United States General Accounting Office 130662

GAO

Briefing Report to Congressional Requesters

August 1986

NUCLEAR SAFETY

Comparison of DOE's Hanford N-Reactor With the Chernobyl Reactor

130662

GAO/RCED-86-213BR

036316

GAO United States
General Accounting Office
Washington, D.C. 20548

Resources, Community, and
Economic Development Division

B-223754

August 5, 1986

The Honorable Mark O. Hatfield
Chairman, Committee on Appropriations
United States Senate

The Honorable James H. Weaver
Chairman, Subcommittee on
General Oversight, Northwest
Power, and Forest Management
Committee on Interior and
Insular Affairs
House of Representatives

This briefing report is in response to your requests for information on the Department of Energy's (DOE's) N-Reactor, located near Richland, Washington. As discussed with your respective offices, we gathered information on

--the similarities and differences in design and safety features of N-Reactor and the Soviet's reactor near Chernobyl,

--DOE's program to extend the life of N-Reactor, and

--emergency preparedness plans for N-Reactor.

On April 26, 1986, an accident occurred at a Soviet nuclear power plant near Chernobyl. While the exact sequence of events is not yet clear, it is evident that an explosion occurred, followed by a large release of radiation, indicating that there had been fuel melting. The realization that the Chernobyl reactor was moderated by graphite focused attention in the United States on DOE's N-Reactor, which is also graphite moderated. N-Reactor is operated by UNC Nuclear Industries under a contract with DOE. It produces plutonium, which is used in the production of nuclear weapons, and steam, which is sold to the local utility for electricity production.

In summary, we found that many differences exist between N-Reactor and the reactor near Chernobyl. One of the most significant of those differences involves the reactors' inherent physics responses to increases in coolant temperature--a situation that could occur during the initial stages of an accident. At the Chernobyl reactor, an increase in coolant temperature results in an increase in reactor power, a situation that could result in a run-away nuclear chain reaction. Many experts believe this situation was a critical element in the progression of the Chernobyl accident. The N-Reactor is quite different in this regard, with reactor power tending to decrease when coolant temperature increases, which in turn reduces the likelihood of a chain reaction.

N-Reactor also has safety systems that apparently were not present on the Soviet reactor. These include a system to cool the graphite moderator and a backup, gravity-operated system to shut down the reactor.

Other characteristics of N-Reactor, however, do not appear to offer clear advantages when compared with the Chernobyl reactor. N-Reactor uses a metal form of uranium fuel, while the Chernobyl reactor uses an oxide form of uranium fuel. If an accident occurs and metal fuel comes into contact with coolant water, it creates more potentially explosive hydrogen than would be created by the oxide fuel. In this respect, the metal fuel is a disadvantage. On the other hand, metal fuel has an advantage in an accident situation because it stores less energy that must be removed by coolant. If coolant is not available, this energy could contribute to fuel melting.

Another characteristic is that N-Reactor uses once-through emergency cooling rather than a recirculating emergency cooling system like Chernobyl's. During an accident resulting in a loss of coolant at N-Reactor, the once-through cooling system draws water from a storage tank, and from the Columbia River when the tank is empty. This water passes through the reactor into a holding tank. If the holding tank fills, the radioactive water is stored in an outdoor, open pit. UNC Nuclear Industries is currently studying the possibility of migration of radioactive water from the pit to the Columbia River.

The Chernobyl reactor probably used some form of containment system to control steam pressures and the release of radioactive materials during an accident. We found that the overall safety of N-Reactor relies heavily on successful operation of a different type of system--a reactor confinement system. This system provides for steam pressure venting and filtering of airborne radioactive materials that may result from an accident. UNC Nuclear Industries' prior analyses have not found a credible accident scenario that would compromise the confinement system at N-Reactor and allow excessive amounts of radioactivity to escape to the environment. In the wake of the Chernobyl accident, UNC Nuclear Industries is analyzing accident scenarios that previously were not considered credible. (See section I.)

N-Reactor has been operating 3 years beyond its expected life, and many systems and components are deteriorating. Maintaining safe operations through the mid-1990's will require considerable upgrading and rehabilitation. To extend safe operation of N-Reactor beyond the year 2000, major renovations--costing as much as $1.2 billion--will be required. (See section II.)

Our work relating to emergency preparedness at N-Reactor revealed that DOE and its operating contractor are in compliance with 7 of 10 prior GAO recommendations. DOE was in partial compliance with two recommendations, involving the need for DOE review of emergency preparedness plans and programs. Although DOE reviews these plans and programs, the reviews are not conducted as often as we previously recommended. The recommendation that has not been implemented relates to an absence of state and local agencies' participation in N-Reactor site-wide emergency drills. DOE and state and local officials agree there is a need for joint participation in the drills; however, neither the state nor DOE budgets provide for funding of state or local participation. (See section III.)

We obtained the information presented in this briefing report primarily from DOE, UNC Nuclear Industries, and state and local government officials and documents. Information was also obtained from two DOE studies on the Safety of N-Reactor that were conducted in the post-Chernobyl time frame. While we believe the information contained in this report represents the best available information at the time of our review, information from the Soviet Union on the Chernobyl reactor and accident is still incomplete and, in some cases, has been conflicting. In addition, DOE has requested two additional studies on the safety of N-Reactor. A group of consultants are conducting a study of the design safety of N-Reactor. Also, the National Academy of Sciences plans to study the safety of N-Reactor later this year. When completed, these studies may provide additional information and new insights on the safety of N-Reactor. (See section IV.)

As requested, copies of this report will not be made available to other interested parties until 30 days after the date of its issuance or upon public release of its contents. If you have any questions or if we can be of further assistance, please feel free to contact me.

J. Dexter Peach
Director

Contents

ABBREVIATIONS

AC	Alternating Current
DOE	Department of Energy
ES&H	Environment, Safety, and Health
FEMA	Federal Emergency Management Agency
GAO	General Accounting Office
MWd/kgU	megawatt days per kilogram Uranium
psi	pounds per square inch
psig	pounds per square inch gauge
WPPSS	Washington Public Power Supply System

SECTION I

DESIGN AND SAFETY FEATURES OF N-REACTOR COMPARED WITH THE CHERNOBYL REACTOR

THE CHERNOBYL ACCIDENT

It is difficult to make a detailed analysis of the Chernobyl accident and compare the features of DOE's N-Reactor and the Soviet Chernobyl reactor because little verified information is available concerning the design of the Soviet reactor or the accident that occurred on April 26, 1986. The verified information available regarding the accident can be summarized briefly: there was an explosion resulting in a breach of the reactor building, and there was a large and extended release of radioactive materials, indicating that there had been extensive fuel melting.

While the Soviets have not released details of the accident progression, there is speculation among reactor experts that part of the accident involved a very rapid increase in the rate of the chain reaction. The possibility that this was part of the accident is supported by official Soviet statements that there was "a rapid rise in power from 6 to 50 percent in 10 seconds." In addition, Soviet scientists have published technical information regarding the physical characteristics of the Chernobyl reactor that make such an accident plausible.

There is little agreement among observers regarding the potential causes of the rapid power rise and the events that followed it. Various alternatives have been offered to explain how the accident was initiated, including experiments that may have lead to loss of coolant or fires that resulted in loss of electric power. There has also been a wide range of expert speculation regarding the events that followed the rise in power to account for the explosion, such as generation of large amounts of steam, generation of hydrogen from a reaction between the hot steam and the fuel cladding material, and the generation of combustible gases from a water-graphite reaction. None has been confirmed by Soviet officials; thus we will not address these issues.

COMPARISON OF CHERNOBYL AND N-REACTOR

N-Reactor has several obvious similarities to the Chernobyl reactor, including the use of graphite as the moderator and water in pressure tubes as the coolant. Numerous differences, however make it difficult to draw a one-to-one comparison between the two reactors, even if more information were available for the Chernobyl reactor. The remainder of this section discusses the similarities and differences of N-Reactor and the Chernobyl reactor in the following areas:

--general information and site characteristics,

--moderator,

--coolant,

--fuel,

--reactor control,

--engineered safety systems, and

--confinement/containment systems.

GENERAL INFORMATION AND SITE CHARACTERISTICS

	Chernobyl	Hanford N-Reactor
Location	Chernobyl, Ukraine U.S.S.R.	Richland, Washington U.S.A.
Population density	150,000-180,000 within 18 miles; 3.5-7 million within 100 miles	0 within 5-1/2 miles, 240 within 10 miles; 10,000 within 20 miles
Date of initial operation	1983	1963[a]
Power rating	1,000 megawatt electric, 3,140 megawatt thermal	860 megawatt electric, 4,000 megawatt thermal
Use	Electricity generation	Plutonium production for nuclear weapons; steam production for electricity generation as a byproduct
Basic configuration	Vertical pressure tubes, water cooled, graphite moderated	Horizontal pressure tubes, water cooled, graphite moderated

[a]Electricity generation began in 1966.

General information

Both reactors are large nuclear plants, with the Chernobyl reactor producing slightly more electrical power and N-Reactor producing more thermal power. Both reactors have large inventories of radioactive materials in the core that could be dispersed in the event of an accident.

The two sites differ significantly in terms of the risk of radiation doses to a large number of people following an accident. The Chernobyl reactor is situated in a densely populated region, with more than 150,000 people within a 10-mile radius of the plant. In contrast, there are no permanent residents within 5-1/2 miles of N-Reactor, and only 240 people reside within 10 miles of the site.

Both reactors are cooled with ordinary ("light") water in more than 1,000 pressure tubes that encase the coolant and fuel. The pressure tubes are arranged parallel to one another in a large stack of graphite blocks that serves to slow down, or moderate, neutrons produced by the fission of uranium fuel, thus allowing a chain reaction to be sustained. This design differs from most commercial reactors in the United States, which use water as the moderator as well as the coolant and a single heavy steel pressure vessel rather than numerous pressure tubes.

MODERATOR DATA

	Chernobyl	Hanford N-Reactor
Type	Graphite	Graphite
Amount	1,700 metric tons	1,980 metric tons
Operating temp.	1,382°F	950°F
Dedicated coolant system	No (heat conduction from graphite to coolant in pressure tubes)	Yes 640 cooling channels
Cover gas	Helium/nitrogen (inlet at bottom, outlet at top of reactor)	Helium (inlet and outlet at bottom of reactor)

Moderator

Both reactors use graphite to moderate the chain reaction. Reactor graphite is a chemically pure form of carbon that is shaped into hard blocks, which are machined and drilled to allow pressure tubes, control rods, and other reactor instrumentation and equipment to pass through them. They are stacked to serve as support for the core components.

Graphite was used to moderate the first nuclear reactor in Chicago in 1942 and has since been considered a suitable material for moderating nuclear reactors (along with light water and heavy water).[1] Graphite is generally considered to have a safety advantage over water in that it can absorb a large amount of heat following a loss-of-coolant accident, thus delaying the onset of fuel melting and allowing time for safety systems or operator action to control the accident. For example, even if all cooling water were lost, the safety analysis report for N-Reactor indicates that the fuel would not begin melting for 7 minutes; in contrast, at a commercial light water reactor, fuel melting could begin within 10 to 30 seconds of a total loss of coolant.

The possibility of a graphite fire appears to be a risk, particularly in light of the published accounts of the events at Chernobyl. It has been speculated that a graphite fire, possibly ignited by hot or melted fuel, complicated recovery efforts and provided a heat source that contributed to the dispersion of radioactive materials to the environment. However, it has not been definitively established that the graphite ignited at Chernobyl, and some safety experts believe that this is unlikely.

Recent events have rekindled interest in an accident that occurred in a graphite-moderated reactor at Windscale, England, in 1957. The accident occurred during a maintenance procedure that was intended to restore the graphite to its condition before prolonged exposure to radiation and high temperatures. Coolant flow was deliberately restricted and the uranium fuel was used to heat up the graphite. Operator error and problems with instrumentation contributed to allowing the fuel to overheat and become exposed to the hot graphite. Although the chain reaction was shut down, the exposed fuel eventually caught fire and caused the failure and combustion of other fuel elements. The official inquiry by the British Government concluded that, while graphite could have ignited after the fuel had failed, it was extremely unlikely that a rapid release of energy from the graphite caused the fuel to fail.

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[1] A molecule of light water is made from one atom of oxygen and two atoms of the lightest form of hydrogen. By contrast, a molecule of heavy water is made with the form of hydrogen called deuterium, which has twice the mass of the lighter form of hydrogen.

After the Windscale accident, experiments were performed at Hanford and Brookhaven National Laboratory to determine the extent of graphite combustibility. More recently, graphite tests have been conducted by UNC Nuclear Industries and an independent testing laboratory. The results of these experiments indicate that it is at least very difficult to ignite reactor-grade graphite, even when ample oxygen is available for combustion.

The graphite moderator block and associated systems at N-Reactor and at Chernobyl are designed to reduce the chance that oxygen (required for a fire) could come into contact with the graphite. The core is sealed to prevent oxygen ingress and inert gas is circulated through the graphite. Even if some oxygen did leak into the sealed graphite core, combustion gases would, in theory, eventually extinguish a graphite-oxygen reaction.

N-Reactor also is equipped with a cooling system for the graphite moderator that is separate from the fuel cooling system. This system is intended to keep the graphite cool and provide an additional source of heat removal that could limit fuel melting in the event that all other normal and emergency cooling fails to function. The only known heat-removal mechanism for the graphite in the Chernobyl reactor core is conductive heat transfer from the graphite to the pressure tubes carrying coolant for the fuel.

While experiments and experience cannot rule out the possibility of a graphite fire in a reactor, it appears that graphite is, at best, difficult to burn. UNC Nuclear Industries officials are confident that the systems in place at N-Reactor make it highly unlikely that a graphite fire could initiate an accident at N-Reactor.

COOLANT DATA

	Chernobyl	Hanford N-Reactor
Type	Vertical pressure tubes, pressurized boiling light water	Horizontal pressure tubes, pressurized light water (no boiling)
Configuration	2 loops, 1,661 channels	6 loops (1 loop in reserve), 1,003 channels
Total coolant flow	37,500 metric tons/hr	38,500 metric tons/hr
Operating pressure		
Inlet	1,160 psig[a]	1,750 psig
Outlet	1,060 psig	1,600 psig
Operating temp.		
Inlet	518°F	400°F
Outlet	543°F	540°F

[a]Pounds per square inch gauge--a measure of the difference between actual pressure and atmospheric pressure.

Coolant

Both reactors are cooled by light water. The water collects heat as it flows past the fuel in small-diameter pressure tubes and transfers the heat to turbine generators to produce electricity. The coolant temperatures in the two reactors are comparable. The pressures, however, are significantly different, with the reactor at Chernobyl operating at much lower pressure than N-Reactor. The higher pressure at N-Reactor prevents boiling throughout the core under normal operating conditions. In the Chernobyl reactor, the coolant begins boiling one-third of the distance along the fuel rod and continues to boil until it exits the reactor. This implies that the Chernobyl reactor operates with less margin to loss of cooling, or that the amount of additional heat required to boil off all the coolant is less at the Chernobyl reactor than at N-Reactor.

The two reactors also differ in the configuration of the coolant loops. At the Chernobyl reactor, two coolant loops split into 1,661 pressure tubes at the bottom of the core. Each of the two loops cools one-half of the core, independent of the operation of the other loop. According to Soviet technical papers, it is possible with this configuration that each half of the core could respond differently if a problem occurred in one of the two loops. For example, one of the accident scenarios hypothesized by Soviet scientists for the Chernobyl reactor is an inadvertent activation of one of its two emergency cooling systems, each of which supplies one-half the core. Injection of cool water into half the core can cause a change in power in that portion of the reactor. Automatic adjustments can cause a rise in power in the other half of the reactor.

At N-Reactor six coolant loops feed into a common manifold to allow mixing before the coolant enters the core. If the system operates as designed, UNC Nuclear Industries officials believe a problem with one coolant loop at N-Reactor would be more equally distributed throughout the core. Therefore, N-Reactor would be less likely to incur localized imbalances of the type that were possible in the Chernobyl reactor.

FUEL DATA

	Chernobyl	Hanford N-Reactor
Type	Uranium dioxide	Uranium metal
Refueling mode	On-line	Off-line; refueled at 6-week intervals
Fuel element features	Fuel pellets inside zirconium alloy cladding, separated by a gap	2 concentrically nested tubes with a bonded zirconium alloy cladding
Configuration in core	18 pins/assembly; 2 assemblies per pressure tube	16-21 elements per channel, stacked end to end
Total uranium in core	189 metric tons	366 metric tons
Enrichment	2.0% U-235	0.95 - 1.25% U-235
Burnup	22.3 MWd/kgU[a]	1 MWd/kgU
Cladding temp.	540°F	525°F
Fuel temp.		
Average core	2,000°F	670°F
Centerline	2,500 - 3,000°F	700°F
Fuel melting temp.	3,300°F	1,995°F

[a]This abbreviation for fuel burnup is megawatt, days per kilogram uranium, a standard measure of how long fuel has been irradiated.

Fuel

Both the Chernobyl reactor and N-Reactor use low-enriched uranium fuel, but there are few other similarities in fuel design. The Chernobyl fuel is an oxide form of uranium, comparable to the type of fuel used in commercial reactors in the United States, while N-Reactor uses a metallic form of uranium. One difference between the two fuel types is that oxide fuel does not react as readily with hot water as metal fuel does. The fuel-water interaction is a safety concern because it generates hydrogen, which could burn or explode if it is allowed to combine with oxygen. Both Chernobyl and N-Reactor are designed to prevent oxygen from coming into contact with the moderator or core internals. (See discussion of graphite moderator on p. 14.)

The two fuels also differ in their operating temperatures and melting points. Uranium oxide fuel melts at a much higher temperature than uranium metal fuel, but it also operates at a much higher temperature. While the Chernobyl reactor operated with fuel temperatures between 300°F and 800°F below its melting point, N-Reactor operates nearly 1,300°F below its melting point.

The difference in fuel form also affects the way an accident might progress. Metal fuel conducts heat efficiently from the center of the fuel, where it is hottest, to the outside where it can be cooled. Oxide fuel, on the other hand, is not as efficient a thermal conductor, and as a result, the center of oxide fuel is hotter than the center of metal fuel when the outside temperatures are the same. One implication of this is that an oxide core operating at the same coolant temperatures as a metal core will have much more energy stored in the fuel. This energy must be dissipated following an accident, even if the chain reaction is interrupted immediately. If cooling is not adequate, this energy could contribute to fuel and/or cladding failure.

In addition to differences in fuel design, there are also differences in the way the two reactors are refueled. The Chernobyl reactor was designed to be refueled while the reactor is operating in order to minimize interruptions in producing power. Some observers have speculated that the accident was initiated by an operator error during the refueling procedure. The N-Reactor is shut down for refueling, similar to the procedure followed at commercial nuclear power plants in the United States. DOE and UNC Nuclear Industries officials believe that this procedure limits the opportunities for mistakes leading to a serious accident during refueling.

REACTOR CONTROL DATA

	Chernobyl	Hanford N-Reactor
Reactivity coefficients		
Moderator temp.	Positive	Positive
Water temp. (void)	Positive in most operating regimes	Negative
Fuel temp.	Negative	Negative
Primary shutdown system	211 boron-carbide rods, vertical	84 boron-carbide rods, horizontal
Secondary shutdown system	None	107 channels of boron-carbide balls, gravity-fed through vertical channels
Time to insert control rods to 75 percent	10 seconds	1.5 seconds

Reactor control

Significant reactor control differences exist between N-Reactor and the Chernobyl reactor in areas such as (1) the reactors' inherent responses to changes in temperature and/or power and (2) design of the safety equipment that ensures rapid shutdown in the event of a malfunction.

Reactivity coefficients measure the inherent physical response--the change in the rate of the nuclear reaction--to changes in the temperatures of the graphite, coolant, and fuel. In graphite moderated reactors, the nuclear chain reaction tends to speed up as the temperature of the graphite increases (over a limited temperature range). In technical terms, this is referred to as a positive reactivity coefficient for moderator temperature. This is an undesirable feature of all graphite moderated reactors, but DOE and UNC Nuclear Industries officials consider it to be of limited significance because graphite temperatures change slowly.

At the Chernobyl reactor, an increase in the temperature of the coolant also causes the nuclear reaction to speed up, and overall the reactor tends to increase in power when the temperature rises. This response is referred to as a positive reactivity coefficient of coolant temperature. This has been a concern of Soviet scientists at reactors such as Chernobyl, and events have been identified that could require rapid operator action to prevent serious accidents from developing. Technical papers written by these Soviet scientists have addressed this issue, and changes have been made to the fuel design to lessen the effect. These changes have not, however, eliminated the basic problem--that the reactor does not inherently reduce the rate of the fission process as the power increases, but requires the operation of safety systems for shutdown. There has been widespread speculation that a rapid and uncontrolled rise in power occurred at Chernobyl and initiated a sequence of events that resulted in a steam explosion or the generation of hydrogen and its ultimate burning or explosion.

UNC Nuclear Industries officials informed us that an important part of the N-Reactor's design effort was to ensure an overall negative coefficient of reactivity. As reported in N-Reactor's safety analysis report and confirmed by measurements of the reactor, an increase in the coolant temperature at N-Reactor causes the rate of the fission reaction to decrease (i.e., the reactivity coefficient of coolant temperature is negative). Analysis presented in UNC Nuclear Industries' safety analysis report concludes that this effect is strong enough to overcome the undesirable response to increased graphite temperature, and that overall the chain reaction tends to shut itself down when any event causes temperatures to rise.

Comparing the shutdown systems, the Chernobyl reactor had 211 safety rods that could be driven vertically into the core. These rods are composed of a boron compound, which absorbs neutrons and rapidly reduces the rate of the fission process. A similar system exists at N-Reactor which has safety rods that are arrayed horizontally rather than vertically. The safety system for shutdown at N-Reactor allows for rapid insertion, with 75 percent of the rod movement and nearly full shutdown occurring within 1.5 seconds. At the Chernobyl reactor, it appears that the same degree of insertion required about 10 seconds.

The literature on the Chernobyl reactor does not indicate that a secondary shutdown system existed. At N-Reactor, a completely independent and diverse secondary system is designed to provide full shutdown if the primary rod system fails to operate or operates too slowly. The secondary system allows boron balls to drop into vertical channels interspersed throughout the reactor, with no dependence on positive action from any mechanical component.