REPORT ON

USE OF LOW ENRICHED URANIUM

IN NAVAL NUCLEAR

PROPULSION

JUNE, 1995

Prepared by: Director, Naval Nuclear Propulsion

LOW-ENRICHED URANIUM
IN NAVAL NUCLEAR PROPULSION

CONTENTS

This report discusses what the impacts would be on Naval nuclear propulsion of using low-enriched uranium in place of highly-enriched uranium, and consists of the following parts:

REPORTING REQUIREMENT

Section 1042 of the Fiscal Year 1995 Defense Authorization Act (Public Law 103-337) directed that not later than June 1, 1995, the Navy shall submit to the Committees on Armed Services of the Senate and House of Representatives a report on the use of low-enriched uranium (instead of highly-enriched uranium) as fuel for Naval nuclear reactors.

EXECUTIVE SUMMARY

This report examines the technical, environmental, economic, and proliferation implications of using low-enriched uranium (LEU) in place of highly-enriched uranium (HEU) in a naval nuclear fuel system.

Naval reactors must meet strict standards for fuel integrity dictated by operation in closed (submarine) environments, battle shock, and other considerations not applying to commercial LEU fuel. An extensive ten to fifteen year development and testing effort at a cost of about $800 million would be necessary to qualify an LEU fuel system to these standards and expand fuel and core manufacturing capacities to use it.

Assuming a reliable LEU fuel system could be developed, the use of LEU in U.S. Naval reactor plants is technically feasible, but uneconomic and impractical. The use of LEU in place of HEU would reduce the amount of fissionable fuel which could be packed into a naval reactor core. There are two ways to develop an LEU fuel system which ensures the essential naval reactor functional requirements would be met:

1) Replace HEU with LEU in current reactor designs. The lower energy content of LEU would translate into reduced core life, requiring at least three times as many cores with two to three refuelings per ship. This would:

   - cause greater occupational radiation exposure;
   - generate more radioactive waste;
   - create need for more shipyard capacity to accommodate many additional refuelings;
   - increase ship maintenance costs by about $1.8 billion per year.

   In addition, as a result of the greater time spent in shipyards, the Navy would need to increase force levels by almost 10% to provide the same effective at-sea force levels as current projections. These additional ships would increase the Navy's annual construction and maintenance requirements by about $0.8 billion.

2) Redesign Naval ships to accommodate larger LEU cores which contain an equivalent amount of energy to modern HEU cores and provide the same lifetimes. The one-time redesign cost would be about $4.7 billion, and construction costs would increase by about 28% for aircraft carriers and 26% for submarines -- about $1.1 billion per year.

The continued use of HEU in Naval propulsion reactors is consistent with this country's policy on non-proliferation. Moreover, the use of excess weapons HEU directly as Naval fuel is a safe, economical way of removing this material from the threat of diversion, and of postponing to the maximum extent the need to obtain a new, costly and politically sensitive enrichment facility. The use of LEU would not decrease the overall cost of providing physical security for Naval fuel and cores.

The use of LEU for cores in U.S. nuclear powered warships offers no technical advantage to the Navy, provides no significant non-proliferation advantage, and is detrimental from environmental and cost perspectives.

LOW-ENRICHED URANIUM
IN NAVAL NUCLEAR PROPULSION

SECTION A -- TECHNICAL CONSIDERATIONS

This section of the report contains:

- a summary of the technology of Naval nuclear propulsion reactors, and
- a study of the specific technical impacts on this technology of using low-enriched uranium in place of highly-enriched uranium for Naval nuclear propulsion.

A discussion of the general theory and practice of nuclear fission reactors is included as Appendix A.

I. DESIGN OF NAVAL NUCLEAR PROPULSION REACTORS

The Naval Nuclear Propulsion Program started in 1948. In the nearly five intervening decades, the Program has made a major contribution to the defense of the United States, providing propulsion systems for the world's first true submarines, making possible the virtually undetectable sea-based arm of the strategic triad, and giving major surface combatant ships essentially inexhaustible propulsion power independent of forward logistical support. Forty percent of the Navy's combatant ships are nuclear-powered, and because of their demonstrated safety and reliability, these ships have access to principal seaports throughout the world.

The Program also has made significant contributions to the civilian nuclear power industry with development of basic technologies, with the Nation's first nuclear central power station at Shippingport, Pennsylvania, and with the world's only light-water-cooled breeder reactor.

A. <u>Essential Functional Requirements</u>:

Applying nuclear power to a mobile military platform imposes unique functional requirements on the reactor that are not encountered in land-based civilian applications:

- Compactness: Reactor must fit within the space and weight constraints of a warship, leaving room for weapons and crew, yet be powerful enough to drive the ship at tactical speeds for engagement or rapid transit to an operating area.
- Crew protection: Crew lives and works for months at a time in close proximity to the reactor.

- Public Safety: Ship makes calls into populated ports throughout the world. Maintaining national and international acceptance demands the most conservative engineering and operational approach toward assuring safety of the public.

- Reliability: Ship requires continuous propulsion and electrical power to be self-sufficient in a hostile and unforgiving environment -- undersea, under ice, in combat.

- Ruggedness: Reactor must tolerate ship's motion and vibration, and withstand severe shock under battle conditions.

- Maneuverability: Ship may require rapid and frequent power changes to support tactical maneuvering.

- Endurance: Reactor must operate many years between refuelings, ideally for the life of the ship, to minimize life-cycle cost, minimize demand on support infrastructure, minimize occupational radiation exposure, and maximize ship availability to the fleet for service at sea.

- Quietness: Submarines must be extremely quiet to minimize the threat of acoustic detection and to be able to detect other ships.

These are essential requirements. Failing to satisfy any of them would make the reactor unusable in the ship or would compromise the safety and survivability of the ship and its ability to carry out its mission.

The Naval Nuclear Propulsion Program has aggressively sought the best way to meet these requirements affordably by investigating a variety of reactor types, fuel systems, and structural materials. The Program has extensively investigated many different fuel systems and reactor design features in the laboratory, and has designed, built and operated over 30 different reactor designs in over 20 plant types to employ the most promising of these systems and features in practical applications. A significant accomplishment has been the continuing increase in core lifetimes, from the original core, which lasted about two years in the NAUTILUS (ex-SSN571), to the core for the New Attack Submarine, designed to last the 33-year life of the ship.

The Program was also a pioneer in transferring basic technologies to the civilian nuclear electric power industry; in demonstrating the feasibility of commercial nuclear power generation in this country by designing, constructing and operating the Shippingport Atomic Power Station; and in showing the feasibility of a breeder reactor fuel cycle in the pressurized light-water environment by designing, fabricating and operating in Shippingport the world's only light-water-cooled breeder reactor, LWBR.

These accomplishments have provided a broad base of design, construction, operational, and decommissioning experience upon which to assess the applicability and usefulness of reactor concepts.

B. State of the Technology:

The pressurized water reactor (Figure 1), with HEU fuel in high integrity fuel elements is currently the optimum design to meet the essential functional requirements for nuclear propulsion for warships, as well as to provide very long core lifetimes of up to 33 years for maximum affordability and ship readiness:

- Compactness: The configuration of the fuel and core in modern Naval reactors gives the maximum heat transfer area for the fuel volume, allowing high power density, and therefore high total power from a small volume. The use of water moderator provides for the most effective neutron thermalization in a small volume.

- Crew Protection and Public Safety: To minimize the exposure of the crew to radiation, the fuel must keep the highly radioactive fission products from getting into the coolant. Current Naval fuel element design, materials and fabrication techniques provide multiple barriers to keep the fission products inside the fuel element, and prevent their migration to the coolant. There has never been a fuel element failure in over 280 of these cores operated or currently operating in ships and prototypes.

  Using water as the coolant in a shipboard reactor assures that there will always be a source of makeup. Water has good heat transfer properties, is not hazardous or aggressively corrosive, and does not have violent chemical reactions with air or water (as does sodium, for example). Water does not have any significant long-lived radioactive states, so after-shutdown radiation levels are low and personnel can safely and rapidly enter the reactor compartment to do maintenance within minutes after the reactor is shut down.

- Reliability: The Naval fuel system maintains its integrity to retain the fission products reliably under extremes of operating conditions, providing maximum flexibility to the propulsion plant to deal with possible casualties and still maintain electrical and propulsion power for the ship. This is particularly important for a submarine, where loss of propulsion may place the ship itself in jeopardy.

- Ruggedness: Naval fuel elements and modules are rigid and very strong, able to withstand extreme shock loads as might occur in a collision or in battle from an adversary's weapons.

- Maneuverability: The Naval fuel element design accommodates rapid changes in power level without excessive thermally-induced stresses on the cladding. The thermal expansion properties of the water coolant-moderator provide a natural reactivity feedback mechanism that makes Naval reactors self-controlling during power changes.

- Endurance: The use of highly-enriched uranium maximizes the amount of fissile material in the small volume of the core, providing very long lifetimes along with compactness. The use of strong, highly corrosion-resistant Zircaloy for the fuel element cladding ensures the long-term integrity of the fuel system.

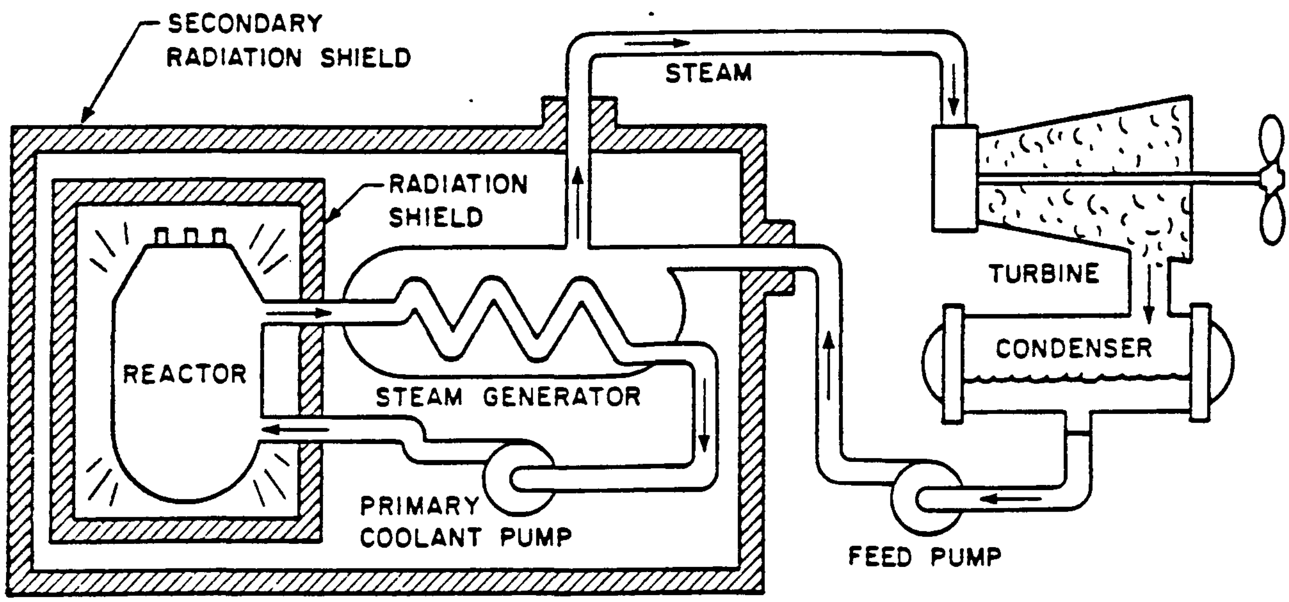

Figure 1: Naval Pressurized Water Reactor

- Quietness: Flow-induced noise increases strongly with flow rate and pump input power. The Naval fuel system has allowed achieving high reactor power for relatively low flow rate and main coolant pumping power, eliminating coolant pumping and flow noise as detectability concerns in modern submarines.

II. IMPACT OF USING LOW-ENRICHED URANIUM ON NAVAL NUCLEAR PROPULSION TECHNOLOGY

A proven fuel system meeting the Naval Nuclear Propulsion Program's stringent technical requirements and based on low-enriched uranium (LEU) in place of highly-enriched uranium (HEU) does not exist.

Developing and testing an LEU-based fuel system, including long-term irradiation testing to the point of being able to commit the fuel system to a warship, would take at least ten years. Building the first core, which serves as the manufacturing qualification, would take at least an additional five years beyond that.

A. Assumptions:

The following assumptions are made for the purposes of this assessment:

The LEU-based alternatives examined are based on 20% enrichment, because this level is just at the internationally recognized breakpoint between LEU and HEU, and has the best chance of working in a Naval application. One case of 5% enrichment for a submarine core has been included for completeness and to illustrate the severe impact of using a level of enrichment nearer that used in civilian reactor fuel.

The functional requirements for a Naval LEU reactor would be no different from the stringent technical requirements to which Naval nuclear propulsion HEU reactors are designed today. Therefore, the Program's performance-proven materials and design bases will be assumed, with no speculation about previously-made fundamental engineering choices for coolant, moderator or fuel system materials and design features.

Specifically, an LEU Naval reactor would:

- be light water-cooled and -moderated, using the same plant temperature and pressure operating ranges as current Naval HEU cores, and

- be based on the same high integrity fuel element and fuel module design, materials and fabrication methods as used in current Naval HEU cores.

B. Fissile Content of LEU:

As noted in Appendix A, the fuels of interest in reactor design vary in their fissile ^{235}U content. This content varies from the lowest, natural uranium at 0.72% ^{235}U, to commercial light water reactor fuel that is typically 1.5% to 4% enriched, to low-enriched non-weapons grade fuel which, by definition, can contain up to 20% ^{235}U, to highly-enriched fuel. Naval cores use fuel enriched to a minimum of 93%. A convenient way to think of the fissile content of these different level-of-enrichment fuels is to look at the volume of fuel which would be required to get the same amount of fissile uranium-235 as one cubic centimeter of 93%-enriched HEU:

TABLE 1

^{235}U Fissile Content of Various Fuels

Enrichment Level	Volume Required to Get Same Fissile ^{235}U Content as One Cubic Centimeter of 93%-Enriched HEU
20%-Enriched	4.7 cc
5%-Enriched	18.6 cc
Natural Uranium	129 cc

That is, the lower the enrichment, the more non-fissile uranium comes along with the fissile uranium. The non-fissile uranium in the lower enrichment fuel represents a very inefficient use of fuel volume. The non-fissile uranium does not produce energy directly, but first has to absorb a neutron and transmute to fissile plutonium -- an inefficient process in small moderated reactors.

Naval reactor cores have evolved in compactness to the point where the maximum amount of uranium is packed into the smallest volume, and the only way to make more volume available for uranium would be to remove cladding, structure or coolant. In other words, no more uranium could be packed into a modern long-lived core without degrading the structural integrity or cooling of the fuel elements. Therefore, using LEU with its lower fissile content in place of HEU wastes volume in the core, and offers only two design choices for a given Naval reactor application:

- Using the same core volumes as in current design ships, pack in about the same amount of uranium, in the form of LEU instead of HEU, and as a consequence reduce the fissile loading and substantially decrease the endurance of the core.

- Alternatively, in redesigned ships, substantially increase the volume of the core, and pack in more uranium in the form of LEU, so that the total amount of energy which can be taken out of the core over its life is the same.

These two choices are further developed below.

C. LEU IN CURRENT DESIGN SHIPS:

1. Submarines: For a modern attack submarine with a 33-year ship life and a life-of-the-ship core, the reduction in fissile content in switching from HEU to LEU has the effect of reducing core endurance by a factor of four, to about seven-and-a-half years, or about one-fourth the life of the ship.

The last ship of USS OHIO (SSBN726) Class of strategic deterrent submarines will be delivered, with its initial HEU core, in 1996. The cores in these ships, designed with late 1970's technology, will operate for over 20 years. The HEU refueling cores to support the one required refueling of these ships will be procured before an LEU manufacturing capability would exist, and therefore the SSBN726 Class ships do not figure directly into this HEU/LEU assessment.

Assuming a strategic force will continue to be maintained, a new class of SSBNs will eventually have to be built to replace the SSBN726 Class. By the time this new class of ships would be designed, a 45-year HEU core should be feasible (see CVN discussion below). For the purposes of this report, the baseline assumption for a new class SSBN will be a ship of about the same size and propulsion power as SSBN726, with a ship life of 45 years and a life-of-the-ship HEU core. The LEU version of this core would have an endurance of about ten-and-a-half years, or about one-fourth the ship life.

TABLE 2

Comparison of LEU and HEU Core Lifetimes in Submarines (SSN and SSBN)

	HEU SSN	HEU SSBN	LEU SSN	LEU SSBN
Core Lifetime, years	33	45	7.5	10.5
Number of Cores in Ship Life	1	1	4	4
Number of Refueling Overhauls in Ship Life	0	0	3	3

2. Aircraft Carriers: The design of the HEU cores used in the USS NIMITZ (CVN68) Class aircraft carriers is based on early 1970's technology, and has mechanical features which facilitate reactor servicing but which make less than fully efficient use of the active core volume. This core operates for over 20 years, so, like the SSBN726 Class, one refueling is required during the approximately 45 year life of the ship.

The current CVN68 Class reactor vessel is judged to be able to accommodate all the fissile fuel, control poison, cladding and support structure required for a life-of-the-ship HEU core. The limiting technical consideration is corrosion of the cladding. Advanced cladding materials are in development and testing, with the goal of realizing core lifetimes as long as 45 years. Although it could not be committed today to a specific carrier construction, a life-of-the-ship HEU core is judged to be achievable within the timeframe of an LEU capability, and therefore has been used as the carrier baseline for HEU/LEU comparison.

The CVN68 Class reactor vessel is large enough that the LEU version of a 45-year HEU core would have an endurance of about one-third the life of the ship, or about 14 years. This is slightly better than the LEU core endurance of one-fourth of the ship life in the smaller submarine reactor vessels.

TABLE 3

Comparison of LEU and HEU Core Lifetimes in CVN68 Class Carriers

	HEU	LEU
Core Lifetime, years	45	14
Number of Cores in Ship Life (Note: Two Reactors in each Ship)	2	6
Number of Refueling Overhauls in Ship Life	0	2

3. Overall Impact: For both submarines and aircraft carriers, LEU cores constrained to fit in current design ships would require more frequent refueling, resulting in a significant increase in life-cycle costs, far greater reactor servicing workload, reduction in ship availability to the fleet, increase in the radiation exposure to shipyard personnel, and increase in the generation of radioactive waste.

D. **LEU IN SHIPS REDESIGNED FOR SAME ENDURANCE**:

If an LEU core were not constrained to fit into an existing design ship, the core could be made bigger to put in more fissile uranium and increase its endurance. From Table 1, one could infer an LEU core would require almost five times the volume of uranium to provide the same endurance as an HEU core. However, optimizing the design to take credit for fissioning of ^{238}U and its fissile transmutation products, ^{239}Pu and ^{241}Pu, and accounting for the lower fissions per unit volume in the fuel, the effect can be reduced to approximately a factor of three increase in the required core volume.

To maintain the same performance (speed and core endurance) with an LEU core, the ship would have to be redesigned. This is because the sizes and weights of the reactor vessel, pressurizer, and other primary plant components must be increased to accommodate the larger core. This in turn increases the size and weight of the reactor compartment and the amount and weight of shielding needed to protect the crew. Consequently, the ship's volume must be increased to add bouyancy to compensate for the increase in reactor compartment and shielding size and weight.

1. Impact of Increased Core Volume on Submarine Design: A study was conducted to assess the overall impact of using a 20% LEU fuel system in an attack submarine propulsion plant with a life-of-the-ship reactor core. The objective of the study was to estimate the increase in propulsion machinery weight, ship size and displacement, and construction costs resulting from this substitution, while maintaining speed and depth capabilities. The baseline for the comparison was an attack submarine (SSN) with a 33-year ship life, a life-of-the-ship HEU core, a length of 376 feet, diameter of 34 feet and displacement of about 7800 long tons. The results were as follows:

TABLE 4

Impact of 20% LEU on a Modern SSN

Attribute	Change for a 20% LEU Core
Machinery weight, % increase	+18%
Hull displacement, % increase	+12%
Hull diameter, feet	+3
Hull length, feet	-10

The LEU-based attack submarine would be heavier and larger in diameter, which would increase costs and be detrimental to tactical characteristics. The heavier submarine would have a longer stopping distance and may be slightly less maneuverable. The increased size would require a ship redesign and result in significantly increased cost, discussed in detail in Section C.

The impact of putting a life-of-the-ship LEU core into a redesigned strategic deterrent submarine (SSBN) was not explicitly modeled. An LEU life-of-the-ship core of SSBN726 power could probably be fit into this ship's 42-foot diameter hull. Weight and moment would be affected by the additional weight of the larger reactor vessel and associated shielding in the after end of the ship. The impact on ship displacement and shipbuilder cost would be non-trivial, but have been neglected for the purpose of this assessment.

2. Impact of Increased Core Volume on Aircraft Carrier Design: A large life-of-the-ship LEU core might be possible for the carrier application. If so, the reactor vessel volume increase from the HEU life-of-the-ship case is not quite as great as the submarine case -- a factor of 2.8 rather than three. However, this reactor would be so large that its being able to meet all the functional requirements on Naval reactors is not necessarily assured. For the purposes of this assessment, it will be assumed feasible and practicable. The larger reactor vessel required for this core would not fit into the current CVN68 Class reactor compartment.

A redesigned reactor vessel and reactor compartment arrangement for this LEU core would require lengthening the ship by eight feet, and would increase the construction costs of the reactor core, reactor and plant heavy equipment, and the ship itself. The economic impact of this option is explored in detail in Section C.

3. Impact of Increased Core Volume on Reactor Reliability: A submarine or aircraft carrier LEU reactor providing the same ship performance would have many more fuel modules and therefore many more moving parts than the HEU reactor, employing up to three times as many control rods and drive mechanisms, and requiring more support equipment such as power supplies, instrumentation and circuit breakers. While these parts today are individually very reliable, they do require maintenance and occasional repair or replacement. Doubling to tripling the number of these parts would increase the cost of emergent maintenance and the potential for operational problems.

4. Impact of 5% LEU on Attack Submarine Design: The above analyses used 20%, the highest level of enrichment within the internationally recognized definition of LEU. This was done to assess use of LEU at the enrichment level that would cause the least adverse impact on Naval reactors. To assess the sensitivity of submarine characteristics to a lower enrichment level, a life-of-the-ship core with 5%-enriched LEU was studied.

The fissile content of 5% LEU is one-fourth that of 20% LEU, so the volume of uranium required in this core to power the submarine for its lifetime is roughly four times that of the 20% LEU case, or twelve times the HEU design base case. The increase in the reactor equipment weight, hull dimensions and displacement are shown below:

TABLE 5

Impact of 5% LEU on a Modern SSN

Attribute	Change for a 5% LEU Core
Machinery weight, % increase	+119%
Hull displacement, % increase	+70%
Hull diameter, feet	+6
Hull length, feet	+54

The impact on a submarine reactor becomes more pronounced with enrichment levels below 20%. The size and displacement of the 5% LEU submarine would make it unacceptable for an attack mission, and its cost would be prohibitive.

Enrichments in the 1.5% to 4% range are acceptable in civilian nuclear power reactors, but not in Naval propulsion reactors, because civilian power reactors:

- are stationary and can be spread out, so the buildings, facilities and equipment for refueling the reactor can be made an integral part of the plant and power station design. Having a reactor servicing capability that is always set up and ready to use minimizes refueling preparation, execution and completion cost and time.

- operate in a less demanding service environment, such as a far less severe set of shock criteria. This allows putting a minimum amount of structure in the core, and a maximum amount of uranium, which increases the density of the fissile loading compared to a combat-rugged Naval plant.

  The less demanding shock criteria allow flexibility in designing the closure head, seal, fuel suspension and control rod drive connections for ease in disassembly and reassembly to support quick turnaround refuelings, minimizing the servicing cost and the impact on station availability.

- can be taken off-line periodically to maximize fuel investment. Per kilogram of ^{235}U, the ^{235}U in LEU is somewhat less expensive to start with than ^{235}U in HEU. To stretch the investment in this fissile uranium even further, the civilian industry has developed a fuel management strategy which consumes a large fraction of the initial ^{235}U, and gets significant energy as well from the ^{239}Pu created in the fuel as it operates. During refuelings, which are performed approximately annually, fully depleted fuel bundles are removed from the core, partially depleted bundles are relocated to regions where their remaining fissile content can be most efficiently used, and new fuel bundles are installed. Over its life, a typical fuel bundle is moved twice to more optimal regions of the core to get out the maximum energy. This strategy is made possible by the reactor and plant design features which facilitate frequent, quick turnaround refuelings.

By contrast, as previously discussed, Naval reactors must:

- be compact and mobile, and cannot carry their refueling facilities around with them;

- operate in a very demanding service environment, including continuing to function under intense shock loadings greater than 50 g's, even at end-of-life when material properties have been degraded by neutron irradiation. This requirement works against designing the reactor for ease of disassembly and refueling; and

- operate many years between refuelings, without fuel management, in order to maximize their time at sea.

III. SUMMARY

Naval cores using LEU would employ the same design, materials and fabrication disciplines and techniques as current HEU cores, in order to ensure meeting all of the functional requirements for a Naval nuclear propulsion reactor. Because of the lower fissile content of LEU, there would be either a reduction in the lifetimes of cores if they were required to be put into the same design ships, or an increase in the size of the cores to preserve lifetime if ships were redesigned to accommodate larger reactor vessels.

LOW-ENRICHED URANIUM IN NAVAL NUCLEAR PROPULSION

SECTION B -- ENVIRONMENTAL CONSIDERATIONS

Using LEU for Naval nuclear propulsion would impact the environment in three areas:

- increase the number of shipments of spent fuel,
- increase the volume of spent fuel requiring disposal, and
- increase the occupational radiation exposure received by shipyard maintenance personnel.

I. IMPACT ON SPENT FUEL SHIPPING AND DISPOSAL

By either putting LEU cores into existing ship designs or redesigning ships for life-of-the-ship LEU cores, the number of spent fuel modules removed, shipped and disposed of during the life of a ship is far greater.

The reference HEU attack submarine design will result in only two container shipments of spent fuel during the 33-year life of the ship -- at the final defueling.

For LEU cores in the same design attack submarine, there would be eight container shipments, at three refuelings and the final defueling. For the redesigned attack submarine with life-of-the-ship LEU core, six container shipments would be required to ship the larger core. Results of this and a similar analysis for SSBNs and CVNs are shown in Table 5.

Table 5 is based on the same simple steady-state model and force level and lifetime assumptions that will be used to estimate lifetime maintenance costs in Section C. In this table, the annual volume of spent fuel requiring disposal in a geological repository in each of these cases is expressed in terms of both the number of M-140 container shipments to temporary storage and the number of "multi-purpose canisters" which the spent fuel would occupy for final disposal.

The M-140 is the Naval Nuclear Propulsion Program's standard railcar-mounted container for shipping spent fuel from a refueling/defueling facility to the Expended Core Facility in Idaho for inspection and temporary storage. The "multi-purpose canister," or "MPC," is a generic container system being designed by the DOE for use in permanently disposing of spent nuclear fuel. It consists of a cylindrical container with approximate inside dimensions of 15 feet height by 5 feet diameter, which is fitted with a holder array for the specific fuel being packed for disposal. The canister is shipped from the spent fuel temporary storage site to the geological repository inside a shielded shipping overpack designed for all possible shipping accidents, and at the geological repository is transferred to a less expensive disposal overpack for final placement in the ground. This MPC, or some variant, is expected to become the basic unit for spent fuel disposal.

TABLE 5

LEU Impact on Average Annual Spent Fuel Shipments

		HEU Baseline	LEU in Existing Design Ships	LEU in Redesigned Ships
SSNs	Spent Cores Shipped	1.7	7	1.7
	M-140 Container Shipments	3	14	10
SSBNs	Spent Cores Shipped	0.3	1.3	0.3
	M-140 Container Shipments	1	5	3
CVNs	Spent Cores Shipped	0.5	1.7	0.5
	M-140 Container Shipments	4	12	10
Total Annual Req'ts	Spent Cores Shipped	2.5	10	2.5
	M-140 Container Shipments	8	31	23
	MPCs Filled	2.4	8.9	6.5

The Naval Nuclear Propulsion Program has always been committed to minimizing the generation of waste from operation of Naval nuclear propulsion plants. Tripling to quadrupling the volume of spent fuel requiring disposal runs counter to that longstanding commitment.

Moreover, the litigation and subsequent dialogue between the State of Idaho and the Departments of the Navy and Energy shows a strong need from the State's perspective to reduce to a minimum the number of shipments, and to limit the increase in volume of spent Naval fuel temporarily stored in Idaho awaiting final disposal. While spent Naval fuel is a small fraction of the total spent nuclear fuel being created and stored throughout the country (about 0.1%), it is a central focus of Idaho's concern. Therefore, tripling to quadrupling the rate of spent Naval fuel shipment also clearly would be objectionable to the State of Idaho.

II. IMPACT ON OCCUPATIONAL RADIATION EXPOSURE

The unit of radiation exposure, used throughout the nuclear industry, is the "rem". One rem is defined as that dose of penetrating radiation which deposits 100 ergs of energy per gram of body tissue. The Federal limit for occupational radiation exposure is 5 rem per year to any radiation worker. The Naval Nuclear Propulsion Program's control level is 2 rem per year. The "man-rem" expended on a job is the sum of the radiation exposures of all the people who participated.

The occupational radiation exposure to shipyard workers in a refueling is influenced most strongly by the number of operations which must be performed in the reactor compartment to prepare for and remove the spent fuel, which is roughly governed by the number of modules. For either LEU case, the number of spent modules which must be removed over the life of a ship would be greater than the HEU baseline case, and therefore the use of LEUwould cause an increase in radiation exposure. Estimates of annual average radiation exposure to shipyard workers for refueling Naval reactors are as follows:

TABLE 6

HEU Baseline and LEU Impact on Occupational Radiation Exposure-
Annual Average Man-Rem Expenditure for Refueling/Defueling Work

	HEU Baseline	LEU in Existing Design Ships	LEU in Redesigned Ships
SSNs	60	249	159
SSBNs	21	93	60
CVNs	63	198	165
Total	144	540	384

The estimates above apply only to the reactor servicing (refueling or defueling) portion of the ship availability or decommissioning. Non-reactor servicing work in the reactor plant, such as valve maintenance, instrumentation and control work, and plant testing or inactivation work, also results in radiation exposure. Currently, the reactor servicing portion accounts for about 20% of the total man-rem expended during ship availabilities. Thus, for LEU cores in existing ship designs, where the exposure due to reactor servicing would nearly quadruple, the total radiation exposure to shipyard workers from ship availabilities could increase by 50%.

An additional complication not accounted for in these calculations would be the increase in high energy neutron radiation levels from transuranic sources in LEU spent fuel. Neutron radiation levels are so low on the outside of Naval Nuclear Propulsion Program HEU fuel handling and shipping containers that neutron dosimetry and special shielding are generally not required. With LEU spent fuel, both special neutron shielding and neutron dosimetry would be required, increasing the cost, complexity and personnel radiation exposure of the refueling or defueling.

In every year since 1966, the Naval Nuclear Propulsion Program has been able to hold constant, and in most cases reduce, the total radiation exposure to shipyard workers. This has been accomplished even as the number of ships in the fleet increased, by constantly improving work procedures and tooling, personnel training and temporary shielding. The development of long-lived reactor cores requiring less frequent refueling also has been a significant factor in this reduction. The increases in man-rem associated with use of LEU would clearly be inconsistent with the overall trend of reducing radiation exposure in the performance of nuclear work in the United States, and with the Naval Nuclear Propulsion Program's longstanding commitment to minimizing the risk to workers.

III. SUMMARY

Using LEU for Naval nuclear propulsion would increase both the annual volume of spent Naval fuel requiring disposal and the annual occupational radiation exposure of shipyard workers. The effect ranges from a factor of nearly three to a factor of four.

LOW-ENRICHED URANIUM
IN NAVAL NUCLEAR PROPULSION

SECTION C -- ECONOMIC CONSIDERATIONS

This section of the report investigates the economic impact of using low-enriched uranium (LEU) in Naval nuclear propulsion reactors instead of highly-enriched uranium (HEU).

I. BACKGROUND

A. Bounding Cases:

A 20%-enriched uranium fuel system qualified for use in Naval nuclear propulsion reactors would take at least ten years to develop. The penalty associated with using an LEU fuel system in place of the current HEU fuel system would be a substantially decreased reactor core endurance or a substantially increased core volume. Two bounding cases from Section A are examined for economic impact:

- Core volume is constrained by existing ship and reactor plant designs; core power and ruggedness would be preserved so as not to adversely affect the military capability of the ship, but core endurance would decrease to accommodate 20%-enriched uranium.

- Core volume is unconstrained; reactors and ships would be increased in size and redesigned, increasing core volume to achieve the same ship speed and core endurance provided by HEU designs.

B. Areas to be Examined:

Substantial economic impact would result from using LEU in either case. This section of the report examines the economic impact under both cases in the following areas:

- Research and development costs, including test reactor operations

- Reactor fuel and core manufacturing infrastructure

- Ship lifetime maintenance costs

- Ship availability

- Ship construction costs

- Shipyard infrastructure

- Spent nuclear fuel shipping and disposal costs

Cost impacts are expressed in FY95 dollars, and are order-of-magnitude estimates based on careful analysis of each element using judgment and extrapolating from past experience.

C. Assumptions on Force Levels and Ship Lifetimes:

A quantitative assessment of the economic impact of using LEU can only be performed within a framework of baseline assumptions on the future composition of the Navy's nuclear-powered fleet. The following long-term baseline assumptions were used:

- Fifty-five attack submarines with a ship life of 33 years, and an HEU core for the life of the ship

  (Note: This is the upper bound of the range of force level of 45 to 55 attack submarines currently under discussion within the Defense Department.)

- Fourteen strategic deterrent submarines with characteristics similar to the existing SSBN726 Class, assuming a ship life of 45 years and an HEU core designed for the life of the ship

- Twelve aircraft carriers with CVN68 Class characteristics, with a ship life of 45+ years and redesigned HEU cores for the life of the ship

  (Note: Congress has authorized ten nuclear-powered carriers to date. This assessment assumes that, as they are retired, old carriers will be replaced with nuclear-powered carriers to maintain a force level of 12 carriers.)

II. IMPACT ON RESEARCH AND DEVELOPMENT COSTS

The technical demands on an LEU fuel system would be the same for either the reduced-endurance or increased-volume case. Fuel and core manufacturing development for an LEU fuel system would cost an estimated $218 million. Irradiation testing and evaluation to qualify the fuel system would cost an estimated $225 million, including irradiation test space for up to ten years in the Advanced Test Reactor, the only facility configured to test materials under Naval reactors irradiation conditions. The total time, from initiating fuel development work to having a fuel system of sufficient proven reliability to commit to manufacture of a warship reactor, would be at least ten years, plus five years to build and deliver the first core.

III. IMPACT ON FUEL AND CORE MANUFACTURING INFRASTRUCTURE

The reactor fuel and core vendor industrial base has shrunk in response to the downsizing of the Navy following the breakup of the Soviet Union, and to the reduced requirements accruing from the continuously increasing lifetimes achieved in HEU reactor cores. A three- to four-fold increase in the rate of production of fuel, fuel elements and fuel modules for LEU cores is required to support either case. To achieve this kind of production rate, a one-time expenditure of $345 to $420 million total at the fuel and core vendors would be required to increase the manufacturing capacity. This is in addition to the per-ship increased core production costs discussed below.

IV. IMPACT ON SHIP LIFETIME MAINTENANCE COSTS

A. LEU in Existing Ship Designs:

1. Submarine Lifetime Maintenance Costs: In an existing submarine design, an LEU core would last only about one-fourth as long as the baseline life-of-the-ship HEU core, requiring three shipyard refuelings instead of none during the life of the submarine.

The baseline attack submarine with a life-of-the-ship HEU core will undergo two major non-refueling overhaul and modernization availabilities, at about ten and twenty years. Therefore, the impact of switching to LEU would be to expand the two overhauls to include refuelings and add a third refueling overhaul. The additional cost to add refuelings to the two overhauls is estimated at $290 million ($60 million each in shipyard costs, plus $85 million for each reload core), and the cost to add a new shipyard availability for the third refueling is estimated at $405 million ($320 million in shipyard costs, $85 million for the reload core), for a total additional lifetime maintenance cost of $695 million per ship. Annualizing this lifetime cost increase for a force level of 55 SSNs gives an annual cost impact of about $1.15 billion.

The baseline strategic deterrent submarine has an HEU core designed for the life of the ship, and would undergo three major overhaul and modernization availabilities at about ten year intervals. The affect of switching to LEU would be to expand these to include refuelings. The reload cores for these ships would cost about $115 million each vice $85 million for the SSN cores, based on the higher reactor power required for the larger SSBN. The additional lifetime cost for each ship to add refuelings to the three availabilities would be $525 million ($60 million for each refueling and $115 million for each reload core), or an annualized cost impact for the 14 ships of about $160 million. Adding this to the annualized cost impact for SSN maintenance of $1.15 billion gives a total annual cost impact on the submarine fleet of about $1.3 billion.

2. Aircraft Carrier Lifetime Maintenance Costs: The baseline aircraft carrier has the current CVN68 Class reactor vessel and plant, but an HEU core designed for the life of the ship. If this core were switched to LEU, it would last about one-third the life of the ship, and the carrier would come into the yard for refueling twice during ship life instead of never. Overhaul and modernization work would be consolidated into these two refueling availabilities to minimize the time spent in yard. The lifetime maintenance cost for each carrier would increase by an estimated $1.78 billion ($300 million in shipyard costs to add a two-

reactor refueling to each of two overhaul periods, and $590 million for each set of two reload cores). There would be cost fluctuations from year to year, but using an annualized assumption, the added refuelings would result in an average annual cost impact on the carrier fleet of about $475 million.

B. LEU in New Ship Designs with Increased Core Volume:

The expected lifetime maintenance cost of operating and maintaining either a submarine or an aircraft carrier with a life-of-the-ship LEU core in the increased-volume case is not appreciably different from that for a life-of-the-ship HEU core. The cost of some reactor equipment periodic maintenance and testing, such as control rod testing, would increase by a few million dollars over the life of the ship due to the larger core, but this effect would be negligible for all practical purposes. The increased cost of this approach comes in ship construction, discussed in **VI.B** below.

V. IMPACT ON SHIP AVAILABILITY

A. LEU in Existing Ship Designs:

Because of the frequent refuelings, each attack submarine would spend an additional two-and-a-half years (8% of its life), and each strategic deterrent submarine an additional two years (4% of its life) in shipyards, unavailable to the force commanders for service at sea. This would result in an equivalent reduction in force level (rounding to the nearest whole submarine) of four attack and one strategic deterrent submarine. To maintain an equivalent force level of 55 SSNs and 14 SSBNs, the Navy would have to construct, operate and support five additional submarines. An LEU submarine based on existing ship designs would have a life-cycle cost of about $3.2 billion, or about $100 million per year, so the annualized additional cost for the five submarines would be about $500 million. This is in addition to the $1.3 billion increased maintenance cost for the original force level in **IV.A** above.

A 7% impact on the availability of the carrier force would result from the 44 months each carrier would spend in the yard during the two refuelings. For a 12-carrier force, this equates to an equivalent force reduction of one aircraft carrier. Assuming that the Navy could not absorb this loss by mission reassignments, an additional aircraft carrier would be required. An aircraft carrier has a life-cycle cost, not counting the air wing, of about $15 billion, or an annualized cost of about $300 million.

B. LEU in New Ship Designs with Increased Core Volume:

There would be negligible impact on the availability of submarine and carrier assets in this case, as the increased-volume LEU cores would last for the life of the ship and not require refueling.

Table 7 summarizes the impact of using LEU in existing ship designs on the annualized lifetime maintenance costs from **IV.A** above, and on the availability of the ships to the force commanders from **V.A** above:

TABLE 7

Impact of LEU in Existing Ship Designs on Maintenance Costs
and Availability to Force Commanders

	Annualized Maintenance Cost Impact on Baseline Force	Effective Reduction in Baseline Force/ Annualized Replacement Cost
Submarines	$1.3 Billion	4 SSNs & 1 SSBN/ $0.5 Billion
Aircraft Carriers	$0.47 Billion	1 CVN/ $0.3 Billion
Totals	$1.77 Billion	5 Subs, 1 CVN/ $0.8 Billion

VI. IMPACT ON SHIP CONSTRUCTION COSTS

A. LEU in Existing Ship Designs:

There would be no impact on aircraft carrier construction costs, but some impact on submarine construction costs. New submarines with life-of-the-ship cores are designed without provisions for refueling (e.g., no large refueling hatches in the hull and secondary shield), which saves on construction cost. These features would have to be put back in, at some increase in ship construction cost. Submarines would receive cores with only 7.5 (SSN) or 10.5 (SSBN) years of useable energy, and aircraft carriers cores with only 14 years useable energy. The increased lifetime costs for maintenance to the baseline force and for replacement force has already been discussed in **IV.A** and **V.A** above.

B. LEU in New Ship Designs with Increased Core Volume:

1. Submarine Construction: The core volume would have to triple for an LEU design to retain the same speed and life-of-the-submarine endurance as provided in HEU designs. Tripling the core volume would lead to a larger hull diameter, a propulsion plant and ship redesign, and a heavier, more expensive ship with a larger, more expensive reactor core and plant. The one-time cost to design a new attack submarine around a long-lived LEU core is estimated at $4.0 billion.

The baseline attack submarine is an SSN with an HEU core that lasts for the life of the ship, as described in Section A. This baseline case submarine is estimated to cost about $1.55 billion per ship.

An attack submarine designed around an LEU life-of-the-ship core, with the same speed, depth and quietness as this baseline case would be three feet larger in diameter and 870 long tons heavier, but 11 feet shorter due to equipment rearrangements made possible by the larger diameter. Each new submarine would cost about $400 million more ($150 million more in shipbuilder costs, $250 million more in government-furnished reactor core and reactor heavy equipment). Thus using LEU in place of HEU would increase the cost of the ship by 26%.

For a new design strategic submarine with characteristics similar to SSBN726, the hull would probably not have to be enlarged to accommodate the life-of-the-ship LEU core, and therefore the LEU impact on ship redesign cost and additional shipbuilder cost would be less than the SSN case. However, the larger strategic submarine requires a core with a higher power rating and longer lifetime than the attack submarine. Scaling up the cost increases for the reactor equipment and core from the SSN case gives a cost increase for this SSBN of about $325 million.

A building rate of slightly more than one-and-one-half attack submarines and one-third of a strategic deterrent submarine per year would be necessary to maintain the assumed force levels. At these rates, the impact of using LEU on the cost of new submarines would be about $770 million per year in increased costs for ship construction and life-of-the-ship LEU cores and reactor equipment.

2. Aircraft Carrier Construction: The aircraft carrier LEU core would need a two-fold volume increase to retain the baseline HEU core power and life-of-the-ship endurance. This larger, heavier reactor would require lengthening the CVN68 hull by about eight feet, and would result in a significant and costly redesign of the propulsion plant and adjacent ship structures and systems. The one-time cost to modify the CVN68 Class carrier design solely to accommodate a life-of-the-ship LEU core is estimated to be about $700 million.

A new CVN68 Class aircraft carrier costs about $4.5 billion. An aircraft carrier designed around a life-of-the-ship LEU core would cost an estimated $1.28 billion more ($50 million in shipbuilder costs, $1.23 billion more in government-furnished reactor core and reactor heavy equipment). Thus using LEU in place of HEU would increase the cost of the ship by about 28%.

A construction rate of one carrier every four years is necessary to maintain the assumed force level. Because of the once-every-four-year authorizations, the $1.28 billion cost impact on each new ship would not occur uniformly on an annual basis, but, spreading out the impact for comparative purposes, the annualized cost impact would be about $320 million.

Table 8 summarizes the impact on average annual construction costs of using life-of-the-ship LEU cores in redesigned ships, from VI.B above:

TABLE 8

Impact of Using LEU Life-of-the-Ship Cores on One-Time Design and Annualized Construction Costs of Nuclear-Powered Ships

Submarines	One-Time Design Cost	$4.0 Billion
	Annual Construction Cost	$0.77 Billion
Aircraft Carriers	One-Time Design Cost	$0.7 Billion
	Annual Construction Cost	$0.32 Billion
Totals	One-Time Costs	$4.7 Billion
	Annual Costs	$1.1 Billion

VII. IMPACT ON SHIPYARD INFRASTRUCTURE

A. LEU in Existing Ship Designs:

The 55 attack submarines would require refueling/defueling every eight years, the 14 deterrent submarines every eleven years, and the 12 carriers every 15 years. This translates to a nearly four-fold increase in the steady-state reactor servicing requirements for LEU reactors compared to HEU -- an average of eight submarine refuelings or defuelings and one aircraft carrier refueling or defueling per year.

This would be an extraordinarily heavy workload for the current nuclear-capable shipyards. A simplistic scenario for illustrative purposes assumes a flat, steady-state model for the workload. In real life there are fluctuations in the workload, and some additional capacity is required to handle the peaks. Even in the simplistic case, however, it is not clear that this heavy workload could be handled by the existing shipyard infrastructure:

- Newport News Shipbuilding is the only shipyard to date which has built and refueled nuclear-powered aircraft carriers. The first refueling of a CVN68 Class carrier (USS NIMITZ) is scheduled to start at Newport News in 1998. The effort estimated for the NIMITZ refueling is the equivalent of about five submarines. Puget Sound Naval Shipyard also has facilities to refuel carriers if necessary. Probably neither yard is capable of executing one carrier refueling or defueling per year with existing facilities. Consequently, the carrier work would likely have to be split between the two yards. Newport News should be able to build a new carrier every four years and refuel and overhaul a carrier every two years -- a high workload far exceeding the present level of work.

- Puget Sound, because of its proximity to the Hanford site, is the logical yard to do all ship final defueling/disposal work. Puget Sound should be able to perform the submarine defuelings and inactivations (about two per year in the steady-state), and a carrier servicing every other year, alternating between a defueling/disposal and a refueling/overhaul.

- Electric Boat Division has not performed a submarine refueling at the yard in 20 years, but potentially could be brought back into refueling/overhaul work at the rate of one submarine every other year.

- Three public yards (Portsmouth, Norfolk and Pearl Harbor Naval Shipyards) would be left to perform the five to six remaining submarine refuelings per year.

This scenario would place an unprecedented, sustained high refueling workload on every nuclear-capable yard, with no room for slippages and no reserve capacity for workload peaks in response to changes in mission requirements or emergent problems. This scenario also does not account for the other ship availabilities these yards would have to perform.

B. <u>LEU in New Ship Designs with Increased Core Volume</u>:

The shipyard industrial base that now supports the nuclear-powered fleet should be able to do so for the case of LEU life-of-the-ship cores in redesigned ships, since there would be no net increase in the number of refuelings or end-of-life defuelings. Two to three times as many spent fuel modules would have to be removed at the end-of-life, so final defuelings would each cost more, take longer and require more spent fuel shipping containers and on-site temporary storage space. However, the existing infrastructure of drydocks and servicing facilities and the skilled labor pool should be sufficient for this case.

VIII. IMPACT ON COST OF SPENT FUEL SHIPPING AND DISPOSAL

The qualitative impact on the environment was discussed in Section B. The annual volume of spent Naval fuel requiring shipment, storage and eventual disposal would triple to quadruple from the baseline HEU case, and this would result in increased costs as well. The 24 Model M-140 spent fuel shipping containers available in the future would not be sufficient to cover the case of LEU in existing ship designs, with its eight submarine and one carrier refuelings/defuelings per year. Up to 12 new shipping containers would be needed to accommodate workload peaks. These containers with their dedicated railcars cost about $4 million each, for a total of about $50 million.

A greater cost impact, which as yet cannot be quantified in dollars, would be associated with the ultimate disposal of three to four times as much spent Naval nuclear fuel each year. An approved geological repository and method of storage for high level waste does not yet exist. However, the cost impact of switching to LEU would not be trivial, and indeed would be in the wrong direction from the standpoint of environmental as well as fiscal responsibility.

IX. SUMMARY

The total economic impact of using LEU in place of HEU is summarized in the following table:

TABLE 9

Economic Impact of LEU on Naval Nuclear Propulsion

	LEU Cores in Existing Design Ships	LEU Life-of-the-Ship Cores in Redesigned Ships
One-Time Costs	$0.9 Billion	$5.5 Billion
Increase in Annual Cost to Build and Maintain Baseline Force	1.77 Billion	$1.1 Billion
Effective Reduction in Baseline Force/ Annualized Replacement Cost	5 SSN/SSBNs, 1 CVN/ $0.8 Billion	None/ None
Total Increased Annual Cost	$2.6 Billion	$1.1 Billion

Neither option for using LEU in place of HEU offers the Navy a technical, military or economic advantage. Either option would be extremely costly. Of two unattractive choices, the case in which ships would be redesigned to accommodate larger life-of-the-ship LEU cores clearly would have the lesser long-term impact in both cost and ability of the industrial infrastructure to maintain the ships.

LOW-ENRICHED URANIUM IN NAVAL NUCLEAR PROPULSION

SECTION D -- PROLIFERATION CONSIDERATIONS

This section of the report discusses:

- The LEU fuel cycle and U.S. nonproliferation policy, and
- The impact on security of using an LEU versus HEU fuel cycle.

I. POTENTIAL EFFECTS OF THE USE OF LEU IN NAVAL SHIPS ON U.S. NON-PROLIFERATION POLICIES

A. Discussion:

In September 1993, the President established a framework for U.S. efforts dealing with nonproliferation and export control. There are many parts to this policy. The focus of this report is on that aspect of the nonproliferation policy which potentially affects the Navy; specifically, maintaining the supply of HEU for nuclear powered ships. This supply could be affected by the portion of the nonproliferation policy which commits the U.S. government to:

> "propose a multilateral convention prohibiting the production of highly-enriched uranium or plutonium for nuclear explosives purposes or outside of international safeguards." (The White House Fact Sheet of Sept 27, 1993)

The U.S. Department of State is currently engaged in preliminary discussions with other countries on this multilateral convention. Thus, the Navy is not in a position to comment on the status of this effort. However, use of HEU to fuel Naval ships is not inconsistent with current U.S. nonproliferation policy since the HEU would be used as a propulsion fuel and not for nuclear explosive purposes. In addition, there is a significant amount of HEU currently in the national stockpile which can be used for naval propulsion so no near term need exists for a new HEU production facility.

B. Delay in Potential Construction of an HEU Enriched Facility:

A new HEU production facility would be required for Naval fuel only if the amount of HEU available from nuclear weapons returns become insufficient to support Naval fuel requirements. So long as current reserves of this material remain available for Naval use, there will be no need to restart HEU production for many decades. If additional weapons are retired, additional reserves could be available to further postpone the need for restarting HEU production. The Navy considers the continued reservation of HEU which is technically acceptable for Naval fuel, to be highly desirable. Any use of this material for other purposes, such as blending down for commercial use, would accelerate the need for construction of a very expensive and politically sensitive HEU production facility.

One consideration worth noting regarding the use of LEU versus HEU for Naval nuclear propulsion is that an LEU fuel cycle produces a signficant amount of plutonium while an HEU fuel cycle does not. Thus, having used HEU for energy production, the resulting spent fuel is in a form which is protected from diversion through final disposal with no significant plutonium present.

II. IMPACT ON SECURITY OF USING AN LEU VERSUS HEU FUEL CYCLE

A. Discussion:

Security of nuclear material is accomplished with two complementary programs:

- Material Control and Accounting (MC&A)), and
- Physical protection

There are separate requirements for both of these areas. Overall security is achieved based on the combination of both.

B. Material Control and Accounting Requirements:

Material Control and Accounting (MC&A) is the process of keeping track of the amount and location of nuclear material. MC&A is applied in the U.S. to all enriched material; LEU and HEU. Thus, the use of an LEU fuel cycle does not eliminate the need to keep track of the material through this formal accounting process.

In general, the amount of effort needed to implement the MC&A requirements is directly related to the amount of material being handled and the number of transfers of material between sites. An LEU fuel cycle would require considerably more material than the HEU cycle and would have more transfers between sites (larger cores with more fuel modules, or more cores). Thus, an LEU fuel cycle would logically require a greater MC&A effort.

C. Physical Protection Requirements:

The requirement for physical protection depends on the material which is being protected. Naval fuel requires protection due to three potential concerns:

1. theft of nuclear material
2. loss of a high value component due to sabotage
3. loss of U.S military technology of significant interest to other nations

The relevance and importance of each of these concerns varies as nuclear material is processed into a nuclear core.

The Naval fuel cycle begins with nuclear material being delivered to the Naval fuel manufacturing facility. Material is delivered from DOE as either UF_6, oxide or metal. The requirement for physical protection of the received material is due to the potential for theft. As the material is processed through the fuel factory, its form is changed and there is an added security concern due to incorporating sensitive military technology. Once the fuel manufacturing process is complete, the material is sent to the core manufacturing facility. At the core manufacturing facility the form of the material is again changed. The finished cores are very large and the potential for theft is greatly reduced. The security concern continues because of the military value of the technology in the finished core.

For this portion of a Naval HEU fuel cycle, the dominant physical security requirements are due to the potential for theft of material. For an LEU cycle, the dominant physical security requirements would be due to the need to protect the military technology. Protecting this information requires guards, a controlled building and other security measures for classified activities. Protecting HEU requires a more capable security force and additional security equipment. However, an LEU facility would be larger than an HEU facility (more material to handle, more storage requirements) and therefore need additional resources to handle the larger facility size and larger work force. When these factors are included, the cost of physical security at the fuel and core manufacturing facilities are only modestly higher for an HEU fuel cycle.

Once a finished naval core is produced, its size, weight and composition make it a very unattractive theft target regardless of whether LEU or HEU is used as fuel. At this point, the security concerns are with sabotage, protection of a high value component and loss of military technology. There would be no difference in physical security requirements between an individual LEU core and an HEU core. However, since an LEU fuel cycle would require more cores to be handled, the total security cost at this stage of the fuel cycle would be higher than for HEU. This higher cost applies to placing the cores into and removing the cores from ships. If additional shipyards are required to support an LEU fuel cycle, then the costs of security would significantly increase.

Once removed from the ship, the core is shipped to an examination location and then to an interim storage location. The protection requirements for an individual spent core are the same for an HEU or LEU fuel cycle, since the security concern is potential sabotage. As an LEU fuel cycle would require more refuelings and more cores to be handled the amount of protection required for spent cores would be greater than for an HEU fuel cycle.

The total security cost for a fuel cycle is based on combining the MC&A and physical protection costs. As discussed above, some portions of the cycle require more security for HEU and some would require more for an LEU fuel cycle. There are too many uncertainties to provide a specific comparison, however, the security costs for an HEU naval fuel cycle are not judged to be significantly different than those for an LEU naval fuel cycle.

D. The Risk of Theft or Diversion of Nuclear Material:

U.S. policy is to prevent the theft or diversion of either HEU or LEU. The risk of theft or diversion of nuclear material is based on the attractiveness of the material and the level of security provided to protect the material. Agency mandated security requirements are higher for more attractive material and lower for less attractive material. Security measures are predicated on reducing the risk of theft or diversion to a low level for either HEU or LEU.

The intent of the requirements is to apply the necessary levels of security to ensure the risk of theft or diversion is the same at all facilities. The objective is for no one facility to be a more likely target than another. The result of this approach is that the risk would not be materially different with different enrichments owing to application of compensatory security measures.

APPENDIX A -- BASIC THEORY AND PRACTICE OF FISSION REACTORS

Fission occurs when a large nucleus, like uranium-235 (^{235}U), absorbs a neutron and splits into two or more fragments, releasing kinetic energy in the recoiling fragments, or "fission products," and radiated energy, for example in gamma rays (high-energy electromagnetic radiation). Such fission events also release an average of at least two high-energy neutrons, which may cause other fissions. When enough fissionable (or "fissile") material is brought together under the right conditions, the configuration of material can sustain a chain reaction, and is called a "critical mass" or "critical configuration."

Fission neutrons can leak out of the configuration, or be absorbed by materials other than the fissile material. But if, on the average, the neutrons from one fission event cause exactly one more fission, then the reaction rate is constant, and the configuration is said to be "critical." The terms "subcritical" and "supercritical" denote decreasing and increasing reaction rates. A reactor is just critical when it is at constant power, and either slightly subcritical or supercritical when it is changing power levels. The degree to which the reactor is subcritical or supercritical is expressed in a parameter called "reactivity." Reactivity is zero when the reactor is just critical, negative when it is subcritical, which usually means power is going down, and positive when it is supercritical, which usually means power is going up. Larger magnitudes of reactivity correspond to greater rates of power change.

The fragments resulting from fission events, called "fission products," are typically unstable and highly radioactive. Over time they emit radiation in the form of beta particles (energetic electrons) and gamma rays (high energy electromagnetic radiation), releasing energy and "decaying" to a lower, more stable energy state. Some fission fragments decay quickly, and have essentially lost their radioactivity in minutes. Some decay more slowly, with half-lives of days or years. (The "half-life" of a radioactive species, or "radionuclide," is the time it takes on average for half of an initial population of the species to decay.) The radiation from the decay of these radioactive fission products makes them a potential hazard to living creatures.

Fissile and Fertile Isotopes:

The isotope of uranium with 92 protons and 143 neutrons in its nucleus (uranium-235 or ^{235}U) is the only naturally occurring material that can sustain a nuclear fission chain reaction. Isotopes with this capability are called fissile. The neutrons produced by the fission of ^{235}U are "fast" -- that is, they are born with kinetic energies mostly in the 1.0 to 10.0 million electron volts (MeV) range. A sufficient mass of ^{235}U can sustain a chain reaction on these fast neutrons alone. However, ^{235}U has a greater preference (a larger effective target area, or neutron "cross section") for slowed-down or "thermalized" neutrons, in the 0.0 to

1.0 electron volt (eV) energy range. Nuclear reactors that use ^{235}U are often designed to use efficient "moderator" materials like water to slow down the neutrons to the more usable thermal energy levels.

When ^{235}U absorbs a thermal neutron, it fissions about six times in seven. About one time in seven it forms highly stable ^{236}U, which is not fissile. ^{235}U is found in natural uranium at a concentration of about 0.72%, that is, one in 139 atoms of uranium mined from the earth is fissile ^{235}U. Almost all the rest is ^{238}U.

For neutrons with energy less than 1 MeV, ^{238}U has a negligibly small probability of fissioning, and it is therefore not considered fissile like ^{235}U. However, it is "fertile," which means it can capture a neutron to become ^{239}U and then transmute by twice ejecting an electron from its nucleus (two "beta decays"), to become a fissile nucleus, plutonium-239 or ^{239}Pu. When ^{239}Pu absorbs a thermal neutron, about three times in four it fissions. About one time in four it becomes fertile ^{240}Pu, which can capture another neutron and become fissile ^{241}Pu. Figure 2 illustrates this process.

^{239}Pu can sustain a chain reaction, and in fact has a somewhat higher fission probability for thermal neutrons than does ^{235}U. ^{239}Pu is even more effective in fissions caused by fast neutrons. This makes ^{239}Pu more suitable than ^{235}U for the unmoderated environment in nuclear weapons and liquid-metal-cooled fast breeder reactors.

The other abundant naturally occurring fertile material is natural thorium, which is composed almost entirely of thorium-232, or ^{232}Th. ^{232}Th can capture a neutron and transmute by two beta decays to fissile ^{233}U. The nuclear reaction probabilities of ^{233}U are similar but superior to those of ^{235}U. The ^{233}U-^{232}Th fuel system was used in the Light Water Breeder Reactor (LWBR) developed by the Naval Nuclear Propulsion Program. This thermal breeder operated for five years and generated 1.8 billion kilowatt-hours of electrical energy for commercial distribution in the pressurized water reactor at the Shippingport Atomic Power Station, and at the same time made more fissile uranium than it consumed. Figure 2 illustrates this process.

Enrichment:

The 0.72% concentration of ^{235}U in natural uranium is just high enough to sustain a chain reaction using the right moderator, such as done in the early large graphite-moderated plutonium production reactors in the United States and in the current large deuterium-oxide-moderated ("heavy" water) CANDU power reactors in Canada. For normal ("light") water-moderated reactors, the uranium has to be "enriched" in the ^{235}U isotope. Since all the isotopes of uranium behave the same way chemically, enrichment in the ^{235}U isotope can only be done by mechanical, laser excitation or electromagnetic means, taking advantage of the slight mass or electron energy level difference between ^{235}U and ^{238}U. In the United States the primary means of uranium enrichment is by gaseous diffusion of uranium-hexafluoride, where molecules of this gas diffuse through permeable membranes at slightly different rates depending on the mass of the individual uranium isotopes.

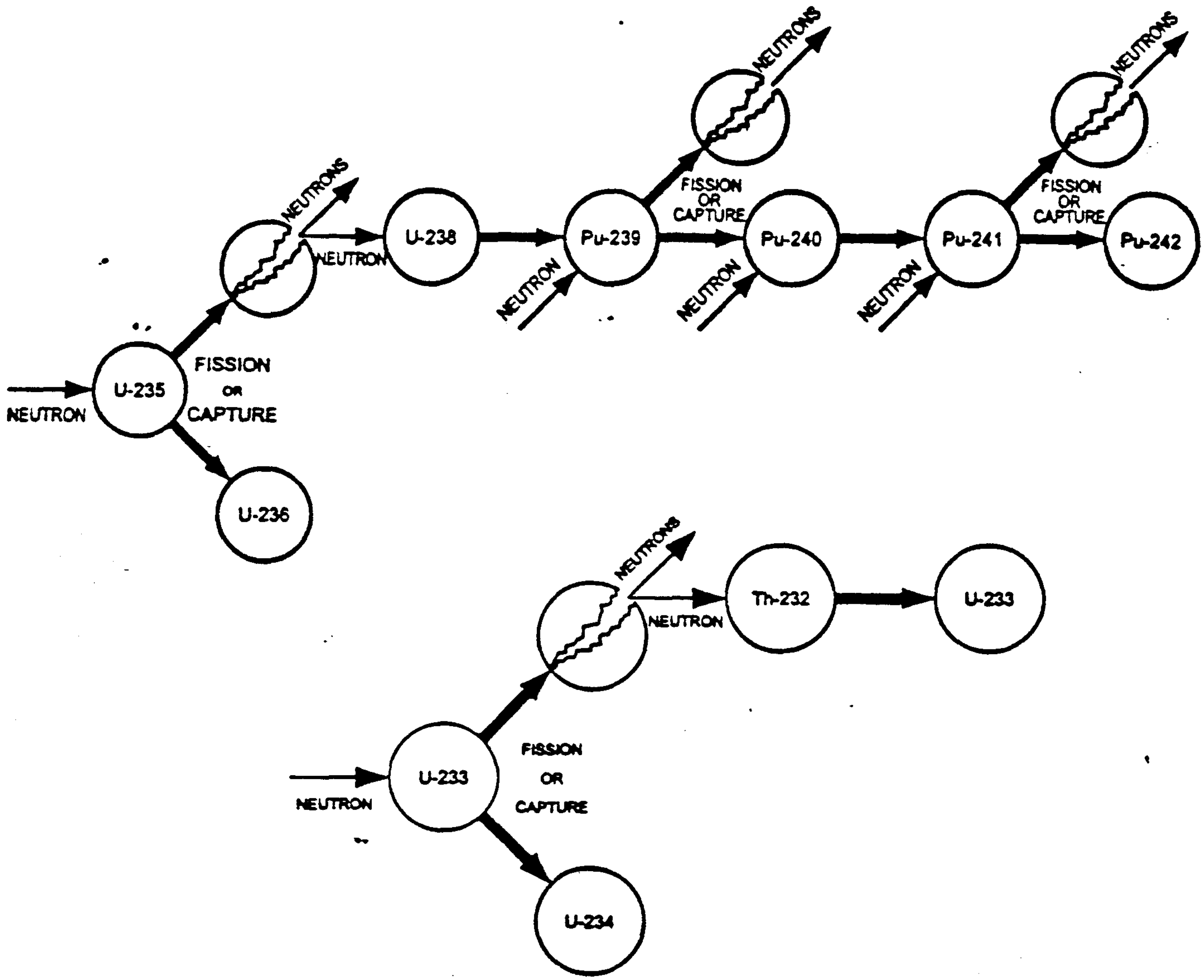

Figure 2: Fission and Creation of Fissile from Fertile Nuclei

Low versus High Enrichment:

For purposes of discussion of nuclear proliferation issues, an internationally accepted distinction between "low" and "high" enrichment has been made at 20% enrichment. This is based on the understanding that it is difficult to fashion an explosive nuclear device out of uranium enriched to levels of 20% ^{235}U or less.

Commercial nuclear reactors in this country use uranium enriched in the 1.5% to 4% range. This level of enrichment is used because it is affordable and because the ^{235}U can be almost completely consumed, making maximum use of the fissile fuel. In addition, fissioning of the ^{239}Pu created from ^{238}U in these slightly enriched reactors nearly doubles the total energy produced by the ^{235}U alone.

By contrast, Naval nuclear propulsion reactors use uranium enriched to at least 93% in ^{235}U. Use of this high enrichment uranium allows packing more fissile uranium into the small volume available to a military propulsion reactor, to achieve both high power density and long life. The latest submarine reactors are expected to last the life of the ship (i.e., with no refueling required).

Moderators:

The moderator is the material that is placed in the reactor to slow down the fast neutrons born from fissions, by billiard-ball-type ("elastic") collisions, to lower, more useable energies for sustaining the reaction. Each time an energetic neutron collides with a nucleus, it gives up some of its kinetic energy and slows down.

A neutron has an atomic mass of one. "Atomic mass" is the mass of an atom or a particle expressed in Atomic Mass Units (AMU). Protons and neutrons, by themselves or in a nucleus, have approximately one AMU mass each. The atomic mass of an atom or a particle may be approximated just by counting up its neutrons and protons. Electrons have only about 0.0005 AMU each, and may be neglected in this approximation.

If a neutron hits a heavy nucleus, such as carbon-12 (atomic mass of 12), it gives up very little of its energy. If on the other hand it hits a hydrogen nucleus (atomic mass of one, same as the neutron), it gives up half its energy on average. The closer the target nucleus mass is to the neutron mass, the more energy on average the neutron gives up in the collision. Thus hydrogenous materials, like water with two hydrogens per molecule, are more efficient at slowing down fast neutrons than materials with heavier nuclei, like graphite (carbon). Since the moderator is only supposed to slow down neutrons and not remove them from the chain reaction by capture, it must have a small neutron capture probability. Carbon and deuterium have a very small capture probability. Hydrogen has a somewhat bigger capture probability, which explains why use of ordinary water requires some enrichment of uranium to sustain a chain reaction.

Heavy water (deuterium oxide, or D_2O) is very expensive to make, and has an advantage over ordinary light water as a moderator only in reactors that rely on very low neutron loss by parasitic absorption, notably the natural uranium CANDU reactors. The hydrogen nucleus in water has a small but finite probability for neutron capture, whereas the deuterium nucleus in heavy water has an extremely small probability.

Graphite is far less effective in thermalizing neutrons than light water, and graphite-moderated reactors need a lot of graphite and therefore have much lower power densities than light water-moderated reactors. Graphite can also be weak and brittle, can burn in air at high temperatures, and is dimensionally unstable with high exposure to neutron flux, making it unsuitable for use in a reactor that must be designed for frequent power changes at high rate, and shock and vibration. (The large quantity of graphite moderator in the failed Chernobyl reactor became a combustion source that proved to be a major contributor to the magnitude of that reactor accident.)

Coolants:

The coolant is the fluid that circulates through the fueled part of the reactor, or the "core," removing the heat from fissioning. This heat is converted into mechanical energy, for example by heat exchange in a steam generator, producing steam to drive a turbine. Coolants used in power reactors include pressurized water, liquid metals and gases like helium and carbon dioxide. Liquid sodium, potassium and lithium are chemically highly reactive with air and water, making them potentially hazardous. Water has the advantage of having good heat transfer properties, being inexpensive and readily available, and not being chemically reactive or toxic. Like the moderator, the coolant also should have a low neutron absorption so as not to parasitically capture too many neutrons from the chain reaction.

In some cases the coolant can also serve as the moderator. The best example is light water in pressurized water and boiling water thermal reactors (PWRs and BWRs).

Fuel Systems:

"Fuel system" refers to the type and form of the fissile material used in the fuel element, the fuel element cladding material, any other material used in the construction of the element, and the geometry of the fuel element. The function of the fuel system is to hold the fissile material in a stable, controllable configuration in the reactor, to conduct the heat produced by fissioning into the coolant, and to retain the highly radioactive fission products and keep them from getting into the coolant throughout the life of the core.

The choice of fuel system is highly dependent on the choice of fissile material, coolant and moderator to be used in the reactor. Each fuel system has performance limits such as maximum achievable burnup, peak temperature, corrosion limits and mechanical strength.

Reactor Control:

Since it is not practical to partially refuel Naval cores, as is done for civilian power reactors, all of the fissile fuel the reactor will consume making power during its lifetime must be built into it at the beginning. To achieve practical endurance, much more fuel must be built in than is required to just sustain a chain reaction (be critical). Fissioning in this excess fuel would produce more neutrons than are required for criticality, and the reactor would be supercritical unless some other materials were added to absorb the excess neutrons. These materials are called "neutron poisons."

Control rods are one type of neutron poison, in the category of "movable poison." They can be moved in or out to compensate for the effects of moderator temperature changes, the accumulation of poisons in fission products, or the consumption of fuel over time. The control rods are used to perform normal startup and shutdown of the reactor, and to provide rapid shutdown for protection, or "scram."

As the fuel is consumed during core life, the reactivity goes down, and the reactor would be subcritical unless some poison material were removed to compensate for it. Control rods can to some extent be used for this function. In civilian PWRs, a soluble control poison such as boric acid is also used in the coolant, and its concentration is adjusted as the fuel is consumed. But to achieve long life in a compact core, additional poisons have to be used, distributed throughout the core. These poisons are called "burnable," and can be built into the fuel elements along with the fissile fuel. As the fuel is consumed during life, the burnable poison is also consumed at a comparable rate, keeping the core net reactivity fairly constant. Materials that can be used for burnable poisons include boron, hafnium, cadmium, silver, erbium, samarium, europium, and indium, and the Naval Nuclear Propulsion Program has had experience with all of these.

Reactor Types:

Reactors are usually categorized by coolant, moderator and fuel materials. Many different combinations of materials have been tried, but only a few have met with success in practical applications. Some examples are tabulated below:

TABLE 10

Examples of Coolant, Moderator and Fuel Material Combinations

Coolant	Moderator	Fuel	Uses (Examples)
Light water	Light water	Uranium (LEU or HEU)	Power reactors (Various civilian PWRs and BWRs, Naval PWRs)
Light water	Heavy water (D_2O)	Natural Uranium	Power reactors (Canadian CANDU)
Light water	Graphite	LEU	Dual-purpose (power/plutonium production) reactors (Russian RBMK, as at Chernobyl)
Liquid sodium	Liquid sodium	Plutonium/ ^{238}U	Power reactors (Various liquid metal fast breeder reactor (LMFBR) concepts)
Liquid sodium	Yttrium hydride	HEU	Low power thermionic space reactor (Russian Topaz)
Helium	Graphite	HEU	Power reactors (Fort St. Vrain High Temperature Gas Reactor (HTGR))
Carbon dioxide	Graphite	Natural uranium	Dual-purpose reactors (British Calder Hall)

Civilian Light Water Reactor Fuel System:

The prevalent fuel system used in civilian water-cooled power reactors is bulk uranium dioxide (UO_2) in the form of high-density ceramic pellets clad in zirconium alloy thin-walled tubing. Zirconium has a moderately low neutron capture cross section, as does oxygen (in both the water coolant and the fuel ceramic). Hydrogen (in the water) has a comparable capture cross section. Zirconium alloy with low concentrations of tin, iron, chromium and nickel (called "Zircaloy") is very resistant to corrosion by pure water. For these reasons Zircaloy has long been the cladding material of choice in water reactors.

The Naval Nuclear Propulsion Program developed: a) the production method for separating zirconium from the highly neutron-absorbing element hafnium, with which it appears in nature, making nearly pure, low-cross-section zirconium available and affordable to the nuclear industry; b) the metallurgy of the

Zircaloy family of corrosion-resistant zirconium alloys; and c) the first Zircaloy-clad oxide-fuel-pellet rods, used in the blanket of the first core in the Shippingport reactor.

The clad tubing is loaded with fuel pellets which fit snugly, with a few thousandths of an inch clearance with the inside wall. The loaded tubing is backfilled with helium and closed at both ends with welded plugs. The resulting fuel element is called a rod. Rods are typically about three-eighths to one-half inch in diameter and about 12 feet long, and are arranged in square bundles of about 14 to 17 rods on a side for PWRs, and 8 to 9 rods on a side for BWRs. Rods are supported at several points along their lengths by thin, egg-crate-like metallic grids.

This fuel system is well-suited to civilian power reactor applications. It is relatively inexpensive to make, and the cylindrical cladding geometry minimizes the volume of the core taken up by structure. This latter is important to the economics of the fuel system, as any material in the core that is not fissile or fertile fuel, moderator or coolant is not contributing to the nuclear process, and is therefore just absorbing neutrons, occupying volume and reducing power density.

As the fuel rods operate, the oxide fuel pellets gradually swell out toward the cladding inside wall, because the fission products take up more volume in the ceramic matrix than the original fissile atoms, and the cladding "creeps" in toward the fuel pellets under the stress of the water pressure in the coolant and the influence of neutron irradiation. As a result, the fuel pellets can use up the original assembly clearance with the clad tubing inside diameter and come into hard contact with the cladding. Under certain circumstances of power history and high rate of power change, this fuel-clad mechanical interaction can produce high stresses in the cladding. These high stresses, which may be further exacerbated by chemical attack from fission product iodine, can cause fractures in the cladding, exposing the oxide fuel and releasing fission products into the coolant. For the way in which most civilian nuclear central power stations are operated (baseload, low rates of power change), this failure mode, which was a major problem in early reactors, is no longer considered significant.

Fuel Systems in Other Reactors:

The nation's first civilian central power station at Shippingport, designed and built by the Naval Nuclear Propulsion Program at the request of Congress to demonstrate practical nuclear power generation of electricity, used fuel elements in the form of plates in the high-power "seed" region of the core. The plates consisted of an inner fuel filler of zirconium-uranium alloy, with a metallurgically bonded Zircaloy cladding layer on either side. The plates were stacked and welded together in assemblies, with spaces in between to form channels for the light water coolant-moderator. This system provided good fission product retention.

The second core for Shippingport was designed to produce higher electric power than Core 1 and used plate-type fuel elements containing oxide wafer fuel. This fuel functioned reasonably well but did not have the transient capability or the resilience of alloy plates used in the first core.

- Liquid metal fast breeder reactor (LMFBR) concepts have been based on stainless steel clad cylindrical fuel elements, shorter and smaller in diameter than the BWR or PWR fuel rods, and called by the more descriptive term "fuel pins." For a variety of reasons, none of the LMFBR concepts has proved to provide a practical, economically viable reactor.

- The Fort St. Vrain high-temperature gas-cooled reactor used fuel in the form of small (approximately 0.020" diameter) coated ceramic particles distributed in half-inch-diameter preformed graphite pins. These unclad pins fit into holes in blocks of graphite. Other adjacent holes accommodated burnable poison pins or helium coolant flow. Each graphite block containing fuel and poison pins was a "fuel element." The graphite block served to moderate the fission neutrons and conduct heat from the fuel particles to the coolant, as well as hold the fuel pins in place. Helium flowed through the graphite blocks to cool the fuel. The removed heat was used to generate steam to drive a conventional steam turbine-generator. The primary fission product boundary with the coolant was the approximately 0.006" thick coating around each fuel particle, of which there were hundreds of thousands in the core. This low power density reactor had a poor operating history, and was finally shut down for economic reasons.