



# Brief Summary – Historical Development of Nuclear Reactor Technology

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Gateway for Accelerated  
Innovation in Nuclear



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Mr. Hildebrandt has over 50 years experience in the nuclear and power generating industries. His experience has been gained through a wide range of engineering and management assignments in the Naval Nuclear Propulsion Program and in commercial nuclear power plants. This experience has included senior management roles and consultation to commercial power generating companies and utilities, and government and government contractors in the recovery/restart, performance improvement, project management and engineering management of reactor facilities and other nuclear/chemical facilities. Mr. Hildebrandt has worked closely with senior and executive management within power generating companies and utilities, as well as the Nuclear Regulatory Commission, the Department of Energy, the Department of Defense, and the Department of Commerce.

As a consultant to the Laboratory Director of the Idaho National Laboratory, Mr. Hildebrandt provides assistance in the development of major projects, industry liaison and regulatory strategy. He is participating in development of a multi-decade strategy for the future of nuclear energy that includes recommendations for rebuilding the U.S. nuclear industrial infrastructure and positioning U.S. industry to continue to be a leader in the global nuclear energy marketplace.

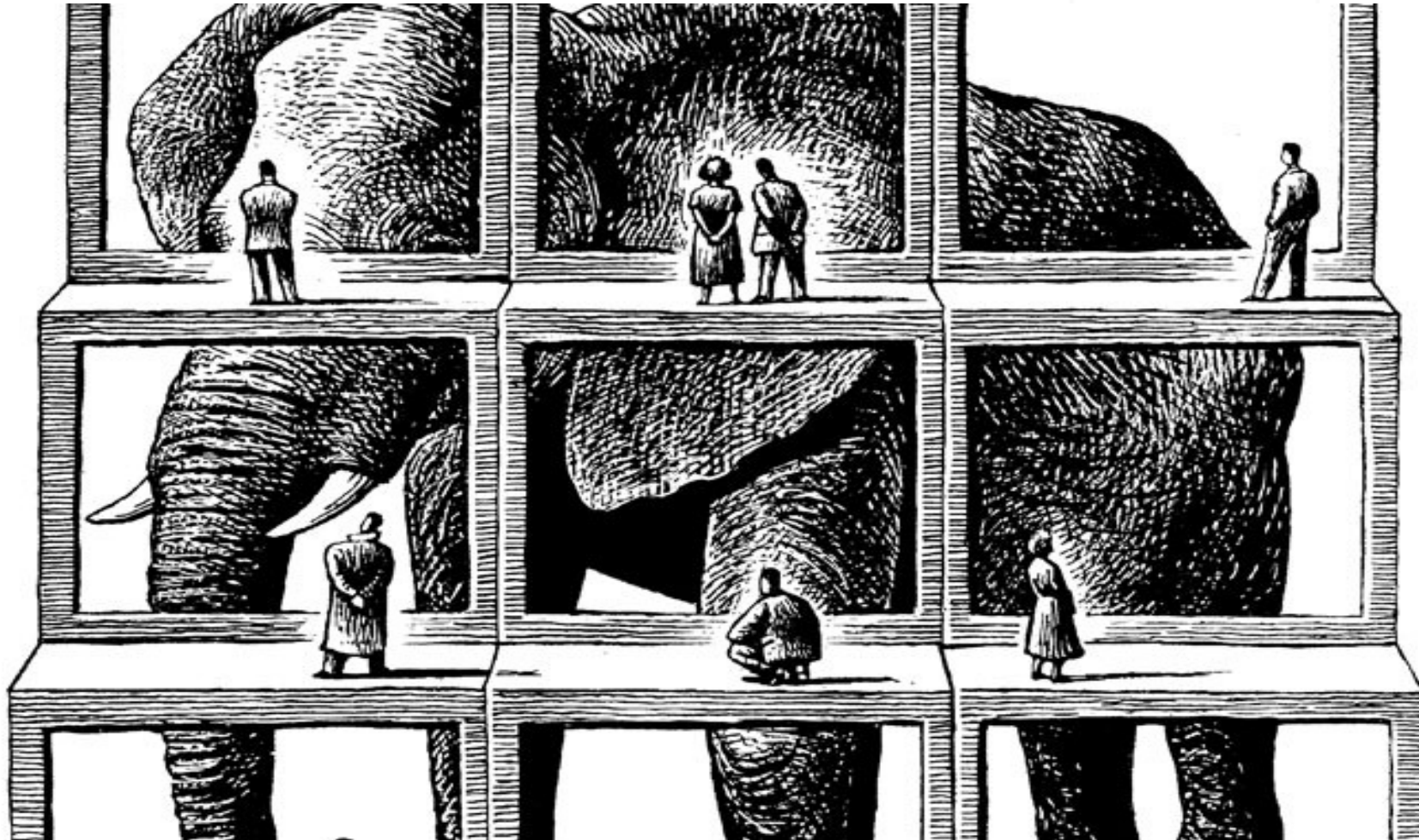
A graduate of Auburn University with a Bachelor of Electrical Engineering, he is a graduate of the Bettis Reactor Engineering School in the Naval Nuclear Propulsion Program and has completed graduate studies in electrical engineering at George Washington University. He is a registered Professional Engineer in Virginia and Ohio.

# Topics

- *Historical context and perspectives in the development of nuclear energy systems – late 1940s to early 1960s*
- *U.S. Navy nuclear propulsion development*
- *U.S. power reactor development programs*
- *The U.S. Power Reactor Project – Shippingport*
- *Global power reactor contenders*
- *U.S. Cold War policy-driven commercialization*
- *Early regulatory uncertainties*



# Context and Perspective



*"You have to know the past to understand the present" — Carl Sagan*

# Reactor Applications

- ***Research and Test*** – basic nuclear science and engineering beginning in the early 1940s.
- ***Production*** – an early focus of reactor development to provide weapons material (e.g., plutonium, tritium). U.S. development and deployment starting in the mid-1940s until the mid-1950s.
- ***Propulsion*** – nuclear energy for military purposes for deploying weapons delivery platforms (e.g., naval ships, aircraft). U.S. development starting in the late 1940s. Naval ship propulsion is mature and continues today. Aircraft propulsion development cancelled by 1961.
- ***Power*** – generation of electric power. U.S. programs starting in the mid-1950s.

Early activities explored combined purposes for singular reactor concepts (e.g., combined power and production) – limited success due to competing and often contradictory objectives and requirements

# Context – Nuclear Reactor Development

- **World War II weapons program emerging into Cold War environment**
  - **Atomic Energy Act of 1946** – *Civilian control via Atomic Energy Commission (AEC); information is born classified; only federal government may produce or possess fissile materials*
  - **Atomic Energy Act of 1954** – *AEC can now regulate; private sector access; licensed use of fissile materials*
- **Power reactor applications often overshadowed by development of nuclear weapons and weapons delivery platforms**
- **Unaligned agendas – President; National Security Council; Congress; AEC; private sector**
- **A vision – “Atoms for Peace”... but who is going to lead development and pay for commercialization?**

***Understanding the historical development of nuclear energy requires a grasp of the forces-at-play – POLICIES, POLITICS, AND PERSONALITIES***



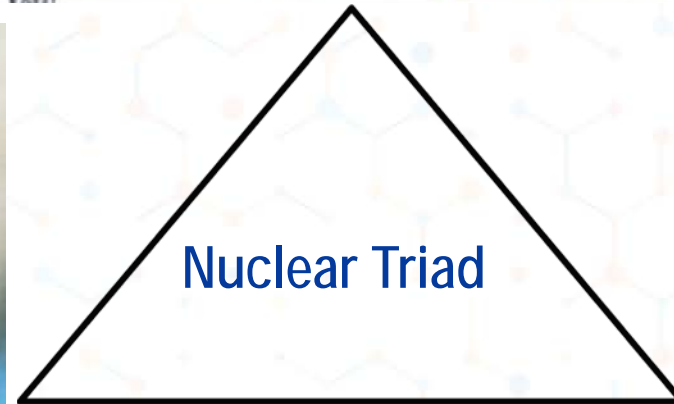
# Cold War – Nuclear Arms Race



B-52G Stratofortress strategic bomber



Titan II ICBM



Nuclear Triad

George Washington class SSBN



# Nuclear Navy

*USS Nautilus (SSN571)*



Fleet Ballistic Missile Submarine



# Nuclear Navy – the Beginning

- U.S. Navy was uncertain what its post-war and future fleet should be
- AEC – exclusive authority over nuclear energy research and development – is uncertain where it wants to put its priorities regarding reactor development
- Emerging perspective that nuclear energy could be transformative in the future of submarine warfare – a true submersible, difficult to detect, practically unlimited cruising range and duration on-station
- Early support of Admiral Chester Nimitz (Chief of Naval Operations) starting in 1946 gave impetus to concept of a nuclear propelled submarine
- By 1950, Captain Rickover, certain AEC commissioners and senior naval officers, the National Security Council and the Congressional Joint Committee on Atomic Energy (JCAE) bludgeoned their way through the bureaucratic maze of the United States Government (USG) to finally achieve agreement to proceed with reactor development for submarine application.

# Nuclear Navy – Who is in Charge?

- AEC owns nuclear energy including reactor development
- Navy owns the ships
- Congress owns the money
- National laboratories fighting for a controlling technology position – but oriented toward the science of nuclear energy rather than its application
- Painfully evolves into Rickover taking on increasing authority in both the AEC and the Navy with Congress (JCAE) as his base of power. Organizationally becomes “Naval Reactors,” with authority in both AEC and Navy.
- Argonne and Oak Ridge national laboratories take on original technology development roles
- Evolves to dedicated AEC laboratories for the Naval program – Bettis and Knolls atomic power laboratories. Bettis (Westinghouse) and KAPL (GE) work hand-in-hand with Electric Boat shipyard to design and build the first nuclear submarines

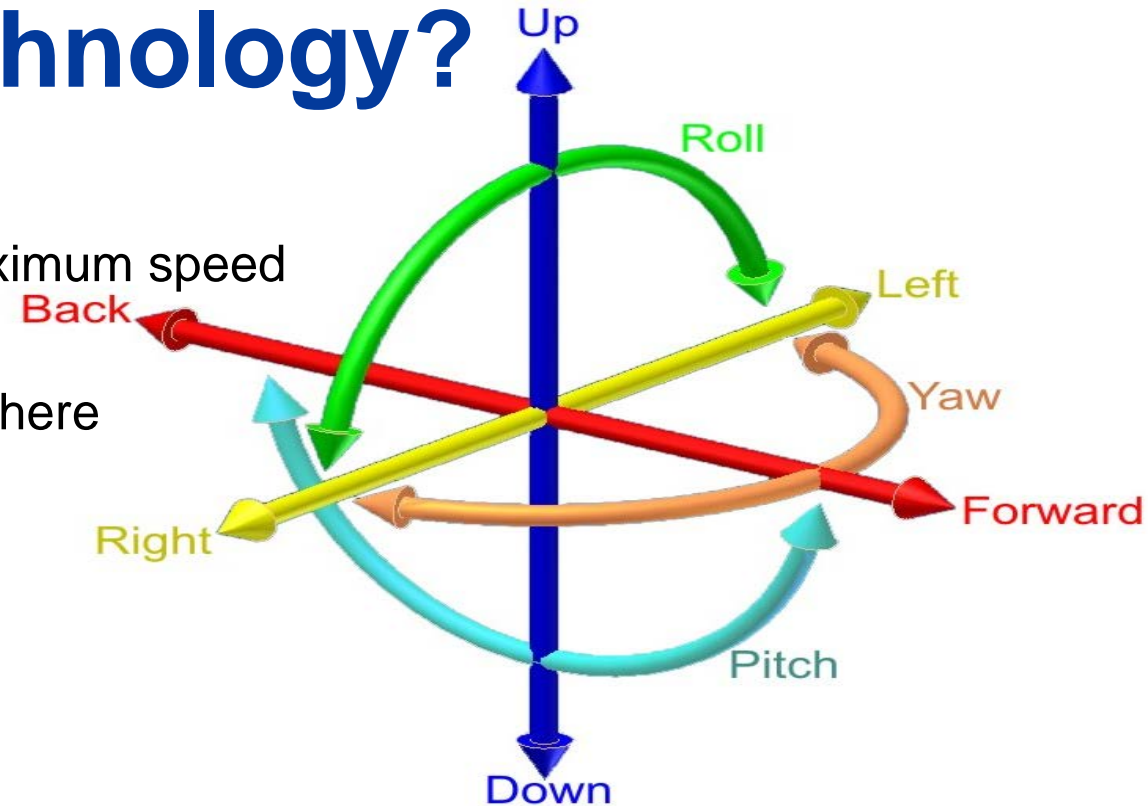


Admiral Rickover and several of his senior staff

# What Nuclear Energy Technology?

## *Simplified requirements for a nuclear submarine*

- Minimum weight and volume for propulsion plant – maximum speed
- Crew protection
- Unlimited submerged duration – self-contained atmosphere
- Platform stability
- **Robust propulsion plant design**
  - Highly maneuverable
  - Unaffected by extreme ship motions
    - Transient rotational – roll, pitch, yaw
    - Fixed rotational – list, trim, skew
    - Transient translational – heave, sway, surge
  - Battle hardened (e.g., shock loadings; transients; “battle short”)
  - Quiet operations
  - Simple to operate – “sailor proof”
  - Largely maintainable by “forces afloat” in remote locations
  - Passive nuclear safety
  - Endurance – many years before refueling



*Military shipboard application of nuclear energy for propulsion is demanding and requires considerably more robust design than for a land-based power plant*



# What Nuclear Energy Technology?

Naval Reactors evaluated several nuclear energy technologies and associated plant design concepts for submarine propulsion

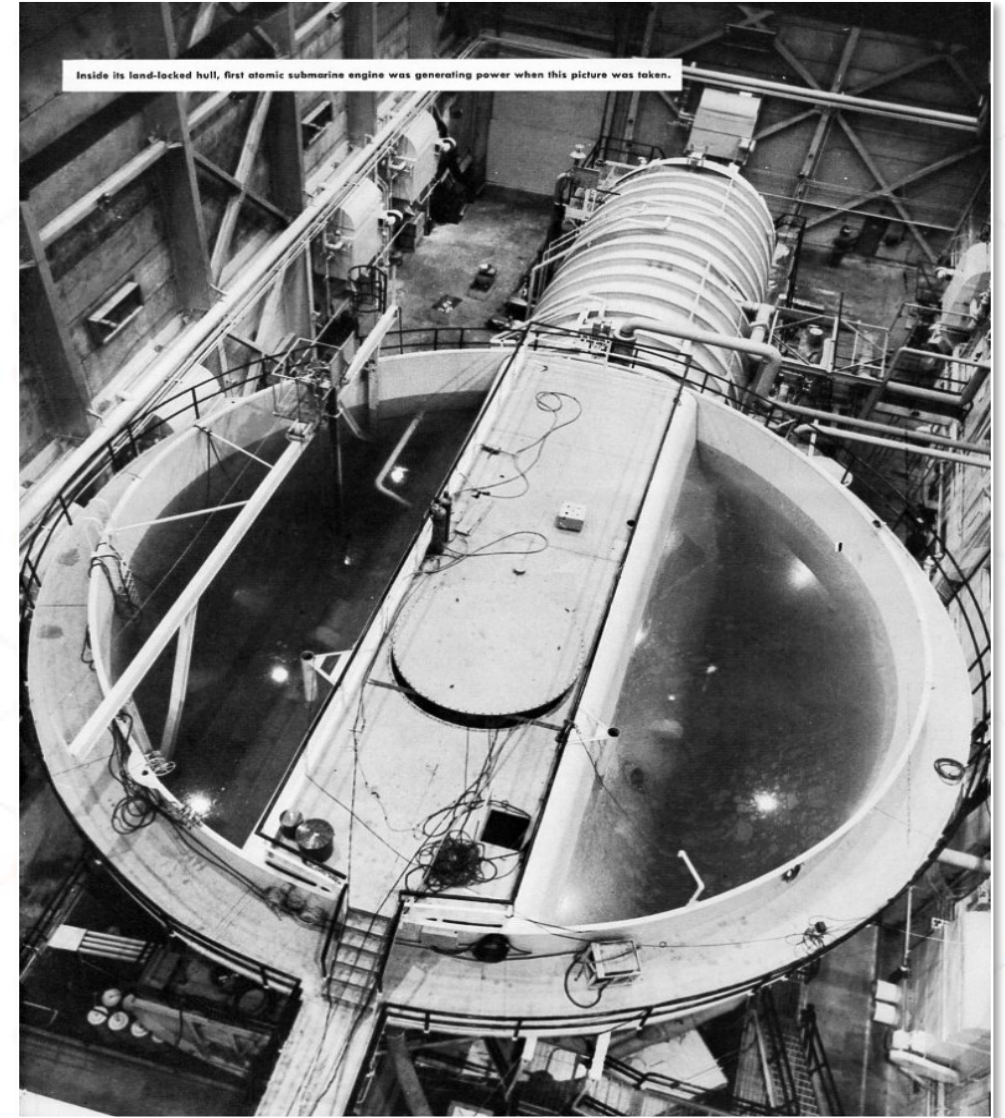
- Pressurized Water Thermal Reactor
- Helium-cooled Epithermal Reactor
- Sodium-cooled Intermediate Reactor

Based on initial studies and development, the following were chosen for the full-scale demonstrations of nuclear propulsion

- Submarine Thermal Reactor (pressurized water reactor PWR) – S1W prototype and S2W [*Nautilus*]
- Submarine Intermediate Reactor (sodium-cooled) – S1G prototype and S2G [*Seawolf*]

# The Full-Scale Demonstrations

- The S1W prototype and the *Nautilus* were operationally successful. The remaining technical hurdles would be accommodated and timely resolved.
- The S1G prototype and *Seawolf* experienced a considerable number of material, equipment and operational issues
  - Leaking superheaters and steam generators limited power levels, high shutdown radiation levels, and considerable maintenance challenges
  - “...expensive to build, complex to operate, susceptible to prolonged shutdown as a result of even minor malfunctions, and difficult and time-consuming to repair...”
  - After a period of operation to gain experience, the S1G prototype was dismantled and the *Seawolf* propulsion plant was replaced with a design like that in *Nautilus*



S1W prototype

# Decision – PWR Technology for Naval Ship Propulsion

- The practical experience with pressurized water and sodium-cooled reactor technologies in full-scale prototypes and submarines led to PWR technology being chosen as the reference approach for all subsequent U.S. submarine propulsion plants, and later surface ship applications.
- The choice of PWR technology was made based on best available information in a fledgling industry – and driven by the demands of response to Cold War priorities for mission and timing
- PWR technology has proven to be the best overall choice for the U.S. Nuclear Navy and continues to be utilized in the latest designs
- Naval Reactors' conservative design philosophy has allowed operational challenges to be accommodated and resolved without having detrimental effect on the mission



# Building the U.S. Navy's Nuclear Fleet

Within the next decade...

- USSR successes in weapons development, nuclear submarines, intercontinental ballistic missiles, and Sputnik propelled the U.S. military-industrial complex into a massive shipbuilding program using nuclear propulsion
- Multiple submarine propulsion plant designs using PWR technology were developed subsequently to meet the increasing demand for submarine applications (attack; ballistic missile; hunter-killer; cruise missile; radar picket) and to evaluate propulsion plant design alternatives to reduce the submarine noise signature
- Surface ship propulsion plants were developed and installed in an aircraft carrier (*Enterprise*) and three guided missile cruisers (*Long Beach*, *Bainbridge*, and *Truxtun*)

This aggressive shipbuilding program extended into the 1980s and beyond with multiple additional nuclear propelled submarines and surface ships. **This program developed much of the U.S. industrial capability that supported the emergence of commercial nuclear power.**

# Power Reactors: Private Sector's Perspective

## – The First Two Decades

### Major hurdles and challenges

- Uncertain which nuclear technologies were economic and reliable – unclear whether nuclear would be economically competitive
- Access to technical information on nuclear energy held closely by USG
- Commercialization – global or domestic?
- Will nuclear power development be led by the private or public sector?
- How much would or should the private sector invest?
- **No comprehensive regulatory framework – plant licensing and export controls**

# Initial Reactor Development and Demonstration

- Numerous Early Reactors
  - Production reactors (e.g., Oak Ridge; Hanford; Savannah River)
  - Thermal and fast reactor experiments (e.g., CP-1; Clementine; F-1; EBR-I; NRX; RBMK; Borax-I; HTRE; Calder Hall; Obninsk; OMRE; SL-1; UHTREX; GCRE; MSRE, etc. )
- AEC Five-Year Plan (1954-1959):
  - Argonne – sodium-cooled breeder reactor experiment – EBR-II
  - Argonne – boiling water reactor experiment
  - Oak Ridge – homogeneous reactor experiment
  - Atomics International/Southern California Edison – Santa Susanna sodium-cooled reactor experiment
  - Shippingport power reactor demonstration



# AEC Power Demonstration Reactor Program

## Round 1 – 1955

- Yankee Rowe – PWR, 185 MWe (1960-1992)
- Fermi Plant Unit 1 – sodium-cooled fast-breeder reactor, 100 MWe (1965-1973)
- Hallam Plant, sodium-graphite reactor, 75 MWe (1963-1964)

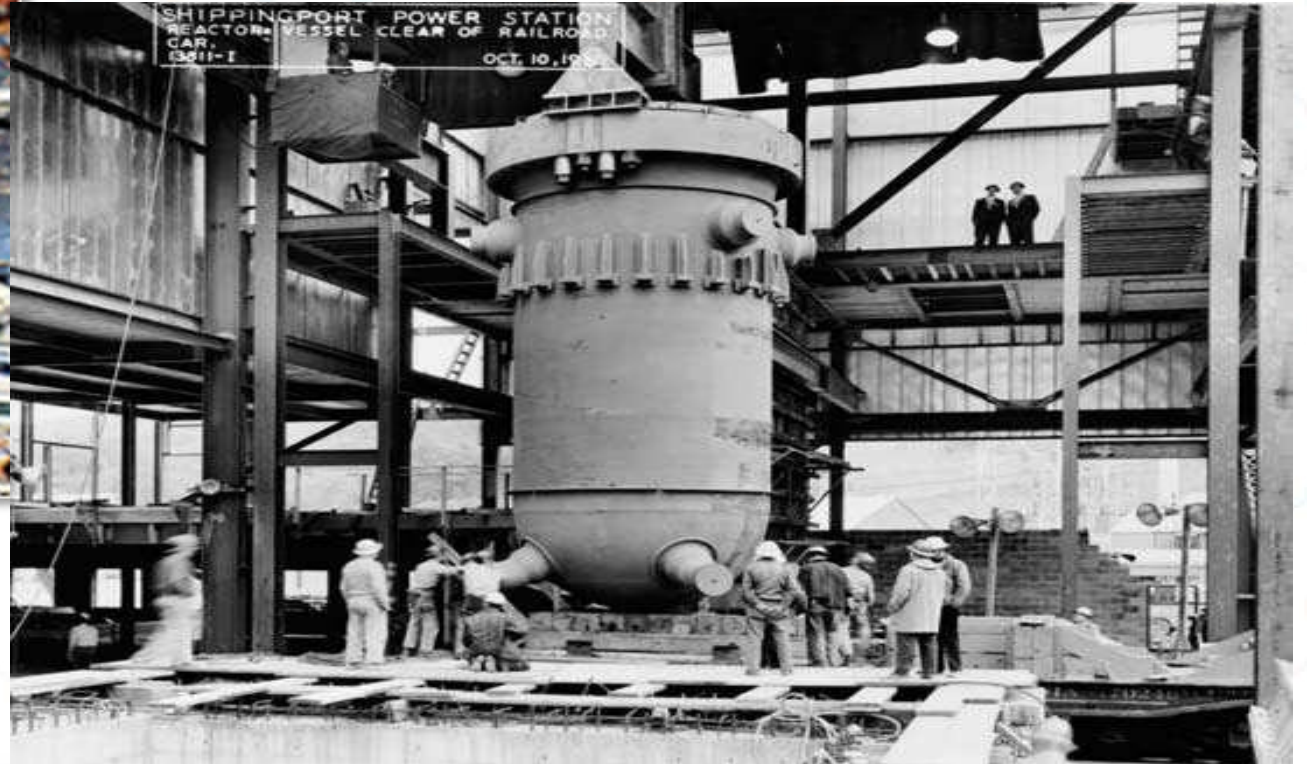
## Round 2 – 1956

- Elk River Plant – indirect cycle BWR, 22 MWe (1964-1968)
- Piqua Nuclear Power Facility – organic moderated and cooled reactor, 12 MWe (1963-1966)
- Boiling Nuclear Superheat reactor BWR with integral nuclear superheat, 17 MWe (1964-1968)
- LaCrosse Plant – BWR, 50 MWe (1969-1987)

## Round 3 – 1957

- Carolinas-Virginia Tube Reactor PHWR, 17 MWe (1963-1967)
- Big Rock Point – BWR, 67 MWe (1963-1997)
- Pathfinder, BWR with integral nuclear superheat, 59 MWe (1966-1967)
- Peach Bottom Unit 1 – HTGR, 40 MWe (1967-1974)
- San Onofre Unit 1– PWR, 440 MWe (1968-1992)

# Shippingport



# Power Reactor Project – Shippingport

- Within only months following the S1W prototype achieving full power operations (May 1953), the USG made the decision for Naval Reactors to build a PWR-based commercial power reactor.
- The demonstration Power Reactor Project, subsequently sited at Shippingport, was designed and built via a partnership between the AEC and Duquesne Light Company with reactor plant design by Westinghouse (Bettis) and Stone & Webster Engineering Corporation, and steam plant design by Burns & Roe, Inc.
- The Shippingport reactor plant design was extrapolated from the preliminary work for an aircraft carrier propulsion plant reactor with the Naval features removed and all else declassified to facilitate technology transfer to the private sector. Thousands of technical reports regarding the technology development, design and operational experience were issued.
- In December 1957 Shippingport achieved full power operations – the U.S.' first large scale nuclear power plant.
- The Shippingport demonstration provided a foundation for future commercial power plants. Although not yet economically competitive, its operating experience was exceptionally useful regarding materials and equipment performance (some important problems were uncovered).



# Successful Engineering Approach

- **Project methodology with focus on engineering and only enough science to complete the design**
- **Conservative technical requirements – primary objective was fulfilling the mission on the first try even though technologies were yet unproven**
- **Measured, step-wise approach to innovation in nuclear propulsion technology achieved continuing success**
- **Socratic method to achieve engineering excellence – nothing was assumed or sacred**
- **Reliance on technically competent personnel rather than management systems**
- **Personal responsibility**

# Snapshot Early 1960s Nuclear Navy + Shippingport



*Shippingport*

# Early Commercialization – no U.S. Government financial support

## Dresden Unit 1 – GE BWR, 197 MWe – Commonwealth Edison (1960-1978)

- Construction permit issued May 1956; operating license issued September 1959



## Indian Point Unit 1 – Westinghouse PWR, 257 MWe – Consolidated Edison (1962-1974)

- Construction permit issued May 1956; operating license issued 1962



**Important to note that financial commitments and construction permit applications for the above plants were made before any operating experience with Shippingport – exceptional business risk positions.**

***Advanced reactors have the opportunity to moderate business risk by drawing on more than 17,000 reactor-years of operating experience from the current global fleet of power reactors.***



# The Contenders

## Europe

- Initial reactor development led by UK and France influenced by military considerations – wanted to develop nuclear weapons capabilities
- U.S. refused to share uranium enrichment technology which forced UK and France to pursue natural uranium reactor technologies
- Interested in indigenous technologies that could be exported
- Gas-graphite technologies became the obvious choice for their civilian power programs



### **Calder Hall (UK)**

- Magnox CO<sub>2</sub> cooled, graphite moderated, natural uranium. Primarily for plutonium production.
- First 50 MWe unit connected to grid in October 1956

# The Contenders

## USSR

APS-1 Obninsk – water-cooled, graphite moderated, 5 MWe (1954-2002)

- First grid-connected nuclear reactor.
- Forerunner of the RBMK reactor design

## Soviet Navy

- 1959 – first nuclear powered attack and ballistic missile submarines
- PWR and LMFR (lead-bismuth) technologies

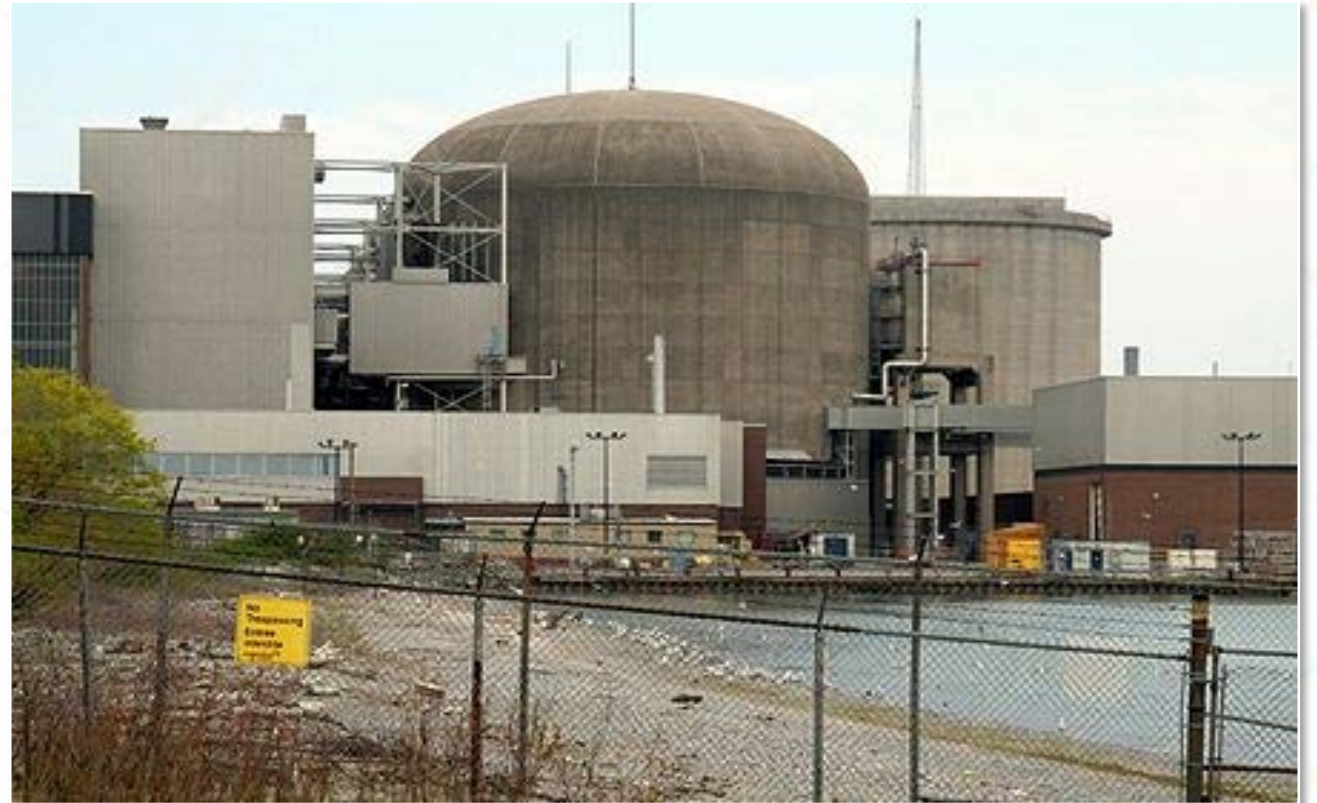
WWER – PWR, 210-1000 MWe (beginning in 1964)



# The Contenders

## Canada

- Heavy water cooled and moderated reactors, natural uranium (CANDU)
- Experimental
  - NRX (1947)
  - NRU (1957)
- Power Demonstrations
  - Rolphton, 22 MWe (1962-1987)
  - Douglas Point, 200 MWe (1967-1984)
- Commercial
  - Pickering, first unit 550 MWe (1971-2007)





# Context – U.S. Power Reactor Commercialization

- “Atoms for Peace” or “Atoms for War”?
- Nuclear energy and nuclear weapons inextricably linked – disarmament; proliferation; safeguards
- Technological progress by USSR – Obninsk nuclear power reactor (1954), thermonuclear bomb (1955), nuclear submarines, intercontinental ballistic missile (1957), Sputnik (1957), manned space flight (1961)
- **Cold War motivation –**
  - **U.S. nuclear weapons superiority gave way to parity with USSR – evolved into Mutually Assured Destruction in the early 1960s**
  - **Important element of national security derived from global nuclear energy leadership and superiority**

# Enabling Commercialization of U.S. Nuclear Power Technology

- **Atoms for Peace (1953)**
  - Operation Candor – acknowledging the nuclear threat while envisioning the “peaceful atom”
  - Peaceful, controlled dissemination of nuclear technology
  - Civilian versus military control of nuclear technologies
- **Euratom formed and a 1958 accord signed for cooperation with the United States Government**
  - U.S. to provide financial and technical aid (amounted to half of the Euratom budget for research and construction) lowered the cost of developing and using light water reactor (LWR) technology compared to gas-graphite technology
  - U.S. to provide enriched uranium
  - Proposed 1000 MWe of nuclear generating capacity to be built under U.S. patents primarily by European subsidiaries of Westinghouse and GE
  - Three European LWRs built under the auspices of the U.S.-Euratom agreement gave momentum to shaping European views about the viability of LWR technology – and cemented its future



# The Result – LWR Technology Became the Global Choice

Driven by LWR technology maturation through the Naval Nuclear Propulsion Program and early commercial LWRs, the large number ordered in the U.S. marketplace, and the provisions of the Euratom/U.S. accord.

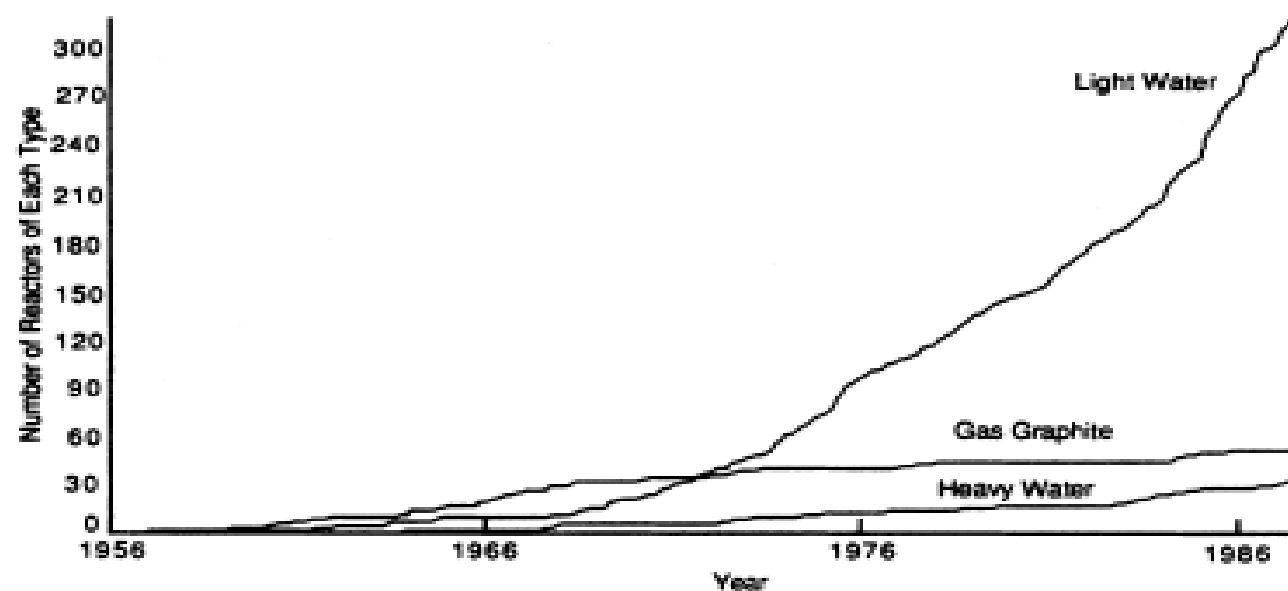


FIGURE 1B

NUMBER OF REACTORS BY TYPE

Source: International Atomic Energy Agency, *Nuclear Power Reactors in the World* (Vienna, 1987).



# Regulatory Uncertainties ~ Early 1960s

- **AEC regulatory activities began focusing primarily on LWR technology**
- **Driven by economics, proposed commercial reactor design choices lacked design and operational experience that could be derived from naval and Shippingport reactors**
  - **Order of magnitude greater power rating**
  - **Structurally less robust fuel design**
  - **Considerably higher operating temperature using same basic materials of construction**
  - **Chemical “shim” reactivity control using boric acid**
- **Unresolved fundamental reactor safety issues (e.g., siting requirements; containment vs confinement concepts; need for Emergency Core Cooling System (ECCS); source term and atmospheric dispersion modeling)**
- **Competing commercial industry demands for flexible regulation versus prescriptive regulation – *inappropriate industry expectation that a licensed reactor is a safe reactor solely as a result of fulfilling regulatory requirements and review by AEC***
- **Underlying conflict between *promotion* and *regulation* of nuclear energy**

# Power Reactor Commercialization – Key Messages

- Commercialization of power reactors was strongly influenced by Cold War priorities. ***Important element of national security was derived from global nuclear energy leadership and superiority.***
- Atoms for Peace program and the Euratom/U.S. accord set the stage for LWR (moderated and cooled) technology to dominate the global marketplace – the result of U.S. national policy, relative technological maturity, and financial and technical assistance, not a search for the most economical, most reliable or safest concept.
- Westinghouse and GE offered turnkey pricing (i.e., fixed price) on commercial LWRs from 1963-1966 which allowed them to become global industry leaders. Consequent underestimation of the actual costs distorted the economics.
- Exceptional business risk was taken by private sector for early power reactor development and demonstration prior to any operating experience. Business risk for developing advanced reactors can be moderated by drawing on more than 17,000 reactor-years of operating experience from the global fleet of power reactors.
- **In the early 1960s, AEC reactor regulation was in its infancy and began focusing on LWR technology. Subsequent resolution of important reactor safety uncertainties and operational experience dramatically changed the regulator's role and approach.**