Viewpoint

Sub-Critical Nuclear Tests: An Option for India?

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As India seeks to develop and maintain its nuclear weapons arsenal, it faces the critical question of how to ensure the reliability and safety of its nuclear weapons, especially as they age, in the absence of full-fledged nuclear explosive tests. Further, India must decide how to increase the yield (or decrease the yield, as needed) and reduce the weights of its existing weapons designs—that is, improve the technical quality and effectiveness of its weapons. India has three obvious choices regarding testing: do no more tests of any kind, break its self-imposed moratorium and conduct full explosive nuclear tests, or continue to develop and refine existing designs via sub-critical tests.[2] This paper presents an analysis of these three options and concludes that sub-critical tests are the most likely route that India will adopt in the near term. Given this possibility, the paper details some recommendations that could help ensure greater transparency in the conduct of future Indian sub-critical tests.

The use of sub-critical tests is preferable to full-scale nuclear explosive tests and could slow the further proliferation of nuclear weapons in South Asia, as new weapons development is more difficult without full explosive tests. The ideal situation, of course, is that India desist from further development and deployment of nuclear weapons. Toward this end, the international community will continue to pressure India to refrain from any additional tests related to the development of nuclear weapons. This pressure may not be entirely successful, however, given the past history of Indian nuclear weapons development in the face of international opposition. In the context of renewed Indian nuclear testing, therefore, if tests occur at all, it is important to keep such tests at the sub-critical level. Furthermore, increased transparency in the conduct of any Indian sub-critical tests, at least to the minimum required to ensure that the tests have indeed remained sub-critical, could be an important confidence-building and confidence-creating measure.

Are there indications that future Indian nuclear tests may indeed remain at the sub-critical level? Does India have, or is India developing, the technical capabilities to conduct and learn from sub-critical tests? What would be to India's advantage in restricting its future testing program to the sub-critical level? And finally, what policy options does the United States have in dealing with India on issues related to possible Indian sub-critical tests? This article attempts to answer these questions.

The article begins by establishing that the two options of doing nothing or conducting full explosive tests are not viable for India. It will then present evidence that the Indian government has itself stated clearly its aim of conducting sub-critical tests in the future and is working to establish the technical capabilities to conduct and learn from sub-critical tests. Next it argues that there are several advantages to India of keeping its future weapons-related tests at the sub-critical level:

- A program of sub-critical tests would retain the ambiguity in India's nuclear weapons programs that has worked to India's advantage in many ways.
- Sub-critical tests will help India maintain its moratorium on nuclear tests involving nuclear explosions and adhere to the emerging global norm against nuclear weapons explosive tests, while strengthening the capability, deterrence quality, and political benefits of India's nuclear force-in-being.
- Sub-critical tests could avoid significant deterioration in India-U.S. relations that may occur if India conducts a new round of nuclear explosive tests.
- Sub-critical tests would help India avoid the possibility of new sanctions that may be imposed by the international community for conducting full-fledged nuclear tests.

Finally, the article discusses a policy option for the United States to consider in dealing with India on the issue of sub-critical tests—namely, to encourage limited and controlled transparency in the conduct of any future Indian sub-critical tests, and to urge India to restrict such tests for safety-related purposes and not for new weapons development. This is an option that deserves consideration given that it could have benefits for both India and the United States.

OPTIONS AT THE EXTREMES

India needs to incorporate lessons learned from the May 1998 tests into the preexisting designs that were tested. Much of this effort will likely focus on optimizing the design of existing Indian fission nuclear weapons by increasing yields for a given size and weight. One of the aims of the redesign process will be to increase the compression of the fissile material used in the weapon, so that a smaller amount of material can reach criticality. As discussed by Aaron Karp in *Ballistic Missile Proliferation*, using such a fractional critical mass or "fractional crit" method is one of the key steps in reducing the size of a nuclear weapon, and the amount of fissile material it carries, to make the weapon more suitable for missile delivery.[3] Indian scientists and engineers will also be interested in reducing the costs of manufacture and maintenance of proven nuclear weapons designs through reengineering. With greater experience in manufacturing, storage, and maintenance will come greater insight and recognition of possibilities for improvement that engineers may seek to exploit. As new delivery systems come into being (most Indian missiles are not yet in their final configurations, and some are still undergoing tests and development), the weapons will have to be certified for the associated vibration loads and stresses. This may also require some redesign. All such modifications will require some form of testing of the weapons. Therefore, it will not be possible for India to adopt a "do-nothing" policy. Meeting these conditions will require some form of testing.

There will also be continuing pressure from within the Indian nuclear weapons scientific community for additional tests. P. K. Iyengar, a former chairman of India's Atomic Energy Commission, has stated, "It is unscientific to embark on a long program of weaponization, and develop elaborate plans for maintaining a credible nuclear deterrent, all based on just one, low yield, thermonuclear test. When we do not do this for the Agni or Prithvi missiles, why would we want to take this risk for nuclear weapons?"[4]

Anthropologist Laura McNamara has studied nuclear weapons designers in Los Alamos.[5] She found that, among this community, being involved in a test explosion is considered a rite of passage. Within the corresponding Indian community, as well, there is likely to be a desire to participate in a test explosion and be anointed into a select inner circle. In addition, weapons designers will continue to develop new weapons designs hoping someday to test them, even though they may not be presently tested under India's existing moratorium on tests. Indian scientists will be motivated also by a desire to prove India's worth as comparable to that of more developed countries. All these factors will create pressure to develop new and more varied weapons designs, and possibly the weapons themselves—though the developers will find themselves stymied by their inability to conduct full-fledged tests.

WHY FULL-FLEDGED EXPLOSIVE TESTS ARE UNLIKELY

Although the Comprehensive Test Ban Treaty (CTBT) has not yet entered into force, a global norm against nuclear testing has begun to emerge by virtue of numerous states having at least signed the treaty, if not yet fully ratified it. India has also publicly announced a self-imposed moratorium on nuclear testing. Both the nascent international norm against nuclear tests and India's moratorium would have to be broken before India could renew a series of nuclear tests.

A renewal of nuclear explosive testing by India would have serious ramifications. U.S. sanctions against India for its 1998 series of nuclear tests have only recently begun to be lifted. Military cooperation between India and the United States resumed in 2002. For example, the United States has sold India Fire Finder battlefield radars, Indian and U.S. Special Forces have undertaken joint exercises, and the United States has lifted restrictions on the sale of F-404 GE aircraft engines for India's Light Combat Aircraft.[6] The Entity List of organizations in India that are restricted from access to U.S. technologies has been revised, and numerous entities have been removed from this list. Renewed nuclear tests by India could jeopardize this military cooperation with the United States. Sanctions could be imposed again, and the Entity List would likely be expanded.

Apart from repercussions from the United States, India will also face considerable opprobrium from the rest of the international community if it undertakes nuclear explosive tests. Japan, the European Union, Canada, and other developed countries will most certainly place additional sanctions on India. Relations with China could also suffer. China's initial response to India's last series of nuclear tests was restrained. However, after press reports indicated that the Indian government had justified its decision to test based on the "China threat," the Chinese government issued a statement strongly condemning India's tests.[7] Future Indian nuclear explosive tests may again elicit negative Chinese responses.

Worse still could be the reaction from Pakistan. The Pakistani government would likely conduct its own full-fledged tests in response. There could even be a further impetus to Iran's efforts to build nuclear weapons. A new series of nuclear explosive tests in South Asia might eventually result, and a spiraling nuclear arms race could ensue.

These concerns must certainly give Indian planners pause and good reason for not embarking on the course of renewed nuclear testing. Sub-critical tests would provide a *modus operandi* to continue with India's plans to create a credible minimum nuclear deterrent, while minimizing adverse international reactions.

To the extent possible, therefore, India is likely to use a series of sub-critical tests to refine its existing nuclear weapons designs. As pointed out by Ashley Tellis in *India's Emerging Nuclear Posture,* in the near future

> India's nuclear estate will be restricted to improving its current advanced designs—to the degree that it can—by means of simulations and laboratory tests while constantly preparing for the possibility of renewed field testing in the event that India's political leadership should change its mind and authorize the formal development and induction of advanced weapons into the country's nuclear inventory.[8]

THE SUB-CRITICAL TESTS OPTION

Given India's current declared moratorium on full-scale explosive nuclear tests, future Indian nuclear weapons development could well rely on sub-critical experiments to generate needed data. These data can validate theoretical and computational models. Once the models are validated, they can be extrapolated to conduct "virtual" nuclear explosions.

A sub-critical test uses an amount of fissile material less than that needed to form a critical mass. When the smaller amount of fissile material is compressed, the test can determine whether the required density is attained in the requisite time and as predicted by computational models. If the test results are in accord with the predictions, then the models are better validated. Ideally, the models should be validated against results from full-scale explosive nuclear tests. India has data from six previous full-scale explosive tests. Sub-critical tests could augment these data, and help in the further validation of models. Nuclear weapons designers could then use the validated computational analyses to predict the behavior of a larger critical mass. Based on the ability to predict the hydrodynamic behavior of a fissile material, they could have added confidence that a larger critical mass, too, would behave as designed, even without a full-scale nuclear explosive test.

The two Indian nuclear tests of May 13, 1998, involved detonations of 0.5 and 0.3 kilotons (KT) each. International seismic monitoring stations did not detect these tests, leading many scientists to doubt whether the devices had performed as planned and as India had proclaimed. However, later publications by Indian scientists involved in the tests refuted these allegations and presented post-shot radioactivity measurements establishing that criticality did occur.[9] Even though there may be doubts regarding the actual yield of these sub-kiloton tests, there cannot be much doubt that the tests did go critical at least to a small extent, given the presence of post-fission radionuclide products in bore holes near the test locations. It appears, therefore, that Indian scientists are able to conduct tests that are barely critical—yet, because such tests will be of very low yield, they will likely not be detectable by the international seismic monitoring network. It is important, therefore, that should India ever conduct underground sub-critical tests, there be a verification mechanism in place to certify that the tests are truly or have remained sub-critical and that they have not been planned to be or may inadvertently become barely critical, undetected, as occurred on May 13, 1998.

On that day, after carrying out the tests, the Indian government released the following statement:

> In continuation of the planned program of nuclear tests begun on the 11th of May, two more sub-kiloton nuclear tests were carried out at Pokhran range at 12.21pm (0651GMT) on the 13th of May 1998. The tests have been carried out to generate additional data for improved computer simulation of designs and for attaining the capability to carry out sub-critical experiments, if considered necessary….

This statement holds out the possibility of India conducting sub-critical tests in the future.

In December 1999, in an interview with a government spokesperson posted on the web site of the Indian Ministry of External Affairs, Dr. R. Chidambaram, the Chief of the Indian Department of Atomic Energy, discussed possible Indian sub-critical tests even more explicitly. In response to this question, "From a scientist's point of view, do you think Indian scientists have the capability of conducting sub-critical tests?", Dr. Chidambaram replied:

> At Pokharan we tested out a range of devices of .5 KT, .3 KT, and .2 KT yields. Our results were very close to our expected yields. Which means our capability to control this multiplication factor has been totally proved. Today, our knowledge of solid state theory is extremely high. We have what are called density functional methods, we've got very powerful computers which calculate the total energy in solids and various compression data. With computers all these calculations can be done very precisely.
>
> The beauty of our computer package is the absolute fit in all devices, between our design yields and the measured yields during the tests. We have computer simulation capabilities. It is already there. We've shown it in all our experiments by proving the matching…because of the excellent match between the calculated yields of the design and the measured yields after the tests.[10]

Although the yield of the Indian nuclear weapons tests has been a much-debated issue, there is no doubt that Indian scientists have succeeded in developing fission and boosted-fission/thermonuclear weapons with a yield on the order of 30–50 KT or more. What Indian weapons designers need to do now is to optimize their weapons designs to reduce the sizes, weights, and costs of maintenance and manufacture, and to increase the yields of their weapons. It appears from the official statements quoted above that India has intentions of continuing nuclear weapons design and manufacture through a program of sub-critical tests.

India's Position on Sub-Critical Tests

Sub-critical tests are allowable under the CTBT. Russia signed the CTBT on September 24, 1996, and ratified it on May 27, 2000. Russia has continued to conduct nuclear weapons-related sub-critical tests at the Novaya Zemlya test site.[11] Currently, the United States has an extensive program of nuclear weapons-related sub-critical tests, some of which are conducted underground at the Nevada Test Site.[12] Several researchers have studied the efficacy of sub-critical nuclear tests and the negative impacts of such tests on disarmament goals, primarily in the context of continuing U.S. and Russian sub-critical tests.[13] One of the intentions of U.S. and Russian sub-critical tests is to ensure the safety and reliability of their nuclear weapons stockpiles. The sub-critical tests also help maintain expertise and knowledge related to nuclear weapons design and manufacture.

Indian sub-critical tests, should they ever be conducted, will also have similar motivations related to safety and aging issues. Some components of India's nuclear weapons inventory are nearing two decades and more in age. India, too, has a need to maintain expertise and knowledge related to nuclear weapons and testing. Sub-critical tests will sustain India's nuclear weapons-related knowledge and expertise.

India's previously stated position at CTBT negotiations was that even sub-critical tests should be banned. After the criticality tests in 1998, however, India stated that it might itself carry out sub-critical tests. In fact, there have been press reports that the Indian Department of Atomic Energy has already developed the capabilities to conduct certain types of sub-critical tests.[14]

Utility of Sub-Critical Tests for India

Nuclear tests involving weapons-grade material may be sub-critical based on either of two options:[15]

- *Option One:* The configuration of the nuclear materials is of a kind that could lead to criticality, but the amounts of material involved are lowered to ensure that during the test there is no possibility of a critical mass being achieved. "A configuration that, assembled, provides two critical masses at the maximum density achieved, will be sub-critical if the mass of every element involved is multiplied by 0.4…radiography of the system is correspondingly easier, because it is less 'thick' at every stage of the assembly."[16]
- *Option Two:* The configuration is of a kind that the test could never result in criticality being achieved. An example of this second kind of test is one in which weapons-grade nuclear material is placed on a flat plate and exposed to a blast from an explosive so that it disperses before a sustained chain reaction can occur. The intent here is to study the properties of the nuclear material at high temperatures and pressures.

The task of the Indian designers is to optimize proven designs—reduce weight and size and increase yields. Some of the changes in engineering design that reduce the weight and size of a nuclear weapon could be tested without a nuclear detonation using a dummy warhead and a surrogate material. To test modifications that are designed to increase yield, a sub-critical test of the Option One type would be required.

Examples of types of data that could be obtained from sub-critical tests (of both Option One and Option Two types) are:

- Densities and velocities of the fissile material and ejected particles
- Validation of the computational predictions of blast and shock data, temperatures, and radiation levels as a function of distance and time
- Nuclear and thermal spectral distributions, and relative intensities of types of radiation, varying over time and distance.

Sub-critical tests involving fissile materials such as plutonium or highly enriched uranium are usually conducted underground if there is a possibility—albeit extremely small—that the material may go critical. Indian weapons are primarily plutonium based. Therefore, India is likely to conduct its sub-critical tests using plutonium. The behavior of plutonium under high pressures and temperatures is especially unpredictable, leading to the safety precautions of underground testing. Above-ground testing of configurations that have the possibility of going critical but are not likely to because of reduced critical masses is simply too great a risk. Even for configurations that can never go critical, the risk of containment failure and the dispersion of plutonium precludes above-ground testing. Therefore, India will be forced to conduct its sub-critical tests underground. It is these underground sub-critical tests that could become problematic for India—they could be misinterpreted as full-fledged low-yield nuclear explosive tests. However, it is these very types of underground sub-critical tests that would be of greatest value to India in generating needed data for validating models and for preserving the knowledge and expertise of its scientists related to testing and nuclear weapons development.

India's Technical Capabilities

India has the capabilities to manufacture hardened sensors and instrumentation. Indian weapons designers also have access to adequate supercomputers and expertise in modeling complex fluid and thermal phenomena. There are indications that India may be generating experimental data using pulse power devices to validate computer codes that model nuclear explosions. Therefore, there appears to be the requisite technology available within India to consider undertaking sub-critical tests to improve the design and yield of Indian nuclear weapons.

Undoubtedly, Indian scientists have either developed or could further develop the required hardened sensors and instrumentation needed for the successful conduct of sub-critical tests. The Indian nuclear industry has designed and built indigenous research reactors as well as nuclear power plants. India has also conducted six nuclear weapons tests. All of this activity has resulted in considerable nuclear expertise within India.

Indian scientists will need supercomputers to model sub-critical tests. The Bhabha Atomic Research Centre (BARC) has developed the ANUPAM Supercomputer, which uses 84 Pentium PCs to attain a sustained speed of 15 gigaflops, or billions of operations per second (which is about 500 times faster than the first computer built in BARC in 1991).[17] In comparison, the Advanced Strategic Computing Initiative (ASCI) of the U.S. Department of Energy (DOE) uses machines that are 1,000 times or more faster than the supercomputer developed by BARC. The ASCI is a part of the U.S. DOE's Stockpile Stewardship Program. Though the computational capabilities available to Indian designers are limited, they are by no means restrictive. In the past, U.S. weapons designers have worked with gigaflops machines.

Through their modeling studies and sub-critical tests, U.S. and Russian nuclear weapons scientists are studying problems of aging and the effects of possible micro fractures in weapons assemblies. Indian weapons designers are dealing with an axisymmetric problem related to modeling the weapon core. Therefore, the dimensionality of the problem they are studying is essentially two-dimensional—one dimension less than the problem faced by those studying three-dimensional problems caused by asymmetric micro fractures.[18] This fact could reduce the Indian computational capability requirement by a factor of a thousand, if we assume that a thousand approximation points are used along each dimension to create a computational model of the physical problem being studied. The gigaflops machines available to Indian weapons designers, therefore, may be adequate for some of the required modeling tasks.

Apart from adequate hardware, Indian weapons designers will also require computational modeling tools. The Indian scientists will have to model thermonuclear reactions, the dynamic response of materials at extremely high pressures and temperatures, and complex fluid phenomena such as turbulence and explosions. India has several advanced centers focused on computational modeling of complex physical systems. A report entitled "Flow Simulation and High Performance Computing in India" by the Asia Technology Information Project and Yajnik Associates of Bangalore, India, lists 62 centers of flow simulation activity in India.[19] Sectors covered by these institutes include aeronautics; atmospheric, automotive, and computational sciences; defense; energy; environment; ocean sciences; petroleum; space; theoretical physics; and water resources. Among the biggest users of computational resources within these 62 centers are BARC, the Institute of Plasma Research, and the Defense Research and Development Laboratory.

Indian scientists at BARC have developed a high-energy pulsed power device, called KALI-5000, that can produce pulsed electron beams for applications in high power microwave generation and pulsed intense neutron sources.[20] One of the possible applications of such a pulsed power device is providing experimental data for the validation of computer codes that model nuclear explosions.[21]

BENEFITS TO KEEPING FUTURE TESTS VERIFIABLY SUB-CRITICAL

India has no announced program for sub-critical tests. Nor are there any indications that India will undertake underground sub-critical tests in the near future. If such tests are ever entered upon at all, it will be several years in the future. Indian scientists will first exhaust the possibilities of laboratory experiments and simulations using surrogate materials, before they will need to conduct underground sub-critical experiments. Therefore, there is a window of opportunity at this time to discuss with India the need to increase the transparency of any future sub-critical tests.

Future sub-critical tests by India may be performed covertly and be hard to detect. They might, however, eventually become public knowledge. This could happen through satellite-based detection and identification of test preparations (if the tests are conducted underground at the Pokhran test site), through leaks of information gathered by external intelligence agencies, or through information leaks from within India's own government infrastructure. The Indian government may well intentionally release information on its sub-critical testing program.

When, and if, Indian sub-critical tests occur, the tests could be suspected of being clandestine full-fledged nuclear tests. This could have a destabilizing effect on regional strategic stability. The currently prevailing global norm against nuclear testing could be weakened.

India's principal nuclear adversaries, Pakistan and China, could both accuse India of using sub-critical tests as a cover for conducting larger yield tests. Although speculative to some extent, it is possible that sub-critical tests conducted by India would encourage Pakistan (and/or China) to begin a series of similar tests. [22] In this case, India would be in a position to doubt the yield of the sub-critical tests of its adversaries, and suspect that they might be using very-low-yield critical tests to develop new weapons. Therefore, encouraging transparency in the conduct of sub-critical tests would serve the interests of all of these countries.

On the other hand, should future Indian nuclear-related tests remain verifiably sub-critical, the following benefits would accrue:

- The ambiguity surrounding India's nuclear program will remain. This ambiguity serves as a brake to more aggressive nuclear postures evolving in the region.

- Weapons developed and tested through sub-critical tests will have a low confidence level among policy and strategic analysts and decision-makers, reducing the likelihood of use. Nevertheless, as the Indian government has publicly stated that it views nuclear weapons as a means of deterrence and has enunciated a "no first use" policy, the sub-critical tests could still enhance the perception of a nuclear deterrent among policy and strategic analysts, and decision-makers, and the potential enemies that India wishes to deter.
- If the sub-critical tests are conducted with limited and managed transparency, the international community will be assured that the tests indeed have remained sub-critical, and the global norm against nuclear tests and various countries' self-imposed moratorium on nuclear tests will be sustained.

Ambiguity has been a defining feature of the Indian nuclear program and the Indian standoff with Pakistan. Although much of this ambiguity has been dispelled since 1998, after India became a self-declared nuclear weapon state, considerable ambiguity remains. India's weapons designers declared after the Pokhran tests of May 1998 that a thermonuclear test was conducted with yields kept purposefully low to prevent damage to communities and structures in the vicinity. However, the maximum yield of a weapon in India's nuclear weapons stockpile has never been clearly stated. The maximum yield of Indian nuclear weapons relates to the efficacy of India's claim to be able to inflict unacceptable damage on an adversary—an expressed goal in India's draft nuclear doctrine. Also, the mix of fission, boosted fission, and thermonuclear weapons in India's stockpile is unknown, as is the number of such weapons. Whether India intends to make weapons using reactor-grade plutonium is also not clear—this would radically alter the maximum number of weapons likely to be in India's stockpile. The aim of listing these examples is not to argue for greater transparency on India's part; rather, it is to establish that, even after becoming a self-declared nuclear weapons state, India maintains ambiguity regarding its nuclear weapons capabilities. For several decades, since 1974, India was content being a demonstrated nuclear-capable state, keeping its nuclear weapons in what is called "recessed deterrence." Even after renewed testing in 1998, the Indian nuclear posture is shrouded in ambiguity. In South Asia, nuclear ambiguity plays a stabilizing role by reducing the inclination for proliferation and reducing the danger of preemptive strikes.[23]

Clearly, sub-critical tests will maintain the ambiguity that is in India's favor. The sub-critical tests would nevertheless strengthen the political benefits of avoiding coercion that India seeks from its nascent nuclear weapons programs. The sub-critical tests could improve the yield-to-weight ratios, the ability to mate the weapons with appropriate delivery vehicles, and—more importantly—the perceived probable capabilities, if not the real capabilities, of India's nuclear deterrent.

A POSSIBLE U.S. POLICY OPTION

U.S. policy options in dealing with new nuclear nations such as India by providing assistance have been thoroughly discussed by Steven Miller in the chapter "Assistance to Newly Proliferating Nations," in *New Nuclear Nations, Consequences for U.S. Policy,* edited by Robert Blackwill and Albert Carnesale.[24] As pointed out by Miller, the United States has provided assistance with nuclear tests only to close allies like the British—with whom joint nuclear tests have been conducted at the Nevada Test Site since 1962—and the French. As India does not enjoy a close military and alliance relationship, U.S. technical assistance to India in the conduct of sub-critical tests is not likely. U.S. opposition to Indian nuclear-related tests is also not likely to deter India from conducting tests it believes are required to meet Indian strategic and national security interests. A third option, however, does present itself: The United States could urge India to consider having limited and managed transparency and offer assistance in developing technologies that ensure transparency in the conduct of sub-critical tests. This engagement could also be used to pressure India to use sub-critical tests only for safety-related tests and not for new weapons development.

To minimize the adverse effects of any future Indian nuclear weapons-related testing, India could be subtly encouraged, if it does appear to be moving toward renewed testing, to keep its nuclear testing program sub-critical. This encouragement could come in the form of assistance to the Indian government in developing technologies that are not overly intrusive, but that can verify whether a test remains sub-critical. Asking the Indian government to allow international inspectors either during or after any future sub-critical tests would in all probability be considered overly intrusive. However, technical assistance to India from the United States in developing sensors and an instrumentation package that can give a yes-or-no indication that a test has remained sub-critical might be more acceptable, and could act as a gesture encouraging future Indian testing to remain sub-critical.

A precedent for such limited and managed transparency exists in the protocol to the treaty between the United States and the former Soviet Union on the Limitation of Underground Nuclear Weapon Tests.[25] The protocol states that, "For each explosion in a test, the trigger conditioner shall receive signals from one or two hydrodynamic yield measurement cables"; and,

> designated Personnel, under observation of personnel of the Testing Party, shall install in each cable from each satellite hole to a hydrodynamic recording facility an anti-intrusiveness device for interrupting the transmission, from the sensing elements and cables and transducers to the hydrodynamic recording facility of the Verifying Party, of any signal unrelated to hydrodynamic yield measurements.

Such types of anti-intrusiveness devices could also be created for sub-critical tests. Detectors that measure "prompt fission neutrons, prompt gammas produced in (n,gamma) reactions, and delayed gammas arising from decay of fission products" could be used to monitor the yield of a sub-critical experiment and ensure that measurable criticality was never achieved.[26] Anti-intrusiveness devices could be placed on the cables of such detectors to intercept the signals emanating from the detectors and ensure that no sensitive information was let through. The signal allowed to pass to foreign observers would be a simple yes-or-no signal indicating whether measurable criticality had occurred. By engaging India on the subject of sub-critical tests, the United States could also pressure India to restrict planned sub-critical tests to safety assurances and not for the development of new nuclear weapons.

CONCLUSION

Indian scientists face daunting challenges in proceeding farther along the path of nuclear weapons development without nuclear explosive tests. These challenges come primarily from the current moratorium on nuclear explosive tests imposed by India's political leadership. Therefore, Indian scientists may use sub-critical nuclear tests as a method of improving and expanding the Indian stockpile's deterrent capability and maintaining needed knowledge and expertise into the future. However, if Indian sub-critical tests, when and if they occur, are not universally accepted as sub-critical, India may face international hostility and a renewed Pakistani challenge. It is important, therefore, that India consider developing a system of cooperative monitoring measures and technologies to increase the transparency of future sub-critical tests. Such technologies could verify that a test had remained sub-critical without allowing unprivileged access to sensitive test data. U.S. support and assistance in such an endeavor—to help India create verification mechanisms for sub-critical tests—could be a positive inducement toward India's restricting its future weapons-related tests to the sub-critical level.

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[2] In a sub-critical nuclear test, a self-sustaining nuclear chain reaction is not established. Weapons-grade materials are used, but they are either of a lesser quantity or in a configuration that does not allow a critical mass and a self-sustaining nuclear chain reaction to develop.

[3] Aaron Karp, *Ballistic Missile Proliferation, The Politics and Technics* (New York: Oxford University Press, 1996), pp. 182-183.

[4] P.K. Iyengar, "Credible Deterrent Through Testing," *The Hindu*, on Ministry of External Affairs India web site, <http://www.meadev.nic.in/opn/2000aug/22toi.htm>.

[5] L. McNamara, "Ways of Knowing About Weapons: The Cold War's End at the Los Alamos National Laboratory," Ph.D. diss., Department of Anthropology, University of New Mexico, 2001.

[6] Wade Boese, "U.S., India Discussing Arms Deals, Military Ties," *Arms Control Today*, December 2001, <http://www.armscontrol.org/act/2001_12/indarmsdec01.asp>.

[7] J.D. Yuan, "India's Rise after Pokhran II Chinese Analyses and Assessments," *Asian Survey* 41, pp. 978-1001.

[8] Ashley Tellis, *India's Emerging Nuclear Posture: Between Recessed Deterrent and Ready Arsenal* (New Delhi: Oxford University Press, 2001), p. 525.

[9] R.B. Attarde, V.K. Shukla, D.A.R. Babu, V.V. Kulkarni, and Anil Kakodkar, "Fission Signatures of Tests on Sub-kiloton Devices," *BARC News Letter* 187 (September 1999), pp.1-2.

[10] Interview with Dr R. Chidambaram, Chief of Department of Atomic Energy, posted on the web site of the Indian Ministry of External Affairs, <http://www.meadev.nic.in/OPn/99dec/04ie.htm>.

[11] The web site of the Nuclear Threat Initiative lists some details of Russian sub-critical tests: <http://www.nti.org/db/nisprofs/russia/weafacl/othernuc/novayaze.htm#53000>.

[12] Excerpt from statement of John A. Gordon, Under Secretary for Nuclear Security and Administrator, National Nuclear Security Administration, U.S. Department of Energy: "President Bush supports a continued moratorium on underground nuclear testing; nothing in the [Posture Review] changes that. Over time, we believe that the stewardship program will provide the tools to ensure stockpile safety and reliability without nuclear testing. But there are no guarantees. It is only prudent to continue to hedge for the possibility that we may in the future uncover a safety or reliability problem in a warhead critical to the U.S. nuclear deterrent that could not be fixed without nuclear testing. Based on a 1993 Presidential directive, NNSA currently maintains a capability to conduct an underground nuclear test within 24 to 36 months of a Presidential decision to do so. Test readiness is maintained principally by the participation of nuclear test program personnel in an active program of stockpile stewardship experiments, especially the sub-critical experiments carried out underground at the Nevada Test Site (NTS)." U.S. Senate, Committee on Armed Services, February 14, 2002, <http://www.nnsa.doe.gov/docs/2002-02-14-TESTIMONY-US_Armed_Services_NPR.pdf>.

[13] See for example, Frank von Hippel and Suzanne Jones, "Take a Hard Look at Sub-Critical Tests," *Bulletin of the Atomic Scientists*, November/December 1996, <http://www.thebulletin.org/issues/1996/nd96vonhippel.html>.

[14] T. Jayaraman states: "…the DAE has acquired the ability to conduct 'equation-of-state' tests by hitting plutonium targets with high-explosive driven projectiles, using X-ray probes to study the behavior of plutonium under these conditions." T. Jayaraman, "The CTBT and Scientific Issues," *Frontline*, October 10-23, 1998, <http://www.flonnet.com/fl1521/15210810.htm>.

[15] Two other types of nuclear weapons-related tests involving nuclear sub-systems but not criticality are also possible. In one, a surrogate radioactive material could be used in implosion tests to simulate the behavior of a weapons-grade material in a primary assembly. Such a test could disperse radioactivity, but has no possibility of going critical—therefore, it is not considered a truly sub-critical test. In the other, a dummy warhead could be used in a test with a delivery vehicle to simulate the behavior of a real warhead. Raj Chengappa describes such a test of an aircraft-deliverable nuclear weapon using a dummy warhead in his book, *Weapons of Peace*. Raj Chengappa, *Weapons of Peace, the Secret Story of India's Quest to be a Nuclear Power* (New Delhi: Harper Collins Publishers India, 2000) pp. 382-384.

[16] Richard L. Garwin and Vadim A. Simonenko, 1996, "Nuclear Weapon Development without Nuclear Testing?" prepared for The Pugwash Workshop on Problems in Achieving a Nuclear-Weapon-Free World, October 25-27, 1996,<http://www.fas.org/rlg/dev_no_test.htm>.

[17] From the web site of India's Department of Atomic Energy: ANUPAM Supercomputer developed by BARC is being continuously upgraded, the latest being an 84-node system based on Pentium-III, which has demonstrated a sustained speed of 15 gigaflops. It is expected that a sustained speed of 50 gigaflops will be reached by the end of the IX Plan. Various versions of ANUPAM have been installed in the units of DAE as well as the organizations such as the Indian Institute of Technology (IIT)-Bombay, Mumbai; Vikram Sarabhai Space Centre (VSSC) , Thiruvan-thapuram; MS University, Vadodara; Indian Institute of Science, Bangalore; Aeronautical Development Agency, Bangalore, and the National Centre for Medium Range Weather Forecasting (NCMRWF), Delhi. Many more systems are in the process of installation. NCMRWF is providing a successful alternative to Cray-X-MP super computer. At BARC a centralized computing facility to cater to the ever-increasing computing needs of scientific community is being set up. See <http://www.dae.gov.in/publ/persp/htd/htd.htm>.

[18] The axisymmetry of the problem is lost immediately after an explosion event occurs in the model, as prediction of the blast effects will require a full three-dimensional model. However, the implosion of the core could be modeled as an axisymmetric problem to predict the density that would be attained by the fissile material in the needed time, before the material flew apart again through the explosive force of the nuclear chain reaction that would occur.

[19] Asian Technology Information Program (ATIP), "Flow Simulation & High Performance Computing In India," April 7, 1997, Report: ATIP97.033, <http://www.cs.arizona.edu/japan/www/atip/public/atip.reports.97/atip97.033r.html>.

[20] The Kali-5000 system is described in publications of the Indian Department of Atomic Energy, <http://www.dae.gov.in/publ/persp/basicr/basic.htm>.

[21] A report by the Lawrence Livermore National Laboratory on the role of the U.S. Advanced Strategic Computing Initiative (ASCI) in Stockpile Stewardship states, "Much of the experimental evidence used to validate instability and mix models is legacy data from rocket-rigs, linear electric motors, shock tubes, *pulsed-power machines*, and past nuclear tests" [emphasis added], <http://www.llnl.gov/asci/overview/asci_role.html>.

[22] A detailed analysis of Pakistan's reaction to Indian sub-critical tests, though an important subject, is beyond the scope of the study presented here and is discussed only briefly. The author anticipates taking up this subject in more detail in collaboration with a Pakistani scientist in the near future.

[23] In the Panel on South Asia's Nuclear Future, involving Gary Samore (Chair), National Security Council Staff; George Pervkovich, W. Alton Jones Foundation; and Ashley Tellis, RAND, organized by the Henry L. Stimson Center as part of its South Asia Luncheon Series, George Perkovich stated, "Ambiguity in strategic relations may have more benefits than commonly recognized. Indian and Pakistani leaders used their ambiguous nuclear capabilities in the late 1980s and the early 1990s to invoke nuclear deterrence against each other while avoiding the costs of building, testing, and deploying nuclear arsenals…. Ambiguous nuclear capabilities and ambiguous invocations of nuclear threats actually may be more effective modes of deterrence in this relationship because the ambiguity allows face-saving."

[24] Steven E. Miller, "Assistance to Newly Proliferating Nations," in *New Nuclear Nations, Consequences for U.S. Policy*, edited by Robert D. Blackwill and Albert Carnesale, (New York: Council on Foreign Relations Press, 1993) pp. 97-131.

[25] Protocol to the Treaty on the Limitation of Underground Nuclear Weapon Tests. See <www.unog.ch/frames/disarm/distreat/undergr.pdf>.

[26] S. Drell et al., "Subcritical Experiments," The MITRE Corporation, JASON Program Office, McLean, Virginia, 1997, <http://www.fas.org/rlg/jsr97300.htm>.