Defining, Explaining, and Detecting Dirty Bombs

J. L. Alvarez, Ph.D., CHP
Auxier & Associates. Inc.
Knoxville, TN 37932

DEFINING

A dirty bomb is a conventional explosive that disperses radioactive material. The intent is death and disruption. Death may be the result of the explosive and could result from sufficient radioactive material. Disruption is the result of panic cause by fear of radiation and the cleanup of the radioactive material and any consequent avoidance of the radioactive location after clean up.

How Much?

The amount of radioactive material is irrelevant to disruption. Something that is contaminated will introduce some degree of denial of access, be it a post office, courthouse, subway, or street corner. How many smoke detectors does it take to contaminate a school cafeteria? How much P-32 will shut down Grand Central Station or will postpone the super bowl? How many curies of unshielded Co-60 will kill a terrorist before a device can be fashioned or delivered? How big must an undetected and unexploded neutron source be to activate a statue in a park?

The Mechanics

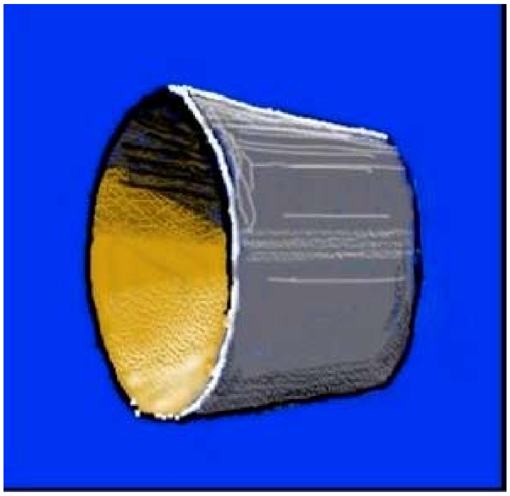
Dispersal of material is the obvious outcome of an explosion.

There are big pieces and little pieces and dusts and smokes. There is a lot of all of it in a relatively small volume trying to move away from the center of mass of the explosion. The direction it goes will depend upon its mass, the relationship to other masses, and the process by which it became a big piece, a little piece, dust, or smoke.

An ideal sphere with an explosive in the center, suspended well above the earth with no wind will spread with nearly spherical symmetry. The hot gas will cause a slight upward deflection. A second object placed near the sphere may substantially affect the shape of the explosion, depending upon its mass, shape, and mechanical properties. The simple laws of motion apply, but it takes a super computer to apply them. Nevertheless, approximations and recipes abound that allow the development of explosive experts whose best attribute is being careful.

An explosive is a decent dispersal device as well as deadly and dangerous. As some of the photos show, the dispersal may be of very large chunks and/or very directional. Maximum dispersal returns us to the ideal sphere with the material to be dispersed outside the explosive. It is also desirable that the material be powdered or highly friable. Maximum dispersal then calls for a bit of engineering. Satisfaction with less than maximum still may require engineering if the material is dense and of a difficult shape.

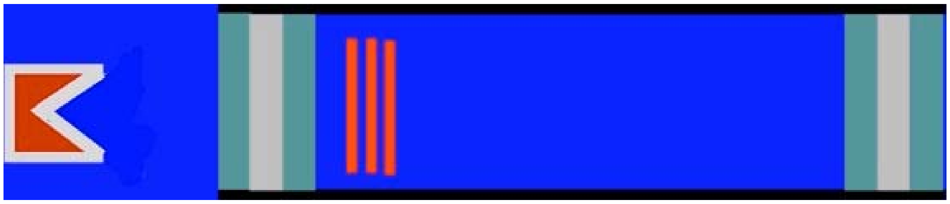
Suppose the material were a steel ball that you placed in the center of the ideal sphere, with the explosive on the outside. You will end up with a steel ball that is quite dirty, sticky, and pitted. The bulk will be densified with improved properties, but it will not be dispersed. Place the ball on the outside of the explosive and it becomes a poorly directed bullet. Should you know to form the explosive into a cylinder with a large conical dimple in one end, then place the steel ball on the axis of the cone about 2 diameters away, you might vaporize the steel ball.



Now consider the ball to be 1000 Ci of Co-60. The explosion should disperse it quite well. The problem is placing the ball in the right position and the assembly at the point of dispersal. The trick is not to die before you get to the point of dispersal. (The gamma constant for Co-60 is 1.3 R/h at 1 m/Ci, so you have on the order of about an hour if the source is unshielded.)

There are numerous options for dispersing a solid using explosives intermediate to the bullet and the shaped charge. All require some handling and preparation of the source. A large enough shaped charge could penetrate the shielding, vaporize the source and continue out the back of the shielding. This is not quite as easy as it sounds unless the charge is large enough to vaporize the shield, also.

In an effort to characterize the effect of a shaped charge on a spent nuclear fuel shipping case, a series of experiments were performed. The first involved as simple mock cask.



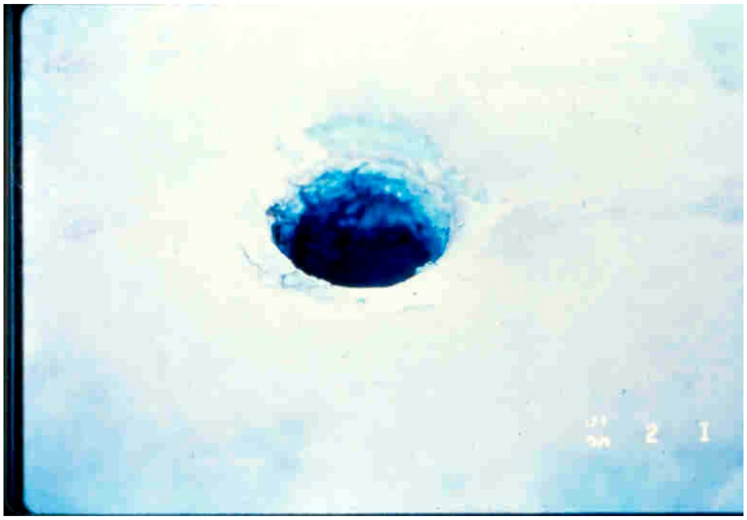
The mock cask comprised a 4” plate of steel, 4” plate of lead, a 4” plate of steel as a sandwich, then short sections of fuel rods filled with depleted uranium, an air space of 4’, then another steel-lead-steel sandwich. A shaped charge was placed several cone diameters away with its axis centered and perpendicular to the first sandwich.

This test was performed in the open air at a highly instrumented site. The explosion was monitored by high-speed photography and x-ray. Air sampling instruments were also employed. Large concrete blocks, 40 tons each, were placed around the experiment to protect the equipment.

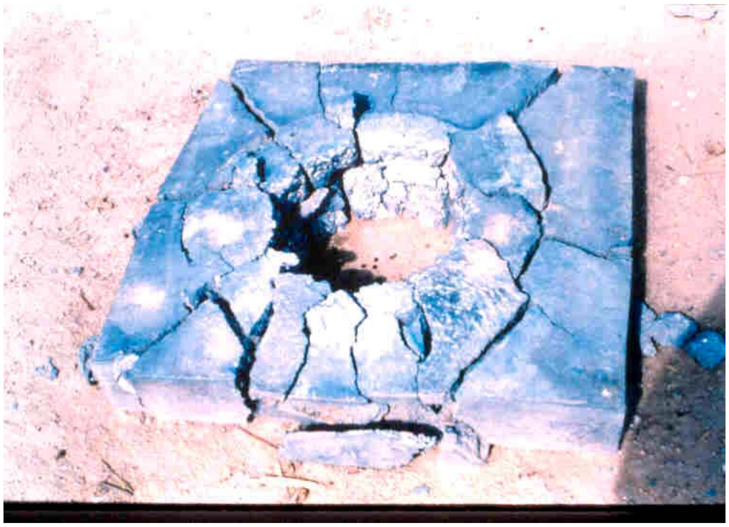
The blast formed the usual rapidly expanding fireball, which was visible as smoke and dust. Note that a helicopter is visible to the left of the cloud, just above and beyond the third power pole. Note that an edge of the blast is between the two closely spaced power poles. The dust cloud eventually obscured the helicopter.

When we zoom in on the first photo of the blast, we see considerable structure to the cloud. The cloud structure is the result of turning over those concrete blocks, the focusing action of the shaped charge, and interactions with the experiment and instrumentation.

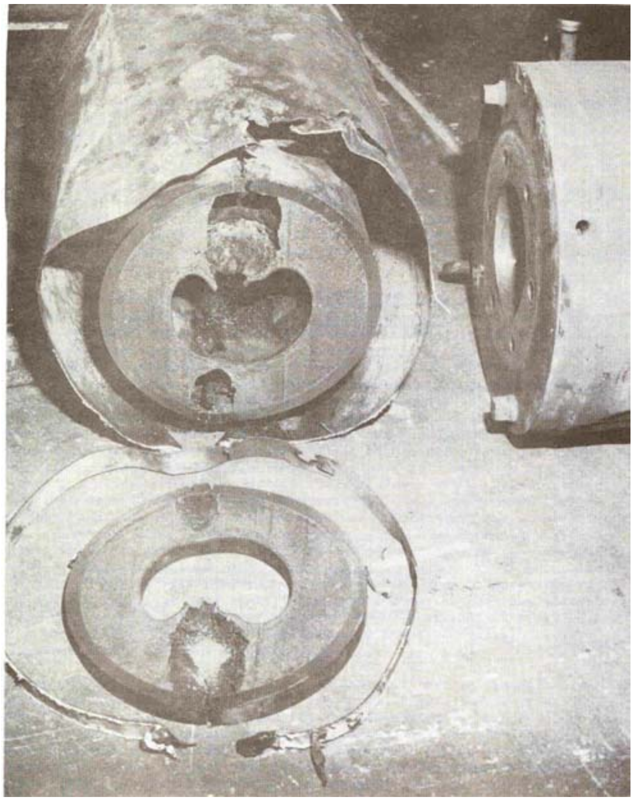
The shaped charge easily penetrated the sandwich. A fairly clean and symmetrical, 4" hole was drilled through the first steel plate.



The lead was a different story. Its mass and mechanical characteristics resulted in about an 8” diameter hole and the ejection of the lead from the sandwich. One piece of lead started a brush fire about a quarter mile away. The picture shows that the hole size was determined after the lead was pieced together.

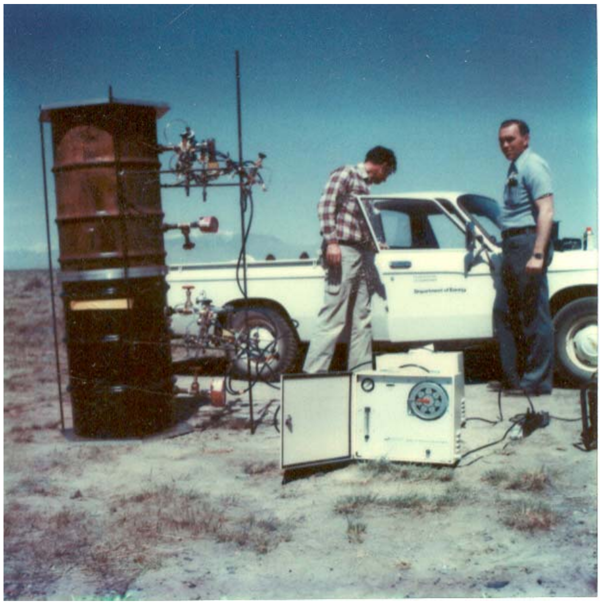


Further tests were performed on full scale and quarter scale casks. These tests were performed in an enclosure that would contain the explosion and allow collection of aerosols. The picture shows the results of a test on a quarter scale cask of a different design. The lead is much thicker in relation to the steel and the cask has an outer water jacket. The hole in the lead is about 4 times the diameter of the hole in the steel. The lead consumes a great deal of the energy from the shaped charge jet and causes some deflection. The fuel rods further deflected the jet. The jet penetrated the entire cask, but the jet was nearly spent in the total penetration. Less than a 0.01% of the damaged UO_2 was released as aerosol and about 0.1% of the $U0_2$ was damaged.



Tests with UO_2 pellets in the fuel rods are not the same as tests with spent fuel, which is already particulates and has radionuclides distributed unevenly among the particulates. Therefore, much smaller scale tests with a single fuel pellet or UO_2 pellet were performed to scale the dispersion of radionuclides to the dispersion of UO_2. These tests were performed in an assembly that allowed real time collection of aerosols and examination of the pellet and debris in a hot cell.

The correlation testing of spent fuel to UO_2 allowed estimation of likely health effects should a single shaped charge of a given size be applied to a spent fuel cask in an urban area. The estimates were 400 immediate deaths from blast effects and neither near term nor long term health effects from the released radionuclides.



The point of all this is that explosives are not an efficient method of dispersing radionuclides. Will that stop someone? Can an efficient explosive method be devised? Yes. Will it take a lot of experimentation and preparation? Yes. Will that stop someone? What is likely, if someone makes the effort to experiment and prepare, they will devise a non explosive method and/or realize that much less material and even very short half-life material will accomplish the same thing. Fear, panic, and denial of access.

EXPLAINING

There are two responses to a dirty bomb attack. The obvious is the physical response. Equally obvious should be the publicity response. Disruption is the major consequence. We know that the radiological consequences are small because dispersion is low, health effects are inconsequential, and cleanup is easy. Therefore, it is important that disruption be controlled.

Widespread panic or cancellation of the super bowl can be accomplished by exploding a bomb containing PCBs, alar, anthrax, or mad cow disease prions. (I just blew up a cow brain in Yankee Stadium.)[*] You have to be careful with this because explosive destruction of all of these is a proposed disposal method.

The point of explaining is to make it clear before it happens and have prepared if it happens a good, cogent accounting of the real, physical consequences.

DETECTING

It is assumed that covert radioactive shipments serve two purposes; they provide material for radioactive dispersal devices or for nuclear weapons. Radioactivity dispersal devices or dirty bombs are explosive devices that spread radioactive material for purposes of contaminating a large area and exposing a large number of people to both internal and

---

[*] Personally, the cow brain could stop me.

external radiation doses. These devices need not cause harm to health, but have sufficient potential for harm that costly cleanup is required and access to areas, materials, or buildings is denied. An effective device must have sufficient impact to cause harm or denial. A device of 100 Ci or more would be required, but a 10 Ci source would cause considerable consternation. The materials considered are those that are readily available for medical or commercial uses. They are listed below by type of radioactive emission:

Table 1 Radionuclides considered for bomb material

Gamma	Beta	Alpha
Cobalt-60	Phophorus-32	Americium-241
Iodine-131	Strontium-90	Plutonium-239/238
Cesium-137		Uranium
Iridium-192		Thorium

Material for nuclear weapons is necessarily fissile material, which is generally limited to Uranium-235 and Plutonium-239. There are other fissile materials, but they are both uncommon in sufficient supply and have particular difficulties for forming a nuclear device. Very small nuclear devices are possible using small amounts of fissile material. It is possible that a single individual could assemble a fissile device in less than a week that is transportable by small sedan. Nevertheless, this presumes sufficient knowledge, access to sophisticated electronics, and sufficient fissile material. A device constructed with a small amount of fissile material requires increased sophistication in knowledge and materials as the amount of fissile material decreases. It is assumed that the minimum mass of fissile material is 1000 g or 2.2 lb.

The assumed package weight for shipment is 150 lb or less. The assumed legal package may read 0.1 mrem/h at the package surface (naturally occurring radiation as in some ceramics). Gamma or x-ray radiation will be the basis for detection. The assumed number of shipments to smuggle sufficient material for either a dispersive or a nuclear device is 10 or less.

Detection

Detection will be based on generic detection devices. Two types of detectors will be considered, these are both scintillators based on sodium-iodide (NaI) or plastic. The initial definition of detection will be at 1-m in a detector 1-cm^3. This simple geometry may be scaled for other distances and other sized detectors. Scaling will require approximations for ranges of detector sizes. Simple approximations should be sufficient to evaluate the nominal range of detection and can be easily adjusted to fit actual detectors.

The generic method is illustrated using Cobalt-60 (Co-60). Co-60 emits two photons for each radioactive disintegration. The energies or the photons are 1.17 and 1.33 MeV. A 10 Ci source will produce 7.4 E+11 photons/s and 1.2 E+5 photons/s/cm^2 at 1-m from the source. The mass attenuation coefficient for NaI is 0.183-cm^{-1} so there will be 9.9 E+5 counts/s in a 1-cm^3 detector. The mass attenuation coefficient for plastic is 0.006-cm^{-1} so there will be 3.5 E+4 counts/s in a 1-cm^3 detector. The number of counts in either detector is more than sufficient for detection.

A method to decrease the number of counts is to shield the Co-60 by placing it in a lead container. The amount of shielding is limited by the weight limit of 150-lb. If we assume the lead shields a cylindrical cavity 5-cm tall by 5-cm diameter, then a cylinder of lead formed by 2.5-cm walls and 2.5-cm end caps will weight just over 150-lb. Shaving the end caps will produce a nearly cylindrical shape just under 150-lb.

The lead shielding will reduce the NaI response to 1.8 E+5 counts/s and the plastic response to 6.5 E+3 counts/s. The same lead shield was assumed for each radionuclide listed in Table 1. The exception is that for the beta emitters, P-32 and Sr-90 the radionuclides were assumed encapsulated in polyethylene of 1.1-cm thickness in order to reduce the bremsstrahlung (x-rays produced when beta rays are stopped).

Detection must be considered as a difference from the background of the detector. A 25-cm diameter x 25-cm long NaI detector has about 2 counts per second (cps) per cm^2 if the detector is considered in cross-section or 1250 cps for the detector. The detection limit for a signal that would be detected 95% of the time is 4.66 times the square root of 1250 or 165 cps. A 100-cm x 100-cm x 25-cm thick plastic scintillator would have a detection limit of 659 cps. Table 2 shows the ability to detect in one second if the alarm level is set at twice the 95% detection level or nearly 10 times the square root of the background count rate[1].

Table 2. Detection ability of generic detectors, X indicates detection.

	NaI				Plastic			
	Unshielded		Shielded		Unshielded		Shielded	
Nuclide	100 cm	200 cm	100 cm	200 cm	100 cm	200 cm	100 cm	200 cm
Co-60	X	X	X	X	X	X	X	X
I-131	X	X	X	X	X	X	X	X
Cs-137	X	X	X	X	X	X	X	X
Ir-192	X	X	X	X	X	X	X	X
P-32	X	X	X	X	X	X	X	X
Sr-90	X	X	X	X	X	X	X	X
Am-241	X	X	X	X	X	X	X	X
Pu-238	X	X			X	X		
Pu-239	X	X	X		X	X	X	
U-235	X	X			X	X		
Thorium	X	X			X	X		
Uranium	X				X	X		

The detection level for Table 2 was set at nearly 10 times the square root of the background in order to minimize false alarms. The same detection result was obtained if

---

[1] In the case of the NaI detector the square root of the background is about 35. At ten times background, the counts for alarming are 350 or 1250 + 350 = 1600. This result is well less than twice background.

the alarm level was set at nearly 5 times the square root of the background. If the alarm set point is moved to nearly 15 times the square root of the background count rate, the same result as Table 2 is obtained, except that Pu-239, shielded at 100-cm for both NaI and plastic is not detectable. Non-licensed radionuclides are in the microcurie range and, therefore, a million times smaller than those considered in Table 1.

False Alarms

Several manufacturers incorporate electronic adjustment of the detection limit to accommodate changes in background. The alarm level should be set so it is insensitive to the changing background. This will necessarily cause a loss in sensitivity, but an over sensitive system with frequent false alarms will cause under response by personnel. The above analysis shows that lowering the alarm level will not result in an appreciable gain in detection. Other considerations should be made for increasing sensitivity. The most obvious is to decrease the distance.

A particular consideration for false alarms is legal shipments of radionuclides, i.e., legally non-radioactive shipments that may contain naturally radioactive materials or non-licensed radionuclides. Natural radionuclides should be well below the thorium and uranium levels of Table 1 (well less than 1000 g) and therefore not detectable.

Conclusions

This analysis shows that most credible shipments can be easily detected at a level of 10 times the square root of the background. Legal shipments may interfere with the system by causing false alarms. These detectors can detect an exempt quantity of Cs-137 (10 μCi). False alarms should be minimal since the alarm level can be set at 10 times background or more.

Scaling a detector from those discussed here is accomplished by multiplying the counts by the increase or decrease in the area facing the shipment. (If the area doubles, multiply by 2, if the area halves, multiply by 0.5). The background changes by the square root of the change. A change in distance will change the counts by the ratio of distances squared. (If the detector moves from 100-cm to 50-cm from the shipment, the counts will increase by a factor of (100/50)(100/50) or 4. If the detector moves from 100-cm to 150-cm from the shipment, the counts will decrease by a factor of (150/100)(150/100) or 2.25.) The background will not change with a change in distance.

These scaling rules are approximate as are the estimates in Table 2. Exact calculations should be performed for actual detector systems and verified by measurement. (Improved calculations for two devices employed for monitoring shipments showed that detection was better than indicated by these rough calculations.) The results of Table 2 can be used to discuss and approximate results of detector systems.