Description of the fuzing system on the Mk4 Reentry Vehicle

The fuzing systems in the Mk4 RV are:

- Airburst Radar with 3 range options – this is the prime system
- G-started timer – this can be a prime or a backup
- Contact fuze – this is a backup [1]

The main system is the radar fuze. If this does not function then the contact fuze provides a backup. The contact fuze is designed to detonate when the RV touches the ground.

The g-started timer has an inertial sensor. This is triggered by the g-force when the RV re-enters the earth's atmosphere. The sensor starts a timer. The warhead can then be detonated a fixed time after re-entry. The g-started timer uses old technology. It is probably not very accurate and only suitable for high airbursts.

Mk4 RV on the Trident C4 and Trident D5 missile

The Mk4 RV was designed for the C4 missile (Trident I). This missile was relatively inaccurate. The combination of C4 missile and Mk4 RV was not effective against hardened targets. The RV was unlikely to land close enough to a missile silo.

The D5 missile (Trident II) is substantially more accurate than C4. It was designed to destroy Soviet SS-18 missile silos.[2] This required a high level of accuracy which was achieved by adopting a system-wide approach. The designers looked comprehensively at all aspects of the Trident system in order to improve accuracy.

To destroy SS-18 silos the D5 missile carries a large, 475 kiloton, W88 Warhead in the Mk5 RV. The closure of the Rocky Flats production plant curtailed the number of W88 warheads which were produced. So most US Trident D5 missiles are armed with the W76 warhead /Mk4 RV. The British Trident system was also designed around the W76/Mk4 system.

The accuracy figures for Trident C4 and D5 are classified. However there is a significant difference between the two. A study carried out in 1999 for the Mk4A upgrade used a measure of normalised effective Circular Error of Probability (CEP) which ranged from 1.0 to 2.5.[3] It is possible that the CEP of the C4 might be as much as 2.5 times greater than that of D5.

When combined with the more accurate D5 missile, the Mk4 RV has the potential to be effective against some hardened targets, but only if the fuze is modified. This is at the heart of the Mk4A upgrade plan.

Relationship between missile accuracy and height of burst

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[1] Survey of Weapon Developments and Technology, Sandia National Laboratory, February 1998

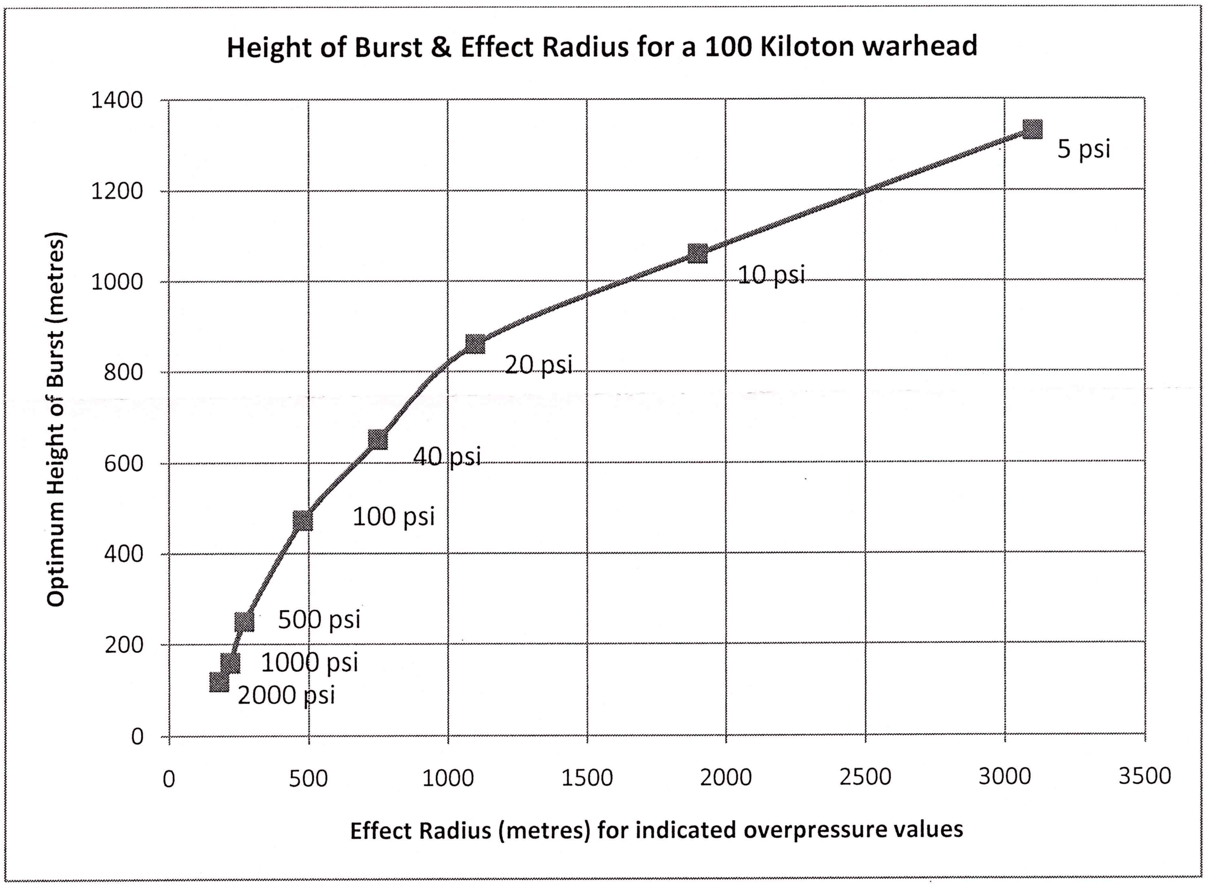
[2] At the time the D5/W88 system was developed it was assumed that SS-18 silos were hardened to 7,000 psi. It was later established that the silos were even harder. Alternate Warhead Study

[3] Weapon Systems Requirement Analysis

Modifying the AF&F does not alter the trajectory that the RV is on. But it can be used to adjust the point on the trajectory when the warhead detonates. In this way introducing a new fuzing system can make a warhead more effective.

One measure for determining the effectiveness of nuclear weapons is peak static overpressure, in pounds per square inch (psi). If the intention is to destroy houses in a city then this can be achieved with around 5 psi. If more substantial properties are the target then 10 psi could be required. In contrast the destruction of missile silos requires between 1,000 and 10,000 psi.

The area over which the planned overpressure will be achieved varies with the height at which the warhead is detonated. The "optimum" height of burst (HOB) for achieving 5 psi from a 100 kiloton warhead is around 1300 m. For 10 psi the optimum HOB is around 1000 m. Very hard targets, such as missile silos, will only be destroyed if the warhead is detonated close to or on the ground.



The chart shows the effect radius for various overpressures and the optimum height of burst associated with this overpressure for a 100 kiloton warhead.

In US nuclear planning, targets are not just assessed by overpressure (psi). Each type of target is given a VNTK rating. VN is the vulnerability number, T is a letter indicating the type of pressure. The basic values are calculated for a 20 kiloton warhead. K is an additional factor which indicates how much the effectiveness varies with higher yields.

In 1994 a study of alternative warheads for Trident was published. The effectiveness of the options was illustrated in a series of graphs. These have all been redacted, but some of the explanatory text has been published. The Measures of Effectiveness for the Mk4 RV on a C4 missile was target type 27P0. This is equivalent to around 150 psi overpressure. The accompanying text says:

> "When the W76/Mk4 was developed, the weapon system CEP was such that this type of target was considered difficult to successfully attack. With the improvements in CEP experienced by the C4 missile, this target is no longer the challenge it once was. Nevertheless the SPETWG [Systems Performance and Effectiveness Technical Working Group] considered it to be an important MOE [Measure of Effectiveness] for this system, and used it in their analysis".[4]

The Height of Burst setting on the Mk4 RV to attack 27P0 (150 psi) is probably between 300 m and 400 m.[5] This is probably the lowest of the three radar settings in the Mk4 AF&F. The highest setting is probably in the region of 1300 m, with a third setting between these two values.

In 1997 Rear Admiral P Nanos, the Director of Strategic Systems Programs said:

> "the Mk4 was never given a fuze that made it capable of placing the burst at the right height to hold other than urban industrial targets at risk."

Proposals to modify the Mk4

A presentation which lists problems encountered with various nuclear warhead components has the following entry beside MC2823 (the radar system for the Mk4 RV) - "customer preferred fuzing option"[6]

The 1994 study of alternative warheads for Trident proposed a number of options for a new Mk4A warhead.[7] It said:

> "The fuze settings in the existing [Mk4] AF&F are not optimal and changing these settings would improve the effectiveness of any of these candidates."[8]

> "Effectiveness studies show significant value to new Mk4A height of burst options for capability against harder targets"[9]

> "The SPETWG [Systems Performance and Effectiveness Technical Working Group] assumed that the HOBs [Heights of Burst] of a Mk4A would be changed from those of the W76/Mk4."[10]

This change was also advocated by Rear Admiral P Nanos in 1997:

> "With the accuracy of the D5 and Mk4, just by changing the fuze in the Mk4 reentry body, you get a significant improvement."[11]

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[4] Joint DoD/DoE Trident Mk4/Mk5 Reentry Body Alternate Warhead Phase 2 Feasibility Study Report, January 1994. p 9-14

[5] Calculations carried out using Weapons Effects, LLNL.

[6] http://smaplab.ri.uah.edu/Smaptest/Conferences/lce/cieslak.pdf

[7] Alternate Warhead Study. In this study Mk4A is used for an RV with an alternative warhead, whereas the current Mk4A is based on the existing warhead.

[8] Alternate Warhead Study, page 7-43

[9] Alternate Warhead Study pdf page 28

[10] Alternate Warhead Study p 9-10

A review of the Stockpile Stewardship Program in 1997 said that one of the areas for development of the W76/Mk4 was:

> "Fuze modification evaluation to enable W76 to take advantage of higher accuracy of D5 missile." [12]

Incorporating the capability of the Mk5 AF&F into the Mk4 RV

The Mk5 RV, which was designed for the D5 missile, has a more sophisticated and accurate fuzing system than the Mk4. The sub-systems available in the Mk5 are:

- Airburst Radar with 5 range options
- Proximity Radar
- Timer – for high airburst
- Path Length – also described as inertial airburst
- Radar-Updated Path Length – this is the main option
- Contact Fuze – this is a backup

Two of the main improvements from the Mk4 are the introduction of a proximity fuze and a Radar-Updated Path Length (RUPL) fuze.

A key aspect of the Mk4A upgrade has been to incorporate the technology of the Mk5 AF&F into the Mk4 RV. From 1995 this was pursued by the SLBM Warhead Protection Program (SWPP). At an early stage of this program Strategic Command were asked to compare the effectiveness of proximity and RUPL options for the Mk4.[13]

One of the goals of the SWPP was:

> "Minimise changes to the functional interface of the Mk4 to allow for Mk5 functionality and Mk5 nuclear safety implementation".[14]

In 1997 one of the key areas of development for the W76 warhead was:

> "Study underway to implement capability of W88/Mk5 AF&F into W76/Mk4 volume"[15]

In 1999 the Department of Energy's Stockpile Stewardship master plan says –

> "[a new modular fuzing system will allow] the incorporation of Mk5 fuzing functionality (including radar-updated path length fuzing, and radar-proximity fuzing) as an option for a replacement of the much smaller Mk4 AF&F."[16]

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[11] Rear Admiral P Nanos, Director of Strategic Systems Programs, US Navy, "Strategic Systems Upgrade" in the Submarine Review April 1997.

[12] Stockpile Stewardship and Management Plan: First Annual Update, DOE, October 1997, obtained under FOIA by Hans Kristensen.

[13] Greg Mello That Old Designing Fever, Bulletin of Atomic Scientists, Jan/Feb 2000

[14] http://portal.unesco.org/en/files/5813/10312388001SCIENCEFORPEACE8light.pdf/SCIENCEFORPEACE8light.pdf

[15] Stockpile Stewardship and Management Plan: First Annual Update, DOE, October 1997, obtained under FOIA by Hans Kristensen.

Contact and proximity fuzing

One way to attack a hard target, like a missile silo, is to detonate the warhead on the surface. This can be more effective than an airburst. The original Mk4 RV has a contact fuze. However this was intended to be a backup rather than a prime fuzing system.

There are a number of concerns about the effectiveness of contact fuzes on ICBM and SLBM. One problem is that there can be no alternative or backup if the contact fuze fails. If two fuzing systems are used in tandem the probability of the warhead detonating is significantly higher than if there is only one fuze.

And there are other concerns. A survey of nuclear weapons developments published in 1998 has the following table:[17]

Contact Fuzing Degree of Difficulty		
	Component	**System**
Design	Easy	Easy
Validate	Fairly Easy	Very difficult

This suggests that it is very difficult to validate that a system which depends on a contact fuze is reliable, even though it is fairly easy to prove that the component itself is reliable.

Many of the subsequent pages in this report have been completely redacted. Some of those which have been published show computer generated forests and trees.[18] One graph is titled "conditional probabilities of tree impacts on Reentry Vehicle Surface". The RV could encounter a variety of uneven surfaces, of which trees are only one example, which can reduce the probability that the contact fuze will detonate.

The report lists the disadvantage of contact fuzes. One of these is - "Dependability concerns (system reliability)".[19] These concerns cannot be addressed by modifying the design of the contact fuze. Such alterations would provide "little, if any, additional protection against impact irregularities".[20]

The solution is to add a proximity fuze. This is a radar system which detonates the warhead immediately before it strikes the ground. A proximity fuze provides "dependable surface fuzing" and will "ensure detonation prior to collision".[21] It gives "adequate survivability for all impact scenarios".[22]

[16] Greg Mello That Old Designing Fever, Bulletin of Atomic Scientists, Jan/Feb 2000
[17] Survey of Weapons Developments p 509
[18] Survey of Weapons Developments p536-539
[19] Survey of Weapons Developments p508
[20] Survey of Weapons Developments p540
[21] Survey of Weapons Developments p490
[22] Survey of Weapons Developments p540

A diagram in the report is shows that the ground shock from using a proximity fuze would be very similar to that from using a contact fuze.[23] The diagram implies that the proximity fuze detonates the warhead 6 metres above the surface. The report says that a radar proximity fuzing results in "little, if any, degradation in burst height effectiveness".

A report into the proposed Small ICBM missile said:

> "An unresolved fuzing issue is the need for a proximity fuze as an alternative for terrain and re-entry conditions where the contact fuze may not be suitable." [24]

This suggests that, in addition to the problems of unpredictable terrain, a contact fuze may be less reliable in certain re-entry conditions. This is probably because the impact velocity varies substantially depending on the type of trajectory.

The Small ICBM report continues:

> "In October 1989 the Air Force directed the Peacekeeper program office to develop a reliable proximity fuze and the Small ICBM program office to retain the ability to use that fuze. Department of Energy officials advised us that a reliable proximity fuze is needed for both the Peacekeeper and the Small ICBM missiles."[25]

Radar Updated Path Length Fuze

In 1982 the US Navy registered a patent for the "Burst Height Compensation" system for an SLBM system.[26] This is probably the basis for the Radar Updated Path Length (RUPL) fuzing system in the Mk5 RV and certainly describes the principles involved.

The actual path of an RV varies from the projected nominal path because of errors including the effects of wind and air density. The Burst Height Compensation system calculates the difference between the actual trajectory and the nominal trajectory and adjusts the point at which the warhead is detonated to take account of this error. The actual trajectory is determined by measuring the velocity of the RV from the point of re-entry with an accelerometer. The addition of a height fix from the radar enables the onboard computer to calculate the deviation from the nominal trajectory. The system can adjust for downrange but not crossrange errors.

The Mk5 RV has the three components required for this system:

- A Force Balanced Integrating Accelerometer (FBIA) (MC3817)
- A radar system (MC3812)
- An onboard computer (MC3811)

[23] Survey of Weapons Developments; The same diagram is also an illustration in Ground Shock from Earth Penetrator Weapons, Paul Yarrington, Sandia, November 1988, p21.
[24] http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA245542&Location=U2&doc=GetTRDoc.pdf
[25] http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA245542&Location=U2&doc=GetTRDoc.pdf
[26] Burst Height Compensation US Patent 4456202

Mk4A Fuzing System

In the 1990s it was planned that the Mk4 fuzing system should be modified to lower the height of burst. There were specific proposals that the new Mk4A system should include a proximity fuze and RUPL, as in the Mk5 RV. The Mk4A AF&F was developed between July 1997 and September 2005.[27]

Some technical details of the Mk4A AF&F are in the public domain. There is no direct confirmation that the new system includes a proximity fuze or AF&F, however some details of the IT system onboard are available.

Some Commercial-Off-The-Shelf (COTS) electronic components are used in the Integrated Circuits in nuclear RVs. However for critical functions special components are developed. These are designed and tested so they can withstand solar radiation and the radiation from other nuclear weapons. Just as commercial IT components have radically increased in performance, so the special components designed by Sandia Laboratory for nuclear weapons have also become more powerful. The size of Sandia's SRAM memory for nuclear warheads increased from 1 kb in 1976 to 250 kb in 1996 and to 1 Mb by 2002.[28]

One reason that the Mk5 AF&F is more advanced than the Mk4 is because of its computing system. But by today's standard the computer in the Mk5 is very basic. The programmer in the Mk5 AF&F has 2 kb SRAM.[29] The Mk4A uses SRAM of at least 1 Mb, 500 times greater.

Between 1999 and 2003 Sandia developed the CMOS7r radiation-hardened Silicon-on-Insulator (SOI) processor.[30] For the Mk4A AF&F they designed the Permafrost Integrated Circuit. These circuits are used in the radar Digital Signal Processor, the main logic board and the driver of the Mk4A AF&F. Permafrost has been described as "the brains of the W76-1 warhead".[31]

A crucial element in the RUPL fuzing system of the Mk5 is the computer system. This performs the calculations needed to adjust the point at which the warhead is detonated. Because of the high speed of the RV these calculations must be made very quickly. With its substantially increased computing power the Mk4AF&F will be able to make more complex calculations. So it can probably correct downwind errors in its trajectory at least as well as the Mk5 system.

A diagram of the fuzing system proposed for the Mk4A shows that the intention was to use an accelerometer in the AF&F.[32] Considerable effort was put into developing the new Digital Signal Processor for the radar on the new system.[33]

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[27] Project details for W76 replacement AF&F, DOE science accelerator.
[28] http://www.osti.gov/bridge/servlets/purl/642714-4ocUvd/webviewable/642714.pdf
http://isandtcolloq.gsfc.nasa.gov/spring2002/presentations/knoll_4-30-02.pdf
[29] W88 Integrated Circuit Shelf Life Program, Sandia Report SAND98-0029, January 1998.
[30] http://isandtcolloq.gsfc.nasa.gov/spring2002/presentations/knoll_4-30-02.pdf
[31] http://www.sandia.gov/mission/ste/capabilities/cap_cover.pdf
[32] Survey of Weapons Developments p566; The Burst Height Compensation patent shows that as an alternative to an accelerometer it would be possible to use several radar fixes.
[33] http://www.sandia.gov/LabNews/LN07-23-04/labnews07-23-04.pdf

The antenna on the Mk5 operates at different frequencies from the Mk4. The review of warhead options in 1994 pointed out that this was an issue that would have to be addressed in the design of the radar system for the Mk4A:

> "The new AF&F is based on the radar technology from the W88. The Mk5 radar operates at different frequencies than the Mk4 antennas are designed for. Whether it would be better for the new radar to operate at the Mk4 frequency (compatible with the Mk4 RB RF system) or operate at the Mk5 frequencies (compatible with the Mk5 radar, but not compatible with the Mk4 antenna cavity) has not yet been evaluated."[34]

[34] Alternate Warhead Study p 7-45f