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Nuclear Weapons Safety: The Case of Trident

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An accidental detonation or ignition of propellant in a Trident missile, or of explosive material in one of the warheads, could lead to dispersal of toxic plutonium into a populated area. We examine the details of Trident nuclear weapons safety and assess the feasibility, cost and consequences of safety-enhancing modifications to the missiles and warheads. We find that the operational impacts of such modifications would be minor, especially if the number of warheads per missile is decreased as a result of START II. Several billion dollars, and a small number of nuclear tests, would be needed to enhance safety for Trident.

I. INTRODUCTION

With the end of the Cold War, the issue of nuclear weapons safety has acquired new significance. The acceptance of these weapons by the American public has always been contingent on the belief that the safety risk is less threatening than the risk of not having an effective nuclear deterrent. With a diminished likelihood of nuclear war, new standards of safety may be in order. In reviewing the safety of the nation's nuclear arsenal, some of the most challenging questions arise in connection with America's premiere strategic weapon: Trident.

The Trident system consists of the Ohio-class ballistic-missile-carrying submarines (SSBNs), the C-4 and D-5 submarine-launched-ballistic missiles (SLBMs), and the reentry vehicles (RVs) and thermonuclear warheads com-

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prising the Mk4/W76 and Mk5/W88 systems. Trident's importance is due to its ability to evade detection and its capacity to rapidly destroy a wide range of targets.

Questions have been raised about the safety of the missiles and warheads. A long-standing debate has been taking place within the Department of Energy (DOE), and between the DOE and Department of Defense (DOD), concerning the likelihood that, as a result of an accident or sabotage, a detonation of explosive material in a Trident missile or warhead might lead to release of toxic plutonium to a populated area. In a worst-case scenario, a very small nuclear yield (in the range of a few tens of tons) could result from a shock or impact accident. The most comprehensive and publicly available examination of this issue to date was conducted by the Panel on Nuclear Weapons Safety, appointed by the House Armed Services Committee, and chaired by Sidney Drell. The Panel called for further studies "to provide data on which to make a more credible analysis of how well, or whether the D-5/W88 meets modern safety standards, (and) to estimate the costs and inevitable time delays of implementing recommended design changes . . ."

Trident was developed in response to stringent military requirements imposed at the height of the Cold War. Decisions were made to maximize capability and survivability at some arguably increased safety risk. These tradeoffs would have been made differently if current national security needs could have been anticipated. As a result, Trident is not as safe as modern technology allows. Whether the system should now be modified is a complex question, the answer to which depends on a variety of factors:

- The military need for Trident in the foreseeable future;
- The likelihood and consequences of an accident;
- The cost and operational impact of safety-related modifications;
- Other policy priorities, including cutting the defense budget, maintaining residual expertise in nuclear weapons design and manufacturing, and international agreements to limit nuclear testing.

This study examines several technical questions bearing on Trident safety, and it enumerates the significant issues and options.[1] The secrecy surrounding nuclear weapons restricts this effort, and, as a result, our study cannot be definitive. Moreover, no one can provide a reliable quantitative analysis of the probability of a serious accident. Nevertheless, in any situation that involves a small, yet finite, chance of a catastrophic event, the hazard must be weighed against the costs of reducing risk. We focus our efforts on analyzing the cost, schedule, and operational impacts of safety-related modifications to Trident. Specifically, our study:

- Examines safety concerns about the Trident configuration, including the possibility of plutonium dispersal or of an inadvertent nuclear detonation in impact and fire accidents.
- Develops options for modifying C-4 and D-5 for enhanced safety that include modifying the missiles, modifying the nuclear warheads and RVs (or using other existing warheads), and combinations of the two.
- Summarizes calculations carried out to determine how missile range, SSBN patrol area, and on-station rate would be affected by safety-related modifications.
- Presents calculations of the cost, schedule, and operational impacts of modifications for enhanced safety.

The Fleet Ballistic Missile (FBM) Program

Table 1 shows the evolution of the FBM program. The advances of the last 30 years resulted from changing requirements and technological innovation. Consistent increases in missile range generally evolved from a desire to expand the SSBN patrol area, thus countering Soviet advances in anti-submarine warfare (ASW). Increases in the number of warheads per missile resulted from the perceived proliferation of Soviet targets, concerns about the Soviet anti-ballistic missile program, and the cost effectiveness of MIRVing.

The combination of the D-5 high-yield warhead and pinpoint accuracy sets it apart from its predecessors in a fundamental way. It defines an offensive capability that, for the first time in the history of the FBM program, is sufficient to threaten "hard" targets, such as missile silos and underground command bunkers. Before D-5, the role of the SSBN force was to deter attack by the threat of retaliation against "soft" targets, including urban and industrial centers and military bases. As a threat to hardened targets, D-5 is comparable to the MX, the most modern U.S. land-based ICBM.[2]

Trident's "counterforce" capability generated controversy from the very beginning. Opponents of Trident branded it a "first-strike" weapon, one that could call into question the survivability, and thus the retaliatory potential, of the enemy's fixed land-based missiles. This uncertainty could lead enemy planners to adopt a hair-trigger "launch-on-warning" policy, which can create an over-reliance on warning sensors and computers, increasing the chance of

Table 1: Evolution of U.S. SLBMs, 1960 to present.[a]

Missile	Year	Launch weight *kg*	Range *n.m.*	Warheads per SLBM	Warhead yield *kilotons*	Accuracy *n.m.*
Polaris A-1	1960	13,100	1,200	1	600	2.0
Polaris A-2	1962	14,800	1,500	1	800	2.0
Polaris A-3	1964	16,200	2,500	3	200	0.5
Poseidon C-3	1971	29,500	2,500	10	40	0.25
Trident I C-4	1979	32,300	4,100	8	100	0.12 (est.)
Trident II D-5	1989	57,700	4,100	8	100, 475	0.06 (est.)

a. Some numbers quoted in table 1 are from D. MacKenzie and G. Spinardi, "The Shaping of Nuclear Weapon System Technology: US Fleet Ballistic Missile Guidance and Navigation: I: From Polaris to Poseidon," *Social Studies of Science* **18** (1988), p. 440. See also, G. Spinardi, "Why the U.S. Navy Went for Hard-Target Counterforce in Trident II," *International Security* **15** (2), Fall 1990, pp. 147–190. The launch weights for C-3, C-4, and D-5 are from the START Treaty Memorandum of Understanding. Nuclear warhead yields for C-3, C-4, and D-5 are from "Modernizing U.S. Strategic Offensive Forces: The Administration's Program and Alternatives," Congressional Budget Office (Washington, DC: U.S. Congressional Printing Office, May 1983).

accidental nuclear war. Supporters of Trident argued that, in the event of war, the national command authority must have the option of using precise, selective strikes as an alternative to a cataclysmic release of the entire nuclear arsenal. Holding a portion of Soviet silos at risk would also stimulate a stabilizing Soviet evolution towards more-survivable, lighter throw-weight, and lower-MIRVed mobile ICBMs. Furthermore, an invulnerable hard target kill capability was certainly less destabilizing than a vulnerable one, such as silo-based ICBMs. Trident proponents also downplayed fears that SLBMs could be used in a first strike, citing the delays and difficulties of communicating with a large fleet of submerged submarines to effect a near-simultaneous launch of several boatloads of missiles.

Trident's counterforce role explains the set of design specifications that are at the heart of Trident safety concerns, as discussed below.

The Trident SLBM Configuration and Why It Raises Concern

The principal challenge in developing the D-5 SLBM was to meet the range and payload requirements with missiles that fit within the fixed volume of the

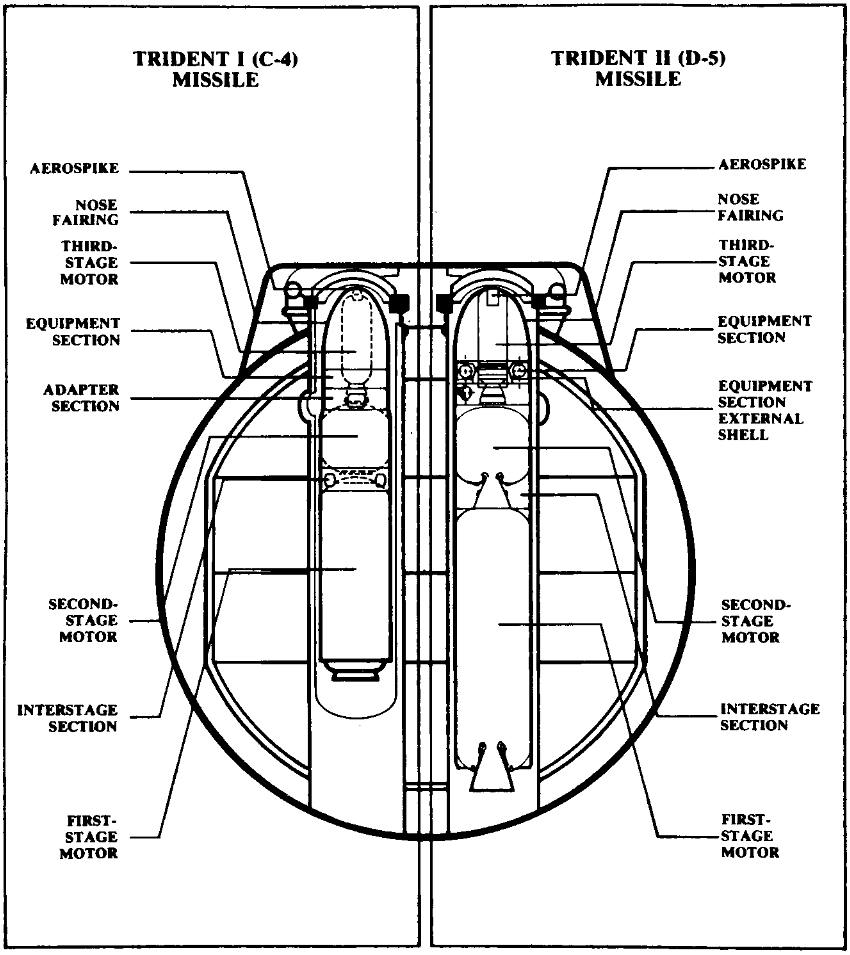

Figure 1: Cut-away view of the Ohio-class SSBN showing the C-4 and D-5 SLBMs.

launch tube of the Ohio-class SSBN. The D-5 requirement was to deliver eight heavy, high-yield Mk5 RVs to the same range that the smaller C-4 delivered eight lighter Mk4s: about 4,100 nautical miles (n.m.).[3] Missile range determines the size of the area of the ocean from which an SSBN can strike its targets. A larger patrol area offers increased survivability to at least one form of ASW: an area sweep by enemy attack submarines and aircraft.[4]

To meet D-5 range and payload requirements, Lockheed designers took an approach similar to that used for C-4. Because of the fixed length and volume of the launch tube, both designs incorporate an unusual feature: the third

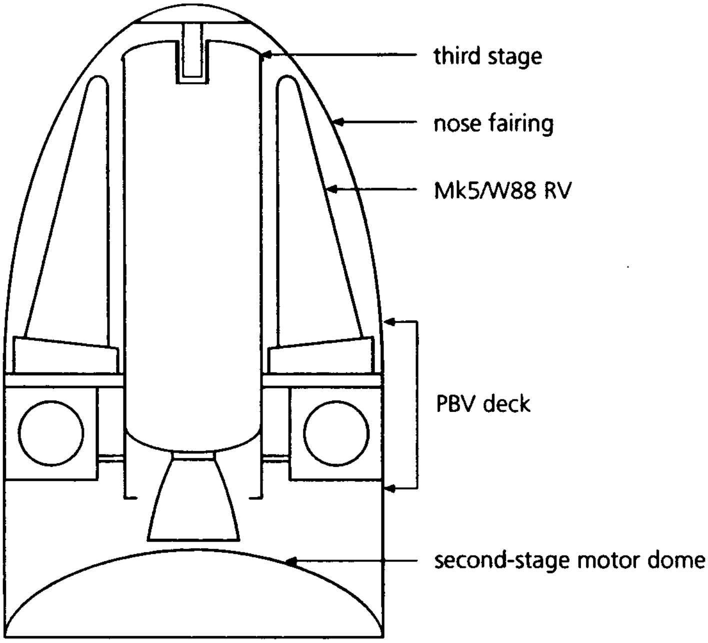

Figure 2: D-5 third-stage, through-deck configuration.

stage projects through the central region of the post-boost vehicle (PBV) deck. This design constrains the RVs to the annular region that surrounds the protruding third stage, placing them very close to the third-stage propellant. Figures 1 and 2 show the so-called "through-deck" design. In contrast, Air Force ICBMs deployed in underground silos are not length-constrained and employ a "clear-deck" design in which the PBV is located above the third stage. This approach provides increased flexibility in RV mounting and isolates the RVs from the third-stage propellant with intervening structural and functional components.

To meet current and anticipated targeting needs, a high-yield warhead, the W88, was chosen for D-5 based on a design that had been tested at full yield prior to the 1974 Threshold Test Ban Treaty. This choice, and the fixed volume of the Ohio launch tube, imposed several additional constraints. To meet the range requirement, minimum RV weight was desired. In addition, the tight spacing in the third-stage annular region constrained RV base diameter. For these reasons, conventional high explosive (HE) was used in the W88, resulting in a lighter and smaller warhead than could be achieved at that time using insensitive high explosive (IHE). The choice of HE produced an RV of minimum weight and base diameter for the given yield.

Conventional HE, however, is much more susceptible to detonation in impact and fire accidents. For this reason, in 1983 the DOD instituted a requirement that IHE be used in new warheads unless an important military need warranted otherwise. Such a waiver was granted for the W88 because the DOE weapons labs could not meet DOD RV size, yield, and weight requirements with an IHE warhead.

A second consideration was the specific impulse (I_{sp}) of the solid rocket propellant. More energetic propellants permit greater thrust per unit volume, hence greater range for a given payload. To achieve maximum range, all three stages of D-5 use very-high I_{sp} material, also known as "high energy" or Class 1.1 propellant. Class 1.1 propellant is much more likely to detonate in impact accidents than the less-energetic Class 1.3 material used in many ICBMs.

Safety concerns arise from the use of conventional HE and Class 1.1 solid propellant coupled with the unique through-deck design. The proximity of nuclear warheads to the detonable third stage makes certain potential accidents more likely and more hazardous.

The through-deck configuration is more sensitive than clear-deck designs to impact and fire accidents, which could endanger not only military personnel on the base but also the public at large via the release of plutonium and its transport by prevailing winds to populated areas.

The C-4 missile, which has about one-half the launch weight of the D-5 and carries warheads with a much lower yield, has the same salient characteristics: detonable propellant, through-deck third stage, and conventional HE. Thus, safety concerns that have been raised about D-5 apply equally to C-4.

Efforts to enhance safety may affect both the survivability and capability of Trident. Using IHE in the warhead might cause a decrease in nuclear yield or could result in heavier warheads that would increase throw-weight and decrease missile range. Decreased range would reduce the SSBN operating area within range of key targets. Converting to a nondetonable propellant in one or more missile stages would also decrease range and patrol area for a given throw-weight.

Current and Future SSBN Deployments

When START I was signed in July 1991, the U.S. SSBN force consisted of 36 SSBNs: 24 Lafayette-class submarines, each with 16 tubes, and 12 Ohio-class Tridents, each with 24 tubes. That force accounted for nearly 6,000 warheads, somewhat more than one-half of U.S. strategic warheads. Twelve of the Lafayette boats were deployed with the Poseidon C-3 SLBM, which carries ten W68 warheads, and twelve were deployed with C-4, which carries eight W76 war-

Table 2: U.S. SLBM and RV deployment (July 1991 START Treaty Memorandum of Understanding).

Number of SSBNs	Number of tubes	SLBM	RVs per SLBM	RV numbers
12 Lafayette	16	C-3	10 Mk3/W68	1,920
12 Lafayette	16	C-4	8 Mk4/W76	1,536
8 Ohio	24	C-4	8 Mk4/W76	1,536
2 Ohio	24	D-5	8 Mk4/W76	384
2 Ohio	24	D-5	8 Mk5/W88	384
				5,760

heads. The Lafayette boats, based at Charleston, South Carolina, are currently being phased out and are slated for retirement by 1997, or possibly sooner.[5] Since July 1991, one additional Trident boat has begun sea trials. Five additional Tridents are funded and will be completed at a rate of about one per year, at a cost of $1.3 billion each. Table 2 summarizes U.S. SSBN deployments as of July 1991.

Eight Trident submarines deployed with C-4 missiles are carrying out regular patrols from their base in Silverdale, Washington. Five additional submarines, based in King's Bay, Georgia, have been equipped with the newer D-5 missile, some deployed with the W76 and some with the W88 warhead.[6]

Under START I, strategic ballistic missile warheads (warheads deployed on ICBMs and SLBMs) are limited to 4,900. If all Lafayette boats are retired as planned, the U.S. SSBN force of the late 1990s would consist of 18 Trident boats. If, under START I, 3,456 Trident warheads are deployed (18 subs carrying 24 missiles with eight warheads each), about 1,500 warheads would remain for MX and Minuteman III.

If the recently signed START II Treaty is ratified and enters into force, the sides would eliminate all MIRVed ICBMs by the year 2003 (or possibly earlier), including MX and the "heavy" SS-18. They would reduce the total number of actual (not "attributed") warheads to no more than 3,500, with a sublimit of 1,750 on SLBM warheads. Total strategic warheads would thus be reduced to about one-third the number permitted under START I, and SLBM warheads would make about up about one-half of the U.S. force. As we show in

Section IV, downloading of warheads can be used to enhance safety without range penalties or other operational impacts.

The Strategic Context of Trident

The end of the Cold War has brought stunning changes in the composition and number of strategic warheads in superpower arsenals.[7] START I, negotiated over the past decade, reduces in one bold stroke the number of strategic nuclear weapons by 20 to 30 percent. Even more striking are the initiatives undertaken by Presidents Bush, Gorbachev, and Yeltsin. In September and October 1991, Bush and Gorbachev took several unilateral and reciprocal steps to:

- Withdraw from deployment, and in some cases eliminate, certain classes of tactical nuclear weapons;
- Reduce even further than was specified by START I the number of strategic warheads, and terminate some modernization programs; and
- Lower the readiness and alert levels of some of the remaining strategic forces.[8]

START II was concluded by Bush and Yeltsin in January 1993, only a year and a half after START I was signed.

America's strategic forces have evolved dramatically over the past five years. The Minuteman II force has been taken off alert and is being retired, the purchase of MX flight test boosters has been cut by about one-third, and the MX Rail Garrison and Small ICBM basing programs, as well as the Small ICBM missile development program, have been terminated. The bomber leg of the triad has been similarly curtailed; for example, strategic bombers have been withdrawn from strip alert. Elements of the strategic command and control and early warning systems are now on partial standdown.

The FBM program has not been immune to the overall deemphasis on strategic forces.[9] Under budgetary pressures, the DOD and Congress have recently begun to examine options to curtail the deployment and alert operations of the Trident force beyond those necessary to meet commitments under START I and START II.[10] Even so, key elements of the Trident modernization program are proceeding apace. All 18 submarines that the Navy plans to acquire are funded and under construction, and D-5 production is progressing for the ten boats that will be based at King's Bay, Georgia.

Under START II, Trident will account for one half of all U.S. strategic warheads. Thus, its relative importance will increase as overall numbers of warheads and alert rates decline.[11] More importantly, Trident SSBNs at sea will be the only element of U.S. strategic forces on day-to-day alert that could survive an attack in which warning was not received, or received but not acted on. Although the risk of surprise attack is remote (and indeed seemed remote even at the height of the Cold War), the U.S. has spent billions to retain an element of strategic forces that is resilient to this threat. In view of the removal from alert of heavy bombers and the significant de-emphasis of ICBMs that will result if START II is ratified and implemented, the capability of Trident to remain invulnerable to any feasible threat assumes special significance.

II. SLBM AND WARHEAD SAFETY ISSUES

In this section, we address the safety of the Trident C-4 and D-5. First, we discuss hazards of high explosives (HEs) and solid rocket propellants. Next, we review the warhead and missile logistics and handling sequence and identify potential accidents. Finally, we examine the consequences of potential accidents.

Comparison of High Explosives and Solid Rocket Propellants

In recent years, U.S. policy has shifted towards the use of IHE in modern nuclear warheads to promote increased safety in manufacturing, transport, and handling.[12] Table 3 shows the trend in HE and propellant use in U.S. missiles, which are divided into three groups: ICBMs, SLBMs, and other missiles. Within each group, the warheads are listed in chronological order. The trend for ICBMs and other missile systems is clearly toward the use of IHE in the more modern warheads. The Navy SLBMs, however, continue to use conventional HE and detonable propellants.

HE is about 40 percent more energetic than IHE; thus, a smaller amount is needed in a given nuclear design to obtain the desired yield. The use of HE results in lighter, smaller primaries and correspondingly larger yield-to-weight ratios. HE, however, is more sensitive to detonation in abnormal shock, pressure, or thermal environments. In contrast, IHE is remarkably insensitive to accidental detonation. Table 4 compares HE to IHE in terms of parameters relating to detonability and performance.

Two types of solid propellants are used in ballistic missiles: Class 1.1 and Class 1.3. Class 1.1 propellant is more energetic than Class 1.3; thus, for a given total weight, it produces a missile of greater range. According to recent Navy studies, Class 1.1 propellant for D-5 has superior handling properties during manufacturing, is mechanically tough, resists cracking, and does not develop regions of granulation; thus, it is less susceptible to accidental ignition.[13, 14] However, Class 1.1 propellants are much more susceptible to detonation than are Class 1.3. As shown in table 4, Class 1.1 but not Class 1.3 propellants are similar to conventional HE in their sensitivity to detonation.

A detonation is initiated in HE or energetic propellant when an external stimulus, which creates sufficient conditions of temperature and pressure, starts a rapid chemical reaction that propagates across the material in a self-sustaining shock wave and releases a large amount of energy.[15] There are three basic modes by which detonation can be initiated. First, an external shock exceeding a threshold pressure (different for each class of material) can transfer sufficient energy to cause a direct shock-initiated detonation. This

Table 3: Warhead HE and missile propellant type for U.S. missile systems.

Missile	Warhead	Propellant	High explosive
		ICBMs	
Titan II	W53	nondetonable[a]	HE
MM I	W56	detonable	HE
MM II	W62	detonable	HE
MM III	W78	nondetonable	HE
MX	W87	detonable[b]	IHE
Small ICBM	W87-1	detonable	IHE
		SLBMs	
Polaris	W58	detonable	HE
Poseidon C-3	W68	detonable	HE
Trident C-4	W76	detonable	HE
Trident D-5	W88	detonable	HE
		Others	
Terrier	W45	detonable	HE
Pershing I	W50	nondetonable	HE
SUBROC	W55	nondetonable	HE
SRAM A	W69	nondetonable	HE
Lance	W70	nondetonable	HE
Spartan	W71	nondetonable	HE
SLCM	W80-0	nondetonable[a]	IHE
ALCM	W80-1	nondetonable[a]	IHE
GLCM	W84	nondetonable[a]	IHE
Pershing II	W85	nondetonable	IHE
SRAM II	W89	nondetonable	IHE

a. The Titan II used nondetonable liquid propellants. SLCM, ALCM, and GLCM use nondetonable jet fuel.
b. Only the third stage of MX has a detonable propellant. The first two stages are nondetonable.

Table 4: Comparison of HE and IHE and Class 1.1 and Class 1.3 solid propellants.[a]

Characteristic	Units	HE	Class 1.1	IHE	Class 1.3[b]
Critical diameter[c]	inches	$\sim10^{-1}$	$\sim10^{-1}$	0.5	>30
Minimum explosive charge to detonate[d]	ounces	$\sim10^{-3}$	$\sim10^{-3}$	>4	>>350
Shock pressure threshold for detonation	kbar	~20	~30	~90	b
Impact velocity to detonate	m sec^{-1}	~45	~60	~1000	n/a
Heat of detonation	kcal g^{-1}	1.42	n/a	1.02	n/a
Detonation-front pressure (Chapman–Jouguet)[e]	kbar	370	350	300	20–80
Specific impulse	seconds	n/a	272	n/a	262

a. This table and notes were compiled with help from Ed Lee and Ed James, private communication. See also, *Notes From Lectures on Detonation Physics*, edited by Frank J. Zerilli (Dahlgren, Virginia: Naval Surface Weapons Center, October 1981).

b. The data provided on Class 1.3 propellants are uncertain because of a lack of experimental results and an incomplete theoretical understanding of associated phenomena. These propellants are often termed "nondetonable," but under certain conditions they can be made to detonate. "Detonations" in these materials, however, propagate at velocities not much greater than bulk sound speed (far below theoretical values) and with shock pressures also far below theoretical, complicating measurements of critical diameter. In the Sophy experiment (1967) an 18,000-pound charge of TNT created a sustained detonation in a 72 inch-diameter, lightly cased Class 1.3 rocket motor having a 30 inch web (i.e., the motor had a hollow bore of 12 inch diameter and a propellant thickness of 30 inches). A 62 inch motor subjected to the same initiating stimulus recorded no sustained detonation; indeed, pieces of unreacted propellant were recovered after the experiment. Measurements have not been made at larger sizes. For comparison, the minimum priming charge for a Class 1.1 stage is about 30 milligrams, almost 10 orders of magnitude lighter than the Sophy charge. Estimates of detonation velocity and pressure for Class 1.3 propellant will no doubt depend on composition but are typically about 3.2 mm μsec^{-1} and 40 kbar versus six mm μsec^{-1} and 350 kbar for Class 1.1 propellants.

c. Critical diameter is the minimum diameter of a cylindrical charge for which it is possible to propagate a steady-state detonation.

d. Minimum explosive charge to detonate is the minimum weight of the priming charge required to generate a steady-state detonation in a cylindrical block of material having a base diameter that is large compared to the critical diameter.

e. Chapman–Jouguet pressure is the shock pressure generated in a steady-state detonation and is a characteristic pressure for a given high explosive.

direct process, called shock-to-detonation transition (SDT), occurs rapidly, within microseconds after the arrival of an initial shock. Second, a shock pressure well below the threshold for SDT can initiate detonation by a process called XDT, which is not well understood. Also referred to as "delayed detonation" because it occurs on the order of milliseconds after the initial shock passes, XDT may result from the coalescence of reflected shocks off interior surfaces or discontinuities in the material. Details of the sequence and timing of reflected shocks, and material composition and configuration (e.g., web thickness of a propellant grain), are factors that make XDT highly unpredictable. Below the threshold for SDT or XDT, an explosive or propellant can undergo rapid burning, leading to a more gradual pressure buildup and eventually to detonation. This third process, known as deflagration-to-detonation transition (DDT), is quite sensitive to physical confinement and granulation of the material and to external pressure loads. The characteristic time for the DDT process can be on the order of seconds.[16, 17]

Warhead and Missile Logistics and Handling

To understand the nature of potential accidents, it is necessary to examine the warhead logistics sequence under custody of the DOE and subsequent warhead handling and transport under Navy custody. Nuclear warheads are assembled at the DOE Pantex facility in Amarillo, Texas. Components come from several sources. In the past, plutonium "pits" have been produced at the Rocky Flats plant in Colorado.[18] Thermonuclear secondaries are produced at the Y-12 plant at Oak Ridge, Tennessee. The integrated fuse and weapons electrical system (WES) is built at the Bendix Kansas City Facility. Mk4 and Mk5 RVs and associated hardware are shipped to Pantex from the RV contractor. Figure 3 shows key warhead, missile, and RV-related facilities. Figure 4 shows the warhead logistics and handling cycle for C-4.

Perhaps the most dangerous operation at Pantex is the machining of HE to the proper size and shape, and its incorporation into the warhead primary. Fatal accidents have occurred in the past. With conventional HE, machining operations must be done remotely, which introduces additional costs and operational complexities. IHE parts, however, can be fabricated by machinists working in contact with the explosive, which saves considerable time, money, and facility space. Machining of explosives is not done in contact with plutonium. The risk of plutonium dispersal begins when the HE and plutonium parts are assembled into a warhead. Safety procedures for handling and storage of warheads employing conventional HE are considerably more restrictive than those for IHE warheads.

Assembled RV/warheads are shipped via DOE "safe and secure" trailers

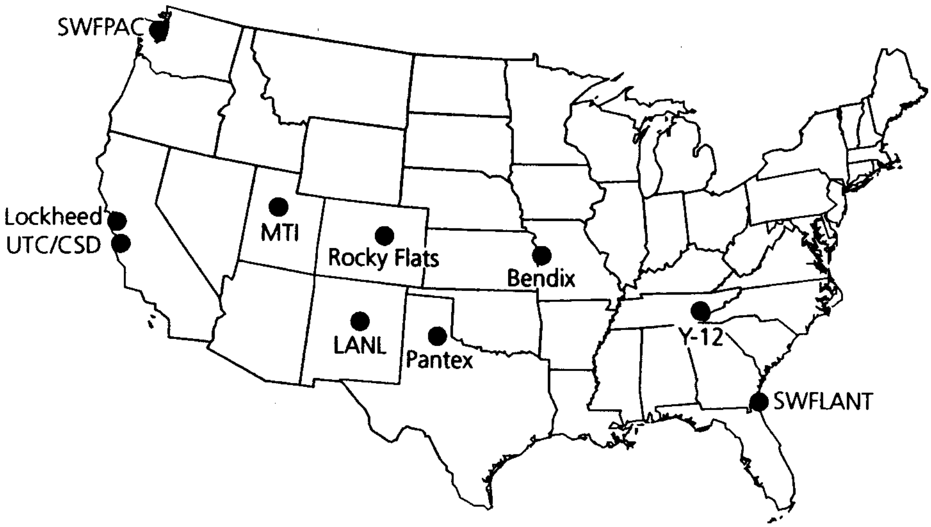

Figure 3: DK/Mk5/W88 associated facilities.

(SST) from Pantex to one of two Trident bases: Silverdale, Washington (SWFPAC), or King's Bay, Georgia (SWFLANT).[19] A shipping container protects the RV from impacts and small-arms fire. Custody of the RV is transferred to the Navy at the warhead receiving area at each base. All subsequent handling, processing, and transport is undertaken within a highly restricted area of operations called the "limited area." After arrival, the RV is stored in a magazine, remaining within its shipping container.

Currently, C-4 SLBMs are assembled from component stages, PBV, RVs, and nose fairing within a single building called the Vertical Missile Packaging Building (VMPB). The mating of the first two stages is carried out in the horizontal position. The missile is then raised to vertical and lowered into a liner situated in a "loading pit" until it is about flush with the ground. (The liner acts as an environmental cover, shielding the missile from view during outside loading operations and providing some protection against small-arms fire.) The PBV/third stage is mated in this configuration. The RVs are then transferred from storage to the VMPB, mated to the PBV, and the nose fairing is attached. The mated missile in its liner is hoisted from the pit, lowered onto a transporter, and returned to horizontal. The unit can then be either stored or transported to the explosives handling wharf adjacent to the Trident submarine. At the wharf, the missile in its liner is erected to vertical, hoisted by crane over the submarine, and lowered (without the liner) into the launch tube. Once the missile is inserted, the liner is taken away, and the launch tube hatch is secured.

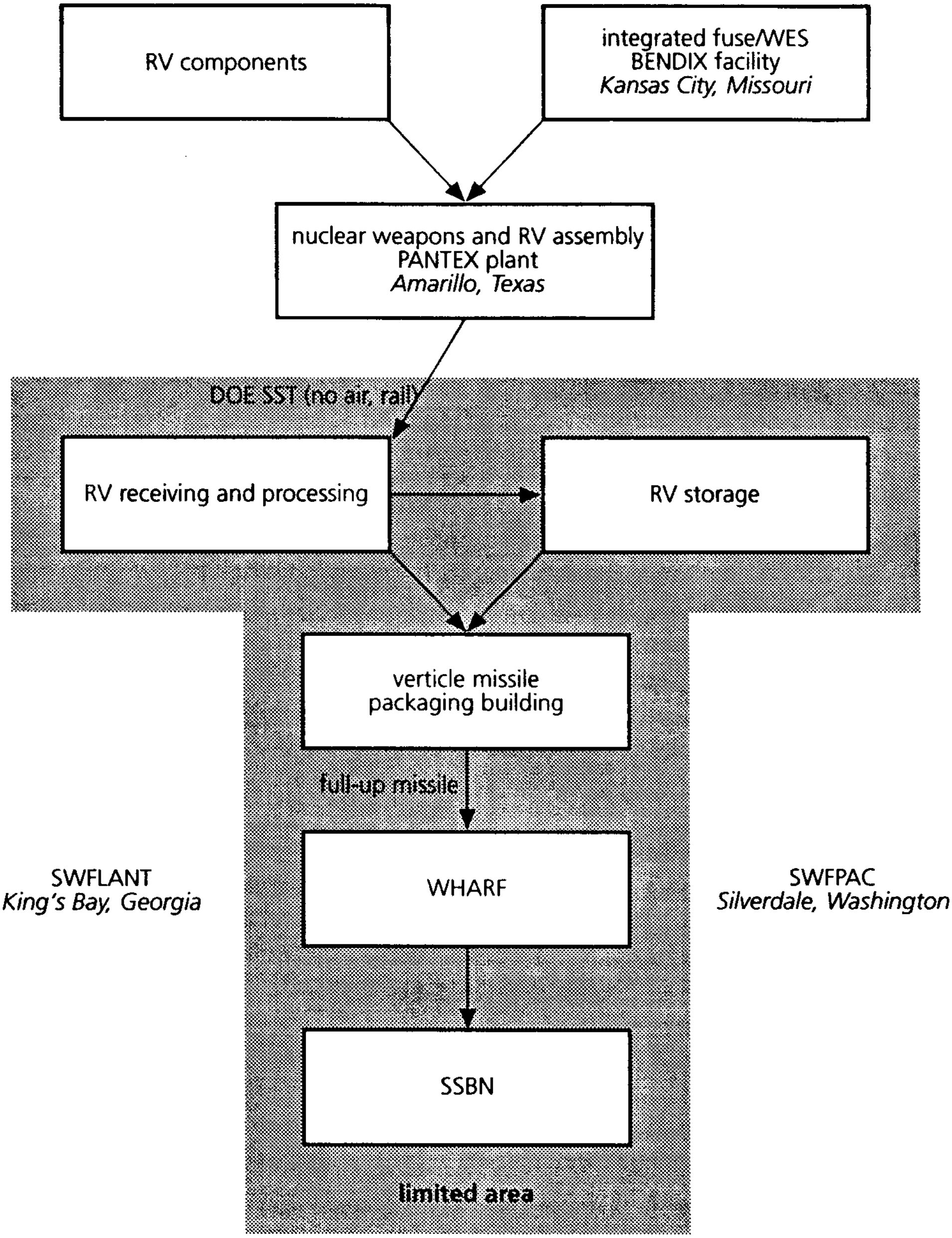

Figure 4: A warhead logistics sequence for C-4 SLBMs.

The handling procedure for D-5 is different. In response to a Drell Panel recommendation, separate transport of missile and RVs was implemented as the preferred approach for D-5. In this case, an environmental enclosure called the "reentry body service unit" is placed over the open launch tube containing a missile, the missile nose fairing is removed, and RVs are attached one by one. RVs are transported in armored containers between the magazine and the service unit. Further analysis is underway by the Navy to establish the degree to which this approach lowers risks in missile and RV handling operations. Because the C-4 and D-5 configurations are so similar, we might expect that the Navy will eventually implement the same handling procedures for both systems.

RVs for both C-4 and D-5 can be demated, mated, or serviced in place without removing the missile from the submarine. The service unit is placed over the launch tube, the hatch opened, the nose fairing removed, and appropriate RV operations performed. The service unit shields RV operations from outside view.

Missiles and warheads may be removed during routine maintenance or submarine overhaul. Every few years, warheads are removed and serviced, typically for replenishment of tritium. The great majority of the time during which the RV is in the custody of the Navy, it is either in storage in its shipping container or deployed aboard the submarine. Only a small fraction of its lifetime (less than a few tenths of one percent) is spent in processing, maintenance, handling, or transport within the limited area. Retired warheads are returned to Pantex for storage or disassembly.

Nature of Potential Accidents

It is difficult to determine the probability that a plutonium dispersal—or even a small nuclear detonation—could result from a warhead accident involving abnormal shock, impact, thermal, or electrostatic-discharge environments. Furthermore, the validity of low-probability accident analysis can be legitimately questioned. While some probability calculations are straightforward, others are quite uncertain or incomplete. For example, it is possible to accurately estimate the chance of a failure of a crane hook during missile loading. It is almost impossible, however, to compute the likelihood that a determined and ingenious individual would slip through Navy security procedures and sabotage a missile during normal operations. Unfortunately, the probabilities that are quoted by experts tend to reflect only those factors that can be computed, while ignoring the unknowns.

We do know that during the 45 years of nuclear weapons operations, the

U.S. has never had an accident resulting in a nuclear detonation of even very low yield. Since 1968, when the Strategic Air Command terminated airborne alert of the heavy bomber force, there have been no known accidents involving dispersal of plutonium.[20] The open record shows that the Navy has never had an accident involving nuclear weapons and ballistic missiles in which there was any plutonium dispersal.[21] By all measures, the record has been outstanding. Safety analysis, however, is a continuous process over the lifetime of a weapons system, and it benefits from independent peer review and constructive criticism.[22]

In the case of accidents involving nuclear reactors, nuclear weapons, or nuclear waste, the social and political dimensions of public response are likely to be far more important than any direct losses from the accident itself.[23] Such a response was clearly demonstrated during the Three Mile Island incident, which provoked an enormous outcry, apparently without injuring a single individual. A nuclear weapons accident, even if localized to a Trident base and resulting in a few injuries or deaths to military personnel, would probably generate a similar reaction. This reaction would intensify if there were any release of radioactive materials outside the base. Military planners must anticipate that, in the event of a plutonium dispersal accident at SWFPAC or SWFLANT, Trident operations could be suspended for an extended period, or operations could be permanently canceled.

Because of the national security implications, we must not only examine accident scenarios that might be highly unlikely, but also—if they occurred—might not present a significant health hazard to the public. We distinguish between accidents that could present a relatively moderate risk to military personnel only (who are generally expected to face some hazardous duty) and those that present a hazard, albeit small, to the public. We do not carry out a detailed risk assessment of Trident handling operations—this beyond the scope of our effort—but instead examine ways in which SLBM warheads could be exposed to abnormal environments that could create health risks, and focus on the costs and operational consequences of reducing these risks.

Here, we briefly examine possible, if unlikely, accident scenarios involving nuclear warheads and Trident missiles, and then proceed to a more detailed discussion of three cases.

At Pantex, a detonation accident could occur during HE machining. There is no risk of plutonium dispersal at this stage because the HE is not in contact with plutonium. During assembly, handling, and transport at Pantex, an HE warhead could be dropped, or suffer impacts from collisions, that could conceivably cause a shock-initiated one-point detonation or, at lower impact thresholds, ignition of the HE. Warheads could also be exposed to fuel fires in transportation accidents. Detonations or fires would be immediately hazardous to personnel in the vicinity and could also result in plutonium dispersal to surrounding areas. Such risks are reduced for IHE warheads.

Highway accidents can occur when RVs are transported between Pantex and a Trident base. Once RV custody is transferred to the Navy, however, additional accident scenarios emerge. In addition to collisions or fires involving the warhead alone, the logistics sequence now includes operations in which RVs come in close contact with many tens of tons of HE equivalent in the form of Class 1.1 solid rocket propellant. Operations including mating and demating of RVs, missile assembly, the subsequent storage, transport, and handling of missiles, and the stationing in-port of a loaded submarine, create a potential for accidents involving a booster fire or detonation. A dropped missile or an airplane crash (accidental or deliberate) inside the limited area could create impact pressures and temperatures sufficient to cause motor detonation or fire. There is also the possibility of sabotage; for example, boosters or RVs could come under heavy weapons fire from a terrorist group during transport to the loading wharf.[24]

A booster detonation in the launch tube of an in-port SSBN would be catastrophic. A chain-reaction detonation of all 24 boosters would likely result. In addition to a major dispersal of plutonium, the reactor core could be breached and its highly radioactive contents released. The health consequences from such an event would overwhelm those from plutonium dispersal. Such an accident would almost certainly result in the extended suspension or termination of the Trident program.

Finally, there is a potential for an accident in local waters as the submarine heads to sea. The collision of a Trident with a large ship in a narrow channel could cause a fire or detonation leading to airborne plutonium dispersal in the Seattle or Jacksonville areas. An accident at sea could result in dispersal of plutonium as well as the loss of a boat and its crew.[25] Such an accident is less likely to create a health risk to the public and, thus, could be more manageable politically than an accident in-port or in local waters.

Recognizing that we are dealing with events of very low probability, we next examine three particular accident classes in more detail.

SLBM Booster Detonation

The most serious accident would involve a detonation of the booster, leading to a detonation of warhead HE. A great amount of energy would then be delivered rapidly to the pit, causing, according to some estimates, transformation of more than 10 percent of warhead plutonium into respirable, micron-sized particles, which, as will be discussed shortly, are the most dangerous.[26] Prevailing winds could transport some quantity of the aerosol over many tens of kilometers, possibly into densely populated areas.

Missile configuration affects the amount and size of plutonium particles likely to be released in an accident. It is useful to compare a Class 1.1 booster detonation for through-deck and clear-deck designs. In the former case, warheads would be exposed to relatively large shocks generated from high-velocity motor case fragments directly striking the RV aeroshell. Such shocks could detonate warhead HE. In the latter case, warheads are not as close to the detonable third stage, and intervening components act to mitigate the shock pressure to the warhead.

Lawrence Livermore National Laboratory (LLNL) conducted a rocket motor detonation test during the development of the W87 warhead for MX—a clear-deck system. The test was designed to verify the plutonium dispersal safety of the Mk21/W87 RV in a booster accident and, in general, to study the ejection of nuclear material and warhead and missile components from the vicinity of such a detonation. The results show that ICBM booster detonation accidents in the clear-deck configuration are unlikely to result in detonation of a W87 warhead's IHE, or in a significant dispersal of plutonium particles of respirable size.[27] More likely, the weapons would be ejected at velocities of several hundred meters per second from the region of the detonation. The reason for the low shock pressure transmitted to the IHE is twofold. First, the greater separation between the third-stage motor and the RV in clear-deck missiles allows the shock to dissipate. Second, the PBV components, missile interstage hardware, and heavy weapons components further mitigate the transmitted shock, in effect cushioning the weapons primary. In contrast, for the through-deck configuration, data and calculations from the rocket motor detonation test suggest that pressures in the range of 100 to 200 kbar could be incident on the Mk 21 RV.[28] In such environments, IHE is likely to detonate via SDT. Even if it did not, the shock pressure could be sufficiently intense that the plutonium would break up into small pieces, including substantial quantities of micron-size aerosol particles.

SLBM Booster Fire

At impact thresholds below those leading to an SDT, fires become the dominant mode of plutonium dispersal. A potential accident that has been extensively analyzed by the Navy and DOE is the dropping or toppling of a missile (e.g., from crane failure) when it is being loaded or unloaded from an SSBN.[29] Because of the low velocities involved, such accidents are not likely to result directly in a shock-induced detonation of a booster.[30] However, they could ignite the propellant of one or more missile stages, leading to at least four scenarios, three of which could result in widespread plutonium dispersal:

- A warhead could become immersed in the fire; the plutonium could melt, breach the warhead containment, oxidize, and disperse;[31]
- The rapid burning of confined conventional HE, which may have cracked or fragmented on impact, could generate gas pressure sufficient to cause a DDT and substantial dispersal; or
- An explosion (less violent than a detonation) generated by the rapid burning of the propellant would cause the warheads to be ejected relatively intact from the vicinity of the fire with only localized dispersal, if any.
- A dropped missile ignites, is propelled through the air, and falls back with sufficient velocity to produce a third-stage motor detonation.[32]

One can now begin to understand why some claim that the Navy Class 1.1 propellants may actually result in safer FBM operations. If, as the Navy claims, the level of impact-generated shocks that could be reasonably expected in potential handling accidents is well below the SDT pressure threshold in either propellant, then the principal mechanism for plutonium dispersal becomes ignition and fire. Contractor studies suggest that Navy Class 1.1 propellants are less susceptible to inadvertent ignition than existing Class 1.3 propellants.[33] On the other hand, once fire occurs, the likelihood of detonation via DDT, or an SDT resulting from impact of a propulsive stage, is greater for Class 1.1 propellant.

Fire-resistant pit (FRP) technology, in which the plutonium is encased in special refractory materials, has been used in the W87 and other warheads, but not the W88.[34] In a warhead having both IHE and an FRP, the plutonium pit has an increased probability of survival in many fire accidents. Experiments have demonstrated that with FRPs, molten plutonium can be contained for one hour or more in gasoline fires, which burn at 800 to 1,100° C. Containment time for a solid propellant fire, which burns at about 2,500° C, would be considerably shorter. IHE, in comparison with HE, can extend containment time for what might be a critical period because of its relatively low burn temperature.[35]

Accident Involving Nuclear Detonation

Nuclear warheads are designed to be "one-point safe"—that is, they will not produce significant nuclear yield in an accident if detonated at one point on the outer periphery of the HE.[36] The Drell Commission noted that the question of nuclear detonation safety is not well understood, particularly for a detonation of an SLBM third-stage motor in the configuration where eight RVs are clustered around it.[37]

Concerns about nuclear yield arise when the HE is initiated at more than one point (i.e., multipoint detonation) within a very short time interval, on the order of a few microseconds. How could such an event occur? If the booster detonated at a point along its central axis, an expanding spherical detonation wave would strike the motor case and generate high-velocity fragments. The fragments would strike the RV aeroshell and generate a planar shock, which would be transmitted to the warhead HE. The point on the HE first struck by the shock could detonate. Because of the symmetry of the through-deck design, all eight of the warheads would be struck at about the same time, possibly causing a massive explosion, but presumably no nuclear yield. But what happens if, as a result of a gunshot for example, a detonation is initiated on the periphery of the rocket motor directly adjacent to one of the RVs? A nonsymmetric shock could generate flying case fragments that would strike that RV causing a one-point detonation of the warhead. As the detonation front proceeded through the propellant, creating additional case fragment impacts on RVs, fragments from the first warhead would be striking adjacent warheads. If the timing were just right, one might argue that the HE of an adjacent RV could be detonated at more than one point, perhaps creating sufficient compression to produce some nuclear yield.

Of course, this discussion is purely speculative; a bullet moving at about one to two millimeters per msec is unlikely to generate a multipoint initiation because detonation fronts move significantly faster, about six millimeters per msec. Even if a multipoint initiation were to occur, it is inconceivable that the warhead, at this precise moment, would be in a configuration where the primary would "boost," thereby giving full yield.[38] Any nuclear yield would be in the range of a few tens of tons, rather than a few hundred kilotons. Even if the possibility is remote, however, the consequences of an accident of even very small yield would be so enormous that a comprehensive evaluation of Trident hazards must include continued analysis of this possibility.[39] For such analysis, sophisticated modeling is needed to understand whether an asymmetric initiation of a rocket motor, or some other mechanism, might result in a multipoint initiation of a warhead's HE. Such modeling requires the use of high-performance computers and complex 3-D hydrodynamic codes with neutronics, and was clearly beyond the scope of this study.

Consequences of Plutonium Dispersal

Plutonium is an alpha particle emitter. Because alpha particles cannot penetrate the skin, plutonium is not a major health hazard, even in substantial quantities, if it remains outside the body. Plutonium is most dangerous when it is inhaled and remains in the lungs for an extended period. (If ingested, it is less hazardous, in part because it is relatively rapidly removed in body wastes.) Thus, dispersal studies "are mainly concerned with assessing what fraction of plutonium becomes airborne, is respirable, and is likely to be retained in the lung."[40] The greatest danger is from particles of five mm or less, which are more likely to lodge in the lung.

If a sufficient quantity of plutonium is inhaled, death can occur rapidly from respiratory failure. In the absence of medical intervention, about 4.3 milligrams (2.6×10^{-4} curie) uniformly distributed in the lungs, can cause death to an adult within 30 days.[41] At lower inhalation levels (< 0.08 milligrams), the effects would not be immediate but would appear as an increased risk of cancer over an individual's lifetime. According to one estimate, based on the standard assumption that risk is linear with dose, the affect on an exposed population could be in the range of 3 to 12 long-term cancer deaths (also termed "latent cancer fatalities" or LCFs) per milligram of inhaled weapons-grade plutonium.[42]

The calculation of the health hazard to an exposed population involves many factors in addition to the amount and size distribution of plutonium particles. One must also consider the degree to which particulates will be entrained in an aerosol cloud, the rise and drift of the plume, the mechanisms for particle "fallout," and the degree to which ground particles could be resuspended into the cloud. The number of LCFs also depends on weather conditions (wind direction or rain) and the surrounding population density.

Fetter and von Hippel have calculated the consequences of an accident at SWFPAC involving a 10-kilogram release of plutonium in aerosol form.[43] A release of this magnitude might occur in an accident involving a third-stage motor detonation in operational configuration. Under worst-case assumptions of dry weather and wind velocity of four m sec^{-1} in the direction of Seattle (30 kilometers to the east of the base), their estimate for the number of LCFs ranges from 20 to 2,000, depending on what is assumed about the height of the cloud and the rate at which particles are removed from it.[44] An accident of this sort, they argue, is unlikely to cause prompt fatalities to people living off the base from exposure to high radiation doses.

We have adapted the "wedge" model described by Fetter and von Hippel to estimate the LCFs that could result from a similar accident at SWFLANT. Results are also highly sensitive to wind direction. Under dry weather conditions and the worst-case assumption that the wind is blowing towards Jacksonville, Florida (which it does less than 10 percent of the time), the expected number of LCFs ranges from 20 to 3,000.[45] This estimate is comparable to that computed for SWFPAC.

Casualties at this level, while significant, represent a modest increment in the cancer risk to the exposed population given that:

- The total dose is spread over a large population;
- The deaths would occur many years after the accident; and
- The individual risk of death from cancer from other causes is already quite high (about one in five).

To place this risk in perspective, consider that, in the hypothetical accident at SWFPAC, about 500,000 people live in the region exposed to the plume. About 100,000 of those on average would be expected to contract and die of cancer over a 30-year period from all other causes. Over 30 years, about 750 LCFs can be attributed to the annual radiation dose from natural causes (about 100 mr per year); this level is in the middle of the range of the 20 to 2,000 LCFs expected from a reasonably serious accident.[46] Thus, the health effects of an accident, if calculated solely in terms of expected LCFs, is small when compared with other causes of cancer.

Even so, based on the Fetter and von Hippel calculations, the increase in cancer death rate can be significant for those near the accident. For example, the rate would double for exposed individuals within two kilometers of the accident.[47] If their close-in calculations are accurate, individuals within a few hundred meters of the accident could inhale sufficient quantities of plutonium to experience mild forms of radiation sickness. Further, cleanup costs, including litigation and decreased property values, would be significant. For example, the 1966 Palomares accident cost the U.S. in excess of $100 million for weapons retrieval, cleanup, and reparations. In today's dollars, the cost would be about $0.5 billion. For an urban area, such as Jacksonville or Seattle, costs could be expected to escalate substantially. Indeed, from the potential accidents described above, ground contamination over wide areas could be two orders of magnitude or more in excess of the draft EPA screening level.[48]

If a small nuclear fission yield were produced in a Trident accident, the energy released from nuclear reactions would almost certainly be a small fraction of the energy generated by the detonation of the SLBM booster (about 100 tons of HE equivalent for D-5). Because of the high rate of energy release, all of the plutonium in the warheads would be transformed into aerosol. Assuming ten tons of nuclear yield, about a gram of radioactive fission products would also be produced and dispersed. The LCFs produced by radioactive particle inhalation would exceed those caused by a booster detonation accident with no nuclear yield, but probably not by more than a factor of two.

Even if the health risks are modest by some measures, an accident of the magnitude described by Fetter and von Hippel, or an accident involving a small nuclear yield, would destroy public confidence in nuclear weapons operations. The resulting outcry could lead to suspension or termination of the Trident program.

III. INCREASING THE SAFETY OF TRIDENT WARHEADS

In this section, we examine three approaches to enhanced nuclear warhead safety for Trident:

- Adapting existing IHE warheads for use with the Mk4 and Mk5 RVs;
- Retrofitting the W76 and W88 with IHE; and
- Developing new, safer warheads for Mk4 and Mk5.

Then we examine the prospects for producing plutonium and beryllium parts, and the current testing constraints that could affect the introduction of new warheads.

Introduction

In his 28 January 1992, State of the Union address, President Bush announced that the U.S. would "cease production of new warheads for our sea-based ballistic missiles"—that is, cease production of the W88 warhead for Trident. Prior to this announcement, the DOE had suspended nuclear warhead production because of health and safety concerns at the Rocky Flats plant, which fabricates plutonium parts for nuclear weapons. Plutonium processing facilities at Rocky Flats were shut down for repairs in 1989, and the prospects are dim for a return to operations in the near term.[49] W88 production ceased at an inventory of roughly 400 warheads, corresponding to about two Trident boat loads at eight RVs per missile. Existing Mk4/W76 RVs will round out D-5 deployment.[50]

The President's statement simply stopped production of the W88. It did not apparently preclude development and production of a new warhead for D-5 if, for example, enhanced safety became a pressing requirement. Nor did it preclude modification of an existing warhead for that purpose. In July 1992, the Navy and DOE joined in a nuclear weapons Phase II study to examine the feasibility of developing warheads with enhanced safety features for Trident. Among other things, this study identified approaches to incorporating IHE and fire resistance in nuclear warheads that are compatible with the Mk4 and Mk5 RVs.

In addition to the potential START II reductions to 1,750 SSBN warheads, another recent event has implications for Trident. In October 1992, Congress imposed restrictions on nuclear testing that could impede development of enhanced safety warheads for Trident.

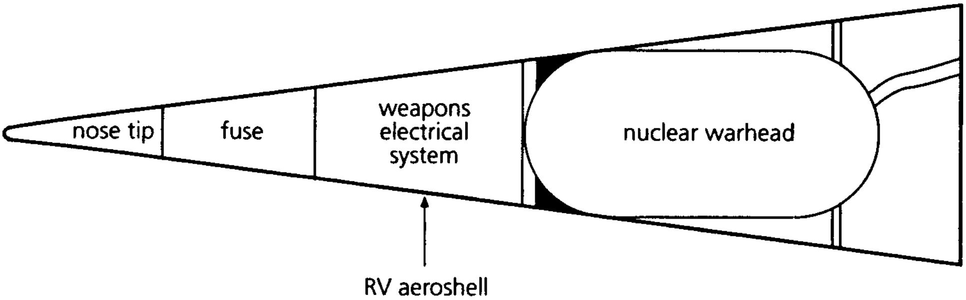

Figure 5: Components of a typical reentry vehicle (RV).

Fundamental Issues in RV Design

RV components include the aeroshell, the nuclear warhead, the weapons electrical system, the fuse, electrical cables for communicating with the PBV, and other items, such as hardware to impart axial spin to the RV prior to its release for greater stability during reentry. The thickness of the RV aeroshell and substructure is governed by the structural and heating loads anticipated during reentry. Figure 5 shows the components of a generic RV.

The RV ballistic coefficient, β, is proportional to RV mass and inversely proportional to the product of the drag coefficient and cross-sectional area. The larger the ballistic coefficient, the less an RV slows down on reentering and traversing the atmosphere. RVs with large β spend less time in the atmosphere and are less affected by atmospheric effects, such as wind, precipitation, and variations in atmospheric density that can knock an RV off course. Modern RVs typically have βs in the range of 2,000 pounds per square foot.[51]

Flight stability within the atmosphere requires that the RV center of gravity be forward of the center of aerodynamic pressure by some minimum fraction of total RV length called the static margin. Static margins ranging from three to 10 percent are typical of modern RVs. Because the nuclear warhead is usually the heaviest component of an RV (as well as the one with the largest diameter), maintaining sufficient static margin may require that the warhead be located as far forward in the RV as is possible, compatible with the placement of other RV components.

Based on these simple considerations, one can understand the design tradeoffs in a conical RV. For example, a designer would want β to be sufficiently high that the contribution to overall accuracy from atmospheric effects is small. For a given warhead and RV apex angle, β can be made large by keeping RV length (hence, base diameter) small. However, the RV must be long enough to assure that the center of pressure is sufficiently aft of the cen-

Table 5: RV weight estimates obtained from START Memorandum of Understanding.

Missile	RV/ warhead	Yield[a] *kilotons*	Number of RVs	Throw-weight[b] *kilograms*	RV weight[c] *kilograms*
MX	Mk21/W87	335	10	3,950	200
D-5	Mk5/W88	475	8	2,800	175
C-4	Mk4/W76	100	8	1,500	95
C-3	Mk3/W68	40	14[d]	2,000	70

a. Nuclear yields are from Modernizing U.S. Strategic Offensive Forces: The Administration's Program and Alternatives, Congressional Budget Office (CBO), (USGPO, Washington, D.C., May 1983).
b. Throw-weight values are from the START Treaty Memorandum of Understanding.
c. RV weight is estimated as follows: weight ·(throw-weight/2)/(# RVs), rounded to the nearest five kilograms.
d. Tested.

ter of gravity. If length is constrained, as it is in SLBMs, the apex angle can be increased slightly to permit the warhead (and the center of gravity) to be shifted forward to maintain static margin. However, such a shift would probably be at the expense of increased base diameter and drag coefficient and, hence, decreased β and accuracy.

Requirements placed on the D-5 system in terms of range, accuracy, and RV size and yield place stringent requirements on RV and warhead design. Subtle tradeoffs in the RV-warhead design space (including warhead size and weight, RV length, base diameter, β, and static margin) are required to optimize an RV system and meet performance requirements. Modifications to meet new requirements, such as IHE for enhanced safety, are usually not straightforward.

RV Weight Estimates

Estimates of RV weight are necessary to calculate the effect on missile range of changes in throw-weight. Such estimates can be made by using the rule-of-thumb that the total RV payload is roughly one-half of throw-weight. Table 5 shows RV weight estimates for MX and several SLBM systems.

An estimate of the weight penalty for an RV incorporating IHE and a fire-resistant pit (FRP) is obtained by noting that the Mk21, which has both, is estimated to be 25 kilograms heavier than the Mk5, which has neither.[52] The difference in weight arises from several sources. First, an IHE warhead will itself be heavier than an HE warhead of the same yield. Second, the larger diameter of an IHE primary will not permit a warhead to be placed as far forward in the RV. This shifts the RV center of gravity aft, reducing static margin. Regaining static margin would require either moving the center of gravity forward by adding ballast weight to the RV nose (if there is room), or lengthening the RV to move the center of pressure aft. In either case, the weight would increase. In addition, a longer RV produces a larger base diameter and drag coefficient, which act to decrease β.[53]

There are other differences between the Mk21 and the Mk5. The RV spin-up mechanism is located on the Trident PBV, whereas it is included on the RV for the Mk21. The Mk5 has an integrated fuse and weapons electrical system, which saves space and weight. The Mk21 aeroshell has been designed for greater heating loads than the Mk5 and it also has a rounded base. In addition to IHE and fire resistance, these other features also act to make the Mk21 heavier than the Mk5. Thus, in subsequent analysis, we use 25 kilograms as an upper limit to the weight penalty for using IHE and an FRP in a 500-kiloton class RV.

Effect of Reduced Nuclear Yield

Deploying Trident with a reduced nuclear yield is worth examining in detail because options for IHE warheads, particularly those that could be compatible with the Mk4 and Mk5, could involve lower-yield systems. As shown in table 5, the W88 has a relatively high yield compared to the W68 and W76 warheads, and it is instructive to consider whether D-5, with its impressive accuracy, could carry out its hard-target mission if some yield were traded for enhanced safety. It cannot be assumed that the D-5 system was optimized for effectiveness against existing hard targets. Indeed, some additional capability may have been built in, so that D-5 could remain effective in the face of potential Soviet evolution to harder targets.[54]

The probability of destroying a target with a blast overpressure is a function of target hardness, weapons system reliability, and RV yield and accuracy. For a target, such as a missile silo hardened to 5,000 psi, kill probabilities are tabulated in table 6 for several values of warhead yield and accuracy and for one and two RVs allocated to each target.

For targets hardened to 5,000 psi, and at D-5 accuracy in the range of 0.05 to 0.10 nautical miles (about 300 to 600 feet), table 6 shows that, depending on accuracy, significant kill probabilities can be attained at a yield substantially

Table 6: Probability of destroying a 5000-psi target.[a]
(Weapons system reliability is assumed to be 0.9).

Yield *kilotons*	**CEP = 0.05 n.m.**		**CEP = 0.075 n.m.**		**CEP = 0.10 n.m.**	
	1 on 1	*2 on 1*	*1 on 1*	*2 on 1*	*1 on 1*	*2 on 1*
100	0.65	0.88	0.39	0.63	0.24	0.43
200	0.78	0.95	0.53	0.78	0.36	0.59
300	0.84	0.97	0.62	0.86	0.43	0.68
400	0.86	0.98	0.68	0.90	0.49	0.75
500	0.88	0.99	0.73	0.93	0.54	0.79

a. The probability of destroying a target with one warhead is:
P_k (one on one) = R × SSPK, where
R = weapons system reliability, and
SSPK = single-shot kill probability = $(1 - 0.5^{(WR/CEP)^2})$, where
WR = weapons lethal radius for 5,000-psi hard targets = 875 feet × $Y(Mt)^{1/3}$.
If two warheads (from different missiles) are allocated to each target, the probability of kill becomes:
P_k (two on one) = (R × SSPK) × (2 − (R × SSPK)).

lower than that of the W88. For the most optimistic circular error probable (CEP), there is a 10 percent drop in kill probability (0.87 to 0.78) associated with switching to a 200-kiloton warhead. Even a 100-kiloton weapon would give a single warhead kill probability greater than 0.6 at a CEP of 300 feet. If the CEP is as bad as 600 feet (about 0.10 n.m.), a 300-kiloton warhead will give a kill probability of 0.4 against a 5,000-psi target, rising to about 0.7 if two RVs are allocated to each target. We conclude that, if accuracy is as good as has been cited (≤ 450 feet), the yield of the Trident warhead could be reduced by 100 to 200 kilotons without significantly decreasing its ability to destroy hardened targets.[55]

Adapting Existing IHE Warheads for Use with Mk4 and Mk5

One IHE candidate for Trident is the Mk21/W87 RV currently deployed on the MX missile. It is a design that is qualified at roughly the W88 yield. Because the W87 is heavier and larger than the W88, it is not likely to be compatible with Mk5, much less Mk4. The Mk21 is somewhat longer and has a larger base diameter than Mk5, although the precise dimensions and layout of its components are not publicly available. The D-5 simply may not accommodate Mk21s, at least while maintaining existing clearances, if the annular region surrounding the third stage is too narrow (see figure 2). Even if it does fit, the electrical and mechanical interfaces between the missile and Mk21 warhead would require modification.

About 500 W87 warheads have been produced for MX. If Mk21 could be made compatible with D-5, new warheads might have to be produced, and the problem of the Rocky Flats shutdown arises.[56] Restarting the W87 fabrication line would require a "production verification" nuclear test to assure that slight changes in the manufacturing process, resulting from restarting production after a long delay, did not affect warhead performance.

The W80 and W84 warheads used, respectively, in the air-launched cruise missile (ALCM) and the retired ground-launched cruise missile (GLCM), are possible SLBM warhead candidates. Both of these warheads use IHE, and the W84 has an FRP. They were designed, however, to be deployed on cruise missiles, which fly at low altitudes and at relatively slow speeds. The environments experienced in their "stockpile-to-target" sequence are significantly different from those experienced by a strategic RV, and extensive testing and development would be necessary to determine whether these designs could be adapted to Mk5. If they could, new warheads would have to be produced, and the Rocky Flats problem arises once again.

Current plans call for the W68 and W76 warheads (deployed, respectively, with the Poseidon C-3 and Trident C-4 SLBMs) to be retired in large numbers, which could be even larger if START II is implemented. These warheads are non-IHE. In addition, the W68 is about one-tenth the yield of the W88 and would have marginal capability against hard targets. The pits from these retired warheads could possibly be reused in new IHE warheads. We discuss this possibility in more detail later in this section.

Incorporating IHE in the W76 and W88

It might seem that the most straightforward approach to enhanced safety would be to replace HE with IHE in the W76 and W88 warheads. Evaluating this approach involves issues of nuclear weapons design where very little public information is available. Therefore, our discussion is necessarily qualitative.

The HE initiates a nuclear detonation of the warhead primary, which triggers a larger thermonuclear detonation in the secondary. Specifically, when the HE is detonated, an inward-directed shock wave compresses a shell of fissile material, making it more likely that fast neutrons from fissioning nuclei will encounter other nuclei before they escape the warhead.[57] Neutron absorption produces yet more fission, and the resulting chain reaction, enhanced by deuterium-tritium "boosting," releases energy that is then focused on the thermonuclear secondary, which is compressed and heated. When critical temperatures and pressures are reached, fusion reactions in the secondary convert deuterium and tritium into helium and fast neutrons. The vast amount of energy released from fission and fusion reactions in the secondary accounts for most of the total warhead yield.

Primary yield and performance are a function of many parameters, including the design configuration, the mass of fissile material, the amount and energy density of HE employed, and the amount of tritium used in boosting. Tradeoffs among these parameters can permit optimizing certain features in the design. The W76 and W88 designers, seeking maximum yield within size and weight constraints, chose conventional HE on the basis of its high energy density.

Redesign or retrofit of warheads, while costly and time-consuming, is not unknown in the history of American nuclear weapons. The following episodes have been reported during the course of the FBM program:

- In the early 1960s, a number of W47 Polaris warhead primaries had to be replaced after corrosion of the fissile materials was observed during routine stockpile maintenance.[58] Later, the entire stockpile of W47s had to be rebuilt with new primaries when problems developed in a mechanical safing system.[59]
- The entire stockpile of Poseidon W68 warheads had to be rebuilt after it was discovered that the HE had decomposed and that the products of decomposition had caused deterioration of the detonators.[60]

An HE primary would not perform properly if its HE were simply replaced by an identical volume of IHE, since IHE has only two-thirds the energy density.[61] Nuclear weapons are designed with a safety margin so that a smaller-than-expected amount of compression will still generate full secondary yield. The large difference in energy densities suggests that the modified primary might neither produce its original design yield, nor produce a yield sufficient to drive the secondary.

One solution might be to increase the amount of fissile material, thus maintaining primary yield at lower levels of compression. We are unable to evaluate the suitability of this method for the W76 or W88. Adding additional fissile material to a primary, however, may affect the one-point safety of the design.

As an alternative, it may be possible to increase the amount of IHE to compensate for its lower explosive power, but the shape and size of the RV could make this difficult. The apex half-angle of the Mk4 and Mk5 RVs is about eight degrees; this means that any component whose size is constrained by the RV aeroshell, and whose diameter is increased by some amount must be moved aft by 3.5 times that amount. There may simply not be enough room in the RVs to accommodate a larger primary. In addition, any shift aft in the position of heavy components would reduce static margin, which, in turn, would decrease flight stability.

Thus, modification of existing SLBM warheads to IHE may not be a productive route if maintaining compatibility with the Mk4 and Mk5 is desired. Such modified warheads could exceed size and weight constraints for those RVs. If feasible, warhead modification could require several nuclear tests and cost a substantial fraction of the cost of a new warhead development program.

Developing New Enhanced Safety Warheads

The most efficient way of introducing IHE into the Trident force may be to design new warheads for Mk4 and Mk5 that incorporate IHE and fire resistance. IHE warheads could be designed at the appropriate size and weight to be compatible with these RVs, but at some yield penalty. Producing new warheads would require a functioning DOE production complex including Rocky Flats (or its equivalent) for plutonium parts if pit reuse were not feasible, the Y-12 plant for secondary components, and Pantex for weapons assembly.

Some savings could result if a warhead already in development could be adapted to a strategic SLBM RV. The W89 program offers an interesting possibility. Full-scale development of the W89, intended for SRAM II, was terminated in July 1992. The design has IHE, an FRP, a modern electrical safety system, and a yield in the range of several hundred kilotons. Perhaps more intriguing, because of the Rocky Flats shutdown, the W89 was designed to use recycled pits and, indeed, has established the feasibility of such recycling in a successful nuclear test.[62]

Certain advantages would accrue if it were possible to adapt the W89 to the Mk5 RV. First, the W89 development program is well along, so the costs to adapt the system and complete its development may not be large. Second, most of the W89 nuclear test program is completed. Third, the need for an expensive program to develop a new RV would be obviated. Finally, an enhanced safety warhead could be fielded without having to restart operations at Rocky Flats. The key question, however, is whether the W89, intended for an air-carried attack missile, could be adapted for use in a strategic RV. Efforts are underway in the Navy/DOE Phase II study to answer this question.

In subsequent discussions, we assume that an IHE warhead, possibly the W89, could be made compatible with the Mk5 RV. The characteristics of such a warhead would be that, if Mk5 weight were held constant, there would be some yield penalty, perhaps in the range of 10 to 20 percent. Because of the relative insensitivity of hard-target kill probability to warhead yield (discussed earlier), we focus on approaches that produce a yield penalty at constant RV weight, rather than maintain constant yield in a heavier RV.

Unlike the W89 for Mk5, there are no IHE warheads under development that could be adapted to Mk4; new warhead development would be required. Compared with Mk5, it may be more difficult to develop a new, small IHE warhead compatible with Mk4 at about its current weight. Thus, we might expect a somewhat larger yield penalty, perhaps in the range of 10 to 40 percent.

Other, more exotic enhanced safety concepts could involve separable components. For example, the plutonium parts in one concept are safely and securely stored away from the high explosive until a launch authorization is received. Such concepts provide inherent safety to plutonium dispersal in accidents. We are, however, unable to assess further the feasibility of these concepts for strategic RVs.

Producing Plutonium and Beryllium Parts for Nuclear Warheads

If pit reuse is not feasible in modified SLBM warheads, then a capability to fabricate plutonium and beryllium parts would be required. There seem to be two options:

- Bring Rocky Flats back into compliance with environmental regulations; or
- Establish a capability for small-scale production of these parts at Los Alamos or Livermore, which have facilities for handling and processing these materials and fabricating parts.

The prospects for restarting Rocky Flats appear dim.[63] A capability at one of the weapons labs to produce 50 to 100 pits per year could prove essential. A major commitment would be required, however, to complete requisite environmental impact statements so that production could begin.

Nuclear Testing and Trident

In September 1992, Congress passed the Energy and Water Development Appropriations Act (1993). This Act halted nuclear testing until July 1993 and imposed a maximum of 15 safety-related tests (including United Kingdom tests conducted at the Nevada Test Site) for the period July 1993 through September 1996. After 30 September 1996, the law decrees that there can be no U.S. testing unless a foreign state conducts a test after that date. In July 1993, the President extended the U.S. moratorium on nuclear testing through September 1994, but indicated that if another nation conducted a test during that time, he would seek approval from Congress to resume testing under the law. In October 1993, the Chinese conducted a nuclear test and the President ordered the DOE to plan to resume testing, but in early 1994, he decided to extend the moratorium through September 1995. During the debate leading up to the first extension of the moratorium, there was little support from either the DOE or the DOD for using some of the permitted nuclear tests to develop and field enhanced safety warheads for Trident.

Developing new nuclear warheads requires nuclear testing. To develop a new IHE primary, and to be confident that it could "drive" the thermonuclear secondary, testing up to 150 kilotons would be desirable, if not essential. Developing the primary itself would require testing at an order-of-magnitude lower yield. A nuclear warhead development program typically entails a five-year research and development effort including about five nuclear tests. If enhanced safety warheads are to be fielded for Mk4 and Mk5, however, only about five or six of the 15 permitted nuclear tests would need to be allocated to these two development programs. This assumes that an IHE warhead previously in development (the W89) could be adapted to the Mk5.

U.S. law and recent actions by the President extending the moratorium may have foreclosed any opportunity to develop and field enhanced safety warheads for Trident. If, however, the U.S. resumes nuclear testing after September 1995 in response to the Chinese or another test, then key decisions will be required to maintain an option to upgrade Trident warheads. First, Trident-related tests could be given a higher priority relative to other nuclear testing demands, such as those for implementing enhanced safety in other stockpile warheads, for stockpile reliability, and for UK warhead development. Second, to meet a September 1996 deadline, accelerated development and nuclear testing programs could be necessary for one or both Trident warheads, requiring dedicated efforts and possibly increased spending on nuclear weapons research and development over the next three years. Finally, if Trident warhead development cannot be completed by 1996, accelerated program or otherwise, then the President must decide whether to press to retain an option to conduct some tests after 1996.

IV. OPERATIONAL IMPACTS OF ENHANCED TRIDENT SAFETY

This section examines the impact of safety modifications on Trident performance and operations, including their effects on survivability and hard-target kill capability. We have calculated how Trident range, SSBN ocean operating area, and on-station time depends on missile throw-weight and on the type of propellant in each stage. Our calculations are based on the following approach:

- We developed simple engineering models of the C-4 and D-5 missiles using information available in the open literature and plausible guesses.
- We used a computer to numerically integrate the missile's equations of motion and to generate a set of trajectories to find maximum range.
- For any given maximum range, we computed the amount of open water in the Atlantic and Pacific Oceans from which U.S. SSBNs would be in range of key targets. (Larger patrol areas can enhance SSBN survivability to ASW.) We also calculated the fraction of time in its patrol cycle that an SSBN is within range of key targets.
- We studied the operational impacts of safety-related modifications by changing the values of various important missile parameters.

The Target Set

A key issue is the target set against which Trident performance is evaluated. We chose the SS-18 launch sites in the former Soviet Union.[64] It is important to explain this choice because some would argue, in light of the current superpower relationship, that it is not critical to continue to hold SS-18s at risk. Further, if START II enters into force, all SS-18 missiles may be removed from their silos by the decade's end. Our approach, however, is to try to understand the effect of enhanced safety modifications on Trident system operations and survivability, and to do so it is necessary to compare the capability of the modified system to carry out a particular mission with that of the original system.

The Trident D-5 was originally designed to hold at risk hardened Soviet targets, including ICBM silos, and, among these, the SS-18s offered a great challenge for two reasons. First, modern Soviet ICBM silos reportedly can withstand air-blast overpressures greater than 6,000 psi and, thus, require an accurate, high-yield warhead for assured destruction.[65] Second, the SS-18s are located deep in the interior of Russia and Kazakhstan. Of all hard targets, they are nearly the most remote. If the SS-18s constituted an important target set for Trident, then it is very likely the one that most seriously constrained system operations and limited SSBN patrol area.[66]

Thus, we chose the SS-18s as a generic target class that poses a particularly demanding, and possibly the most difficult, challenge to Trident. This choice does not necessarily mean that we believe that SS-18 launch sites will continue to be critical targets (although it is not implausible that future threats could emerge from the region in which they are located). Rather, if we can establish that safety-related modifications to Trident do not significantly affect the more demanding SS-18 mission, then we can reasonably claim they will not affect the capability of Trident to hold other less-demanding target sets at risk.

The Missile Model

The inputs to the computer program are missile launch weight, throw-weight, mass of propellant, propellant burn time, propellant specific impulse, and cross-sectional area of each stage.[67] The density of the atmosphere and the speed of sound in air, as functions of altitude, are input in tabular form.

The specific impulse, I_{sp}, which is a good measure of the efficacy of a propellant, is given by:

$$I_{sp} = \frac{\text{thrust}}{\frac{dM}{dt}} \cdot g$$

where dM/dt = rate of propellant consumption (in kg $\sec^{-1}$), and g = acceleration of gravity. One can consider I_{sp} as the ratio of the thrust produced by a given amount of propellant to the weight of that propellant, expended over one second.

The calculation is based on the assumption that each stage flies with a fixed thrust. Two other forces are in effect: gravity and aerodynamic resistance. The latter depends on the cross-sectional area and velocity of the missile, and on the density of air through which the missile is moving. Based on the resultant force, the acceleration, velocity, and position of the missile as a function of time are calculated by numerical integration.

At launch, the orientation of the missile is a few degrees from vertical. The first two stages execute "gravity turns"—that is, the thrust and velocity vectors remain parallel to the longitudinal axis of the booster. This type of trajectory, or a close approximation to it, is often followed by ballistic missiles because it tends to minimize nonaxial aerodynamic forces. After the second

Table 7: Parameters of a "standard" D-5 missile.

Launch weight	56,525 kg (124,350 lb)
Throw-weight (with 8 Mk5s)	2,700 kg (5,940 lb)
Nose faring and end cap weight	180 kg (400 lb)
Missile diameter	2.11 m (83 in.)
Propellant	Class 1.1 in all three stages
Nominal range	4,100 n.m.

Stage	Stage mass *kg*	Propellant mass *kg*	Mass fraction	Thrust *Newtons*	I_{sp}[a] *seconds*	Stage burn time *seconds*
1	39,742	37,500	0.929	1,559,000	271	64
2	11,874	11,060	0.931	448,500	281	68
3	2,207	2,050	0.929	124,500	303	49

[a] The increase in I_{sp} from the first to the third stage is due to the drop in external (atmospheric) pressure. The third stage thrusts in what is essentially a vacuum.

stage completes its gravity turn, the third stage thrusts so that the resulting burnout velocity will achieve maximum range during ballistic (unpowered) flight.[68]

Based on the above algorithm, we defined a standard missile such that plausible values of the parameters given in tables 7 and 8 resulted in a maximum range of 4,100 nautical miles (n.m.). Although some parameters, such as launch weight, are well known, others are not. For parameters that were uncertain, we varied them within very reasonable ranges of their values to test the sensitivity of the results. In this manner, we developed confidence that our models are reasonable and, specifically, that important derivatives (e.g., range partials) are reproduced.

The D-5 flight profile generated by the program is shown in figures 6 and 7, which depict the powered and ballistic portions of the trajectory. The total flight time is 28 minutes, with an apogee of 560 n.m. Impact occurs at an angle of 25 degrees from horizontal, with a velocity of 6.7 km sec^{-1}, which does not,

Table 8: Parameters of a "standard" C-4 missile.

Launch weight	30,900 kg (68,000 lb)
Throw-weight (with 8 Mk4s)	1,400 kg (3,080 lb)
Nose faring and end cap weight	100 kg (220 lb)
Missile diameter	1.88 m (74 in.)
Propellant	Class 1.1 in all three stages
Nominal range	4,100 n.m.

Stage	Stage mass *kg*	Propellant mass *kg*	Mass fraction	Thrust *Newtons*	I_{sp}[a] *seconds*	Stage burn time *seconds*
1	19,070	17,700	0.928	783,460	271	60
2	8,590	7,930	0.923	363,960	281	60
3	1,840	1,700	0.924	140,220	303	36

[a] The increase in I_{sp} from the first to the third stage is due to the drop in external (atmospheric) pressure. The third stage thrusts in what is essentially a vacuum.

however, take into account the effects of air resistance during the warhead's descent.

Results from Missile Model Calculations

Using our computer model, we examined the sensitivity of missile range to propellant I_{sp} and throw-weight. To provide insight into the sensitivity of missile range to SSBN survivability, we also calculated, for various values of I_{sp} and throw-weight, SSBN patrol area and time on-station within range of key targets.

Range versus I_{sp}

By varying the thrust of a stage without changing the burn time or the propellant mass, we were able to study the effect of a variable I_{sp} in that stage's pro-

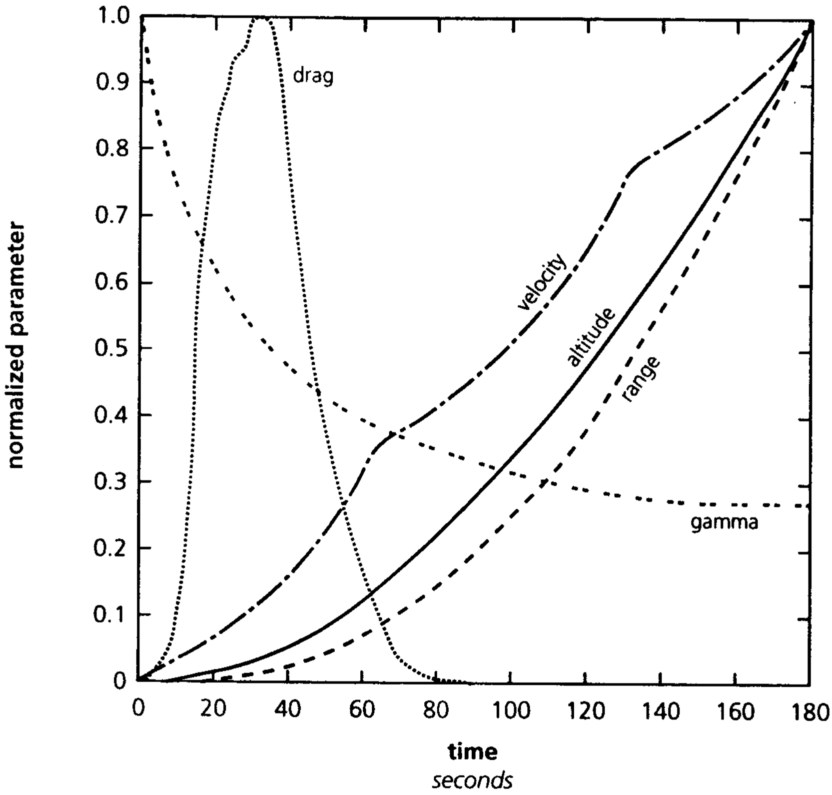

Figure 6: Trajectory parameters are plotted for the "standard" D-5 missile, as computed by the flyout program for powered flight. "Gamma" is the angle between the missile's velocity vector and the local horizontal. The normalization for range, altitude, velocity, and gamma, respectively, are 275 n.m., 130 n.m., 6.4 km sec^{-1}, and 87.3 degrees.

pellant. Figure 8 shows the results for modified propellants in the D-5 third stage only, in second and third stages only, and in all three stages. Assuming nondetonable Class 1.3 propellants have an I_{sp} that is 10 seconds lower than that of Class 1.1 propellants, the corresponding reductions in range for a modified D-5 carrying eight Mk5 RVs are 110 n.m. (–2.7 percent), 350 n.m. (–8.5 percent), and 575 n.m. (–14 percent).[69] The equivalent range reductions for a modified C-4 carrying eight Mk4s are 160 n.m. (–3.9 percent), 380 n.m. (–9.3 percent), and 560 n.m. (–14 percent).

We configured the D-5 model to eliminate the third stage altogether, both propellant and inert material.[70] The resulting missile flew to a range of 3,360 n.m., about 82 percent of nominal range. If three Mk5 RVs are then offloaded, missile range increases to 4,140 n.m., slightly above nominal. Another modifi-

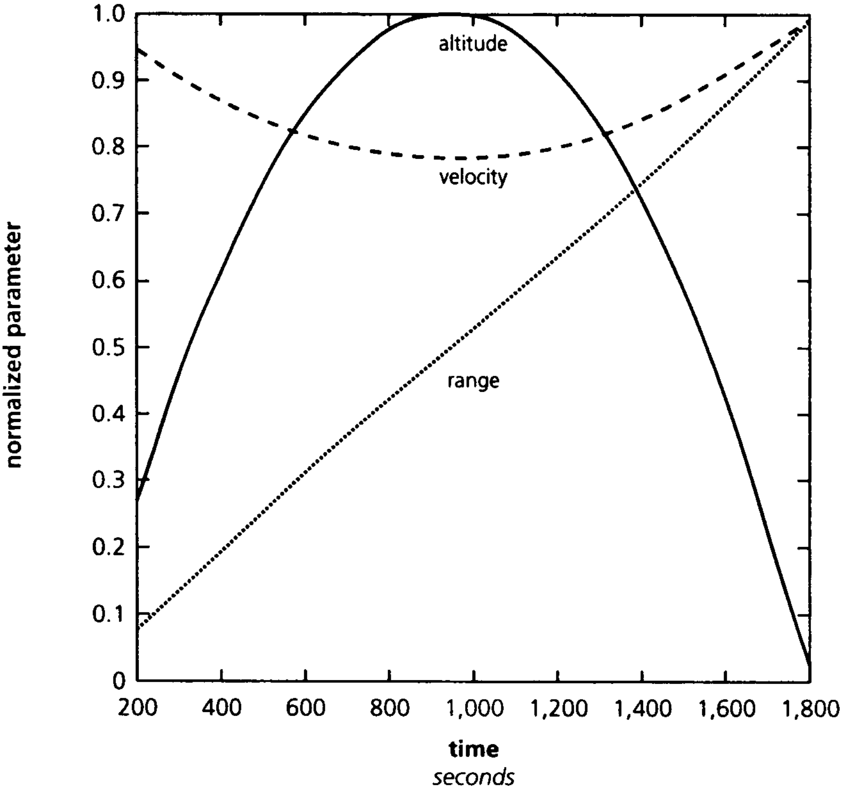

Figure 7: The ballistic (unpowered) portion of the "standard" D-5 missile's flight is shown. The time (horizontal) axis is compressed by a factor of 10 compared with figure 6. Total flight time is approximately 28 minutes. The normalization for range, altitude, and velocity are, respectively, 4,100 n.m., 560 n.m., and 6.7 km $\sec^{-1}$.

cation involves replacing the third-stage propellant with an equal mass of inert material. Our calculations show such replacement results in a dramatic D-5 range reduction, to 1,900 n.m.

Range versus Throw-weight

We calculated range versus throw-weight for several missile options. For each throw-weight value, the initial launch angle corresponding to the beginning of the first-stage's gravity turn was adjusted to maximize range for a minimum energy trajectory. In all cases, this angle is within a few tenths of a degree of the nominal value of 2.6 degrees from vertical. For the "standard" (unmodified) missile at a nominal throw-weight of 2,700 kilograms, the decrease in

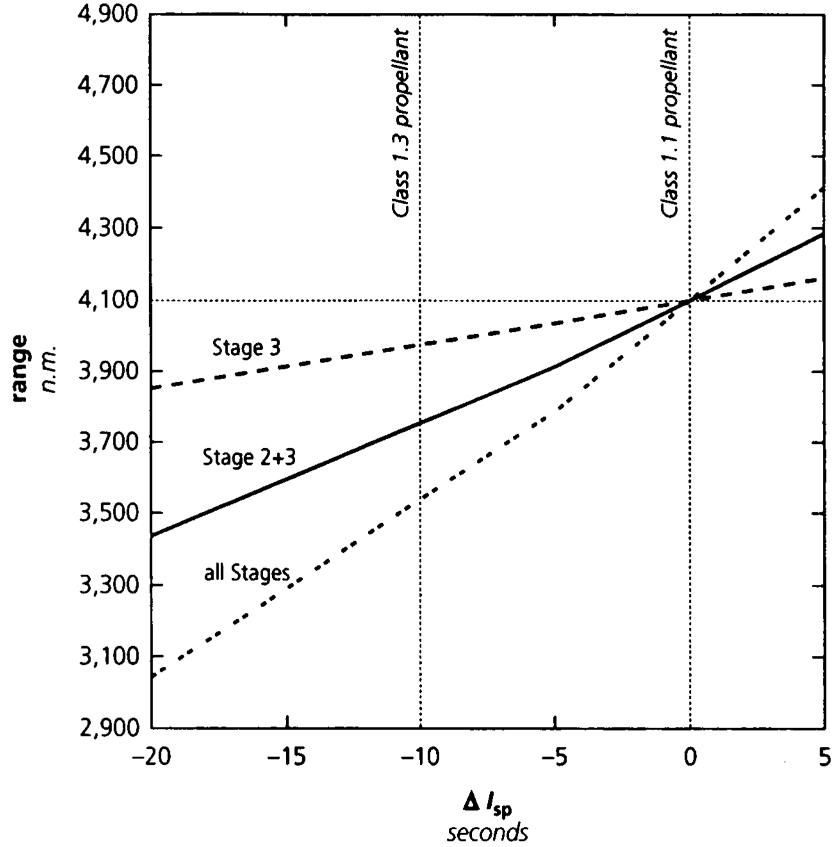

Figure 8: D-5 range is plotted versus propellant specific impulse. The ΔI_{sp} = 0 data is for the "standard" D-5 with eight Mk5 RVs and a nominal range of 4,100 n.m. The three curves correspond to propellant changes in the third stage only, in the second and third stages, and in all three stages. Class 1.3 propellants have an I_{sp} that is about 10 seconds less than comparable Class 1.1 propellants. The corresponding reductions in range for Class 1.3 propellant are, respectively, 110 n.m. (–2.7 percent), 350 n.m. (–8.5 percent), and 575 n.m. (–14 percent).

range for each incremental kilogram of throw-weight is 2.0 n.m.

Table 9 and figure 9 show how D-5 range increases when warheads are offloaded. As expected, removing warheads yields appreciable increases in range. The maximum drag force experienced by the missile also rises because of the higher flyout velocity.[72] It is interesting to note that the range penalty resulting from a redesigned third stage incorporating Class 1.3 propellant can be more than recovered by offloading one Mk5 RV. If the third stage is eliminated altogether, nominal range can be recovered by offloading three Mk5 RVs or four Mk21s. Finally, eight Mk4 RVs can be carried to slightly more than nominal range even with no third stage present. In this case, offloading Mk4s

Table 9: Effect of offloading Mk5 RVs (175 kilograms each) on "standard" D-5 range.

#Mk5 RVs	Throw-weight *kilograms*	D-5 range *n.m.*	Increase in range *percent*
8	2,700	4,100	nominal
7	2,525	4,470	9
6	2,350	4,920	20
5	2,175	5,480	34
4	2,000	6,220	52
3	1,825	7,280	78

Table 10: Effect of offloading Mk4 RVs (95 kilograms each) on "standard" C-4 range.

#Mk4 RVs	Throw-weight *kilograms*	C-4 Range *n.m.*	Increase in range *percent*
8	1,400	4,100	nominal
7	1,305	4,470	9
6	1,210	4,930	20
5	1,115	5,500	34
4	1,020	6,280	53

would substantially increase the range.

Table 10 and figure 10 show the results for C-4. In comparing tables 9 and 10, we note that the range of a standard C-4 with a given number of Mk4 RVs is about the same as that of a standard D-5 with the same number of Mk5s. For the same number of RVs, the range of a modified C-4 with Class 1.3 third stage and Mk4 RVs is consistently 40 to 50 n.m. lower than the range of a similarly modified D-5 carrying Mk5s. In our models, the C-4 third stage delivers

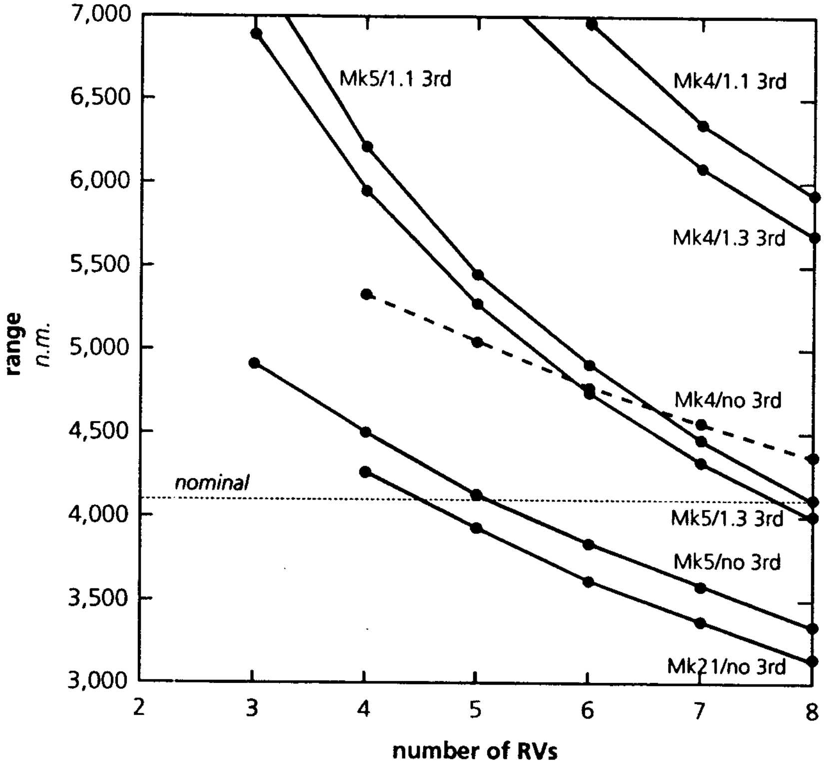

Figure 9: D-5 range is plotted for various missile configurations and RV loading. Curves represent the "standard" D-5 missile with Mk4 and Mk5 RVs, a modified D-5 with a Class 1.3 third stage with Mk4 and Mk5 RVs, and a modified missile with no third stage with Mk4, Mk5, and Mk21 RVs. The dotted horizontal line indicates the nominal range of 4,100 n.m.

a greater percentage of total velocity than does the D-5 third stage; thus, C-4 range will be somewhat more degraded if a lower I_{sp} propellant is used in the third stage. This last point is magnified in the "no-third-stage" data, where C-4 range, for the same number of RVs, is significantly less than that of D-5.

Sea Room versus Throw-weight

An important consequence of varying the range is the effect on the amount of patrol area available to the submarine within range of the target set. In certain ASW models, SSBN patrol area is directly related to the amount of area an enemy must "sweep" to seek out and destroy the SSBN and, thus, directly related to SSBN survivability. We compute patrol area by assuming that, for our principal target set—the SS-18 launch sites—all open water in the Atlan-

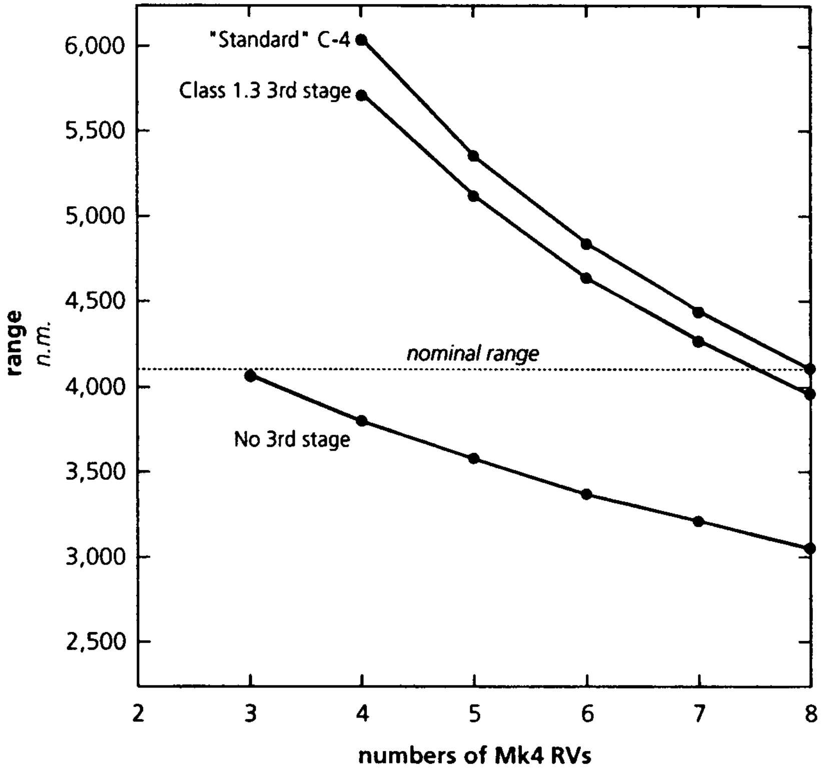

Figure 10: C-4 range is plotted for various missile configurations and RV loading. Curves represent the "standard" C-4 missile with Mk4 RVs, a modified C-4 with a Class 1.3 third stage and Mk4 RVs, and a modified missile with no third stage and Mk4 RVs. The dotted horizontal line indicates the nominal range of 4,100 n.m.

tic and Pacific Oceans within range of those targets is available to the SSBN. We do not consider the depth of the water, the topography of the ocean floor, the proximity to friendly or hostile forces, and other factors that may affect detectability and survivability.

Figure 11 shows the SS-18 launch sites and the boundaries of the areas in the Atlantic and Pacific Oceans from which a Trident submarine is within 4,100-n.m range of all SS-18s. The figure is a Mercator projection, which is convenient for providing an overall view of the situation, but severely distorts areas. Subsequent maps in this paper reproduce areas faithfully, i.e., any two regions that have equal areas on the map also have equal areas on the Earth's surface.

Our computation was purely geometrical (i.e., it was based on calculating the distance from a point on the ocean's surface to a target), except for one fac-

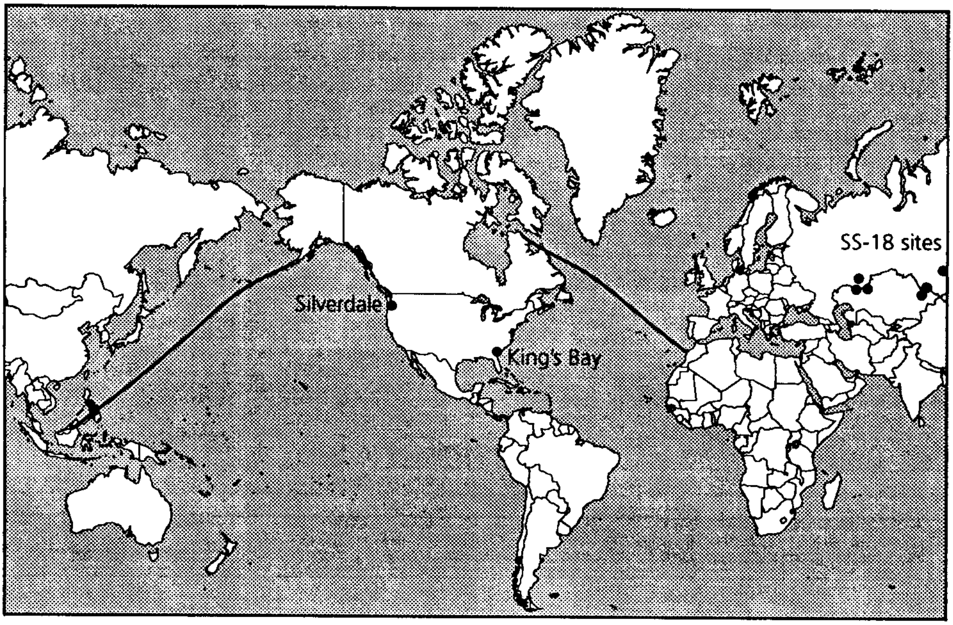

Figure 11: The six SS-18 launch sites. The curves show the boundaries of the areas in the Atlantic and Pacific Oceans from which a Trident submarine is within 4,100-n.m. range of all six SS-18 sites. The Mercator projection does not faithfully reproduce areas of the Earth's surface.

tor: we included the effect of the Earth's rotation. Any missile that is launched towards the east (e.g., from the Atlantic Ocean towards Russia) at a target located at a higher latitude obtains a velocity boost from the planet's west-to-east rotation. The Earth's rotation varies from 0.46 km $\sec^{-1}$ at the equator to 0.30 km $\sec^{-1}$ at a launch latitude of 50 degrees. Only a fraction of this boost is, in fact, exploitable because the target itself is rotating away from the launch point. Missiles launched in the Pacific Ocean suffer a corresponding decrease in range unless they are launched from a latitude that is higher than that of the target.

We defined the northern boundary of the Atlantic Ocean at the Arctic Circle. We did not perform any area computations for the Arctic Ocean because we assume that U.S. SSBN commanders would be reluctant to patrol so close to the home ports of enemy attack submarines. In addition, large parts of the Arctic Ocean are very shallow and/or covered with ice, making it more difficult to remain undetected while preserving the capability of launching a missile strike at any time. Figure 12 does indicate, however, that SS-18 silos are highly vulnerable to attack from the polar regions, even if missile range is significantly reduced.

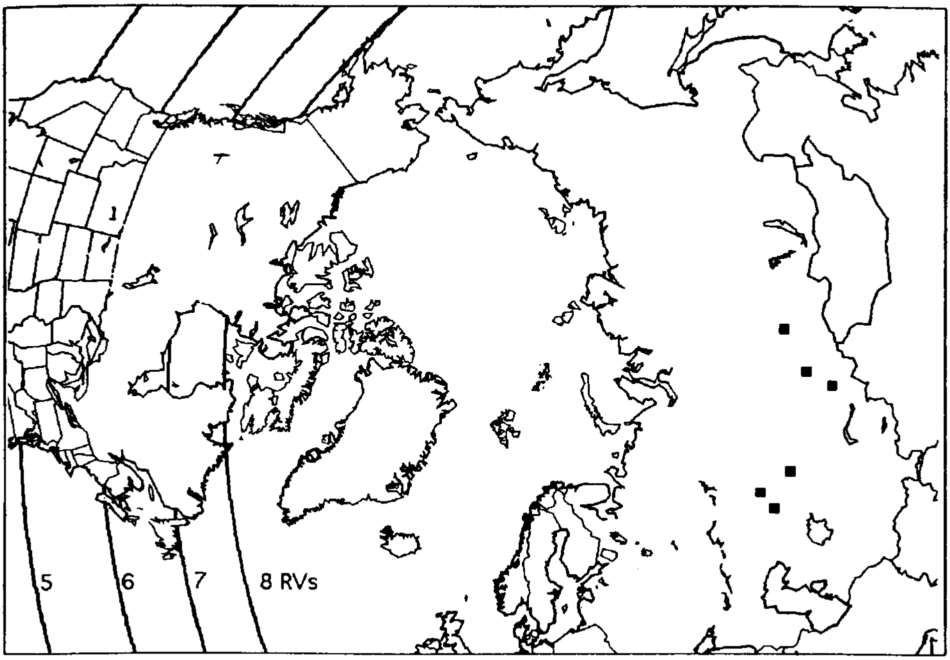

Figure 12: View of the accessibility of all six SS-18 launch sites from the Arctic Ocean. A correction has been applied for the Earth's rotation. The polar-azimuthal projection depicts areas accurately. The four curves are labeled according to the number of Mk5 RVs carried by a "standard" D-5 missile. The curve for eight RVs corresponds to a nominal range of 4,100 n.m. The curves also apply to a "standard" C-4 missile carrying the same number of Mk4 RVs.

The Mediterranean Sea is another body of water that is probably shunned by Trident submarines. One disadvantage is the undesirable "choke point" at Gibraltar. In addition, the confined space and large amount of noisy surface traffic makes the Mediterranean an uncomfortable region for ballistic missile submarines, whose commanders prefer large reaches of open water where they can cruise silently while listening intently for the enemy. We excluded the Baltic Sea from our analysis for similar reasons.

Results of area computations are tabulated in tables 11 and 12 and plotted in figures 13, 14, and 15. It is instructive to give results for the SS-18s in two separate groups: the three eastern-most sites (Aleysk, Uzhur, and Zhangiz Tobe) and the three western-most sites (Dombarovskiy, Kartaly, and Imeni Gastello), which are separated by about 650 n.m. For example, table 11 shows that 10.9×10^6 km^2 of ocean area in the Atlantic is available for launching D-5 missiles with 2,900-kilogram throw-weight at any of the three western-most SS-18 sites. This represents a 26 percent reduction in sea room compared with the nominal throw-weight of 2,700 kilograms. The estimated accuracy of ± 2

Table 11: Effect of throw-weight on the amount of patrol area within range of key targets for Trident SSBNs operating in the Atlantic or Pacific. Percentages are with respect to a "standard" D-5 with eight Mk5 RVs, a throw-weight of 2,700 kilograms, and a range of 4,100 n.m. The first five data entries also apply to a "standard" C-4 carrying, respectively, 4, 5, 6, 7, and 8 Mk4 RVs. Not all of the calculated patrol area may be available to an SSBN; it will depend upon average cruising speed.

# RVs (T-W)	**Range** *n.m.*	**SSBN patrol area** *million km^2*				
		SS-18: 3 Eastern sites		***SS-18: 3 Western sites***		***SS-19 sites***
		Atlantic	*Pacific*	*Atlantic*	*Pacific*	*Atlantic*
4 Mk5 (2,000 kg)	6,250 (153%)	45.6 (490%)	78.3 (233%)	(>400%)	67.8 (346%)	—
5 Mk5 (2,175 kg)	5,480 (134%)	26.7 (287%)	61.8 (184%)	43.8 (296%)	50.2 (256%)	—
6 Mk5 (2,350 kg)	4,920 (120%)	17.5 (188%)	50.1 (149%)	30.0 (203%)	38.2 (195%)	44.3 (163%)
7 Mk5 (2,525 kg)	4,470 (109%)	13.2 (142%)	41.6 (124%)	18.7 (126%)	27.6 (141%)	34.5 (127%)
8 Mk5 (2,700 kg)	4,100 (100%)	9.3 (100%)	33.6 (100%)	14.8 (100%)	19.6 (100%)	27.1 (100%)
2,800 kg	3,895 (95%)	7.0 (75%)	28.9 (86%)	12.6 (85%)	15.7 (80%)	22.8 (84%)
8 Mk21 (2,900 kg)	3,760 (92%)	5.7 (61%)	26.1 (78%)	10.9 (74%)	13.2 (67%)	20.5 (76%)

Table 12: Effect of propellant Isp on SSBN patrol area. The table assumes $\Delta I_{sp} = -10$ seconds for Class 1.3 propellants. Percentages are with respect to the "standard" D-5 with eight Mk5 RVs and a range of 4,100 n.m. These results are quite similar to those computed for a C-4 missile carrying eight Mk4 RVs and modified to use Class 1.3 propellants in the various missile stages.

Missile	**Range** *n.m.*	**SSBN patrol area** *million km^2*				
		SS-18: 3 Eastern sites		***SS-18: 3 Western sites***		***SS-19 sites***
		Atlantic	*Pacific*	*Atlantic*	*Pacific*	*Atlantic*
Standard D-5	4,100 (100%)	9.3 (100%)	33.6 (100%)	14.8 (100%)	19.6 (100%)	27.1 (100%)
Stage 3 Class 1.3	3,990 (97%)	8.1 (87%)	31.1 (93%)	13.6 (92%)	17.8 (91%)	24.5 (90%)
Stages 2 and 3 Class 1.3	3,750 (92%)	5.6 (60%)	25.8 (77%)	10.8 (73%)	12.9 (66%)	20.3 (75%)
All stages Class 1.3	3,525 (86%)	4.0 (43%)	21.0 (63%)	8.3 (56%)	8.7 (44%)	16.5 (61%)

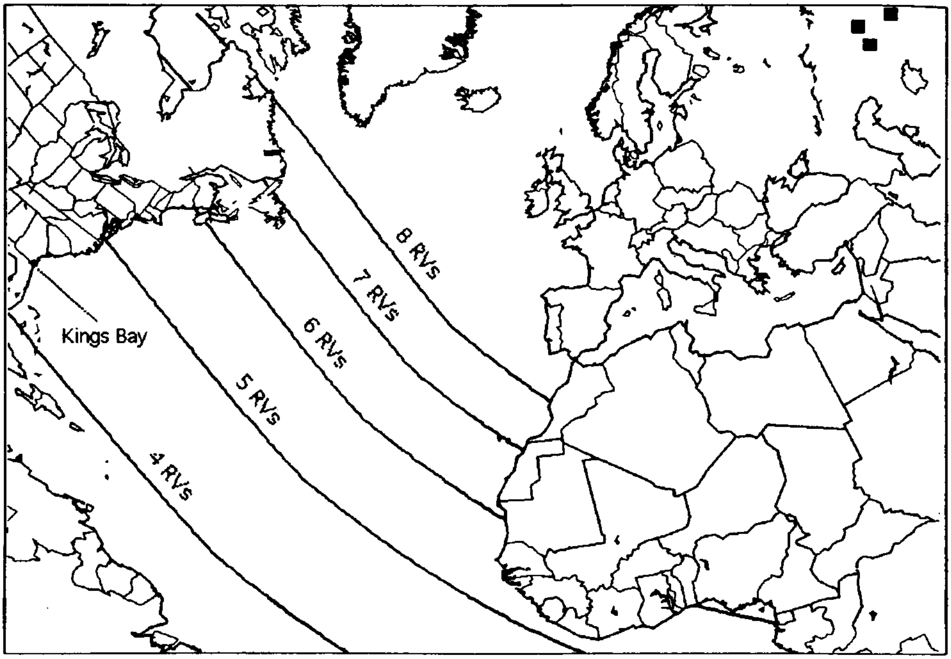

Figure 13a: Curves show the patrol area in the Atlantic and Pacific Oceans within range of all six SS-18 launch sites for a "standard" D-5 carrying the indicated number of Mk5 RVs. Only three launch sites are shown on each map; the scale is the same for both maps. The curves also apply to a "standard" C-4 missile carrying Mk4 RVs. For the Pacific, the five- and seven-knot (n.m. per hour) curves indicate the maximum distance an SSBN moving at those average speeds can travel from Silverdale during one-half of its 70-day patrol cycle. This gives a rough estimate of the fraction of the calculated patrol area that is accessible to an SSBN moving at those average speeds. The Albers projection (with two standard parallels) distorts geographical features, but depicts areas accurately.[71]

percent is based on the mesh size used, the exclusion of smaller islands, and inaccuracy caused by representing geographical features as finite polygons. For comparison, we note that the total area of the Earth's surface is 500×10^6 km^2, the area of the Earth's oceans is about 350×10^6 km^2, the land area of the U.S. is about 9.5×10^6 km^2, and the area of the state of Alaska is 1.5×10^6 km^2.

The patrol area in the Pacific that is accessible to Trident SSBNs depends on the average SSBN speed and the number of days on patrol. For a 70-day patrol, figures 13 and 14 show, for typical patrol speeds of 5 to 10 knots, the furthest distance that an SSBN can steam from port in 35 days. We see that an SSBN moving at an average speed of 7.5 knots can access nearly all of the calculated patrol area on a 70-day patrol. At five knots, it can access about one-half of patrol area. In the Atlantic, an SSBN moving at five knots can

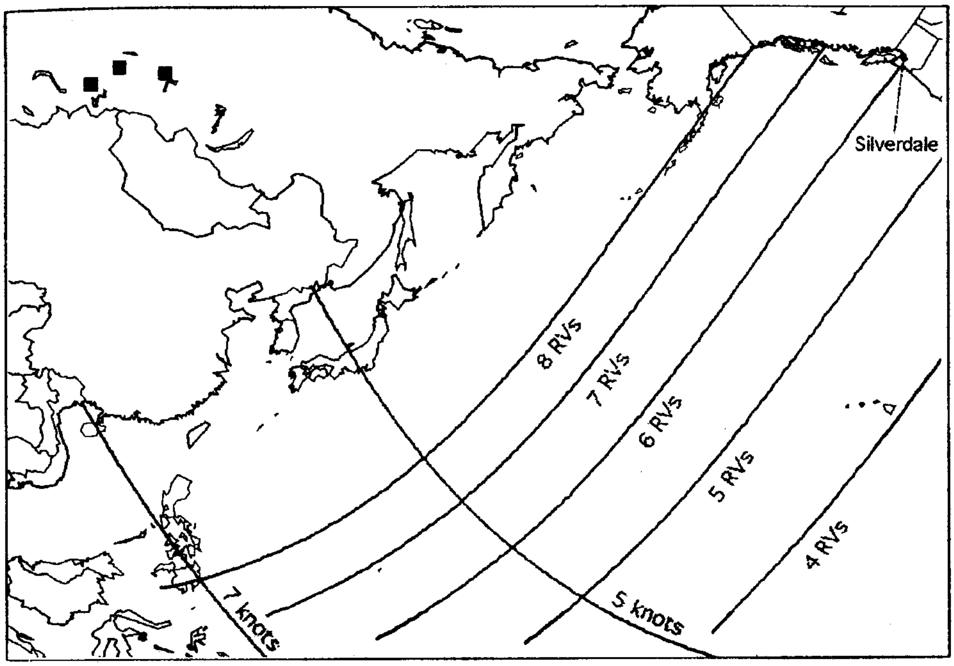

Figure 13b.

access all of the calculated patrol area.

SSBN Time On-Station

Any decrease in missile range necessitates additional steaming time before the submarine is on-station with respect to any particular set of targets. A typical Trident SSBN has a 95-day cycle in which it puts out to sea, steams to within range of its targets, carries out its operational patrol, returns to port where it is refurbished, refit, and made ready for sea. About 70 of the 95 days are spent at sea. To generate as little noise as possible and to allow the towable sonar array to operate at high efficiency, Trident SSBNs typically cruise at speeds in the range of five knots.

We define "on-station time" as the number of days at sea during which an SSBN is within range of its target set. This time depends on the range of the missile, the distance an SSBN must travel from port to the point where it is within range, and the speed with which it can travel without being detected. In general, an SSBN's "target package" is adjusted so that in the early stages of the patrol, it is given a more geographically accessible target set. Later on, when far from port, it can accept packages such as the SS-18 silos, located in more remote regions, further from the oceans. For this discussion, we consider

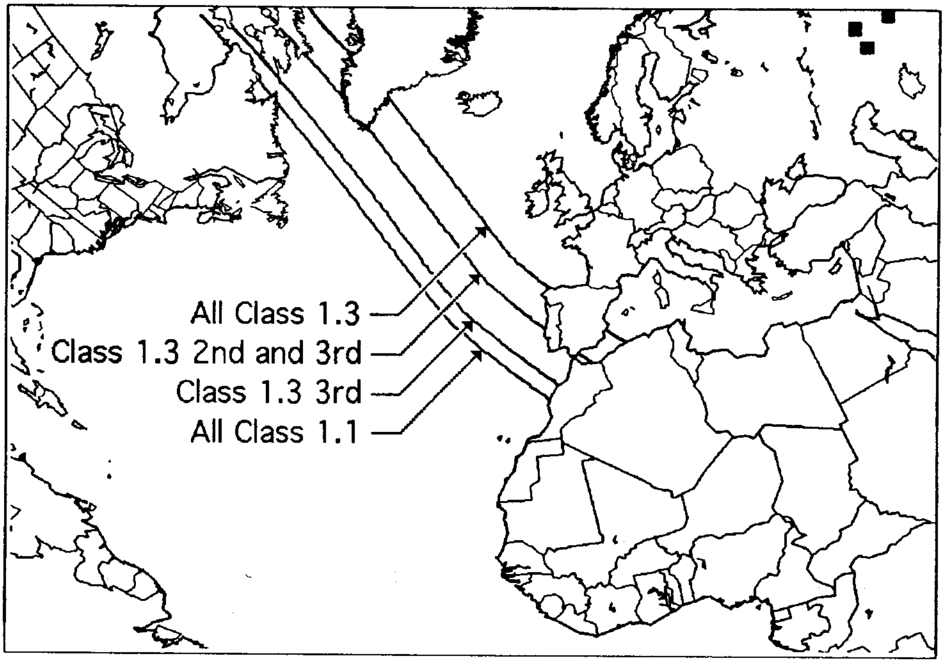

Figure 14a: The four curves show the patrol area in the Atlantic and Pacific Oceans within range of all six SS-18 launch sites for various missile configurations. The outermost curve corresponds to "standard" C-4 or D-5 missiles carrying eight RVs and having a nominal range of 4,100 n.m. The other curves represent D-5 missile configurations with Class 1.3 propellant in the third stage only, the second and third stages only, and all three stages that give range reductions, respectively, of 110 n.m., 350 n.m., and 575 n.m. The corresponding curves for C-4 nearly overlap those for D-5. The scale is the same for both maps.

only SS-18 targets; this assumption results in a conservative assessment of how missile range penalties affect on-station time.

In calculating on-station time, we first determine the range of a particular missile configuration. Second, we calculate the set of points in the Atlantic and Pacific Oceans (corrected for the Earth's rotation) from which a missile of that range could reach the third closest SS-18 base. For Tridents deployed from Silverdale or King's Bay, this base is usually Kartaly or Imeni Gastello, respectively. The third closest base is chosen because three SS-18 bases comprise roughly one-half of the force (75 to 150 silos), and, when an SSBN (carrying 100 to 200 RVs) first moves within range of a group of three, the number of targets and the number of warheads that can be devoted to those targets become comparable. Next, we determine the distance from the Trident base to the nearest point on the range contour, and add 20 percent to this number to take into account that an SSBN would not necessarily move in a straight line to that point. Finally, we calculate the number of days it would take an SSBN

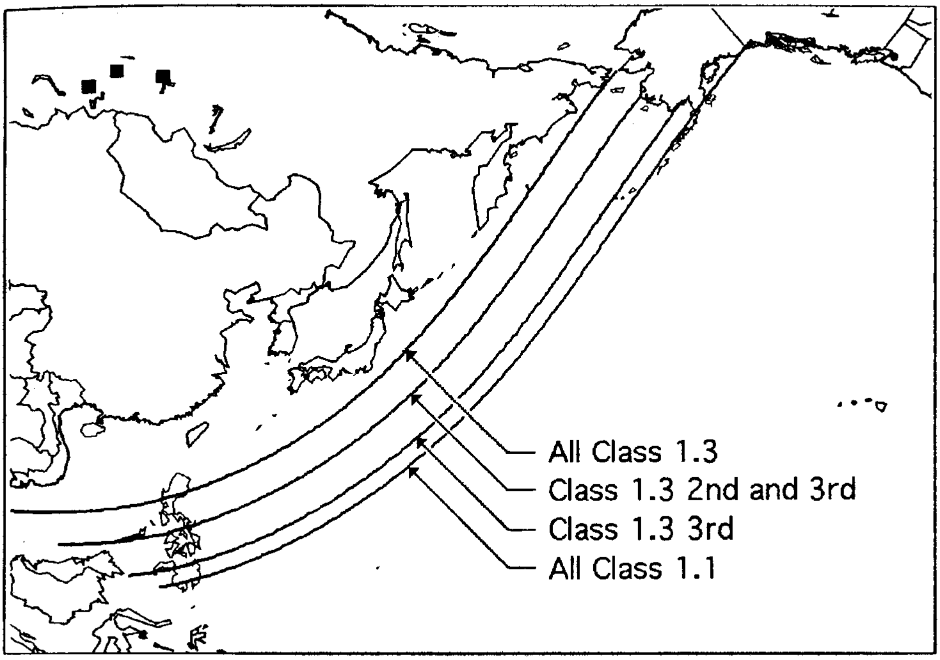

Figure 14b.

moving at a nominal speed of five knots to travel that distance. Doubling that time (to get round-trip transit time) and subtracting from an estimated total of 70 days at sea yields days on-station for the SS-18 target set.

Table 13 summarizes our results for various missile configurations. For the SS-18 mission, basing at Silverdale is generally more favorable than basing at King's Bay, with the difference varying from zero to 14 on-station days, depending on missile range. For missile range greater than 5,600 n.m., a maximum of 70 days on-station is achieved independent of base. For ranges between 5,300 to 5,600 n.m., the difference is less than six days. Between 4,100 and 4,500 n.m., the advantage is significant: SSBNs based at Silverdale can be on-station an additional two weeks (of 10 total weeks at sea) in comparison with identically configured SSBNs based at King's Bay. As missile range falls below 4,000 n.m., however, Silverdale basing has only three to four days of on-station advantage over King's Bay.[73]

We tested the sensitivity of our results to SSBN transit speed. By doubling transit speed to 10 knots, transit time is halved and days on-station increase correspondingly, with the greater increases associated with the longer steaming distances. For basing at Silverdale, the days on-station corresponding to the above missile configurations range from a maximum again of 70 days, a

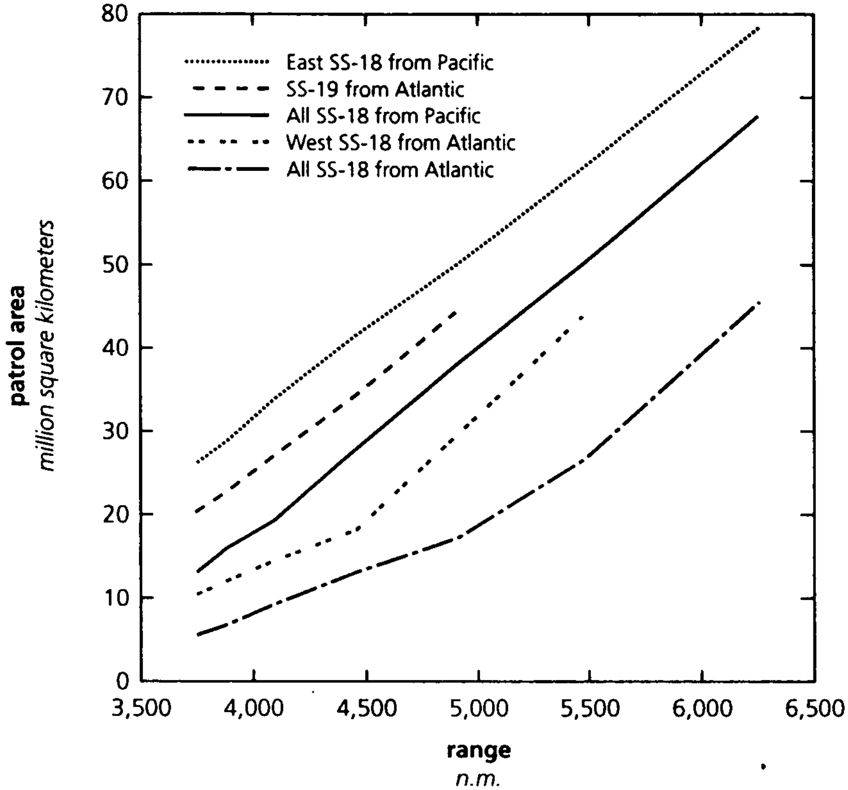

Figure 15: Submarine patrol area versus missile range. Each curve is labeled with the ocean in which an SSBN is cruising and a target set. For example, the curve "East SS-18 from Pacific" represents the patrol area in the Pacific that is within range of the three eastern-most SS-18 silo deployment areas. Correction for the Earth's rotation has been applied.

nominal 61 days for 4,100-n.m. range, and a minimum of 43 days. For King's Bay, the corresponding numbers are a maximum of 70 days, a nominal 53 days, and a minimum of 41 days. Thus, for certain configurations, significant increases in on-station time can be achieved by increasing SSBN transit speed.

Table 13: For several C-4 and D-5 missile configurations, this table gives the range and the number of days at sea, out of a maximum of 70, that an SSBN deployed from Silverdale, WA, or King's Bay, GA, is within range of the three closest SS-18 launch sites.[a]

		Silverdale, WA		King's Bay, GA	
C-4 or D-5 missile configuration	**Missile range** *n.m.*	**Steaming distance** *n.m.*	**Days on-station**	**Steaming distance** *n.m.*	**Days on-station**
Baseline-START I					
D-5 w/8 Mk5, C-4 w/8 Mk4	4,100	970	50.6	1,680	36.4
D-5 w/8 Mk21	3,760	1,860	32.8	2,040	29.3
D-5 w/8 Mk4	5,930	0	70.0	0	70.0
Baseline-START II					
D-5 w/4 Mk5, C-4 w/4 Mk4	≈ 6,250	0	70.0	0	70.0
D-5 w/4 Mk4	> 6,500	0	70.0	0	70.0
Shock mitigation[b]					
D-5 w/8 Mk5	3,760	1,860	32.8	2,040	29.3
D-5 w/8 Mk4	5,180	0	70.0	460	60.8
D-5 w/Class 1.3 third stage					
8 Mk5	3,990	1,630	37.5	1,800	34.0
8 Mk4	5,690	0	70.0	0	70.0
4 Mk 5	5,950	0	70.0	0	70.0
C-4 w/Class 1.3 third stage					
8 Mk4	3,940	1,680	36.5	1,850	33.0
4 Mk4	5,910	0	70.0	0	70.0
Eliminate third stage					
C-4 w/ 8 Mk4	2,920	2,740	15.2	~2,900	12.0
D-5 w/ 8 Mk21	3,130	2,530	19.4	~2,690	16.2
D-5 w/ 8 Mk5	3,360	2,300	24.0	~2,460	20.8
C-4 w/ 4 Mk4	3,770	1,850	33.0	2,030	29.4
D-5 w/ 4 Mk21	4,280	790	54.2	1,500	40.0
D-5 w/ 8 Mk4	4,360	710	55.8	1,420	41.6
D-5 w/ 4 Mk5	4,500	570	58.6	1,280	44.4
D-5 w/ 4 Mk4	5,350	0	70.0	290	64.2

[a] The steaming distance is the shortest distance an SSBN must travel to come within range of its targets. To obtain SSBN transit time, the steaming distance is increased by 20 percent and then divided by SSBN patrol speed, assumed to be five knots.

[b] Shock mitigation ≈ 25 kg/RV.

Summary of Results

- Significant increases in range result when RVs are offloaded. The C-4 and D-5 missiles deployed, respectively, with four Mk4 and four Mk5 RVs, can reach targets at ranges greater than 6,000 n.m.
- Several START II options with four RVs per missile would permit SSBNs to patrol within reach of distant SS-18 targets for their entire 70-day patrol cycle.
- Decreases in missile range result in proportionally much greater decreases in patrol area: for example, a 5 percent reduction in range produces a 25 percent decrease in the amount of patrol area that is available to a King's Bay-based SSBN targeting the most distant SS-18 silos.
- For basing at Silverdale, there can be a sharp drop-off in on-station rate for relatively small decreases in missile range below 4,100 n.m. This drop-off does not apply to basing at King's Bay.
- Using Class 1.3 propellant in C-4 or D-5 third stages would give a 3 to 4 percent decrease in range, and typically an 8 to 13 percent reduction in patrol area. Offloading one of the eight RVs would recover all the lost range.
- Missiles with no third stages have significant range, patrol area, and on-station rate penalties unless RVs are offloaded. For a modified D-5 with no third stage and eight Mk5 RVs, the range penalty would be about 20 percent; the reduction in patrol area would be between 50 and 75 percent. The nominal range of 4,100 n.m. could be recovered by offloading three Mk5s. Such a system could deliver eight Mk4 RVs to a range in excess of 4,100 n.m.
- For a modified C-4 with no third stage, offloading five of eight Mk4 RVs would be required to reach 4,100-n.m. range. Thus, a "no-third-stage" option may be less desirable for C-4 than for D-5.
- In general, SS-18 launch sites are much more accessible from the Pacific than from the Atlantic. Other key installations in the European part of the former Soviet Union, however, are more accessible from the Atlantic.

V. OPTIONS FOR MODIFYING TRIDENT MISSILES AND WARHEADS

Safety-related modifications to C-4 and D-5, possibly including redesigned stages, new warheads, and new RVs, will affect Trident program cost and schedule. A preliminary cost analysis is developed below, but caution must be exercised in its interpretation. Our estimates may be closer to "factor of two," rather than "10 percent," estimates and should be helpful primarily in comparing the different options.

Developing a New Third Stage and Other Missile Modifications

Incorporating Class 1.3 propellant in the third stage would require a research and development program, including ground and flight testing, to formulate a new propellant with the desired properties, develop a redesigned stage, and assure its compatibility with the rest of the missile. The cost of the program would be in the range of $250 to $500 million, plus 5 to 15 flight tests at about $30 million each. To complete development and begin production could take three to five years. Unit procurement cost for a new third stage (not counting research and development) would be about $0.7 million.[74]

An alternative approach would be to eliminate C-4 or D-5 third stages, creating a clear-deck configuration.[75] A substantial range penalty would be incurred unless RVs were offloaded. A development program to eliminate a third stage, however, could be more complex then one might think. With its third stage removed and fewer RVs, an SLBM would accelerate more rapidly through the lower atmosphere and thus would experience higher dynamic pressures and drag loads. The missile's center of mass would also be different, altering flight characteristics and requiring changes to the flight control system. The current through-deck third stage provides structural support for the front end, so alternative support structures would be needed. A development program would have to establish that resulting modifications did not unacceptably degrade SLBM performance and reliability. We estimate that a two- to four-year development program costing $500 million and five flight tests could establish feasibility of eliminating a third stage. Procurement costs estimated at $0.5 million per missile would be required for hardware and other modifications.

Rather than eliminating third stages, minimal changes to existing missiles could be achieved by replacing active with inert propellant in C-4 and D-5 third stages. Some savings might result because all the missile flyout characteristics and mass properties would be the same through second-stage flight. This, however, is likely to be unacceptable in view of the dramatic range and RV footprint penalties that result, even when four RVs are offloaded.

Developing a New Nuclear Warhead

Developing a new warhead typically requires a five-year research and development effort, at a cost of $500 to $750 million. To meet an urgent need, however, an accelerated program could complete development in a shorter period, perhaps three years. Both nonnuclear high-explosives testing and three to five developmental nuclear tests would be required. If an existing IHE warhead could be adapted, research and development costs would be lower, as would nuclear test requirements. Much of the development for the W89, for example, which was intended for the recently canceled SRAM II, has been completed. Perhaps another $200 million would be required to complete its development for use in a strategic RV, such as Mk5. An IHE warhead compatible with the Mk4 would likely require a new development program because existing warheads of the appropriate size and weight are not available.

Unit warhead procurement costs would be about $0.5 million. This estimate includes costs of retooling, labor, and materials. Producing new warheads, however, requires a functioning DOE manufacturing complex, and unless plutonium pits were recycled from retired warheads, the Rocky Flats plutonium parts fabrication facility would need to be repaired or replaced.[76]

Developing a New RV

If a new IHE warhead is not compatible with an existing RV, then a development program would be required that would take three to five years and include 5 to 10 flight tests. Total development cost would be in the range of one to two billion dollars. The unit procurement cost of a new RV and associated nonnuclear components would be about $0.2 million. None of the options examined below would require new RV development.

Options for Modifying Trident SLBMs

Because Trident will be the mainstay of the U.S. nuclear deterrent force well into the next century, it is important to evaluate the costs and benefits of various alternatives for enhanced safety. Of the specific options developed below, the current C-4 and D-5 programs are included as the baseline approach. All options retain the current first two stages of each missile, which use Class 1.1 propellant.[77]

Option 1: No Change to Existing SLBM Systems (Baseline)

The baseline case assumes that eight Trident SSBNs, each with 24 C-4 SLBMs, are based at Silverdale, and 10 boats, each with 24 D-5s, are eventually based at King's Bay, all operating at current alert rates. Increments in cost and schedule from this baseline are calculated for the remaining options.

Option 2: Deploy Current C-4 and D-5 SLBMs with IHE RVs

Option 2 would make no changes to existing SLBMs, but would field two IHE warheads with fire resistant pits compatible with the Mk4 and Mk5. C-4 and D-5 missiles would be deployed with four or eight RVs each, resulting in a Trident force of 1,750 or 3,500 IHE RVs.

Option 3: Deploy Current C-4 and D-5 SLBMs with IHE and Shock Mitigation

This approach would depend on the feasibility of installing shock-absorbing materials between the RVs and the third stage to cushion an IHE warhead and prevent sympathetic detonation in a booster accident.[78]

Option 4: Develop New C-4 and D-5 Third Stages with Class 1.3 Propellant

New third stages with Class 1.3 propellant would be installed on modified C-4 and D-5 SLBMs. Existing (nonIHE) W76 and W88 warheads would be used.

Option 5: New Class 1.3 Third Stages for C-4 and D-5 and IHE RVs

This option combines new warheads incorporating IHE and FRPs with new third stages having Class 1.3 propellant. It would give increased dispersal safety in fire and impact accidents. The risk of inadvertent nuclear yield would probably be at the lowest practical level.

Option 6: Modified Missiles with Third Stages Eliminated

SLBM third stages would be eliminated, creating a clear-deck configuration. Existing Mk4 and Mk5 RVs could be retained with HE warheads or replaced with IHE warheads. Substantial range penalties would apply, except for D-5s with eight Mk4s, or downloaded Mk5s.

Option 7: All Modified D-5 force with Class 1.3 Third Stages and Offloaded IHE RVs

This is a variant of Option 5, offered for cost comparison. It entails developing a new Class 1.3 third stage for D-5, backfitting the C-4 boats at Silverdale with modified D-5s, and deploying IHE warheads in Mk4 and Mk5 RVs.

Evaluating the Options

Table 14 summarizes each option in terms of the number of SSBNs carrying each missile type, the types and numbers of RVs, and the differences in cost and schedule referenced to the baseline case. Incremental costs range from $1.8 billion to $5.0 billion, and time required to complete development and begin first production ranges from two to five years.

We draw upon the analysis of Section IV to assess the operational impacts of each of the options. Because system capability was evaluated against the more demanding SS-18 target set, we examine the D-5 variants for each option. Because it is more accurate, the D-5 missile, deployed with either Mk4 or Mk5 RVs, is much more likely than C-4 to be allocated to the hard-target mission.

For each D-5 option, table 15 gives the range, patrol area, on-station time, hard-target kill, and prompt hard-target kill capability. The last two columns are figures of merit related to the ability of a D-5 variant, on patrol in the Atlantic, to destroy hard targets. The column "Hard targets killed per SLBM" gives the expected number of SS-18s destroyed by a D-5 on patrol. This number is a function of the number of RVs per missile, warhead yield, D-5 accuracy (assumed 0.075 n.m.), system reliability (assumed 0.9), and target hardness (assumed 5,000 psi). We assume that one Trident warhead is devoted to each target. The column "Prompt hard targets killed per SLBM" gives the expected number of targets destroyed per missile within a short period after a launch order is received. This figure of merit is for day-to-day alert conditions and is obtained by multiplying the expected number of hard targets killed per SLBM by the probability that an SLBM is available and within range of its targets.[79]

From our summary of options, we make the following conclusions:

- Very substantial increases in range, patrol area, and on-station rate above the baseline case (4,100-n.m. range) are obtained for D-5 missiles deployed with four Mk4 or four Mk5 RVs, or with eight Mk4s.

- The expected number of hard targets destroyed clearly declines for D-5s deployed with four rather than eight RVs, or with RVs of lower yield. It is, however, quite interesting that the expected number killed promptly (a key criterion for the Cold-War Trident) is relatively insensitive to whether eight Mk5s or eight Mk4s are deployed per missile, or whether eight or four Mk5s are deployed per missile. The decreased yield in the former case, and the decreased number of RVs in the latter, is roughly compensated by the increased number of days on-station available to the lighter-throw-weight, longer-range variants.

- If shock mitigation is feasible for C-4 and D-5, then Option 3 is a relatively low-cost approach to enhanced missile system and nuclear warhead safety.

- Options 5 and 6, in which a Class 1.3 third stage, or no third stage, is combined with IHE warheads, are of roughly the same cost, and perhaps have comparably enhanced safety. A downloaded missile with no third stage, however, would be less responsive to a START II treaty breakout (possibly including increased enemy ASW activity) than a missile with a third stage.

- Option 7 differs from Option 5 only in that it would involve backfitting the C-4 boats at Silverdale with D-5. Given our assumptions, Option 7 is lower cost because only one Class 1.3 third-stage development program would be needed.

- An all-D-5 force may be of interest for reasons other than the lower cost of fielding a force with Class 1.3 third stages. First, shock mitigation may be more feasible for D-5 deployed with the smaller Mk4 RV because of the extra room (and weight) available for absorbing materials. Second, a "no-third-stage" option may be implemented with a smaller range penalty for a given number of RVs. Third, enhanced capability against SS-18 or similar hard targets in south central Asia could be achieved by deploying D-5 boats in the Pacific.

Evaluating the Options

Table 14 summarizes each option in terms of the number of SSBNs carrying each missile type, the types and numbers of RVs, and the differences in cost and schedule referenced to the baseline case. Incremental costs range from $1.8 billion to $5.0 billion, and time required to complete development and begin first production ranges from two to five years.

We draw upon the analysis of Section IV to assess the operational impacts of each of the options. Because system capability was evaluated against the more demanding SS-18 target set, we examine the D-5 variants for each option. Because it is more accurate, the D-5 missile, deployed with either Mk4 or Mk5 RVs, is much more likely than C-4 to be allocated to the hard-target mission.

For each D-5 option, table 15 gives the range, patrol area, on-station time, hard-target kill, and prompt hard-target kill capability. The last two columns are figures of merit related to the ability of a D-5 variant, on patrol in the Atlantic, to destroy hard targets. The column "Hard targets killed per SLBM" gives the expected number of SS-18s destroyed by a D-5 on patrol. This number is a function of the number of RVs per missile, warhead yield, D-5 accuracy (assumed 0.075 n.m.), system reliability (assumed 0.9), and target hardness (assumed 5,000 psi). We assume that one Trident warhead is devoted to each target. The column "Prompt hard targets killed per SLBM" gives the expected number of targets destroyed per missile within a short period after a launch order is received. This figure of merit is for day-to-day alert conditions and is obtained by multiplying the expected number of hard targets killed per SLBM by the probability that an SLBM is available and within range of its targets.[79]

From our summary of options, we make the following conclusions:

- Very substantial increases in range, patrol area, and on-station rate above the baseline case (4,100-n.m. range) are obtained for D-5 missiles deployed with four Mk4 or four Mk5 RVs, or with eight Mk4s.
- The expected number of hard targets destroyed clearly declines for D-5s deployed with four rather than eight RVs, or with RVs of lower yield. It is, however, quite interesting that the expected number killed promptly (a key criterion for the Cold-War Trident) is relatively insensitive to whether eight Mk5s or eight Mk4s are deployed per missile, or whether eight or four Mk5s are deployed per missile. The decreased yield in the former case, and the decreased number of RVs in the latter, is roughly compensated by the increased number of days on-station available to the lighter-throw-weight, longer-range variants.

Table 14: Summary of Trident options and their cost and schedule impacts. For numbers separated by a comma, the first number corresponds to a START I assumption of eight RVs per missile; the second corresponds to a START II assumption of four RVs per missile.

Option	**Description**	**Number of SSBNS**	**Missile**	**Number of RVs/missile**	**Number of RVs**	**Δ Cost** *$ billion*	**Δ Time** *years*
1	Baseline (START I, II)	2, 4	D-5	8, 4 Mk5/W88	400, 400	nominal	nominal
		8, 6	D-5	8, 4 Mk4/W76	1600, 600		
		8	C-4	8, 4 Mk4/W76	1600, 800		
2	Baseline + IHE	9	D-5	8, 4 Mk5/IHE	1800, 900	3.1, 2.0	3–5
		1	D-5	8, 4 Mk4/IHE	200, 100		
		8	C-4	8 ,4 Mk4/IHE	1600, 800		
3	Shock Mitigation +IHE	10	D-5	8, 4 Mk4/IHE	2000, 1000	3.2, 2.1	3–5
		8	C-4	8, 4 Mk4/IHE	1600, 800		
4	Class 1.3 third stage + HE	2, 4	D-5 (mod)	8, 4 Mk5/W88	400, 400	1.8, 1.8	3–5
		8, 6	D-5 (mod)	8, 4 Mk4/W76	1600, 600		
		8	C-4 (mod)	8, 4 Mk4/W76	1600, 800		
5	Class 1.3 third stage + IHE	9	D-5 (mod)	8, 4 Mk5/IHE	1800, 900	4.9, 3.8	3–5
		1	D-5 (mod)	8, 4 Mk4/IHE	200, 100		
		8	C-4 (mod)	8 Mk4/IHE	1600, 800		
6	No third stage + IHE	9	D-5 (mod)	8, 4 Mk5/IHE	1800, 900	4.7, 3.6	3–5
		1	D-5 (mod)	8, 4 Mk4/IHE	200, 100		
		8	C-4 (mod)	8, 4 Mk4/IHE	1600, 800		
	(HE warheads)			(HE RVs)	(3600, 1800)	(1.6, 1.6)	(2–4)
7	All D-5 force	9	D-5 (mod)	8, 4 Mk5/IHE	1800, 900	4.1, 3.0	3–5
	class 1.3 third stage + IHE	9	D-5 (mod)	8, 4 Mk4/IHE	1800, 900		

Table 15: Summary of operational impacts of options for modifying D-5 SLBMs for enhanced safety. The patrol area and on-station rate is given for SSBNs operating in the Atlantic within range of the three westernmost SS-18 launch sites. Heating loads generated during reentry may exceed the capabilities of existing SLBM RV designs for ranges exceeding 6,500 n.m. The expected number of hard targets killed per survivable (i.e., at sea) D-5 SLBM, and the expected number killed *promptly*, are given for each option. See text for details.

D-5 option		**RV yield** *kilotons*	**Range** *n.m.*	**Patrol area (Atlantic)** *million sq. km*	**On-station (Atlantic)** *days*	**Hard targets killed per SLBM**	**Prompt hard targets killed per SLBM**
1	Baseline D-5:						
	8, 4 Mk5/W88	450	4,100; 6,220	14.8, 62.2	36.4, 70.0	5.7, 2.8	1.9, 1.9
	8, 4 Mk4/W76	100	5,930, > 6,500	55.2, >70.0	70.0, 70.0	3.1, 1.6	2.0, 1.0
2	Baseline + IHE:						
	8, 4 Mk5/IHE	350	4,100; 6,220	14.8, 62.2	36.4, 70.0	5.3, 2.6	1.8, 1.7
	8, 4 Mk4/IHE	80	5,930, > 6,500	55.2, >70.0	70.0, 70.0	2.7, 1.4	1.8, 0.9
3	Shock mitigation						
	8, 4 Mk4/IHE	80	5,180, > 6,500	36.6, >70.0	60.8, 70.0	2.7, 1.4	1.6, 0.9
4	1.3 3rd stage + HE:						
	8, 4 Mk5/W88	450	3,990; 5,950	13.6, 55.6	34.0, 70.0	5.7, 2.8	1.8, 1.9
	8, 4 Mk4/W76	100	5,690, > 6,500	49.1, >70.0	70.0, 70.0	3.1, 1.6	2.0, 1.0
5	1.3 3rd stage+IHE:						
(&7)	8, 4 Mk5/IHE	350	3,990; 5,950	13.6, 55.6	34.0, 70.0	5.3, 2.6	1.7, 1.7
	8, 4 Mk4/IHE	80	5,690, > 6,500	49.1, >70.0	70.0, 70.0	2.7, 1.4	1.8, 0.9
6	No third stage:						
	8, 4 Mk5/IHE	350	3,360; 4,500	6.6, 19.2	20.8, 44.4	5.3, 2.6	1.1, 1.1
	8, 4 Mk4/IHE	80	4,360; 5,350	17.6, 41.0	41.6, 64.2	2.7, 1.4	1.1, 0.8
	8, 4 Mk21/W87	300	3,130; 4,280	4.7, 16.8	16.2, 40.0	5.0, 2.5	0.8, 0.9

Should Trident be Made Safer?

Does it make sense to spend money on safety modifications for Trident? An elementary exercise in risk analysis can shed some light on the answer. For any potential hazard, the following mathematical relationship expresses a common sense notion of when it is wise to invest in eliminating risk:

$V_{\text{fix}} = C \cdot P_{\text{A}}$ where,
V_{fix} = the appropriate amount to invest to significantly reduce risk,
C = cost of accident that is to be prevented,
P_{A} = probability of a serious accident if nothing is done.

For Trident, we have shown that V_{fix} is in the range of $1 to 5 billion. We cannot compute the likelihood of an accident that results in plutonium dispersal, but we can bracket the range of probabilities that correspond to a prudent safety investment by considering the range of conceivable costs of an accident. A number of factors go into this evaluation including: the direct loss of human life, the indirect loss of life (i.e., the value of a person's life to friends and family), property value loss, clean-up and litigation costs, tangible and intangible losses to the communities affected, and the cost of the Trident system itself including, if Trident operations were shut down after an accident, the associated decrease in strategic deterrence value.

Let's assume a near worst case dispersal accident at Silverdale or King's Bay involving 1,000 latent cancer fatalities. Risk analysts often assign a dollar value to accidental death based on a person's willingness to pay a given amount to reduce risk. Studies demonstrate that a value in the range of $1 to 10 million per life saved is not unreasonable.[80] Clean-up and other litigation costs could range from $5 to 20 billion. A sufficiently serious accident could lead to termination of the Trident program; assuming a Trident lifecycle cost of $150 billion, such an accident would produce an expected loss in program value of $75 billion, one half of a system lifetime. A lower bound program value loss of $7.5 billion results by assuming a 10 percent probability that an accident would end the program. By summing these contributions, we estimate the cost of a serious accident in an urban area to be in the range of $15 to 100 billion. Then, from our simple equation, an expenditure of $3 billion (in the midrange of $1 to 5 billion) to reduce risk would be reasonable if accident probabilities were in the range of 0.03 to 0.20.

Another way to view this problem is to consider that the risk of nuclear war could increase if the Trident program, our most survivable strategic system, was shut down after a major accident. Although we believe nuclear war is very unlikely, and was even unlikely during the Cold War, its consequences are sufficiently catastrophic that an investment to increase Trident safety may be justified. Indeed, the probability of nuclear war was deemed sufficiently high during the Cold War to warrant the original Trident investment.

It is straightforward to show that an appropriate investment in safety in order to avoid the increased risk of war associated with termination of the Trident program is:

$V_{\text{fix}} \leq P_{\text{A}} \cdot P_{\text{L}} \cdot V_{\text{d}}$ where
V_{fix} = cost to enhance safety ($\approx$ \$1–5 billion)
P_{A} = probability of a dispersal accident
P_{L} = probability that Trident operations are terminated after a major accident
V_{d} = lifecycle cost to deploy Trident $\approx$ \$150 billion.[81]

In this case, a \$3 billion investment in safety would make sense if one believed that the probability of a major dispersal accident leading to program termination was 0.02 or greater over a 30 year Trident system lifetime.

Needless to say, the above analysis is merely a "back of the envelope" estimate. It assumes, for example, that a few billion dollars would significantly reduce accident probability. Nor does it take into account that the "original" Trident lifecycle cost may not, in the post Cold War period, be the most appropriate baseline for calculating additional safety investment. Still, it suggests that if one believes that the probability of an accident over a 30 year program lifetime is of order 0.01 to 0.10, than an expenditure of a few billion dollars to increase safety is not out of line with reasonable estimates of the consequences of potential accidents.

CONCLUSIONS AND RECOMMENDATIONS

The signing and ratification of START I, and the recent signing of START II, offer new opportunities for enhancing safety and security of remaining American strategic forces. First, the deep cuts in numbers of warheads (and targets) under START II, and the likely offloading of four warheads from each Trident SLBM, permit safety-related modifications to be made without range penalties or other operational impacts. Second, the deep cuts will save money, a portion of which could be devoted to enhanced safety and security of remaining forces. Third, with the end of the Cold War, deploying new systems, such as Trident, is now less urgent, and some delay in program completion is acceptable. Finally, implementing safety-related modifications will, as a by-product, assist in maintaining core competence in nuclear warhead design, development, and manufacturing, and in solid-propellant missile systems. Keeping design and manufacturing teams engaged in these activities will assist in retaining critical capabilities in the U.S. defense R&D and industrial base.

We believe that the Navy and DOE labs should examine and, if appropriate, vigorously pursue enhanced safety for Trident. Modifications should be considered for both missiles and warheads. Although we cannot definitively identify the best option for modifying Trident SLBMs, we recommend that special attention should be focused on three options:

- IHE warheads and shock mitigation for D-5.
- Modified missiles with new Class 1.3 third stages and four to eight IHE RVs.
- Modified missiles with no third stages and offloaded IHE RVs.

We recommend that the DOD and DOE should join in developing and fielding safer nuclear warheads for Trident, regardless of whether missiles are modified. "Safer" means, at a minimum, that the design include insensitive high explosive (IHE), a fire-resistant pit, and an electrical system with enhanced nuclear detonation safety, or achieve equivalent safety features from other approaches. New warhead development will require some of the 15 safety-related nuclear tests provided under current law.

The consequences of an accident involving even very small *nuclear* yield would be enormous, almost certainly leading to suspension or termination of the Trident program. Thus, a comprehensive evaluation of Trident hazards must include continued analysis of this remote possibility.

If a decision is made to go ahead with safety modifications, it is absolutely critical that sufficient funding be allocated. Attempts to cut corners to save money may result in a system that is less safe than the existing one. Sometime in the next century, if Trident is replaced by a next-generation SLBM, strong consideration should be given to deploying a system with safe warheads and nondetonable propellant in all stages.

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Of course, an individual's willingness to read our drafts, or otherwise offer comments and criticism, should not be construed as an endorsement of our work.

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NOTES AND REFERENCES

1. This article is a condensed version of the full report, "Nuclear Weapons Safety and Trident: Issues and Options," John R. Harvey and Stefan Michalowski, Center for International Security and Arms Control, Stanford University, August 1993.

2. Each MX carries ten high-yield warheads and has a reported accuracy of less than 400 feet.

3. The D-5 SLBM was also designed to carry 12 Mk4 RVs.

4. The C-4 was initially designed for the smaller-volume launch tubes of the Poseidon SSBNs, but was later redeployed on Ohio-class SSBNs. In anticipation of D-5, these boats were designed with launch tubes that could accommodate a larger missile than C-4. The original design, introduced in the Carter administration, called for the D-5 to have a greater range than the C-4 for improved submarine survivability. This would be at the expense of hard-target kill capability. Later, in the Reagan administration, the priority for hard-target kill was increased, leading to a requirement for higher-yield warheads and enhanced accuracy, which led to greater throw-weight and decreased

range. William Perry, private communication.

5. Retirement is indeed moving rapidly. By early 1993, all Lafayette-class submarines deployed with C-3 had been withdrawn from service. Approximately seven are currently deployed with C-4. Two Lafayette boats may be converted for special operations as swimmer delivery vehicles.

6. A decision has been made to defer the retrofit with D-5 missiles of the Trident SSBNs based at Silverdale, at least for the near future, although the Navy still wants D-5 on the Pacific boats. Thus, the Silverdale facility will not at this time be upgraded to handle the D-5. See Bruce W. MacDonald, "The Emerging Consensus on Strategic Modernization," *Arms Control Today* (July/August 1991), p. 11; and *Aviation Week and Space Technology* (18 March 1991), p. 48.

7. Strategic warheads are those nuclear weapons deployed on heavy bombers—air-launched cruise missiles (ALCMs), gravity bombs, and short-range attack missiles (SRAMs), intercontinental ballistic missiles (ICBMs), and submarine-launched ballistic missiles (SLBMs).

8. See "Remarks by President Bush on Reducing U.S. and Soviet Nuclear Weapons," *New York Times*, 28 September 1991.

9. In January 1992, President Bush ordered a halt to the production of the W88 warhead for D-5, but the extended shutdown of Rocky Flats, and the resulting inability to produce plutonium parts for the W88, in essence rendered that decision moot. Prior to the halt, there were about 400 W88 warheads in inventory, enough for two Trident D-5 boatloads assuming eight warheads per missile. The remaining D-5s will carry W76 warheads. See also footnote 12.

10. See Robert Holzer and George Leopold, "U.S. Navy Mulls Retirement of Trident Subs," *Defense News* 8 (7), 22–28 February 1993. See also "Reducing the Deficit: Spending and Revenue Options," U.S. Congress, Congressional Budget Office (Washington DC: U.S. Congressional Printing Office, February 1993), pp. 30–33. Earlier, Senator Bumpers had called for a halt to production of the D-5 missile, but his proposal did not gain widespread support; see Bert Robinson, "Lockheed's Trident II Faces Vote," *San Jose Mercury News*, 22 July 1992.

11. See, for example, T. Reed and M. Wheeler, "The Role of Nuclear Weapons in the New World Order" (Arlington, Virginia: System Planning Corporation, December 1991). Elements of START II are consistent with a recent report of the National Academy of Sciences. That study recommended, under future agreements that might bring total warhead numbers to 3,000 to 4,000, or even less, and barring an unforeseen increase in submarine vulnerability, that SLBMs carry approximately one half of all strategic warheads. See *The Future of the U.S.–Soviet Nuclear Relationship*, Committee on International Security and Arms Control (Washington DC: National Academy Press, 1991), p. 32. See also "Rethinking the Trident Force," Congress of the United States, U.S. Congressional Budget Office (Washington DC: U.S. Government Printing Office, July 1993).

12. This is outlined in two memoranda (see note 9 of "Nuclear Weapons Safety," Report of the Panel on Nuclear Weapons Safety of the Committee on Armed Services, House of Representatives, December 1990. On 28 April 1983, then Assistant to the Secretary of Defense for Atomic Energy [ATSD(AE)] Richard Wagner wrote: "In most of the newer nuclear weapons we are using this insensitive high explosive and, where appropriate, plan to retrofit older nuclear warheads in the stockpile with IHE . . . the DOD policy for new nuclear weapon development is that IHE will be used unless the

Military Department responsible for the nuclear weapon development requests an exception from USDRE (Under Secretary of Defense for Research and Engineering) through the ATSD(AE). Such requests will be considered favorably where the military capability of the system clearly and significantly would be degraded by the incorporation of IHE." The then Director of Military Application in DOE, Major General William Hoover, wrote: "Based on this policy, we should expect IHE to be included in the draft Military Characteristics for most new systems. It is our intention to support these requirements whenever feasible." Earlier, on 17 May 1978, the Senate Armed Services Committee under Chairman John Stennis "strongly recommended" that "IHE be applied to all future nuclear weapons, be they for strategic or theater forces." See U.S. Senate Report No. 95-961; p. 10. More recently, the DOE has issued guidelines that require "positive measures to prevent plutonium dispersal in nuclear weapons" and the DOD reaffirmed its policy on IHE and added language urging that fire resistant pit technology be implemented, wherever feasible, in new or retrofitted warheads. See W. Bookless, "Nuclear Weapons Safety," *Energy and Technology Review*, Lawrence Livermore National Laboratory, UCRL-5200-92-1/2 (January/February 1992).

13. See Letter to Les Aspin, Chairman, House Armed Services Committee, from Sidney Drell, John Foster, and Charles Townes, dated 15 November 1991. Congress has appropriated $15 million per year for FY 1992–94 to support Navy studies of solid rocket motor detonation phenomenology including: (1) experiments and calculations to understand the behavior of the D-5 third-stage motor in accident environments, (2) experiments to understand the shock initiation of HE and IHE in motor detonations, (3) measurement of propellant ignition and detonation thresholds, (4) fault-tree analyses of D-5 logistics and handling operations, and (5) manufacturing and deployment advantages of Class 1.1 versus Class 1.3 propellants.

14. Due to its mechanical resilience and lower electrical resistivity, the D-5 Class 1.1 propellant is apparently less sensitive to friction ignition or electrostatic discharge than current Class 1.3 propellants. See "The Joint Venture Analysis of the Nuclear Weapons Safety Report of the Panel on Nuclear Weapons Safety (December 1990)," Hercules–Thiokol Joint Venture, prepared at the request of the Navy Strategic System Project Office, 22 April 1991. It is believed that a new Class 1.3 propellant could be developed with roughly the same ignition properties as D-5 propellant. More plasticizers would be required, resulting in a two- to four-second penalty in propellant specific impulse in comparison with existing Class 1.3 propellants. Ed Lee and Ed James, LLNL, private communication, 29 October 1992.

15. It is important not to confuse a "detonation" with an "explosion." Explosions can occur, for example, from rapid pressure buildup in a rocket motor having a fractured grain, and they can release significant amounts of energy. In a propellant detonation, a comparable amount of energy is released much more rapidly, and a high-pressure shock wave is generated in the material.

16. In a fire, conventional HE under light confinement characteristic of strategic RVs could undergo a DDT under certain conditions of dynamic pressure loading or material granulation. A fire involving an IHE warhead is unlikely to undergo a DDT under any such conditions.

17. Conventional HE and Class 1.1 propellant may detonate if struck with a high-velocity rifle bullet. In tests in which a single 30 to 50 caliber ball and armor piercing round was fired at velocities of about 1,000 m sec^{-1} into a heavily confined sample of C-4 Class 1.1 propellant, the propellant did not detonate but underwent deflagration. Prompt detonation of the propellant did occur when hit with 70- to 150-mm steel pro-

jectiles at velocities above about 250 m sec^{-1}. Neither Class 1.3 propellants nor IHE would be expected to detonate under these or substantially more rigorous conditions. For an interesting discussion of the phenomenology of motor detonation from bullet impact, and of the complexity of trying to evaluate specific cases, see, S. Hamaide et al., "Tactical Solid Rocket Motors Response to Bullet Impact," *Propellants, Explosives, Pyrotechnics* **17**, pp. 120–125 (1992).

18. The Rocky Flats plutonium facilities are currently shut down because of severe contamination. It is unlikely they will reopen soon.

19. SLBM warheads are not currently transported by rail or air.

20. Most nuclear weapons accidents involving plutonium dispersal have occurred from incidents involving aircraft, including crashes resulting in impacts and fires. Prior to 1969, there were four serious dispersal accidents: a B-47 accident at Sidi Slimane, Morocco (31 January 1958), an explosion of a Bomarc missile at McGuire AFB, New Jersey (7 June 1960), a mid-air collision involving a B-52 over Palomares, Spain (17 January 1966), and a B-52 crash at Thule, Greenland (21 January 1968). The warheads involved were, respectively, the B36 bomb, the W40 warhead for BOMARC, and B28 bombs carried by the B-52s. See "Narrative Summaries of Accidents Involving U.S. Nuclear Weapons 1950–1980," Department of Defense, May 1981; and "U.S. Nuclear Weapons Accidents: Danger in Our Midst," *The Defense Monitor* **10** (5), 1981, (Washington DC: Center for Defense Information). There was a "close call" in the B-52 fire at Grand Forks AFB on 15 September 1980. See *USAF Mishap Report*, Report Serial No. 80-9-15-101, dated 29 September 1980.

21. The Navy has had several incidents, some involving SLBMs, where a nuclear weapon was or could have been subjected to "abnormal environments." In at least one case, a submarine has been lost at sea, reportedly with nuclear weapons aboard. There have also been collisions at sea or in coastal waters involving ships carrying nuclear weapons. See *SIPRI Yearbook 1977: World Armaments and Disarmament* (Cambridge, MA: M.I.T. Press, 1977), p. 52 ff. As far as is known, there have been no accidents in the Navy FBM program involving dispersal of nuclear weapons' hazardous materials to the public. We have no way of knowing, however, if any accidents or "close-call" incidents with U.S. Navy systems have gone unreported. There have been, for example, several unreported near-accidents with U.S. Air Force systems. See Scott D. Sagan, *The Limits of Safety: Organizations, Accidents and Nuclear Weapons* (Princeton, New Jersey: Princeton University Press, 1993).

22. Certain institutional obstacles to enhanced safety may be uncovered during outside review since learning from near-accidents may be restricted by the common organizational mindset and biased interests of an organization. See *Ibid.*

23. See P. Slovic, "Perception of Risk," *Science* **236**, 1987, pp. 280–285; and R.E. Kasperson, O. Renn, P. Slovic, H. Brown, J. Emeo, R. Goble, J. X. Kasperson, and S. Ratick, "The Social Amplification of Risk: A Conceptual Framework," *Risk Analysis* **8**, June 1988, pp. 172–187.

24. There is also the possibility that people with authorized access to nuclear weapons could become emotionally unstable and intentionally cause an accident. In one case in 1958, a sergeant involved in nuclear weapons maintenance "went berserk and threatened to fire a pistol at a nuclear bomb in a suicide attempt." See Jack Raymond, "U.S. Tightens Screening Rules for Handlers of Atom Bombs," *New York Times*, 29 November 1962, p. 1. Also see Herbert L. Abrams, "Sources of Human Instability in the Handling of Nuclear Weapons," in Fredric Soloman and Robert Q. Marston (editors) *The Medical*

Implications of Nuclear War (Washington DC: National Academy Press, 1986).

25. For example, an operational test launch failure could result in an SLBM booster exploding or detonating at very low altitude, possibly delivering sufficient energy to the SSBN conducting the launch (and cruising fairly close to the surface) to cause violent reactions in the other boosters deployed with live warheads. Test launch failures are not a rare occurrence.

26. See Ralph. H. Condit, "Plutonium Dispersal in Fires: Summary of What is Known" (Livermore, California: Lawrence Livermore National Laboratory, October 1986). This source provides useful insights into the mechanisms for, and health hazards of, plutonium dispersal.

27. The shock pressure transmitted to the warhead IHE was measured to be less than one kbar, making it unlikely that even conventional HE would undergo SDT. A substantial fraction of the IHE was recovered in chunks; it had neither detonated nor burned. The mock pit material was recovered in large pieces, relatively intact, and only moderately damaged.

28. Private communication, Edward Lee, Lawrence Livermore National Laboratory.

29. Over the lifetime of the FBM program, the Navy has conducted over 30,000 missile-hoisting operations without a serious accident involving dispersal of nuclear weapons materials. In one incident at the SSBN base in Holy Loch, Scotland, a Poseidon C-3 missile was being winched between the submarine U.S.S. Holland and its tender. The winch inadvertently ran free, and the missile dropped 17 feet before automatic brakes caught it just above the Holland's hull. The SLBM, "swinging wildly," hit into the tender. See D. Campbell and N. Solomon, "Accidents Will Happen," *New Statesman*, 27 November 1981. There have been one or two other cases of "dropped" boosters.

30. The impact on a steel plate of a C-4 or D-5 third-stage motor with a velocity in the range of 150- to 200-feet sec^{-1} could generate a shock of about 30 to 40 kbar, sufficient to cause motor detonation with 50 percent probability. This corresponds to a free-fall drop in vacuum of about 350 to 600 feet. According to the Navy, the worst-case drop velocity in a missile toppling accident would be about 60 mph (88 feet sec^{-1}) corresponding to a drop height of about 120 feet. Such an accident is extremely unlikely to result in a direct, shock-induced detonation. See "Trident II (D-5) Strategic Weapons System—Nuclear Weapons Safety," briefing charts presented by RADM Kenneth C. Malley, former Director, Navy Strategic Systems Program Office (undated), and the unclassified briefing charts addressing Trident I propellant sensitivities in "Trident II Missile Performance Impacts of Employing IHE in the Mk5 Reentry Body" (Livermore, California: Lawrence Livermore National Laboratory, March 1983).

31. For a warhead immersed in a fuel fire (800 to 1,100° C), a smaller fraction of warhead plutonium (0.001 to 1.0 percent) would be released in inhalable form than in an HE detonation. A solid rocket motor propellant fire is much hotter (~2,500° C); thus, substantial plutonium may be vaporized, which would increase the fraction of smaller, respirable particles. See Condit, op. cit. p. 10.

32. See "The Joint Venture Analysis of the Nuclear Weapons Safety Report," op. cit., p. 30.

33. See "The Joint Venture Analysis of the Nuclear Weapons Safety Report," op. cit., p. 17.

34. For an interesting discussion of fire environments and the utility of FRPs see, Douglas R. Stephens, "Fire-Resistant Pits: Reducing the Probability of Accidental Plu-

tonium Dispersal from Fuel Fires" (Livermore, California: Lawrence Livermore National Laboratory, March 1992) report no. UCRL-ID-110556.

35. The insulation provided by an intact RV can also add several minutes to containment time in a solid propellant fire.

36. One-point safety" means specifically the following: (a) In the event of a detonation initiated at any one point in the high explosive system, the probability of achieving a nuclear yield greater than four pounds TNT equivalent shall not exceed one in one million (1×10^6), and (b) One point safety shall be inherent in the nuclear design—that is, it shall be obtained without the use of a nuclear safing device. See Letter from C. Walske, Chairman, Military Liaison Committee to Brig. Gen. Giller, AEC, 4/68.

37. See Drell Commission Report, op. cit., p. 29.

38. The yield of a primary can be "boosted" by injecting a small amount of deuterium and tritium (DT) into the core. The flood of 14-Mev neutrons produced from DT reactions induces many more fissions, resulting in a significant increase in primary yield.

39. In analysis subsequent to the Drell report, the DOE labs are working to identify any credible mechanisms that produce greater than four pounds of nuclear yield in a third-stage motor detonation.

40. See Condit, op. cit. p. 3.

41. Condit, op.cit., p. 5. For comparison, the EPA limit for total lung burden is 0.3 micrograms or about 1.6×10^{-8} curie. Another source cites a 30-year dose of 3,800 rad per milligram of weapons-grade plutonium inhaled into the lungs. See S. Fetter and F. von Hippel, "The Hazard from Plutonium Dispersal by Nuclear-Warhead Accidents," *Science & Global Security* **2** (1), 1990, p. 23.

42. Fetter and von Hippel, op. cit., p. 22–24.

43. Fetter and von Hippel, op. cit., p. 24 ff.

44. The wind velocity of four km $\sec^{-1}$ directed east towards Seattle is a worst-case assumption. Prevailing winds are mainly north and south due to the channeling by the Olympic and Cascade ranges. Winds from the south are the most probable. The wind used by Fetter and von Hippel occurs about 5 percent of the time. The rest of the time (due to the anisotropy of the Seattle population distribution), the winds lead to substantially less dose to the population. When used in a model that takes terrain into account, such winds reduce the population dose by two to three orders of magnitude. Ted Harvey, LLNL, private communication.

45. A. Lin and J. Harvey, *Plutonium Dispersal in Nuclear Weapons Accidents*, Center for International Security and Arms Control, Stanford University (in draft).

46. At the current risk factor of about 5×10^{-4} LCFs per whole-body man-rem, the number of LCFs expected over 30 years from natural radiation is:

$$(5 \times 10^5 \text{ people}) \times (0.1 \text{ rem}) \times (5 \times 10^{-4} \text{ LCFs / rem}) \times 30 \text{ years} = 750 \text{ LCFs.}$$

About 1,000 to 5,000 cancer deaths were expected worldwide from plutonium oxide inhalation due to atmospheric nuclear testing in the 1950s and early 1960s. See Fetter and von Hippel, op. cit. p. 27 (footnote). Estimates of the collective dose to the world's population from all isotopes produced during atmospheric nuclear testing conducted from 1945 to 1963 range from 400 to 800 million man rad (or man-rem since the dose is mostly from beta and gamma radiation, where $Q = 1$). This translates to about 200,000 to 400,000 additional LCFs as a result of the whole period of atmospheric testing, or an average of 10 to 20 thousand LCFs induced per year. For comparison, the *annual* collective dose to the world population from natural radiation is about 300 million man rad, which translates to about 150,000 LCFs induced per year. See "Sources, Effects and Risks of Ionizing Radiation," United Nations Scientific Committee on the Effects of Atomic Radiation, 1988 Report to the General Assembly (New York: United Nations, 1988). We are grateful to Charles Shapiro, LLNL, for pointing this out.

47. Fetter and von Hippel, op. cit., table 7 indicate that, under stated worst-case assumptions, unprotected individuals within two kilometers of the accident would inhale, on average, about 0.02 milligrams of plutonium. Assuming 10 expected deaths in 30 years per milligram inhaled, this would yield about 10×0.02 milligrams $= 0.2$ deaths, equivalent to a 20 percent chance to such an individual of dying of cancer from the accident. Since the overall cancer death rate from all causes is 20 percent, the accident would increase the risk to 36 percent [= 20 percent + $(0.2 \times 80\%)$], almost double.

48. Under certain atmospheric conditions, resuspension and inhalation of ground particles can significantly add to total dose. Draft EPA regulations recommend a value of 0.2×10^{-6} Ci m^{-2} as a screening level for ground cleanup of transuranium elements. This value is based upon guidance of one mr per year of alpha radiation to the lungs or three mr per year to the bone. A resuspension model is used to derive the screening level for samples collected on the ground to a depth of one centimeter and for particle sizes under two mm. The screening level is *not* intended to be a trigger level above which cleanup is required. Rather, its intended use is to provide a conservatively based threshold for the purpose of eliminating lands at or below this level from further, more detailed evaluation.

We can estimate ground contamination (σ) from the potential accident in the vicinity of Seattle. According to equation 7 in S. Fetter and F. von Hippel, op. cit., $\sigma = (v \times I) / b$, where σ is in mg m^{-2}; I is the amount of plutonium that a person located at that point would inhale during plume passage; v is the deposition velocity (assumed 0.01 m sec^{-1}); and b is the average breathing rate (3.3×10^{-4} m^3 sec^{-1}). From table 7 of the same reference, we estimate that I is about 0.01 milligrams at 5 to 10 kilometers downwind from the accident. This leads to a ground contamination level of 0.3 mg m^{-2} or (given 0.08 Ci per gram of weapons grade plutonium) 2.4×10^{-5} Ci m^{-2} at a radius of 5 to 10 kilometers. This figure is about 100 times the draft EPA screening level. The ground contamination at one kilometer from the accident would be a factor of 300 above the screening level.

Cleanup to *background levels*, if required, would be a much more stringent criterion. For example, the plutonium deposited from atmospheric testing of nuclear weapons gives about 100 times less area deposition in the mid-latitudes than the draft EPA screening level. Nearly all is uniformly distributed in the first 10 centimeter of soil. If one considers the amount of plutonium in the first centimeter (the most important part for resuspension), then background from atmospheric testing would be about three orders of magnitude less than the draft screening level. Plutonium contamination from an accident would be detectable to those levels and lower since the isotopic mixtures from atmospheric testing would be different. Cleanup to background plutonium contamination levels (about 0.1×10^{-9} Ci m^{-2}) could involve land areas an order of magnitude larger than for the draft screening level. See *Interim Recommendations on Doses to Persons Exposed to Transuranium Elements in the General Environment* (draft), U.S. Environmental Protection Agency (1987). We thank Doug Stephens, LLNL, for allowing us to adapt some of his unpublished writing and research in this note.

49. See Keith Schneider, "U.S. Plans Big Cuts In Its Production of Nuclear Arms," *New York Times*, 17 December 1991.

50. George Leopold, "Navy Officials Wrestle With Nuclear Arms Shuffle," *Defense*

News, 8–14 June 1992.

51. A "sphere-cone" strategic RV might weigh 400 pounds and have a base diameter of 22 inches. The drag coefficient depends only on RV shape. For a typical RV with an eight degree conical half-angle and a bluntness ratio (ratio of nose radius to base radius) of about 0.05, drag coefficients range between 0.05 and 0.1. This gives a ballistic coefficient of between 1,500 and 3,000 pounds per square foot. For drag coefficients of conical objects with rounded nose tips as well as other interesting RV data, see Frank J. Regan, *Reentry Vehicle Dynamics* (New York: American Institute of Aeronautics and Astronautics, 1984), p. 139.

52. Both the W87 and W88 belong to same class of high-yield warheads. During the 1980s, when MX and other nuclear weapons were being introduced at accelerated rates, a shortage of enriched uranium necessitated deploying MX W87 warheads at less-than-maximum yield. The W87 yield, if desired, could be raised to that of the W88 without the need for additional nuclear testing.

53. Detailed design work would determine the effect on β of a longer RV—that is, the degree to which the increased mass of a longer RV would offset the increased base diameter and drag coefficient.

54. Probably just as important, the W88 developers wanted to exploit a secondary design that had undergone full-yield testing prior to the 1974 Threshold Test Ban Treaty, which limited tests to 150 kilotons.

55. A CEP value for D-5 of 130 meters (430 feet) is cited in *Modernizing U.S. Strategic Offensive Forces: The Administration's Program and Alternatives*, U.S. Congress, Congressional Budget Office, (Washington DC: U.S. Government Printing Office, May 1983).

56. Under START II, MX would be eliminated by the year 2003. Existing Mk21/W87s could be redeployed on Minuteman III ICBM (at one warhead each) or made available for Trident. Even if not used on Minuteman III, these warhead would probably not be available for Trident in the short term.

57. The fissile material shell may be composed of plutonium, enriched uranium, or both.

58. C. Alonso et al., *Report to Congress on Stockpile Reliability, Weapon Remanufacture and the Role of Nuclear Testing* (Livermore, California: Lawrence Livermore National Laboratory, October 1987) report no. UCRL-53822, p. 20.

59. C. Alonso et al., op. cit., pp. 20 and 29.

60. C. Alonso et al., op. cit., p. 26.

61. The two materials have a similar mass density, about 1.8 gm cm^{-2}.

62. George Leopold, "Weapons Labs Scour for W88 Replacement," *Defense News*, 2 March 1992.

63. President Clinton's FY 1994 budget request would cease funding for plutonium parts production at Rocky Flats. See, George Leopold, "DOE Eyes Cleanup of Nuclear Sites," *Defense News*, 12–18 April 1993.

64. The two-stage, liquid-fueled SS-18 is deployed with 10 accurate, multi-hundred-kiloton warheads. It has an assessed counterforce capability against U.S. ICBM silos. With its 11,000-kilometer range, it can reach all important U.S. targets. Currently, about 308 SS-18s are deployed. Under START I, that number will be reduced to 154. If

implemented, START II will eliminate the SS-18. Under START II, however, about 90 SS-18 silos could be converted for deployment with single-warhead missiles.

65. Soviets Testing New Generation of ICBMs," *Aviation Week and Space Technology*, 3 November 1980, p. 28.

66. The two-stage, liquid-fueled SS-19 ICBMs may also be considered potential targets for Trident. Each carries six warheads with a yield of several hundred kilotons. The SS-19s are deployed in the western part of Russia and in Ukraine and, thus, are more accessible to Trident submarines patrolling in the Atlantic than are the SS-18s. Under START II, the SS-19 silos will either be retired or deployed with single-warhead missiles.

67. The computer program consisted of approximately 1,500 lines of Pascal code. It was developed by Nick Gentile of LLNL and required only minor modifications.

68. We assume that the PBV maneuvering is devoted totally to RV "footprint" and not to range extension.

69. These calculations assume that Class 1.1 and Class 1.3 propellants have the same density. More accurately, the density of Class 1.3 propellant is about 5 percent less than Class 1.1. For a modified D-5 with a Class 1.3 third stage and eight Mk5 RVs, the range penalty assuming lower density would be about 150 n.m. (–3.7 percent) rather than 110 n.m. A new Class 1.3 propellant with the same mechanical properties and resistance to ignition as current D-5 propellant might have an I_{sp} penalty of about –14 seconds, as well as five percent lower density. In this case, the range penalty for a modified D-5 would be about 195 n.m. (–4.7 percent).

70. The actual weight saved by eliminating the third stage will be somewhat less than the weight of the stage. The third stage provides structural support to the PBV; some reinforcement of the PBV structure will be required, at some weight penalty, if that stage is removed.

71. See F. Pearson, *Map Projections: Theory and Applications* (Boca Raton, Florida: C.R.C. Press, 1990), pp. 110–117.

72. Maximum drag for a nominal D-5 with eight Mk5 RVs occurs about half-way through first-stage burn at an altitude of about 8.5 kilometers and a velocity of about 0.75 km sec^{-1}. Peak dynamic pressures are about 10 percent greater for a D-5 missile with only four Mk5s. We are unable to assess the effect of increased drag forces on the structural integrity of the missile. Such complex evaluations would necessarily be carried out in any missile redesign effort.

73. The reason arises from the Pacific geography. For missile range of 4,100 n.m. or greater, an SSBN minimizes transit time by steaming north from Silverdale into the Gulf of Alaska, where it first comes within range of SS-18s based at Kartaly. It can then move along the Aleutian chain into the north Pacific or Bering Sea, all the while staying within range of its targets. For missile range less than 4,000 n.m., there is little or no room in the Gulf of Alaska in which an SSBN is within range of Kartaly. Rather, minimum transit time is achieved by steaming directly to the Unimak Pass in the Aleutian chain and crossing through to the Bering Sea. For example, an SSBN carrying 4,100-n.m.-range missiles must travel about 970 n.m. from Silverdale to go on-station in the Gulf of Alaska. If missile range is 100 n.m. through Unimak and into the Bering Sea before it moves within range of Kartaly, adding an additional 13 days to total round-trip transit time (including the 20 percent correction). On-station rate in the Pacific, therefore, is quite sensitive to missile range; this sharp drop-off with range

is not manifest in the Atlantic.

74. We can obtain a rough estimate of stage procurement costs by noting that, as part of a life extension program for Minuteman III, about 620 new third-stage motor cases will be manufactured and filled with new solid propellant at a procurement cost of about $370 million, or $0.6 million per motor. See *Minuteman III Life Extension Report—A Report to Congress*, Department of Defense [USD(A)], 29 July 1992. It is unclear how much of the hardware from the current D-5 third stage (e.g., case, insulation, nozzle, or TVC system) could be reused. Our procurement cost estimate of about $0.7 per motor, however, is probably conservative because the Minuteman III third stage is nearly twice the weight of the D-5 third stage, and propellant cost is a substantial fraction of total stage cost.

75. This was suggested by the Drell Commission in their letter to Les Aspin, Chairman of the Committee on Armed Services, U.S. House of Representatives, dated 15 November 1991.

76. Our cost estimates for new warheads do not include costs to restart or replace the Rocky Flats plant.

77. All of the options are described in greater detail in the full report, "Nuclear Weapons Safety and Trident: Issues and Options," John R. Harvey and Stefan Michalowski, Center for International Security and Arms Control, Stanford University, August 1993.

78. Preliminary calculations carried out at LLNL during 1986 and 1987 suggest, however, that the tight spacing between the third stage and RVs (for C-4/Mk4 and D-5/Mk5) would not permit installation of sufficient shock-absorbing materials to prevent detonation. For D-5 deployed with the smaller Mk4, shock mitigation may be more feasible since there is more room to install materials that lower the peak shock to the warhead. If shock mitigation were feasible, then a small development program could cost in the range of $50 million for each missile and take one to two years. Such a program could be done in parallel with IHE warhead development.

79.The calculation to determine "prompt hard targets killed (HTK) per SLBM" is as follows:

$$\text{Prompt HTK} = R \times \text{SSPK} \times (\#\text{ RVs / missile}) \times (\text{fraction of time SSBN is within range}),$$

where

$$R = \text{system reliability} = 0.9 \text{ (assumed)}$$
$$\text{SSPK} = \text{single-shot kill probability} = [1 - 0.5^{(WR/CEP)^2}],$$

where

$$WR = \text{weapons lethal radius for 5,000-psi hard targets} = 875 \text{ feet} \times Y(\text{Mt})^{1/3}$$
$$CEP = 450 \text{ feet}.$$

Assuming a 95-day cycle (70 days at sea and 25 days in port) and a 12-month overhaul every 10 years yields an average at-sea rate for the Trident force of 0.66 over a 10-year cycle. (Higher at-sea rates can be sustained for short periods during generated alerts.) Thus, the "fraction of time within range of the SS-18 target set (during normal day-to-day alert)" for each missile configuration and basing location is determined from table 16 by multiplying the days on-station by 0.66/70 days. For example, for the baseline D-5 with eight Mk5/W88 RVs deployed from King's Bay, we have:

$R = 0.9$
$\text{SSPK} = 0.79$
fraction of time within range = (36.4 days) × (0.66/70 days) = 0.34
RVs per missile = 8,
which gives Prompt HTK = number of SS-18 silos killed promptly per missile = 1.9.

80. See Ann Fisher et al., "The Value of Reducing Risks of Death: A Note on New Evidence," *Journal of Policy Analysis and Management* 8 (1), 1989, pp. 88–100. We are indebted to Jim Miller for pointing out this reference.

81. From simple risk analysis, and ignoring accidents for the moment, the appropriate investment to make in deploying Trident is related to the probability of nuclear war and its consequences as follows:

$V_d = C_w (P_{wnt} - P_{wt})$, where
V_d = lifecycle cost to deploy Trident $\approx$ \$150 billion
C_w = "cost" of a nuclear war,
P_{wt} = probability of nuclear war assuming Trident is deployed,
P_{wnt} = probability of nuclear war with no Trident,

Let us now assume that the original investment to deploy Trident has been made and we now want to determine what amount should be spent to increase system safety to avoid a serious accident that terminates operations. Here:

$V_{fix} = C_w (P_{wta} - P_{wt})$, where,
P_{wta} = probability of war assuming Trident is deployed but with a finite chance of a serious accident.

With a little arithmetic it is straightforward to show that:

$$P_{wta} = P_A \cdot P_L \cdot (P_{wnt} - P_{wt}) + P_{wt}.$$

This leads to:

$$V_{fix} = P_A \cdot P_L \cdot [C_w (P_{wnt} - P_{wt})] = P_A \cdot P_L \cdot [V_d] = P_A \cdot P_L \cdot [\$150 \text{ billion}].$$