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In the debate over whether the United States should pursue a new generation of nuclear weapons designed to target underground bunkers and weapons of mass destruction, non-nuclear options for destroying those same facilities have been inadequately explored. Irrespective of their views on the desirability of developing new nuclear arms, most analysts have argued or assumed that a direct non-nuclear attack on a chemical or biological agent stockpile would either be ineffective in destroying that target or would spread live agent downwind, potentially endangering masses of civilians. This has consistently been the backdrop against which nuclear options are judged. But it is not necessarily correct.

I will address two problems that have plagued assessments of non-nuclear agent-defeat weapons. First, for non-nuclear (and nuclear) weapons that neutralize their targets using heat, analysts have tended to be overly pessimistic in assessing the threshold temperature for target neutralization. Second, analysts have tended to focus narrowly on high explosives as the alternative to nuclear arms, ignoring a host of non-nuclear technologies other than primitive bombs.[1] [2]

[1] Further expansion on a number of my points, particularly those on alternative weapon design, can be found in Michael A. Levi, *Fire in the Hole: Nuclear and Non-Nuclear Options for Counterproliferation* (Washington, DC: Carnegie Endowment for International Peace), November 2002.
[2] For other recent analysis related to new nuclear weapons, see Michael A. Levi, "Dreaming of clean nukes", *Nature* **428**, 2004, p892; Michael A. Levi, "Learning to love the tiny bomb?", *Foreign Policy* (March/April 2002).

Most agent defeat options – including nuclear weapons and high-explosives – neutralize chemical or biological agents by raising the target's temperature.[3] Thus, to assess any weapon's effectiveness, we must first determine the threshold temperature for rapid agent neutralization. Most studies have assumed that a threshold temperature of between 1000-1500 K must be sustained for times on the order of at least tens of milliseconds (some suggest several seconds), independent of the target agent[4]. But while such exposures may be necessary to neutralize certain agents, they are far from necessary for neutralizing most agents – including the most dangerous ones – as we show below.

The most important distinction to be made is between chemical and biological agents: Chemical agents are much harder to neutralize than biological agents, even as they are at the same time less dangerous to the United States or to civilians. Yet the high temperature requirements cited for neutralization are often driven solely by the temperature needed to destroy chemical agents. Indeed, the figures cited above – 1000-1500 K for times on the order of tens of milliseconds – are correct for certain chemical agents. The Defense Threat Reduction Agency reports the following exposure times are necessary to kill 99.999% of target agent at given temperatures:

	Temperature[5]		
Agent	800 K	1000 K	1500 K
Sarin (GB)	20 s	1 s	0.02 s
VX	0.7 s	0.01 s	0.0001 s
Mustard (HD)	0.03 s	0.002 s	0.00005 s

If the goal of neutralizing Sarin in effect sets requirements for all agent defeat weapons, then approximately one second at 1000 K or 20 milliseconds at 1500 K will be required,

[3] In some nuclear cases, radiation might be the dominant mechanism. See Hans Kruger, *Radiation-Neutralization of Stored Biological Warfare Agents with Low-Yield Nuclear Warheads*, rep. no. UCRL-ID-140193, (Livermore, CA: U. of California, Lawrence Livermore National Laboratory), 2000.
[4] See, for example, Michael May and Zachary Haldeman, *Effectiveness of Nuclear Weapons against Buried Biological Agents* (Palo Alto, CA: Stanford University), 2003; Robert W. Nelson, *Science and Global Security*, 2004, in press; Lawrence Livermore National Laboratory scientist, unpublished slides, 2004.
[5] Note that reducing the neutralization goal to only 90% would only decrease the times needed by a factor of five, since this is a first-order reaction.

consistent with what has been claimed in the past. If, however, the weapon's performance is judged against each chemical agent separately, the requirements would vary widely. For example, used against VX – a particularly pernicious agent – less than one second at 800 K would be necessary.

Destroying even the hardiest biological organisms is far easier. Those biological agents that do not form spores – including the organisms that cause plague, brucellosis, tularemia, Q-fever, and smallpox – are the easiest to neutralize. Though data is uneven, the following are illustrative of this category. Note that though the numbers here appear to be precise, they should only be taken as rough indicators of what would be necessary in a given scenario; temperatures can be expected to vary by as much as ten degrees in either direction.

- *Coxiella burnetti*, the organism that causes Q-fever, is the most heat resistant of the non-virus organisms in this category. Still, one second of exposure at 72 degrees C is sufficient to kill 90% of exposed cells; 1 millisecond at 84 degrees has a similar effect, and 5 milliseconds at 84 degrees should thus kill 99.999% of the organisms.[6]
- A sample of *Brucella abortus*, an organism that might be used to cause brucellosis, is reduced by 90% in viability by a 10 millisecond exposure to 66 degrees C.[7] Thus a 50 millisecond exposure to only 66 degrees C would kill 99.999% of the target agent. Moreover, for each 4.3 degree C increase in temperature, that exposure time is cut by a factor of ten.
- A sample of *Variola* virus, which causes smallpox, will be 90% inactivated by exposure to 55 degrees C for 6.6 minutes.[8] Given data at 40, 45, and 50 degrees[9], and since we know that the thermal inactivation is approximately a first order

[6] The underlying data are the basis of FDA regulations for milk pasteurization, which require holding a sample at 72 degrees for fifteen seconds to assure 12-log inactivation.
[7] D.O. Cliver, *Predictive Microbiology and Its Use in HACCP*, lecture notes, University of California, Davis, 2003.
[8] Nicholas Hahon and Edmund Kozikowski, "Thermal Inactivation Studies with Variola Virus", Journal of Bacteriology, **81** (4), 1961, pp 609–613.
[9] Nicholas Hahon and Edmund Kozikowski, "Thermal Inactivation Studies with Variola Virus", Journal of Bacteriology, **81** (4), 1961, pp 609–613.

reaction, we infer that each 17.4 degree increase in temperature will yield a 10-fold reduction in the number of surviving organisms. This means that 85 degrees C should yield 90% inactivation in 7.5 seconds; one second at 100 degrees C should kill 90% of the target; and one second at 112 degrees C should kill 99.999% of the target agent. *Variola* is much harder to kill than *C. burnetti* or *B. abortus*, but it is still much easier to kill than the chemical agents discussed above.

Spore-forming organisms are much harder to kill than those organisms just discussed. Among biological agents, these are represented primarily by *Bacillus anthracis*, which causes anthrax. Though public data for *B. anthracis* itself is scarce, its response to heat can be inferred from that of several related organisms. Three organisms are particularly interesting: *B. subtilis*, which is commonly used as an anthrax simulant in biowarfare and public health studies; *C. botulinum*, which the Centers for Disease Control and Prevention (CDC) reports is more resistant to thermal inactivation than *B. anthracis*[10]; and *B. stearothermophilus*, considered to be among the hardiest biological organisms. Looking at these organisms together helps suggest an upper bound on the heat needed to neutralize anthrax well below the 1000-1500 K figures cited above.

First, note that the difficulty of killing spores depends on their physical form and on how heat is applied to them. Dry heat applied to dry spores, as might occur if stored anthrax powder if exposed to an explosion, is least efficient; dry heat applied to moist spores, as might be observed if an anthrax slurry aerosol were exposed to hot gas from an explosion, is of intermediate effectiveness; and moist heat applied to moist spores, as might be seen if the energy from an explosion were used to heat bulk anthrax slurry, is the most effective.

The broadest range of data is available for *B. subtilis*. Wallhausser reports that 121 degrees C of moist heat must be applied to *B. subtilis* for 0.4-0.7 minutes to reduce the viable spore count by 90%; and that for every 8-13 degree C increase in temperature, this

[10] E. A. Spotts Whitney et al., "Inactivation of *Bacillus anthracis* Spores", *Emerging Infectious Diseases*, **9**(6), 2003, pp 623-627.

time is cut tenfold.[11] Assuming the time needed at 121 degrees C is 0.7 minutes, and that a 13 degree C increase is needed to cut that time tenfold, we obtain a pessimistic estimate that at 150 degrees C, a 250 millisecond exposure is needed to obtain 90% neutralization; and that at 180 degrees C, a one millisecond exposure will result in 90% neutralization, while a five millisecond exposure will result in 99.999% neutralization. Alternatively, assuming the time needed at 121 degrees C is 0.4 minutes, and that a 8 degree C increase cuts that time tenfold, we obtain an optimistic estimate that at 150 degrees C, a six millisecond exposure is sufficient to obtain 90% neutralization, and a 28 millisecond exposure will obtain 99.999% neutralization.

Mullican et al. report on experiments involving dry and moist spores of *B. subtilis* exposed to dry heat for 0.02 seconds in an experiment meant to simulate the performance of biowarfare decontamination equipment.[12] For wet spores, 90% neutralization is achieved at approximately 200 degrees C, while 99.999% neutralization is achieved at approximately 220 degrees C; for dry spores, those temperatures are roughly thirty degrees higher.

Finally, Nicholson et al. display curves showing the sensitivity of *B. subtilis* to both wet and dry heat.[13] Their data for moist heat is similar to that from Wallhausser, falling within his broad range. For dry heat, the authors claim that 1 day at 120 degrees C is required to obtain 90% neutralization, and that the time needed is reduced tenfold for every 15 degrees increase in temperature. Put together, this implies that at 200 degrees C, 0.4 seconds is needed to achieve 90% neutralization; and that at 240 degrees C, 1 millisecond is needed for 90% neutralization, 5 milliseconds yield 99.999% neutralization. This appears to agree with Mullican's data for dry spores, and provides a useful upper bound on the time/temperature combination needed for neutralization.

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[11] Karl Heinz Wallhäusser, *Sterilisation, Desinfektion, Konservierung, Keimidentifizierung, Betriebshygiene*, (Thieme), 1978.
[12] Charles L. Mullican et al., "Thermal Inactivation of Aerosolized *Bacillus subtilis* var. *niger* Spores", Applied Microbiology, vol. 22, no. 4 (1971) pp 557-559.
[13] Wayne L. Nicholson et al., "Resistance of *Bacillus* Endospores to Extreme Terrestrial and Extraterrestrial Environments", Microbiology and Molecular Biology Reviews, vol. 64, no. 3 (2000), pp 548-572.

B. subtilis is not our only source of public domain data. Decades of food sterilization experience has confirmed that the viable population of *C. botulinum*, is reduced by 90% after exposure to 121 degrees C (394 K) of moist heat for 15 seconds, and that this time interval is reduced tenfold for each 10 degree C increase in temperature. For a temperature of 150 C, this implies 90% reduction in viable spores after a 15 millisecond exposure, or alternatively a 99.999% reduction after a 75 millisecond exposure.

B. stearothermophilus is much harder to destroy at lower temperatures: it must be exposed to 121 degrees C (394 K) of moist heat for 3.3 minutes to obtain a 90% reduction in viable spores, in contrast with 12 seconds for *C. botulinum*[14]. But here, the time required is reduced approximately tenfold for each 7 degree C temperature increase. For a temperature of 150 C, this implies 90% reduction in viable spores after a 14 millisecond exposure, or alternatively a 99.999% reduction after a 70 millisecond exposure.

From these data, we can infer that a temperature of at least 150 degrees C sustained for tens of milliseconds will be needed to obtain meaningful neutralization of an anthrax target; that a temperature of 180 degrees C sustained for tens of milliseconds may be desirable; and that if the target is powdered anthrax, a temperature between 200 and 250 degrees C will be required to ensure 99.999% neutralization.

Putting together this data on various chemical and biological agents, what lessons should we learn? Unless our goal is a magic bullet, our approach to agent defeat should account for the strong variations between target agents of concern. It must recognize the sharp differences between chemical and biological agents. To see why, consider the following typical yet flawed case for why nuclear weapons are the only agent defeat solution:

[14] F.E. Feeherry et al., "Thermal inactivation and injury of *Bacillus stearothermophilus* spores", *Applied and Environmental Microbiology*, Vol. 53, No. 2 (1987), pp 365-370.

1. A weapon incident on a CBW target might disperse the CBW and kill 100,000 civilians. (Note: This is implicitly predicated on the target being anthrax or smallpox, not a generic CBW, and certainly not CW.)
2. It takes at least 1000 K for times on the order of tens of milliseconds to neutralize CBW. (Note: Here, the 1000 K temperature is implicitly set by the need to neutralize CW, specifically Sarin, and certainly not BW.) Conventional arms cannot deliver these sustained temperatures, but nuclear arms can.
3. Nuclear arms will produce radioactive fallout, but it will be more than offset by the casualties avoided through neutralizing the target agents.
4. Nuclear arms will thus cause fewer total casualties than non-nuclear arms.

This appears to show that nuclear weapons will invariably yield less collateral damage than non-nuclear weapons. (Whether that damage is tolerable in any case is another question.) But consider CW and BW separately. A non-nuclear weapon might not be effective in neutralizing CW, given the criteria developed above, but dispersed CW might not cause large numbers of collateral deaths (and certainly would not cause the 100,000 deaths cited above.) At the same time, though dispersed BW might pose a major problem, a non-nuclear weapon might be effective in neutralizing the BW (given the lower temperature thresholds discussed above), thus preventing dispersal.

The analysis summarized above that lumps together all CBW misses some of the most important technical details of the agent defeat problem. A proper assessment of agent defeat will require unpacking the different agents from the counterproductive concept of CBW before assessing agent defeat options.

Armed with a more solid understanding of what it takes to neutralize chemical or biological agents, we can say much more about agent defeat in general. First, a warning a warning about the simplest analyses: We must take care when making simple energy arguments about agent defeat. Several authors – arguing both for and against nuclear agent defeat weapons – have attempted to find upper bounds on the effectiveness of agent

defeat weapons by distributing the weapon's energy over the target, calculating the resultant increase in temperature, and then comparing that temperature to some neutralization threshold. This is a reasonable approach, but only if done very carefully. First, the simple energy argument described above does not actually calculate whether the target agent can be heated to the required temperature for some finite time; it calculates whether the target can be permanently heated to that temperature. It does not account for the possibility that the energy initially used to heat one part of the target might later be transferred to and used to heat another part. It may be that such transfer of heat from one part of the target to another happens too slowly to be relevant, but that must be calculated.

In addition, any analysis must be careful not to assume that a liquid target must be boiled off before it can be heated past its normal boiling point. This is often assumed for water suspensions of agent, particularly anthrax, and makes a major difference to the analysis, since the energy required to evaporate water is the same as that required to heat it by 540 degrees, and since some agents require heating above water's boiling point. But since the heating in question takes place in the vicinity of an explosion, we must account for the possibility that the ambient pressure will be considerably greater than standard pressure, thus raising the boiling point of the target liquid. For example, a 10 atmosphere pressure would raise the boiling point of water to 180 degrees C, and a 20 atmosphere pressure would raise it to 215 degrees C – well over the required temperatures for destroying wet biological agents. Of course, the raised pressures, which are fleeting, would have to coincide with the deposition of energy in the target, and the temperature increase that causes. But this possibility should be assessed before assuming that the a liquid target must be vaporized before it can be neutralized.

Given these general consideration, what can we say about specific weapons? Most comparisons of nuclear and conventional agent defeat have juxtaposed nuclear bombs with high explosives (HE). But it is essential that when comparing nuclear to non-nuclear options, the non-nuclear option *not* be assumed to be HE. No military planner, given other options, would think of using simple HE against an agent defeat target – yet that is almost always the foil against which nuclear agent defeat options are compared.

(Of course, a planner might not know that his target contained WMD, and thus would not know to use an agent defeat weapon – but then he would not know to use a specialized nuclear weapon either.) Several far better options exist, especially if one focuses on neutralizing biological, rather than chemical, agents. (Such a priority makes strategic sense: CW are less deadly than BW, and can be more easily defended against.) The options can be applied either individually or in combination.

Fuel Air Explosives (FAE) appear to be the most obvious alternative to HE. These weapons disperse fuel in a cloud before igniting it. They create a moderate sustained overpressure and a high temperature region, but lack the high central blast pressure of HE. However, for an agent defeat weapon, high blast pressure is generally unnecessary, and possibly even counterproductive. (If greater blast is needed to break open canisters of target agent before they can be heated, a small fragmenting warhead can be used as a precursor to or in tandem with the FAE.) Moreover, an FAE can use fills with ten or more times the energy density of ordinary TNT. The primary drawback is the massive amount of oxygen required for an FAE to burn, which in a confined bunker could limit the amount of energy released.

An effective FAE delivers a peak overpressure of 20 atmospheres, or enough to let water-based target materials reach over 200 degrees C without boiling.[15] For a bomb filled with one ton of kerosene – a representative fuel fill – this overpressure is essentially constant over a region with diameter 30 meters; the corresponding diameter for the same mass of TNT is 17 meters.[16] Moreover, the temperatures in this region typically reach 5000 degrees C; for same mass of TNT, the corresponding diameter is 5 meters. (Simply breaking open the target using a fragmenting warhead, and then dumping the kerosene on the bunker floor and igniting it, might be just as effective, though it would sacrifice any possible synergy between heating and pressure, as discussed above.)

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[15] M. J. Tang and Q. A. Baker, "A New Set of Blast Curves from Vapor Cloud Explosion", *Process Safety Progress* **18**(4), 1999, p235.

[16] Figures for TNT obtained using the program *High Explosive Blast (HE); Computational Aid Version 1.0* (Washington, DC: Defense Nuclear Agency) 1994.

To demonstrate how revising agent defeat requirements while shifting from HE to an FAE might affect the assessment of conventional options, we revisit a typical estimate of how ineffective conventional options might be. A typical scenario pitting an HE weapon against a CBW target would assume a TNT weapon yielding 4 MJ/kg; it would require the target be heated by 1000 K to be neutralized; and it would assume a 4 J/g-K heat capacity for the target, consistent with a water-based slurry. This yields the conclusion that one kilogram of weapon is required to neutralize one kilogram of target agent – a ratio that would make it extremely difficult for the US to quickly neutralize even hundreds of tons of enemy agent. However, imagine that chemical agent could be ruled out as a target (perhaps the target is the far more worrying anthrax or smallpox) – the temperature needed to neutralize the target is likely to be closer to 200 degrees C, and the change in temperature closer to 180 K; and that using an FAE, the attacker can deliver 40 MJ/kg of weapon. Put together, this suggests that 1 kg of FAE can neutralize roughly 60 kg of target – still small compared to nuclear weapons, but a far more manageable ratio than before. (Higher temperatures would be required for dry anthrax, but 1 kg of FAE might still neutralize as much as 50 kg of target agent.)

Heat is not the only way to kill biological agent targets; chemicals might be effective too. Simple concentrated bleach can kill all biological agents if delivered in sufficient quantities; more advanced payloads might lower the bleach-to-bugs ratio. For bleach against anthrax, that ratio (measured by mass) is roughly one-to-one[17]. Depending on the target size, that might be manageable. Again, a fragmenting precursor warhead would have to be used to expose the target before it could be neutralized. In addition, chemical agents would likely be immune to these attacks, though specialized payloads tailored to specific target agents might be developed.

These types of approaches have languished for two main reasons. First, the desire to develop weapons that neutralize chemical as well as biological agents has obscured effective solutions for smaller – yet especially dangerous – classes of agents. Thus, for

[17] Thomas Ricks, "U.S. Military Considers Weapons That Disable Bunkers, Spare People", *Wall Street Journal* (July 1, 1999).

example, a payload that would be effective against Smallpox – the most feared biological weapon – but not against Sarin – a dangerous but manageable poison – would typically be rejected as being ineffective. As described above, this is not a productive requirement.

Second, in exploring non-nuclear options, the perfect has too often been the enemy of the good. Those who think about conventional weapons are used to thinking of tens of civilians as excessive collateral damage. Thus, for example, the Agent Defeat program rejected a promising approach that used a penetrating bomb that sealed its entry hole with foam, thus trapping dispersed CBW agent, because alternate exits to the target bunker might eventually have allowed some agent to leak out, killing some number of nearby civilians. Under a philosophy that allows for no risk of significant collateral damage – typical for conventional weapons – such an approach appropriately went nowhere.[18] But while we reject such conventional concepts for carrying small a small risk of collateral damage, we entertain the use of nuclear weapons as an alternative. This should be transparently ridiculous. It is fine to explore "immaculate" options for agent defeat. But it would be wiser to take the same approach to conventional agent defeat weapons as we already do to nuclear agent defeat weapons – explore any conventional option that reduces collateral damage, not only those that reduce it to near zero. Only such a broad-based effort is likely to yield conventional options that can compete with their nuclear counterparts.

[18] Thomas Ricks, "U.S. Military Considers Weapons That Disable Bunkers, Spare People", *Wall Street Journal* (July 1, 1999).