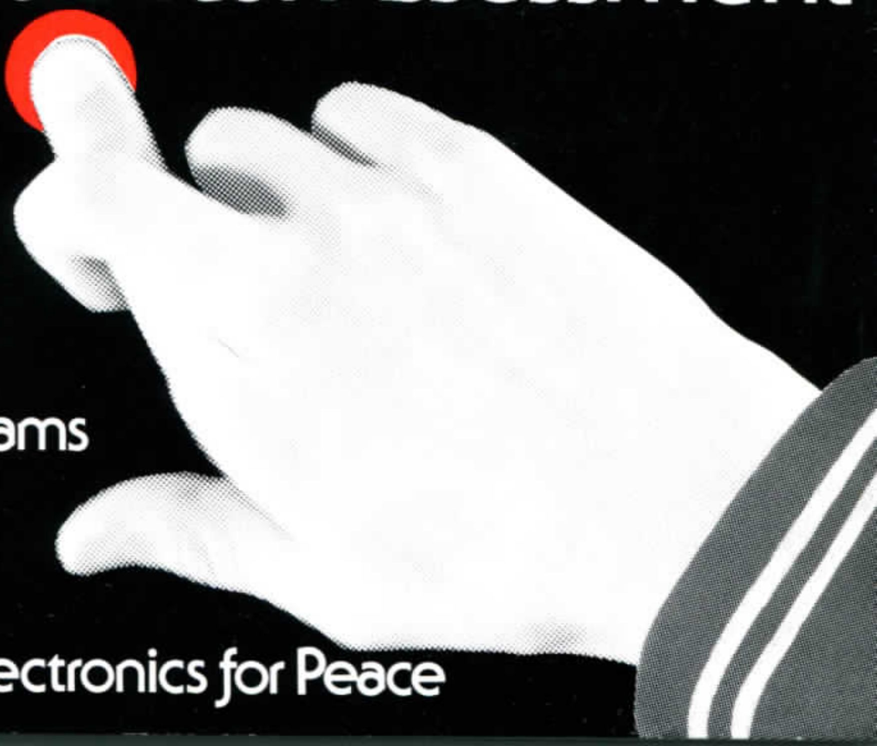
THE GROUND LAUNCHED CRUISE MISSILE

A Technical Assessment



Tim Williams

Electronics for Peace

ISBN 0 946 862 00 1

Published by Electronics for Peace, 151 Courthouse Road Maidenhead Berkshire

Designed by Paul Mepham
Typset and printed by Redesign, 9 London Lane E8

THE GROUND LAUNCHED CRUISE MISSILE

A Technical Assessment

by Tim Williams

Electronics for Peace

ELECTRONICS
for PEACE
151 Courthouse Road,
Maidenhead, Berks SL6 6HY

The global arms race is driven in large part by the technological sophistication of the weapons themselves, in which the electronics industry plays a key role. The Electronics for Peace network was formed in November 1982 to link those working in electronics and computing who share a concern for the military implications of their profession. Its aims include:

- opposing the involvement of the electronics industry in the arms race
- promoting the peaceful, socially appropriate uses of electronics
- making available technical information to those working in the disarmament movement

It publishes the EfP Journal quarterly. It has no political or other affiliations, and exists purely to keep its members in touch and active.

Tim Williams, BSc. (Eng), is an electronics design engineer working in the process control industry. He gained his degree from Southampton University in 1976 and has since been active in a number of environmental, anti-nuclear and disarmament groups. He is a co-founder of Electronics for Peace.

Acknowledgement must be made to: David Guinness, Chris Hobbs and others of EfP, John Page and Owen Green of SANA, Malcolm Spaven and others at ADIU, Graham Richards, Paula Williams and Brian Yates for their advice and help in determining the final shape of this study. Final responsibility is of course the author's own.

Contents

Introduction

The deployment in Europe of the Ground Launched Cruise Missile (GLCM) by the US Air Force is a decision which has aroused considerable political controversy, principally because it radically alters and destabilises nuclear strategy in Europe and makes verification of arms control agreements virtually impossible. Also, the deployment is viewed as a political move rather than a response to a particular military requirement.

This booklet is not concerned with the political and strategic questions surrounding GLCM deployment. These have been well covered elsewhere[1]. Instead, it seeks to investigate the technical characteristics of the missile, its launch platform and associated systems, from the point of view of the host country which is expected to accept their presence on its soil.

Nuclear weapons, both American and British, have been stored in the UK since their inception. Despite stringent safety precautions, they have been subject to their fair share of accidents. A frequently cited "near miss" was the July 1956 B-47 crash at Lakenheath, Suffolk, in which three nuclear weapons in storage were damaged;[2] had the high-explosive component detonated, part of East Anglia would have become a radioactive desert. This, along with other more serious accidents (see later) led to a continuous series of improvements to nuclear warhead safety devices, and to the abandonment of nuclear bomber airborne alert flights.

However, the GLCM system is qualitatively different from other presently-deployed nuclear weapons systems. Not only will the warhead components be stored at its main operating base, but in times of "heightened international tension" it will be moved around the country with the warheads fitted. Thus any part of the country within operational reach of the bases – which in practice means most of Southern England – will be subject to the risk of an accidentally-triggered radioactive discharge, in addition to the risk of a pre-emptive "blanket" strike by the Soviet Union that such a deployment policy entails. In the light of this it would seem reasonable to raise a number of questions relating to the safety and reliability of the GLCM system as a whole.

A 1981 review of the cruise missile programme observed that "the primary selling point was low cost. Because the weapon was a one-shot deal, expected to perform only once and then for a few hours at most, cheaper materials, lower manufacturing tolerances, and other shortcuts could be made in design and production."[3] The author was listing its advantages over manned aircraft. But if this approach permeates the entire cruise missile project, what effect has it had on safety and reliability?

Other factors, to do with the actual performance of the system, combine to raise further doubts. It will be seen later that, because of the insistence on early deployment, the first missiles will be installed with a "less than optimum" software configuration. The low power of the miniature turbofan engine, and the fact that its terrain-following radar altimeter looks downwards not forwards, do not allow the missile to fly at the low altitudes required for radar invisibility without the danger of it crashing into hillsides. Guidance maps of sufficient quality and quantity for targeting the Soviet Union will not be available for some years; when they are, it is not certain that they will be sufficiently accurate to compare with the maps used in testing. All these instances of criticism of the system give the impression that it is being rushed into production and deployment without sufficient testing. If this is the case, what assurances to the European public have that they are not being sold a turkey on the back of a political requirement?

The rest of this study will be devoted to an examination of the technical aspects of the GLCM system. It must be remembered that the GLCM is only part of the total US cruise missile program. Air-launched and sea-launched versions are also being built, and an advanced cruise missile is in the pipeline, which will have improved range and "stealth" (low radar visibility) capabilities. The ALCM is already in operational service (since December 1982) on converted B-52s based in the US; around 1700 of these will be built in total. The sea-launched version has three sub-variants: nuclear land attack (very similar to the GLCM), anti-ship and conventional land attack (though the future of the latter is in some doubt). These three, and the GLCM, are all built by General Dynamics, while Boeing is responsible for the ALCM. General Dynamics use the generic name Tomahawk to cover all variants of their cruise missiles. Many of the major subsystems are identical in all versions; relevant experiences from the ALCM and SLCM programmes will therefore be included where appropriate.

The Problem of Risk

The phenomenon of risk in the public domain has two dimensions. One dimension is the probability of a given accident occurring, the other is the magnitude of the consequences of that accident. Thus if we imagine a graphical representation, events such as car accidents, which happen quite frequently but involve at most a few people, would appear in one corner of the graph, whilst accidents associated with nuclear weapons and nuclear power, which have arguably the worst consequences both for people and for the environment but which are intended to occur with an extremely low frequency, would appear in the opposite corner. The notional product of the two quantities is sometimes assigned to the risk of a particular event; by this means it is deemed possible to compare risks of different natures, for example car accidents and nuclear accidents.

This is a spurious equation. One reason is that the concept of the product of consequences and probability of occurrence breaks down when we are dealing with events such as nuclear accidents. On the one hand the consequences are almost literally unimaginable and impossible to enumerate; on the other hand the probability of occurrence cannot be tested, only predicted. The result is akin to trying to multiply an infinite number by zero.

However, a more important consequence follows from this attempt to define risk. This is that those to whom the risk applies–which in the case under consideration is effectively all of us – are not in a position to judge the nature and magnitude of the risk individually. Knowing that the consequences of an accident are enormous, we are forced to accept the experts' pronouncements that they have made the system safe enough, by reducing its probability of accident to a minimum. In a field as emotive and as technical as nuclear weapons, this would be difficult enough to do with an expert who was trusted implicitly, because of the problem of determining a value for the actual probability. We can add to this the difficulty of trusting the expert to have defined "safe enough" in terms satisfactory to the individual under threat. In practice such difficulties are resolved, however unsatisfactorily, by delegating trust to an institutional framework within which the expert is expected to operate. This is one reason for the existence of the engineering institutions, and the status of chartered engineer.

Such a solution assumes that the institutional framework acts in such a manner as to retain that trust. Once it starts "getting it wrong", in ways that ordinary people can understand – such as ignoring behavioural faults, assuming that maintenance personnel and operators will invariably follow a set procedure, and so forth – then the less trustworthy in its own field it is naturally seen to be. Once the precarious conditions of public trust in responsible institutions have been breached, then it becomes natural for judgement of risk to be based on the worst possible physical case, since there is no longer any credence given to the institutional behaviour that might restrict that physical possibility to an extremely low probability.[4]

All the foregoing has assumed that the institutional framework which regulates the risk, is both familiar and responsible to those exposed to the risk. However, in the case of cruise missiles in Europe, the institutional framework in question is the American military and American aerospace contractors. Neither of these are familiar to most Europeans. Nor is their responsibility clearly defined. In addition, such information about the *modus operandi* of these bodies as does reach Europe, is not such as to inspire trust in their expertise or reliability.[5] Indeed, in the USA mistrust is itself institutionalised in legal procedure (the "sue me, sue you" syndrome).

An example of the kind of military-industrial politics that goes on can be found in the decision in early 1983 to cut the purchase of Boeing's ALCMs from an original target of 4,348 to only (sic) 1,499. The official reason given for this was the need to speed procurement of the advanced cruise missile (ACM) to counter "improved Soviet air defenses"; to everyone's surprise, the ACM contract was given to General Dynamics, not Boeing. Suspicions are that the real motive for the switch was as a punishment to Boeing,[6] who had caused the Air Force considerable embarrassment the previous year when they had mounted a spirited campaign to win the C-5A strategic transport aircraft contract from Lockheed, whom the Air Force favoured. Lockheed eventually won, but only after a bitter fight which caused the Pentagon a lot of trouble. The ALCM cuts are being interpreted as a sign to other defence contractors not to mess around with the service bureaucracies.

General Dynamics is now the US government's prime defence contractor; in Fiscal Year 1982 it received $5,900m of defence work compared with McDonnell Douglas' $5,600m.[7] (As a comparison, the UK's largest defence contractor, British Aerospace – who in 1979 told the government that they could build an all-British cruise missile – had outstanding orders with the MoD worth a total of around £1,370m at the end of 1980.) Its main contracts (besides Tomahawk) are the F-16 fighter, the M-1 tank and the Trident and other submarine programmes. A corporation of that size and with that amount of political weight is not going to be coy about having its way. As one financial commentator ominously put it, "about the company's only near-term risk right now is some kind of broad disarmament program. And that is not much of a risk."[8] With this kind of military-industrial-political background, the European public can be forgiven for being critical of the stationing of untried American nuclear weapons systems in their countries – indeed, can be expected to be critical.

System Description

Ground launched cruise missiles will be stored at, and deployed from, a main operating base. In the case of the UK, these are Greenham Common in Berkshire and Molesworth in Cambridgeshire. The special feature of the base is the GLCM Alert and Maintenance Area (GAMA), a fenced off section where the missiles and vehicles are stored and maintained. This includes a number of hardened concrete Quick Reaction Alert (QRA) shelters, each of which can hold a flight of 16 missiles together with the six principal road vehicles. The shelters are designed to survive an attack with conventional weapons. The crew for the QRA flight is accommodated in the shelter also, rather like a fire station.

The basic operational cycle includes four flights: one on QRA, one training, one undergoing maintenance and one in ready storage. Details of the length of time spent in each phase are not available. Although some maintenance can be performed in a QRA shelter major overhauls take place in a separate Integrated Maintenance Facility (IMF).

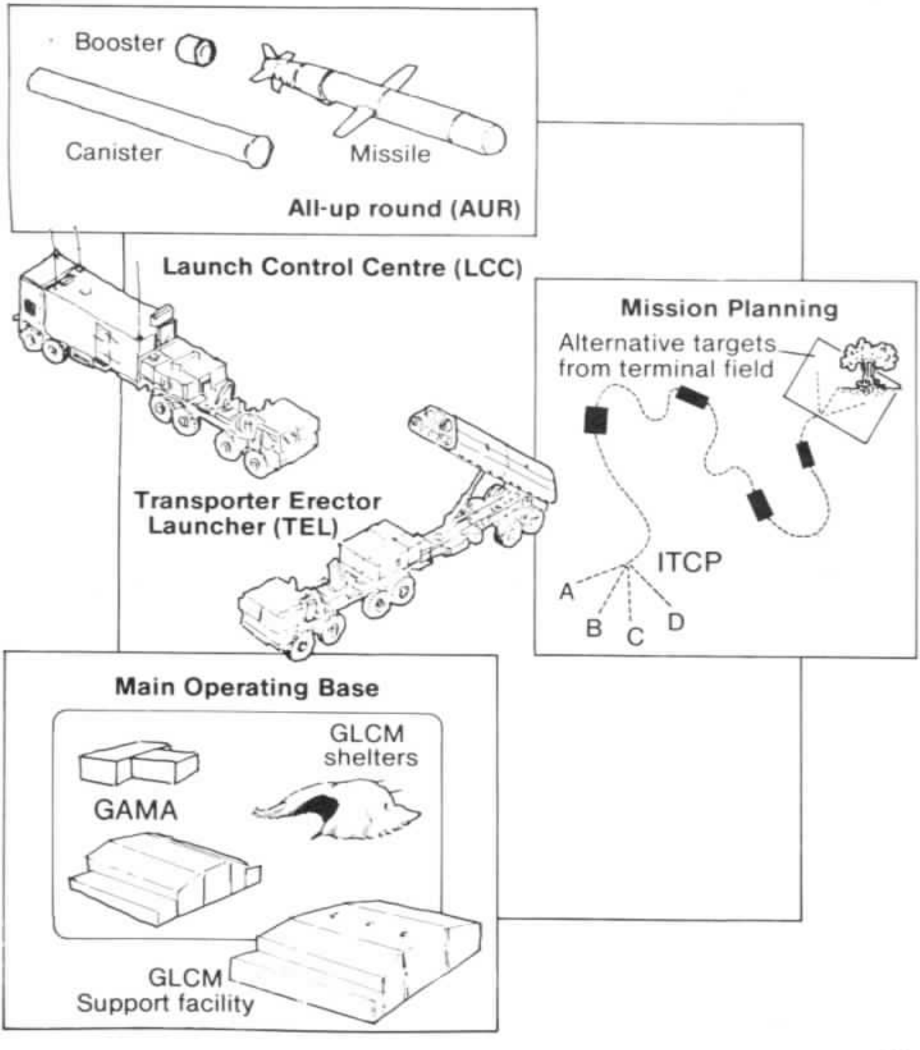
The deployment schedule allows for a European Repair Facility to be built (probably in West Germany) by 1987. This facility will carry out missile recertification and selected intermediate and depot-level maintenance, and will be operated by the contractor rather than the Air Force. Production deliveries of the missile are expected to be complete (560 rounds, 464 located in Europe) in 1988, with peak deliveries in 1985. In June '83, the unit cost of the missile – which includes a proportion for its launch infrastructure – had reached \$6.4m, an escalation of nearly three times its original estimate of \$2.2m.

The Convoy

The flight of 16 missiles is carried by a convoy of 22 road vehicles manned with a complement of 69 people, 44 of whom are security personnel. In the UK, the RAF Regiment will be providing some personnel, but it is not clear whether these are merely for base security or if they will accompany the convoy. The missiles themselves are carried by four Transporter-Erector-Launchers

(TELs) taking four missiles each. Control of these is provided by two Launch Control Centres (LCCs) – one for primary use, the other as a backup. Armoured personnel carriers and various maintenance and supply vehicles make up the other 16 vehicles of the convoy. It is not expected that the convoy would move more than 100 miles from its main operating base. All the vehicles have some capability for cross country travel.

The convoy will travel in two "critical elements" – one LCC, two TEL, plus support vehicles – to the dispersal site, each of which will take one flight, in order to increase the flight's "survivability" en-route. The sites will be pre-surveyed during peacetime, presumably covertly to avoid compromising specific positions. Sites earmarked for wartime deployment will not be used for peacetime exercises.

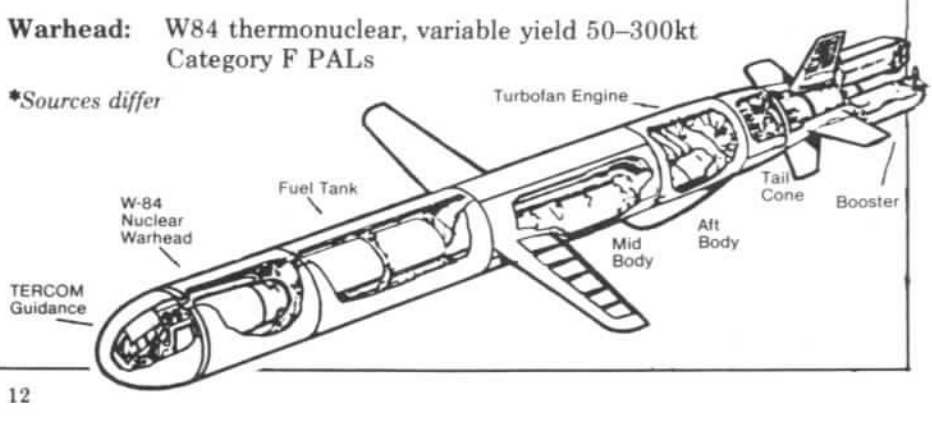


Tomahawk Missile Specifications[10]

Weight (with booster) 3,200lb (1450kg)
Length (with booster) 20.5ft (6.2m)
Max diameter 21in (53cm)
Wing span 8.6ft (2.6m)
Cruise speed .... up to 550mph (880km/hr)
Cruise altitude 1500–3000m
Terrain following altitude 30–100m*
Operational range .... 1500 miles (2500km)
Fuel payload .... around 1300lbs TH-Dimer

Engine:	Williams Research F-107-WR-400 two-shaft dual-flow turbofan / Weight 130lb (58.5kg) / Length 80cm / Diameter 30.5cm / Thrust 600lb (270kg) max, 300lb in cruise flight / Specific Fuel Consumption 1lb fuel/lb thrust/hour
Booster:	Atlantic Research Mk 106 Mod 0 / Thrust 8000lb (3700kg) Solid propellant grain Arcadene 228G
Guidance:	TERCOM Assisted Inertial Navigation System Main Contractor McDonnell-Douglas Astronautics including: Litton 4516C computer with 64k-word memory, Litton LN35T inertial system with P1000 platform, Honeywell 48GHz radar altimeter, 13-15° beamwidth, Weight 81lb (37kg) Inertial error ±900m/hr Navigational accuracy 50–200m*
Actuation systems:	fin deployment – electrical wing & engine inlet deployment – pneumatic booster separation & cable guillotine – pyrotechnic
Warhead:	W84 thermonuclear, variable yield 50–300kt Category F PALs

**Sources differ*



Launch Vehicle Specifications

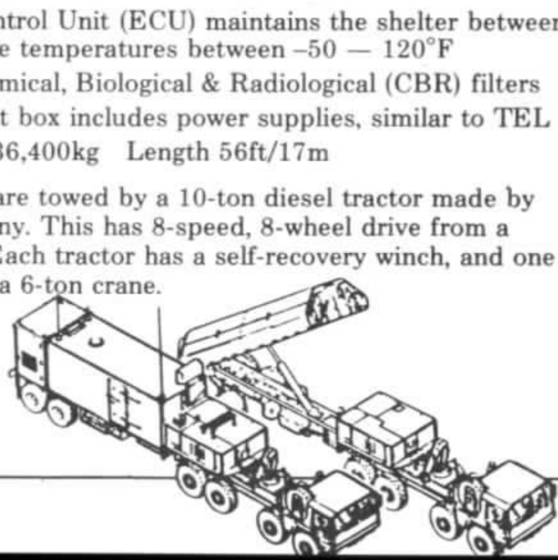
Transporter-Erector-Laucher (TEL)

- Four all-up rounds carried in armoured body section
- Body section can be raised 45° to horizontal by electromechanical lift mechanism
- Missiles loaded through rear armoured doors
- Doors swung open before launch; missile bursts through front of canister when fired
- Forward equipment box includes: weapon control system, gas turbine power generator, battery assembly, control panels
- Fibre optic cable data connection to LCC
- Weight: 77,900lb/35,400kg without missiles
- Length: 55ft 8in/17m

Launch Control Centre (LCC)

- One main, one as standby
- Radio communications: HF/SSB, VHF/FM & UHF units
- Antennas: HF, VHF, UHF whips, UHF satellite rectangular, VHF deployable, UHF satellite hemispheric (omnidirectional)
- Omnidirectional UHF antenna allows Emergency Action Message (EAM) to be received via satellite while convoy in transit
- Highly automated common weapon control system, handles all 16 missiles simultaneously in all pre-launch phases
- Control system software programs the missiles with launch position and target from instructions fed in by the two-man crew
- EAM and action by both crew members needed to launch missiles
- Environmental Control Unit (ECU) maintains the shelter between 65–80°F for outside temperatures between –50 — 120°F
- ECU contains Chemical, Biological & Radiological (CBR) filters
- Forward equipment box includes power supplies, similar to TEL
- Weight: 80,000lb/36,400kg   Length 56ft/17m

Both LCC and TEL are towed by a 10-ton diesel tractor made by MAN of West Germany. This has 8-speed, 8-wheel drive from a 365hp V-10 engine. Each tractor has a self-recovery winch, and one tractor per flight has a 6-ton crane.



Guidance and Mission Planning

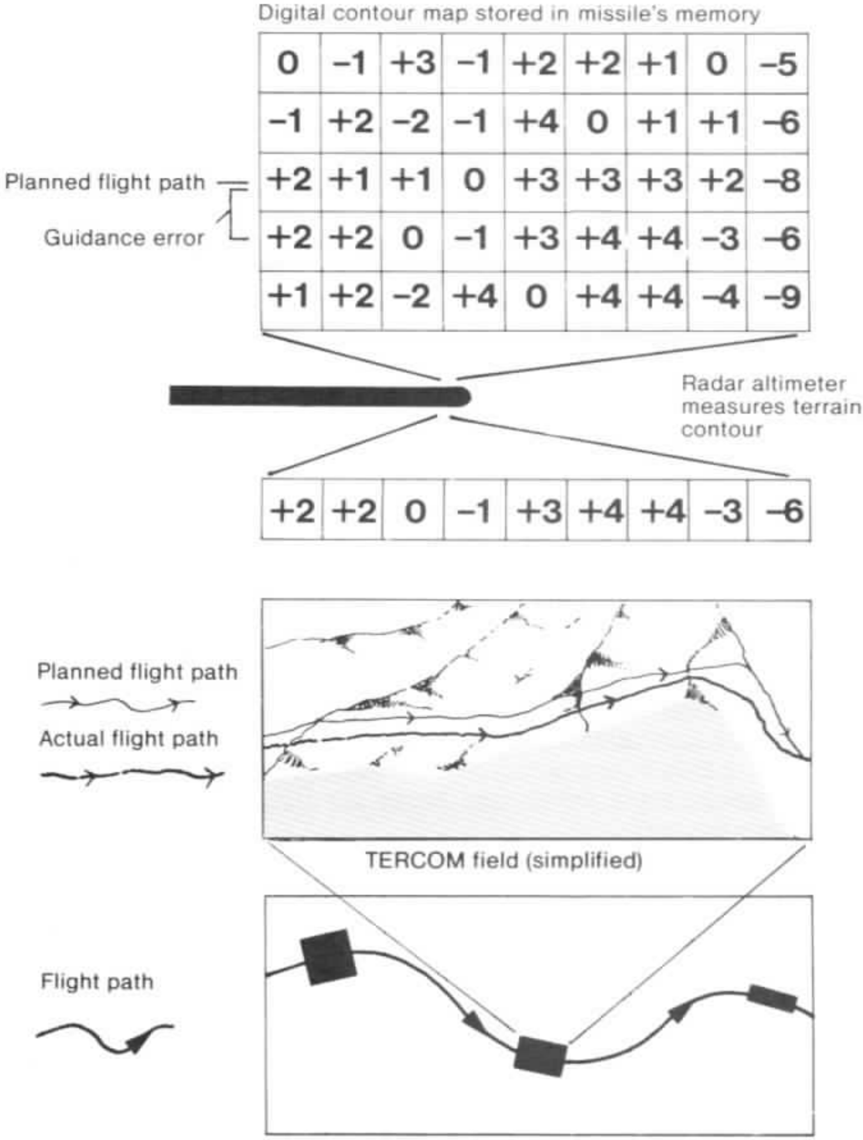
The GLCM is intended to be launched from a number of different but pre-determined launch sites, fly across Europe and into the Soviet Union, and there to strike at one of a number of different but pre-determined targets, with a terminal accuracy of around 50 metres. To achieve this it uses two complementary guidance techniques: inertial navigation and Terrain Contour Matching (TERCOM). The first technique is already widely applied in other missiles and manned aircraft, but the second is unique to Cruise.

Once launched, the missile flies out to its initial timing control point (ITCP), at which point its inertial guidance computer is reset. Inertial navigation works on the principle of continuously measuring acceleration, integrating it to give velocity, and integrating again to give distance from a reference point. Its accuracy is limited by drift of the double-integration circuitry over time: ie, the longer the flight time, the less accurate the inertially-derived position. The inertial system is therefore reset at various points along the route by a series of TERCOM measurements.

The TERCOM system incorporates a radar altimeter and a computer. When the inertial system needs updating, the radar altimeter measures the height variations – in the form of a string of differential readings, rather than absolute values – of the terrain over which the missile is flying. This data is then compared by the computer with a digitally-stored table of height data which represents a "map" of the area over which it should be flying. In most cases a TERCOM field consists of three closely spaced maps. If at least two of the three fixes agree, the computer issues instructions to reset the inertial system to the new position and to carry on to the next update area. Obviously the combination of inertial drift and size of the TERCOM field must be such that the missile does not miss the field completely and hence lose its update. The navigation system has been compared to a very narrow road map: if you get off the road you're supposed to be on, you're totally lost. However, the inertial drift is measured at each update and allowance is made for it in subsequent course instructions. Thus the missile should get progressively more accurate as its flight progresses, and the TERCOM fields which start out several miles wide reduce to a few tens of yards at the final update.

The digital TERCOM maps are therefore the heart of the guidance system of the GLCM. They will be produced by the Defense Mapping Agency (DMA) from satellite data. However, the actual route chosen for each missile is determined by a central mission planning facility which takes targets nominated by SACEUR (Supreme Allied Commander Europe), information on Soviet air defenses from the Defense Intelligence Agency, and missile performance data from the prime contractors (General Dynamics and McDonnell-Douglas Astronautics) and combines these with terrain data from the DMA to come up with the best route. Clearly this process will take several tries to produce the optimum, or even a possible, route. Reports say that adequate maps (for operational purposes) will not be available until 1986.[11] This is principally because of the magnitude of the task facing the DMA.

A 1982 GAO report[12] on the ALCM said that "planning an ALCM mission is a highly complicated and detailed task requiring some 1,200 inputs for a typical mission. Intended to be a fully automated task using the mission



planning system, this work is currently being done manually with some computer assistance by Strategic Air Command mission planners. A complete test of the fully integrated mission planning system is not planned until after initial operating capability." (Toomay[13] suggests that five thousand maps of 150-by-150 data points would require that over 100 million data points be gathered, evaluated for average radar altimeter characteristics, digitized and assembled into TERCOM maps. He quotes the cost of map generation to be around a billion dollars for the whole cruise missile programme.)

Failure Modes

Each of the component parts of the GLCM system can fail in a number of ways. It is the purpose of this section to attempt to identify some of these modes and to investigate the nature of the risks posed by them.

The Tomahawk Missile

From the point of view of the civilian population in the locality of the flight convoy, the risk of spurious detonation of the warhead is the most central aspect of its safety. Discussion of the missile and its TEL will concentrate on this theme. In the immediate vicinity there is the additional crash risk posed by the heavy vehicles, and the fire hazard from the missiles' fuel payload.

While the GLCM convoy is dispersed, during an alert condition, its missiles will have to be fitted with live warheads. The British Government has stated[14] that no live missiles will be used on exercises and there will be no test flying in the UK. (The western states of Canada – Saskatchewan, Alberta and the Northwest Territories – are expected to be used for test flying of ALCMs, though many Canadians think otherwise.) However the American military will be responsible for the conduct of the exercises; and it is not impossible to conceive of an operational situation arising in which live warheads have to be moved. An example of this could be seen in the Falklands war, in which the haste with which the British task force was assembled led to several ships sailing for the South Atlantic with nuclear weapons on board[15] – though this has not been publicly admitted by the MoD. This was in direct contravention of the Treaty of Tlatelolco to which both Britain and the US are signatories. If Britain can ignore a UN treaty, why should the US take note of a British Parliamentary answer?

Operational considerations – notably the fact that missile rounds remain sealed and inaccessible in their protective canisters for several months while on station – may make it more convenient for the USAF to use 'live' rounds on exercise. To employ dummies would put a considerable extra load on their assembly, test and maintenance facilities. Almost certainly, the US government has assured the British government that this will not be the case. Equally certainly, the British government has not insisted on checking. To do so would mean monitoring the assembly of each missile and validating the seal on each launch canister, and would call for a degree of political independence which the present British government has not demonstrated. It would therefore not be too politically dangerous for the USAF to waive their assurances.

Thus the civilian population can, at least under some circumstances, expect to find nuclear warheads trundling past their front door. To what risk does this expose them?

There are two significant possibilities:

– the detonation of the high explosive part of the warhead leading to the destruction of the nuclear component and dispersal of the plutonium;

– accidental arming of the warhead leading to an actual nuclear explosion.

Details of the W-84 warhead (about the size of a large waste-paper basket) used in the cruise missile are of course classified. However the general principle of warhead design and construction is well-known.[16] A hollow spherical shaped chemical charge is fired by a number of electrical detonators igniting simultaneously; the implosive force generated by this charge compresses a core of fissile material to supercriticality. At precisely the right instant a beam of high-energy neutrons is fired into the core to initiate a chain reaction. This "primary" nuclear reaction then triggers a fusion reaction which, in turn, sets off the secondary fission reaction which provides the main yield of the weapon. Thus the actual nuclear explosion requires the accurate co-ordination of several sequences of events, which makes the unintended activation of these in the correct order unlikely (though not impossible) in an accident scenario, even if the warhead had been accidentally or deliberately pre-armed.

In other words, full nuclear yield would require that the arming and firing sequence be carried out precisely and completely. The design requirement is that the weapon should have a less than one-in-a-million chance of exploding during an accident.[17] Assessing whether this level of reliability has actually been achieved is of course something of an academic exercise, since empirical data is hard to come by at that frequency; assessment must perforce be based on computer modelling, whose results are dependent on the base assumptions fed in and cannot be tested. The validity of the one-in-a-million figure is rather dubious.

However, the philosophy behind the protection devices is of interest. Warhead design safety provisions include:

- Category F Permissive Action Links
- Insensitive high explosive
- Critical components encased in steel

A Permissive Action Link (PAL) works along the following lines:[18] two different unique coded signals have to be applied to two separate "strong link" switches before the warhead electrical system is activated. One of these signals is generated by human action at the launch centre, the other by the launch environment. In the case of the cruise missile, final arming is dependent on the correct sequence of in-flight events, of which the launch environment is one.

Packaged together with the strong link switch – which is designed to withstand quite severe accident conditions – is a component called the "weak link". This component is essential to generating the energy to fire the weapon detonators, but is designed to fail at environments much less severe than the strong link can withstand. Thus by packaging the two together, whatever the nature of the pressures or temperatures resulting from an accident, the components will fail in a prescribed sequence: the first one to go is the necessary one to make the warhead go off, and the second to fail is the one that holds off any firing signals.

Thus the prospect of actual warhead detonation is limited principally to the prospect of the necessary coded signals being spuriously applied to the PALs, which is a software reliability problem; or of the PALs simultaneously failing "on", which is a consideration principally of their quality of manufacture.

All US nuclear warhead components are finally assembled at one plant, the Pantex facility at Amarillo, Texas, which is operated for the Department of Energy by Mason and Hanger-Silas Mason Co. The PALs are made at the Kansas City plant of Bendix Corp. We can be fairly sure that quality control procedures at these plants are among the most stringent in the world.

The possibility of spurious generation of the two coded signals is more serious; after all, it must be possible to generate them at some point or the weapon would not work at all. One of them will be generated by the common weapon control system at launch from the combined instructions of the two launch officers. The GLCM common weapon control system software is known to be causing problems (see later). The other will be generated by a microprocessor-controlled arming sequencer (developed jointly by Sandia Labs and McDonnell-Douglas Astronautics) when it believes that 24 different in-flight events have been carried out. Reliance on microprocessor control for a function as critical as this is risky. A latent, undiscovered software bug could bypass the sequencer completely, allowing the missile to be armed at launch; a hardware fault could do the same. As is shown in the section on hardware reliability, advanced components such as microprocessors and memories may not be available to full military specifications. The speed with which the software has been developed means that latent bugs are a real possibility.

A greater threat, in the sense that it is probably more likely to occur, is posed by the triggering of just the high explosive (h.e.) component. The h.e. is described as "insensitive", by which is presumably meant insensitive to shock. However, the warhead is located next to the jet fuel payload in the missile. An accident which involved the burning of this fuel might detonate the h.e. in the heat. Whatever the cause, an accidental h.e. detonation is quite possible: eleven of the 32 serious accidents involving US nuclear weapons over the period 1950–1980, reported by the US Department of Defense, included high explosive detonations.[19] Though it is true that modern explosives are comparatively more stable, and jet fuel is not as volatile as liquid rocket fuel.

The consequences of such an accident are fairly simple to describe. The explosion would destroy the missile and pierce the launcher assembly's armoured cladding. The plutonium inventory of several kilograms would be vapourised and dispersed on the wind over the surrounding countryside. Pu-239 has a half-life of 24,131 years; a speck of dust weighing one microgram, if ingested or inhaled, is enough to induce fatal cancer. The implications may be judged from the aftermath of the infamous Palomares incident. On January 17th, 1966, a B-52 carrying four H-bombs crashed after a mid-air collision over Palomares in southern Spain. Two of the bombs scattered plutonium over the surrounding fields when their high explosive material detonated. Estimates for the amount of radioactive soil and vegetation removed range up to 1,750 tons. By 1967, a US commission had settled 522 claims by Palomares residents totalling $600;000. Two years later, after a similar accident near Thule, Greenland, some 237,000 cubic feet of contaminated ice, snow, water and crash debris had to be removed to a storage site in the US during a four-month clean-up operation.[20]

(Plutonium is not the only contaminant: an H-bomb also includes a capsule of tritium which though less long-lived, is more volatile.)

The Transporter-Erector-Launcher

The principal danger relating to the TEL, while it is carrying four missile rounds in its launch assembly, is that of crash damage leading to damage to the missile AURs as described above, or equipment malfunction.

The TEL is a very large, heavy vehicle (35.5 tonnes, 55ft 8in long), ie definitely in the juggernaut class. (For comparison, the Armitage report of December 1980 recommended increasing maximum lorry weight in the UK from 32.5 tonnes to 44 tonnes. A compromise of 40 tonnes was eventually adopted.) Its drivers will, particularly if they are driving out on alert, be under psychological (and possibly narcotic – see later) stress, be driving left-hand-drive vehicles along unfamiliar roads in a foreign country, and will probably be using roads which are unsuitable for heavy vehicles – if the requirement for a concealed dispersal site is to be met. A further point is that British HGV driving standards are generally very high, and USAF drivers will not have been trained to the same degree. These conditions must be conducive to a fairly high risk of accident. It can be assumed that the convoy escort – sixteen support vehicles per convoy, which is split up into two "critical elements", travelling separately – will be able to pre-empt normal traffic hazards, though whether they could deal with a determined and deliberate sabotage attack is open to question.

In November 1982 an accident involving a Pershing 1 transporter caused the evacuation of 1,200 residents of the village of Waldprechtsmeier near Karlsruhe in West Germany. The accident, which killed one civilian in an oncoming car, was reportedly caused by brake failure. The evacuation was prompted by fears that the highly inflammable propellant of the Pershing missile could explode.[21] While the cruise missile's propellant is not so unpredictable as rocket fuel, four missiles carrying a total of two and a half tons plus solid booster fuel would be a formidable problem for the emergency services to cope with.

The TEL power unit, on the front section of the trailer, will be particularly susceptible to crash damage, if the vehicle jack-knifes, for example. This unit includes the weapon control system, which is responsible for the successful programming and launch of the missile,next to a gas turbine power generator. Moreover, the control panels are all at the front of the power unit housing and therefore exposed to impact. Possibly the most serious circumstance here would be a minor collision, such as striking the side of a building, which damages the power unit and impairs its subsequent operation without being obvious; in other words the convoy personnel would notice a crash and take appropriate action, whereas a small bump which nevertheless damages the sensitive equipment within may be ignored. Indeed, reports that the manufacturers are experiencing serious problems[22] – apparently because of the need to marry sophisticated electronics with vehicles able to travel on rough ground – suggests that this factor is causing headaches even *before* the trucks hit the road.

The other possibility which should be considered, and which is affected by reliability considerations in all three of the sub-systems – the AUR, the TEL and the LCC – is a launch accident. This would be caused by a hardware failure: for example in the booster section or the fin/wing deployment or engine inlet deployment systems of the AUR, or a failure in the launch control system of the TEL or LCC. A perfect launch takes 14 seconds to the start of cruise flight, during which the rocket booster is firing and the fins, wings and engine inlet are deploying. If this sequence of events did not happen correctly – and given the test results some missiles would be sure to fail soon after launch – the missile would plunge back to earth, perhaps close to, perhaps many miles from the point of launch. The result could be the destruction of the warhead in the manner described earlier, by detonation of the high explosive component.

The fin, wing and engine inlet deployment systems rely on a combination of pyrotechnic, pneumatic and electrical actuators. The four tail fins are electrically actuated. The wings and engine inlet are pneumatically actuated, the pneumatic pressure being derived from a gaseous nitrogen bottle, and the control valves being operated by explosive charges. Booster separation is pyrotechnic, and the engine uses a pyrotechnic starting cartridge; booster thrust vector control, which determines the initial trajectory of the missile before it starts cruise flight, uses another gaseous nitrogen pneumatic system.[23]

The seventh test of the GLCM in December 1982 failed when the missile's engine inlet did not deploy. Or, as the American magazine Defense Week somewhat gleefully put it, "during a December trial, the ground-launched model "went into the dirt," says a chagrined Navy expert, because a scoop which supplies air to its turbofan engine failed to drop into place after the missile's booster rocket disengaged. The scoop is operated by a bottle of compressed nitrogen "and we're checking for leaks"."[24] Perhaps because of the unreliability of the pneumatic system, the cruise designers admit that in retrospect they would probably have selected pyrotechnic actuation and suffered a slight loss of testability.[25] Some doubts have been expressed about the reliability of the AURs after long periods of dormant storage[26] – leaky gas bottles, plus the possibility of engine corrosion, could be two contributory factors.

The Launch Control Centre

Safety aspects of the LCC are not relevant until the convoy has arrived at its dispersal point and connected the LCCs and TELs together, except that it too is a juggernaut (slightly heavier than the TEL at 36 tonnes) so that the comments made above apply equally to it, with particular emphasis on non-obvious, incidental crash damage. The major concern here is that a malfunction of the LCC could lead to a false launch or a launch accident. This might not need to involved nuclear-armed missiles; for example, an accidental launch on exercise could, if detected by the Soviet Union and if the flight progressed far enough, lead to a serious diplomatic incident or even a retaliatory strike, initiated by launch-on-warning.

Factors that could lead to an accidental launch are

- a hardware or software malfunction, particularly if the launch sequence had already progressed some distance through its preparatory stages. The conditions for launch once an Emergency Action Message is received are that the warhead is unlocked and pre-armed, the booster is armed and the guidance has been programmed. We can note here that the environment within the LCC cabin is closely controlled by the environmental control unit (ECU) mounted to the rear of the cabin, which contains an air conditioner and CBR filters for the benefit of the crew. The LCC suite includes a sophisticated weapon control system (linked to each TEL) which may be affected by a breakdown of, or damage to, the ECU, particularly if it is designed to operate in a controlled environment. It is this weapons control system – intended to handle all 16 missiles simultaneously in all phases of prelaunch preparations – which has been holding up the GLCM testing.

As well as preparing each of the missiles' hardware for launch, the control system must also calculate the flight path from the launch point to the starting point (ITCP) for each mission, and transfer this and all other mission data down the fibre-optic link to the TELs and thence to the missiles themselves.[27] Because this system is peculiar to the GLCM, experience gained in other parts of the cruise missile programme cannot be applied here. (Though it is worth noting that some failures of ALCM test flights were attributed to faulty pre-launch software aboard the B-52s.) As a result of this, plus the fact that all this sophisticated equipment has to ride in an armoured vehicle capable of negotiating rough terrain, production of the LCC and its operating software is running into considerable problems.

● crew error. Missile launch requires the simultaneous action of both crew members. However, several observers have commented on the psychological effects of stress on missile crews. Dumas[28] quotes a former missile crewman, "under near maddening conditions of isolation, boredom and frustration, missile crews develop a different perspective than superiors . . . A crew member tries not to think about his ultimate responsibility, which could lead to the killing of millions of people . . . He learns to contrast his personal feelings and the role he is expected to play, unquestioningly and automatically . . . He tends to see his personal life and official life as totally separate, the launch officer becomes schizoid." In each of the years 1975, '76 & '77, around 5000 people each year were removed from the nuclear forces under the Human Reliability Program for reasons including drug and alcohol abuse, and aberrant physical or mental behaviour. Which raises the question: how many "unstable" crew members does the Human Reliability Program *not* screen out?

It may be argued that conditions in a Launch Control Centre cabin are not the same as in an ICBM missile capsule. However, considerations of mission security are likely to dictate that once the convoy has reached its dispersal point and having set up, is awaiting the message to launch, its launch crew will be as isolated from the rest of the world as if they were in an ICBM capsule. In addition they have to face the insecurity and vulnerability of being exposed to a "blanket" enemy nuclear attack with a comparatively fragile life-support system (in the form of the environmental control unit). It is also noticeable that although provision is made for the crew's toilet needs, there does not appear to be any provision – in terms of food supplies – for an extended stay on station. Conditions inside the LCC are extremely cramped – virtually the whole of both side walls are taken up with computer and communications equipment, leaving only a narrow strip maybe three feet wide down the middle for the crew to move in. There are no windows.

Indeed, the whole concept of the convoy has been inadequately thought out in terms of human requirements, for the support personnel as well as the launch officers. Under these circumstances, and given the prevalence of personnel problems (drug taking, alcoholism, mental instability) in the US military as noted by Dumas,[29] there may be grounds for doubting the predictability of response of the launch crew.

● a final factor is communications failure. Theoretically the crew have to receive an Emergency Action Message before launch preparations are permissible. The LCC is provided with communications at HF to US national ground and airborne command posts, US Air Force Europe in Germany, and SHAPE (Supreme HQ Allied Powers Europe); at VHF/UHF to its main operating base, and at UHF via the USAF's satellite network to the US European Command. Thus there are several redundant communication pathways. However, it is possible that under conditions of abnormal radio interference or jamming, or perhaps due to equipment failure, the LCC may not receive a correct EAM or may conceivably receive a false one. It is equally conceivable that, with several separate links, the crew may receive contradictory or confusing messages. Whether or not this would lead to a false launch is debatable, but the fact remains that the Command, Control & Communications (C^3) network is the most fragile part of the entire western nuclear weapons system.[30]

Much of the concern over C^3 has centred on its inability to survive a nuclear strike, due to the effects on the equipment of the electromagnetic pulse and on the ionosphere of the ionizing radiation, plus considerations of radiation hardening of the equipment. Such questions are outside the scope of this study, which is concerned with reliability before a nuclear strike. However, a 1981 GAO report[31] noted that the GLCM communications link was potentially vulnerable to enemy jamming. It acknowledged that the equipment was being developed to resist such jamming; however, the accepted technique for communications jam-proofing, known as frequency hopping, has only this summer gone into production in the US with the award to ITT of the contract for the SINCGARS VHF system. (British companies such as Racal and GEC are already marketing frequency-hopping radios, but not to the US.) Therefore early versions at least of the LCC will not have jam-resistant communications; even when it is installed, frequency hopping does not ensure immunity if an enemy is prepared to jam a large band of frequencies.

Finally, because of the long lead times inherent in developing complex military systems, the Pentagon is trying to get equipment into the field faster by emphasizing the use of off-the-shelf commercial communications equipment.[32] This may well be used in the LCC since it does not have to put up with the arduous environmental conditions encountered in most military applications, and because the short time-schedule for the GLCM cannot tolerate delays in procurement. But this course will bring with it more reliability problems, because commercial equipment generally is built to less exacting standards than fully-specified military equipment.

Logistic Support

The main question here is around the security and stability of the warheads, both in storage at the main operating base and in transit to and from it. The considerations are exemplified by the Lakenheath accident referred to in the introduction, ie how safe is the storage facility from external factors? In fact the storage shelters themselves will be reasonably secure – the government has referred to the construction of underground shelters[33] – however warhead maintenance is performed on-site and it is this sequence of operations (removal, inspection, maintenance and re-installation) which are routine but critical, which present the greater threat.

A 1981 report to the Pentagon[34] revealed that there were 21 "mishaps" at Titan ICBM sites in 1980, of which 12 were caused by human error. The report was submitted after an explosion destroyed a Titan missile in September 1980, killing one technician. It said that the main reason for the increase in accidents was the inexperience of many of the crews who man and maintain the missiles. It was more and more difficult for Strategic Air Command to attract and keep qualified people, and the manpower shortage would be compounded when the GLCM and MX missiles were deployed. Manning in key technical and supervisory positions is low, largely because of a lack of willingness to re-enlist. The report concluded that "personnel comprise a greater safety concern than does hardware".

The ALCM is already running into problems when tested in operational situations. Two operational tests of randomly-selected ALCMs, in December '82 and May '83, failed when the missiles lost their course. An air force official was reported[35] as saying "looking at the development tests, we thought the cruise missile was great. But having a 19-year-old munitions guy working on it is very different from having a Boeing rep, who knows how it was put together." To compound the problem, it is unlikely that the best personnel would be posted to such a minor part of the overall US nuclear weapons program, particularly one removed from the US and whose tactical significance is minimal. And Tactical Air Command, the branch of the USAF who will actually be operating the GLCM, have had no previous experience with ground-launched tactical missiles.

In connection with the stability of the warheads, it is worth quoting some remarks of Senator John Warner, conducting the FY 1983 DoD hearings, on the safety of handling nuclear and chemical weapons in general. In the course of the hearings, he said to some senior military officers, "for example, gentlemen, I visited Tooele, Utah. I presume your stockı iles in Europe are suffering some of the same decomposition problems." to which General Fulwyler of the US Army responded, "you are talking about the chemical stockpiles, sir?" "Yes." General Fulwyler's reply was deleted from the record, but it prompted Senator Warner to say "I really don't want to put this on the record even though it is an executive session . . . If we had an incident needless to say either here in the United States or abroad it would just retard the work that Secretary Perle (Richard Perle, Assistant Secretary of Defense for International Security Policy) and the others are doing on the diplomatic fronts *maybe to the point where it is irretrievable.*"[36] (emphasis added) From which we may infer that the Americans are having serious problems with the long-term safety of their weapons stockpiles.

Mission Planning and Navigation Reliability

Particular criticisms of the cruise missile program in general have been principally aimed at its navigational capabilities. Once the missile has passed its Initial Timing Control Point, it flies from one TERCOM field to the next using inertial navigation, until it reaches its target. The accuracy and drift constraints of the inertial navigation set minimum requirements for the number and resolution of the TERCOM fields that are programmed in during mission planning. A particular problem that is causing concern is whether the terrain of European Russia is sufficiently varied (in height) to permit reliable correlation and identification of a particular TERCOM field, or whether false updates are possible. In fact, large areas of the Soviet Union are flat plain, not suitable for TERCOM. A glance at the map shows that this restricts the number of entry routes to Czechoslovakia and the Carpathians in the south, and northern Poland, Kaliningrad and Minsk in the north, if the missiles are to fly across East Germany; or it must fly across Sweden, a neutral country, to attack the Leningrad area.

Additionally, the data from which the operational maps will be prepared is unlikely to be of as high a quality as that used in testing, which was carried out over US-controlled territory (accuracies of perhaps ten feet are expected from satellite reconnaissance); plus the maps will be susceptible to man-made or natural alteration of the terrain. 86% of the maps of the European operational area show a terrain roughness (height variation) of less than 100 feet, while only 26% of the test maps showed such little roughness. No more than 7% of the operational maps show terrain roughness of greater than 200 feet.[37] In at least one ALCM flight test, a missile cleared a peak by less than 30 feet – more importantly, this peak *did not appear on the computer map.* The US Air Force Test and Evaluation Center (AFTEC) which reported this incident, predicted that "such errors can also be expected in the data base for operational areas."[38]

Theoretically the missile's warhead is only finally armed when it reaches the terminal guidance stage and is about to strike the target. False updates resulting in loss of the flight path should prevent the arming function so that, when the missile finally lands, the warhead does not explode. However, the set of possible flight paths, the likelihood of software faults confusing or misleading the map comparison and the chances of a false update being undetected, given the difficulties of resolving terrain height data to the desired accuracy, all combine to allow the remote possibility that a missile could follow a completely different flight path and end up attacking an unexpected and unintended target.

It should also be mentioned here that the flight event sequence detector and arming mechanism – which requires 24 correct in-flight events before enabling the warhead arming mechanism – was not in the original guidance system specification. It was developed by McDonnell-Douglas in conjunction with Sandia Labs as a "bolt-on goodie", in the early competition to select the guidance system contractor. It is evidently not considered the most critical part of the missile; in the rush to deploy the system, it is possible that its reliability has been compromised.

In fact, the Americans are quite sanguine about the failure of TERCOM. If it proves impossible to obtain a correct update at any point, the missile will continue to fly into the Soviet Union with its warhead deactivated, under inertial guidance only, in order to "saturate" anti-aircraft defences. At some point it will fly into the ground, or get shot down. They are equally unconcerned about its in-flight altitude: "a probability of crash unacceptable in a manned aircraft is entirely satisfactory in an unmanned weapon."[39] Presumably this is because it will be crashing into and contaminating Russian, East European or neutral, rather than Western, hillsides.

Hardware Reliability

The first, obvious, factor applicable to mechanical parts, is wear and corrosion. Any car owner is familiar with these, and knows that they are both held in check by regular inspection and maintenance. Most of the missile's components are not likely to be subject to any significant degree of wear. Corrosion is another matter however, particularly with regard to the miniature jet engine. This component is of extremely advanced design, and although it operates on well-proven principles it does not have the benefit of years of operating experience that accrue to larger engines.

A 1982 GAO report[40] expressed some concern over the long-term reliability of the engine. It said, "the ALCM's 36-month maintenance concept requires that the missile rotate between aircraft on alert status and storage bunkers for periods of 30 months before its engine is removed and tested for 6 months. Initial testing of the engine's storage reliability to validate the ALCM's maintenance concept, however will not be completed until about mid-1983 ... Should the planned maintenance concept *prove too optimistic*, logistics support costs could increase substantially. In its report on preproduction decision testing, AFTEC stated that storage reliability *could not be overemphasised.*" (Emphasis added) It is not clear whether the GLCM follows the same maintenance cycle as the ALCM, but since the engine is common to both versions it is likely that engine maintenance will follow a similar pattern.

A further source of mechanical failure is fatigue due to handling. Many air-launched missiles fail or are taken out of service for this reason. Transporting the missiles across rough ground, particularly with a full fuel load, could fatigue critical components.

Electronic parts do not wear out in the same way as mechanical parts. Although some electronic components do wear out, failure in modern electronic devices is characterised mainly by two phases: infant mortality, where parts fail within the first few hours of operation, and stress-related failure, which can occur at any point in the equipment's lifetime and is due to a combination of environmental and circuit stresses. The first phase is minimised by screening and burn-in of components before they are incorporated in the equipment, and the second is minimised by careful design, derating of components and environmental shielding. Sources of hardware unreliability other than component failures can generally be traced to bad quality control in manufacture, for example mistaken use of the wrong parts, bad soldered joints, insufficiently tight bolts and so forth.

It is instructive to examine the measures taken to protect reliability in the Minuteman III missile, on which one leg of the American strategic nuclear triad rests. Precautions taken in design, development and testing of each missile include:

- screening of 100% of parts
- 250-hour operational acceptance test for major subsystems
- use of highly reliable parts through standardization
- strict review of parts application in circuit design
- the use of a contractor whose only role is to ensure that reliability is implemented.[41]

None of these techniques come cheaply; neither do they lend themselves to long production runs done to a tight schedule. For these reasons it is highly unlikely that they are applied in anything more than a rudimentary fashion to the cruise missile program. The last factor is particularly important. It is impossible at the time of manufacture to be sure that quoted procedures are being adhered to without an independent overseer to keep other contractors in line. The cruise missile program does *not* have an independent reliability contractor.[42]

Component quality control is a continuing sore point. The US Government introduced a program in 1969, known as MIL-M-38510, to allow selected commercial devices that had undergone screening tests to be used in military projects. However the rapid pace of change in the electronics industry, coupled with the long time it takes for new devices to achieve MIL-M-38510 approval, has meant that advanced chips, particularly memories and microprocessors, are being procured to quality standards less rigorous than 38510.[43] At the same time the complexity of these devices makes testing for complete functioning before assembly well-nigh impossible. It is even doubtful that full military approval ensures consistent quality. In February 1982 one of the largest US semiconductor makers, National Semiconductor, was removed from the list of approved suppliers after it admitted taking short cuts in testing military components,[44] though it appears to have crept back on again. The skimping of test procedures was revealed during an investigation by a Federal Grand Jury set up after accidents when computer errors in US early warning systems gave false alarms of nuclear attack.

A result of insufficiently-rigorous quality procedures is that the hermetic sealing of integrated-circuit packages may be suspect. The tiny silicon chip which is the heart of the IC must be sealed off from the outside world to prevent contamination of the highly sensitive surface of the silicon by moisture or corrosive substances. Quality-control specialists at Litton Industries Guidance and Control Divison, who make the inertial guidance system for Cruise, have reported unacceptably high numbers of ICs arriving from the manufacturers with leaky packages.[45] Faulty sealing is particularly serious since it does not cause failure until weeks, months or years after the equipment has been installed. Litton now claim to test all incoming ICs for hermetic sealing, but the size of the problem is threatening to overwhelm quality assurance procedures.

Another cause of intermittent failure in hermetically-sealed ICs and transistors was traced to minute metallic particles moving around inside the package, and causing damage or electrical shorts.[46] MIL-M-38510 tests now include particle impact noise detection. What of those components that are not so tested?

One of the most serious aspects of the cruise missile program to date has been the row over General Dynamics' overall quality control.[47] Aside from the compressed nitrogen incident mentioned earlier, other test flights have failed because a circuit board was improperly mounted, or because of inept wiring. The faults prompted a massive restructuring of the Tomahawk program, which also includes the sea-launched variants, in the latter half of 1982. The director of the Joint Cruise Missile Project Office, Rear Admiral Walter M. Locke, was replaced, as were the top management of GD's Convair division in San Diego, California, which makes the missile. The Department of Defense issued a Method D notice to GD in June '82. This detailed a number of changes in production methods the company was required to make; it is a warning that is issued only in the most severe cases, and includes the threat that the company might lose its contract. Announcing the program restructuring, the Pentagon said that cruise missile problems included "immature manufacturing procedures and practices and quality assurance".

One of the root causes of the problem appears to have been inexperience. GD themselves admitted to problems in transferring the programme from development to production status. The Convair division hadn't had a major contract for over a decade; though their development team were very bright – a decisive factor in winning the Tomahawk contract – they were lacking in production experience. The new management, vice-president John McSweeny and program director Michael Keel, were both from the firm's Pomona division which makes the successful Phalanx automatic gun. But quality control is based on the shop floor, and it is questionable whether a change of top management would be successful in eradicating the problems.

Another factor was the overall project management. Though GD was the prime contractor, the final integration of the missile – bringing together the airframe, guidance package, engine, and launch system – lay with the JCMPO two and a half thousand miles away in Washington. One Pentagon official said that the design and production of the missile had been hobbled by the fact that "nobody was ultimately responsible for seeing that the whole thing was put together properly".

The major effect of the restructuring of the Tomahawk program in early 1983 was to postpone deployment of the conventional land-attack and anti-ship versions, principally as a result of financial constraints. The GLCM was given the highest priority because of the political need for it to meet its December '83 deadline. However, even assuming that all the problems are sorted out, this takes time. A Defense Department official admitted that "it would be better to reduce acceptance of Fiscal 1981 missiles (those that will be deployed in '83/84) until problems are resolved". This does not appear to have been politically acceptable.

What then are the prospects for in-service reliability of the cruise missile and its associated launch and communications system? The US military know quite well that their equipment is prone to failure. In addition to parts and manufacture quality control, military systems in general face other reliability problems:

- military designers are often required to create a "perfect" design at an early stage, in contrast to commercial designers, who tend to use iterative approaches, solving problems as they arise.
- in the case of nuclear systems, military designers get very little, if any, feedback as to the operational success of their system. Test flights are rarely conclusive as the cost of the tests limits the numbers so as to make statistical analysis impossible.
- military systems are expected to operate in harsh environments (shock, temperature, humidity, vibration) which have proved difficult to simulate under test conditions. Experience has shown that some equipment in the field is only about one third as reliable as it was during final test.
- the armed services are chronically short of experienced and qualified operators, maintenance personnel and reliability engineers.
- manufacturers cannot always guarantee the reliability of spare parts or the adequacy of maintenance once the system is in the field.

Maintenance of the cruise equipment is an integral part of its operational cycle: whilst one flight is on quick-reaction alert, another is in ready storage, a third is undergoing training and a fourth is being maintained. Much of the equipment is designed as replaceable plug-in units that can be changed after a fixed time. The electrical and electronic systems contain built-in-test (BIT) functions so that the equipment can regularly test itself.

But there are two major objections to be raised: firstly, the chronic shortage of maintenance personnel, mentioned earlier, does not engender confidence that the specified maintenance tasks will actually be carried out; in any case, military economies often result in a reduction in the maintenance and testing of a system when deployed over that intended by the designers. This is because it is a hidden cost saving. Secondly, routine maintenance and BIT testing can never rule out malfunctions, only reduce their likelihood. Even this can only apply to those functions which *can* be tested and maintained. Much of the missile, in particular, cannot be inspected or maintained once it is loaded into its canister; the vital launch functions cannot be tested without actually being carried out.

These considerations, plus those already raised about the initial quality of the equipment, combine to force the conclusion that the GLCM will, at the very least, turn out to be an expensive and unreliable addition to the Western arsenal; at the worst it could turn out to threaten those it was sent to protect.

Software Reliability

"Almost anything in software can be implemented, sold, and even used given enough determination. There is nothing a mere scientist can say that will stand against the flood of a hundred million dollars. But there is one quality that cannot be purchased in this way – and that is reliability. The price of reliability is the pursuit of the utmost simplicity. It is a price which the very rich find most hard to pay." Prof Tony Hoare, in "The Emperor's Old Clothes", 1980 Turing Award lecture.

Software is that part of a computer system which instructs the hardware how to perform its function. The first test launch of the GLCM was delayed on two occasions (until 25th Feb '82) by the common weapon control system software. In March 1982 the USAF's General Burke said "We have had some technical problems with it (the GLCM) primarily associated with the software. I think that was the inability of the selected contractor to come to grips with it and we are running behind on that . . . We may well make the initial deployment with a *less than optimum* software configuration but it will still work."[48](Emphasis added)

It may be worth a small digression here to explain the problem of software reliability. It is very different from hardware (machine) reliability and not so well understood. A machine is built with a certain life in mind. It is expected that parts will gradually wear out and that their replacement will eventually be necessary. As the parts wear out, assuming replacement to be timely, the performance of the machine is generally not affected dramatically: a car will begin to use more petrol as a particular component ages but the replacement of the component cures the problem. Software reliability is different: there are no parts to wear out and once a program is correct it will remain correct for ever. The problem is to determine when the program is correct.

Naturally no program for the control of missiles would be used unless it had been very thoroughly tested, but the testing of a program is no easy matter: it can, for example, be assumed that the programs used to control the space shuttle were very well tested and yet the first space shuttle flight in April 1981 was delayed because of a software mismatch. This presence of errors in spite of testing reflects the complexity of a computer program. Not only must it be tested to ensure it performs as specified, but it must also be tested to ensure that it never performs *outside* specification – and given that a computer can assume a virtually infinite number of states during program execution, complete testing of any but the most trivial program is accepted to be impossible. In any case, no test can do more than prove that the software is consistent with its specification. In a complex system, the analysts who write the specification may themselves omit important functions or introduce unexpected interactions.

This characteristic is reflected in the length of time it takes to deliver working software. It has to be done slowly and carefully. A 1979 survey by the US GAO,[49] analysing nine government software contracts totalling $6.8

million, produced the following results:

software delivered but never successfully used	\$3.2m
software paid for but not delivered	\$1.95m
software used but extensively reworked	\$1.3m
software that could be used after changes	\$198,000
software that could be used as delivered	\$119,000 or **1.7%**

In terms of the life cycle of a typical avionics software package of, say, 15 years, a third of the lifetime cost goes on development, together with a further 7% on system integration. But experience shows that the remaining 60% of the cost will be consumed by later program modification: one-third for corrections, and the rest for specification changes, improvements, and adaption to new hardware.[50]

Therefore we can see that late, non-working, insufficiently tested software is the norm rather than the exception. General Burke's comment is not particularly surprising or unusual. However, in the same hearings, Mr Mullen of the Office of the Under-Secretary of Defense for Research and Engineering, stated "the GLCM system development and deployment are being pursued on an expedited basis to counter the rapidly expanding Soviet threat and meet the December 1979 NATO decision. As a result there is a high degree of concurrency and with the test program just getting underway, there is considerable schedule and cost growth risk." In other words, the program is being rushed.

The "selected contractor" to whose inability Gen Burke was referring is Automation Industries, Inc's Vitro Laboratories at Silver Spring, Maryland. Flight International magazine of 16th October 1982 reported that the USAF had hired Systems Development Corp to "support" software efforts by Vitro Laboratories. The Americans use the term "Tiger Team" to describe a group of specialists formed to deal urgently with a particularly difficult problem. In many fields of engineering it can be quite effective. But taking this approach with software – attempting to speed up software development by assigning more manpower to the task – was effectively discredited in 1974 by Prof. Frederick P. Brooks of the University of North Carolina's computer sciences department.[51] Adding manpower to a software project Brooks compares to dousing a fire with gasoline. "The bearing of a child takes nine months, no matter how many women are assigned. Many software tasks have this characteristic because of the sequential nature of debugging." Sequential constraints are not the only problem: since software construction is complex, the communication overhead between members of the team is great. Adding more men can *lengthen*, rather than shorten, the schedule, because of the need to integrate the newcomers into the project. This effect is likely to be worsened if, as in the case under consideration, the extra effort comes from outside the contractor's organisation.

It is under precisely these conditions that the reliability of the software package is most in doubt. "Bugs" take time to be discovered and eliminated; and even with a large-scale testing program it is impossible to be sure that every last one has been ironed out. The effect of any particular bug is unpredictable. It could be quite insignificant; it could render the system inoperable under certain conditions; or it could conceivably make the system operate in a totally unforeseen way. It is this last possibility which makes the over-hasty deployment of a nuclear missile system subject to such high risk.

Conclusions

This study has indicated areas in which the Ground-Launched Cruise Missile system may present a serious risk – in technical terms – to the European population. It has also identified factors which will aggravate this risk.

The hazard posed by a system which involves transportable nuclear warheads is greater than for any other currently deployed nuclear weapon. To lessen this hazard, as well as to increase its credibility as an effective weapon, attention must be paid to designing and operating the system for the utmost reliability. *The GLCM program does not meet this criterion.* Particular areas for concern are:

– manufacturing quality control. General Dynamics, the prime contractor, has already been severely criticised in this respect, before the program was fully under way;

– insufficiently tested system software, particularly that for the launch control. Rigorous software testing cannot be rushed, yet this phase has already been delayed, and the requirement for early deployment means that the time allocated for testing has in fact been reduced;

– in-service reliability of sophisticated electronic and mechanical equipment. Both long periods of storage, and rough handling when the flights are dispersed on exercise or for real, can adversely affect system reliability. Some system concepts unique to Cruise have yet to be proven in this respect;

– the competence and training of maintenance personnel and operators, and the likelihood of shortcuts in maintenance procedures. The US armed forces have an endemic personnel problem, and failure to properly look after the system will have repercussions on its overall reliability.

In addition, there are known faults in the operational characteristics of the GLCM – in particular, the performance deficiencies of its guidance package and terrain-following abilities. These faults naturally impair confidence in the remainder of the system.

In the light of these considerations, deployment of GLCM in Europe should be treated with *extreme caution*. If deployment were to go ahead, then it is imperative that independent monitoring is carried out on a continuous basis of American operations, at the main operating bases and at the missile manufacturers, of quality control and maintenance. Equally, the operating characteristics and design of the GLCM system should be independently evaluated and tested. Considerations of military and commercial security should not be allowed to obstruct the monitoring.

Not to do so would be tantamount to relegating Europe to the status of a mere appendage to the US's military operations – the phrase "unsinkable aircraft carrier" has already been used in this context. Indeed, the fact that the

British government has shown itself willing to accept the GLCM without even a request for an evaluation period, or for dual-key control, indicates that it has virtually assumed this status. There is no fundamental technical reason for not adopting dual-key control, or for not insisting on monitoring. The government's present position demonstrates a quite extraordinary lack of political will. If the situation was reversed – ie, if Europe wished to station its weapons in America – the US would insist on evaluating and monitoring their technical characteristics. The fuss over Concord a few years ago is a case in point. Described as an "unnecessary, unwelcome intruder" it was subjected to vigorous scrutiny on noise and environmental grounds before being allowed to use American airports; this for a civil airliner that was only an occasional visitor.

As stated in the introduction, this study has not attempted to consider the political and strategic questions surrounding GLCM deployment in Europe. It has been shown, however, that acceptance of deployment is not only a commitment to a particular NATO weapons policy; it is also an offer of hospitality to an untested, unreliable, bug-ridden system that could turn out to be fatal to its hosts. If European governments are willing to ignore this aspect of the cruise missile, their political independence is cast in doubt, and they are neglecting their responsibilities towards the well-being of their populations.

Appendix

List of Acronyms

ACM	Advanced Cruise Missile
AFTEC	Air Force Test & Evaluation Center
ALCM	Air Launched Cruise Missile
AUR	All-Up Round (Missile + Booster +Canister)
BIT	Built-in Test
CBR	Chemical, Biological & Radiological
C^3	Command, Control & Communications
DMA	Defense Mapping Agency
DoD	Department of Defense (The Pentagon)
EAM	Emergency Action Message
ECU	Environmental Control Unit
FM	Frequency Modulation (a type of radio transmission)
GAMA	GLCM Alert & Maintenance Area
GAO	General Accounting Office (US Congressional watchdog)
GD	General Dynamics
GLCM	Ground Launched Cruise Missile

HF	High Frequency (radio frequencies between 1 and 30MHz)
IC	Integrated Circuit (the "silicon chip")
ICBM	Intercontinental Ballistic Missile
IMF	Integrated Maintenance Facility
ITCP	Initial Timing Control Point
JCMPO	Joint Cruise Missile Project Office
LCC	Launch Control Center
MAN	Maschinenfabrik Augsburg-Nurnberg AG
PAL	Permissive Action Link
QRA	Quick Reaction Alert
SLCM	Sea Launched Cruise Missile
SSB	Single Sideband (another type of radio transmission)
TEL	Transporter-Erector-Launcher
TERCOM	Terrain Contour Matching
UHF	Ultra High Frequency (radio frequencies above 300MHz)
USAF	United States Air Force
VHF	Very High Frequency (radio frequencies between 30 and 300MHz)

References

1) See for example Simon Lunn, "Cruise Missiles and the Prospects for Arms Control", *ADIU Report*, Vol 3 No 5 Sept/Oct '81; or Owen Greene, "Europe's Folly: the Facts & Arguments about Cruise", CND, 1983; or "The Cruise Missile: Opening Pandora's Box", *Defense Monitor* Vol XII No 4 1983, Center for Defense Information. There are two major reference books on the subject: *Cruise Missiles: Technology, Strategy, Politics*, ed. Richard K. Betts, Brookings Institution 1981; and *US Cruise Missile Programs*, Charles A. Sorrels, Brassey's Defence Publishers, 1983

2) *Defense Monitor*, Vol X No 5 1981, p4, Center for Defense Information

3) Kenneth P. Werrell, "The Cruise Missile, Precursors and Problems", *Air University Review*, Vol 32, Jan-Feb '81, p36

4) For a fuller discussion of the social dimensions of risk in a parallel context see Dr Brian Wynne, "Public Perception of Risk", paper presented to the GLC Conference on Urban Transport of Irradiated Fuel, 13th April 1983

5) For example Ian Mather's report "How they Hard Sell the Cruise", *The Observer*, 31st July 1983; or Richard L. Garwin, "Who proposes, who disposes, who pays?", *Bulletin of the Atomic Scientists* June/July 1983, Vol 39 No 6 pp9-11, for inside criticism

6) *The Economist*, February 26th 1983

7) *Flight International*, 26th March 1983 p807

8) "General Dynamics: Striking it Rich on Defense", *Business Week*, May 3rd 1982, pp42-46

9) Much of the information in this section was derived from system review notes published by General Dynamics. See also: Ezio Bonsignore and Norman Friedman, "The Cruise Missiles and their Technology", *Military Technology* 4/83, pp64-77; J. Philip Geddes, "The Cruise Missile Era Dawns", *Interavia* 9/82 pp919–923; "Improving the Cruise Missile", *Flight International*, 16th Oct '82, pp1112–1116; or Dr David Baker, "The Cruise Missile: formula for a new equation" Pt 2, *Jane's Defence Review* Vol 3 No 2 1982 p124

10) Sources for this table include those in ref 9 plus: *Tomahawk Design Evolution*, ref 23; Kaplan, ref 38; and *Aviation Week & Space Technology*, ref 27

11) *Flight International*, Aug 28th '82

12) "Air Launched Cruise Missile Shows Promise But Problems Could Result in Operational Limitations", GAO C-MASAD-82-13, Feb 25th 1982 p7

13) John C. Toomay, "Technical Characteristics", in *Cruise Missiles: Technology, Strategy, Politics*, ed. Richard K. Betts, Brookings Institution, 1981, p.39

14) Mr Francis Pym, Defence Secretary, in *Hansard*, col 1343, 17th June 1980

15) *The Guardian* 3rd Nov '82; *The Times* 3rd Nov '82

16) See for example Howard Morland, *The Secret That Exploded*, Random House, New York 1981

17) Dr Sparks, Sandia Labs, *House Armed Services Committee Hearings (DOE) FY80*, Feb 15th 1979,p156

18) ibid.

19) *Defense Monitor*, as ref 2

20) ibid., p10

21) *The Times* Nov 4th 1982

22) *The Guardian* 15th June 1983

23) Bob Lynch, *Tomahawk Design Evolution*, General Dynamics Convair Division

24) Richard Barnard, " 'Sloppy' Management Corrodes Tomahawks", *Defense Week*, Jan 10th 1983 p2

25) see ref 23 p68

26) "Most Critical Testing Still Lies Ahead For Missile in Theater Nuclear Modernization", GAO MASAD-81-15, March 2nd 1981, p21

27) Bruce A. Smith, "Tomahawk Ground Control Evaluated By Air Force", *Aviation Week & Space Technology*, June 21st 1982 p48

28) Lloyd J. Dumas, "Human Fallibility and Weapons", *Bulletin of the Atomic Scientists* Vol 36 No 9 Nov 1980, pp15-20

29) ibid.; see also Stewart Britten, *The Invisible Event*,

30) Eric J. Lerner, "Strategic C³: A Goal Unreached", *IEEE Spectrum* October 1982, vol 19 No 10, pp53–55

31) See ref 26 p15

32) Eric J. Lerner, "Tactical C³: Survival under Duress", *IEEE Spectrum* October 1982, Vol 10 No 10 p56

33) *Hansard*, 17th June 1980, col 1350

34) Quoted in *The Observer*, Sunday 8th February 1981

35) *The Guardian*, 6th June 1983

36) DoD Authorization for Appropriations for Fiscal Year 1983, Hearings before the Committee on Armed Services, Part 7: Strategic and Theatre Nuclear Forces, p4389

37) see ref 26 p15

38) Fred Kaplan, "Cruise Missile: Wonder Weapon or Dud?" *High Technology*, February 1983 Vol 3 No 2 p31

39) Ezio Bonsignore and Norman Friedman, "The Cruise Missiles and their Technology", *Military Technology* 4/83 p66

40) see ref 12 p6

41) Major Gary Houchens and Captain Kenneth Jackson, "Guidance and control subsystems "think" Minuteman is constantly in flight", *IEEE Spectrum* October 81 Vol 18 No 10 p64

42) Of the 158 contractors listed in NARMIC's "Makers of the Cruise and Pershing II" (AFSC/NARMIC, 1501 Cherry Street, Philadelphia, PA 19102), not one is billed as having responsibility for reliability.

43) William Twaddell, "MIL-M-38510 Qualification lags for VLSI; users turn to alternative approaches", *Electronic Design News*, June 23rd 1983 p51

44) *Electronics Times* 4th February 1982

45) Robert Bernhard, "Overlooking the Obvious", *IEEE Spectrum* October 1981 Vol 18 No 10 p85

46) Edgar A. Doyle Jr., "How Parts Fail", *IEEE Spectrum* October 1981 Vol 18 No 10 p40

47) The quality control and program restructuring saga is covered in the following articles: "'Sloppy' Management Corrodes Tomahawks", *Defense Week* Jan 10th 1983; "Problems Delay Tomahawk Cruise Missile by Two Years", *Los Angeles Times* 5th Jan 1983; "Navy Planning Tomahawk Program Revisions", *Aviation Week & Space Technology*, 3rd Jan 1983; and "Tomahawk Program Restructured", *Flight International*, 15th Jan 1983

48) Dod FY 83 *Hearings*, p4388 (ref 36)

49) GAO FGMSD-80-4, November 1979

50) Max Schindler, "Software Testing: A scarce art struggles to become a science", *Electronic Design* July 22nd 1982

51) Frederick P. Brooks Jr, "The Mythical Man-Month", *Datamation* 1974

52) See ref 24 p3

In December 1983, the U.S. Government intends to station ground-launched cruise missiles at Greenham Common in Britain. But how do cruise missiles work? More importantly, will they work properly?

This study looks at the technical aspects of cruise – how it has been designed, how it is being produced – and concludes that the political need for early deployment has seriously compromised its performance and reliability. Insufficiently tested control software, and inadequate manufacturing quality control are two areas of particular concern. On these grounds alone, there is a real case for refusing to accept cruise in Europe.

"Acceptance of cruise is not only a commitment to a particular NATO weapons policy; it is also an offer of hospitality to an untested, unreliable, bug-ridden system that could turn out to be fatal to its hosts."

ISBN 0 946 862 00 1

75p