RECENT ADVANCES IN FUEL PRODUCT AND MANUFACTURING PROCESS DEVELOPMENT

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ABSTRACT

This paper discusses advancements in commercial nuclear fuel products and manufacturing made by the Westinghouse Electric Corporation in response to the commercial nuclear fuel industry's demand for high reliability, increased plant availability and improved operating flexibility. The features and benefits of Westinghouse's most advanced fuel products--VANTAGE 5 for PWR plants and QUAD+ for BWR plants--are described, as well as "high performance" fuel concepts now under development for delivery in the late 1980s. The paper also discusses the importance of in-process quality control throughout manufacturing towards reducing product variability and improving fuel reliability.

INTRODUCTION

The Westinghouse Electric Corporation, the largest and most experienced manufacturer of fuel for pressurized water reactor (PWR) nuclear power plants in the world, has played a major role in the evolution of both nuclear fuel design and manufacturing technology. Through 1986, Westinghouse had fabricated over 22,000 fuel assemblies at its Columbia, S.C., facility. Today there are over 55 nuclear reactors operating with Westinghouse fabricated fuel. Additionally, over 65 reactors are now operating with fuel supplied by Westinghouse licensees.

The worldwide development of nuclear power throughout the 1950s and 1960s was greatly accelerated by technology exchange and licensee agreements between countries. Westinghouse, for instance, developed licensee agreements for fuel design and manufacturing with suppliers in six different countries. Approximately two-thirds of all PWR fuel contracted in the world from the present date through 1993 will be supplied either by Westinghouse or a Westinghouse licensee.

In addition to licensee agreements, the Corporation has entered into technology exchange agreements with several countries, resulting in the two-way transfer of technology. These international agreements have provided significant benefits for both the licensing organization and the licensee. First, they have broadened the foundation of operating data and experience required to verify codes and design adequacy. In addition, they have provided additional technical support in obtaining host country regulatory approvals. Such agreements also ensure that the manufacturing technology is kept current. Finally, they provide for early detection and resolution of engineering and design issues.

This global-wide evolutionary process has thus provided fuel vendors with a broad foundation of experience for evaluating fuel performance and incorporating design enhancements.

The design evolution of nuclear fuel historically has been driven by a wide range of complex economic, social and technological factors. When the first large scale commercial reactor (Yankee Rowe in Connecticut) was placed in operation in 1960, the design objective was to demonstrate technical and economic feasibility.

Throughout the 1960s, the U.S. economy was expanding. Uranium costs were relatively low and initial fuel designs assumed that the back-end of the fuel cycle would be closed, making it possible to recycle plutonium for use as mixed oxide fuel.

In the mid and late 1970s, an inflationary U.S. economy contributed to a slowdown in utility construction and an increase in the cost of uranium, while government regulations raised uncertainty about closing the fuel cycle. The design emphasis shifted to improving the utilization of fuel in a once-through cycle. Since 1982, the inflationary factor has decreased, as has the price of uranium. Today the primary design emphasis is upon improving the reliability of fuel products, increasing operating margins (and thus operating flexibility and plant availability) and improving uranium utilization.

Worldwide, a major effort is also under way to advance reprocessing, plant decommissioning and waste handling and storage technologies.

In response to these needs, Westinghouse has continued to advance the design and manufacturing technology of its nuclear fuel products. In addition, the Corporation has consolidated all of its fuel-related businesses that address the total fuel cycle--including uranium supply management, uranium separation and processing, zirconium production, tube fabrication, waste handling and storage (interim and terminal) and related operations--into a centrally managed organization. This integration permits total control of the quality process--from source material to final product--and permits rapid introduction of new technologies to the nuclear industry worldwide.

NUCLEAR FUEL DESIGN EVOLUTION

Westinghouse's decision in the late 1950s to develop pressurized water reactors (as opposed to boiling water or gas-cooled reactor designs) represented a pivotal point in the evolution of nuclear engineering. The anticipated advantages of PWR over other technologies have been borne out over the past 25 years. Over 300 PWRs are now operating or are under construction, making the PWR the most prevalent reactor type throughout the world.

This extensive irradiation experience has enabled PWR fuel designers to analyze the performance of several generations of nuclear fuel and advance the technology based upon hundreds of years of in-reactor experience.

The first large scale PWR utilized fuel assemblies composed of several bundles which used slightly enriched uranium clad in thick-walled stainless steel. The bundles were brazed to form a rigid structure and mechanically joined to form an assembly. Cruciform control rods were positioned between assemblies.

Throughout the 1960s, Westinghouse continued to make technological changes to this fundamental design. Grid springs were introduced to support each rod independently. This allowed for a reduction in fuel clad wall thickness, thus minimizing the high volume of neutron-absorbing material in the assembly. Mixing vanes were also incorporated into the assembly to provide for a greater degree of interchannel mixing, reduce the local temperature and afford a greater margin to thermal limits.

In 1967, Westinghouse introduced the rod cluster control assembly (RCCA). Individual control rods were grouped as a cluster and operated inside guide thimbles that comprised the basic assembly skeleton. This also helped to reduce parasitic material and minimized local peaking factors when rods were withdrawn.

Other important contributions made by Westinghouse during the 1960s were the introduction of chemical shim (boric acid) reactivity control, which provided greater flexibility in fuel management, and an improved grid structure made of Inconel, which yielded further improvements in thermal margin.

In 1968, in order to further reduce parasitic material, Westinghouse introduced a new fuel rod cladding material--Zircaloy. It has since been widely accepted as the preferred material for cladding and other assembly components, as a result of its favorable non-parasitic, mechanical and corrosion-resistant properties.

Also during the late 1960s, Westinghouse pioneered and patented the pre-pressurization of fuel rods. This concept significantly reduced fuel rod susceptibility to cladding failures because of its improved heat transfer.

In the 1970s, Westinghouse developed the 17 x 17 fuel array to replace the 15 x 15 array while retaining the same geometric envelope. This advancement reduced rod power, improved thermal and safety margins and reduced enrichment requirements.

In the mid-1970s, a variety of external economic and regulatory forces made improved uranium utilization a major design objective. In response, Westinghouse introduced the Optimized Fuel Assembly (OFA), which significantly improved fuel cycle economics while further reducing parasitic material.

Still another important design effort during the 1970s focused on reducing the residual reactivity penalty of burnable absorbers, which are required to control excess reactivity early in fuel life. In 1978, Westinghouse introduced an improved discrete burnable absorber design called the Wet Annular Burnable Absorber (WABA), consisting of annular pellets of aluminum oxide boron carbide contained within two concentric Zircaloy tubes. This short-term solution was followed by a totally different concept in burnable absorbers--a design that made the absorber a part of the fuel itself. This concept--the Integral Fuel Burnable Absorber (IFBA)--provided improved fuel management flexibility and required no excess parasitic material and no water displacement, resulting in a smaller residual reactivity penalty at end of life.

CURRENT DESIGN OBJECTIVES

The current market climate has brought about a new set of fuel performance demands, which nuclear fuel fabricators are responding to with new design and manufacturing concepts.

The primary focus today is upon quality and reliability. "Zero-defect" performance, in terms of fuel rod integrity, remains the all-encompassing objective. Power plant operators are also placing added demands on fuel performance. The industry as a whole is seeking higher burnups, improved operating flexibility, enhanced plant availability and lower fuel cycle costs.

In response to these needs, Westinghouse continues its comprehensive product development program. The thrust of this program has been to address the specific operating concerns of our customers, while at the same time continuing to advance fuel reliability. The program has addressed both product engineering and manufacturing.

An examination of the four fundamental design goals--reliability, higher burnups, operating flexibility and fuel cycle cost reduction--is a prerequisite to understanding the current trends in product development and manufacturing.

Reliability is usually defined in terms of activity within the primary coolant loop water, as expressed in PWRs by microcuries of Iodine-131 per cc. The activity itself results from "leakage" of radioactivity into the coolant due to breaching of the rod cladding, which in turn might be traced back to either the manufacturing process or plant operating conditions. Pellet-cladding interaction, corrosion, hydriding, debris and fuel rod fretting are all possible causes of damage and increased coolant activity. Since the early 1980s, there has been an order of magnitude reduction in coolant activity in plants using Westinghouse fuel. Westinghouse's current goal is to reduce this activity by another factor of ten. This represents only one rod leaking per every 200,000 rods in operation. The ultimate objective is zero defects from known causes, such as PCI and corrosion.

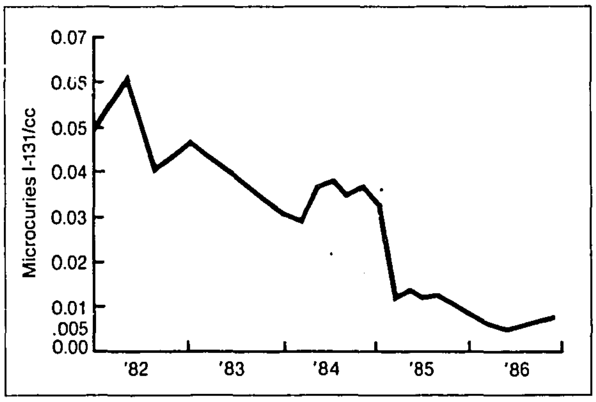

Figure 1: Average coolant activity

Westinghouse believes that the technology and manufacturing know-how are available to attain zero-defect fuel performance from known causes by 1990. To achieve this level of performance in a high burnup, long cycle environment, Westinghouse designers are focusing on improved corrosion-resistant alloys, and exploring ways to alleviate and/or control PCI, fission gas build-up, baffle jetting and debris.

Higher burnup, as a design objective, is largely dependent upon the same set of reliability factors. Corrosion resistance, particularly the need to prevent accelerated corrosion, is a major concern as burnups become ever greater. It is also a concern in high operating temperature plants. Higher burnup also demands greater structural integrity. Rod growth and assembly and rod bowing must thus be addressed in design and manufacturing.

During the first decade of nuclear power, fuel burnup levels were in the 20,000 to 30,000 MWD/MTU range. Many utilities now want to achieve burnup levels of 45,000 MWD/MTU to 50,000 MWD/MTU in the near future.

The industry's demand for greater operating flexibility has placed increased emphasis upon improving margin to thermal limits, overcoming axial power peaking limits and ramp rate restrictions, and facilitating reload cycle core management. Finally, the demand for improved fuel cycle costs has focused attention on finding ways to reduce enrichments, lower spent fuel costs, increase neutron economy and extend the life of components.

NEW DEVELOPMENTS IN PWR FUEL

With these objectives in mind, Westinghouse now offers its latest PWR fuel--VANTAGE 5. VANTAGE 5 represents a major departure from other commercial offerings in that it is not offered as a generic or standard product response for all plants. Rather, VANTAGE 5 fuel is five distinct product features that can be specified by the customer to accommodate specific operating requirements.

These five product features can be combined synergistically to provide the benefits outlined above, including reduced fuel cycle costs, improved operating margins, plus improved design and operating flexibility.

The features and benefits of VANTAGE 5 fuel are:

1) Integral Fuel Burnable Absorbers (IFBAs)--IFBAs integrate the burnable absorber material directly into the fuel rod in the form of a thin coating of zirconium diboride on the fuel pellet

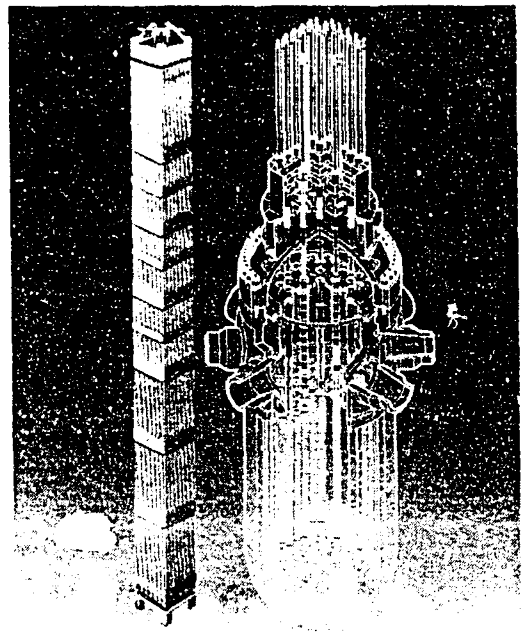

Figure 2: VANTAGE 5 17x17 PWR fuel

surface. In addition to a smaller residual reactivity penalty and a reduction in parasitic material, IFBA improves cycle design flexibility since IFBA-containing assemblies can be placed anywhere in the core.

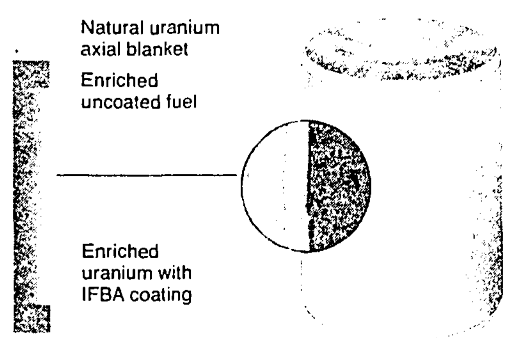

Figure 3: IFBA-coated pellet

In VANTAGE 5 fuel, an IFBA rod typically contains fuel and burnable absorber material arranged in five zones. The top and bottom zones contain unenriched pellets, while the center zone (80% of rod length) contains IFBA-coated pellets. The middle zones contain enriched uncoated fuel (Figure 3). IFBA rods can be strategically located to obtain the desired peaking factor.

2) Intermediate Flow Mixing (IFM) Grids--These additional low parasitic Zircaloy grids increase the turbulence in the upper part of the core. As a result, more water comes into contact with the fuel rods, improving heat transfer and providing increased margin for Departure from Nucleate Boiling (DNB) by up to 25 percent. This permits operators to increase the radial power peaking factor limit. Increasing the limit allows a larger number of burned assemblies to be used on the core periphery, an important feature for efficient radial blankets. The IFMs also provide a LOCA margin benefit and offer added design flexibility in the event of cycle redesign.

3) Axial and radial blankets--VANTAGE 5 fuel also incorporates axial blankets, comprised of regions of natural enrichment uranium dioxide at the top and bottom of the fuel rods, and burned radial blankets, which are an extension of the low leakage loading patterns (LLLP) currently in use in many plants. These blanket regions serve to reduce neutron leakage, which in turn improves uranium utilization and lowers fuel cycle costs. The radial blankets also reduce reactor vessel fluence, which is an important consideration for many plants.

Axial blankets can be used in conjunction with IFBA to provide a flatter axial burnup shape and generally improve uranium utilization. The axial blanket also reduces the total U-235 inventory since it places more enriched uranium in those core regions with the best fuel utilization.

4) Enhanced burnup capability--VANTAGE 5 fuel offers enhanced burnup capability made possible by two design modifications--thinner top and bottom nozzle plates and increased plenum space in the rod. The thinner plates provide more room for fuel rod growth during high burnup, while the added plenum space accommodates a larger release of fission gas in the rod.

5) Reconstitutable top nozzle--VANTAGE 5 fuel includes a removable top nozzle to facilitate inspection and rod replacement. It can be removed numerous times throughout the life of the assembly. Like OFA, VANTAGE 5 also has a reconstitutable bottom nozzle.

Collectively, these features can be combined for a significant improvement in neutron economy and fuel cycle costs, while offering enhanced margins, improved plant availability and greater operating flexibility.

VANTAGE 5 fuel is currently in production at the Westinghouse Fuel Fabrication Facility. Its features are receiving wide acceptance throughout the U.S. and international utility industry.

DEVELOPMENTS IN BWR FUEL

In 1981, in response to the needs of U.S. utilities operating BWRs to improve operating margins and fuel utilization, Westinghouse introduced its advanced BWR fuel, QUAD+. It features a unique "water cross" channel that divides the assembly into four mini-bundles, or quadrants, each containing 16 rods. The water cross improves neutron moderation by delivering non-boiling water to the center of the fuel assembly. QUAD+ eliminates the need for water rods, thus permitting more fuel rods to be utilized. This in turn provides PCI and LOCA benefits as a result of a lower average linear heat rate.

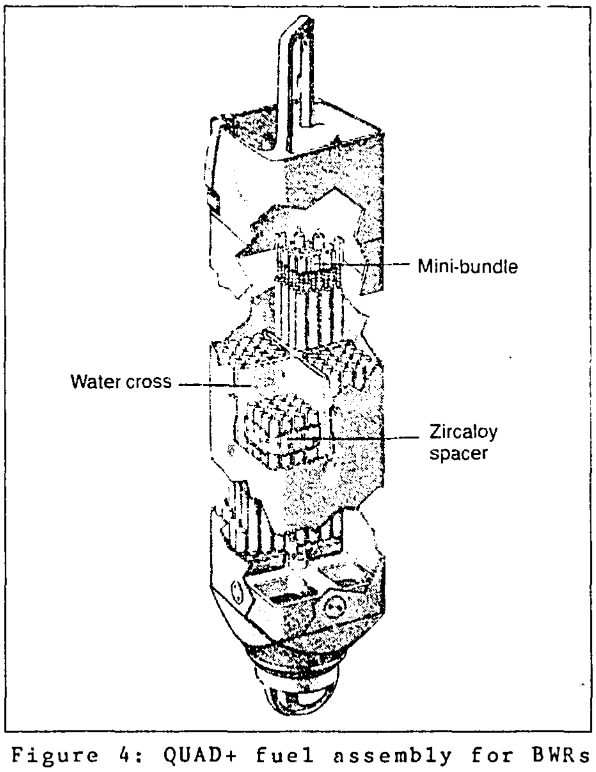

Figure 4: QUAD+ fuel assembly for BWRs

QUAD+ fuel incorporates an integral channel design, which means the fuel and channel can be handled and installed as a single unit. This enhances the structural integrity of the assembly and thus reduces the possibility of fuel failure resulting from stress induced during handling.

Another important feature of QUAD+ fuel is its low pressure drop spacer. The spacer features a streamlined design that reduces flow turbulence upstream and also reduces the pressure differential across the channel wall. It directs the water flow toward the center of the mini-bundle. The spacer leads to an overall improvement in critical power performance.

These design features add up to significant economic and margin benefits. In conventional designs, the center of the assembly is undermoderated. As a result, a wide range of enrichments must be used. QUAD+ fuel uses a much more uniform enrichment range (1.8 to 3.2 weight percent, compared to 1.2 to 3.8 for conventional arrays). Resulting uranium savings are on the order of 5 percent in enriched uranium loaded, 8 percent in U_3O_8, and 9 percent in SWUs.

ADVANCED HIGH PERFORMANCE FUEL

Through ongoing interaction with nuclear power plant operators, Westinghouse has obtained valuable insights into the fuel requirements of the 1990s. Clearly, to perform reliably at even higher burnup levels, the nuclear fuel products of tomorrow must incorporate further design advancements.

Demand for higher burnups and longer cycles means that the very materials utilized in the assembly itself will have to be much more corrosion resistant and endure higher temperatures. All components must be structurally capable of functioning through longer cycles. Rod failure factors, such as baffle jetting, PCI, and debris must be controlled or eliminated. Such modifications, of course, must be achieved without sacrificing fuel cycle costs.

In response to these design objectives, Westinghouse has under development several new fuel concepts. These concepts, all of which are based upon proven technology and considerable irradiation experience, suggest the technical features--and resulting benefits--likely in the next generation of light water reactor nuclear fuel. Since they are based upon proven technology, Westinghouse is currently offering these advanced fuel concepts, as individual product features or as an integrated product, for delivery within two years.

Perhaps the single most important technical innovation currently being tested is a new cladding alloy called ZIRLO, which represents a milestone in the history of zirconium development. ZIRLO, which Westinghouse has had under development for 17 years, is a zirconium-niobium based alloy, with additional alloying agents, that offers 50 percent greater corrosion resistance than Zircaloy-4 (Figure 5). ZIRLO has been subjected to extensive irradiation experience, and has demonstrated total resistance to accelerated corrosion, which can cause nodular corrosion, under simulated high burnup and high temperature operating conditions.

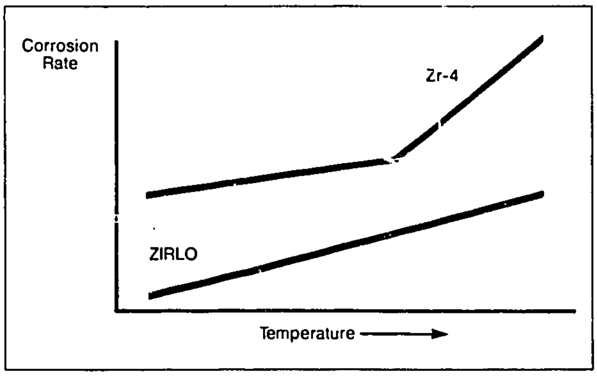

Fig. 5: Corrosion resistance of alloys

Another important feature of the fuel of the 1990s will be the use of liner cladding--that is, a zirconium liner is added inside the fuel rod to increase resistance against pellet cladding interaction. The liner is made from an ultra high purity zirconium that is produced in a special electron beam (EB) furnace. Liner fuel is incorporated into Westinghouse's QUAD+ fuel for BWR plants. Use of liner fuel in BWR plants significantly reduces PCI problems, which can occur when stress is placed on the fuel during rapid changes in load demand (during load follow operations).

This same concept can be applied within high temperature, high burnup PWR operating environments.

Westinghouse is also developing and testing a debris filter for PWR assemblies. It will trap particles that can be carried hydraulically in the fuel assemblies and cause fuel damage through fretting. The filter effect is obtained through a modified bottom nozzle. In tests it has proven to be highly effective in trapping particles as small as 0.4 cm in length.

To accommodate additional fission gas released during very high burnup conditions, Westinghouse has designed and tested a new spring clip, which provides additional plenum space in the rod, and is exploring the use of annular pellets in certain rod regions.

In recent years, Westinghouse has explored several design solutions to baffle jetting, including the use of a clip to join several rods in assemblies subject to baffle jetting. A new approach, however, was recently adopted which eliminates many of the problems associated with clips. A partial grid, consisting of the three outer rows of grid cells, is being recommended on selected assemblies destined for plants that have experienced baffle jetting problems. This approach permits such assemblies to be installed anywhere in the core and eliminates the need to remove any fuel rods.

Many of the additional advancements required to attain higher reliability and fuel performance are dependent upon the manufacturing process. For example, assembly and rod bowing, which is a natural occurrence after extensive irradiation, can be controlled by ensuring that the rods and assemblies are not subjected to undue stress during the manufacturing process. Also, it is important that key components, such as thimbles, are made from the same metallurgical lot.

Collectively, these concepts are combined into an advanced fuel product offering unprecedented performance and reliability.

RECENT ADVANCEMENTS IN MANUFACTURING

To meet the industry's demands for higher levels of product performance and reliability, Westinghouse recognizes that the quality of the product itself must be carefully controlled throughout the entire fabrication process--from the processing of zirconium ores and Zircaloy tubing, through pellet fabrication and final assembly.

Over the past decade, Westinghouse has embarked upon an effort designed to reduce product variability through the implementation of advanced manufacturing technologies and statistical in-process quality control techniques. In-process statistical quality control has played a critical role in Westinghouse's effort to produce "zero-defect" fuel and reduce coolant activity to world leadership standards.

Two examples of the application of statistical in-process quality control can be seen at the Westinghouse Columbia plant. To reduce variability in pellet composition, the Columbia facility has applied in-process quality control to pellet powder production and pellet fabrication. A major component of the pellet quality effort has been to reduce hydrogen content. (Improved pellet uniformity and reduced hydrogen content have been shown to contribute to improved fuel performance.)

An analysis of powder fabrication statistics revealed non-uniformity in the microstructure of UO_2 powder. Through the application of artificial intelligence (AI) principles, uniformity is now controlled much more effectively. In addition to reducing the vulnerability of the pellet surface to cracking, the pellet has less open porosity, making it more immune to hydrogen pickup and fission gas release.

Additional steps have been taken in manufacturing to further reduce hydrogen content within the pellet (such as eliminating pellet contact with plastics and hydrocarbons). Collectively, these steps have resulted in a 50 percent reduction in hydrogen content

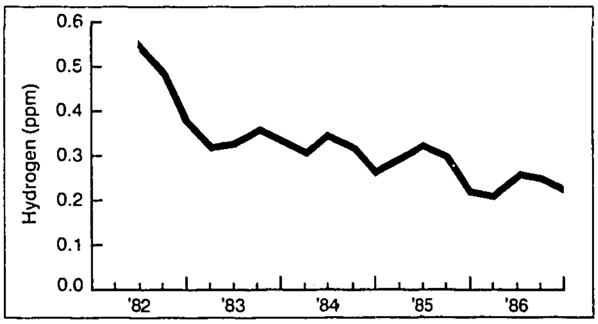

Fig. 6: Pellet average hydrogen content

and a higher average pellet density (Figure 6). Hydrogen content within a fuel rod has been reduced to levels far below one part per million. (Tests have shown that levels of two parts per million can cause hydriding and subsequent rod failure upon irradiation.)

To further eliminate the pellet's vulnerability to chipping, all pellets are now produced with a chamfered edge along both the top and bottom.

Similar quality control efforts have resulted in reduced variability in the production of fuel rods at Columbia, including a major effort to enhance weld quality. A typical core could contain nearly 700,000 feet of tubing and 120,000 welds on the fuel rods alone. A computer-controlled laser welding technique is now being used to weld Zircaloy grids and a computer-controlled TIG welding technique is being used to weld end plugs. A "double pass" approach is being used to ensure a high quality weld. Inspection is currently being done with ultrasonic testing equipment, which provides a much higher level of inspection confidence than X-ray systems.

To reduce mechanical stress on rods and assemblies during the manufacturing process (which can contribute to assembly and rod bowing), new fixtures have been developed, which have helped Westinghouse maintain a very tight fabrication tolerance over the length of the fuel rod.

Another major manufacturing trend which has had significant impact upon both product quality and facility productivity has been the increased reliance upon computer-aided manufacturing, computer-aided design, robotics and related automation systems. At Columbia, Westinghouse has installed a highly automated, computer-controlled manufacturing line called the Manufacturing Automated Process (MAP). MAP, which represents a $40 million investment, integrates uranium gas conversion, pellet production and rod fabrication into a single computer-based manufacturing system. Now in production, MAP is the most advanced facility of its kind in the world.

Integral to MAP is a built-in system of data feedback and computerized diagnostics which ensure that process variables remain within specified controlled tolerances.

Critical to fuel reliability is the ability of the fuel cladding and related metal components to perform as specified throughout the life of the assembly, without metallurgical deterioration. Westinghouse has taken a number of steps in the production of zirconium and Zircaloy to further enhance product consistency, improve the mechanical properties and make it more corrosion resistant. These steps have been implemented at the Corporation's zirconium fabrication facility in Ogden, Utah, where Zircaloy tube reduced extrusions (TREX) are produced, and at its Specialty Metals plant near Blairsville, Pennsylvania, where the TREX is converted to fuel rod cladding.

The tube reduction process requires comprehensive in-process quality control to ensure that the desired metallurgical and mechanical properties are maintained throughout the various production steps, which include several "cold pilger" passes. Following reduction by pilgering, the tubing is surface-etched and annealed. Ultrasonic inspection is now being utilized to test the tubing. Surface stress, corrosion resistance, chemical composition and heat transfer properties are carefully examined in on-site laboratories.

To ensure that the inside and outside diameters and wall thickness of the tubing are within tolerance, Westinghouse has developed a laser pattern recognition system that uses the reflection and refraction of laser beams to guard against the slightest flaw.

FUTURE DIRECTIONS

Clearly, the future direction of manufacturing will be strongly driven by the quest to produce zero-defect fuel. In the manufacturing area, new technologies, including greater use of automation, artificial intelligence and laser-based inspection systems, will be integrated by computers to ensure step-by-step in-process quality control.

Future engineering efforts will be largely focused on materials enhancement, with the goal of achieving even higher burnups. Additional advancements are expected in fuel reconstitution and consolidation, as well as back-end fuel cycle services, such as waste processing and storage. The primary objective of all future manufacturing and engineering efforts will be to ensure maximum plant availability and reliability.