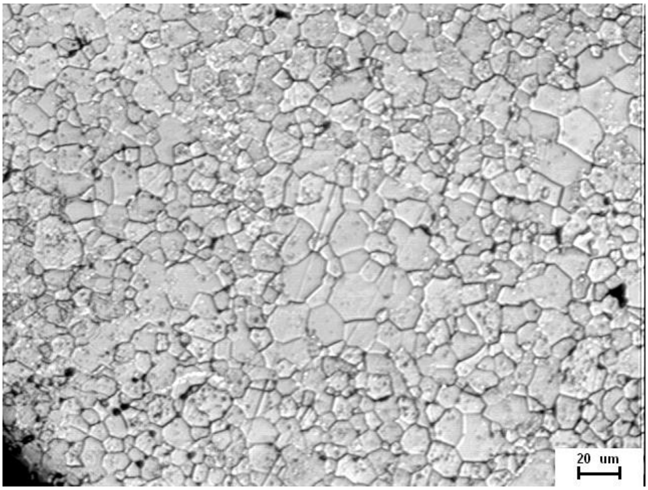

FIG. 36. Grain size distribution of an etched MOX pellet.

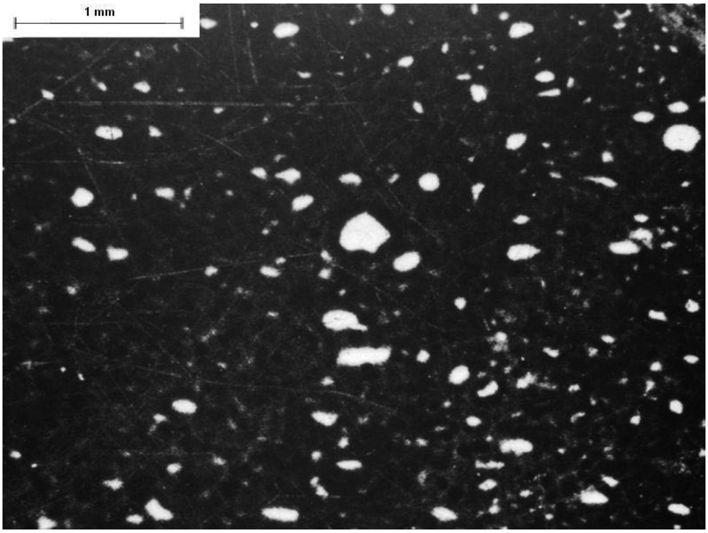

FIG. 37. Alpha autoradiography of a MOX pellet.

Figure 37 shows a typical autoradiograph of a MOX pellet. From the alpha autoradiography, it was concluded that a uniform distribution of plutonium rich areas was normally produced with the MOX powder blending process.

6.4.3. Calibration and control of measuring and test equipment

The equipment used for measuring and test procedures for the various manufacturing steps always need to have the necessary accuracy and precision of measurement. To ensure the reliability of the measurements, a system for its verification needs to be established. Such a calibration system needs to take care of the selection, calibration, adjustment, maintenance and control of inspection, measuring and test equipment. All the calibration standards need to be traceable via secondary standards to the national and international standards. If required, these secondary standards also need to be calibrated frequently enough with the primary standards available at the national level. Measuring instruments, gauges, pressure gauges, temperature controllers, mechanical weighing scales and electronic balances, among other things, are periodically calibrated and the details of the same are maintained in the respective quality assurance plans.

Much analytical instrumentation is comparative and therefore requires a sample of known composition (reference material) for accurate calibration and measurement. Reference material is material or substance one or more of whose property values are sufficiently homogeneous and well established to be used for the calibration of an apparatus, the assessment of a measurement method or for assigning values to materials. Certified reference material, accompanied by a certificate, is reference material with one or more property values certified by a procedure which establishes traceability to an accurate realization of the unit in which the property values are expressed, and for which each certified value is accompanied by an uncertainty at a stated level of confidence. Certified reference materials are available and the suppliers for the nuclear materials are given in Tables 5 and 6.

Effort to generate the standard for hydrogen in zirconium alloys was undertaken in 1998–2002 by laboratories from eleven States in the framework of the IAEA coordinated research project Delayed Hydride Cracking in Zirconium Alloys in Pressure Tube Nuclear Reactors [96]. Target concentration for hydrogen addition in Zr-2.5Nb samples was predefined as 47 ppm for each sample. Forty random hydrided samples were selected and analysed by hot vacuum extraction isotope dilution mass spectrometry [97]. The results showed that the combined population was approximately normal with a mean value of 49.8 ppm and a standard deviation of 0.5 ppm — was ideal for the interlaboratory comparison.

TABLE 5. CERTIFIED REFERENCE MATERIALS AVAILABLE FOR NUCLEAR MATERIALS

Reference material	Properties and relative uncertainties	Measurement methods
U metal	U content (0.005%) Isotopic composition (0.1–0.001%)	Titration IDMS TIMS
UF_6	U content (0.05%) Isotopic composition (0.1–0.001%)	GSMS Titration IDMS
U_3O_8	U content (0.01%) Isotopic composition (0.1–0.001%)	Titration TIMS IDMS
UO_2 fuel pellet	U content (0.05%) U-235	Titration TIMS
U enrichment	Range from <0.02% U-235 to >99% U-235	TIMS MC-ICP
Pu metal	Pu content (0.03%) Isotopic abundance (0.001%)	IDMS TIMS Coulometry
Pu oxides, nitrates	Pu content and/or isotopic composition	Various
MOX pellets	U, Pu content (0.01%)	Various
ThO_2	Th content (uncertainty 0.01%)	Gravimetry ICP-AES
$ThO_2 + UO_2$	UO_2 content 2.5% (uncertainty 0.02%)	Gravimetry Volumetry ICP-AES

Note: GSMS — gas source mass spectrometry; ICP-AES — inductively coupled plasma atomic emission spectrometry; IDMS — isotope dilution mass spectrometry; MC-ICP — Multicollector Inductively Coupled Plasma; MOX — mixed oxide; TIMS — thermal ionization mass spectrometry.

TABLE 6. CERTIFIED REFERENCE MATERIAL PRODUCERS AND SUPPLIERS

Certified reference material producer	Web site
Analytical Methods Committee (CETAMA, Commission d'etablissement des méthodes d'analyse)	http://www-cetama.cea.fr
Institute for Reference Materials and Measurements (IRMM)	http://irmm.jrc.ec.europa.eu
New Brunswick Laboratory (NBL)	http://science.energy.gov/nbl
Nuclear Fuel Complex (NFC)	http://www.nfc.gov.in

The main measurement methods used with respect to the reference material as given in Table 5 are the following spectrometry methods:

— Thermal ionization mass spectrometry (TIMS);
— Isotope dilution mass spectrometry (IDMS);
— Inductively coupled plasma mass spectrometry (ICP-MS);
— Gas source mass spectrometry (GSMS).

See Ref. [98] for techniques and methods for destructive examination of reactor materials.

An often underestimated problem with measuring and test procedures is measurement uncertainty, which often leads to interpretation difficulties of measurement or test results. These difficulties can be overcome by describing the inherent variability of the used measurement processes by stochastic models.

6.4.4. Training and certification of inspection personnel

It should be noted that the specific activities in nuclear fuel quality control are interrelated. The need for highly qualified and trained personnel in the QA/QC is well justified. It is extremely important that these people are motivated and dedicated to their task as described in Section 6.3.4. They also need to be experienced with regard to the process steps they are watching and the control methods they are applying.

6.4.5. Documentation policy

Documentation of data is one of the most challenging problems in nuclear fuel technology. There is a large amount of data that needs to be handled and stored, and to be accessible easily for a long period for the analysis. To evaluate the fuel performance on the basis of the manufacturing data, it is extremely important to pay attention to the design of the data collection, its maintenance and its retrieval.

Care needs to be taken in establishing data collection systems to ensure that the life of the product corresponds to the storage life of the data. The storage of quality control data required for long lived reactor components is longer than for the shorter lived fuel assemblies. However, in case of post-irradiation examination of the fuel, even longer storage time for the data for the fuel manufacturing is required. The storage time and storage conditions of the data are to be clearly specified for each group of products and be consistent with the lifetime of the product.

Most documents today are created electronically. In order to expedite their handling, the fuel supplier requires a system of electronic inspection and approval. Distribution of documents to the customer in electronic form would also shorten the total time needed for their approval by the customer and the licensing authority.

6.4.5.1. Identification and coding of materials

The following is the methodology adopted for identification and coding of materials in the shop floor.

(a) Route/travel card comprising of the following data is attached to the product. This card travels along with the material and all the processing details are entered at each workstation:
   - Material identity;
   - Fabrication route;
   - Stages of fabrication and inspection status;
   - Deviations observed at various stages.

(b) Quality control label indicating product, lot number, stage and status of inspection, quantity. Alternatively the details of the quality control and the comments can be included.

(c) Engraving of components with numbers wherever possible.

(d) Colour coding of the containers and process equipment.

6.4.5.2. *Handling, storage and delivery*

The quality of the component manufactured is dictated by how it is handled during each stage of processing. It is necessary to identify the sources of contamination, the introduction of defects and damages during the handling at each stage of production. Special jigs and fixtures are designed for movement of the assemblies from one station to another. The handling of the materials to be used (raw materials, tools and consumables) is also to be given importance. All parts need to be stored properly in containers or shelves for further processing. To prevent damage or deterioration, special handling and transport equipment for fuel tubes, elements, bundles is designed and used.

According to Ref. [99]:

> "The most important issues concerning the delivery of nuclear fuel to the customer [utility] are the delivery on time and the use of a transportation method which preserves the quality of the fuel during transportation. To make sure and to demonstrate for the customer that during the transportation no incidents have occurred that could affect the quality of the fuel assemblies, accelerometers should be installed in the transportation containers The set points of the accelerometers should be set based on experiments determining the safe range of accelerations on the fuel assemblies.
>
> "In addition to the delivery of the fuel assemblies themselves, a Perfect Fuel Supplier supplies the customer with a quality certificate and a documentation package demonstrating that the fuel assemblies and their components have been manufactured in accordance with the manufacturing documentation approved by the customer [utility] (and the Safety Authority of the customer's country)."

These include:

— Fuel supplier's quality certificate confirming that the fuel has been manufactured in accordance with agreed documents;

— Traceability files that enable the identification of which particular material batches, components or component batches have been used in which particular components, subassemblies and completed fuel assemblies [99].

If not delivered together with the fuel assemblies, at least the following documents (or their copies) need to be readily available for the inspection by the utility at the fuel supplier's premises [99]:

"— material certificates of all component materials and welding materials;
— manufacturing certificates of components, sub-assemblies and completed fuel assemblies;
— documents showing the results of inspections made in accordance with the inspection plans ... ."

6.4.5.3. Traceability

Data of quality control tests or other quality control actions are reliable only insofar as it is possible to relate them to the material or the component to be investigated and to the equipment or process leading to the stated quality. Therefore, the traceability of all fabrication steps and their consequences on the product is one of the most important aspects of QA/QC in nuclear fuel technology.

According to Ref. [99]:

"Every document, batch of material (and small components), every sub-component and complete fuel assembly as well as every piece of equipment used in the manufacturing and inspection of the fuel shall have its individual identification code. The history of all manufacturing and inspection stages shall be recorded with reference to these identifiable materials/batches/components and manufacturing and inspection documents.

"A reliable traceability system is essential for assuring that the fuel is manufactured in accordance with the correct design specifications and manufacturing and inspection plans and using correct materials, components and equipment. A good traceability system enables also to create reliable evidence for the supplier itself as well as for the customer that the final product fulfils all the requirements. In case of mistakes in the manufacturing (batches of wrong material or failures of equipment etc.) a good traceability system helps to limit the amount of suspect material batches or components. Thereby, the consequences of such mistakes can be minimised."

6.5. QUALITY CONTROL SYSTEM

Often there is no clear distinction between quality control and quality assurance, although they differ fundamentally. Quality control is all observation techniques and activities used to prove that the requirements for quality and safety are fulfilled and, as stated in Section 6.4, quality assurance could be defined as all those planned or systematic actions necessary to provide confidence that safety or all requirements of a product or service will be fulfilled [91]. Accordingly, a quality control system is an important part of the quality assurance system and serves to search for deviations from specifications or requirements in order to subsequently remove them.

A quality control system lists the processes, services and products to be monitored, how monitoring is to be performed for each of the listed entity and the specifications to be met, including rejection criteria. The quality control system includes detailed instructions which corrective actions are to be performed depending on the monitoring result. Quality control is traditionally classified in process control and product control, where the former was initiated by W.A. Shewhart (see Section 6.4.2 for more details), while the latter goes back to H.F. Dodge and H.G. Romig [100]. Besides the classical differentiation in process and product control, new fields arose with information security and software reliability.

6.5.1. Specific quality control standards

The QMS standards listed in Section 6.2.2 may be used with general ISO quality control standards and with standards that are specific to the nuclear industry fuel industry, and developed by the ANSI, the ASTM and ISO, such as:

(a) For inspection processes:
   - (i) ASTM C1156, Rev. 3, Standard Guide for Establishing Calibration for a Measurement Method Used to Analyze Nuclear Fuel Cycle Materials [101];
   - (ii) ANSI Z540-1-1994, Calibration Laboratories and Measuring and Test Equipment General Requirements [102];
   - (iii) ISO 10012:2003 Measurement Management Systems: Requirements for Measurement Processes and Measuring Equipment [103];
   - (iv) ASTM C1297, Rev. 3, Standard Guide for Qualification of Laboratory Analysts of Nuclear Fuel Cycle Materials [104];
   - (v) ASNT-TC-1A, Recommended Practice, Personnel, Qualification and Certification in Non-destructive Testing [105].

(b) For materials and components:
   (i) ASTM B-811-02, Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding [14];
   (ii) ASTM B-353, Standard Specification for Wrought Zirconium and Zirconium Alloy Seamless and Welded Tubes for Nuclear Service (Except Nuclear Fuel Cladding) [13];
   (iii) ASTM C934 (1985), Rev. 2, Design and Quality Assurance Practices for Nuclear Fuel Rods [106].

(c) For information security:
   (i) ISO/IEC 27002:2005, Information Technology: Security Techniques, Code of Practice for Information Security Management [107].

(d) For software:
   (i) NUREG/BR-0167, Software Quality Assurance Program and Guidelines [108];
   (ii) ISO/IEC 90003:2004, Software Engineering: Guidelines for the Application of ISO 9001:2000 to Computer Software [109].

Besides these nuclear specific standards, the whole range of quality control standards developed by ISO and the International Electrochemical Commission (IEC) is applied in nuclear industry for process control and product control, for internal as well as for external control activities.

6.5.2. Monitoring, inspection and repair

Quality control methods provide generally for three different actions:

— Periodic monitoring actions;
— Inspection;
— Repairs.

If monitoring indicates a deviation from requirements and triggers an alarm, an inspection may be performed to verify and localize the deviation. If a deviation is confirmed by the inspection, it is removed, for instance, by repair. There are in-house quality control and controls performed by external inspectors.

Each of the actions performed in the framework of quality control relies on a correctly calibrated measurement device (see Section 6.4.3). The interpretation of any obtained monitoring and inspection result needs to be uniquely determined, otherwise it is impossible to make an appropriate decision. It needs to be made sure that unacceptable product or faulty processes are detected for timely corrections.

The activities, observations and reactions need to be documented according to specified regulations and need to be approved by the corresponding authorities. Moreover, the quality control staff and their awareness need to be maintained by adequate measures.

6.5.3. Process control

Process control involves the comparison of the output of a process with a standard and the taking of remedial actions in case of a discrepancy between the two. It involves the determination of the ability of a process to produce a product that meets desired specifications or requirements. Usually, statistical tools are used to establish the process control which generally consists of monitoring the output from a process. If the process observation is consistent with the given standard, the process is assumed to be in control, otherwise a deviation from the standard is indicated and leads to further actions. Note that ideally the standard is given by a validated stochastic model, which increases the reliability and the accuracy of the necessary comparison.

6.5.3.1. Process monitoring

In many practical situations it is impossible to carry out 100% monitoring of the process, or if an additional supervision is necessary, surveillance is performed. In a monitoring programme to be followed, it is necessary to define the scope (type and extent) and intervals of the monitoring actions. Monitoring functions as an indirect control of the production methods, the equipment and the personnel which affect the quality. The results of process monitoring, such as recent rejection rate, type and number of repair actions, are to be made available to external inspectors as well to enable a judgement of the actual state of the process. Some of the check-points of surveillance include:

— Validity of the applied procedure and test instructions;
— Calibration (date) of the test and measurement equipment;
— Use processing parameters according to instructions;
— Checking the manufacture of released material only;
— Comprehensive documentation of the accompanying records;
— Processing and handling in accordance with instructions;
— Labelling and identifying of items;
— Qualifications of procedures, machinery and personnel;
— Validity and availability of standards for comparison.

6.5.4. Product control

Product control aims at identifying non-conforming products and eliminating them. The subject of product control may be single items or lots or batches of items. In the former case, one or several measurements can be performed depending on the number of the quality characteristics and their nature. In the latter case, it is often not possible to test each item in a lot, if testing is too expensive, too time consuming or destructive. In such cases, acceptance sampling plans are used for deciding about the quality of the lot or batch.

In Sections 6.5.5 and 6.5.6, the quality control actions for different types of nuclear fuel are listed and briefly explained.

6.5.5. Product control for PWR/BWR and VVER fuel

This section deals with quality control of the components of PWR, BWR and VVER fuel. The focus is on product control and deals with the quality characteristics, with the type of inspections, and with taking and analysing samples.

6.5.5.1. Zirconium alloy products

Product and process control methods need to be applied for zirconium alloys to cover sensitive product characteristics and sensitive process parameters. A specific know-how is required because of the properties of zirconium alloys regarding, for example, their anisotropy or high chemical affinity to oxygen and other gases.

(a) Sponge

The sensitive chemical elements in zirconium sponge analysis are given in Table 7, in accordance with the ASTM B-349 standard [110].

In addition to chemical analysis, visual inspection is performed to eliminate individual grains of sponge presenting a discolouration due to oxide or nitride zirconium.

The process for separating zirconium and hafnium by extractive distillation developed and used in AREVA represents a best practice for environment free impact compared to existing chemical separation processes, and a guarantee of very low hafnium content in the final zirconium product [47].

TABLE 7. SENSITIVE CHEMICAL ELEMENTS IN ZIRCONIUM SPONGE ANALYSIS

Chemical element	ASTM limit (ppm)	Relevance of preceding process steps	Relevant points for further use
Cl	1300	Chemical separation and reduction	Melting
Hf	100	Chemical separation	Neutron economy
Mg	n.a.[a]	Reduction	Ingot specimen
N	50	Reduction	Scrap recycle
O	1400	Reduction	Scrap recycle

[a] n.a.: not applicable.

(b) Ingot

Three points are of major interest for the characterization of the final ingot:

— The chemical composition and homogeneity (see Table 8);
— Workability, which means deformability during the subsequent reduction steps;
— Sampling is monitored to have the cross-section and the top middle bottom positions of the ingot.

The element analysis is mainly performed by plasma emission spectrometer and great care is to be taken to use the right reference materials because of structural impact.

(c) Semi-final product

The main NDT techniques used to control the thick walled seamless zirconium alloy tubes are given in Table 9.

TABLE 8. SENSITIVE CHEMICAL ELEMENTS IN ZIRCONIUM ALLOY INGOT ANALYSIS

Chemical element	ASTM limit (ppm)	Relevance of proceeding process steps	Relevant points for further use
Alloying elements			
Sn	According to Zircaloy specification	Melting and scrap recycling	Mechanical and corrosion properties
Fe			
Cr			
Ni			
O		Scrap recycling	Mechanical properties
Impurities			
N	≤80	Melting and scrap recycling	Gas uptake during subsequent process steps Corrosion
H	≤25		
C	≤270	Scrap recycling	Mechanical properties

Source: Table B3/IV in Ref. [51], but with peak nitrogen concentration corrected according to ASTM B350 [111], which was published in 2011.

TABLE 9. NON-DESTRUCTIVE TESTING TECHNIQUES FOR THICK WALLED SEAMLESS ZIRCONIUM ALLOY TUBES (HOLLOWS AND TREXs)

Test target		Test technique	Calibration	Accuracy or resolution
Overall	Specific			
Dimensions	OD/ID/wall thickness	Ultrasonic transit time method	Standard test tube	±50 µm
	Straightness	Comparison with straightness standard	n.a.[a]	0.1 mm
Defects	Inclusions Cracks Shrink holes Imperfection	Ultrasonic pulse echo method in four directions	Standard defects V and U shaped notches at ID/OD transverse and longitudinal	Cracks and notches ≥ 100 µm
Surface	Imperfections	Visual inspection	Standards	5–10x magnification
	Contaminations	Roughness measurement device	Standards samples	0.1 µm
	Roughness	Microscope		

Note: ID — inner diameter; OD — outer diameter.

[a] n.a.: not applicable.

(d) Cladding and thimble tubes

Non-destructive and destructive testing is used to control the final tube, flat or bar products as given in Table 10.

Destructive testing techniques are mainly used for mechanical properties, chemical composition, corrosion properties, microstructure and texture measurement. Standard ASTM E8 [112] and ASTM E21 [113] specify the requirements to apply to a tensile test.

Room or elevated temperature tensile tests are performed to measure yield strength, ultimate yield strength and uniform or fracture elongation. As far as qualification tests are concerned, creep tests, or burst tests, can be requested as characterization of the multiaxial properties of zirconium alloy tubing. By comparison for flat products, bending tests and or dimple tests can be performed.

If metallographic techniques are used to check grain size on a manufacturing lot, texture measurement by X ray diffraction methods could be performed for the purpose of product qualification.

Corrosion measures are performed in steam according to the ASTM G2 standard [114] for uniform corrosion resistance acceptance for the lot reception. The corrosion rates should be less than 22 mg/dm^2 after 3 days or 38 mg/dm^2 after 14 days.

Tests with samples exposed to pressurized water could be applied to test welding or mechanical conditioning. The in-reactor chemical conditions can be simulated in such tests to characterize the material performance.

(e) Bars

Bars are mainly used to machine cladding end plugs and need to be controlled dimensionally but also by UT and visual inspection like that presented in Table 11.

(f) Flat products

Flat products are used for strips for grids or sheets for channel boxes. Mechanical properties in longitudinal and transverse directions, microstructure and corrosion tests are performed on each manufacturing lot by sampling. The relevant NDT methods are presented in Table 12.

TABLE 10. NON-DESTRUCTIVE TESTING TECHNIQUES FOR THIN WALLED SEAMLESS ZIRCONIUM ALLOY TUBES FOR CLADDING

Test target		Test technique	Calibration	Accuracy or resolution
Overall	Specific			
Dimensions	OD/ID/wall thickness	Ultrasonic transit time method	Standard test tube	±3 μm
	Straightness	Comparison with straightness standards	n.a.[a]	0.01 mm
Defects	Inclusions Cracks Shrink holes Imperfection	Ultrasonic pulse echo method in four directions	Standard defects V and U shaped notches at ID/OD transverse and longitudinal	Rejection level according to specification
		Eddy current inspection	Standard defects according to specification	Rejection level according to specification
Surface	Imperfections Contamination	Automatic optical inspection	Standards	n.a.[a]
	Roughness	Roughness measurement device	Standards samples	0.1 μm

Note: ID — inner diameter; OD — outer diameter.

[a] n.a.: not applicable.

TABLE 11. NON-DESTRUCTIVE TESTING TECHNIQUES FOR ZIRCONIUM ALLOY BARS

Test target		Test technique	Calibration	Accuracy or resolution
Overall	Specific			
Dimensions	Diameter	Gauges at middle and ends	Standards	±0.01 mm
	Straightness	Gauges check space to straightness standards	Standards	±0.02 mm
Defects	Imperfections	Ultrasonic immersion pulse echo technique	Standard defects radial and axial	≤0.8 mm according to specification
	Inclusions	Metallography cross-sections at ends by sampling	Holes	10 μm
	Shrink holes		Microscopic examination	
Surface	Imperfections Contamination	Visual inspection	Standards	5–10x magnification
	Roughness	Visual inspection	Standards	5–10x magnification

TABLE 12. NON-DESTRUCTIVE TESTING TECHNIQUES FOR ZIRCONIUM ALLOY SHEETS

Test target		Test technique	Calibration	Accuracy or resolution
Overall	Specific			
Dimensions	Thickness	Electromagnetic probe micrometer	Calibration gauges Standard samples	±0.004 mm
	Length	Ruler measurement	Calibration gauges Standard samples	±0.05 mm
	Width	Calliper with gauges	Calibration gauges Standard samples	±0.01 mm for channels ±0.1 mm for spacer strips
	Flatness	Gauges	Calibration gauges Standard samples	±0.01 mm
	Camber	Gauges measure space to standard straight edge	Calibration gauges Standard samples	±0.01 mm To 0.25 mm depending on RA
Surface	Roughness	Roughness measurement device	Standard samples	±0.08 mm
	Imperfections Contamination	Optical/visual		5–10x magnification
Defects in slabs	Imperfections Inclusions Shrink holes	Ultrasonic immersion pulse echo technique	Standard defects: flat bottom holes in standard block	n.a.[a]

Note: RA — rod assembly.

[a] n.a.: not applicable.

6.5.5.2. Quality plan to meet the requirements and expectations of designer and customer

A summary of the successive manufacturing steps is given in Fig. 20, Section 5.3. The product delivered at the exit of this process should have the features as required by the designer in the drawings or specifications. Table 13 provides a synthetic view of the nature of the product quality requirements placed at the different key points of the manufacturing sequence. Section 9 describes in more detail what needs to be done at the main successive steps to contribute to a product having the appropriate quality at the exit of the manufacturing line.

TABLE 13. PRODUCT QUALITY REQUIREMENTS AT KEY POINTS OF THE MANUFACTURING SEQUENCE

Product	Main quality points to be managed
Powder	Powder materials features
Pellet	Pellet materials final features Pellet dimension: diameter Visual aspect Cleanliness
Fuel rod	Welding process quality Fuel rod content (pellet column, spacer and rod spring) Visual aspect Incoming components and rod cleanliness
Spacers, end parts and skeleton	Part materials features Process quality: welding, brazing, conventional machining, electropolishing, electrical discharge machining, sand blasting and deburring Cleaning process quality Materials special heat treatment Part final dimensions Part cleanliness

TABLE 13. PRODUCT QUALITY REQUIREMENTS AT KEY POINTS OF THE MANUFACTURING SEQUENCE (cont.)

Product	Main quality points to be managed
Assembly	Assembly manufacturing operations: rod loading and end part installation
	Cleaning operation (blowing or washing)
	Assembly handling conditions
	Assembly dimensional features
	Assembly cleanliness
	Assembly shipping conditions: installation in container and container handling

To achieve and confirm the final product conformity, three types of actions contribute (see also Section 9):

(1) Action 1: Preparatory engineering actions to control the manufacturing process:
   (a) The product is elaborated through successive steps where it is transformed (i.e. conversion, pressing and sintering) or assembled (i.e. pellet loading and skeleton welding) or stored or handled.
   (b) At each of these steps, the equipment and the operating conditions need to be attentively prepared and defined by the equipment engineer and the process engineer to be sure that this step will contribute efficiently to the expected final quality of the product.
   (c) The manufacturing phase needs to be prepared and to identify some ranges in which the important operating conditions are to be contained to provide stable and repetitive manufacturing situations.
(2) Action 2: Manufacturing samples collected and test on samples:
   (a) In the course of the manufacturing at appropriate steps, representative samples need to be produced, and destructive tests on these samples will prove that the process is in-control and generates correct products repetitively.
(3) Action 3: Direct examinations on line on the actual manufactured product:
   (a) In the course of the manufacturing, direct non-destructive inspections are performed on the product itself to check the conformity to the requirements concerning dimensions, visual aspect and cleanliness.

6.5.6. Quality control of PHWR fuel

6.5.6.1. Fuel tubes

(a) Tests on the ingots

(i) To determine chemical composition [115], it is required to take samples from different regions of the ingot (preferably top, middle and bottom) and to analyse for the alloying elements and impurities, which should meet the requirements of ASTM B350 [111].

(ii) UT of the billets is carried out using the contact method (straight beam) using the recommended practice of the ASTM E114 [116]. For the reference standard, flat bottomed holes are drilled radially to different depths. A distance–amplitude correction curve is drawn from the flat bottom drilled holes. Indications exceeding the reference indications are considered rejectable.

(iii) Hardness measurements are carried out on the ingots and recorded in accordance with ASTM E10 [117] or ASTM E18 [118]. Several readings are taken along the length of the ingot. The qualified material is taken up for further processing to hollows and tubes.

(iv) The microstructure of the billet is monitored for confirming the β quenched structure. Optical and electron microscopy techniques are used for evaluation of the microstructure. For evaluating the phase and texture of the billet materials, X ray diffraction techniques are used.

(b) Chemical analysis of the product (tube)

(i) Billet/ingot analysis is considered sufficient for chemical analysis of the tubes produced except for hydrogen, nitrogen and oxygen [119]. These three elements are analysed for each lot of finished tube. A good number of samples representative of each lot of finished tube are to be taken for these analyses.

(c) Mechanical properties

(i) For evaluation of mechanical properties, an adequate number of tubes are selected at random from each lot. Specimens are cut from each tube, one for tension testing and one for burst testing. The test results are used to determine the acceptability with regard to the longitudinal tensile properties and closed end burst properties.

(ii) Room temperature tensile test: the specimens should be tested as ASTM E8 [112] at room temperature to determine the ultimate tensile strength (UTS), yield strength (0.2% offset) and percent elongation.

(iii) Samples from the same tubes as those taken for room temperature tension testing should be taken for closed end burst testing. The results of the closed end burst test are recorded as total circumferential elongation (percent of thermal coefficient of expansion, TCE) and hoop stress. Statistical results (mean and standard deviation) of the TCE should be calculated and used for acceptance of the lot.

(d) Corrosion test

(i) Samples are cut from finished tubing and subjected to corrosion testing by autoclaving in dry steam at a temperature of 400ºC and a pressure of 10 MPa [120]. The conduct of the test is as per ASTM G2 [114]. The samples are autoclaved in steam at test temperature and, pressure for three days, and are weighed to determine the increase in weight. The surface area of each sample should also be measured to calculate the corrosion in mg/dm^2. On completion of the test, the samples should show a uniform lustrous black oxide film on the surface.

(e) Ultrasonic testing

(i) UT of the tubes is carried out for flaw detection, OD measurement and wall thickness measurement [121]. For UT of tubes, ASTM E213 [122] is used for flaw detection. UT inspection is carried out with 100% coverage, using the immersion technique.

— Flaw detection: For bidirectional testing of flaws four lines focused transducers of high frequency are used and a standard tube with artificial defects made with precision for calibration. The standard tube should contain notches made on the OD and ID, and oriented in both longitudinal and transverse directions. The depth and length of the notches are quantified and meet very strict tolerances. All four probes should be calibrated taking the reference notch of specified depth. The probes are calibrated to get equal echo heights from outer and inner surface reference notches. The calibration is recorded on permanent multi-channel fast response recorders; a microcomputer is used for automatic flaw testing, marking and sorting of tested tubes. Any flaw indication exceeding the notch indication should be rejected.

— OD measurement: OD should be measured using the normal beam probes. This is recorded on fast response recorder. The recording of an OD standard should be done at the same speed as the test speed on regular tubes. The calibration should be checked every hour.
— Wall measurement: Wall thickness should be measured and recorded with the help of a fast response recorder and two spherical focused ultrasonic transducers of high frequency. High pulse repetition frequency is used and standardization is done with a carefully prepared tube with thickness known within a very narrow tolerance. The calibration check is done every hour. Those portions of tube showing wall thicknesses beyond the tolerance limits are marked for discarding during final cutting.

(f) Hydride orientation, texture and microstructure [121]

(i) Hydride orientation: Samples from each lot are tested for determination of the hydride orientation factor, F_n. This is defined as the ratio of radial hydride platelets to the total platelets in a given area. A radial platelet is defined as that lying between angles of 0–40° from the normal drawn to the transverse section of the tube at that point. For the purpose of determining the F_n factor, samples charged with hydrogen as small rings showing transverse sections are prepared and examined under a metallurgical microscope using bright field illumination. The total number of hydride platelets as well as the number of radial hydride platelets within the square should be counted. The F_n factor is to be calculated on each sample at several randomly selected areas around the circumference of the tube.
(ii) Texture: The mechanical, metallurgical and corrosion properties of the clad are dependent on the crystallographic texture which is determined using X ray diffraction. For characterization of the crystallographic texture, an X ray diffractometer with a goniometer attachment is used to generate a pole figure. The texture of the material undergoes modification during the thermomechanical processing. The finished tube has a strong radial basal pole (0002) texture.
(iii) Microstructure: Specimens from each lot are examined for microstructure in transverse and longitudinal sections of the tube. The prepared samples are etched and examined under a metallurgical microscope. Since zircaloy is optically anisotropic, polarized light is used to distinguish grains clearly. A suitable magnification (e.g. 250x) should be selected which will render a detailed examination of re-crystallization, grain size and presence of second-phase precipitates, among other things.

(g) Dimensional examinations

(i) Tubes cut to length are inspected for length, bow, OD and ID. Every tube is visually examined for pits or any surface imperfections. The length of each tube is checked on the surface plate. ID and OD measurements are performed using an air gauge. The tubes are checked for freedom from bands or kinks and bow. Tubes are sorted into different groups on a minimum ID basis for optimal pellet to cladding gap.

(h) Visual and surface examinations

(i) Each tube is visually inspected under adequate illumination for pits, tool marks, gauges and any other type of imperfection. Surface finish measurement is performed both on ID and OD using a profilometer after calibrating it on a standard piece.

6.5.6.2. Rod and flat products

(a) Chemical analysis in the product

(i) Ingot analysis and product analysis for rods and plates are carried out as discussed above for the tubes.

(b) Mechanical properties

(i) Longitudinal samples are taken from each lot for room temperature tension testing to determine UTS, yield strength (0.2% offset) and percent elongation in 50 mm gauge length for rod material. For sheet material, tension tests are carried out in the transverse and longitudinal directions. The testing is done in accordance with ASTM E8 [112].

(c) Corrosion test

(i) Corrosion tests are carried out on the bar and sheet samples in a similar way as for the fuel tubes as discussed above.

(d) Ultrasonic non-destructive testing

(i) Each length of finished bar is tested by an UT immersion method capable of detecting planar defects like cracks, scoring lines, seams, laminations and laps, and volumetric defects such as piping, stringers and porosity [123].

The UT system is calibrated with high frequency focused probes, using a reference standard having notches and holes. For sheets, UT is carried out using the immersion technique using reference notches in the longitudinal and transverse directions.

6.5.6.3. Uranium dioxide powder

In powder production using the wet ADU route followed by calcination and reduction, the following key parameters are monitored [124–126]:

— Settling volume of ADU;
— Precipitation temperature of ADU;
— NH_3 flow rate during precipitation;
— Calcination temperature of ADU;
— Specific surface area of U_3O_8;
— Reduction temperature of U_3O_8;
— Uranium content and chemical analysis of impurities.

The samples are analysed using the techniques in Table 14 [127]. The physical properties of the powder are analysed using the techniques in Table 15.

TABLE 14. TECHNIQUES TO ANALYSE KEY PARAMETERS OF URANIUM DIOXIDE POWDER

Analysis	Technique
Enrichment (U-235)	Mass spectrometry
O/U ratio	Redox titrimetry
Purity analysis	Inductively coupled plasma atomic emission spectrometry
C and S analysis	Combustion method (C–S analyser)
N	Spectrophotometric method
Moisture content	Pressure manometric method

TABLE 15. TECHNIQUES TO ANALYSE PHYSICAL PROPERTIES OF UO_2 POWDER

Analysis	Technique
Specific surface area	Brunauer–Emmett–Teller method
Particle size distribution	Laser based particle size distribution analyser
Bulk density and tap density	Physical tapping method

6.5.6.4. Sintered uranium dioxide pellets

The sinterable UO_2 powder is converted into high density pellets following the classical powder metallurgy route [128]. Qualification of critical processes such as final pressing, sintering and centreless grinding is carried out before the regular production batch is started. The following checks are carried out during pelletization.

(a) Pre-compaction of powder

After pre-compaction, the following parameters are measured:

— Bulk density: It is the density of the granulated powder. It is defined as mass/volume. The volume is determined by pouring the powder into a graduated jar.
— Size and size distribution: The pre-compacted and granulated powder is subjected to sieve analysis by using a sieve shaker. The percentage of the fines is an important parameter which is monitored.

(b) Final compaction

Random checks and measurements carried out during final compaction include:

— Dwell time;
— Compaction pressure;
— Green pellet integrity (visual);

— Acetone dip test (further integrity check on the green pellet);
— Green density.

During pellet production and stacking, the pellets in each boat are checked for evidence of bulging, oxidation or weathering. The techniques for analysis are listed in Table 16 [129].

TABLE 16. TECHNIQUES TO ANALYSE CHEMICAL PARAMETERS OF THE UO_2 PELLETS

Analysis	Technique
Enrichment (U-235):	Mass spectrometry
O to U ratio	Spectrophotometric method
Purity analysis	Inductively coupled plasma atomic emission spectrometry
C and S analysis	Combustion method (C–S analyser)
N	Spectrophotometric method
Moisture content	Pressure manometric method
F	Potentiometric method using ion selective electrode
H	Inert gas fusion technique (H determination)

(c) Density

The sintered UO_2 pellet density is measured by physical (geometric) and immersion techniques [130–133].

(d) Microstructure

In conventionally sintered UO_2 pellets, the porosity is distributed in general uniformly within the grains [134]. No segregated porosity, large grain size variations (like coring) or metallic inclusions are allowed.

(e) Visual and dimensional examination

Visual examination is carried out on the pellets using the unaided eye [135]. In sintered pellets defects such as pits, chipping, end capping defect, cracks and inclusions are commonly observed. A defect greater than a predetermined size is cause for rejection of the pellet. Pellet dimensions (diameter, length, dish depth and chamfer) are measured.

6.5.6.5. Fuel pins

(a) Appendage weld/braze examination

Most PHWR fuel manufacturers use beryllium brazing to attach appendages (bearing and spacer pads) to the fuel sheath, but some have developed appendage welding techniques. After the appendages are attached to the fuel sheath, the following non-destructive examinations (NDEs) are done on selected fuel sheaths:

(i) A visual examination is conducted:
   — To ensure a complete bond around the base of the appendage (to prevent the formation of sites for crevice corrosion);
   — To identify any sheath surface anomalies or appendage side erosion or growth;
   — To confirm the absence of beryllium braze alloy on the top of the appendage (for brazed appendages);
   — To confirm that the appendages are located properly on the sheath (using special location gauges).

(ii) A dimensional examination is performed including measurement of the sheath inside and outside diameters and sheath bow, and use of stainless steel inside tube gauges the same size as fuel pellets to assess pellet loading. Additional tests done during attachment qualification testing, investigations of process concerns or anomalous observations, and verification that the technical specification is being met include the destructive examinations listed below.

(iii) Metallographic examinations to determine:
   — Voids and free beryllium (accumulated lengths of voids and free beryllium as a percentage of appendage length and their size and location with respect to the outside of the fillet for brazed appendages);

— Length and location of cracks;
— Depth of re-entrant fillet, braze alloy or weld thickness;
— Remaining thickness of zircaloy sheath undissolved in braze alloy or weld zone;
— Number and type of grains across the sheath thickness.

(iv) Impact (or shear) testing is done to measure the strength and demonstrate integrity of the brazed joint up to the point of failure on appendages. The load and force experienced on these joints to failure exhibit the possible external forces that could occur during fuel handling and in-reactor use. The impact test is successful if failure occurs in the sheath wall, rather than the brazed/welded joint.

(v) Tensile or burst testing of the tube with appendages is not normally required, but the customer may request these tests to assess the effect of appendage attachment on tube strength.

(b) Examination of graphite coating [126]

A thin layer of graphite is coated on the inside surface of the machined fuel tubes after appendage attachment. A graphite suspension consisting of a nuclear grade colloidal solution of fine graphite powder along with other organic binders in alcohol is used. The colloidal graphite suspension is filled through gravity filling and drained to give a uniform layer. These coated tubes are dried and baked in a vacuum furnace to impart adequate adherence and strength to the graphite coating. The following tests are carried out on tubes selected randomly after coating:

(i) Visual examination of inner surface.
(ii) Coating thickness measurement.
(iii) Wear test: A stack of steel plugs is passed one at a time through tubes selected at random, holding the tube at the loading angle and passing the steel plugs through the tube. The tubes are weighed after passing the steel plugs and the weight loss is recorded.
(iv) Hydrogen analysis.
(v) Bend test: The tubes are bent by 180° on the outer side and visually examined after cutting and opening.

(c) Process qualification of graphite coating

The process is qualified and fit for production if the following criteria are met:

(i) All the tubes should be free from coloration, scratch marks, pits, porosity and discontinuities in the coating.
(ii) Graphite coating thickness after baking is uniform and meets the desired thickness.
(iii) Weight loss of graphite on passing one stack of steel pellets through a tube should not be more than 1 mg.
(iv) The hydrogen content in the coated tube as measured by the inert gas fusion technique (hydrogen determination) meets the acceptance criterion (typically <1 mg per fuel element).
(v) After the bend test, there should not be any cracking or flaking off of graphite. The coating observed on the vertically slit tube portions should be uniform.
(vi) If all the above criteria are met, the process is qualified; otherwise, the process is improved and this qualification procedure is repeated.

(d) End plug weld examination

Table 17 lists the applications and types of tests that are used.

(e) Helium leak testing

Helium leak testing is carried out on the elements and bundles (unautoclaved and autoclaved) using pressure chambers for back filling with helium and argon followed by leak testing with commercial helium leak detectors. The pressure chamber is designed to withstand helium and argon gas mixtures up to a pressure of 10 kg/cm^2, with an inlet valve for helium and argon, and ports for a pressure gauge, safety valve and vent valve. It is used for back filling of the elements.

The helium leak testing equipment uses a mass spectrometer to measure the leak rate of helium. The elements/bundles are loaded into a vacuum chamber made of stainless steel and designed to withstand a vacuum of 1 μm (of mercury). Elements are placed in a stainless steel chute and loaded inside the vacuum chamber which is connected to the helium leak detector. The testing is carried out and the leak rate is determined. An external standard leak is used for calibration of the unit.

TABLE 17. TESTS FOR END PLUG WELD EXAMINATION

Test	Applicable situation	Typical number of samples used for testing	Type of test
Machine qualification	For newly procured machine or machine after major shutdown of 6 months or more.	300 welds (150 elements) need to be produced by welding the end caps on both ends of the loaded coated tube	(i), (ii), (iii), (iv) and (v)
Machine requalification	Machine is idle due to major break down Modifications are carried out on the machine Quality process checks fail	300 welds (150 elements) need to be produced by welding the end caps on both ends of the loaded coated tube	(i), (ii), (iii), (iv) and (v)
Set up	At the beginning of the day	One empty tube weld and one element weld	(i), (ii) and (iii)
Process check	During the production	After every 20 elements welded	(i), (ii), (iii), (iv), (v) and (vi)
Random check	During the production	From every production lot 2 elements	(vi)

Note: (i)–(vii) correspond to:

(i) Visual inspection;
(ii) Eccentricity between end cap and tube axis;
(iii) Metallographic evaluation;
(iv) Cover gas analysis;
(v) Total hydrogen content analysis (for a few elements for process check);
(vi) Percentage of helium by the gas chromatographic method;
(vii) Ultrasonic testing of the welds: This is carried out on the heavy water reactor (HWR) fuel element end cap welds for detecting weld defects, such as sparking, incomplete weld, leaky weld and tube folding. The test is carried out using the immersion technique, in which an element is positioned on rollers and rotated with the help of a motor. The probe is positioned such that the ultrasonic beam is focused on the weld and scanned from the upset towards the tube side up to one skip distance. The defects in the weld can be seen by signal indications on the flaw detector monitor [136].

(f) Visual and dimensional examination

A final visual inspection of the welded elements is carried out to ensure that only accepted elements are used for making fuel bundles. The following checks are carried out:

(i) Check the element traveller card.
(ii) Check the cleanliness of the elements visually (oil marks or patches).
(iii) Visually examine the end plug weld with 10x lens and ensure no sparking, pinhole or improper weld. Rotate the element slowly and scan throughout the length of the element, checking for undercuts, dents, rough surfaces, cracks, pits and surface defects.
(iv) Visually examine the spacer and bearing pad weld/braze zones for any metal flow (use 10x lens), check for absence of weld/braze, reverse weld, orientation and discolouration, among other things.
(v) Check the dimensions of the elements.

6.5.6.6. Fuel bundle assembly

(a) End plate weld examination

The fuel element end plugs are welded to the bundle end plates using resistance welding. Torque tests are conducted to ensure the weld has sufficient strength to hold the bundle together during on-line fuelling operations. The torque test consists of securing the element or end plug while twisting off a welded test strip (in the case of weld qualification tests) or end plate section (for actual bundle assembly weld tests) and measuring the torque required breaking the weld. The minimum requirement for bundle assembly weld strength is specified and included in the inspection and test plan. A typical assembly weld specification is that the torque strength should be at least 4.5 Nm.

Although not normally a requirement for bundle assembly welding, metallographic examination of the weld cross-sections gives added information on the process and weld quality. It is an option that is to be considered for each bundle fabrication campaign. A typical assembly weld sample is mounted and sectioned longitudinally through the centre The microstructure is examined using a microscope (at 100x) for continuity along the line of fusion, presence of microcracking along the weld periphery and extent of heat affected zone.

(b) Helium leak test

The procedure used for the leak testing of the bundles is similar to that of the fuel rods [137].

(c) Visual, dimensional and weight examination

The following inspections are done on each bundle to ensure that it satisfies the requirements of the drawing.

(i) Ring gauge test: The bundle is placed vertically on the surface plate and ring gauges are passed to ensure that the diameter of bundle is not more than the specified maximum at the end bearing pads and at the central bearing pads.
(ii) Interelement spacing: The bundle is placed vertically on a surface plate. Using an interelement spacing gauge of the required thickness, all interelement spaces between end caps of adjacent elements are checked at the identified end of the bundle.
(iii) Kinked tube test: To ensure that the bundle does not stick inside the coolant channel, a kinked tube gauge is used.
(iv) Bundle weight: The bundle is weighed prior to shipment.

(d) Cleanliness check

Ash less filter paper is used to swipe the bundle on the ends and also on the elements. These swipe papers are put into polythene packets with identification of bundle number and sent for analysis. A typical contamination limit is 5 μg of uranium. If the value exceeds the limit, all the bundles in that batch should be subjected to cleaning.

7. MEANS TO ACHIEVE TROUBLE FREE FUEL PERFORMANCE

This section includes, as well as Sections 8.1–8.3, the actions the fuel vendor, the utility and regulators are doing to obtain trouble free fuel performance. The fuel vendor develops design of new/advanced fuel. The regulators will perform a fuel design review so the fuel can be licensed in a specific State. The utility may also do a fuel design review as well as a fuel design audit at the vendor. This section describes interaction of fuel designers/vendors, utilities and regulators in the area of new fuel development, testing and licensing, and is also devoted to achievement of trouble free performance of regular and newly developed nuclear fuels.

7.1. R&D ORGANIZATION AND MANAGEMENT

In the organizational structures of industrial companies, the management of R&D is often identified as a specific function. To assure this control, the R&D activities are gathered in a 'R&D portfolio'. To set up this portfolio, several steps are necessary:

(a) Definition of the R&D perimeter (i.e. accurate definition of the activities which are considered as R&D). For this, international rules can be used, such as the Frascati Manual [138].
(b) Definition of domains of activity, in order to structure this portfolio. There are two main ways to organize these domains of activity, either by technical areas (material, chemistry and mechanics) according to the skills, or by 'objects' — that is, according to what needs to be developed. Industrial companies will often choose a structure mainly directed by objects, while research laboratories will adopt the structure by technical areas. For fuel designers/vendors, domains are typically:
   — Development of fuel assemblies and components;
   — Manufacturing processes;
   — Test facilities;
   — Tools for manufacturing;
   — Simulation software for the behaviour of fuels under irradiation as well as for simulation of the manufacturing processes. Accident conditions are taken into account.
(c) Clarification of the development objectives in each domain of activity. For fuel designers/vendors, the objectives result above all from its strategy, from the analysis of the needs of its customers and the analysis of its strengths and weaknesses. It leads to a market pulled portfolio. In contrast, research laboratories organize their portfolios mostly by using a 'technology pushed' approach. For fuel designers/vendors, the main objectives are the improvement of the performance of its products and cost reduction. It is then necessary to deduct from these objectives, the needs in terms of product and new software (or model) development, and the needs of new manufacturing processes or new equipment.

(d) Establishing the projects list and appointment of the project managers, who have as their first task to identify all the tasks, the resources and the schedule necessary to reach the objectives. The management of the R&D projects follows the usual rules of project management especially paying attention to the follow-up of the progress and the achievement of the objectives. One of the key success factors for efficient management is the regularity of project reviews, reporting and project tracking in order to be able to define reorientations as needed to mitigate the contingency inherent to R&D. According to the importance of the project a steering committee can be set up to reinforce the follow up of the project.

It is also important, to describe these processes of R&D management in the most precise way and to include these processes in the quality system to allow continuous improvement.

7.2. VALIDATION PROCESS FOR NEW CONCEPT DEVELOPMENT

The development activities cover a large scope starting from the research of ideas (creativity) to solve a problem, up to being able to put new product on the market (industrial use). It is important to segment the development activities into phases, moving from one phase to the next one via gate reviews — that is, reviews allowing validation of the development performed and the relevant results (tests and studies) to make sure that the probability of success is high enough before entering the following phase.

In the field of nuclear fuel, the closer the industrialization phase, the more stringent are the quality assurance requirements. Part of the results obtained during the development process will be used later in the licensing process. For that reason, it is important to identify in each phase of the project, all the tests and studies which will later prove that the proposed solutions meet the design criteria and the safety rules.

The robustness of the solutions which will be proposed to the customers depends on the quality and on the exhaustiveness of the test and study programme implemented. This requires having (or having access to) many test facilities including irradiation facilities and hot cells when material development is concerned.

In the field of nuclear fuel, components need to undergo tests under irradiation to ensure that they will not perturb the power plant operation and will not affect the safety.

7.3. QUALIFICATION PROCESS FOR PRODUCT LICENSING

The fact that the new fuel product will need to obtain an operating license from safety authorities needs to be taken into account during all the development steps. As a consequence, the development programme needs to include not only tests proving the relevance but also all the tests necessary for the demonstration of the safety of the proposed innovations.

The licensing programme is then mostly based on irradiation tests (in test reactors and in power reactors). The advantage of power reactors is to allow tests under representative conditions, but the drawback is the lack of flexibility inherent to their energy production function; it is impossible to test operating conditions at the limits there (e.g. fast variations of power and impact on the fuel behaviour). As a consequence, only concepts tested beforehand and which can be manufactured with almost industrial tools and processes are irradiated in such power reactors.

However, there are few test reactors in operation today and sometimes they are only partially representative in terms of operating conditions (e.g. irradiation duration, neutron flux and pressure level). As a result, the use of power reactors to validate new concepts is generalized. The prerequisites are:

— To have established ‘convincing’ files based on the numerous tests realized before (see above);
— To involve as soon as possible the power plant operator and the safety authority;
— To define a strategy of progressive introduction of the new components;
— To perform inspections on-site and in hot cells after each cycle.

The experimental campaigns in power reactors, the examinations on-site and in hot cells which complete them, are mandatory steps in the development process of new products. They are used to validate the new designs and to quantify the performance of the new components in representative conditions for irradiation and interactions with the reactor environment.

The experimental campaigns ensure that future operation with reloads can be performed on an industrial scale without contingency. The extension of campaigns beyond the normal irradiation duration allow the study of the behaviour of components of well characterized assemblies in conditions which are representative of operational limits (ramp tests for example) and of accident conditions (LOCA and RIA tests) for the safety files.

Furthermore, as the current discharge burnup target is beyond 60 GWd/t, a long duration (around ten years) is required including manufacturing time and all post irradiation examinations and tests to achieve convincing results. The costs of measurements and tests on irradiated material or under irradiation are very high and nuclear fuel R&D represents huge investments over long periods.

7.4. TYPICAL STEPS FOR QUALIFICATION PROCESS FOR NEW TYPE OF FUEL

Phases of the qualification are the responsibility of the fuel supplier on one side and the utility on the other. Analyses of the primary circuit and reactor behaviour can be the responsibility of the utility. The thermohydraulic boundary conditions would then be passed over to the fuel supplier for fuel behaviour analyses. In any case, it is important that the responsibility of each party in performing the analyses is clearly defined.

One example of a typical qualification process is as follows. After the fuel designer/vendor develops a new type of nuclear fuel, which was not previously manufactured and installed at a nuclear power plant, it communicates with operator to start the qualification process.

A first step consists of a general design description presented to the operator for preliminary evaluation of fuel compatibility, fuel design and main characteristics of new fuel. At this step, full scale demo's fuel assemblies are usually presented (together with their drawings).

The second step is data presentation, concerning nuclear design, core physics methodology, description and qualification report for computer codes and nuclear design reports.

The third step is the fuel assembly thermomechanical design, the fuel assembly mechanical design methodology, the description and qualification report for computer code and fuel assembly mechanical design report. At this step, a presentation is made regarding the full scale dummy assembly fabrication process, the results of the mechanical tests, a stress justification, under normal and under LOCA+SSE conditions.

Together with fuel assembly thermomechanical design, the fuel rod thermomechanical design is considered with the fuel rod design methodology, the description and qualification report for computer code, the zirconium alloys properties and the fuel rod mechanical design report.

The fourth step is the fuel assembly thermohydraulic design with the fuel assembly thermohydraulic design methodology, the description and the qualification report for computer code and fuel assembly CHF and thermohydraulic design reports. At this step, the results of hydraulic and lifetime tests of the full scale dummy assembly are presented and discussed.

The fifth step is the safety evaluation. At this step, the following are reviewed and discussed:

— Description and the qualification report for computer code;
— LOCA analysis methodology;
— Behaviour of zirconium alloys in LOCA and RIA conditions;
— LOCA analysis report;
— Compatibility report.

If required, a produced transport container design review is provided.

After the completion of all the steps, related to design, compatibility and safety of new fuel, a fuel vendor preliminary qualification needs to be done. Requirements for the fuel vendor qualification depends on operator, safety authority and State nuclear and safety laws. However, the usual sequence of such a process is:

— Preparation of requirements for qualification of fuel manufacturing process;
— Development and coordination of qualification plans;
— Qualification of zirconium components manufacturing process;
— Qualification of fuel assembly and components manufacturing process;
— Audit of design process.

7.5. ACHIEVEMENT OF FREE FAILURE FUEL PERFORMANCE

To ensure that fuel does not fail during normal operation and AOO and that coolability is maintained during postulated accidents, fuel design criteria (mechanical, nuclear and thermohydraulic) are specified by the regulators (see Section 4) [17]. In most States, the regulators apply the same criteria as the NRC. The regulators also perform a fuel design review of new fuel designs to ensure that the design criteria are met (i.e. fuel meets the design criteria in that specific State (see Refs [16, 17] for more details).

The fuel vendors use fuel performance codes to determine the thermal limits on their fuel design that will ensure that the fuel design criteria are met [4, 5, 17, 36, 37]. When the fuel vendor makes significant design changes of a specific design or develops a completely new design, a design review is carried out. The next step may be to insert a small number of assemblies with the modified/new design, lead test assemblies, in several reactors to verify its performance. For each fuel design criteria, there will be a thermal limit varying with burnup and the most limiting thermal limit will establish the operating regime of the fuel design. There may also be a PCI curve above which it is possible to operate but power increases above this curve are restricted to ensure that PCI failures does not occur (see Refs [4, 17] for more details).

In addition, the cycle specific analysis is done “either by the fuel vendor or the utility to ensure that the core loading is appropriate and that thermal limits will not be exceeded. Finally, the utility must supervise the core with the core monitoring systems to ensure that thermal limits provided by the fuel vendors for their fuel is not exceeded” [17].

To ensure trouble free performance of the fuel, it is crucial that the utility carries out:

— Design audits to ensure that the utility has received the design according to the contract with the fuel vendor;
— Fuel fabrication audits to ensure that the manufacturing processes used results in fuel with good quality.

INPO, a US organization, has also issued guidelines for the utilities how to reach “trouble free fuel” [90] (see Section 8.1). Other examples of good practices used by EDF are provided in Section 8.2. Fuel services provided by fuel suppliers are described in Section 8.3, and a summary of NDT techniques is supplied in Section 8.4.

The interested reader is directed to Ref. [3] for a description of fuel fabrication quality control and Ref. [16] for fuel design review and auditing.

8. EXAMPLES OF GOOD PRACTICES

8.1. INPO GUIDELINES FOR ACHIEVING EXCELLENCE IN NUCLEAR FUEL PERFORMANCE

INPO Report 07-004, Guidelines for Achieving Excellence in Nuclear Fuel Performance [90], summarizes seven key attributes necessary for achieving and sustaining failure free fuel performance. Characteristics of each attribute are described to help define station specific standards and expectations. The INPO web site currently provides additional detailed information that can be used to enhance performance in each of these areas. The seven attributes are as follows:

(1) Attribute 1: The management team focuses the organization on achieving and maintaining failure free fuel performance.
(2) Attribute 2: Effective controls are used to prevent foreign material (debris) from causing fuel cladding failures.

(3) Attribute 3: Design and operating practices minimize the potential for cladding failures caused by PCI.
(4) Attribute 4: Changes to plant design and operation, core design and fuel management practices, and chemistry programmes are appropriately monitored, and chemistry parameters are controlled, to prevent corrosion related and crud induced fuel failures.
(5) Attribute 5: GTRF failure mechanisms are systematically addressed and eliminated.
(6) Attribute 6: Fuel monitoring and inspection activities assess current margins, evaluate the impacts of changes and determine the causes of fuel cladding failures.
(7) Attribute 7: Fuel fabrication oversight activities provide additional assurance that new fuel delivered to the station will not result in a fuel cladding failure.

8.2. EDF SURVEILLANCE ON FUEL MANUFACTURING

8.2.1. EDF surveillance activities on fuel manufacturing

In order to operate its fleet of 58 PWRs, EDF needs to manage a continuous annual supply of approximately 2500 fuel assemblies. Those fuel assemblies are of different designs, provided by different companies and originate from factories all other the world.

Nuclear fuel is a critical component involved in the core, thus fuel safety and reliability are major stakes. In this context, risks of a generic manufacturing issue need to be permanently decreased at the lowest possible level. The principles and the way EDF has organized these activities are explained in Ref. [139] and in the following paragraphs.

8.2.2. Surveillance principles

Surveillance is stated as the following principles:

(a) EDF is legally and morally responsible for the safety of its power plants. The main objective of the surveillance is to have all safety requirements fulfilled: secure an appropriate behaviour of the fuel during normal operation, and guarantee safety margins in accidental or incidental conditions.

(b) In order to ensure long term constant quality in the manufacturing, an independent surveillance process different from the supplier's own controls is needed. Customer surveillance cannot interfere with the supplier's controls and internal decisions in order not to jeopardize its responsibility, but also not to be bound to the supplier's quality management, in order to avoid common modes. This policy is shared with the French regulator, which has legally required the independency of such surveillance.

(c) Surveillance is not a continuous activity even if it may be built to ensure a permanent monitoring of a continuous manufacturing process (this continuous process is an obligation when factories need to work all year long to supply a fleet of reactors). It cannot be thought and organized to cover 100% of the manufacturing steps of all delivered products (redundant control leads to inefficiency). The goal for the customer is to define the tools that evaluate the quality of the supplier processes, and by this mean to judge of the confidence level of the safety and reliability of the delivered products. Thus, it is always built on sampling actions, and consequently needs to cover all activities related to manufacturing — all the way from the initial definition and documentation to the delivery.

(d) Surveillance is a good input to induce continuous improvement within the quality system of a supplier. Surveillance also helps suppliers to maintain and improve a good level of performance in their manufacturing processes. A cooperative approach between the customer and the supplier is an absolute requirement considering fundamental human factors involved in the surveillance process like transparency, interrogative attitude and proactivity.

8.2.3. Answering principles: Surveillance methodology

EDF describes the following rules relying on the defined surveillance principles (see also Fig. 38):

(a) To focus surveillance on important matters, fuel critical characteristics have been determined between EDF and the suppliers to ensure that the safety requirements are efficiently mastered. Important manufacturing activities (sometimes called quality related activities) related to these characteristics are subject to surveillance and can be considered as the backbone of a surveillance programme.

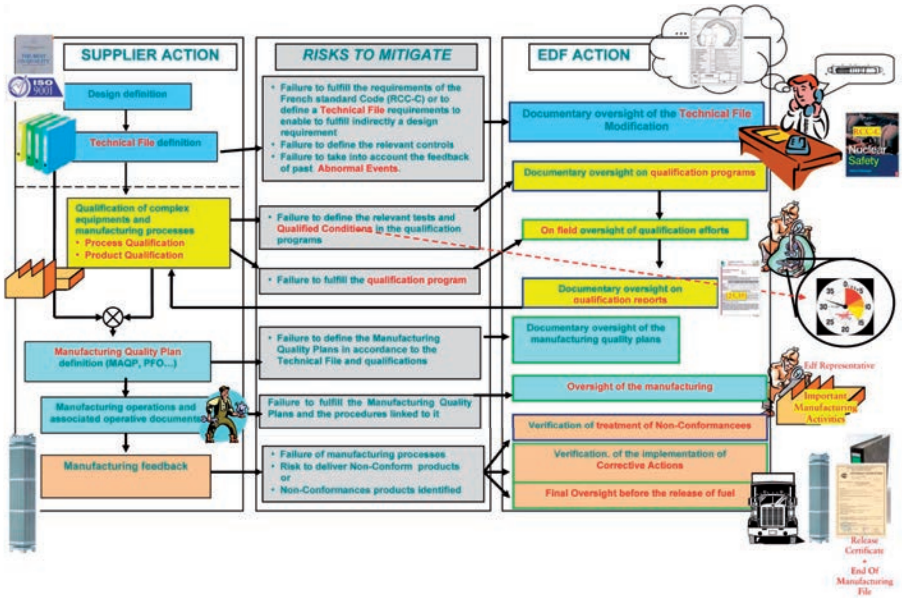

FIG. 38. Overview of EDF surveillance actions on the manufacturing process.

(b) Manufacturing documents linked to the design file (which provides input for safety evaluations), gathered in the so called technical file, are mainly validated by EDF or at least known before any manufacturing starts in the workshops: technical specifications for materials (steel, nickel or zirconium alloy), products (cladding, pellet and nozzles) or processes (bulging, welding and brazing) and drawings. Agreement for manufacturing will be based on conformity to the applicable code, standards, design requirements and the state of the art for manufacturing engineering. This agreement gives a minimum assurance on conformity to the customer.

(c) Delivered products are not documents but fuel assemblies. It is essential to check that the way operators work in the workshop are coherent with the package of documents known and validated by the customer. Consequently, EDF representatives are present in the workshop during product manufacturing to check at random the conformity of working activities to manufacturing documentation: equipment set-up, manufacturing key parameters used, conformity of product process flow with qualification process flow, coherence between workshop operating procedures and the technical file.

(d) Particular actions such as qualifications and non-conformance treatments link the real life of manufacturing: equipment performances, manufacturing possibilities due to chemical or physical properties of the involved materials, sampling test justifications, issues always associated with any production activities and the theory: design file and technical file documentations.
(e) Qualifications provide the qualified conditions (processes key parameters) and the justification of the capacity of a process flow to deliver a product that has the adequate quality.
(f) Non-conformance treatments are necessary for product acceptance (product assessment) and safety authority information, but represent also a feedback loop to continuously improve the manufacturing processes.

8.2.4. Manufacturing surveillance

Surveillance mainly involves four different entities which work together interactively, each one in charge of a specific aspect. The coordination should be ensured by the entity in charge of negotiating and applying the fuel assembly procurement contract. Those activities are:

— Contractual relationship with suppliers (including contractual technical requirements defined in the technical part of the contract) and legal relationship with safety authorities;
— Evaluation of the quality system;
— Design verification;
— Manufacturing surveillance activities.

EDF’s surveillance organization needs to be pragmatic and responsive because of industrial realities but also relevant in terms of analysis to fulfil its mission. Integrated structure combining people in charge of office work and people in charge of on-site verification is understood as efficient in obtaining reactivity when an issue occurs. Interactions between the engineering team and the inspector’s team are important to provide a relevant feedback.

An integrated (office and on-site work), specific, specialized team is dedicated to manufacturing surveillance. The organization is described as follows:

— A group of six engineers specialized in manufacturing technologies, NDT and materials related to nuclear fuel who that perform documentary surveillance;
— A team of ten inspectors who conduct on-site surveillance activities.

8.2.4.1. Engineering surveillance activities

The team of engineers verifies the relevancy of the following manufacturing documents:

— Specifications and drawings and all documents that may contain requirements for a given component;
— Qualification programmes and reports for both complex equipment and manufacturing processes;
— Product assessments in case of non-conforming products;
— Abnormal manufacturing events reports.

The team of engineers is also in charge of defining the guidelines followed by the inspectors during the on-site surveillance.

Engineers' analyses is supported by a database of all the abnormal manufacturing events of the past for all the suppliers. This feedback supports the engineers in their review and enables risk mitigation at different levels (e.g. it offers a possibility to improve the guidelines).

8.2.4.2. On-site surveillance activities

The inspectors create an annual surveillance programme every year which takes into account:

— Important manufacturing activities;
— Additional activities to survey;
— Qualification efforts of complex equipment and qualification efforts of manufacturing processes;
— Verification of the declaration of abnormal manufacturing events and the implementation of corrective actions related to them.

For the important manufacturing activities, the surveillance programme is described as a table with a list of components and guidelines to follow during surveillance. All surveillance information is traced in a system so that the surveillance can be audited by the French Nuclear Safety Authority. Important discrepancies are reported to the supplier by means of a specific document — Fiche de constat d'écart (discrepancy sheet). The supplier is required to provide a relevant answer in a contractually defined schedule.

EDF does not perform contradictory controls on products except at a final stage on the fuel assembly. One reason is that it does not buy intermediate parts, so in its view there is no need to control intermediate parts. Another reason is that qualifications have demonstrated the adequate behaviour of the manufacturing process to produce parts, and it is more logical to monitor the qualified conditions than the parts.

The surveillance programme is revised each year to take into account the feedback of the previous year. Adjustments of surveillance are made for each manufacturer within the supplier organization in terms of frequency of visits according to their surveillance results.

8.2.5. Critical characteristics and important manufacturing actions

8.2.5.1. Critical characteristics

For the treatment of non-conformances, critical characteristics — those which have a major effect on product behaviour in case of a deviation (in particular with respect to safety considerations) — were determined between EDF and the suppliers.

A provisional list of critical characteristics is provided by EDF in the contract. This is a living list which evolves in agreement with the supplier according to the experience feedback (e.g. treatment of the non-conformances and analysis of product design evolutions).

8.2.5.2. Important manufacturing actions (quality related activities)

Important manufacturing activities are all activities involved in a manufacturing process related to an important product characteristic for safety or reliability of the fuel assembly. At the first stage, considering the complexity of the global manufacturing process, a complete list of important manufacturing activities is not so easy to determine because the scope is very large.

Usually, things become more obvious when the usability of the fuel is at stake because of a deviation. Each time a deviation is analysed, the exhaustiveness of the list may be checked and improved if necessary. The basic questions are:

(a) Has the deviation an impact on a characteristic involved in the safety analysis, or does it penalize power plant operation? If yes, then it is considered to be important.

(b) What is the important manufacturing activity related to this characteristic?

A basic process to elaborate the list could be to consider the functional requirements and the phenomena that face the fuel in operational conditions and then determine what the activities to survey (see Fig. 39):

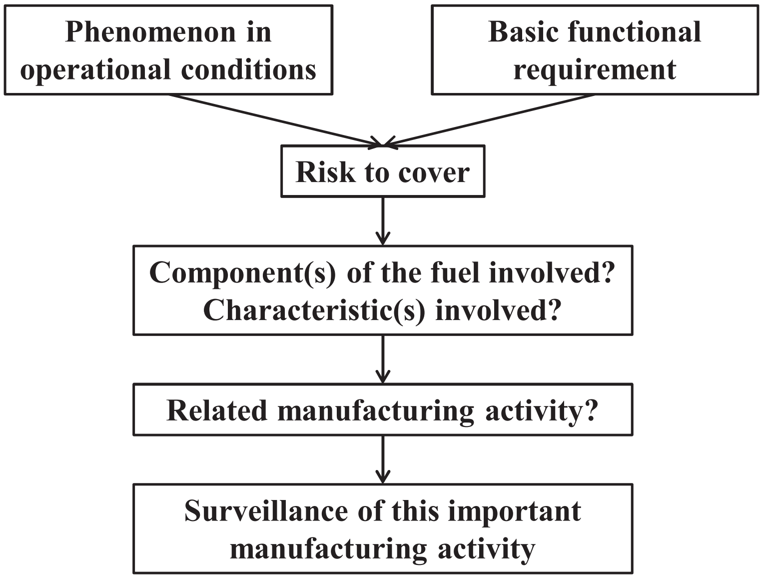

FIG. 39. Functional requirements and the phenomena that face the fuel in operational conditions and then determine what are the activities to survey.

For instance, a well known functional requirement on the fuel is to ensure a barrier between the primary circuit and the pellets and fission products. Fretting is a phenomenon that may affect the fuel under operational conditions. A known risk is to have fretting issues for instance because of a non-conformance of spring–dimples distance for some grid cells. Therefore, this parameter is a critical characteristic. The related important manufacturing activity is the control of these distances, and thus needs to be surveyed.

8.2.6. Qualification surveillance

Three types of qualifications may be encountered:

- Operator qualification;
- Process qualification for a process or an operating mode;
- Product qualification linked to a product manufacturing line and a process flow (a product is defined in the contract and can be, e.g., a grid, pellet or fuel rod).

8.2.6.1. Qualified conditions and qualified process flow

Qualified conditions are manufacturing conditions of a product, identified for the importance of their effect on this product (in particular considering safety and reliability). Their observance during manufacturing guarantees the expected quality. Qualified conditions are encountered in product and process qualifications. Generally, the non-observance of a qualified condition has consequences on critical characteristics of a product. The qualified conditions can be of different nature:

— Equipment;
— Operations order in a manufacturing sequence;
— Number of times that a specific operation is permitted (i.e. for repairing);
— Substance in contact with the product (e.g. lubricant or detergent);
— Quantifiable parameters of a process (e.g. voltage, amperage or temperature);
— Sampling plan for an inspection.

EDF requires qualified conditions to be clearly identified and their content to be provided so that their real use can be verified during the manufacturing of EDF batches.

Product qualification is the global qualification of a specific manufacturing line for a particular product in industrial conditions following a well identified process flow. Product qualification provides the evidence that product may be manufactured industrially with an adequate quality (the product undergoes a test programme to verify this quality). When the qualification is obtained (tests are acceptable), the process flow used during the qualification is then considered qualified and associated qualified conditions used during the qualification runs are validated. Qualified conditions are referenced or written in the process flow.

Only later is the supplier authorized to manufacture a product with those qualified conditions and a process flow similar to the qualified one (the only allowed discrepancies are to suppress actions specific to the qualification effort such as oversampling or a destructive test).

8.2.6.2. Product and process qualifications

Product qualification is complementary to process qualifications which concern particular equipment of the manufacturing line (i.e. welding equipment or optical automatic inspection equipment). The border between process qualifications and product qualifications is not intangible for components which are assemblies: grids; and skeleton qualification tests such as specific measurements or controls can be carried out under one or the other. For parts such as pellets and cladding tubes results on the final product of the different processes overlap so that processes are very difficult to qualify independently (the interactions between the succession of manufacturing steps, even if those steps are qualified processes, can be too difficult to evaluate). For those products, changes in a process need to be checked on the finished product in the frame of a product qualification.

To ensure that the product qualification is comprehensive and accurate, an analysis is needed to identify the risks associated with the characteristics of the product which are important regarding its behaviour in a reactor (in particular the non-conformity to critical characteristics), and for which the quality cannot be adequately verified solely by controls and tests of the technical documentation, or by a process qualification. This analysis is called evaluation of qualification needs (EQN).

EQN leads to defining the possible risks that the product qualification needs to cover. Risk evaluation is based on the following questions:

— Is there a risk for the quality of the input products?
— Is there a risk for the sampling requested by the technical file to be not representative?
— Is there a risk that a control required by the technical file would not be efficient?
— Is there a risk for the quality of the output products?
— Are there product characteristics requested by the design that are not covered by controls defined by the technical file?

8.2.6.3. EDF surveillance

The use of product qualification and EQN is required by EDF. Results of EQN are transmitted for information. EDF validates the qualification programme and the ensuing report and participates to the workshop qualification efforts. Later on, an EDF representative verifies in the workshop the reality of the use of qualified conditions for an EDF batch.

8.2.7. Non-conformance treatment surveillance

A situation affecting or liable to affect the quality of a product can be classified according to two different types, depending on how the problem was detected.

If the discrepancy is detected normally and taken into account by the supplier’s controls, and its consequences are delimited and restricted, it is considered to stay under the control of the supplier quality system. On the other hand, if the origin has not been determined or if it was discovered by chance, or if affected products were delivered, the quality system has failed. In this case, the non-conformance is called an abnormal event and may be reported to the safety authority depending on its importance. EDF asks its suppliers to report all detected abnormal events, to provide a report describing the treatment of the event and if there is a risk or a possibility that non-conforming products might have been supplied.

A contractual flowchart defines the way to proceed for the supplier to determine:

- Whether the issue is linked to design or manufacturing;
- The type of an abnormal situation abnormal event or product non-conformity;
- The level of information to be provided to EDF;
- The level of gravity (in particular if the events need to be declared to safety authority);
- If the treatment is subject to EDF's approval or if only an information is required.

The justification of the usability of a fuel assembly when there is an impact on the product behaviour cannot be handled unilaterally by a supplier.

- EDF surveys that the justification of the usability of products in case of a non-conformance is submitted for validation when the deviation has an impact on critical characteristics.
- The relevancy of those justifications is verified.

Accordingly:

- EDF discusses and validates the corrective actions proposed by the supplier to secure its manufacturing processes when an abnormal event has an impact on critical characteristics of the fuel.
- The corrective actions are implemented in the manufacturing plants are verified.

More globally, the process described by the contractual flowchart is itself placed under surveillance. EDF surveys the declaration of the non-conformances by checking whether non-conformances whose treatment stays internal in the quality system of the supplier ought to be declared to EDF.

8.2.8. Supplier's subsuppliers

Whenever a manufacturing process has a potential risk on the quality of a product, an adequate surveillance is applied. Outsourcing a manufacturing activity should not be a barrier to this principle. Therefore, the contract specifies that subsuppliers may be subject to surveillance and their cooperation is vital to the viability of the contract. Main subsuppliers are consequently submitted to the same rules for surveillance as the ones for the supplier, so their workshops should also be widely open to EDF representatives. This is a key point because poor quality on raw material may lead to issues on a very wide range of products.

8.2.9. Contractual requirements

All the requirements needed to organize EDF surveillance are described in the technical part of the contract (specification of requirements and technical conditions).

(a) The list of the applicable documents is given, in particular: laws, codes (French RCC-C code — design and construction rules for fuel assemblies) and standards.
(b) Definition of important words, and general principles for EDF surveillance, are explained.
(c) Content of documents, rules for documents exchanges (schedule, type of transmission for approval or only information) to be provided by the supplier to enable the EDF representative to be present during qualifications or manufacturing are described explicitly.
(d) Provisional list of critical characteristics, flowchart and any necessary information to manage non-conformance are detailed.

8.2.10. Exchange meetings

In order to facilitate the exchange of information, EDF and the supplier meet periodically in technical and contractual meetings where they examine jointly the state of progress of manufacturing, important incoming working actions (qualifications, new products and implementation) and main issues occurred (non-conformances, misunderstandings or difficulties with contractual requirements). Depending on the subjects, schedule encounters vary from annual to weekly, and people involved from workshops operational teams to contractual responsible.

If necessary for working on specific difficult issues (repetitive non-conformances or qualification of a new process using unknown equipment), technical inquiries or audits might be launched by EDF in a cooperative way with the supplier with the goal of improving the robustness of the manufacturing processes.

That cooperation is deemed essential for a good relationship between the supplier's teams and EDF staff in charge of the surveillance. EDF holds these meetings valuable to incite the supplier's interrogative attitude about its organization and to encourage the supplier to always improve its quality culture.

8.2.11. Conclusion

General principles applied by EDF are shared by other customers and regulators. Comparable surveillances are performed in other types of business as in the automotive or pharmaceuticals industry.

EDF surveillance is based on a permanent monitoring by a continuous sampling of the manufacturing processes in the workshop associated with a systematic validation of the manufacturing framework: technical file, qualifications and process flow, among other things. To achieve this task, specific teams of engineers and inspectors observe all important manufacturing actions of the manufacturing process in a cooperative way with the suppliers and their subcontractors using all available tools proposed in Section 6.5.

One key for the efficiency of customer surveillance is to convince the supplier to promote and stimulate quality culture in its organization. To achieve this, sensitive aspects in human behaviour need to be well managed as, for instance, supplier and customer transparency.

8.3. FUEL SERVICES PROVIDED ON-SITE BY THE FUEL SUPPLIER

AREVA has been continuously developing service techniques and devices for LWRs and VVERs which support the aim of utilities to achieve safe and economic reactor operation. The main emphasis of fuel services is placed on equipment and effort which assist the power operating companies to fulfil the restraints for examination core components (fuel assemblies, fuel channels, reactor control cluster assemblies/rods and thimble plugs) during outage just as well to reduce the needed time for that examinations and to reconstitute the core components for further use or depository. Visual inspections and measurements carried out on fuel assemblies and other core components provide feedback on operating performance. Fuel services accompanies the core components from the first placement at the nuclear power plant (e.g. as lead test assemblies) via the operating phases up to preparation for disposal.

Distinctive technologies of fuel services which represent the state of the art for example are:

(a) The automated sipping technique (for BWRs, PWRs and VVERs, in-core or mast sipping) to detect defective fuel assemblies in short time and high reliability);
(b) The inspection device (PWR, e.g. MULTIINSPECTION; BWR, with a camera manipulator) for visual or measuring examination of fuel assemblies or RCCAs, which enables a reduction in the required time, sometimes at the critical path, during outage;
(c) Detecting the failed fuel rod of a fuel assembly (e.g. with the UT device ECHO 330 or with the single rod sipping device);
(d) The reconstitution facility (PWR, e.g. advanced fuel assembly repair or fuel assembly repair equipment; an adequate reconstitution facility also exist for BWRs) for quick exchange in a save manner of defective fuel rods at the same fuel assembly skeleton or to transfer in a new one and additional the single rod inspection position for deeper examinations (e.g. root cause analysis);
(e) Checking the structural integrity of RCCAs (PWR) by using eddy current testing especially with a view to friction wear marks and absorber induced swelling.

By exchanging the defective fuel assembly, the radiation level in the primary circuit can be kept as low as possible. For safety relation it is obviously needed to check the RCCAs. State of the art technologies reduce the number of service personnel required on site and the applied radiation dose consequently to as low as reasonably achievable.

8.3.1. Sipping test

As a rule, sipping tests are not performed regularly in all plants, but only when an increase in the radiation level of the coolant, measured continuously during the reactor cycle, indicates a leak in one or more fuel rods. In this case, the objective is always to prevent increased radiation exposure through early detection and removal of leaking fuel rods.

The test is based on the fact that water soluble or gaseous fission products escape from defective fuel rods in the event of a temperature increase or pressure decrease.

When testing fuel assemblies inside the reactor core (in-core sipping, used at BWRs), such an effect is achieved by using a sipping hood placed on several fuel assemblies (e.g. with SIPPING 16, a number of 16 fuel assemblies in one step). The sipping hood is like an air cushion to temporarily interrupt the flow of coolant inside the fuel assembly and increase the temperature. The fuel assembly then begins to heat up and fission products escape through the leakage points also achieving the sipping hood. With the control cabinet, a continuous water sample, taken via the sipping hood, is degasified and the gas activity is measured. The comparison with the underground measurement of activity concludes to sound or defective declaration of the fuel assembly.

When testing fuel assemblies within a PWR, the common technology is mast sipping. During extraction, the fuel assembly will be lifted out of the core and the environmental water pressure decreased. By water pressure equalization of a defective fuel rod fission products also released into the ambient water. There, a continuous water sample is taken for analysing. Degasifying, measurement of the gas activity and declaration of sound or defective is similar as in-core sipping.

Analysing fuel assemblies with a longer decay time and stored several years, and therefore generate only minimal internal heat, at the spent fuel pool the common sipping method is can sipping. The can is generally equipped with an additional heater for optimizing the sipping sequence. After moving the fuel assembly into the can, the sipping method itself is similar to in-core sipping. The flow of coolant is interrupted by covering the whole fuel assembly — the can will be closed with a lid. After heating up, a water sample will be taken out of the can for analysis.

8.3.2. Inspection device: MULTIINSPECTION and camera manipulator

In many PWR plants, MULTIINSPECTION can be combined with the new fuel elevator in the spent fuel storage area. The available closed basket will be replaced with a new basket which is opened from one side. This enables access to a fuel assembly inserted into the basket of the MULTIINSPECTION system. At the open side, a carriage is mounted which can be fit with components for inspection or measuring equipment. The carriage can be moved in the longitudinal direction of the fuel assembly. Instead of a modified basket, the storage rack can also be modified and used to take up the fuel assembly to be inspected.

Inspection work can be performed in parallel with other work in the spent fuel pool because the refuelling machine is free after a fuel assembly has been placed in the MULTIINSPECTION basket. The new basket, now part of the MULTIINSPECTION system, retains its old tasks of the fuel elevator and is equipped with a fuel assembly rotation system which enables inspection of all surfaces.

The carriage, which travels along the basket, is equipped with an x-y table with, for example, a pivot mounted underwater television camera. Control is performed by a movable control cabinet which is placed in the pool area and additional by a remote control unit.

MULTIINSPECTION was developed to perform visual inspections in PWR plants, and on demand other service modules — for example, the measurement of oxide layer thickness and dimensional examinations at a fuel assembly or visual inspection of a RCCA and diameter measurement or profilometry of the control rods.

Reduction in radiation exposure is a result of the need for fewer personnel and the fact that personnel carry out their work beside the fuel pool instead of from the refuelling machine.

At BWRs, a camera manipulator is used to inspect fuel assemblies. The camera manipulator is installed at a swivel arm or railing in front of a parking position (dechanneling machine) for the fuel assembly. Thanks to degree of freedom of the camera manipulator and the possibility to adapt several service modules (e.g. for inspection and measurement), many activities are possible. The camera manipulator is hand operated.

8.3.3. Ultrasonic testing of fuel assemblies: ECHO 330

The location of any defective fuel rods can be detected using the UT device ECHO 330. This can be performed on LWR fuel assemblies pretested either by means of a sipping test to identify the leaking fuel rods. The system indicates water penetration into the fuel rod.

The test device is normally set down on the storage rack in the spent fuel pool using a crane and can be activated remote controlled. This system, which is equally well suited to PWR and BWR fuel assemblies, requires less time per fuel assembly to test all fuel rods, evaluates the results, displays the results on-screen and generate a printout.

Single rod sipping can be carried out during fuel rod exchange by combination of the fuel rod exchange device (FRED) and control cabinet of the mast sipping or in-core sipping system and is described below.

8.3.4. Fuel assembly reconstitution and single rod inspection

Irritated fuel assemblies, containing defective fuel rods and having not yet reached their scheduled burnup, can be reconstituted for further use in the reactor by exchanging the defective fuel rods. Fuel assembly reconstitution results in two main advantages for the plant owner:

(1) Since in the majority of cases, only single rods suffer defects or fuel assembly structure is marginally damaged, reconstitution allows to operate the fuel assembly at least to its envisaged burnup (utilization of resources).
(2) Defective fuel rods can be prepared for waste disposal (e.g. encapsulation of the defective fuel rod to keep radioactive particles back).

In LWRs, a defective fuel assembly will be reconstituted by exchanging leaking fuel rods with donor rods or rod dummies. For the operation, suitable fuel assembly repair facility is used. Through the use of this equipment all necessary steps can be performed under water on irradiated fuel assemblies.

Some LWR nuclear power plants are provided with standard reconstitution equipment which is used to detect and replace defective fuel rods and to withdraw individual fuel rods for detailed examination (e.g. fuel assembly repair equipment — at PWRs and dechanneling machine at BWRs). One set of transportable reconstitution equipment is also available for use in all other reactors for the same tasks.

The reconstitution equipment is designed for assemblies with removable upper and/or lower end fittings, depending on the design of the assembly. The tilting device, which is part of the PWR reconstitution equipment at some nuclear power plants, is used for inverting the assemblies for access to the lower end fitting.

Fuel assembly repair facility is capable of:

- Dechanneling the BWR fuel assembly;
- Exchanging the upper and/or lower end fitting;
- Removing defective fuel rods;
- Collecting fuel pellet debris and the subsequent safe storage thereof.

The fuel rods can be withdrawn from the fuel assembly, one at a time, using the FRED. During extraction of the fuel rod integrity examination will be done with an eddy current coil. A second method for integrity examination is to carry out a Single Rod Sipping test. Therefore, the control cabinet of the mast sipping or in-core sipping system needs to be connected by a hose with the FRED. The method is similar to mast sipping — during lifting of the fuel rod inside the FRED, continuous water samples are taken and analysed.

If the fuel rod is identified to be sound, it is reinserted into the fuel assembly. If a fuel rod is identified to be defective, it is replaced either by a dummy or a donor rod. Defective fuel rods are transferred to the fuel rod canister after they are examined at the single rod inspection position.

Fuel rods exhibiting irregularities during the standard eddy current test or tested by single rod sipping are subjected to an additional test in the single rod inspection position. An eddy current probe, together with roller guides, provides a more detailed inspection possibility and is used for a closer inspection of the damage parallel to visual inspection. A catcher tube is attached to the bottom in case parts of the fuel rod come loose as the rod is being handled in the single rod inspection position. With the single rod inspection position, and depending on the stage of expansion, oxide measurement at the fuel rod cladding and diameter measurement of the fuel rod is possible.

The final inspection of the fuel assembly completes the work. The documents and protocols describing the reconstitution work and results are handed over to the power plant.

After the reconstitution has been carried out, a sipping test of the fuel assembly can be performed to document the success of the work. Fuel assemblies treated in this way can be reinserted into the reactor core.

8.3.5. Rod control cluster assembly tests and repair

RCCAs in LWR are safety related core components. In addition to routine functional tests for ease of movement and reactivity worth, they therefore undergo regular inspections and NDEs during outage to verify their mechanical and structural integrity.

Future operating performance can be anticipated based on the results of specific measurements (e.g. depth of wear marks). Four methods for testing control assemblies are used:

(a) Visual inspection (BWR and PWR) for a more detailed assessment of general operating performance and particular indications;
(b) Eddy current examination (PWR) as a fast and simple non-destructive method of checking the mechanical integrity and swelling of the control rods;
(c) Profilometry (PWR; see MULTIINSPECTION) for identifying local material thinning;
(d) Measurement of control rod diameters (PWR; see MULTIINSPECTION) for long term evaluation of dimensional stability.

The most frequently used method at PWRs is the eddy current examination, which can be used to check the integrity of all rods in a control assembly in short time.

In general, the refuelling machine is used to pass all of the control rods through the eddy current probes in one step per control assembly. The probes are arranged in a testing head which is located in the fuel pool during the test. The same system can also be employed in conjunction with other manipulators for RCCA handling.

A data processing system records and processes the test data and prints out an event log. The results are expressed in terms of percentage of reduction in cross-section and diameter according to control rod location and axial elevation, and are compared with calculated erosion depths referred to the standard erosion geometries (flat sickle shapes and notches).

If only one control rod in the cluster assembly is damaged, replacement of the entire RCCA is normally necessary. To avoid increasing the amount of radioactive waste, an RCCA repair method exists which allows replacement of any damaged control rod.

8.4. NON-DESTRUCTIVE EXAMINATION TECHNIQUES IN FUEL FABRICATION

The quality assurance programme in nuclear fuel manufacture consists of NDT at stages of fabrication of components as well as in the assembly at the final stage. Some of the application of the conventional NDT techniques in the manufacture of fuel is as follows (see also Ref. [51]):

- UT of the zirconium alloy billets, finished tubes, bars, sheets, plates and end plug welds;
- Eddy current testing of zirconium alloy bars;
- Radiography of the end plug welds;
- Helium leak test of the encapsulated fuel rods (elements) and final fuel assemblies;
- Visual examination (by manual or machine vision) for the components and the assemblies.

Other advanced techniques, such as infrared thermography and acoustic emission, have also been applied in the manufacturing process of the fuel. In the conventional techniques, several developments have taken place to detect fine defects efficiently and at the same time improve the inspection speed. The NDT tests mentioned above are applied on 100% basis to ensure soundness of the material and welds in the fuel assemblies. Before NDT tests are used as a regular practice on a day to day basis, they involve:

— Calibration of the equipment;
— Establishment of the test procedure;
— Certification and training of the personnel.

The standards to be used for calibration are generally specified in the specifications. Calibration of the unit with respect to the reference standard is a critical. The procedures to be followed are written on the basis of the existing codes and approved. The personnel carrying out tests, verifying and reporting the results are also certified to different levels by international and national certified bodies.

Various NDT techniques are employed in fuel clad manufacturing. The tubes are ultrasonically inspected for flaws covering the complete surface. The defects standards having depth as 10% of wall thickness are employed. Figure 40 shows the details of the set-up for UT and the defect standards. The rod material used for fabrication of end plugs is tested by eddy current testing in addition to UT. Figure 41 provides the set-up for eddy current testing for rods and the different defects that are intercepted. The appendages are manufactured from sheet material, which is tested ultrasonically.

High frequency ultrasonic shear wave technique is employed in testing of the end plug welds [140, 141]. Figure 42 shows an example of the results of the test and its correlation with the observed defect.

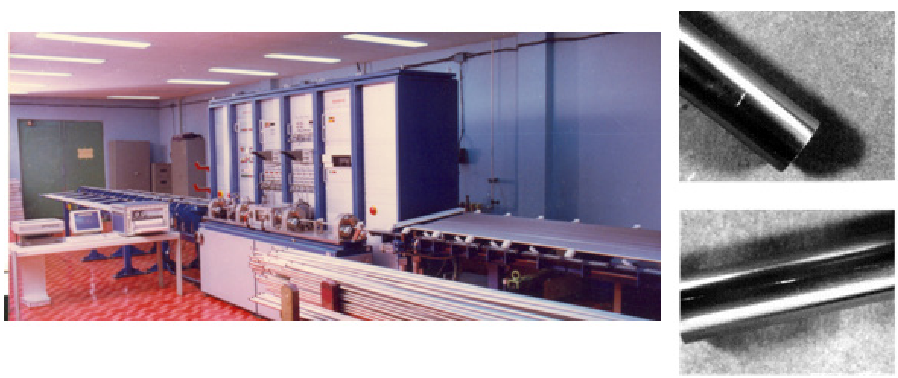

FIG. 40. Set-up of UT for clad tubes and the defect standards (courtesy of NFC).

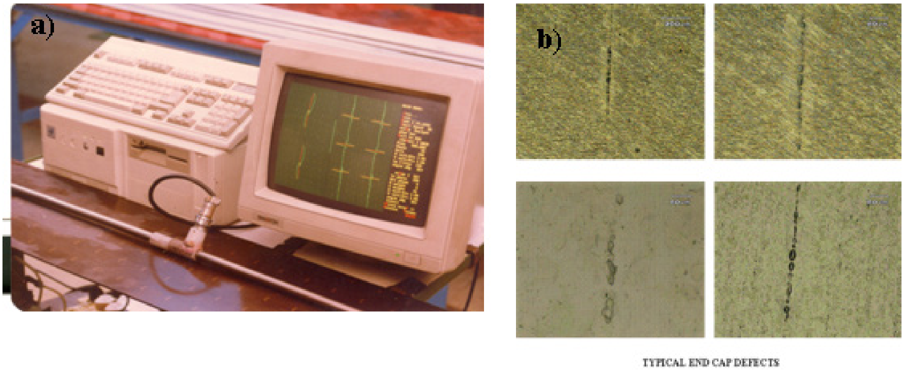

FIG. 41. Eddy current set-up for rod inspection (a) and type of defects being intercepted (b) (courtesy of NFC).

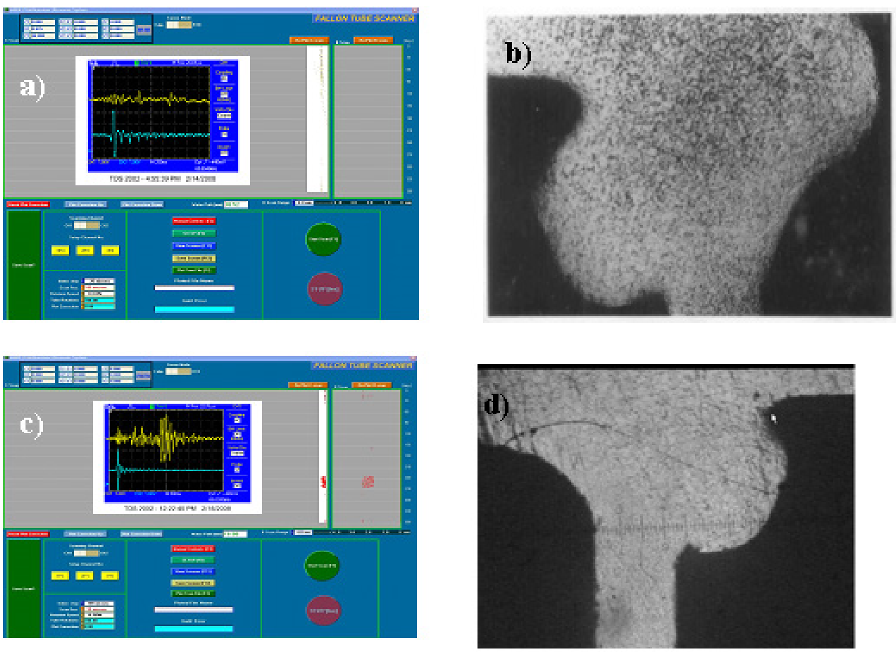

FIG. 42. UT signals and corresponding microphotographs of HWR end cap welds without defects ((a) and b)). UT signals and corresponding microphotographs of HWR end cap welds with defects ((c) and (d)) (courtesy of NFC).

Helium leak testing is carried out on the fuel assemblies using bombing chambers for back filling with helium and argon followed by leak testing by helium leak detectors. Generally, a leak rate is greater than 10^{-8} standard cm^2/s is considered leaking due to lack of fusion, which is the most common defect in the end plug welding.

Radiography is carried out on the fuel element end plug in the case of TIG welds. Defects observed in the radiographs include:

— Porosity;
— Lack of fusion;
— Cracks;
— Tungsten inclusion;
— Absence of plenum and retainer springs;
— Fusion of plug and spring mating surface.

8.5. SOFTWARE QUALITY ASSURANCE

The purpose of software quality assurance is to establish the software quality assurance programme (SQAP) for software developed or maintained to demonstrate the acceptability of quality and safety related functions of products and services (e.g. product design, online core monitoring and engineering services). The programme enables and encourages quality engineering work in the development and maintenance of engineering software used by the company. Some definitions include:

(a) Access control system (ACS): Refers to a method by which users are permitted to run software in a manner that assures the integrity of the software.
(b) ACS administrator: Responsible for promoting approved codes archived in the ACS ‘to use’ status.
(c) Certification file: Refers to the collection of the documents relevant to this code release.
(d) Code custodian: Recognized as the person familiar with the theoretical, design and application basis for the software. The code custodian is responsible for assuring that all code modifications are consistent with the code architecture and identifying the potential for impact of any modification on the licensing methodology.
(e) Full certification: This certification is applied to software items that have been subjected to careful examination for modelling accuracy, and results have been verified, validated and documented according to procedure.

(f) Software configuration administrator: Responsible for access control of software archived in the ACS.

8.5.1. General conditions

Software needs to be uniquely identified and the software name, version identifier and certification status will be included in the code output. Certified software executable is to be used from controlled access locations that provide safeguards to ensure integrity of these files. Associated source code, compilation directives, inputs and outputs of test cases are to be stored as in lifetime records. The software certification will only be modified by the software configuration administrator according to specifications (procedure needed). The documentation of all software modifications should be retained in the software certification file supplied to the software configuration administrator. All aspects of the development project will be subject to independent review for certified software.

8.5.2. Software requirements and development authorization

For any new software development or modification the following information is to be considered:

- Functional requirements, including specific input, processing and output details;
- Performance requirements, design constrains or particular quality concerns;
- Any customer or project specific requirements, such as external interfaces, quality concerns and project design reviews, among other things;
- Code modification requests that are open.

8.5.3. Software development or modification

During the course of development, the responsible programmer documents the software design and implementation details. This software design documentation should include a description of the end product via the detailed software documentation.

8.5.4. Software verification and validation plan

Each computer code version and revision is to be tested according to the software verification and validation plan (SVVP) that is included in the certification file. The SVVP includes a description of the methods to be employed by the responsible programmer or engineer to assure accurate implementation of the software design.

A good example with this respect is one of the most important AREVA NP software development projects: the CONVERGENCE project. A new neutronics thermohydraulics code system — ARCADIA — was developed. From the beginning, developers had been requested to use the Unified Modeling Language (UML) in order to preclude software design and conceptual errors (i.e. to ensure inherent quality). The code its self was generated automatically by using an extra developed code generator. Testing was also atomized. Figure 43 and (a)–(e) show the scheme of the process.

(a) When material properties are introduced, it is verified that they are appropriate and valid over the range of application.
(b) When empirical correlations are introduced, it is verified that they are implemented correctly, especially with respect to their range of applicability.
(c) When new models, functions, and features have an impact on upstream and downstream computer codes, it is confirmed that the upstream and downstream computer codes continue to function properly or that appropriate changes in those computer codes are initiated.

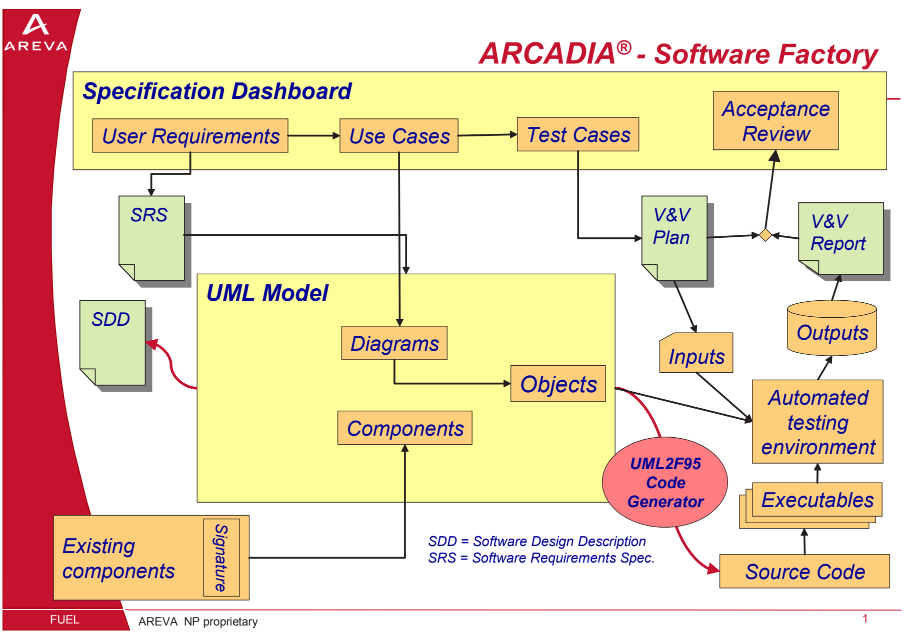

FIG. 43. AREVA NP Software Factory.

(d) For code modifications, a baseline of test cases is required. This baseline should include representative assessment or validation cases from a previous software qualification. The baseline should be defined with sufficient analytical scope such that the continuity of assessment can be demonstrated adequately through its execution. If the software assessment is documented in a Licensed Topical Report (LTR) approved by the NRC, the baseline cases should include representative cases from the validation cases and sample applications from the approved LTR.

(e) If the baseline is not sufficient to test new models, functions or features, new test cases should be created:
- To verify that the new software function is consistent with the equations and models as described in the software documentation;
- To validate the new models, functions and features relative to its accuracy and applicability;
- To extend the baseline to capture evolving user techniques, expanded user applications or updated methodology guidelines.

Each test case specified in the SVVP should include acceptance criteria for the qualification of the software. The acceptance criteria should consider conservatisms required for consistency with applicable regulations and regulatory guidelines.

8.5.5. Software qualification

Software qualification should be demonstrated by satisfactory execution of the SVVP. Execution of the SVVP is to be documented in the certification file and includes:

- Record of execution of the SVVP;
- Documentation of important input, output and script files;
- Comparison of test case results with experimental data or reference output;
- Demonstrate that test results comply with the code requirements one method to demonstrate this compliance is through the requirements traceability matrix;
- Review of differences relative to acceptance criteria;
- Justification of all unexpected differences between test case results and reference output;
- Statement of conclusions.

8.5.6. Software review

The software development and maintenance activities performed under this SQAP should be confirmed by independent review. This independent review should be performed by one or more qualified individuals who did not prepare any of the materials being reviewed. The reviewer may be from the same organization, including the direct supervisor or manager, provided that the reviewer did not prescribe or limit the methods or inputs to be reviewed and the supervisor or manager is the only competent reviewer available within the schedule requirements of the software project. Justification for review by a manager should be documented to include the extent of the reviewing manager's input into the software items, and approved by the next higher level of management on each occasion.

The independent reviewer reviews the entire code certification file for the software to be released. Satisfactory completion of the independent review is evidenced by the reviewer's signature on the software release authorization (SRA).

8.5.7. Software release

An SRA is used to authorize the installation of the software on the computer system for production use. The SRA includes the following:

(a) For all installed software, applicable computer platforms or specific machines definition;
(b) Description of the code modifications impact on topical reports approved by the regulatory body;
(c) For internally developed or qualified software, a designation of the end product version to be installed as certified software in a controlled access system and its level of certification.

8.5.8. Software documentation

Certified software is to be documented and available at the time the SRA is signed. The following guidelines apply:

(a) The documentation should address functional (theory), application (user) and programming information for the software.
(b) To the maximum extent practical, the user and theory documents are to be maintained in a complete, non-fragmented form to minimize the confusion of multiple references in the official documentation.

(c) Regardless of the documentation structure (multiple manuals or a single manual), the following elements need to be addressed:
- — Application information (user manual);
- — Functional definition (theory manual);
- — Programming information (programmer manual).

8.5.9. Problem reporting

If an error is discovered in any software version or related documentation that could impact past results, error reporting for software is to be accomplished in compliance with a clear procedure.

8.5.10. Software retirement

When it is determined that a computer code is no longer required, software retirement is to be accomplished by issuance of an SRA which authorizes and announces the retirement and disablement of all remaining versions of the computer code.

9. HOW TO PREPARE, OBTAIN OR CHECK THE PRODUCT QUALITY AT THE SUCCESSIVE STEPS OF THE MANUFACTURING SEQUENCE

In Table 18, the first column gives the reference of the material or component (i.e. powder, pellet and end parts) and the identification number of the manufacturing step (see Section 5). An “X” in the second column indicates a step for sampling or to perform a quality control. The third column describes the manufacturing or controlling step. The fourth column provides comments on the main product quality expectation. This table presents only major steps of manufacture, including quality control operations, for powder (steps 1–8), pellets (steps 10–20), fuel rods (steps 23–34), end parts (steps 37 and 38), skeleton (step 39) and fuel assemblies (steps 40–48). Not mentioned in Table 18, steps 9, 21, 22, 35 and 36 relate not to major fabrication process but to recovery of rejects and recycle of chemical reagents. Steps 1–35 are described in Section 5 and Table 18, and might be seen in consecutive order on Figs 9, 10 and 21, but steps 37–48 are only described in Table 18.

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
Powder			
1		Install the UF_6 cylinder in the autoclave	None
2		UF_6 vaporization from autoclave	Vaporization process needs to be stable to feed the reactor with a UF_6 constant flow
3		UF_6 hydrolysis	Hydrolysis process needs to be stable to feed the next calciner with homogeneous UO_2F_2
4		UO_2F_2 calcination	Driving parameters (heater temp., vapour flow and H_2 flow) controlled to achieve a full transformation of UO_2F_2 into UO_2 throughout the calciner
5		UO_2 powder cooling	Powder is cooled down and dried into a N_2 inert flow
	X	Powder sampling and powder quality measurement	Powder conformity features are measured by destructive tests on samples (U5 content, isotopy, O/U ratio, low level of moisture, low level of impurities (F) and powder sinterability features)
6		Powder storage container	None

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
7		Powder preparation	This operation will contribute to powder homogeneity
8		Powder pneumatic transfer	Move through pneumatic transfer cannot alter the powder homogeneity (prevent reagglomeration)
Pellet			
10		Procure and prepare additives	None
		Blending	Constitute the blending batch (UO_2 + U_3O_8 + pore former + lubricant At the end of blending cycle, achieve a homogenized batch
11		Pre-compact press	Press is set to achieve a given density for the pellet
		Granulator	The granulator forces the product to pass through a calibrated sieve and then generates granulates of homogeneous size
		Download granulate into internal transportation container, add lubricant and perform spheroidization	Spheroidization rounds the shape of granulate Lubricant addition needs to be performed carefully to be well distributed over the volume of the batch

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
12		Pellet press	Press force is set to achieve a given density for the pellet
	X	Pressed pellet inspection	Pellet solidity is controlled through this on line inspection
13		Pellet boot loading	An automatic equipment arranges pellets layers into the sintering boxes
14		Move of the pressed pellets boot to the sintering furnace	None
	X	Sintering furnace	Main parameters to operate the sintering process are: temp. profile, flow of gas sent inside the furnace (N_2, H_2), level of moisture, furnace atmosphere, speed of boxes In the preheating zone the organic additives are evacuated At the middle of the furnace, the pellets get the final sintered features required by the designer Sintered pellet samples are collected at the exit of the furnace to check the pellet density

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
15	X	Pellet diameter grinder	Grinder process is monitored through a control chart Diameter of ground pellet is periodically measured Grinder is reset when deviation is observed on diameter control chart
16	X	Pellet diameter sorting	A machine automatically inspects in line every pellets and ejects immediately any pellet whose diameter is out of the range specified Some lines are equipped with equipment to check pellets also for surface imperfections
17		Pellet installation on trays	A machine automatically arranges pellets on the trays
18	X	Pellet visual aspect sorting	In case there is not automated surface inspection in place, all the pellets are inspected to eliminate any pellets showing abnormal visual aspect (chips or cracks of unacceptable size)
19	X	Pellet sampling and pellet quality measurement	Pellet conformity features could be measured by destructive tests on samples (e.g. U5 content, O/U ratio = 2, low level of impurities)

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
20		Pellet trays storage	Trays of pellet are stored until they are used to constitute fuel rods
Rod			
23	X	Rod components preparation (tube, plug, spring, spacer, mixing grids, gas helium pressure)	Components as received are clean and ready to be used When unpacking and installing the components on the line, cleanliness is confirmed through an over inspection
24 and 26	X	Bottom plug welding	Weld quality is obtained first by controlling the welding process: some main parameters of the process need to be operated within predetermined range Periodic weld samples are made and appropriate destructive tests (tensile test, metallographic examinations, corrosion) on theses samples will prove that the process is efficient and stable
25	X	Weld dimension and visual examination	In addition to the above actions to control and check the quality of the welding process, different examinations (dimensional, visual) are performed on line on every rod

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
27		Pellets loading	Parameters of the loading process need to be selected to prevent any damage on the pellets
28	X	Pellet stack final length adjustment	Conform length of pellet stack is checked and necessary pellets are added or removed
		Tube end face preparation	After having loaded the pellet stack, it is cleaned to make sure that the end face of tube where the top weld is free of any UO_2 random debris
		Spring installation	None
29	X	Pressurization and top plug welding	He is used in the welding chamber at the pressure required by the designer for the rod pressure When the pressure has been installed in the rod, the top plug is pushed against the tube end and the weld closing the rod can be performed; alternatively, the rod could become pressurized after welding of the upper end plug by a filling hole which is sealed afterwards The welding process is controlled as already described for the bottom plug (welding parameters control + tests on weld samples)

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
30	X	Top weld dimension and visual examination	Examinations (dimensional, visual) are performed on line on every rod, as described for the bottom plug
31	X	Gamma scanner	Rod conformity features are verified from the gamma scanner, such as conformity of pellet stack constitution Gamma scan can detect any abnormal event which could have changed the U5 linear density along the pellet stack, such as a pellet of different enrichment or a gap in the pellet stack
	X	Densitometry	Rod conformity features are verified from the densitometry picture analysis (spring plenum dimension, spring presence, a gap in the pellet stack)
32	X	Rod weight	Measurement could give complementary information on the UO_2 quantity per rod
33	X	He leak test	Rod conformity features are verified from the He leak test If the helium sensor does not detect any helium, the rod welds are tight

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
34	X	Rod visual examination	Attentive examination of the rod confirms that the rod tube has not experienced any concerning event (mechanical damage, incidental pollution) during the travel on the line
End parts			
37	X	Procure the incoming metallic raw materials (stainless steel, Ni based alloys)	Quality of the raw materials used is obtained through the following actions: — Technical requirements on materials delivered are specified to the supplier selected — Supplier manufacturing sequence is reviewed — Source inspections are performed to release the materials lots
		Operate the different processes used to make subcomponents (machining, cutting, bending)	When implementing the different processes to obtain the parts, it needs to be verified that every process selected can generate parts which will contribute to the expected final quality (part dimensional features and materials surface features)

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
	X	Operate the different fastening processes (welding, brazing)	Weld or brazing quality is obtained first by controlling the process: some main parameters of the process need to be operated within predetermined range Periodic samples are made and appropriate destructive tests (tensile test, metallographic examinations, corrosion) on theses samples will prove that the process is stable (repetitive)
		Operate different finishing processes (electrical discharge machining, electropolishing, sand blasting, pickling)	Quality of the resulting parts is obtained first by controlling the process: some main parameters of the process need to be operated within appropriate selected range
	X	Operate different materials heat treatment processes	Tests on part samples prove that when operating within this range the resulting part will have the expected materials quality
	X	Operate different cleaning processes	Cleanliness of the parts is obtained by controlling the main parameters of the washing process (washing cycle, washing and rinsing liquid properties) Tests on part samples prove that when operating within this range the resulting parts will have the expected cleanliness quality

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
	X	Perform dimensional inspection of the parts performed at different steps of manufacturing	Measurements of parts dimensions are performed at the some steps of the manufacturing sequence by the use of tactile and optical coordinate measuring machines and gauges
	X	Perform visual aspect examinations of the parts at different steps of manufacturing	Visual examinations of parts are performed at the some steps of the manufacturing sequence and address the following aspects of quality: — Confirm cleanliness of the part examined — No presence of foreign object in the part examined
38	X	Procurement of incoming metallic raw materials (Zr alloy strip, Ni based alloys strip)	Quality of the raw materials used is obtained through the following actions: — Technical requirements on materials delivered are specified to the supplier selected — Supplier manufacturing sequence is reviewed — Source inspection are performed to release the materials lots

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
	X	Operate stamping processes used to obtain spacer and mixing grid subcomponents: strap and spring	When implementing the stamping processes to obtain the parts, it needs to be verified that every process selected can generate parts which will contribute to the expected final quality as to the dimensional features, the materials features Quality of the parts is over checked by regularly performed surveillances at the subsuppliers manufacturing shop
	X	Operate different cleaning processes (strap washing, spring washing)	Cleanliness of the parts is obtained by controlling the main parameters of the cleaning process (washing cycle, washing and rinsing liquid properties) Tests on part samples prove that when operating within this range the resulting parts will have the expected cleanliness quality
	X	Operate different materials heat treating processes (Ni based alloys aging treatment for spacer grid components and complete spacer grids, Zr strap stress release treatment)	Quality of the treated parts is obtained first by controlling the process: some main parameters of the process need to be operated within selected ranges Tests on part samples prove that when operating within these ranges the resulting part will have the expected materials quality

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
	X	Operate different mounting and fastening processes (spacer welding, spring welding)	Weld quality is obtained first by controlling the welding process: some main parameters of the process need to be operated within predetermined range Periodic weld samples are made and appropriate destructive tests (tensile test, metallographic examinations, corrosion) on theses samples will prove that the process is stable
	X	Perform dimensional inspection of the parts manufactured at the different steps of manufacturing (strap, spring, strap with spring installed, completed spacer)	Measurements of parts dimensions are performed at the successive steps of the manufacturing sequence (strap, spring, strap with spring installed, completed spacer)
	X	Final visual aspect of the parts made at the different steps of manufacturing (strap, spring, strap with spring installed, completed spacer)	Visual examinations of parts are performed at the different steps of the manufacturing sequence and address the following aspects of quality: — Conform aspect of the weld points or weld fillets — Confirm cleanliness of the part examined — No presence of foreign object in the part examined — Assure a strap configuration according to the technical file

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
Skeleton			
39		Positioning of the parts to be fastened on the skeleton welding equipment	Accurate position of the different parts is requested to contribute to the final dimensional quality of the completed skeleton
	X	Different fastening processes (welding, swaging)	Weld or swaging quality is obtained first by controlling the fastening process: some main parameters of the process need to be operated within predetermined range Periodic samples are made and appropriate destructive tests (tensile test, metallographic examinations, corrosion) on theses samples will prove that the process is stable
	X	Measurement of dimensional features of skeleton	Measurements cover overall dimensions length, straightness, verticality For some products, these are performed on the level of the completed fuel assembly

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
	X	Final visual aspect of skeleton	Visual examinations of skeleton address the following aspects of quality — Conform aspect of the weld points and swaging junctions — Confirm cleanliness of the skeleton examined — No presence of foreign object
Assembly			
40		Install and position of the skeleton to be loaded	The skeleton needs to be accurately installed and strongly clamped on the assembly bench
		Rod loading operation	The pulling/pushing forces the rod to slide through the spacers
		End parts installation	An accurate position of the parts needs to be obtained to contribute to the final quality features of the completed assembly (verticality, length)
41		Move of the assembly from the horizontal position to the vertical position and further handling by hoist system	When completed, the assembly is stored and handled in vertical position Handling is performed at very low speed to minimize the risks of overload and damage

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
42		Cleaning operation	None
43	X	Measure the dimensions of the completed fuel assembly	Features measured include assembly length, verticality, straightness and spaces between rods Some features could be checked on skeleton stage already
44	X	Check control rod insertion (PWR only)	The control rods need to be moved without any significant friction effort
45	X	Final visual aspect of the assembly	Attentive examination checks that the assembly has not experienced any concerning event (mechanical damage, pollution) during the travel on the line
		Fuel channelling (BWR only)	Mount the fuel channel to the fuel assembly
46		Storage in rack of released assemblies	The assembly is handled and stored in a vertical position The handling and storage conditions look like the further conditions applied in the nuclear plant

TABLE 18. MAJOR STEPS OF NUCLEAR FUEL MATERIALS, COMPONENTS, FUEL RODS AND FUEL ASSEMBLIES MANUFACTURING AND RESPECTIVE METHODS OF PROCESS QUALITY CONTROL (cont.)

Manufacturing step number[a]	Quality control or sampling step	Successive activities to manufacture the product or check the product quality	Comments on the main product quality expectation being considered when driving the manufacturing or inspection activities
47		Prepare the container used to ship the assemblies	There are precise quality requirements for the fixture where the assembly will be placed and clamped to prevent any damage at the assembly installation
		Install the assembly into container	The assembly is installed and clamped on the container fixture Then the assembly is moved at very low speed to prevent any damage A detailed instruction defines the right way the assembly needs to be installed and clamped of on the supporting fixture
48		Handle the loaded container when preparing the shipping of the assemblies to the nuclear plant	The loaded container is moved at very low speed to prevent any damage

Note: BWR — boiling water reactor; PWR — pressurized water reactor.

[a] See Section 5.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Energy Basic Principles, IAEA Nuclear Energy Series No. NE-BP, IAEA, Vienna (2008).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Nuclear Fuel Cycle Objectives, IAEA Nuclear Energy Series No. NF-O, IAEA, Vienna (2013).

[3] STRASSER, A., RUDLING, P., Fuel Fabrication Process Handbook, Rep. ANTI 05-0008R, ANT International, Surahammar (2004).

[4] COX, B., GARZAROLLI, F., ADAMSON, R., RUDLING, P., STRASSER, A., Fuel Material Technology Report, Vol. I, ANT International, Skultuna (2006).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Computational Analysis of the Behaviour of Nuclear Fuel Under Steady State, Transient and Accident Conditions, IAEA- TECDOC-1578, IAEA, Vienna (2007).

[6] NUCLEAR ENGINEERING INTERNATIONAL, Fuel design data, Nuclear Engineering International **54** 662 (2009) 36–48.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Design of Fuel Handling and Storage Systems for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.4, IAEA, Vienna (2003).

[8] TAYAL, M., et al., "ACR-1000 fuel acceptance criteria for normal operation and for anticipated operational occurrences", Proc. 10th Int. CNS CANDU Fuel Conf. Ottawa, 2008, CNS, Toronto (2008).

[9] RUDLING, P., et al., Effects of Coolant Chemistry on Fuel Performance, ANT International, Mölnlycke (2013).

[10] AKSENOV, P., et al., "Improving the VVER-440 fuel design and technology", WWER Fuel Performance, Modelling and Experimental Support (Proc. 8th Int. Conf. Helena Resort, 2009), BAS/INRNE, Sofia (2009).

[11] LAVRENYUK, P., MOLCHANOV, V., TROYANOV, V., IONOV, V., "Nuclear fuel for VVER reactors. Current status and prospects", WWER Fuel Performance, Modelling and Experimental Support (Proc. 7th Int. Conf. Albena Congress Center, 2007), BAS/INRNE, Sofia (2008).

[12] SAMOILOV, O.B., et al., "Results of TVSA fuel assembly development and 10-year operation in VVER-1000 reactor cores, development trends", WWER Fuel Performance, Modelling and Experimental Support (Proc. 8th Int. Conf. Helena Resort, 2009), BAS/INRNE, Sofia (2009).

[13] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Specification for Wrought Zirconium and Zirconium Alloy Seamless and Welded Tubes for Nuclear Service (Except Nuclear Fuel Cladding), ASTM B-353, ASTM, West Conshohocken, PA (2007).

[14] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Specification for Wrought Zirconium Alloy Seamless Tubes for Nuclear Reactor Fuel Cladding, ASTM B-811-02, ASTM, West Conshohocken, PA (2007).

[15] RUDLING, P., ADAMSON, R., COX, B., GRAZAROLLI, F., STRASSER, A., High burnup fuel issues, Nucl. Eng. Tech. **40** 1 (2008) 1–8.

[16] STRASSER, A., EPPERSON, K., HOLM, J., RUDLING, P., LUNDBERG, S., Fuel Design Review Handbook, ANT International, Skultuna (2010).
[17] RUDLING, P., et al., Fuel Material Technology Report, Vol. II, ANT International, Skultuna (2007).
[18] ADAMSON, R., COX, B., RUDLING, P., STRASSER, A., WIKMARK, G., The Annual Review of Zirconium Alloy Technology for 2000, ZIRAT5/IZNA1 Annual Report, ANT International, Skultuna (2000).
[19] ADAMSON, R., COX, B., STRASSER, A., RUDLING, P., ZIRAT6/IZNA1 Annual Report, ANT International, Skultuna (2001).
[20] STRASSER, A., ADAMSON, R., COX, B., WIKMARK, G., RUDLING, P., ZIRAT7/IZNA2 Annual Report, ANT International, Skultuna (2002).
[21] STRASSER, A., ADAMSON, R., COX, B., WIKMARK, G., RUDLING, P., ZIRAT8/IZNA3 Annual Report, ANT International, Skultuna (2003).
[22] ADAMSON, R., COX, B., GARZAROLLI, F., STRASSER, A., RUDLING, P., ZIRAT9/IZNA4 Annual Report, ANT International, Skultuna (2004).
[23] ADAMSON, R., et al., ZIRAT10/IZNA5 Annual Report, ANT International, Skultuna (2005).
[24] ADAMSON, R., et al., ZIRAT11/IZNA6 Annual Report, ANT International, Skultuna (2006).
[25] STRASSER, A., et al., ZIRAT12/IZNA7 Annual Report, ANT International, Skultuna (2007).
[26] STRASSER, A., ADAMSON, R., COX, B., GARZAROLLI, F., RUDLING, P., ZIRAT13/IZNA8 Annual Report, ANT International, Skultuna (2008).
[27] ADAMSON, R.B, GARZAROLLI, F., PATTERSON, C., RUDLING, P., STRASSER, A., ZIRAT14/IZNA9 Annual Report, ANT International, Skultuna (2009).
[28] FORD, F.P., Environmentally-Assisted Degradation of Structural Materials in Water Cooled Nuclear Reactors, ANT International, Skultuna (2006).
[29] FORD, P., SCOTT, P.M., COMBRADE, P., Environmentally-Assisted Degradation of Stainless Steels in LWRs, ANT International, Skultuna (2010).
[30] ADAMSON, R.B., GARZAROLLI, F., STRASSER, A., RUDLING, P., WIKMARK, G., High Burnup Fuel Issues, IZNA-3 Special Topics Report, ANT International, Skultuna (2004).
[31] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of Fuel Failures in Water Cooled Reactors, Technical Reports Series No. 388, IAEA, Vienna (1998).
[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of Fuel Failures in Water Cooled Reactors, IAEA Nuclear Energy Series No. NF-T-2.1, IAEA, Vienna (2010).
[33] RUDLING, P., ADAMSON, R.B., GARZAROLLI, F., Loss of Coolant Accidents, LOCA, and Reactivity Initiation Accidents, RIA, in BWRs and PWRs, IZNA4 Special Topics Report, ANT International, Skultuna (2005).
[34] KLINGER, W., PETIT, C., WILLSE, J.T., "Experience and reliability of Framatome ANP's PWR and BWR fuel", Fuel Failure in Water Reactors: Causes and Mitigation (Proc. Tech. Mtg Bratislava, 2002), IAEA-TECDOC-1345, IAEA, Vienna (2003) 21–29.
[35] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Design, IAEA Safety Standards Series No. SSR-2/1, IAEA, Vienna (2012).

[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Analysis of Differences in Fuel Safety Criteria for WWER and Western PWR Nuclear Power Plants, IAEA-TECDOC-1381, IAEA, Vienna (2003).
[37] ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Fuel Safety Criteria Technical Review: Results of OECD/CSNI/PWG2 Task Force on Fuel Safety Criteria, NEA/CSNI/R(99)25, OECD, Paris (2000).
[38] INTERNATIONAL ATOMIC ENERGY AGENCY, Design of the Reactor Core for Nuclear Power Plants, IAEA Safety Standards Series No. NS-G-1.12, IAEA, Vienna (2005).
[39] INTERNATIONAL ATOMIC ENERGY AGENCY, Accident Analysis for Nuclear Power Plants with Pressurized Water Reactors, Safety Reports Series No. 30, IAEA, Vienna (2003).
[40] INTERNATIONAL ATOMIC ENERGY AGENCY, Accident Analysis for Nuclear Power Plants with Pressurized Heavy Water Reactors, Safety Reports Series No. 29, IAEA, Vienna (2003).
[41] INTERNATIONAL ATOMIC ENERGY AGENCY, Accident Analysis for Nuclear Power Plants, Safety Reports Series No. 23, IAEA, Vienna (2002).
[42] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Commissioning and Operation, IAEA Safety Standards Series No. SSR-2/2, IAEA, Vienna (2011).
[43] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Fuel Cycle Facilities, IAEA Safety Standards Series No. NS-R-5, IAEA, Vienna (2008).
[44] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Uranium and Plutonium Mixed Oxide Fuel Fabrication Facilities, IAEA Safety Standards Series No. SSG-7, IAEA, Vienna (2010).
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Uranium Fuel Fabrication Facilities, IAEA Safety Standards Series No. SSG-6, IAEA, Vienna (2010).
[46] INTERNATIONAL ATOMIC ENERGY AGENCY, Review of Fuel Element Developments for Water Cooled Nuclear Power Reactors, Technical Report Series No. 299, IAEA, Vienna (1989).
[47] BAUR, K., VON COLLANI, E., Nuclear Fuel Quality Management Handbook, Volume I: Fabrication, Operation, Disposal and Transport of Nuclear Fuel, ANT International, Skultuna (2010).
[48] INTERNATIONAL ATOMIC ENERGY AGENCY, Advanced Fuel Pellet Materials and Fuel Rod Design for Water Cooled Reactors (Proc. Tech. Comm. Mtg Brussels, 2003), IAEA-TECDOC-1416, IAEA, Vienna (2004).
[49] INTERNATIONAL ATOMIC ENERGY AGENCY, Advanced Fuel Pellet Materials and Fuel Rod Design for Water Cooled Reactors, IAEA-TECDOC-1654, IAEA, Vienna (2010).
[50] INTERNATIONAL ATOMIC ENERGY AGENCY, Quality Assurance and Control in the Manufacture of Metal-clad UO_2 Reactor Fuels, Technical Report Series No. 173, IAEA, Vienna (1976).
[51] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidebook on Quality Control of Water Reactor Fuel, Technical Report Series No. 221, IAEA, Vienna (1982).

[52] GAGARIN, A.E., YASHIN, S.A., GRABELNIKOV, K.V., “Production and control of quality of ceramic powders and fuel pellets of low enriched uranium oxide for light water reactors”, Characterization and Quality Control of Nuclear Fuels (GANGULY, C., JAYARAJ, R.N., Eds), Allied Publishers, New Delhi (2002) 563–573.

[53] OJHA, P.B., MEENA, R., RADHAKRISHNA, C., RAO, S.M., GANGULY, C., “Dry recycling of off-grade uranium oxide powder for improving sinterability”, Proc. 8th Int. CNS CANDU Fuel Conf. Muskoka, 2003, CNS, Toronto (2003).

[54] JAYARAJ, R.N., SINGH, A., GANGULY, C., “Production of nuclear fuels for water cooled power reactors in India”, Characterization and Quality Control of Nuclear Fuels (GANGULY, C., JAYARAJ, R.N., Eds), Allied Publishers, New Delhi, (2002) 177–186.

[55] DORR, W., “Fuel manufacturing and pellet properties for a superior operational behaviour” (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).

[56] RUDLING, P., et al., Impact of Manufacturing Changes on Zr alloy In-Pile Performance, Skultana (2009).

[57] GUPTA, C.K. (Ed.), Special Issue: Chemistry and Metallurgy of Refractory and Reactive Metals and Materials Extraction and Processing, Part 1, Vol. 9, No. 24, Freund Publication House, London (1990): and High Temperature Materials and Processes, Part 2, Vol. 11, No. 14, Freund Publication House, London (1993).

[58] GANGULY, C., “Fabrication, characterization and quality control of nuclear fuels for power reactors in India”, Characterization and Quality Control of Nuclear Fuels (GANGULY, C., JAYARAJ, R.N., Eds), Allied Publishers, New Delhi (2002) 37–64.

[59] GANGULY, C., “Manufacturing experience of natural and enriched uranium oxide fuels in India”, Proc. Int. Symp. on Nuclear Power on the Threshold of the XXI Century, Electrostal, Russian Federation (2000) 540–550.

[60] GOTTUSO, D., CANAT, J.-N., MOLLARD, P., “High mechanical performance of AREVA upgraded fuel assemblies for PWR in USA”, LWR Fuel Performance Meeting/Top Fuel 2007, ANS, San Francisco, CA (2007) 30–35.

[61] KRYLOV, D.V., “Operational experience of the combined absorbing rods of RCCA for WWER-1000 reactors”, WWER Fuel Performance, Modelling and Experimental Support (Proc. 6th Int. Conf. Albena, 2005), BAS/INRNE, Sofia (2005).

[62] PERSSON, K.D., IAEA safety standards on management systems and safety culture, Atom Indonesia **33** 1 (2007).

[63] DOES, R.J.M.M., ROES, K.C.B., TRIP, A., Statistical Process Control in Industry, Kluwer, Dordrecht (1996).

[64] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-R-3, IAEA, Vienna (2006).

[65] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Management Systems: Fundamentals and Vocabulary, ISO 9000:2005, ISO, Geneva (2005).

[66] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Quality Management Systems: Requirements, ISO 9001:2008, ISO, Geneva (2008).

[67] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Managing for the Sustained Success of an Organization: A Quality Management Approach, ISO 9004:2009, ISO, Geneva (2009).
[68] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Environmental Management Systems: Requirements with Guidance for Use, ISO 14001:2004, ISO, Geneva (2004).
[69] INTERNATIONAL ATOMIC ENERGY AGENCY, Management System Standards: Comparison between IAEA GS-R-3 and ISO 9001:2008, Safety Reports Series No. 69, IAEA, Vienna (2012).
[70] INTERNATIONAL ATOMIC ENERGY AGENCY, Application of the Management System for Facilities and Activities, IAEA Safety Standards Series No. GS-G-3.1, IAEA, Vienna (2006).
[71] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Technical Services in Radiation Safety, IAEA Safety Standards Series No. GS-G-3.2, IAEA, Vienna (2008).
[72] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for the Processing, Handling and Storage of Radioactive Waste, IAEA Safety Standards Series No. GS-G-3.3, IAEA, Vienna (2008).
[73] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for the Disposal of Radioactive Waste, IAEA Safety Standards Series No. GS-G-3.4, IAEA, Vienna (2008).
[74] INTERNATIONAL ATOMIC ENERGY AGENCY, The Management System for Nuclear Installations, IAEA Safety Standards Series No. GS-G-3.5, IAEA, Vienna (2009).
[75] INTERNATIONAL ATOMIC ENERGY AGENCY, Radiation Protection Programmes for the Transport of Radioactive Material, IAEA Safety Standards Series No. TS-G-1.3, IAEA, Vienna (2007).
[76] NUCLEAR REGULATORY COMMISSION, Domestic Licensing of Production and Utilization Facilities, 10 CFR 50, US Govt Printing Office, Washington, DC (2014).
[77] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Culture: A Report by the International Nuclear Safety Advisory Group, Safety Series No. 75-INSAG-4, IAEA, Vienna (1991).
[78] INTERNATIONAL ATOMIC ENERGY AGENCY, Key Practical Issues in Strengthening Safety Culture: A Report by the International Nuclear Safety Advisory Group, INSAG-15, IAEA, Vienna (2002).
[79] SCHEIN, E.H., Organizational Culture and Leadership, John Wiley and Sons, San Francisco, CA (2004).
[80] NUCLEAR REGULATORY COMMISSION, Statement of Organization and General Information, 10 CFR 1, US Govt Printing Office, Washington, DC (2014).
[81] AMERICAN SOCIETY OF MECHANICAL ENGINEERS, Quality Assurance Requirements for Nuclear Facility Applications, ASME NQA-1-2012, ASME, New York (2013).
[82] BRITISH STANDARDS INSTITUTION, Occupational Health and Safety Management Systems: Requirements, OHSAS 18001:2007, BSI, London (2007).

[83] Regulation (EC) No. 1221/2009 of the European Parliament and of the Council of 25 November 2009 on the voluntary participation by organisations in a Community eco-management and audit scheme (EMAS), repealing Regulation (EC) No. 761/2001 and Commission Decisions 2001/681/EC and 2006/193/EC, Official Journal of the European Union L 342, Publications Office of the European Union, Luxembourg (2009).
[84] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Assessment for Facilities and Activities: General Safety Requirements, IAEA Safety Standards Series No. GSR Part 4, IAEA, Vienna (2009).
[85] INTERNATIONAL ATOMIC ENERGY AGENCY, Deterministic Safety Analysis for Nuclear Power Plants: Specific Safety Guide, IAEA Safety Standards Series No. SSG-2, IAEA, Vienna (2009).
[86] HELMERSSON, B., YOUNG, M., WIKMARK, G., HAHN, P., "Maintaining and improving fuel reliability", WRFPM Top Fuel 2009 (Proc. Water Reactor Fuel Perf. Mtg Paris, 2009), SFEN, Paris (2009) 85–93.
[87] EDSINGER, K., et al., "Recent US fuel reliability experience", WRFPM Top Fuel 2009 (Proc. Water Reactor Fuel Perf. Mtg Paris, 2009), SFEN, Paris (2009) 100–106.
[88] TOMPKINS, B., Advancing the cause of fuel reliability, Nucl. News **51** 7 (2008) 34–36.
[89] STRASSER, A., EPPERSON, K., HOLM, J., RUDLING, P., "Design reviews for reliable fuel performance", WRFPM Top Fuel 2010 (Proc. LWR Fuel Perf. Mtg Orlando, 2010), ANS, LaGrange Park, IL (2010) 1–10.
[90] INSTITUTE OF NUCLEAR POWER OPERATIONS, Guidelines for Achieving Excellence in Nuclear Fuel Performance, INPO Rep. 07-004, Atlanta, GA (2009).
[91] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Safety Glossary: Terminology Used in Nuclear Safety and Radiation Protection (2007 Edition), IAEA, Vienna (2007).
[92] UNITED STATES DEPARTMENT OF ENERGY, Safety Software Guide for Use with 10 CFR 830, Subpart A, Quality Assurance Requirements, and DOE O 414.1C, Quality Assurance, DOE G 414.1-4, USDOE, Washington, DC (2005).
[93] SHEWHART, W.A., Economic Control of Quality of Manufactured Product, D. Van Nostard Company, New York (1931).
[94] SHEWHART, W.A., Application of Statistical Methods to Manufacturing Problems, Bell Telephone Labs, New York (1938).
[95] GRANT, E.L., LEAVENWORTH, R.S., Statistical Quality Control, 6th edn, McGraw-Hill, New York (1988).
[96] INTERNATIONAL ATOMIC ENERGY AGENCY, Delayed Hydride Cracking in Zirconium Alloys in Pressure Tube Nuclear Reactors, IAEA-TECDOC-1410, IAEA, Vienna (2004).
[97] BICKEL, G.A., et al., The determination of hydrogen and deuterium in Zr-2.5Nb material by vacuum hot extraction mass spectrometry, J. Nucl. Mater. **306** (2002) 21–29.
[98] INTERNATIONAL ATOMIC ENERGY AGENCY, Guidebook on Destructive Examination of Water Reactor Fuel, Technical Report Series No. 385, IAEA, Vienna (1997).

[99] TERÄSVIRTA, R., “A perfect fuel supplier”, WWER Fuel Performance, Modelling and Experimental Support (Proc. 7th Int. Conf. Albena Congress Center, 2007), BAS/INRNE, Sofia (2008).
[100] DODGE, H.F., ROMIG, H.G., Sampling Inspection Tables, John Wiley, New York (1944).
[101] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Guide for Establishing Calibration for a Measurement Method Used to Analyze Nuclear Fuel Cycle Materials, ASTM C1156, Rev. 3, ASTM, West Conshohocken, PA (2003).
[102] AMERICAN NATIONAL STANDARDS INSTITUTE, Calibration Laboratories and Measuring and Test Equipment General Requirements, ANSI Z540-1-1994 (1994).
[103] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Measurement Management Systems: Requirements for Measurement Processes and Measuring Equipment, ISO 10012:2003, ISO, Geneva (2003).
[104] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Guide for Qualification of Laboratory Analysts of Nuclear Fuel Cycle Materials, ASTM C1297, Rev. 3, ASTM, West Conshohocken, PA (2011).
[105] AMERICAN SOCIETY OF NONDESTRUCTIVE TESTING, Recommended Practice, Personnel, Qualification and Certification in Non-destructive Testing, 8th edn, ASNT-TC-1A (2011).
[106] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Design and Quality Assurance Practices for Nuclear Fuel Rods, ASTM C 934 (1985), Rev. 2, ASTM, West Conshohocken, PA (1990).
[107] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, INTERNATIONAL ELECTROCHEMICAL COMMISSION, Information Technology: Security Techniques, Code of Practice for Information Security Management, ISO/IEC 27002:2005, ISO, Geneva (2005).
[108] NUCLEAR REGULATORY COMMISSION, Software Quality Assurance Program and Guidelines, Rep. NUREG/BR-0167, US Govt. Printing Office, Washington, DC (1993).
[109] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, INTERNATIONAL ELECTROCHEMICAL COMMISSION, Software Engineering: Guidelines for the Application of ISO 9001:2000 to Computer Software, ISO/IEC 90003:2004, ISO, Geneva (2004).
[110] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Specification for Zirconium Sponge and Other Forms of Virgin Metal for Nuclear Application, ASTM B349/B349M, ASTM, West Conshohocken, PA (2009).
[111] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Specification for Zirconium and Zirconium Alloy Ingots for Nuclear Application, ASTM B350, ASTM, West Conshohocken, PA (2011).
[112] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Test Methods for Tension of Metallic Materials, ASTM E8/E8M, ASTM, West Conshohocken, PA (2009).
[113] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Test Methods for Elevated Temperature Tension Tests of Metallic Materials, ASTM E21, ASTM, West Conshohocken, PA (2009).

[114] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Test Method for Corrosion Testing of Products of Zirconium, Hafnium, and Their Alloys in Water at 680°F (360°C) or in Steam at 750°F (400°C), ASTM G2/G2M, ASTM, West Conshohocken, PA (2011).
[115] YADAV, R.B., "Chemical quality control of fuels and structurals" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2009).
[116] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Practice for Ultrasonic Pulse-Echo Straight-Beam Contact Testing, ASTM E114, ASTM, West Conshohocken, PA (2010).
[117] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Test Methods for Brinel Hardness of Metallic Materials, ASTM E10, ASTM, West Conshohocken, PA (2010).
[118] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Test Methods for Rockwell Hardness of Metallic Materials, ASTM E18, ASTM, West Conshohocken, PA (2008).
[119] ACHARYA, R., NAIR, A.G.C., SUDARSHAN, K., REDDY, A.V.R., GOSWAMI, A., "Compositional analysis of fuel cladding materials by a standard-less method of instrumental neutron activation analysis" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).
[120] STEHLE, H., KADEN, W., MANZEL, R., External corrosion of cladding in PWRS, Nucl. Eng. Des. **33** (1975) 155–169.
[121] SRIVASTAVA, R.K., HEMANTH RAO, G.V.S., "QA and NDT of clad and fuel for PHWRs" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).
[122] AMERICAN SOCIETY FOR TESTING AND MATERIALS, Standard Practice for Ultrasonic Testing of Metal Pipe and Tubing, ASTM E213, ASTM, West Conshohocken, PA (2009).
[123] GRAHAM, R.A., "Inspection, NDT, and testing of zirconium alloy mill products" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).
[124] YANG, Q., "QA and QC practice of PWR fuel fabrication in China" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2002).
[125] PÉREZ, L., et al., "Characterization studies in CANDU and KWU-types nuclear fuel pellets" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).
[126] PRASAD, P.N., TRIPATHI, R.M., DWIVEDI, K.P., "Effect of fuel manufacturing parameters on pellet cladding interaction in reactor: A review" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2009).
[127] AGGARWAL, S.K., et al., "Electroanalytical techniques for the determination of U and Pu in fuel materials" (Proc. Int. Conf. International Conference on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).
[128] KUTTY, T.R.G., et al., Densification behaviour of UO_2 in six different atmospheres, J. Nucl. Mat. **305** (2002) 159–168.

[129] BALAJI RAO, Y., SATYANARAYANA, M., RAVINDRA, H.R., GOPALAN, B., "Quantitative determination of impurities including rare earths in nuclear grade Thoria", Proc. 8th Int. CNS CANDU Fuel Conf. Muskoka, 2003, CNS, Toronto (2003).

[130] KAPOOR, K., PRAMANIK, D., OJHA, P.B., RAJKUMAR, J.V., KUMAR, K., "Quality control in pellet fabrication-handling two different sources of UO_2" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).

[131] GUYEN, N., DOAN, V., "The quality control results of UO_2 powder and UO_2 pellets prepared at ITRRE laboratory" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2005).

[132] BALAKRISHNA, P., et al., Uranium dioxide powder preparation, pressing, and sintering for optimum yield, Nucl. Tech. **127** (1999) 375–381.

[133] CHAKRABORTHY, K.P., et al., "Effects of loading pattern on high temperature sintering of UO_2 pellets", Proc. 6th Int. CNS CANDU Fuel Conf. Niagara Falls, 1999, CNS, Toronto (1999).

[134] SONG, K.W., KIM, K.S., KANG, K.W., JUNG, Y.H., Grain size control of UO_2 pellets by adding heat-treated U_3O_8 particles to UO_2 powder, J. Nucl. Mat. **317** (2003) 204–211.

[135] KAMALESH KUMAR, B., VISHWANATHAN, B., LAXMINARAYANA, B., GANGULY, C., "Development of innovative inspection tools for higher reliabililty of PHWR fuel", Proc. 8th Int. CNS CANDU Fuel Conf. Muskoka, 2003, CNS, Toronto (2003).

[136] HEMANTHA, R.G.V.S., JAYARAJ, R.N., PRAKASH, M.S., GUPTA, U.C., GANGULY, C., "Performance of Indigenous resistance welding equipment for PHWR fuel fabrication: NFC experience", Proc. 6th Int. CNS CANDU Fuel Conf. Niagara Falls, 1999, CNS, Toronto (1999).

[137] RAVI, M., PRASAD, P.N., BAJAJ, S.S., BHARDWAJ, S.A., "Effect of design, manufacturing and quality on fuel performance" (Proc. Int. Conf. on Characterization and Quality Control of Nuclear Fuels, Hyderabad, 2002).

[138] ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development, OECD, Paris (2002).

[139] TON-THAT, M., BONNET, E., "EDF' surveillance on fuel manufacturing", WRFPM Top Fuel 2009 (Proc. Water Reactor Fuel Perf. Mtg Paris, 2009), SFEN, Paris (2009) 129–134.

[140] SHANKAR KUMAR, J., LAKSHMINARAYANA, B., "Quality control of PHWR fuel tube closure welds" (Proc. Symp. on Zirconium Alloys for Reactor Components, Mumbai, 1991).

[141] CHOI, M.S., YANG, M.S., Quality evaluation and control of end cap welds in PHWR fuel elements by ultrasonic examination, J. Nucl. Mat. **178** (1991) 321–327.

ABBREVIATIONS

ACS	access control system
ADU	ammonium diuranate
ANSI	American National Standards Institute
AOO	anticipated operational occurrence
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AUC	ammonium uranyl carbonate
BWR	boiling water reactor
CANDU	Canada deuterium–uranium
CHF	critical heat flux
CRDM	control rod drive mechanism
CRUD	chalk river unidentified deposits
DNB	departure from nucleate boiling
EDF	Électricité de France
EMAS	Eco-Management and Audit Scheme
EQN	evaluation of qualification needs
FRED	fuel rod exchange device
GNF	Global Nuclear Fuel
GTRF	grid to rod fretting
HWR	heavy water reactor
ICID	in-core instrumentation device
ICP-MS	inductively coupled plasma mass spectrometry
ID	inner diameter
IDMS	isotope dilution mass spectrometry
IEC	International Electrochemical Commission
IMS	integrated management system
INPO	Institute of Nuclear Power Operations
ISO	International Organization for Standardization
L/D	pellet length to diameter ratio
LHGR	linear heat generation rate
LOCA	loss of coolant accident
LTR	Licensed Topical Report
LWR	light water reactor
MOX	mixed oxide
NDE	non-destructive examination
NDT	non-destructive testing
NFC	Nuclear Fuel Complex
NRC	United States Nuclear Regulatory Commission
OD	outer diameter

PCI	pellet cladding interaction
PCMI	pellet cladding mechanical interaction
PHWR	pressurized heavy water reactor
PWR	pressurized water reactor
QA/QC	quality assurance and quality control
QMS	quality management system
RBMK	high power channel type reactor (Russian graphite moderated light water cooled reactor)
RCCA	rod cluster control assembly
RIA	reactivity initiated accident
SCC	stress corrosion cracking
SQAP	software quality assurance programme
SRA	software release authorization
SS	stainless steel
SSE	safe shutdown earthquake
SVVP	software verification and validation plan
TBP	tributyl phosphate
TCE	thermal coefficient of expansion
TIG	tungsten inert gas
TIMS	thermal ionization mass spectrometry
UML	Unified Modeling Language
UT	ultrasonic testing
UTS	ultimate tensile strength
VVER	water cooled water moderated power reactor (Voda Voda Energo Reactor, Russian pressurized light water cooled reactor)

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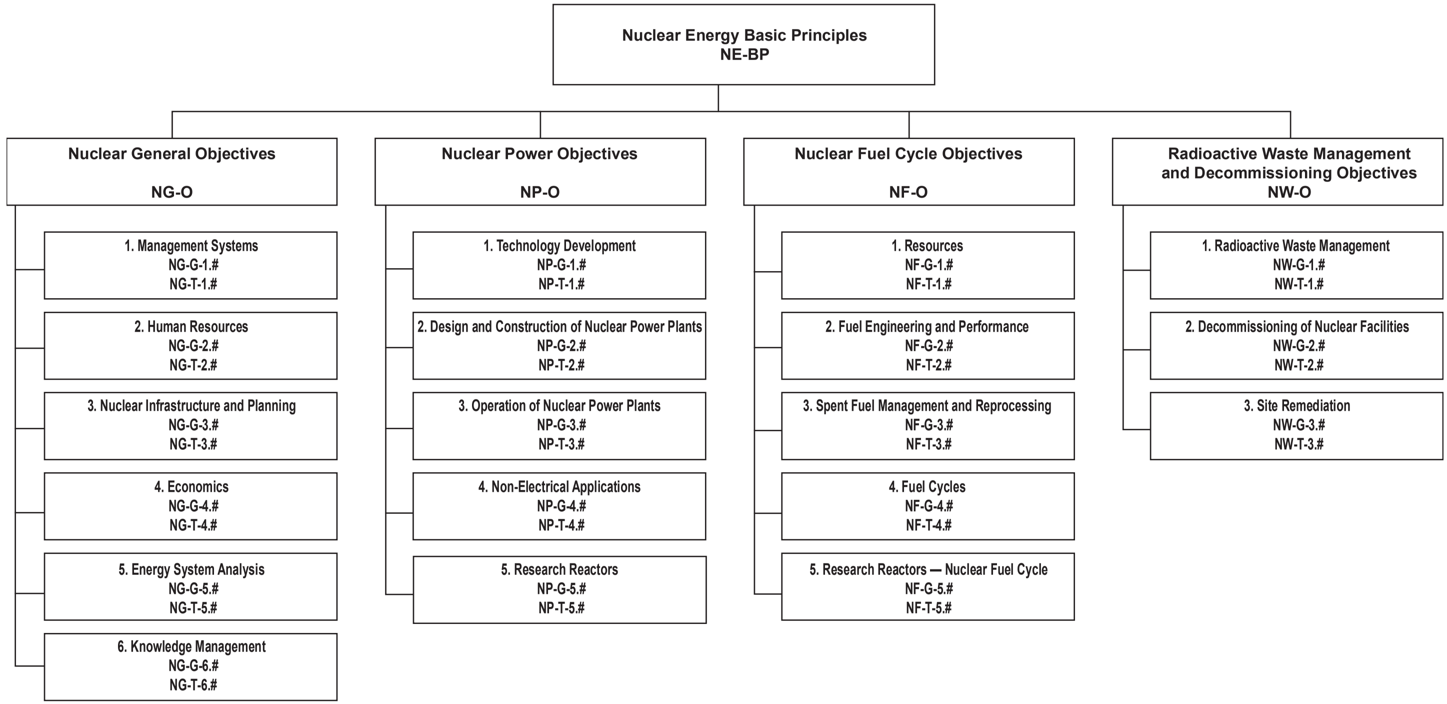

Key

BP: Basic Principles
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