Articles

Dispelling Myths About Verification of Sea-Launched Cruise Missiles

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It is widely believed that an arms control limit on nuclear-armed sea-launched cruise missiles would be nearly impossible to verify. Among the reasons usually given are: these weapons are small, built in nondistinctive industrial facilities, deployed on a variety of ships and submarines, and difficult to distinguish from their conventionally armed counterparts. In this article, it is argued that the covert production and deployment of nuclear-armed sea-launched cruise missiles would not be so straightforward. A specific arms control proposal is described, namely a total ban on nuclear-armed sea-launched cruise missiles. This proposal is used to illustrate how an effective verification scheme might be constructed.

THE UNITED STATES AND THE SOVIET UNION ARE NOW engaged in negotiations to reduce their arsenals of strategic nuclear weapons. These Strategic Arms Reduction Talks (START) would limit both the number of strategic delivery systems such as ballistic missiles and bombers and the total number of nuclear warheads that these systems may carry. The Soviets have insisted that sea-launched cruise missiles (SLCMs) be limited under START; U.S. objections have centered on the difficulty of verifying such limits without an unacceptable degree of intrusiveness. Following the Washington summit in December 1987, President Reagan and General Secretary Gorbachev issued a joint communiqué which stated that "the sides shall find a mutually acceptable solution to the question of limiting the deployment of long-range, nuclear-armed SLCMs." Nonetheless, SLCMs remain one of the key obstacles to completion of START. To date, no progress has been made on this issue. The prospect that disagreement over SLCM verification could greatly delay or even prevent the successful conclusion of START requires that this verification problem receive careful analysis.

U.S. and Soviet SLCMs

To understand the issues associated with verification of limits on SLCMs it is necessary to review the characteristics of U.S. and Soviet SLCMs and the numbers deployed by the two countries. There are several types of SLCMs, of widely varying ranges, designed for ship attack or land attack, carrying nuclear or conventional warheads. The START negotiations will determine which types will be controlled under the treaty.

In 1983 the United States began deployment of a new SLCM, the Tomahawk. The Tomahawk (Fig. 1) is a small, unpiloted jet aircraft, which flies subsonically and is capable of highly accurate delivery of nuclear or conventional warheads. There are several Tomahawk variants, which have essentially identical airframes, but with internal differences to accommodate the different warheads and different missions. The short-range, anti-ship variant, which carries only a conventional warhead, has an operational range of approximately 450 km and uses radar to seek its target. There are three long-range, land-attack variants: one carries a nuclear warhead, has a range of over 2500 km, and uses terrain contour matching to update its inertial guidance; the other two carry conventional warheads (either submunitions, or a unitary warhead), have about half the range (because the conventional warheads leave less room for fuel), and have additional guidance based on digital scene matching in the terminal phase to achieve the precise accuracy required for conventional munitions (*1*).

All Tomahawk variants are deployed in canisters and can be launched in a variety of ways and from a variety of platforms (Fig. 2). There are currently about 70 U.S. surface ships and submarines capable of firing Tomahawks, and current plans call for this number to increase to nearly 200. The United States has procured approximately 370 nuclear and 1650 conventional Tomahawks to date and plans to purchase about 2000 more Tomahawks between now and 1994, including approximately 390 nuclear ones (*2*). The only other SLCM deployed by the United States is the Harpoon, a conventionally armed, anti-ship weapon with a range of about 100 km.

The Soviet Union has deployed SLCMs since the early 1960s. Over the years they developed several short-range models, designed primarily for ship attack. Their ranges vary from approximately 50 to 550 km, and most are capable of carrying either conventional or nuclear warheads. All are larger than the Tomahawk and are launched from surface ship or submarine launchers, not from torpedo tubes (*3*). It is estimated, based on a count of launchers, that the Soviet Union currently has approximately 1000 short-range, dual-capable SLCMs deployed on a wide variety of surface ships and submarines. The number of Soviet short-range SLCMs that carry nuclear warheads is unknown, but it has been estimated that roughly 400 of these short-range Soviet SLCMs may be nuclear armed (*4*).

In 1986 the Soviets began deploying their first long-range, land-attack SLCM, the SS-N-21. This missile appears to be quite similar to the Tomahawk. It has a small jet engine, flies subsonically and at low altitudes, and is small enough to be launched from torpedo tubes. At present there is only a nuclear-armed version of the SS-N-21. It is believed that at most a few tens are currently deployed and on only a few submarines. Figure 3 provides an overview of the types and ranges of the SLCMs of both countries.

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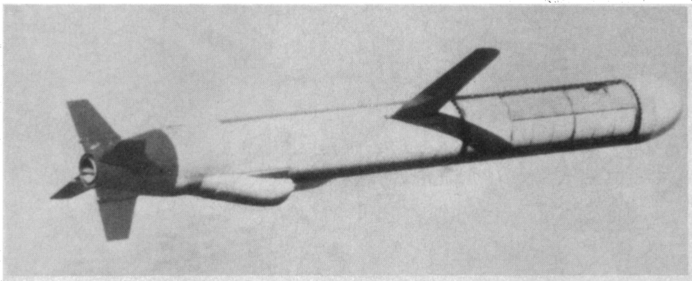


Fig. 1. A Tomahawk sea-launched cruise missile in flight. A Tomahawk is 18.2 feet long (20.3 feet with rocket booster) and has a wingspan of 8.6 feet. [Photo courtesy of General Dynamics, Convair Division]

Verification

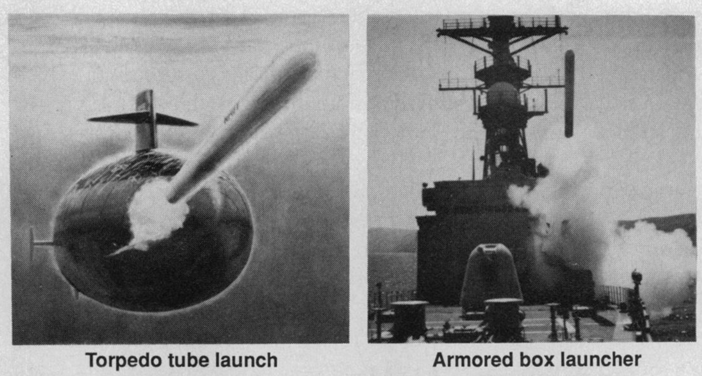
We now turn our attention to the issue of verifying limits on the production and deployment of SLCMs. It is commonly argued that such a SLCM verification regime cannot be effective without being unacceptably intrusive. This is because it is commonly noted that SLCMs are small and easy to hide and can be produced in nondistinctive facilities, and the conventional and nuclear variants are difficult to distinguish. However, although a SLCM is small relative to an intercontinental ballistic missile, it is, nontheless, a complex weapons system that requires a sophisticated industrial infrastructure for its production and maintenance. In addition, SLCMs are likely to be the largest objects that are loaded onto or stored on their platforms and cannot be readily, or safely, moved about or hidden on such ships. SLCMs on U.S. ships are found only in their launchers or in torpedo rooms and are not reloaded at sea. Furthermore, conversion of a Tomahawk from conventional to nuclear, although technically feasible, would be a complex and time-consuming operation that, practically speaking, could be performed only at a factory. Considerations such as these, taken together, suggest that SLCM verification is not the intractable problem it is often presented to be and that effective monitoring of SLCM deployments is possible without an unprecedented degree of intrusiveness.

In what follows we examine the issue of verification within the context of a specific arms control option: a ban on nuclear SLCMs of all ranges, with no constraint on conventional SLCMs. Over the period of implementation of the treaty this option would eliminate the SS-N-21 and all nuclear variants of the Soviet ship-attack SLCMs (possibly several hundred missiles), leaving the Soviets with short-range conventional anti-ship SLCMs and the freedom to develop a long-range conventional SLCM. The United States would give up the long-range nuclear variant of the Tomahawk (approximately 370 deployed missiles). The Harpoon and the anti-ship variant of the Tomahawk would remain unconstrained, as would the long-range, land-attack conventional Tomahawk. Thus both sides would, over the course of the agreed period, have to eliminate a comparable number of currently deployed, nuclear-armed SLCMs. Moreover, both sides would have a comparable number of surface ships and submarines subject to verification efforts. Another practical advantage to a total ban is that the difficult problem of determining a SLCM's maximum operational range—which must be determined if a range limit on SLCMs is specified in the treaty—would be eliminated.

The Special Verification Facility

Verification of a treaty that would ban all nuclear SLCMs with conventional SLCMs unconstrained would require that all SLCMs be checked to verify they are in compliance with the treaty. In the verification scheme described in this article, much of the technical work associated with the inspecting, tagging, and sealing of SLCMs would be carried out in a special verification facility. Such a special verification facility could be located outside each site where SLCMs are assembled, or there could be one or more central verification facilities to which SLCMs could be sent. In this case the progress of SLCMs from the final assembly facility to the verification facility would have to be monitored in order to insure that only legally produced SLCMs are certified for deployment. At the special verification facilities in each country representatives from the other country would:

1) Check all legally produced SLCMs to assure that they do not carry nuclear warheads and to verify that their design does not permit nuclear arming in the field. There are a number of techniques available to detect a nuclear warhead, including passive detection in which the neutron or gamma radiation emitted by the warhead is observed or active detection in which the SLCM is interrogated with a pulsed beam of neutrons or the number of photons transmitted through the SLCM is measured. Both active and passive detection methods might be used in the special verification facility in order to prevent deception. In particular, for active detection with high energy photons, the beam attenuation produced by the large cross section of the high-Z material characteristic of a nuclear warhead provides a clear signature of the presence of nuclear material (Fig. 4). The measurements of each SLCM would be



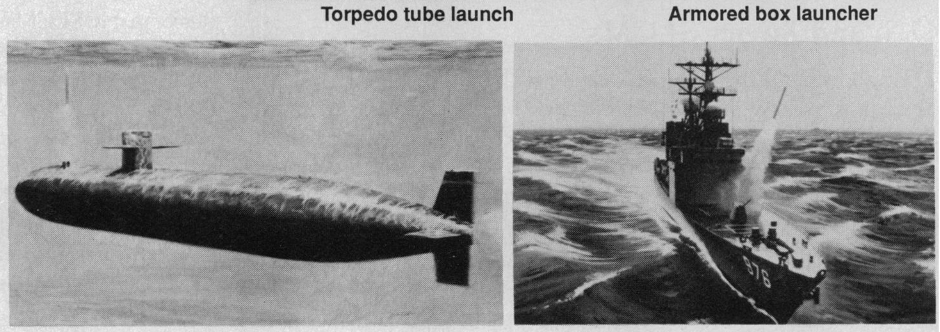


Fig. 2. The Tomahawk can be launched from three different types of launchers, as well as from torpedo tubes on submarines. The vertical launch system, to be installed on 34 U.S. attack submarines, and the armored box launchers, installed on 4 battleships and on 12 cruisers and destroyers, launch only Tomahawks. The vertical launch system, to be installed on 75 U.S. cruisers and destroyers, also fires other missiles, such as the Standard anti-air missile. [Figure supplied by General Dynamics, Convair Division]

required to correspond with the signature for a specific type of missile that had been established during a data exchange.

2) Tag the SLCM for later identification. The tag must be durable and tamper-proof, that is, nontransferable and nonreproducible. Technologies exist to make such tags and to make them unique, that is, to "fingerprint" each SLCM. One example of a tag, developed at Sandia National Laboratories, is a reflective particle paint consisting of a clear plastic material embedded with small particles of crystalline micaceous hematite. Such a tag involves three-dimensional, randomly generated patterns so that it cannot be reproduced. The tag is read by illuminating it with a sequence of lights at well-defined angles. The reflection patterns, which can be easily verified under field inspection conditions, as well as other features such as the shapes of individual particles in the tag, provide a unique fingerprint that is secure against counterfeiting (*5*).

3) Apply a seal that would reveal tampering with the missile upon subsequent inspection. A good seal, like a good tag, must be durable, nonreproducible and tamperproof, and therefore sealing the cruise missile in its canister may also simultaneously tag the missile for later identification. An interesting example of a seal is a mesh of optical fibers that would enclose the canister and would not impede launching of the missile. The seal is effected by locking the ends of fibers together in a device that cuts randomly some of these fibers. When the fibers are illuminated, a pattern is produced that can serve as a tag. Removing the cruise missile from the mesh or trying to break the lock would cut more of these optical fibers, changing the pattern (*6*).

A Verification Regime

The verification of an arms control agreement relies on a collection of measures designed to ensure compliance with the agreement and to assure that militarily significant violations can be detected in time to be countered. A well-designed verification regime should not be vulnerable to circumvention without exposing the potential cheater to multiple risks of detection, and no single verification provision should be expected to carry the full burden of verification. The verification measures, together with national technical means and other sources of information, should combine to confront a potential cheater with multiple layers of obstacles which would have to be circumvented.

An effective verification regime could be constructed from the following key elements:

1) A comprehensive data exchange covering the numbers, types, and relevant design characteristics of SLCMs already produced, as well as information about their launchers, platforms, and production and assembly facilities. A data exchange, once validated, would establish baseline conditions and support monitoring of the agreement.

2) Perimeter-portal monitoring of all declared facilities that assemble conventional SLCMs. Stations would be set up at exits on the perimeter of these facilities; then SLCMs leaving these facilities would be monitored until they reached a special verification facility.

3) A special verification facility. SLCMs leaving a declared production facility or SLCMs returning from the field for maintenance or recertification would first go to this special verification facility for checking.

4) Inspections of a sampling of deployed SLCMs. The purpose of these inspections would be to verify that only treaty-approved SLCMs were being deployed. Inspectors would select SLCMs from their launchers and then verify that they were properly tagged and that the seals were unbroken. This would be done in port and need not require inspectors on board SLCM platforms, as will be explained below.

5) A limited number of challenge inspections of both declared facilities and suspect sites. This would increase the risk of covert production and deployment of nuclear SLCMs.

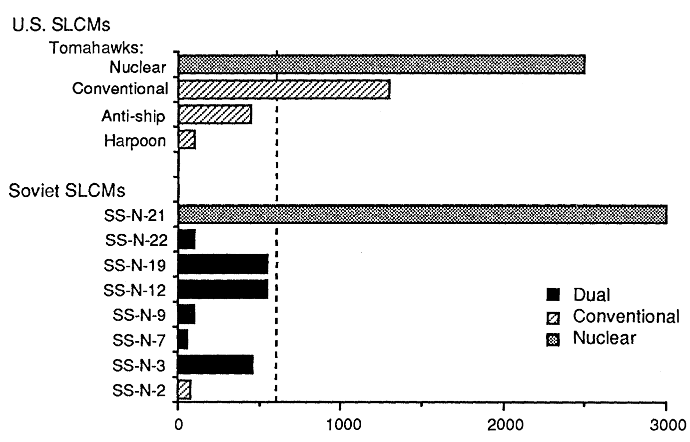


Fig. 3. The SLCMs currently deployed by the United States and the Soviet Union, their ranges, and types of warheads. The dashed line indicates the Soviets' proposed definition of long range. While both the United States and the Soviet Union have well over 1000 short-range, anti-ship missiles deployed, all those of the United States are conventional, whereas about 400 of the Soviet missiles are thought to be nuclear armed. The United States has deployed many long-range nuclear SLCMs, while the Soviets have deployed at most only a few. Clearly, any proposal that would limit only long-range SLCMs would affect U.S. naval forces more than those of the Soviet Union.

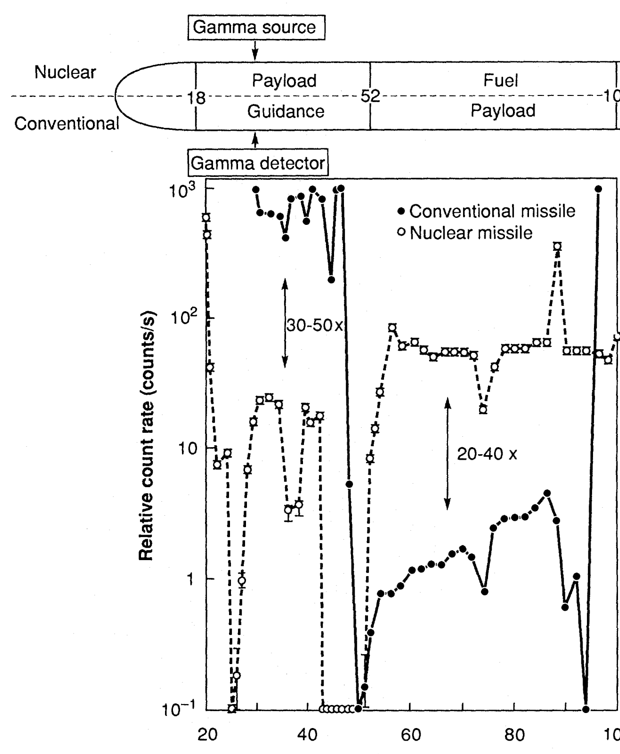


Fig. 4. The axial variation in transmissivity of 662-keV radiation from a cesium source for conventional and nuclear cruise missiles using a simulated (concrete) conventional warhead, a mock W84 nuclear warhead, and water to simulate fuel. From stations 54 to 90, the 662-keV transmissivity for the nuclear cruise missile is 20 to 40 times greater than for the conventional version. From stations 28 to 42, the conventional missile shows 30 to 50 times more transmissivity. Between stations 43 and 50, only the nuclear version completely absorbs the 662-keV radiation. [Data provided by D. C. Camp, Lawrence Livermore National Laboratory]

The verification elements would impose a series of barriers to cheating. The combination of perimeter-portal monitoring and tagging would prevent illegal SLCMs from leaving a declared facility; this means that a covert production infrastructure would have to be established to manufacture illegal SLCMs. Challenge inspections would help deter the establishment of this infrastructure by increasing the risk of detection. An additional measure that could be implemented would be to require that only tagged SLCMs be flight tested. This would further deter covert production by making it difficult to certify any covert production line. The inspection of deployed SLCMs would provide confidence that only legal SLCMs are deployed on declared platforms and would deter covert deployment.

Although it might be possible to circumvent any one of these barriers, the combination of constraints imposed by all of the barriers would strongly deter cheating. For example, given the verification scheme outlined here, covert production of nuclear SLCMs would require a potential cheater to:

- Establish a covert assembly facility. At least some part of this facility must handle explosive materials, particularly the solid-rocket booster.
- Divert parts from factories to the covert assembly site or establish an entirely covert production infrastructure.
- Conduct covert flight testing, or forego flight testing and accept the associated decreased confidence in the weapon.
- Tie into the nuclear logistics network in order to install the warheads. If there is a ban on nuclear SLCMs, the nuclear logistics system and the SLCM logistics system would not normally intersect.
- Store and transport the SLCMs covertly.

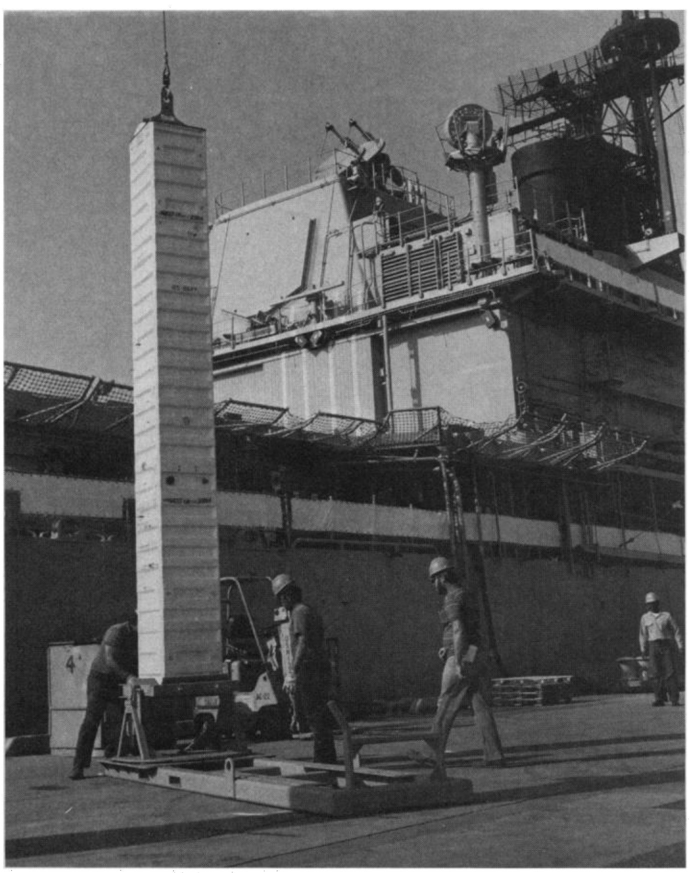


Fig. 5. A missile being prepared for loading into a vertical launch system (VLS) aboard a U.S. cruiser. This type of cruiser has 122 VLS tubes that can be used to launch Tomahawks or Standard anti-air missiles. The VLS is equipped with its own crane for loading Standard anti-air missiles. However, the Tomahawk is too heavy for this crane and is loaded or unloaded only in port. [Photo courtesy of the U.S. Navy]

Each of these steps would involve risks. Collectively they would represent a substantial level of activity, which would be difficult to hide. Even a small probability of detection associated with each of these steps could lead to a substantial overall risk (7).

The risks enumerated above would have to be taken simply to produce the weapons. In order for SLCMs to be reliably available for use, they should be deployed on platforms which are regularly used to launch SLCMs and which are operated by an experienced, well-trained crew. Thus the verification regime should provide an effective inspection of SLCMs deployed on declared platforms (*8*). If desired, this inspection of deployed SLCMs can be accomplished without shipboard inspections—it can certainly be accomplished without intrusive shipboard inspections. U.S. Tomahawks are deployed on battleships, cruisers (see Fig. 5), destroyers, and attack submarines. SLCMs on U.S. surface ships are stored only in their launchers—these ships do not carry reloads. There are sound reasons for this practice. These include lack of storage space for objects the size of SLCMs (*9*); lack of large elevators, hatches, and moving and handling equipment; the small amount of vertical space between decks and the generally cramped nature of a ship's internal passageways; the need for stringent safety precautions when storing and handling explosives; and the need for nuclear security precautions. Generally speaking, although it is not physically impossible to store a nuclear SLCM elsewhere on one of these ships, it is both difficult and hazardous to attempt to do so. The constraints are even more stringent for U.S. attack submarines: SLCMs cannot be moved into or out of torpedo rooms at sea. Although U.S. ships do not carry Tomahawk reloads, SLCMs could, in principle, be transferred from ammunition ships at sea. This is not current practice on surface ships (in fact, U.S. SLCM platforms do not even carry cranes certified for lifting objects as heavy as Tomahawks), and it is not a viable practice for submarines (*10*).

Since SLCMs are limited to their launchers or torpedo rooms, an inspector need not board a ship or submarine. An inspector on the dock could request that a specified missile from a launcher be unloaded from the ship and observe its removal. The inspector could either check its tag and seal there or send it to a separate verification facility for checking. Although the most straightforward approach would be to permit an inspector to enter the torpedo room of a submarine to select the missiles that would be unloaded, this selection could be done remotely with, for example, a video camera lowered through the weapons-loading hatch directly to the torpedo room.

The inspection procedure outlined above should have minimal impact on naval operations. For example, a violation consisting of the deployment of 50 nuclear-armed SLCMs in launchers for a side with 5000 launch tubes would be detected with 90% (50%) probability by checking 230 (70) of the missiles in these launchers for tags and seals. This is to be compared with the roughly 1000 Tomahawks that will be returned to the factory each year for regular maintenance if the United States deploys 4000 of these missiles.

We believe that the verification framework outlined here—at least to this level of detail—would apply to the Soviet system as well. In particular, the majority of the operational considerations described above are likely to apply. As we have already noted, all Soviet short-range SLCMs are larger (and presumably heavier) than the Tomahawk. Although relatively little information is available on Soviet ships and submarines, this suggests that it would be even more difficult for them to store nuclear SLCMs covertly on most of their SLCM platforms (Fig. 6). However, some ships, such as Soviet aircraft carriers, might require special treatment. In general, it should be emphasized that more information about Soviet SLCMs and their related logistics is needed in order to develop the verification regime beyond the level of detail presented here.

The verification measures discussed in this paper are based primarily on current U.S. practices for handling and deploying SLCMs. It is not difficult to imagine different ways of deploying and handling SLCMs that would make them more difficult to verify. However, there are sound reasons underlying current practices, and costs associated with trying to handle SLCMs differently. Part of the task of a SLCM arms control agreement would be to codify operational practices in ways that impede cheating and promote verification.

A further concern requires discussion: Could legal SLCMs be converted to nuclear on ships? The conversion of the present generation of U.S. conventional Tomahawks is sufficiently complicated that attempting to carry out such a conversion on ships would greatly undermine confidence in the weapon. The testimony of Admiral Hostettler (director of the Joint Cruise Missile Project from 1982 to 1986) before the Senate Armed Services Committee on 8 March 1985 speaks to this issue: "The current cruise missile is a highly complex vehicle which was not designed for field maintenance. Each missile is thoroughly tested before it leaves the factory and remains intact until it is fired or returned for recertification in 30 to 36 months. During the period the missile is in the fleet, electrical continuity is maintained. To change a variant from conventional to nuclear or vice versa would require replacement of the entire front one-third of the missile. Nuclear surety requirements would dictate a complete retest of the missile requiring each ship be outfitted with highly sophisticated test equipment and highly trained technicians to interpret the results. Clearly this is beyond the scope of normal Navy maintenance concepts and will be performed only at shore-based depots. The capability to modify variants in the fleet is not planned for the Tomahawk."

It is not known whether any of the current generation of Soviet SLCMs are convertible in the field. If they are, they would have to be rendered nonconvertible or else destroyed. A treaty banning nuclear SLCMs should require that future generations of SLCMs be designed so as to preclude nuclear arming or conversion in the field (*11*).

The military significance of covertly produced nuclear SLCMs should not be exaggerated. Because of the difficulty of conversion on ships, and the lack of capability to store SLCMs covertly on ships and load them at sea, covert nuclear SLCMs would be stockpiled on land, not at sea. Therefore, in a rapidly developing crisis, covert SLCMs would not be available for use. Furthermore, preparations for a rapid deployment of illegal SLCMs in violation of the treaty would have to be made well in advance. The measures discussed above, together with national technical means, would make such preparations risky. There would be little incentive to attempt such cheating, since doing so would provide little in the way of reliable, available military capabilities that are not already provided by other weapons such as air-launched cruise missiles and submarine-launched ballistic missiles.

Discussion

In this article we use one specific SLCM arms control limit, that of a complete ban on nuclear SLCMs of all ranges, to illustrate a potential SLCM verification regime. We believe that this ban has a great deal of merit. The elimination of shorter range nuclear SLCMs, of which the United States has none, can only enhance the security of our naval forces. Further, the widespread deployment of nuclear SLCMs on platforms that have roles in a conventional war creates unique pathways for nuclear escalation. Long-range nuclear SLCMs also raise a particular concern: The lack of early warning of a SLCM attack could reduce each side's confidence that it could detect a surprise attack against its own command-and-control system and bomber bases. Although the deployment of nuclear SLCMs does increase the number of nuclear-armed platforms with which an attacker must contend, this argument for additional platforms is not compelling given the existing capabilities of other U.S. strategic forces (*12*).

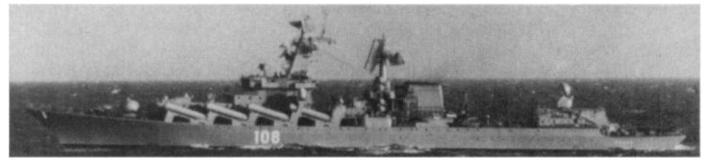


Fig. 6. A Soviet Slava-class cruiser. This ship carries 16 SS-N-12 SLCMs in eight pairs of launch tubes, four of which are visible in this photograph. Due to the size of the SS-N-12 missile (approximately 39 feet in length) and the geometry of the launch tubes, it would be extremely difficult to reload these launchers at sea. [U.S. Navy photo by PHI Paul D. Goodrich, courtesy of N. Polmar, *Guide to the Soviet Navy*]

We have constructed a verification framework that might be employed to verify a ban on nuclear SLCMs. Although our approach has a special simplicity when applied to this particular arms control option, similar approaches could be used to verify other limits on SLCMs. For example, if nuclear SLCMs were limited but not banned, the U.S. Navy is likely to insist that the verification measures should not interfere with its policy of neither confirming nor denying the presence of nuclear weapons aboard a particular ship or submarine. In this case inspections of deployed SLCMs would have to assure that SLCMs were legal without revealing whether they were nuclear. Although not as straightforward as the procedure used to verify a complete ban on nuclear SLCMs, this could be accomplished using tags that establish legitimacy without distinguishing among the tagged population.

In conclusion, the verification of arms control limits on nuclear-armed SLCMs does not present insuperable problems and can be accomplished at a level of both effectiveness and intrusiveness, which is likely to be characteristic of the other verification provisions of START.

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7. Here we note that time is a natural ally in the validation of the data exchange. An attempt not to declare nuclear SLCMs that have been previously produced would force a side to run many of the risks associated with covert production. In particular, these nuclear SLCMs would eventually require covert maintenance as well as a covert connection to the nuclear logistics chain for tritrium boosting of their nuclear warheads.
8. Challenge inspections could also be used to deter covert deployment on nonmilitary vessels.
9. The only significant exception to the lack of storage space on SLCM platforms of which we are aware occurs on warships that carry helicopters. In that case it may be possible to store SLCMs in the helicopter hangar of the ship, but the contents of this hangar can be viewed from outside the ship with the hangar door open. It should be noted that U.S. aircraft carriers do not carry SLCM launchers.

10. Occasional challenge inspections of ammunition ships could be used to verify that reloads are not carried with the fleet.
11. A related issue would be to require that nuclear air-launched cruise missiles (ALCMs) are not capable of being fired from existing SLCM launchers. Current U.S. ALCMs meet this condition, but it is not known if this holds for Soviet ALCMs.
12. For a discussion of the missions of U.S. SLCMs, see T. Terriff, *Survival*, (January/February 1989), pp. 52–69.
13. Some of the background information for this article was obtained through visits at the unclassified level to U.S. naval facilities, the technical on-site inspection unit at Sandia National Laboratories, and cruise missile production and assembly facilities. This paper was prepared while the authors were in residence at the Center for International Security and Arms Control, Stanford University. We acknowledge the support of the Carnegie, Hewlett, and MacArthur Foundations. We also express our appreciation to D. Bernstein and S. Drell for their advice and encouragement.

Photoemission Spectroscopy of the High-Temperature Superconductivity Gap

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Superconductivity is related to the presence of a narrow forbidden gap in the spectrum of the possible energies for the electrons in the material. These "superconductivity gaps" have traditionally been studied with tunneling and infrared absorption experiments. A third, powerful technique has been made possible by the discovery of high–transition temperature materials: the direct observation of the gap in photoemission spectra. The data analysis requires a careful reconsideration of the standard Einstein-Fermi model of the photoelectric effect. The conclusions are surprisingly simple and offer an alternate way to measure superconductivity gaps. This approach can also be used to study the directional properties of the gap, phenomena related to the coherence length, and possible departures from Fermi-liquid behavior.

Superconductivity is caused by a change in the state of electrons that are close in energy to the Fermi level, E_F. In order to clarify the nature of high–transition temperature (high-T_c) superconductivity, it is important to learn as much as possible about these states. A traditional probe used by materials scientists to investigate electronic states in solids is photoemission spectroscopy (*1*). In the past, however, photoemission methods failed to make substantial contributions to superconductivity research.

This situation has been reversed in the past 12 months: photoemission has become one of the leading techniques in high-T_c research (*2*), and the opening of the superconductivity gap has been detected in photoemission spectra (*3–6*). The gap width has been measured in well-characterized samples, with values much larger than the predictions of the conventional Bardeen-Cooper-Schrieffer (BCS) theory of superconductivity. Angle-resolved photoemission experiments are exploring directional effects in the gap, which reflect the anisotropic properties of high-T_c materials (*4–6*). Careful studies of the photoemission spectral edge should be sensitive to departures from a basic concept in today's solid-state physics: the Fermi liquid (*7, 8*).

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This article describes the rapid progress of photoemission experiments on the superconductivity gap. With photoemission spectroscopy it has also been possible to investigate other aspects of the electronic structure of high-T_c materials. We briefly review the use of photoemission resonances in these studies. We do not, however, describe the many different electron spectroscopy experiments that have been performed on these materials since 1987. Such experiments are described in a number of recent reviews (*2*).

Photoemission experiments on superconductors pose stimulating fundamental questions. The interpretation of solid-state photoemission data is based primarily on the model developed 84 years ago (*9*) by Einstein: an electron inside the solid absorbs the energy $h\nu$ of a photon and is emitted into the vacuum. Consider the case of an ideal Fermi gas model of a metal. Before the process, the electron is an independent particle of energy E_i. After the process, the electron is free and with energy E_p, and the Fermi gas has a hole of energy E_h. Energy conservation requires that $h\nu = E_p + E_h$. In turn, E_h (measured from the Fermi level, E_F) equals $-E_i$; hence, the well-known linear relation between E_p and $h\nu$: $E_p = E_i + h\nu$. This simple model does not account for phenomena caused by particle-particle interactions. In the practice of photoemission spectroscopy, such effects are treated as corrections to Einstein's single-electron picture (*10*).

Once this simple framework of interpretation is adopted, photoemission produces a wealth of information on the electronic states of solids (*10*). For example, the energy distribution of the photoelectrons outside the solid corresponds to the energy distribution inside the solid, shifted to higher values by $h\nu$. One can also retrieve information on the directional (*k*-space) properties of the electronic states from the direction of emission of the photoelectrons. In the past 30 years, photoemission techniques have been used extensively to investigate the electronic structure of metals, insulators, and semiconductors.

Why, then, have they failed in the case of superconductivity, perhaps the most interesting phenomenon caused by electrons in solids? The main reason is the limited energy resolution. The superconducting state involves electrons close to the Fermi level; the width of their energy range is determined by the magnitude of the