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# Nuclear Winter and the Anthropocene

***Jon Spencer,*** *Dept. of Geosciences, University of Arizona, Tucson, Arizona 85721, USA, Spencer7@arizona.edu*

## ABSTRACT

In 2019, the Anthropocene Working Group proposed the creation of an Anthropocene chronostratigraphic time unit to follow the Holocene Epoch. The Anthropocene time period would begin in the mid-twentieth century, coincident with rapid acceleration of multiple, ongoing anthropogenic changes to Earth's surface and environments. Radioactive isotopes dispersed during the 1952–1962 period of atmospheric thermonuclear-bomb tests form a proposed global marker for the beginning of the Anthropocene. This marker is proposed for purely geological reasons as it is reasonably precise and global in scope. These isotopes are also a marker for the initiation of a new human capacity to trigger global environmental change in a period of hours. The possibility of a global, multiyear nuclear winter following a nuclear war between North Atlantic Treaty Organization nations and Russia is suggested by recent studies of wildfires that injected sunlight-blocking smoke into the stratosphere, and by increasingly sophisticated numerical simulations of global climate following a major nuclear war. Although the proposal for an Anthropocene time period was made without consideration of the consequences of nuclear war or nuclear winter, designating the period of thermonuclear weapon tests as initiating an Anthropocene time period is supported here specifically because it indicates a new human capability for rapid and destructive environmental change on a global scale.

## INTRODUCTION

The Anthropocene is a proposed time period that would begin with geologic evidence of human modifications of Earth's surface and environments, but with an unspecified future end date (Zalasiewicz et al., 2019). The abundance and severity of such modifications since the industrial revolution provoked consideration of an anthropic (human-related) time period following the Holocene (Crutzen, 2002). The "Great Acceleration" of environmental change associated with rapid post-WWII economic growth and technological innovation (Steffen et al., 2015) is now the leading candidate for the beginning of the Anthropocene (Anthropocene Working Group, 2019). The Great Acceleration also coincides with hundreds of atmospheric nuclear-bomb tests, primarily by the United States and the Union of Soviet Socialist Republics (USSR), that injected radioisotopes into the global atmosphere. Some of these isotopes will be measurable in various materials for tens of thousands of years, thus providing a geologic marker for the beginning of the Anthropocene (Waters et al., 2015). The purpose of this paper is to outline some of the environmental and geological consequences of a major nuclear war as suggested by recent studies in atmospheric sciences that indicate the possibility of severe global cooling following such a war, a consequence termed "nuclear winter" (e.g., Turco et al., 1983, 1990; Robock et al., 2007). Mid-twentieth-century radioisotope fallout is not simply a convenient marker for accelerated environmental change and a new geologic time period but indicates a new human capacity to abruptly initiate catastrophic global change.

## THE BEGINNING OF THE ANTHROPOCENE

The International Commission on Stratigraphy (ICS) defines and modifies units of the International Chronostratigraphic Chart (Cohen et al., 2013). In 2009, the ICS tasked the Subcommission on Quaternary Stratigraphy with forming an Anthropocene Working Group to study possible designation of a formal Anthropocene chronostratigraphic time unit and to make recommendations regarding modification of the geologic time scale. Consideration of a formal lower boundary for the Anthropocene requires conformity with criteria used to establish other boundaries within the geologic time scale, including global synchroneity or near synchroneity (Waters et al., 2018). Although the beginning of the industrial revolution was initially proposed as the beginning of the Anthropocene (Crutzen and Stoermer, 2000), the great acceleration of anthropogenic environmental change following WWII (Steffen et al., 2007, 2015) led the Anthropocene Working Group to propose that an Anthropocene epoch begin in the mid-twentieth century.

### Radioisotope Fallout

Explosive energy is derived entirely from nuclear fission in atomic bombs ("A-bombs") whereas an atomic bomb is the trigger for second-stage nuclear fusion in thermonuclear bombs ("H-bombs"). Atmospheric atomic-bomb tests dispersed radioactive fission products to the troposphere where fallout was largely confined to the general region around the test site. In contrast, much larger thermonuclear weapon tests during 1952–1962 (Fig. 1A) each produced a fireball that ascended into the stratosphere and resulted in global dispersal of radioisotopes (UNSCEAR, 2000). Two plutonium isotopes in thermonuclear-bomb fallout, plutonium-239 ($^{239}Pu$) with a half-life of 24,110 years and plutonium-240 ($^{240}Pu$) with a half-life of 6563 years, will be identifiable in sediment and ice for tens of thousands of years (Fig. 1B; Hancock et al., 2014).

Earth's upper atmosphere is bombarded with high-energy protons and atomic nuclei derived from the Sun ("solar wind") and from outside the solar system ("cosmic rays") (Damon and Sternberg, 1989). Resulting nuclear reactions include transformation of nitrogen-14 ($^{14}N$) to carbon-14 ($^{14}C$), which has a half-life of 5730 years. This carbon promptly reacts with oxygen to produce $CO_2$ and is well mixed with the atmosphere within a few years. Roughly one in a trillion $CO_2$ molecules in Earth's

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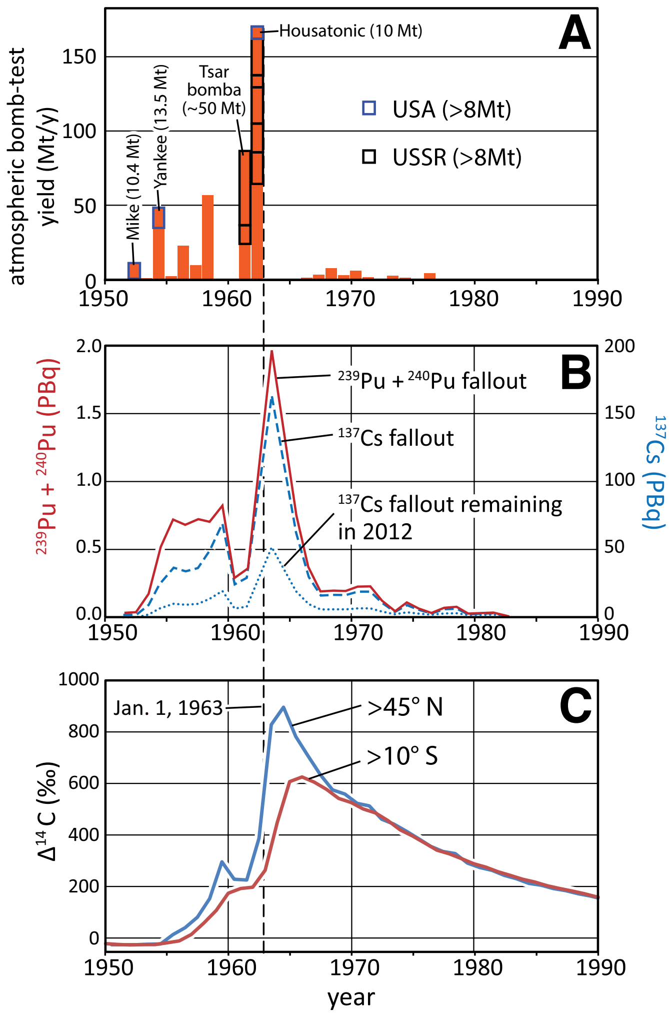


**Figure 1. (A) Histogram of annual yield, in megatons of TNT equivalent, for atmospheric nuclear-bomb tests (UNSCEAR, 2000; USDOE, 2015). Atomic bomb-test yields before the first thermonuclear bomb test in 1952 are too small to plot at the scale shown. Names of some major tests are also shown. Atmospheric testing by the United States (USA) and Union of Soviet Socialist Republics (USSR) ended with the 1963 Partial Test Ban Treaty. Later atmospheric tests were conducted by China and France. (B) Combined $^{239}$Pu and $^{240}$Pu fallout as calculated from more readily measured $^{137}$Cs and $^{90}$Sr fallout, with higher ($^{239}$Pu+$^{240}$Pu)/$^{137}$Cs in earlier U.S. (neutron-rich) tests versus later Soviet tests (Koide et al., 1985; UNSCEAR, 2000; Hancock et al., 2014). (C) Graph of $^{14}$C as measured in tree rings and in the atmosphere showing the high values measured at sites >45° N and low values measured at sites >10° S before global atmospheric mixing (modified from fig. 4 of Hua et al., 2021).**

atmosphere contain $^{14}$C rather than stable $^{12}$C or $^{13}$C (e.g., Dutta, 2016). Neutrons produced by nuclear explosions also cause transformation of $^{14}$N to $^{14}$C. Thermonuclear-bomb tests during 1952–1962 produced so much $^{14}$C that concentrations of $^{14}$C in atmospheric $CO_2$ almost doubled (Fig. 1C; Hua et al., 2021). Elevated $^{14}$C concentrations are measurable in tree rings and ice cores (e.g., Levchenko et al., 1996) and have been proposed as the most precise geologic marker for the beginning of the Anthropocene (Turney et al., 2018).

## NUCLEAR WAR

Radioisotope fallout in the mid-twentieth century occurred during the development and deployment of thousands of nuclear weapons by North Atlantic Treaty Organization (NATO) nations and the USSR. The military posture represented by these nuclear weapons, known as "mutual assured destruction," ensures a catastrophic nuclear response to a major nuclear attack, thus restraining adversaries as long as those in charge behave rationally and command and control infrastructure performs as intended.

The United States currently has ~1400 thermonuclear warheads deployed on land- and submarine-based ballistic missiles and another ~400 at U.S. Air Force bases (Kristensen and Korda, 2021). A recent estimate of Russian nuclear-weapon deployment is similar (Kristensen and Korda, 2022). Both nations have several thousand additional nuclear warheads in storage and available for deployment, with a total of ~8300 warheads and bombs available for use in a major nuclear war. NATO members France and UK have another ~500 nuclear weapons. The nuclear-weapon arsenal of the United States is intended to defend the 30 member nations of NATO, with a population of ~950 million, plus an additional 200 million people in Japan, South Korea, and Australia. The Russian arsenal is intended to defend the ~146 million people in Russia plus the additional 47 million people in allied countries of the Collective Security Treaty Organization.

The primary targets of Russian and American nuclear weapons are the nuclear weapons of the opposing countries (Hafner, 1987). Stationary land-based missile sites would be targeted with the intent of destroying the missiles before launch. Other military facilities, including those in and near cities, would be targeted, with higher-elevation detonation for more dispersed targets. The number and types of non-military targets, including infrastructure, industry, and cities, is not public knowledge, but enormous destruction and loss of life could result from attack on these targets with a small fraction of either nation's nuclear forces (Glasstone, 2020).

## NUCLEAR WINTER

Nuclear winter is the concept that, during a major nuclear war, firestorms caused by nuclear explosions will engulf cities and inject smoke into the stratosphere where it will spread around the globe and reduce sunlight at ground level to the point where winter-like conditions persist for months or years (e.g., Crutzen and Birks, 1982; Turco et al., 1983, 1990). The severity of a nuclear winter would depend on the fuel load and flammability of targeted areas as well as atmospheric conditions and other environmental factors. While the primary targets of U.S. and Russian nuclear weapons are the opposing nation's nuclear weapons and command and control infrastructure, most of which are not particularly large or flammable, potential secondary targets include all other military bases, many of which are near or within cities or their surrounding suburbs. Other likely targets include infrastructure for manufacturing and transportation, power generation and distribution, and oil and gas refining and distribution. Many if not most of these targets are within or near cities and suburbs. Even cities themselves could be targets if the intention is to prevent, for as long as possible, an adversary's ability to recover and re-arm (Richelson, 1985). Of the 1.35 billion people under the U.S. and Russian protective nuclear umbrellas, 85% of them are potentially targeted by Russian nuclear forces. This makes Russian nuclear-weapon–targeting far more important in determining the potential for nuclear winter.

The severity and duration of a nuclear winter would also depend on the amount of smoke that ascends to the upper troposphere and lower stratosphere. The tropopause, which is the boundary between the troposphere and stratosphere (Fig. 2A), is typically 10–15 km above sea level, with lower altitudes in polar regions and higher in the tropics. At this boundary, the vertical temperature gradient reverses so that temperature increases upward above the tropopause. Heating of the stratosphere, due to absorption of solar ultraviolet radiation by ozone, creates a global inversion layer that generally prevents dust, water, and smoke from rising into the stratosphere. This boundary must be breached for smoke to cause global nuclear winter.

Pyrocumulonimbus (pyroCb) clouds produced by rising hot air and smoke from large wildfires can inject smoke into the upper troposphere and lower stratosphere (Fromm et al., 2010, 2021). PyroCb clouds are similar to typical thunderstorm clouds and form under similar conditions (Fig. 2B), but they receive an extra boost from hot air rising above a fire (Fromm et al., 2006; Rodriguez et al., 2020). Rainout of smoke due to water condensation on smoke particles is suppressed because of the warmth of the pyroCb cloud, the rapid ascent rate of heated air, and the small size of the abundant water-condensation droplets (Rosenfeld et al., 2007). As a result, smoke particles in large pyroCb clouds are effectively delivered to the upper troposphere and lower stratosphere.

Unlike volcanic aerosols and wind-blown mineral dust, the black carbon (soot) content of smoke absorbs sunlight and warms the surrounding air, which can result in gradual rise in a process called "self-lofting." In nuclear-winter scenarios, convective ascent of smoke to the upper troposphere and lower stratosphere is followed by self-lofting to higher altitudes in the stratosphere where very low water content prevents condensation and particulate rain-out. Furthermore, the black carbon component of smoke is highly resistant to degradation by sunlight and can have a residence time of months to years in the stratosphere (Peterson et al., 2021).

The potential for smoke to enter the stratosphere and remain there for a long time is illustrated by recent studies of pyroCb clouds generated by large forest fires. PyroCb clouds during a 2017 forest fire in southern British Columbia injected, or delivered by lofting, an estimated 33–300 thousand metric tons (0.033–0.300 Tg) of smoke particles into the lower stratosphere (Yu et al., 2019; Fromm et al., 2021) where their presence was apparent for ~10 months as the smoke traveled around Earth (Torres et al., 2020). The enormous New Year fires in southeastern Australia (2019–2020) burned ~74,000 $km^2$ and produced 38 pyroCb events, leading to injection and self-lofting of 400–900 thousand tons (0.4–0.9 Tg) of smoke into the stratosphere (Khaykin et al., 2020; Peterson et al., 2021; Yu et al., 2021). The black-carbon fraction of smoke ascended to 35 km and was detectable for at least 15 months (Khaykin et al., 2020; Peterson et al., 2021).

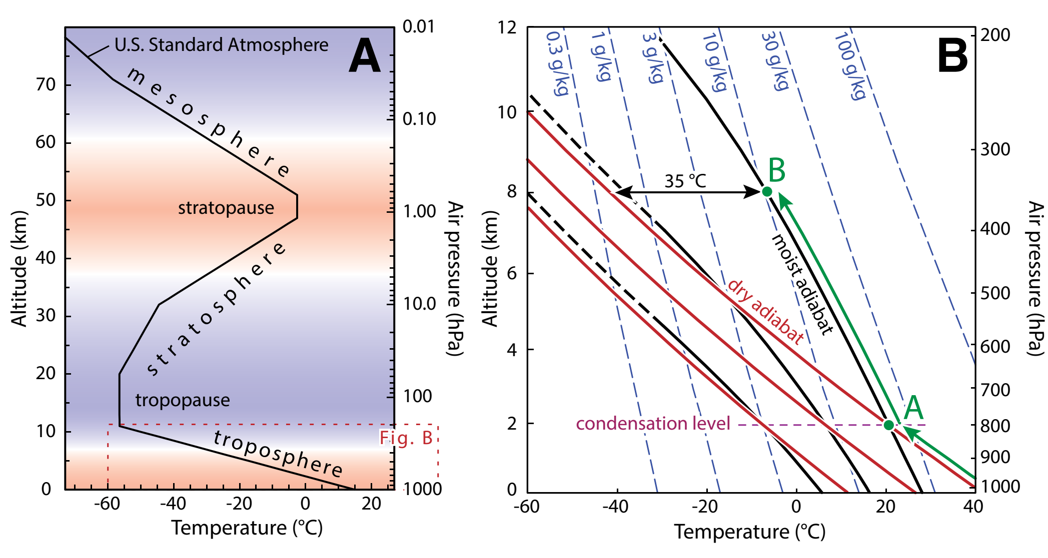


**Figure 2. (A) Profile of atmospheric temperature as represented by the U.S. Standard Atmosphere. (B) Profile of three pairs of dry and moist adiabats in Earth's atmosphere intended to illustrate thermodynamic processes involved in exothermic condensation of ascending air masses. Each pair crosses a condensation level at 2 km altitude. The green arrow highlights the adjacent ascent path of a parcel of air rising from sea level to 2 km along a dry adiabat. The starting temperature of this ascent path (>40 °C) is unusually high for typical weather but low for air heated by fire. Humidity reaches 100% at the condensation level (point "A") and exothermic water condensation begins with further ascent. Ascent to 8 km (point "B") produces so much heat from water condensation that the temperature of the air parcel is 35 °C greater than it would have been if there had been no water condensation. Blue dashed lines represent water content of saturated air. In a skew-*T*/log-*P* diagram (*T*—temperature; *P*—pressure) used by weather forecasters to plot conditions during weather-balloon ascent, the entire diagram is sheared top-right so that the adiabatic ascent path is closer to vertical (Petty, 2008).**

Evaluating the severity of nuclear winter following a major nuclear war between the United States and Russia is hampered by many unknowns and poorly constrained variables, including specifics of weapon targeting, number of targets hit during a war, flammability and fuel load of targeted areas, quantities and properties of resulting smoke, weather conditions, effectiveness of updrafts and self-lofting at delivering smoke to the stratosphere, and the fraction of black-carbon aerosol delivered. Weather conditions will affect fire intensity and pyroCb genesis while self-lofting by solar heating will be affected by the latitude and season.

Regardless of these numerous uncertainties, increasingly sophisticated numerical simulations of global atmospheric response to an all-out nuclear war have attempted to determine the possible duration and severity of a nuclear winter. The recent study by Coupe et al. (2019) modeled the consequences of direct injection of 150 million metric tons (150 Tg) of soot into the stratosphere above the United States and Russia during a time (15 May) of high and increasing northern-hemisphere insolation. Model results include an ~10-year period of soot residence in the stratosphere (Fig. 3A) and depressed temperatures at Earth's surface with a huge reduction in precipitation (Fig. 3B). Temperatures would be so depressed north of ~30° N latitude that crop failures would be widespread (if crops were even planted) (Fig. 3C).

One criticism of the relevance of this numerical simulation to real-world fires and nuclear winter is that black carbon is only a minor constituent of most fire smoke (estimated at ~12% for open-air burning [Bond et al., 2004]; and estimated at only 2%–2.5% for stratospheric smoke injection from two wildfires [Yu et al., 2019, 2021]). Smoke particles produced by burning vegetation and fossil-fuel combustion consist of complex carbonaceous compounds typically containing some hydrogen and oxygen (brown carbon). Black carbon, the most carbon-rich fraction, is the most resistant to degradation by sunlight and the most effective at absorbing sunlight and warming the air around it (Turco et al., 1990; Bond et al., 2013). Brown carbon can attract moisture, adhere to black carbon, and contribute to aggregation and settling of smoke particles and removal of soot from the stratosphere (Bond et al., 2013; Pausata et al., 2016), processes that were not modeled by Coupe et al. (2019). Smoke from burning cities would have compositional differences and could be substantially higher in black carbon than from forest fires, but 100% black carbon is unlikely if not impossible.

On the other hand, some aspects of the simulations may represent underestimates of potential environmental consequences. (1) Estimates for the mass of injected smoke used by Coupe et al. (2019) were originally made by the National Research Council (1985) before a 40% increase in U.S. population and associated construction of housing and other potentially flammable infrastructure over the past 37 years (see also Toon et al., 2008). (2) Numerical simulations with only 5 Tg of soot injected in the stratosphere suggest 20%–50% ozone depletion and resulting 30%–80% increased UV radiation at mid-latitudes, along with significant global cooling (Mills et al., 2014). (3) Abrupt, nuclear-explosion–triggered fires over large, roughly circular areas, and ascent of mushroom clouds and inward-flowing near-surface air, might be particularly effective at creating firestorms that loft large amounts of soot. (4) Rapidly growing Chinese housing and infrastructure materials add greatly to the fuel load for climate-modifying soot if China is targeted in a nuclear war (Toon et al., 2008).

Nuclear war and nuclear winter would leave a significant geologic record in areas affected by nuclear explosions. Destroyed cities and suburbs might be surrounded by dusty and nearly lifeless environments due

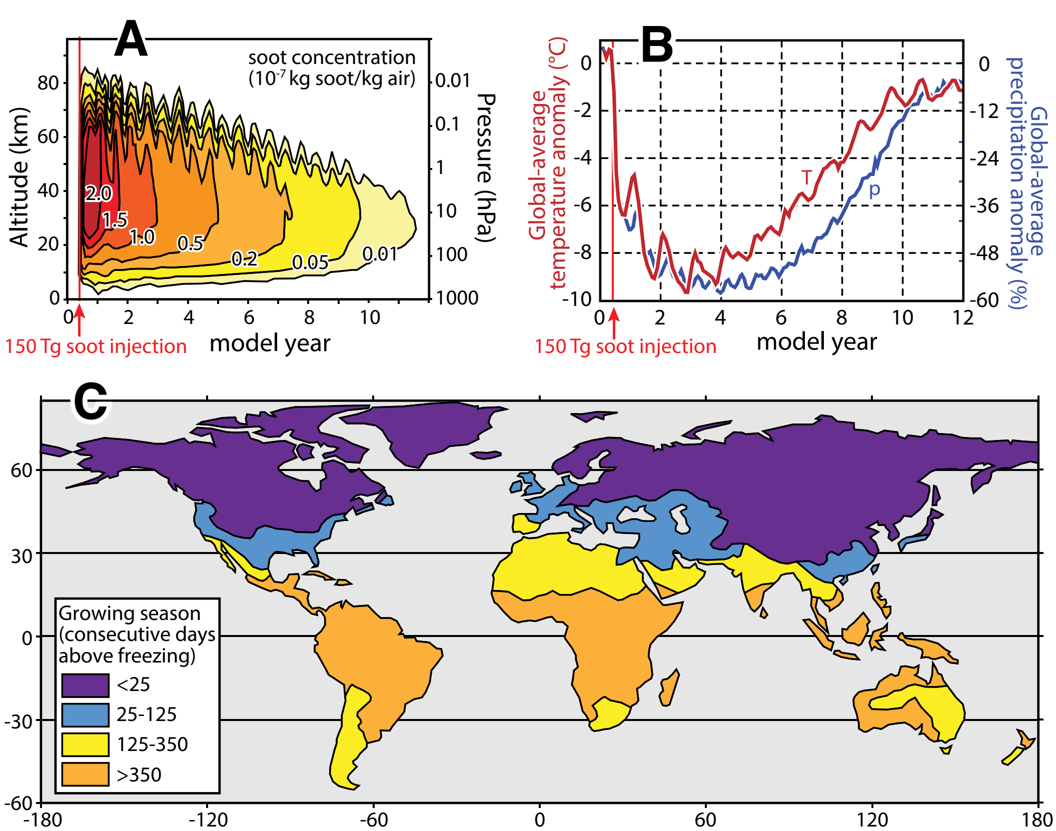


**Figure 3. Simplified results from the numerical simulation of Coupe et al. (2019) showing the predicted consequences of injecting 150 million tons (150 Tg) of black-carbon aerosol (soot) into the stratosphere. (A) Soot concentration over time. hPa—hectoPascal. (B) Depression of global average temperature and precipitation due to solar radiation absorption above the troposphere. (C) Map showing approximate duration of growing season (without frost) following soot injection for the growing season in the year following soot injection.**

to intermittent freezing over most of the year during a multiyear nuclear winter. Debris and other artifacts of civilization would be dispersed and buried by geologic processes, perhaps over decades before reconstruction and re-occupation. Materials most resistant to long-term environmental degradation would potentially add long-term economic value to a nuclear-war debris layer (Fig. 4). Some materials such as concrete and brick would have been melted on surfaces that faced a nearby nuclear detonation. Multiple such layers could be produced over future geologic time. The Anthropocene is thus a time when such disasters have become a potential contributor to the geologic record.

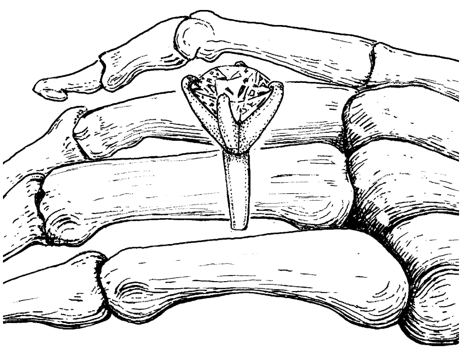

**Figure 4. Index fossil for major nuclear war.**

## CONCLUSION

Designation of an Anthropocene time period is motivated partly by concern that ongoing human environmental modifications will leave a damaged planet to future generations (e.g., Steffen et al., 2007). Designation of the time period will highlight the fact that people are now agents of rapid environmental change and non-renewable resource destruction, and that we have a responsibility to minimize damage and destruction so that future generations can thrive. This is understandably difficult because so much of this environmental change is the result of activities that directly improve people's lives. Similarly, mutual assured destruction has restrained nuclear warfare between opposing world powers and contributes to ongoing peace among allied countries (Rauchhaus, 2009). Leaders and voting citizens in major nuclear-armed states, and in allied counties, also have a responsibility to ensure that these arsenals are never discharged in a manner that might precipitate a planet-wide catastrophe. Designation of an Anthropocene time period as beginning with atmospheric tests of thermonuclear weapons might help focus human minds on possibilities for reducing the threat of a major nuclear war. This is a reason to support the proposal of the Anthropocene Working Group for such a designation, although a reason not directly related to strictly geologic criteria.

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