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U.S. ICBM VULNERABILITY IN THE 1990s by Art Hobson*, Physics Department, University of Arkansas, Fayetteville, AR 72701

The Midgetman missile is one proposed solution to the perceived problem of U.S. ICBM vulnerability. The system puts some 500 small, single-warhead missiles into a less vulnerable basing mode, possibly either superhard silos, or hardened mobile launchers (HMLs) silos ready to dash on warning. We calculate the vulnerability of each of these three modes, and evaluate the 1990s survivability of the full U.S. ICBM force under a range of assumptions.

The standard theory of silo destruction¹ implies that the "single shot probability of survival" of a silo attacked by one warhead is $SSPS = 0.5^x$ where $x = RD^2/CEP^2$. Here, RD is the radius of destruction for that warhead against that silo, and CEP is the inaccuracy of the warhead, defined as that radius inside of which 50% of an "ensemble" of warheads would fall. We note that SSPS is just a Gaussian in the ratio RD/CEP , and that it is a consequence of a Gaussian assumption for the spatial distribution of an ensemble of attacking warheads.

There is now general agreement that "superhard" silos can be built to withstand nuclear effects right up to the edge of a nuclear crater, but that no silo can survive within the crater². For such silos, $RD = RC$ ("radius of the crater"). Since the crater's volume should be roughly proportional to the energy released, $RC^3 \approx cY$ where Y is the warhead's yield and the proportionality constant c is dependent on the geology in which the blast occurs. U.S. officials have stated

that, in favorable (small c) geology, $RC \approx .075$ km for $Y = 0.5$ megatons (MT)³. Thus, $c \approx (0.075)^3/0.5 = 8.4 \times 10^{-4}$ km³/MT. Experimentally, the blast pressure (in atmospheres) at distance r (kilometers) from a ground burst¹ of yield Y (MT) is $6.31Y/r^3$. At the edge of the crater, where $r = RC$, this becomes $6.31Y/RC^3 = 6.31/c \approx 7500$ atm (110,000psi). Superhard silos, defined as silos that must be inside the crater in order to be destroyed, must be able to withstand this blast pressure. Silos much harder than this are superfluous, for they would be destroyed by the crater anyway. For superhard silos,

$$SPSS = 0.5^x \text{ where } x = RC^2/CEP^2 \quad (1)$$

But the preceding calculation implies $RC^3 = 6.31Y/7500$, so that

$$x = (6.31Y/7500)^{2/3}/CEP^2 = Y^{2/3}/110 CEP^2 \quad (2)$$

More simply, $x = L/110$, where $L = Y^{2/3}/CEP^2$ is commonly known as the attacking warhead's "lethality."

Today's MIRVed SS-18s and SS-19s (CEP = 0.25 km, Y = 0.5 MT) have $L = 10$, so $SSPS = 94\%$, a high survival rate. But the older un-MIRVed SS-18 carries 20 MT with the same CEP, implying $SSPS = 50\%$. So superhard silos are vulnerable even today. In the future, the Soviets should attain⁴ the .090 km CEP of today's MX. The survival probabilities of superhard silos attacked by several such high accuracy warheads are shown in Table 1. The Table is, of course, only an approximation to the real world. The caption of Table 1 lists the most important of the effects not accounted for in these calculations.

TABLE 1

Single Shot Probability of Survival of a superhard silo attacked by present and plausible future Soviet warheads.

Missile	Fractionation (MIRVing)	Yield Y	CEP	Lethality $L=Y^{2/3}/CEP^2$	SPSS $=0.5^{L/110}$
SS-18 mod 3	1	20 MT	0.25 km	120	.47
SS-18 mod 4	10	0.5	0.25	10	.94
SS-19 mod 2	1	8	0.25	65	.66
SS-19 mod 3	6	0.5	0.25	10	.94
Future SS-18	1	20	0.09	920	.003
	2	7.1	0.09	460	.06
	3	3.8	0.09	302	.15
	4	2.5	0.09	228	.24
	10	0.5	0.09	77	.61
Future SS-19	1	8	0.09	505	.04
	2	2.8	0.09	249	.20

A "superhard silo" means one that must be inside the crater to be destroyed, i.e. hardness = 7500 atm. These survival rates neglect several factors such as fratricide, unreliable attacking warheads, and the possibility that the silo might be destroyed by other effects even if it is outside the crater.

Mobile launchers could be hardened to 2 atm (30 psi) and be capable of moving at 22 m/s (50 mph). If based on large military reservations they will roam randomly over some 10,000 km² during peacetime and 20,000 km² during alert, prepared to dash off this area in the event of attack. If based at MM silos, they would be prepared to dash onto surrounding access roads and farmland. We denote these basing modes Random Mobile (RM) and Dash Mobile (DM).

The most plausible attack on either mode would be an area barrage, either against the entire RM operating area, or against small regions surrounding each of the 500 DM sites. Simple geometry implies that the number of warheads needed to barrage an area A is $A/4 RD^2$, where RD is the radius of destruction of a warhead against an HML. This result assumes a "loose" barrage pattern in which the circles of destruction just touch. This pattern is only 80% effective since 20% of the HMLs are outside all the circles. This calculation also ignores the additional survival of mobile missiles because attacking warheads will not hit their aim points precisely. The number of MIRVed missiles needed is $N = A/4 f RD^2$ where f is the "fractionation" (number of warheads per missile) of the missile. In practice, for a given missile the individual warhead yield decreases with increasing f roughly in accordance⁵ with $Y \approx f^{-3/2}$. Scaling considerations imply $RD^3 \approx Y$, so that $RD^2 \approx Y^{2/3} \approx f^{-1}$. Thus f cancels in the formula for N, i.e. for a given missile, MIRVing has no effect on area barrage, to first order.

As an important example, the number of SS-18 missiles needed for our 80% effective area barrage is calculated to be 7.6 SS-18s per 1000 km², assuming that the warheads are airburst at a height that maximizes RD. It is interesting to estimate the implied "exchange ratios" in a Soviet attack. If 500 Midgetmen were spread out on 20,000 km², as might be the case, there would be 25 Midgetman missiles (or 25 warheads) per 1000 km². If SS-18s are 10-MIRVed, these 25 Midgetmen would be barraged by 76 SS-18 warheads, resulting in the destruction of about 20 Midgetmen (80% of the 25). So the warhead exchange ratio is about 4 SS-18 warheads to 1 destroyed Midgetman warhead. From another point of view, the missile exchange ratio is 1 SS-18 to 2.6 Midgetmen. Whether these ratios are favorable for the Soviets, or favorable for the U.S., or immaterial, depends on many considerations. For example, one consideration is cost: How much do 7.6 SS-18s cost, versus 20 Midgetmen? We leave these questions for others. For example, the recent Defense Science Board Task Force ("Deutch panel") report⁴ calculates the cost in dollars per surviving U.S. warhead, and compares basing modes on this basis.

To calculate in more detail the Soviet attack required to barrage the mobile modes, it is most instructive to study the operating area as a function of dash time. We assume that the dash begins from the 20,000 km² alert area for RM, and from 500 MM silos for DM. The 20,000 km² alert area is reported⁶ to be located on 5 separate military reservations. For simplicity, we will assume that these 5 regions are each circles of area 4000 km², or radius $R_0 = 35.7$ km.

Assuming a constant $v = 22$ m/s speed during the entire dash, and assuming that the dash can proceed in any direction, the area "generated" after a dash time t is $5\pi (R_0 + vt)^2$ and $500\pi v^2 t^2$ for RM and DM respectively.

Thus we calculate the two graphs of Figure 1 for the first 10 minutes of dash time, still assuming 7.6 SS-18s are needed per 1000 km². The graph is surely optimistic for Midgetman survival, since real-life HMLs would need some time to get moving, would move slower than an average 22 m/s (especially during off-road travel), would be restricted mostly to roads, would require time to deploy, etc. The times graphed should be compared with the 15 minute SLBM flight time to the central U.S. from 200 miles offshore, or 8 minutes with depressed trajectories. This barrage leaves a theoretical 20% survival rate, or 100 surviving Midgetmen in a force of 500. But these 100 survivors will each experience four near-threshold blasts, so their post-attack condition could be questionable. A 100% effective barrage may be shown to require twice as many attacking missiles as the 80% effective barrage. Other factors, such as unreliability of the attacking missiles (i.e. duds), are neglected here. Despite the approximate nature of these results, they show that the mobile modes could be barraged by SLBMs (8-15 minute flight time) with a plausible hope of success. On the other hand, the 30-minute flight time of ICBMs would probably make ICBM barrage unsuccessful. Thus, mobile Midgetmen will have the same "failure mode" as bombers: vulnerability

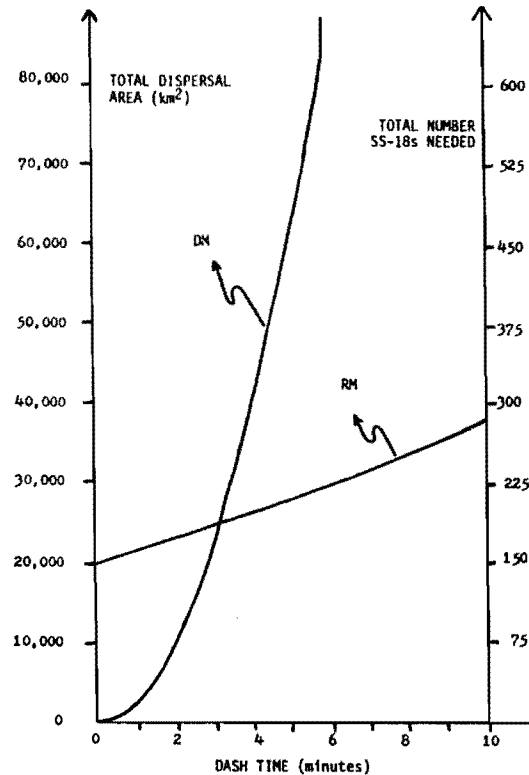


Figure 1. Total dispersal area and total number of SS-18s needed to barrage this area at 80% effectiveness, as a function of HML dash time for the Random Mobile (RM) and Dash Mobile (DM) modes.

How vulnerable would a 1990s ICBM force of 500 Midgetmen plus 1000 MM and MX missiles be under plausible Soviet attacks? We study four plausible Soviet force levels. If one assumes that SALT II constraints are maintained, the 1990s Soviet force might include some 1400 high-accuracy ICBMs and 900 medium-accuracy SLBMs. This force could destroy the full U.S. ICBM force. Under superhard silo basing, some 50% of the Soviet ICBM force would be needed (SLBMs wouldn't do, as they aren't lethal enough to destroy superhard silos). Under the mobile modes, the entire SLBM force would be needed (ICBMs wouldn't do, because the HMLs would have 30 minutes to get out from under an impending ICBM barrage), leaving their ICBM force for other purposes.

With no arms control constraints, anything is possible. The Soviets could obviously destroy nearly all our ICBMs with a small fraction of their missiles, if the Soviets had enough missiles.

Under the 50% cuts proposed in differing versions by both sides, the Soviets might retain 900 ICBMs and 300 SLBMs. The attack on superhard silos would still be possible, but it would then consume most of the Soviet ICBM force, a bad trade for the Soviets because it leaves their SLBM/bomber force facing the much stronger U.S. SLBM/bomber force. The SLBM threat to RM would vanish due to insufficient SLBMs, but SLBMs could still attack DM in hopes of striking with very short dash time (see Figure 1 for short t). So under 50% cuts U.S. ICBMs might be significantly more survivable in the 1990s than they are today, unless DM basing was chosen.

Finally, a "finite deterrence" regime⁷ of say 2000 warheads on each side would make U.S. ICBMs essentially invulnerable, still assuming 500 Midgetmen, for the Soviets would lack sufficient warheads for an effective attack.

Midgetman makes sense with arms control, but is a waste of money without controls that reduce strategic forces significantly below present levels.

1. For example, K. Tsipis, Arsenal (Simon and Schuster, New York, 1983).
2. E. Ulsamer, Air Force Magazine, January 1984.
3. Defense Daily, 22 May 1985.
4. Defense Science Board, Report of the Task Force on Small ICBM Modernization. (Department of Defense, March 1986).
5. I. Bellany, Nuclear Vulnerability Handbook (Center for the Study of Arms Control, Lancaster, England, 1981)
6. J. Medalia, Congressional Research Service, Report No. 83-106F, 26 May 1983.
7. H. A. Feiveson, R. H. Ullman, F. von Hippel, Bulletin of the Atomic Scientists, August 1985.

*I thank the Stockholm International Peace Research Institute, where most of this work was done, and also Peter Zimmerman and Peter Lamas. A much longer version of this paper will appear in Applied Physics Communication.

THE CHERNOBYL REACTOR ACCIDENT: SCANDINAVIAN PERSPECTIVES by Allan M. Din, Department of Theoretical Physics, Royal Institute of Technology, Stockholm and Stockholm International Peace Research Institute, SIPRI, Bergshamra, S-171 73 Stockholm, SWEDEN

During the weeks following the Chernobyl accident, Sweden was subject to two somewhat different kinds of exposure, both having rather unpleasant consequences. First, the monitoring stations at the nuclear reactor facility at Forsmark north of Stockholm were able to call, on April 28, the Initial alert on unusually high environmental levels of radioactivity coming from abroad. Secondly, Stockholm became for almost a week the number one rallying point of the international press with the result that many non-Swedes probably got the impression that Sweden had become a radioactive wasteland. The director of the National Tourist Board was seen on TV lamenting that American tourist bookings had come down 20% because of the mere fact that Sweden was an open society with an effective environmental monitoring system!

The system for monitoring radioactivity, which consists of 25 measuring stations around the country, including those at or near the 4 reactor sites, worked all right but was nevertheless found to have some flaws. Initially, it was thought that the radioactivity originated from the Forsmark reactor, but after similar readings at other stations it was concluded that the origin was abroad and, probably, in the Soviet Union since the winds were coming from the south-east. Eventually the Swedes deduced that the radioactive fallout originated from the burning reactor in Chernobyl near Kiev.

Later, it was discovered that a number of measuring stations had not been working properly for some years with the result that a complete map of the fallout in the country could not be made until mobile measuring apparatus had criss-crossed certain regions. The levels of radioactivity were generally about 5 times the normal background level of 10 $\mu\text{rem}/\text{hour}$, but there were exceptions. On the islands of Gotland and Oland in the Baltic Sea closer to the Soviet border the levels were a little higher than average as might be expected from regular fallout patterns but, somewhat ironically, in the region of Uppsala and Gavle, not far from the Forsmark site, the levels were more than 100 times normal. The general fallout pattern¹ is displayed in Figure 1. Table 1 shows a list of different isotopes found in the fallout¹.

These irregular patterns were due to the occurrence of a moderate rainfall in the mid-eastern part of the country 3-4 days after the reactor accident. Such a wash-out phenomenon is of course not unexpected since the experience from atmospheric tests of nuclear bombs has often indicated much irregularity in fallout patterns due to special circumstances of wind and precipitation. The countermeasures recommended by the Radiation Protection Authorities were therefore enforced

with a varying degree over the country. People were told not to drink rainwater, not to eat fresh vegetables and to keep cows from grazing until further notice; 3 weeks after the accident these measures were still in force in the most contaminated regions.

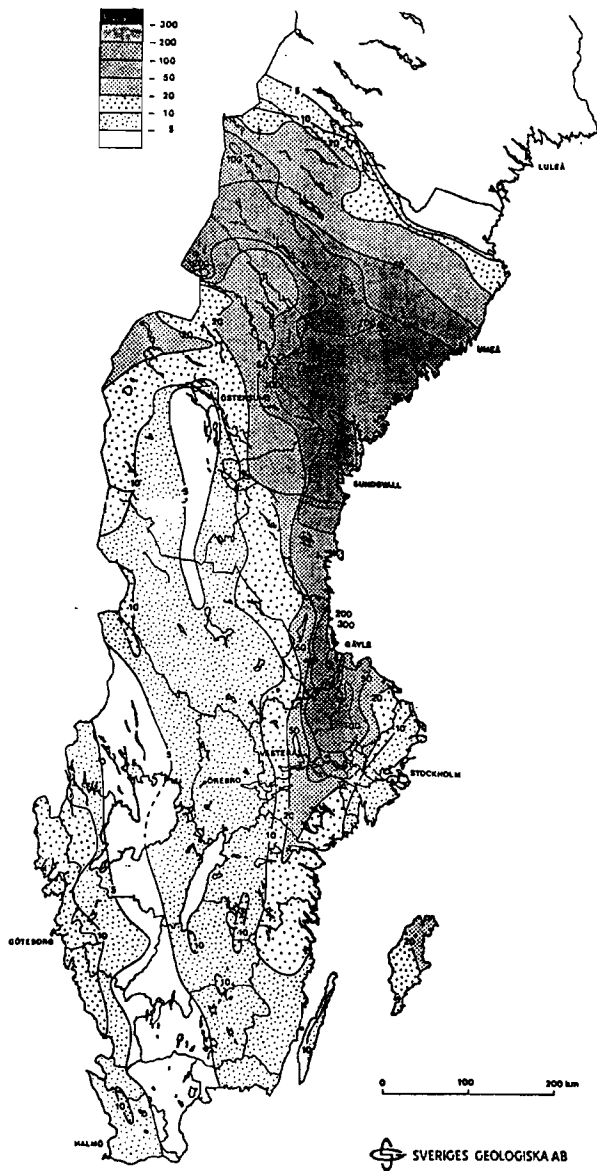


Figure 1. FALLOUT PATTERN. Computed surface intensity in $\mu\text{R}/\text{hour}$ as of May 9, 1986 based on airplane measurements conducted May 9-June 3, 1986.

As in many other countries which were exposed to fallout from the Chernobyl reactor, there has been a lively debate on precisely what will be the effects on public health and environment. Concerning the possibility of increased rates of cancer, it was generally acknowledged that it is difficult to determine the exact threshold for radiation exposure above which cancers are produced. Lacking precise information on this point, the threshold is pessimistically put quite low, and as a result any increase in radiation above normal background levels may be said to generate so and so many additional cancer cases over a certain number of years.

TABLE 1. Isotopes found in the Chernobyl fallout:

Isotope	Half life
Sr-89	50 days
Sr-90	28 years
Zr-95	65 days
Nb-95	35 days
Mo-99	3 days
Tc-99m	6 hours
Ru-103	40 days
Te-132	3 days
I-131	8 days
I-132	2 hours
I-133	21 hours
Cs-134	2 years
Cs-136	13 days
Cs-137	30 years
Ba-140	13 days
La-140	2 days
Ce-141	33 days
Ce-144	285 days
Np-239	2 days
Pu-238	86 years
Pu-239	24,000 years
Pu-240	6,000 years

The uncertainties over thresholds were apparent, for example, concerning the admitted levels of radiation in milk. In Sweden, the allowed limit had been set at 2000 Becquerel per liter of milk, whereas in the European Common Market countries the limit was 4 times lower. Under the threat of adverse effects on food exports, which many other countries have experienced, Sweden was forced to adapt its limits to what had been accepted by a majority of European states. In general, one now sees a trend to impose stricter and more uniform limits on the presence of radioactive substances in food and in the environment. Concomitantly, the preparedness for enforcing emergency measures in case of future alerts is being reassessed.

While the physical effects of the fallout definitely should not be underestimated, it is fair to say that the psychological ones have been dominating the scene. The fact that iodine drugs in Sweden were sold out at pharmacies in a matter of hours is hard to explain by anything else but an eruption of latent fears. Those fears are probably also going to be quite decisive in determining the precise fate of Sweden's nuclear reactor program. According to the result of the referendum in 1980 (following the Three Mile Reactor accident), the present 12 nuclear reactors must be dismantled not later than the year 2010 but, although this decision was also mandated by parliament, the exact procedure and rate of phasing out nuclear energy were not quite clear.

Put concisely, the message of the referendum was that civilian nuclear energy was not in Sweden going to be the one-way street that it appears to be in most other countries which have developed the nuclear option. With due consideration to national energy needs, alternative energy

resources were to be developed gradually over the next few decades so as to make a phasing out of nuclear energy practically possible. Lately though, the commitment to developing alternative options has not appeared to be very strong and the political community sent out test-balloons with the purpose of allowing nuclear energy to survive.

The Chernobyl accident has, however, underlined the desire of most people to implement the referendum result; also the Energy Minister has recently made strong statements endorsing a dismantling of the 12 reactors and, if both warranted and possible, at an accelerated rate. The problem is particularly acute with the Barseback Reactor situated close to Malmö in Southern Sweden and only 20 km from Copenhagen across the Strait of Oresund. In Denmark, which has no civilian nuclear reactor program, many people have, since the construction of this reactor, been feeling very uncomfortable living in what demonstratively is called the evacuation zone of a reactor situated on foreign soil, and very recently the parliament issued a strong appeal to the Swedish government to get rid of the Barseback Reactor as quickly as possible. These political recriminations joined the chorus of criticism directed towards the Soviet Union for failing to alert their neighbors and the world about the possible danger of radioactive fallout. The Chernobyl accident has certainly been exploited politically, as the Soviet Union has complained and others, including the nuclear reactor industry, would most certainly not like to go too far in the debate. The many different discussions following the accident are, nevertheless, not likely to ebb out quickly. The important thing is that people in the process become more aware of dangers which are manyfold greater than nuclear reactor melt downs, namely the risks of nuclear war. Among others, the risks involved in nuclear attacks on reactor sites² deserve to be better known and more studies are warranted which describe the serious long-term consequences such attacks could have to densely populated areas such as Europe.

1. From T. Bennerstedt et al., Tjernobyl - nedfall, matningar och konsekvenser, SSI-rapport 86-10, Stockholm
2. S.A. Fetter and K. Tsipis, Catastrophic releases of radioactivity, Scientific American, vol. 244, 33, 1981.

4. UNSCEAR, 1982, p. 220, Table 13 on p. 234.
 5. UNSCEAR 1977, p. 141.
 6. UNSCEAR 1982, p. 225 and Table 27, p. 240.
 7. UNSCEAR 1982, p. 222.
 8. UNSCEAR 1982, Table 31 on p. 242.
 9. UNSCEAR 1982, p. 220.
 10. THE EFFECTS ON POPULATIONS OF EXPOSURE TO LOW LEVELS OF IONIZING RADIATION, (BEIR, 1980, National Academy Press, Washington, DC). Tables V-15, V-17 and V-31.
 11. RECOMMENDATIONS OF THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, (Pergamon Press, ICRP Report 26, 1977), p. 10-12.
 12. BEIR 1980, p. 304. INDUCTION OF THYROID CANCER BY IONIZING RADIATION (WASHINGTON, DC, National Council on Radiation Protection and Measurement, 1985), Table 11.3.

ESTIMATING LONG-TERM HEALTH EFFECTS FROM CHERNOBYL: SOME USEFUL PARAMETERS by Barbara Levi, Center for Energy and Environmental Studies, Princeton University.

In the wake of the reactor accident at Chernobyl, many have made estimates of the long-term health impacts. Among these early assessments is an estimate present by the Soviets as part of their accident report to the International Atomic Energy Agency last August. The Soviets predicted that the roughly 75 million in the Western part of the USSR might receive a collective dose over the next 50 years of about 29 million person rem from external exposure to the radiocesiums released from Chernobyl. The collective dose from ingestion of cesium might be about the same. At roughly 1 cancer death expected for every 10,000 person-rem of exposure, the estimated collective doses might cause about 5000 cancers over and above the approximately 9.5 million deaths in the Western USSR expected from the normal incidence of cancer. Other studies are attempting to evaluate the collective dose to the rest of Europe.

Estimates such as those made by the Soviets are plagued with uncertainty. Even if the distribution of radionuclides were perfectly known, it would still be difficult to calculate the dose imparted through diverse pathways: direct inhalation of radionuclides in the cloud, external irradiation from deposits on the ground and ingestion through the food chain. Several studies, relying primarily on data from atmospheric nuclear weapons tests, have estimated the various transfer functions, from levels of radiation in the environment to levels in the diet, from levels in the diet to levels in the body, and from radiation activity in the body to biological doses. These transfer functions are of course all specific to each radionuclide. They are only estimates, and can vary significantly with the soil and plants of a given region and with the ages, living patterns and diets of residents.

For those who wish to give some perspective to the measured or projected levels of radiation reported in units like Bq/l in milk or Bq/m³ in air, we have accumulated here some relevant parameters relating source to dose. They are consistent with those used in the estimates by Cochran and von Hippel.¹ Table I reviews the various units for measuring radiation. The other tables summarize transfer factors for two of the radionuclides which escaped from Chernobyl: iodine-131 and cesium-137. The Soviets have estimated that about 7M Ci of I-131 and 1M Ci of Cs-137 fell within the Soviet Union alone.

TABLE I: RADIATION UNITS

1 Roentgen	creates 1.61×10^{12} ion pairs/gram in air deposits 88 erg/gm of air at STP
1 rad	deposits 100 erg/gm in any material (gamma exposure of 1 R roughly equals absorption in tissue of 1 rad for photon energies of .3-3 MeV)
1 gray	deposits 10,000 erg/gm or 1 Joule/kg of tissue (1 gray = 100 rad)
1 rem	has the biological effect of 1 rad of x- or gamma radiation
1 Becquerel (Bq)	has 1 disintegration/sec
1 Curie (Ci)	has 3.7×10^{10} disintegrations/sec