OCCASIONAL REPORT

NUCLEAR WARHEAD SAFETY

The following is an extract from the Report of the Panel on Nuclear Weapons Safety of the Committee on Armed Services House of Representatives, December 1990. The members of the panel were Sidney D. Drell, chairman, John S. Foster Jr, and Charles H. Townes.

Concerns that have been raised recently about the safety of several of the nuclear weapons systems in the US arsenal have led the government to take immediate steps to reduce the risk of unintended, accidental detonations that could result in dispersing plutonium into the environment in potentially dangerous amounts, or even generate a nuclear yield. These steps include temporarily removing the short-range air-to-ground attack missiles, SRAM-A, from the alert bombers of the Strategic Air Command and modifying some of the artillery-fired atomic projectiles (AFAPs) deployed with US forces. In addition, the Departments of Defense and Energy, which hold dual responsibility for the surety of the US stockpile of nuclear weapons systems—i.e., for their safety, their security, and their control—have initiated studies looking more broadly into safety issues.

This is a very important, as well as opportune, moment to undertake a safety review of nuclear weapons for reasons that go well beyond the immediate concerns of several specific weapons. As we enter the last decade of the 20th century, the world is in the midst of profound, and indeed revolutionary, changes in the strategic, political, and military dimensions of international security. These changes, together with a continuing rapid pace of technical advances, create an entirely new context for making choices in the development of our nuclear forces for the future. It is likely that, in the future, the US nuclear weapons complex will evolve into a new configuration—perhaps smaller and less diverse and at lower operating expense but with enhanced requirements for security and control.

In this report we propose organizational initiatives to strengthen and make more fully accountable the safety assurance process, and we identify priority goals for enhancing safety in a timely fashion. We emphasize the importance of developing the data bases and performing credible safety analyses to support weapons design choices. We also affirm the importance of vigorous R&D efforts in the DoE weapons laboratories in search of new technologies leading to significant advances in safety-optimized designs....

Because the consequences of a nuclear weapons accident are potentially so harmful, both physically and politically, major efforts are made to protect nuclear weapons systems from detonating or dispersing harmful radioactive material if exposed to abnormal environments, whether due to accidents or natural causes, or resulting from deliberate, unauthorized intent....

Safety requirements for nuclear weapon systems apply both to the warheads themselves and to the entire weapon system. For the warheads this implies design choices for the nuclear components as well as for the electrical arming system that meet the desired safety standards. For the weapon system—i.e., the rocket motors and propellant to which the warhead is mated in a missile and the aircraft or transporter that serves as the launcher—safety implies, in addition to design choices, operational, handling, transportation and use constraints or controls to meet the desired safety standards....

Technical advances have permitted great improvements in weapons safety since the 1970s. At the same time technical advances have greatly increased the speed and memory capacity of the latest supercomputers by factors of 100 and more. As a result it has become possible, during the past three years, to carry out more realistic calculations in three-dimensions to trace the hydrodynamic and neutronic development of a nuclear detonation. Earlier calculations were limited to two-dimensional models. The new results have shown how inadequate, and in some cases misleading, the two-dimensional models were in predicting how an actual explosion in the real three-dimensional world might be initiated leading to dispersal of harmful radioactivity, or even to nuclear yield. A major consequence of these results is a realization that unintended nuclear detonations present a greater risk than previously estimated (and believed) for some of the warheads in the stockpile.

These new findings are central to an assessment of nuclear safety and of the potential to improve stockpile safety. We will discuss their specific implications for existing and planned nuclear weapons systems in the next (classified) section of this report. Here we first describe individual components that contribute to the over-all safety of a nuclear weapon system as a basis for evaluating how the design choices affect the safety of the weapons system.

ENHANCED NUCLEAR DETONATION SAFETY

The ENDS system is designed to prevent premature arming of nuclear weapons subjected to abnormal environments. The basic idea of ENDS is the isolation of electrical elements critical to detonation of the warhead into an exclusion region which is physically defined by structural cases and barriers that isolate the region from all sources of unintended energy. The only access point into the exclusion region for normal arming and firing electrical power is through special devices called strong links that cover small openings in the exclusion barrier. The strong links are designed so that there is an acceptably small probability that they will be activated by stimuli from an abnormal environment. Detailed analyses and tests give confidence over a very broad range of abnormal environments that a single strong link can provide isolation for the warhead to better than one part in thousand. Therefore, the stated safety requirements of a probability of less than on in a million requires two independent strong links in the arming set, and that is the way the ENDS system is designed.... Both strong links have to be closed electrically—one by specific operator-coded input and one by environmental input corresponding to an appropriate flight trajectory—for the weapon to arm.

ENDS includes a weak link in addition to two independent strong links in order to maintain assured electrical isolation at extreme levels of certain accident environments, such as very high temperatures and crush. Safety weak links are functional elements (e.g., capacitors) that are also critical to the normal detonation process. They are designed to fail, or become irreversibly inoperable, in less stressing environments (e.g., lower temperatures) than those that might bypass and cause failures of the strong links.

The ENDS system provides a technical solution to the problem of preventing premature arming of nuclear weapons subjected to abnormal environments. It is relatively simple and inexpensive and lends itself well to probabilistic risk assessment.... ENDS was developed at the Sandia National Laboratory in 1972 and introduced into the stockpile starting in 1977. As of the beginning of this year slightly more than one-half of the weapons in the stockpile (52 percent) will be equipped with ENDS. The remaining ones await scheduled retirement or modernization under the stockpile improvement program. Until then they do not meet the established stockpile safety criteria.

The weapon without the modern ENDS system that has caused the greatest concern as a result of its means of deployment is the W69 warhead of the SRAM-A missile aboard the strategic bomber force and various older models of aircraft-delivered tactical and strategic bombs. Since 1974 concerns have been raised on a number of occasions about the safety of this deployed system. A particular concern is the potential for dispersal of plutonium, or even of the generation of a nuclear detonation, in the event of a fire aboard the aircraft during engine-start readiness drills, or of an impact involving a loaded, ready-alert aircraft (i.e., the ALFA force) should an accident occur near the landing and take-off runways during routine operations of other aircraft at a SAC base. In spite of these warnings, many remained on alert or in the active stockpile as recently as six months ago. Since then, following public disclosure of the safety concern, the SRAM-A has been taken off the alert SAC bomber force,* with its ultimate fate awaiting completion of an Air Force SRAM-A safety study now in progress.

INSENSITIVE HIGH EXPLOSIVES

Nuclear warheads contain radioactive material in combination with high explosives. An accident or incident causing detonation of the high explosive would result in radioactive contamination of the surrounding area....

The consequences of a violent accident, such as an airplane fire or crash, may be very different depending on whether the high explosive is the insensitive (IHE) or conventional (HE) type. In such incidents HE would have a high probability of detonating in contrast to the IHE. The importance of this difference lies in the fact that detonation of the HE will cause dispersal of plutonium from the weapon's pit. The following table shows several measures that are indicative of the different detonation sensitivities of the two forms of explosives:

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* The decision on the SRAM-A was announced by Secretary [of Defense] Cheney on June 8, 1990.

Table 1: Insensitive high explosive (IHE) compared to conventional high explosive

	Conventional HE *order of*	*IHE*
Minimum explosive charge to initiate detonation *ounces*	10^{-3}	>4
Diameter below which the detonation will not propagate *inches*	10^{-1}	0.5
Shock pressure threshold to detonate *kilobars*	20	90
Impact velocities required to detonate *miles/hour*	100	1,200–1,300

In contrast to the safety advantages, IHE contains, pound for pound, only about two-thirds the energy of HE and, therefore, is needed in greater weight and volume for initiating the detonation of a nuclear warhead.

It is generally agreed that replacing warheads with HE by new systems with IHE is a very effective way—perhaps now the most important step—for improving safety of the weapons stockpile against the danger of scattering plutonium. The understanding between DoE and DoD in 1983 calls for the use of IHE in new weapon systems unless system design and operational requirements mandate use of the higher energy and, therefore, the smaller mass and volume of conventional HE. It was also "strongly recommended" by the Senate Armed Service Committee in 1978, under Chairman John Stennis, that "IHE be applied to all future nuclear weapons, be they for strategic or theatre forces."

Although IHE was first introduced into the stockpile in 1979, as of the beginning of 1990 only 25 percent of the stockpile is equipped with IHE. The reason for this is that in decisions made up to the present, technology and operational requirements were judged to preclude incorporation of IHE in Artillery-Fired Atomic Projectiles (AFAPs) and Fleet Ballistic Missiles (FBMs). The small diameters of the cannon barrels (155 millimeters or 8 inches) pose very tight geometric constraints on the design of AFAPs. As a consequence there is a severe penalty to nuclear artillery rounds relying on IHE. On the other hand, options existed to go either with HE or IHE in choosing the warhead for the Trident II, or D5, missile. Of course, there are also geometric constraints on the Navy's FBMs that are set by the submarine hull design. However, the missile dimensions have expanded considerably in the procession from the Poseidon C3 and Trident I(C4), which were developed before IHE technology was available, to the D5 missile which is 44 feet long and 83 inches in diameter. When the decision was made in 1983 to use conventional HE in the D5 warhead it was based on operational requirements, together with the technical judgment that the safety advantage of IHE relative to HE was relatively minor, to the point of insignificance, in view of the geographic protection and isolation available to the Navy's FBMs during handling and deployment.

A major requirement as perceived in 1983, that led to the decision to use HE in the W88 was the strategic military importance attached to maintaining the maximum range for the D5 when it is fully loaded with eight W88 warheads. If the decision had been to deploy a warhead using IHE the military capability of the D5 would have had to be reduced by one of the following choices:

- retain the maximum missile range and full complement of 8 warheads, but reduce the yields of individual warheads by a modest amount.
- retain the number and yield of warheads but reduce the maximum range by perhaps 10 percent; such a range reduction would translate into a correspondingly greater loss of target coverage or reduction of the submarine operating area.
- retain the missile range and warhead yield but reduce the number of warheads by one, from 8 to 7.

MISSILE PROPELLANT

Two classes of propellants are in general use in long range ballistic missiles of the US. One is a composite propellant and is dubbed as "1.3 class". The other is a high energy propellant dubbed as "1.1 class". Their relevant properties are listed in table (2):

Table 2: Safety properties of composite and high-energy solid missile propellants

	Composite 1.3	High-energy 1.1
Minimum explosive charge to initiate detonation *ounces*	>350	10^{-3}
Diameter below which the detonation will not propagate *inches*	>40	10^{-1}
Shock pressure threshold to detonate *kilobars*	(*)	30
Specific impulse *seconds*	260	270

* no threshold established

The important safety difference between the two propellant classes is that, although both ignite with comparable ease, Table (2) shows that it is very much more difficult, if not impossible, to *detonate* the 1.3 class propellant, in contrast with 1.1 class. On the other hand, the 1.1 propellant has the advantage of a 4-percent larger specific impulse which propels a rocket to greater velocity and therefore to longer range. For example, if the third stage propellant in the D5 were changed from 1.1 to 1.3 class with all else remaining unchanged, the decrease in missile range would amount to 100–150 nmi, which is less than 4-percent of maximum range.

The safety issue of concern here is whether an accident during handling of an operational missile—viz., transporting and loading—might detonate the propellant which in turn could cause the HE in the warhead to detonate leading to dispersal of plutonium, or even the initiation of a nuclear yield beyond the four-pound [of TNT equivalent] criterion.... This issue is of particular concern for the Navy's FBMs. The D5 missile, like its Trident I, C4, predecessor, is designed with through-deck configuration in order to fit within the geometric constraints of the submarine hull and at the same time achieve maximum range with three boost stages. In this configuration the nuclear warheads are mounted on the post-boost vehicle (PBV) in a circular configuration around, rather than on top of, the third stage motor. Thus if the third stage motor were to detonate in a submarine loading accident, for example, a patch of motor fragments could impact on the side of the reentry bodies encasing each warhead. The concern is whether some combination of such off-axis multipoint impacts would detonate the HE surrounding the nuclear pit and lead to plutonium dispersal or possibly a nuclear yield. In order to assess this concern, it is necessary to make a reasonable estimate of the probability of accidentally detonating the 1.1 propellant in the third stage motor and to calculate or measure the probability of subsequently detonating the HE in the warhead. This could then be compared with results in the event of an accident for such a missile with non-detonable 1.3 class third stage propellant and/or IHE in the warhead and the trade-off between enhanced safety and military effectiveness judged analytically.

Concerning military requirements for the Trident II system, we face the prospect that further reductions in the numbers of warheads will be negotiated in follow-on rounds of the START negotiations. There may then be a need to reduce the number loaded on each missile in order to maintain a large enough submarine force at sea to meet our concerns about its survivability against the threat of anti-submarine warfare. With a reduced loading a safety-optimized version of the D5, equipped with IHE, non-detonable 1.3 class propellant and a fire-resistant pit, could fly to even longer ranges than at present....

PLUTONIUM DISPERSAL

There are at present no quantitative safety standards for plutonium dispersal. The effort now in progress to see if it is feasible to establish such standards is due to be completed in October 1991. Any proposed standard will necessarily be critically dependent on the type of incident or accident being considered because there is an important difference between dispersing plutonium via a fire, or deflagration, and via an explosive detonation. In the latter case the plutonium is raised to a higher temperature and is aerosolized into smaller, micron-sized particulates which can be inhaled and present a much greater health hazard after becoming lodged in the lung cavity. In the former case fewer of the particulates are small and readily inhaled; the larger particulates, although not readily inhaled, can be ingested, generally passing through the human gastrointestinal system rapidly and causing much less damage. As a result, there is a difference by a factor of a hundred or more in the areas in which plutonium creates a health hazard to humans in the two cases.* This means it is necessary to specify both the amount of material and the manner in which it is dispersed in setting safety standards....

SAFETY OPTIMIZED DESIGNS

Important contributions to weapons systems safety result from equipping the warheads with modern enhanced nuclear detonation safety systems (ENDS) and insensitive high explosives (IHE), together with composite propellants of the 1.3 class in the missile engines.... But it remains physically impossible to *confirm quantitatively for all contingencies that* risks such as no more than one in 10^6 or 10^9 have been achieved. What one can do—and this is important to do—is identify the potential sources of the largest safety risks and push ahead with searches for new technologies that do away with them and further enhance weapons safety.

One such technology is a fire-resistant pit (FRP) that would further reduce the likelihood of plutonium dispersal in fire accidents involving warheads equipped with IHE. In particular, current FRPs are designed to provide molten plutonium containment against the (~ 1,000° C) temperatures of an aircraft fuel fire that lasts for several hours. They may fail to provide containment, however, against the much higher temperatures created by burning missile propellant. They would also fail in the event of detonation of the HE and are therefore of primary value to safety only if introduced in weapons equipped with IHE. Some of our newest warheads already incorporate FRPs. Beyond that, however, one can envisage advanced weapons design concepts, familiar in the world of binary chemical weapons, that separate a very hard-

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* In the event of a detonation of the IHE of a typical warhead or bomb, an area of roughly one hundred square kilometers downwind could be contaminated with radioactivity. Published assessments of clean-up costs for such an area vary greatly; they are estimated to be upward of one-half billion dollars. If a chemical detonation were to occur in several warheads, the contaminated areas and clean-up costs would be correspondingly larger. The number of latent cancer fatalities would be sensitive to the wind direction and the population distribution in the vicinity of such an accident. In the event of a deflagration, or fire, the contaminated area would be approximately one square kilometer.

ened plutonium capsule from the high explosive prior to arming the weapon; or similarly separating the high explosive into two non-detonable components. We do now know whether such, or other advanced design concepts will prove practical when measured against future military requirements, availability of resources, and budget constraints. However, they should be studied aggressively. R&D is not cheap but the payoff can be very valuable in terms of higher confidence in enhanced weapons safety. DoE should support such work with the necessary resources.

PANEL FINDINGS

The safety criteria that have been specified for modern nuclear weapons are very demanding. The majority of the weapons in the current stockpile will have to be modified to meet them, unless they are retired. Moreover, for some weapons we still lack necessary data to perform credible safety analyses. With a vigorous R&D program at the weapons laboratories in search of new technologies for advanced design concepts, it should be possible to achieve higher confidence in enhances weapons safety, particularly with respect to plutonium dispersal for which there currently is no quantitative standard. Although plutonium dispersal is a much less threatening danger than a sizable nuclear yield, it is nevertheless a potentially serious hazard, particularly if the plutonium is aerosolized in a chemical detonation.

RECOMMENDATIONS

1. Adopt and implement as national policy the following priority goals for improving the safety of the nuclear weapons systems in the stockpile using available technology:

- equip all weapons in the stockpile with ENDS.
- build all nuclear bombs loaded onto aircraft—both bombs and cruise missiles—with IHE and fire-resistant pits. These are the two most critical safety features currently available for avoiding plutonium dispersal in the event of aircraft fires or crashes.

There are no technical reasons for the DoD and DoE to delay accomplishing these safety goals for existing stockpile weapons; they should be given higher priority than they currently receive. For too long in the past the US has retained older weapons that fail to meet the safety criteria proclaimed in 1968.*... The SRAM-A is one such example, but not the only one. It is not sufficient to pull such weapons off the alert ALFA force but retain them in the war reserve stockpile in view of the hazards they will present under conditions of great stress should we ever need to generate strategic forces in times of heightened crisis.

2. Undertake an immediate national policy review of the acceptability of retaining *missile systems* in the arsenal without IHE or fire-resistant pits in their nuclear warheads and without using the safer non-detonable 1.3 class propellant in rocket stages that are in close proximity with the warheads. Such a review will have to look at each missile system on a case-by-case basis, considering such factors as they way they are handled and loaded and the military requirements, as well as making a technical determination of how important are the choices of IHE versus 1.1 class propellant, and fire-resistant pits.

The Trident II (D5) missile system presents a special case to consider in the recommended policy review. It is a new, modern system that is slated to be a major component of the future US strategic deterrent. At the same time the design choices that were made for the W88 in 1983 raise safety questions: the warheads are not equipped with IHE and are mounted in a through-deck configuration in close proximity to the third-stage rocket motor that uses a high energy 1.1 class detonable propellant. Today, seven years after these design choices were made, we have a new and better appreciation of uncer-

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* Those safety criteria are: 1) "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 4 pounds TNT equivalent shall not exceed one in one million [and that] one point safety shall be inherent in the nuclear design; that is, it shall be obtained without the use of a nuclear safing device; 2) The probability of a premature nuclear detonation of a warhead due to warhead component malfunctions...in the absence of any input signals except for specified signals (i.e. monitoring and control), shall not exceed: a) prior to receipt of prearm signal (launch) for the normal storage and operational environments described in the stockpile-to-target sequence (STS), 1 in 10^9 per warhead lifetime, b) prior to receipt of prearm signal (launch) for the abnormal environments described in the STS, 1 in 10^6 per warhead exposure or accident."

tainties in assessing, for example, the probability that accidents in handling the D5 missile system might lead to dispersal of harmful radioactivity; the country has different perceptions of its strategic needs in the post-Cold-War era; the public has very different perceptions about safety; and the acquisition of W88 warheads for the D-5 missile is still in the early stages and has been interrupted for the present and near-term future by the shut-down of the Rocky Flats plant where new pits for nuclear primaries are manufactured.

These circumstances present the country with a tough choice: Should we continue with production and deployment plans for the D5/W88 as presently designed or should we use the lull in production to redesign the missile with a safety-optimized design incorporating, at a minimum, non-detonable 1.3 class propellant in the third stage and IHE and FRP in the warhead?

This is clearly a critical issue to be resolved by the recommended policy review. It will be necessary to weigh the safety risks of continuing to deploy the present design against the costs and delays of a system redesign in order to make an informed choice. But to be able to do this, further studies are needed.

- to provide the data on which to base a more credible analysis of how well, or whether, the D5/W88 meets modern safety standards
- to estimate the costs and inevitable time delays of implementing any recommended design changes
- to evaluate the impact on anticipated national security requirements if changes to enhance weapons safety resulted in fewer warheads, lower explosive yields, or reduced maximum ranges of the missiles.

To do this requires a broad and in-depth examination that is beyond our present review.

3. Continue safety studies, and in particular fault tree analyses such as recently initiated and currently in progress for evaluating safety of the SRAM-A missile and of the DoD/DoE weapon transportation system. Such fault tree analyses which calculate overall risk and safety levels in terms of the individual stops in the operational procedures and sensitivities of the system components to abnormal environments, provide the necessary analytic

tools for evaluating overall systems safety. Very important to such analyses is developing a data base to provide the necessary factual input. The weapons and military laboratories should give priority to doing the experiments for building such a base. They should also receive the resources necessary to support this effort. We believe that it is no longer acceptable to develop weapons systems without a factual data base with which to support design choices that are critical to the systems safety. A critical role of the Red Team in the safety process is to challenge this process by searching out overlooked circumstances that could pose threats to the weapon systems safety.

4. Affirm enhanced safety as the top priority goal of the US nuclear weapons program and direct DoE and DoD, in fulfilling their national responsibilities, to develop nuclear weapons for the future that are as safe as practically achievable, consistent with reasonable military requirements. In particular, the DoE should task and appropriately fund its weapons laboratories to develop truly innovative warhead designs that are as safe as practically achievable. In this connection the requirement of "inherent" one-point safety...should be reexamined. The enhanced safety resulting if the plutonium capsule is physically separated from the IHE prior to arming may well prove to be more important than whatever weight penalty or decrease in reliability—if any—would result from such a design. All advanced design concepts should be studied aggressively. Subsequently the utility of such designs, together with whatever weight or range penalties they require, would be measured against established military requirements.

Finally, we comment that the above recommendations are concerned directly with weapons safety, which was the focus of this review. However, it is appropriate to add how very impressed we were by the nuclear weapons security measures that we observed at the Navy Trident II Base at Kings Bay, Georgia, and the Air Force SAC Base at Minot, North Dakota. During the limited period of this study we had no opportunity to visit field deployments of Army nuclear weapons.

Concerning use control of nuclear weapons, we are satisfied by the technical measures, including permissive action links (PALS), and the serious attention that use controls receive on Air Force missiles and bombs. Great care is also given by the Navy to maintaining a tight system of use controls on its Trident missiles at sea. However, the Navy's fleet ballistic missile system differs in that, whereas launch authority comes from outside the submarine, there is no requirement for external information to be provided in order physically to enable a launch. It is also important to evaluate the suitability of continuing this procedure into the future.