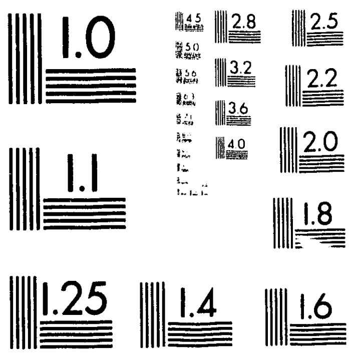
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WAPD-T-3007

THE SHIPPINGPORT PRESSURIZED WATER REACTOR AND LIGHT WATER BREEDER REACTOR

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FOR PRESENTATION AT:

25TH CENTRAL REGIONAL MEETING
AMERICAN CHEMICAL SOCIETY
PITTSBURGH, PENNSYLVANIA
OCTOBER 4-6, 1993

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ABSTRACT

The Shippingport Atomic Power Station, located in Shippingport, Pennsylvania, was the first large-scale nuclear power plant in the United States and the first plant of such size in the world operated solely to produce electric power. A program was started in 1953 at the Bettis Laboratory to confirm the practical application of nuclear power for large-scale electric power generation. It led to the development of zirconium alloy (Zircaloy) clad fuel element containing bulk actinide oxide ceramics (UO_2, ThO_2, ThO_2 - UO_2, ZrO_2 - UO_2) as nuclear reactor fuels. The program provided much of the technology being used for design and operation of the commercial, central-station nuclear power plants now in use.

The Shippingport Pressurized Water Reactor (PWR) began initial power operation on December 18, 1957, and was a reliable electric power producer until February 1974.

In 1965, subsequent to the successful operation of the Shippingport PWR (UO_2, ZrO_2 - UO_2 fuels), the Bettis Laboratory undertook a research and development program to design and build a Light Water Breeder Reactor (LWBR) core for operation in the Shippingport Station. Thorium was the fertile fuel in the LWBR core and was the base oxide for ThO_2 and ThO_2 - UO_2 fuel pellets.

The LWBR core was installed in the pressure vessel of the original Shippingport PWR as its last core before decommissioning. The LWBR core started operation in the Shippingport Station in the autumn of 1977 and finished routine power operation on October 1, 1982. Successful LWBR power operation to over 160% of design lifetime demonstrated the performance capability of the core for both base-load and swing-load operation. Post-irradiation examinations confirmed breeding and successful performance of the fuel system.

OUTLINE

THE SHIPPINGPORT PRESSURIZED WATER REACTOR AND LIGHT WATER BREEDER REACTOR

J. C. CLAYTON

I. INTRODUCTION

The development of nuclear reactors as useful sources of power began before the end of World War II. The early effort in the United States was directed towards the development of nuclear-powered submarines. This program at Argonne National Laboratory and the Bettis Atomic Power Laboratory produced the pressurized water reactor concept. The outstanding success of the concept led to adaptation of this system to a central station demonstration power production plant designed by the Bettis Laboratory.

The Pressurized Water Reactor (PWR) project was formally authorized in July 1953 under the direction of the Naval Reactors Branch, Division of Reactor Development, U. S. Atomic Energy Commission. The Duquesne Light Company furnished the plant site at Shippingport on the Ohio River about 25 miles west of Pittsburgh. Official ground breaking took place on September 6, 1954; actual construction started in May 1955. The Shippingport Pressurized Water Reactor first went critical on December 2, 1957. Sixteen days later power was fed into the Duquesne system. On December 23rd the Shippingport PWR achieved full power.

That date marked successful completion of more than four years of planning, development, design, and construction to build the first commercial central station nuclear generating plant for producing electric power (Reference 1).

II. SHIPPINGPORT PWR CORE 1 (REFERENCES 1, 2, AND 3)

A. Physics

The first Shippingport PWR core consisted of a relatively small annular shaped "seed" region, containing highly enriched uranium alloy fuel assemblies, and a "blanket" region of natural uranium dioxide fuel rods arranged in a lattice surrounding the seed regions both inside and outside. The seed was self-sustaining, but the blanket was slightly subcritical. The blanket thus operated at a neutron deficit and, if it were not for the seed, would quickly have stopped producing power. However, neutrons from the seed into the blanket compensated for the deficit and, by producing plutonium in the blanket, enabled the blanket to produce more than half of the core power. The seed continued to drive the blanket. Hafnium control rods were required only in the seed.

B. Reactor

The seed-and-blanket core used a relatively small amount of enriched uranium and a large amount of natural uranium. A metallic alloy of enriched uranium (~93% U-235) in the form of plates was contained in 32 assemblies collectively called the "seed", while the natural uranium was contained in 113 stacks of assemblies collectively called the "blanket". The fuel in the blanket region was natural uranium in the form of UO_2 pellets clad in 10.25-inch-long Zircaloy-2 tubes. Seed assemblies were arranged in a square annular array with blanket assemblies both inside (45) and outside (68). Thus a core was produced in which neutrons leaking from the highly enriched seed caused plutonium production and fission in the plutonium and natural uranium of the blanket assemblies. The seed fuel contained approximately 165 pounds of U-235. The blanket was made up of 14.2 tons of natural uranium in the form of uranium dioxide. The water-cooled natural uranium could not by itself sustain a chain reaction.

Furthermore, the seed assemblies alone in their square annular array, even in the presence of water and without their control rods, could not by themselves sustain a chain reaction. The neutron multiplying and reflecting characteristics of at least a portion of blanket material were required to sustain the chain reaction.

C. Operation

Core 1 was refueled with three additional seeds and operated for a total of 27,781 effective full power hours (EFPH).* Core 1 total electrical gross output was 1.8×10^9 kilowatt hours. Core 1 operation with Seed 4 was completed on February 9, 1964 to prepare for Core 2 refueling.

III. SHIPPINGPORT PWR CORE 2 (REFERENCE 4)

One of the principal objectives of the second Shippingport PWR core was the demonstration of a high performance seed and blanket core in terms of both power density (160 kW/liter) and lifetime ($\geq$ 10,000 EFPH per seed and $\geq$ 20,000 EFPH for the blanket). The second core had more than five times the design energy output and twice the power density of the first Shippingport core.

The blanket fuel for the first Shippingport PWR core was bulk UO_2 in the form of cylindrical pellets. The second core used this ceramic material in plate shapes to take advantage of greater heat transfer area and lower fuel temperatures. This was coupled with the development of Zircaloy-4 as a long-life cladding material. The compartmented oxide plate fuel element, developed for both the seed and blanket, was especially suitable for meeting the higher power density, higher total energy, self-shielded boron burnable poison, and zoned fuel loading requirements of the second core.

The second seed-blanket core for Shippingport consisted, as did the first core, of a relatively small, annular-shaped seed region (~21% of core volume) surrounded on the inside and outside by blanket regions. The seed fuel was highly enriched UO_2 diluted with ZrO_2 or ZrO_2-CaO, contrasted with the uranium-Zircaloy alloy of Core 1. From the standpoint of neutron regeneration, the seed was self-sustain-

*EFPH are the hours of reactor operation multiplied by the fraction of rated power.

ing, while the blanket was not. Accordingly, the seed was the reactivity controlling region and control rods were required only in the seed. The seed had 20 assemblies, each containing a hafnium cruciform control rod; the blanket had 77 assemblies. The seed and blanket assemblies extended the full 8-foot height of the reactor.

The Shippingport PWR Core 2 operated, with one seed refueling, from April 1965 until February 1974 for a total of 23,812 EFPH. The station was then shut down for minor modifications and installation of the LWBR core.

IV. SHIPPINGPORT LIGHT WATER BREEDER REACTOR (REFERENCES 5 THROUGH 11)

A. Purpose

The objective of the LWBR program was to develop and demonstrate the technology to breed more fuel than consumed in a commercial light water reactor and thereby to expand nuclear fuel resources. Thorium is a relatively abundant, naturally occurring fertile material that can be used to generate fissile uranium in a thermal reactor. All of the commercial power reactors currently in operation in the United States are of the light water reactor (LWR) type. Thus, technology was developed to design, fabricate, and operate a breeder reactor - based on a thoria-urania fuel system - in the existing Shippingport plant.

B. Core

The LWBR fuel system was based on generation of fissile U-233 from thorium. The LWBR core contained 12 hexagonal-shaped modules arranged in a symmetric array surrounded by 15 reflector modules. Each of the hexagonal fuel modules was composed of a central movable seed assembly surrounded by a stationary blanket assembly. The movable seed assemblies were used instead of control rods or soluble poisons to control reactivity. This minimized parasitic neutron capture and made breeding possible in the core. Fuel was in the form of ceramic pellets sealed within 10-foot-long Zircaloy-4 tubes. Fuel pellets in the seed and blanket assemblies were composed of the mixed oxides of uranium-233 and natural thorium (essentially, one isotope, Th-232). In short sections at the tops and bottoms of the seed and blanket fuel rods, the fuel pellets were ThO_2. The reflector region, surrounding the power-producing seed-blanket modules, contained fertile thoria fuel that absorbed escaping neutrons. The capture of neutrons by the thorium produced new fissile uranium-233 fuel. The seed-blanket-reflector configuration of the LWBR core had 17,287 fuel rods containing approximately 1.6 million ThO_2-UO_2 pellets and 1.3 million ThO_2 pellets.

C. Operation

The LWBR core started operation in the Shippingport Station on September 7, 1977 and finished routine power operation on October 1, 1982. The reactor operated for 29,047 EFPH (about 5 years) with an availability factor of 86% and had a gross electrical output of over 2.1×10^9 kilowatt hours. After shutdown the expended core was examined, and no evidence of any fuel element defects was found. Nondestructive assay of 524 fuel rods and destructive analysis of 17 fuel rods determined that 1.39% more fissile fuel was present at the end of core life than at the beginning-thereby establishing that breeding had occurred. Successful LWBR power operation to over 160% of design lifetime demonstrated the performance capability of this fuel system.

V. CONCLUSIONS (REFERENCES 1, 10, 11)

As the first U.S. nuclear plant in public utility service, the Shippingport Atomic Power Station laid the groundwork for the design, construction, and operation of future commercial nuclear power plants and provided the foundation for today's PWR industry. Shippingport was a facility in which several different designs of light water cooled and moderated reactor cores were successfully operated. Reactor fuel materials and the fuel element shapes into which they can be fabricated constitute the fundamental building blocks around which a nuclear reactor is designed. The fuel element that became the cornerstone of the nuclear power reactor industry was a Zircaloy rod containing uranium dioxide fuel pellets (Reference 2).

Although current LWRs use a low enrichment uranium-plutonium fuel cycle, the successful operation of the Shippingport LWBR demonstrated the feasibility of using the thorium-uranium fuel cycle in a light-water environment. Because LWR technology is so widespread, this could provide a way of rapidly progressing to a more advanced technology-primarily with the purpose of improving uranium utilization. Either new reactors could be designed or, more easily, old reactors could be refitted. The latter would require only minimum changes in design and operation of the reactor plant. The LWBR is thus highly relevant to the world's energy potential and a viable alternative as a PWR replacement in future generations of nuclear reactors.

Uranium-233/thorium cores can be designed and built, can be operated in existing LWR plants to produce electricity, and can breed enough fissile fuel to overcome modest losses in reprocessing and refabrication. For the United States in particular, this means that the plentiful domestic supply of thorium, a material with no other significant use, can become an important energy source. This resource can provide about 50 times as much energy as the domestic supply of uranium used in current LWRs. The light-water breeder thus has an energy potential that could meet the entire electrical needs of the United States for centuries.

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