6 - PROTECTION FROM EXTERNAL RADIATION

INTRODUCTION

The fundamental aims of Radiation Protection are:

1) to avoid fatalities

2) to avoid disabilities

3) to keep radiation exposures ALARA.

Protection against radiation is concerned with two separate situations:

External Radiation - from sources outside the body;

Internal Radiation - from sources inside the body.
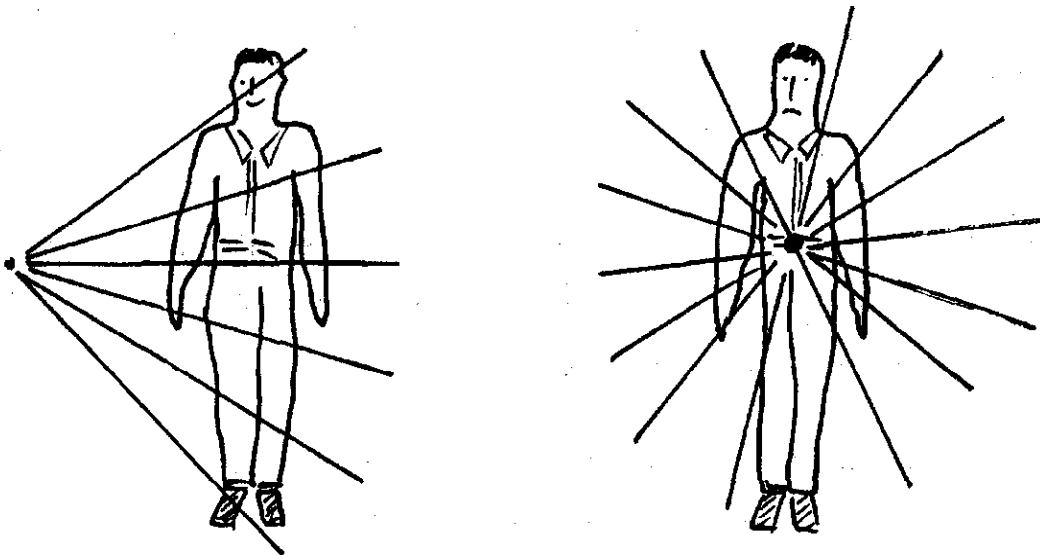

Fig. 6.1. External and Internal Exposure

The general biological effects of ionizing radiation from external and internal sources are the same. However, as we progress it will become evident that precautions taken against the one hazard are of little use in protecting against the other, and that the corresponding methods of estimating dose are different. Therefore, external and internal radiations are treated separately, and in this chapter we shall consider the methods of controlling external exposure.

TIME, DECAY, DISTANCE & SHIELDING

External radiation exposure can be decreased by:

1) reducing the **time** spent near a source;

2) allowing the source to **decay** before approaching it;

3) increasing the **distance** between yourself and the source;

4) absorbing the radiation in **shielding** material placed between yourself and the source.

TIME

Radiation exposure can be lowered by simply limiting the time a person spends near the source. No different from sunburn: if you don't want one, don't stay out too long in the sun. For example, if the radiation level in an area is 150 μGy/h and it takes 6 hours to complete a job, the dose received would be

$$150 \text{ μGy/h} \times 6h = 900 \text{ μGy.}$$

Proper job planning may reduce the time spent at the job site to 3 hours; in this case the absorbed radiation dose would be

$$150 \text{ μGy/h} \times 3h = 450 \text{ μGy.}$$

Another example: if the radiation field (or dose rate) in an area is 500 μGy/h and it takes 3 hours for you to complete a job, the dose you will receive is

$$500 \text{ μGy/h} \times 3h = 1500 \text{ μGy.}$$

Perhaps it's possible to complete the job in 2 hours instead of 3, and then you'd only receive a dose of 1000 μGy.

If you wish to limit the dose received by a person to a certain value, and you know the radiation dose rate, you may calculate the maximum exposure time by using the formula:

$$\textbf{Time} = \frac{\textbf{Dose}}{\textbf{Dose Rate}}$$

If you wanted to limit your dose to 750 uGy, how long could you work in a dose rate of 500 μGy/h? Easy:

$$\text{Time} = \frac{\text{Dose}}{\text{Dose Rate}} = \frac{750 \text{ μGy}}{500 \text{ uGy/h}} = 1\frac{1}{2} \text{ hours}$$

The Units Must Be Consistent.

If the dose rate is given in μGy/h, then the dose should be in μGy and the time should be in hours. If the units don't match, you have to bend them into shape. Here are a couple of examples:

a) The gamma radiation field in an area is 150 μGy/h. If you are to receive a dose no greater than 200 μSv, how long can you work there? Assume that there are no other hazards.

   We notice that the units are not the same. However, we know that for gamma radiation $Q = 1$, and a 200 absorbed μGy dose would result in a 200 μSv equivalent dose (if you don't remember this, now would be a good time to review the first part of Chapter 3). We can now use the formula, and so

$$\text{Time} = \frac{\overline{\text{Dose}}}{\text{Dose Rate}} = \frac{\overline{200\ \mu\text{Gy}}}{150\ \mu\text{Gy/h}} = 1.33 \text{ hours} = 1 \text{ h } 20 \text{ min.}$$

b) How long can a person stay in a radiation field of 0.2 Gy/h if he is to be limited to a total dose of 2.5 mGy?

$$\text{Time} = \frac{\overline{\text{Dose}}}{\text{Dose Rate}} = \frac{\overline{2.5\ \text{mGy}}}{200\ \text{mGy/h}} = \frac{\overline{1}}{80} \text{ h} = \frac{3}{4} \text{ min}$$

Work in radiation fields should be completed as quickly as possible in a safe manner. The job should be planned before it is started. A good plan results in an efficient procedure and consequently the lowest possible exposure. Work in very high radiation fields should not only be planned, but practised on a similar set-up with no radiation present (a dummy run). In this way mistakes can be eliminated before any exposure occurs.

An example of this occurred during the 1984 shutdown, for which a dummy boiler was built. Workers practised entering and leaving it dressed in plastic suits before they did their thing in the real boiler with gamma fields of up to 30 mGy/h.

DECAY

A second way of reducing exposure is to wait for the source to decay before you start work. The radiation field will drop by a factor of 2 for every half-life you wait. This is a good approach when work has to be done in a radiation field that will decrease very quickly with time (half-lives of minutes or hours).

If there is no need for the work to be done immediately, then waiting for a day or so will reduce the dose rate quite appreciably. This is always considered when planning work for a shutdown, because many radiation fields drop considerably during the first 24 hours.
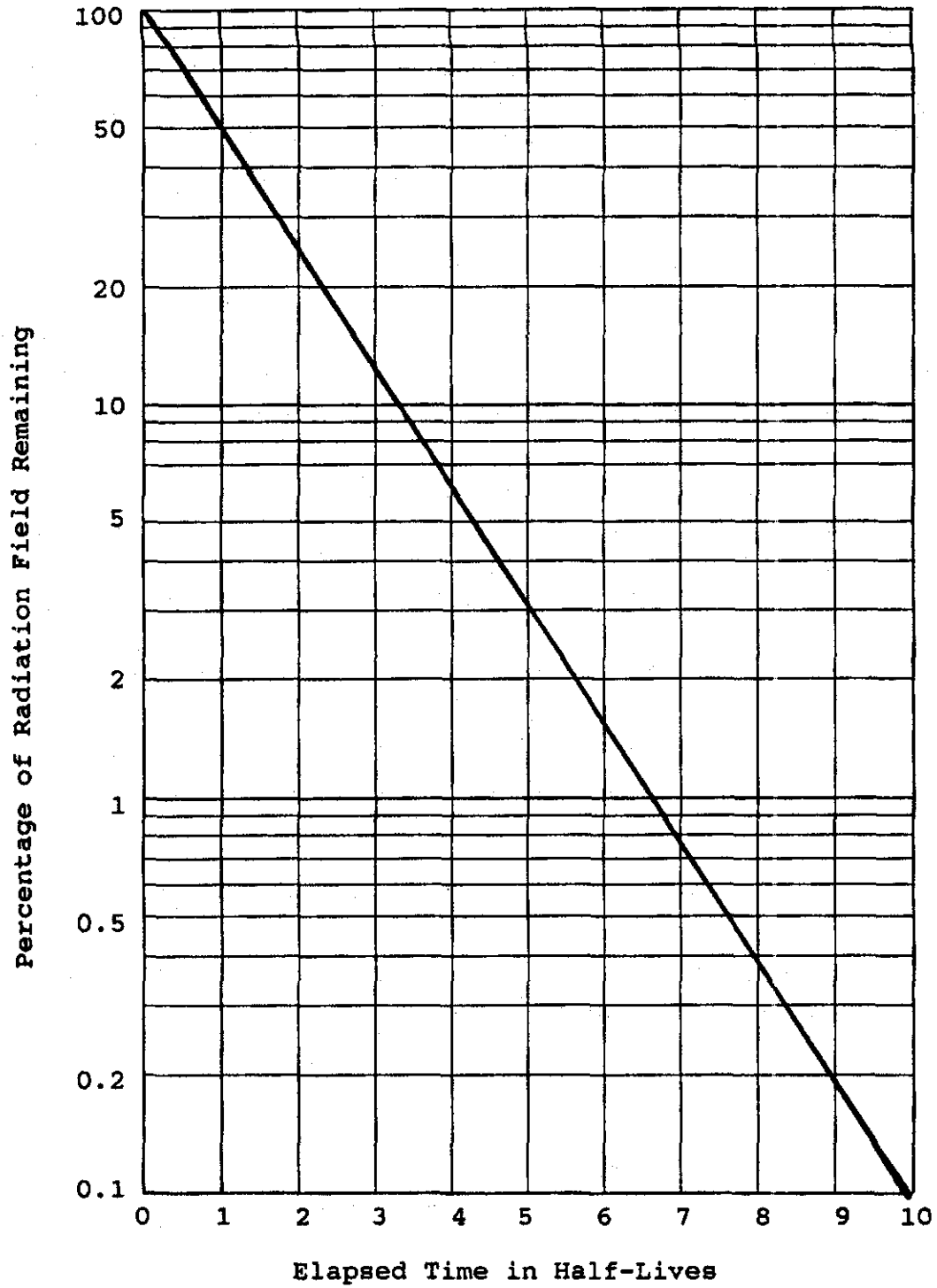
Fig. 6.2. Decrease of Radiation Fields With Time

Example:

You have to work for half an hour near the snout of the fuelling machine. The radiation field is 3.2 mGy/h and the activation products causing this field have an apparent half-life of 2 h. How long should you wait before doing the job, so that the dose you receive will be 0.1 mGy or less?

Initially, the dose rate will be 3.2 mGy/h or 1.6 mGy per ½ hour. This will decrease by a factor of 2 for every 2 hours delay owing to the radioactive decay of the activation products. Therefore, after 2 hours the dose received will be 0.8 mGy; after 4 hours 0.4 mGy; after 6 hours 0.2 mGy; and after 8 hours 0.1 mGy. Therefore, if you first wait 8 hours, you will receive only 0.1 mGy in half an hour.

Incidentally, this problem assumed a constant half-life of 2 hours. In practice, the effective half-life might well increase because the short-lived activation products would decay faster than the longer-lived. This means that you might get less decay than you would expect. Therefore, before you start the job, you must check the radiation field again.

Figure 6.2 on the previous page shows how radiation fields will decrease as more and more half-lives elapse. You can see that waiting for 3 half-lives will drop radiation levels considerably. Waiting for 7 half-lives will reduce radiation levels to less than 1%. A useful rule of thumb:

> **Radiation fields will be reduced by a factor of 100 for every 7 half-lives that elapse.**

DISTANCE AND THE INVERSE SQUARE LAW

If you increase your distance from a small radiation source, there will be a marked reduction in the radiation field.
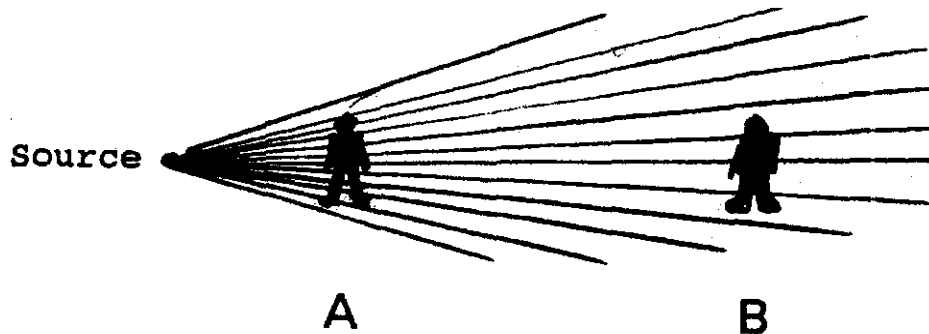

Fig. 6.3. Decrease of Radiation Field With Distance

Figure 6.3 shows why. A small (point) gamma source emits photons equally in all directions. If you stand at A, you will intercept 10 gamma photons every second, whereas if you move out to B, only 3 photons hit you each second. Therefore, as you move away from the source,

the gamma radiation field decreases. This is entirely due to the spreading cut of the emitted photons.

The **INVERSE SQUARE LAW** describes the decrease in gamma radiation field with distance.

> **The intensity of gamma radiation varies inversely with the square of the distance from the source; that is, doubling the distance drops the exposure rate to ¼, tripling the distance drops it to 1/9, and so on.**

It is important to realize that the inverse square law applies to gamma radiation only, and then only for point sources and not to beams. **In practice, we consider a point source to be one whose largest dimension is smaller than 1/5th of the distance from it to you.**
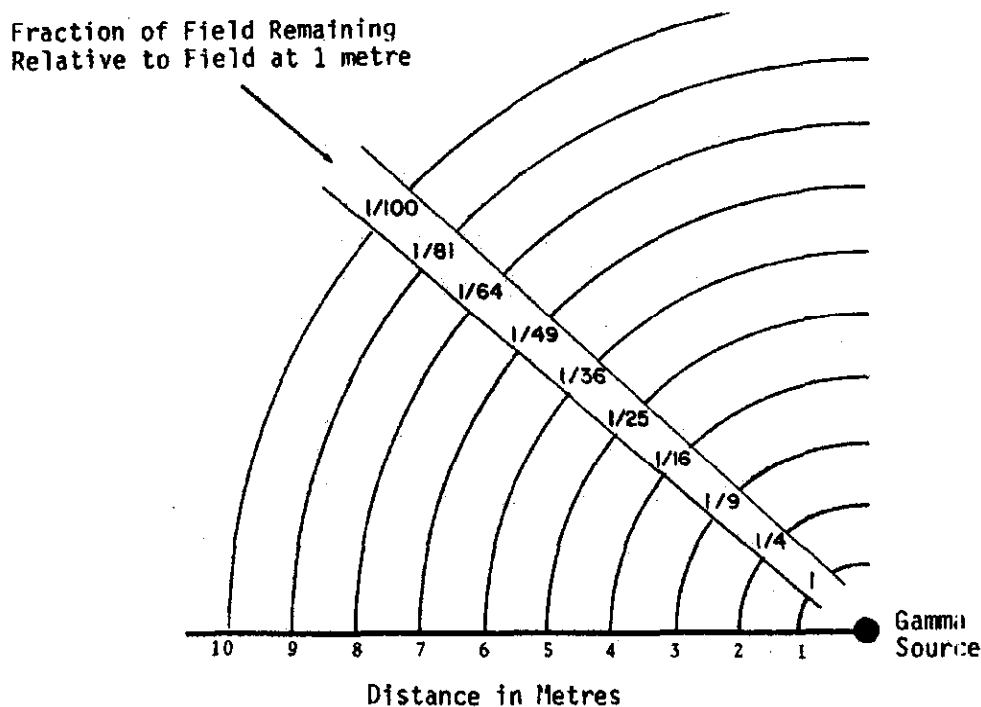
Fraction of Field Remaining
Relative to Field at 1 metre

1/100
1/81
1/64
1/49
1/36
1/25
1/16
1/9
1/4
1

Gamma
Source

10 9 8 7 6 5 4 3 2 1

Distance in Metres

Fig. 6.4. Fraction of Radiation Field Remaining

Examples:

(a) If the gamma radiation field at 1 metre from a source is 320 µGy/h what is it at 4 metres?

Figure 6.4 indicates that the field has been reduced to 1/16 of its level at 4 metres. Therefore it will be

$$(1/16) \times 320 \ \mu Gy/h = 20 \ \mu Gy/h$$

(b) If the gamma radiation field at 10 m from a source is measured to be 20 μGy/h, what radiation field would you expect at 4 m from the source?

Figure 6.4 shows that the field at 1 m would be 100 times greater than at 10 m, and that the field at 4 m would be 1/16 of that at 1 m. Hence

field at 4 m = (100/16) x 20 μGy/h = 125 μGy/h

The second example leads us into an easy method to use, if you want to calculate gamma radiation fields at various distances from the source.

It is based on common sense applied to a **distance factor**. Divide the larger distance by the smaller distance and square the result; this is your distance factor. Now multiply or divide the known dose rate by this distance factor. Multiply if the dose rate should increase and divide if it should decrease.

Look again at example (b). The larger distance is 10 m and the smaller distance is 4 m. The distance factor is $(10/4)^2 = 2.5^2 = 6.25$. Since we are moving towards the source, the radiation field will increase. Therefore, we multiply the dose rate of 20 μGy/h by 6.25 to get 125 μGy/h for the dose rate at 4 m.

Example:

If the gamma radiation field is 500 mGy/h at 3 metres from a source, what will it be at 1 metre and at 10 metres?

(a) Radiation field at 1 m:

The field will be greater because we are going closer. The distance factor is (3/1)2 = 9. Therefore, the field is 500 x 9 = 4500 mGy/h.

(b) Radiation field at 10 m:

The distance factor is $(10/3)^2 = 3.33^2 = 11.1$. The field will be smaller, so we divide: 500/11.1 = 45 mGy/h.

The above example illustrates that if you move from 1 metre to 10 metres away from a source (i.e., by a factor of 10), the radiation level drops by a factor of 100. Just as startling an increase will occur if you move closer to a source. Calculations of this kind illustrate the fact that a few feet of distance from a point source can make a tremendous difference in the dose that a person receives.

For example if a point source (such as a small chunk of broken spent fuel) is emitting gamma radiation at a dose rate of 10 Gy/h at 0.5 m, then a person standing 0.5 m away from the source for a one hour exposure would receive a dose of 10 Gy. This is certainly enough to kill him. If he stands 2.5 m away, the dose rate would only be 0.4 Gy/h or 400 mGy/h. There would be no significant effects if he stood there for one hour. In this example, a couple of metres makes the difference between death and no real effect (other than exceeding the dose limit).

The Inverse Square Law will show that if a person is very near a small gamma source, some parts of his body may receive a much higher exposure than other parts.

Consider your friendly Maintenance Supervisor shown in Fig. 6.5. If the gamma field at his waist level is 5 mGy/h at 90 cm from the source, and if his head is 30 cm from the source, the dose rate to the head would be much greater than to the waist.

Fig. 6.5. Lepreau Maintenance Supervisor

You should be able to work out that the dose rate at his head is 45 mGy/h, and if he were to move his head closer to the pipe it would be higher still.

If you pick up sources, the distance to the sensitive part of your skin becomes negligible, and will result in enormous dose rates compared to those at a few cm. The moral is pretty obvious: **don't pick up sources with your hands.** Handling tongs or even a pair of pliers should be used.

Limitations of the Inverse Square Law

1) The law is valid only for gamma rays because you can neglect any shielding by the air. This is not true for alpha or beta radiation. Alpha particles have only a small range in air (less than 10 cm for the highest energy alpha particles). Once the distance from the source becomes greater than this, no alpha particles are detected. The range of beta particles is usually much greater, but the same reasoning applies.

   Furthermore, beta particles all have different ranges, even if they all come from the same source. Because of scattering, they won't travel in straight lines anyway.

2) In theory, the Inverse Square Law holds true only for "point" gamma sources. In practice, a source may be quite large and the detector will still "see" it as a point source when the detector is sufficiently far away from it. We assume that the Inverse Square Law won't hold until the detector is about five source diameters from the source.

3) When shielding is placed between the source and the detector, the inverse square law can only be applied if due allowance is made for the gamma photons absorbed by the shielding.

4) If the gamma radiation is in the form of a beam, the inverse square law won't apply either.

When Point Lepreau was first taken to high power levels, radiation beams were found coming from the horizontal flux detector housings located in the north reactor wall (just inside the Equipment Airlock). These beams were only about 10 cm in diameter, which made them hard to find. At 10% of full reactor power, the beam intensities were about 3 mGy/h gamma and 1 mSv/h neutron. Lead blankets were strategically placed to minimize this hazard, and were later replaced by permanent shielding.
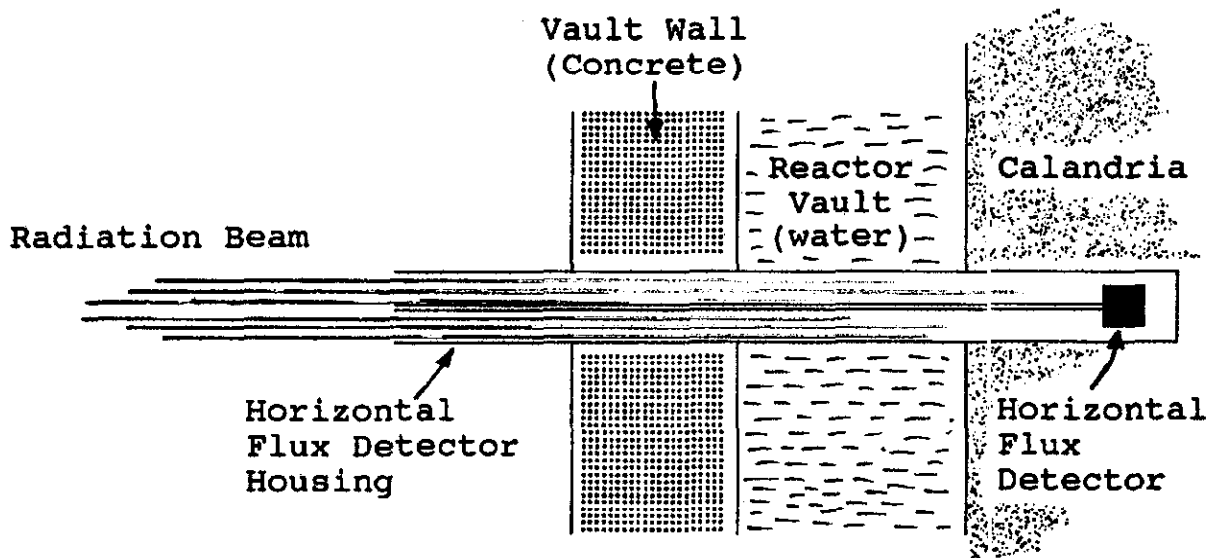

Fig. 6.6. Radiation Beams

Other radiation beams are found at the flexible ventilation ducts around the PHT main circulating pumps. These ducts (four for each pump) exhaust air from the pump bowl cavity through a one metre thick concrete platform to the Boiler Room. At 100% power, these beams amount to about 5 mGy/h gamma and 3 mSv/h neutron. Because they shine directly upwards, they are not normally a problem.

LINE SOURCES AND PLANE SOURCES

We have pointed out that the Inverse Square Law applies only to point sources. For a line source, e.g., a pipe carrying radioactive fluid, the gamma field does not drop as rapidly as you move further away from it as it would for a point source.

If you look at Fig. 6.7, I think you will understand why this is so.
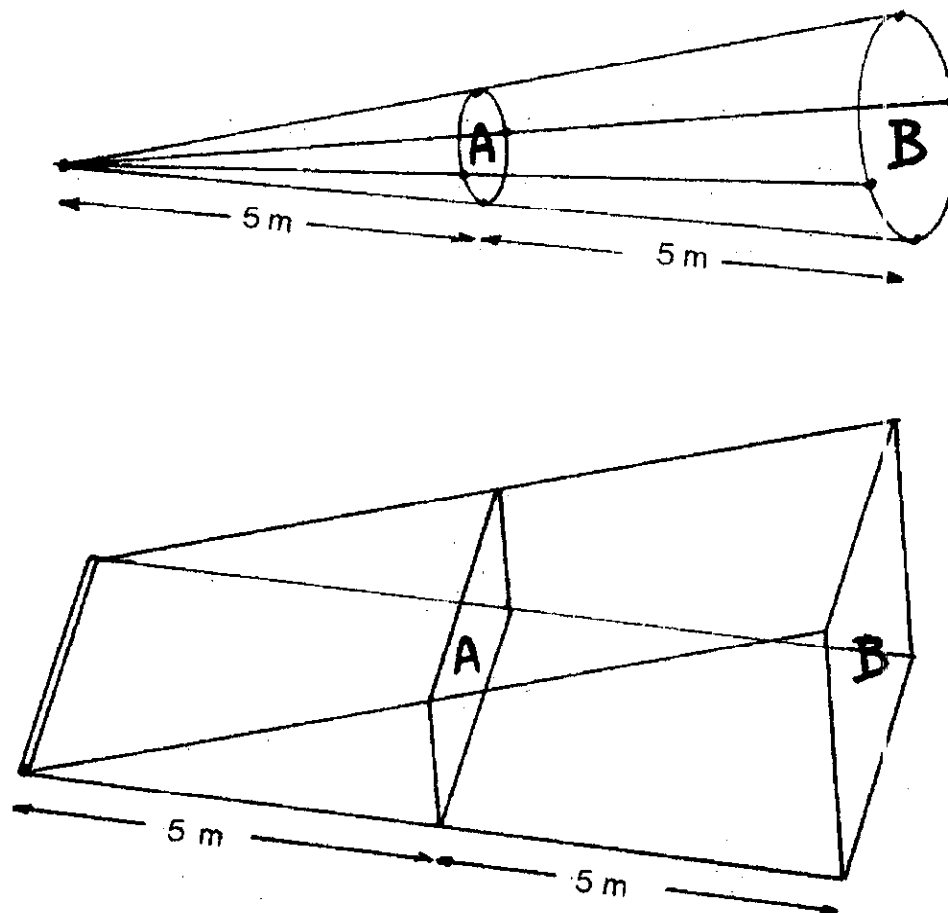
*Fig. 6.7. The Spread of Gamma Radiation From
a Point Source and a Line Source*

For a point source, all the gamma photons in the cone passing through Area A will also pass through Area B. B is twice as far away as A, and therefore has four times the area of A (twice as high and twice as wide.

The number of photons passing through one square metre located at B will therefore only be one quarter of the number passing through one square metre at A. In other words, increasing the distance by a factor of 2 reduces the gamma field by a factor of 4. That's the Inverse Square Law.

For the line source, Area B is only twice as large as Area A, and the radiation field therefore will be half of what it is at A. For example, if you go ten times as far away, the field will only drop by a factor of 10, and not by the factor of 100 that would apply to a point source.

For a large plane (or area) source, there will be only very little reduction in the gamma field as you move away from it. This is shown in Fig. 6.8, which shows the Fuelling Machine Vaults at Point Lepreau.

For example, the gamma dose rates at 2 m away from the reactor end face or at 4 metres away shouldn't change much. A detector would see pretty well the same number of gamma photons in either location. You would not be able to measure a significant drop in gamma radiation intensity until you moved far enough away from the plane source for the spreading out of the gamma photons to become significant.

Now see if you can think of some examples of line sources and plane sources that you might encounter in your work at the station.

- ① REACTOR OUTLET HEADER
- ② REACTOR INLET HEADER
- ③ FEEDER TUBE SPRING HANGERS
- ④ CALANDRIA END SHIELD FACE
- ⑤ SUPPORT BRACKETS
- ⑥ WALKWAY
- ⑦ END FITTINGS
- ⑧ STEAM GENERATORS
- ⑨ INSULATION CABINET
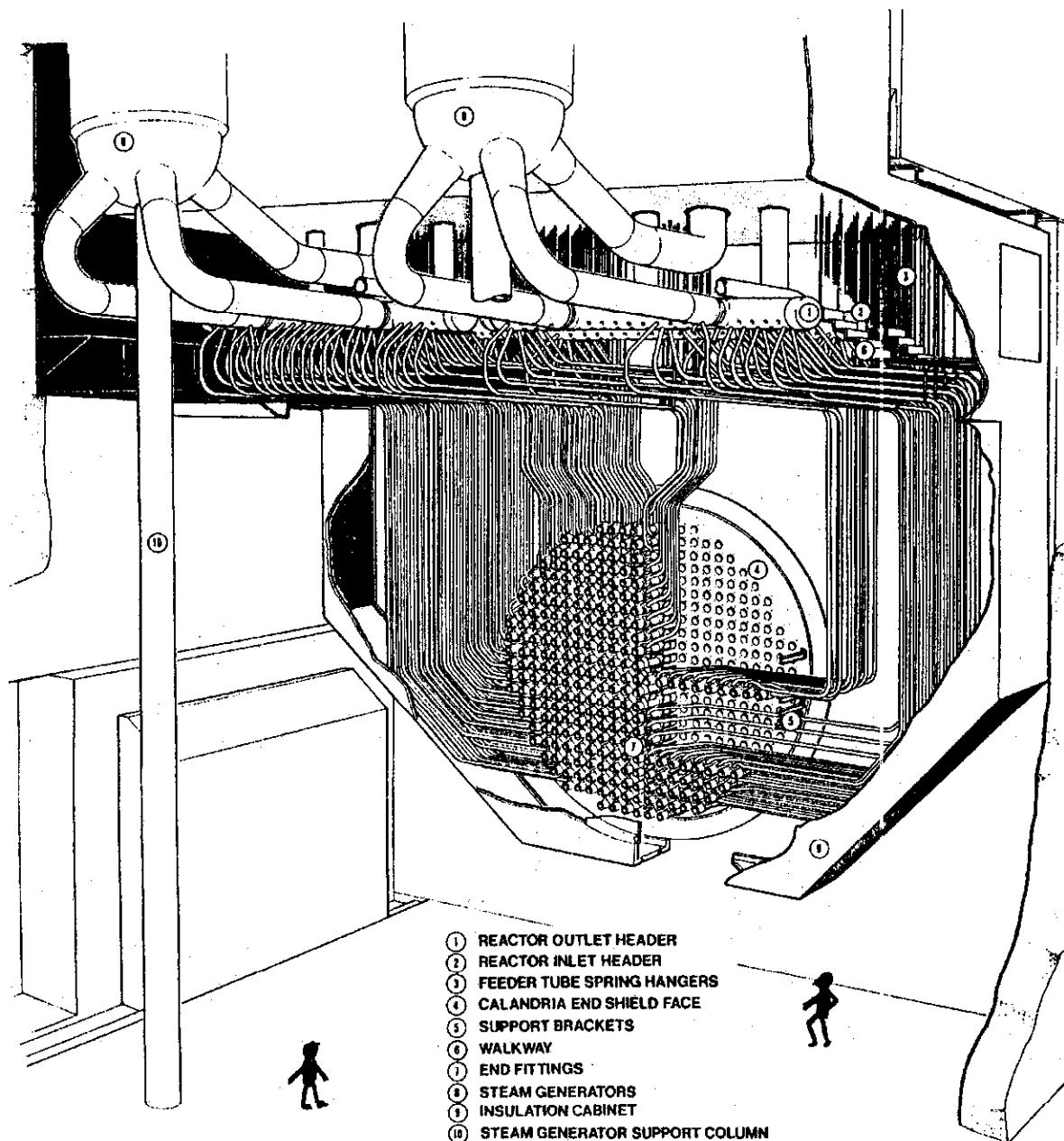- ⑩ STEAM GENERATOR SUPPORT COLUMN

Fig. 6.8. An Example of a Plane Source

BETA EMITTERS AS EXTERNAL SOURCES

Exposed (unshielded) beta emitters can cause some surprising external radiation fields. Why? Because of the limited range of beta particles, we would expect beta radiation to drop off much more quickly with distance than gamma radiation — if you turn this argument around, it is obvious that beta radiation will increase much more rapidly than gamma radiation as you approach the source.

> **Decreasing the distance from a beta source will very sharply increase the radiation level.**

Most sources at Point Lepreau contain a mixture of beta and gamma emitters. Beta radiation from a source which is enclosed in a pipe or other container will be effectively absorbed and only the gamma emitters need be considered.

HANDLING SMALL BETA-GAMMA SOURCES

Usually beta-gamma sources have enough shielding to absorb all the beta radiation. But if they do not, beware! A 10 MBq beta source delivers a dose rate of 200 mGy per hour at 2 cm. At the point of contact, the dose rate would be greater than 1000 Gy/h. This is not a misprint.

> **Always use tongs when handling small sources.**

Never use tongues.

SHIELDING

We have discussed Time, Decay and Distance as ways of keeping radiation doses low.

In some cases the only practical way of reducing radiation exposures to an acceptable level is to install shielding between the source and yourself. Radiation shielding is a very complex subject, and therefore only a few elementary ideas are discussed here.

ALPHA SHIELDING

You may recall from page 39 that alpha particles have a relatively small penetrating ability - even in air the most energetic alpha particles cannot travel more than 10 cm. The dead layer of your skin will stop them completely. Because of this, alpha sources outside the body do not present an external hazard and **shielding against alpha particles is therefore quite unnecessary**. However, alpha particles with their Q of 20 are a very serious internal hazard and great care must be exercised to ensure that alpha sources are kept out of the body.

BETA SHIELDING

At Point Lepreau radioactive materials are normally contained in systems that completely shield people from beta particles. You may remember from page 42 that not very much shielding is required for this purpose.

However, when radioactive materials are released into the plant (like Ar-41), or when systems are opened for maintenance (e.g., removal and maintenance of pumps and valves), the shielding surrounding the beta source is removed. Then an external hazard can exist, because beta particles have a considerable range in air depending on their energies (up to several metres, see page 41).

The tissues exposed to external beta radiation are the skin (500 mSv/year) and the lens of the eye (150 mSv per year). The hazard to the eye lens, which is already shielded by the cornea, may be further reduced by the routine wearing of safety glasses. However, this applies only to beta radiation, and not to gamma radiation. Why?

Since beta particles are so easily absorbed, no one should receive an appreciable external dose from beta radiation if proper techniques are used.

TABLE 6.1. ABSORPTION OF BETA RADIATION
FROM Sr-90 AND Tl-204

	Percent Absorption	
Type of Material	Sr-90	Tl-204
Safety Glasses (Lens)	95	100
Full-Face Respirator (Lens)	80	100
Plastic Suit	10	60
Rubber Gloves (for suit)	10	60
Cotton Gloves (new)	0	80
Disposable Hood (for suit)	0	25
Brown Coveralls (new)	0	15

We made some measurements with TLDs to find out to what extent beta radiation is absorbed by the protective clothing that we use. We used two different pure beta sources, strontium-90 and thallium-204. The max- imum beta energies are 2.2 MeV (from the yttrium-90 daughter) and 0.763 MeV respectively. The results are shown in Table 6.1.

GAMMA RAY SHIELDING

We already know that gamma rays will penetrate to great depths in materials and that no amount of shielding will stop all of the radiation. The effectiveness of gamma ray shielding is frequently described in terms of the half-value layer (HVL), which is the thickness of absorber required to reduce the gamma radiation to half its former intensity. You have already been introduced to this idea on page 43.

The first HVL reduces the radiation field by one-half. The second HVL reduces the radiation by one-half again, i.e., to one quarter of the original level. The radiation levels after successive HVLs are:

Radiation after 1 HVL $= (1/2)^1 = 1/2$ of the original

Radiation after 2 HVLs $= (1/2)^2 = 1/4$ of the original

Radiation after 3 HVLs $= (1/2)^3 = 1/8$ of the original

Radiation after 4 HVLs $= (1/2)^4 = 1/16$ of the original

Radiation after 5 HVLs $= (1/2)^5 = 1/32$ of the original

After n HVLs, a gamma radiation field will be reduced to $(1/2)^n$. This leads to the following useful guides:

> **7 HVLs reduce the radiation field to 1/100 or 1%.**
> **10 HVLs reduce the radiation field to 1/1000 or 0.1%.**

Gamma photons interact with electrons. Therefore those materials that have a large number of electrons per atom and a large number of atoms per unit volume will be the most effective gamma shields. Heavy metals like uranium, tungsten, gold and lead are good examples of such materials.

Concrete is a good structural material, but lead is not because large lead shields require some sort of supporting frame. On the other hand, lead shields will be thinner than shields made of less dense materials, so for semi-permanent shielding we often use lead blocks, lead blankets or bags of lead shot. With these, the shield can be built up to fit the requirements. Lead blankets are convenient for the shielding of awkwardly shaped objects. They can be wrapped around pipes, for example.

Water may be used where it is necessary to see the source of radiation or to work on the source with remote tools. Spent fuel is usually stored in deep bays filled with water. This water also absorbs the heat being generated by the fuel elements, and the water is easily cooled and purified.

Figure 6.9 shows the HVLs of various materials for a range of gamma energies. The HVLs are not constant for a given material, because the relative probabilities of the three gamma absorption processes (photo-electric effect, Compton effect, pair production) vary with gamma energy. In the range of energies that interest us, the HVL usually will increase with energy. In other words, for higher energy gamma photons you will need more shielding than for lower energy photons.
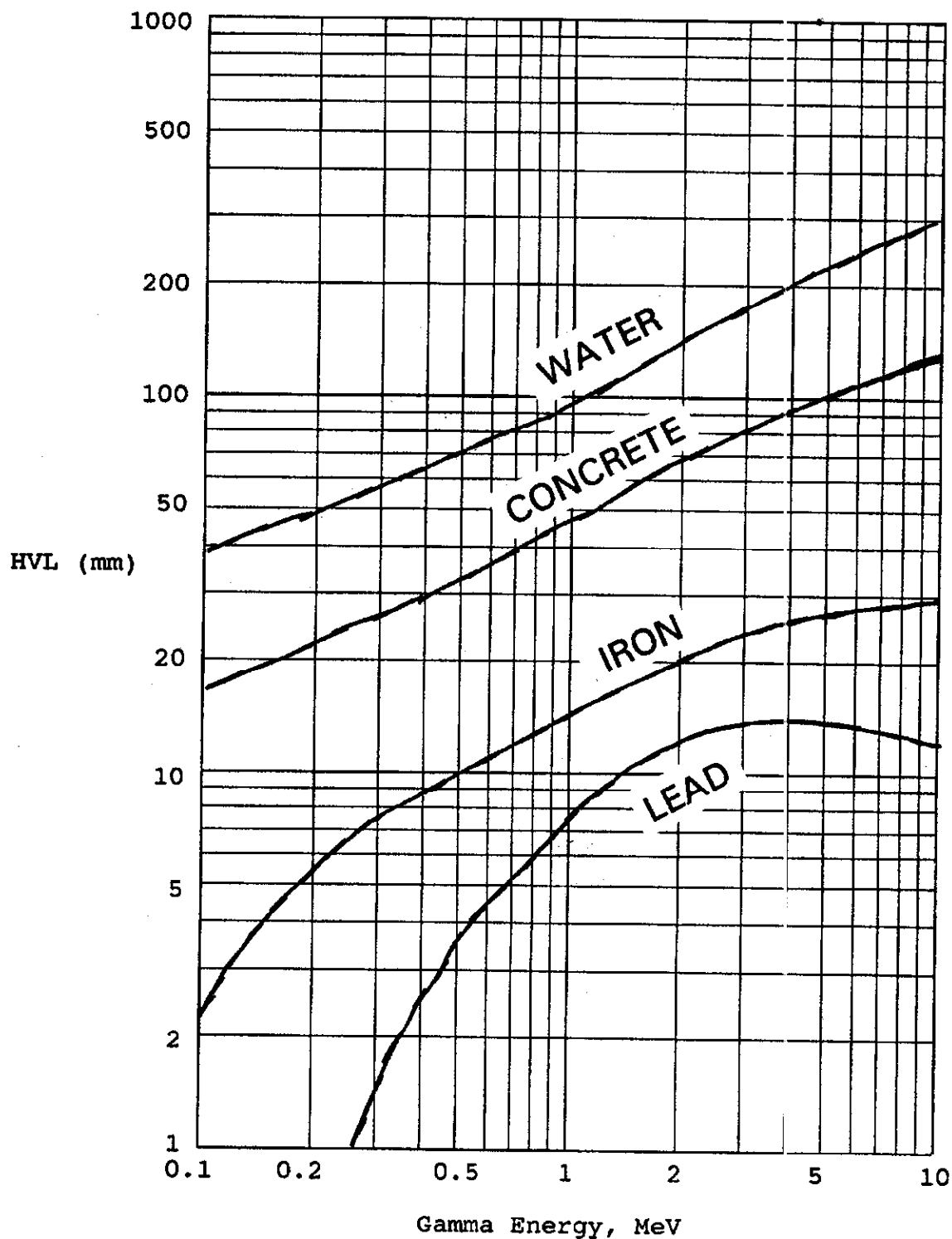
Fig. 6.9. HVLs of Various Materials

For gamma radiation with energies in the range where Compton scattering is the predominant absorption process, the weight of material required for a shield is generally about the same, regardless of the material used. For instance, the HVL of iron for 1 MeV gamma radiation is about 15 mm as compared with 30 mm for heavy concrete. Since iron is about twice as dense as heavy concrete, the total mass required for a shield will be roughly the same for both materials.

Example:

A beam of gamma radiation is found to be coming up through a small hole in the floor. A gamma survey meter shows a reading of 200 mGy/h at the hole. The gamma energy is assumed to be around 1 MeV. The radiation field has to be reduced to less than 50 μGy/h. We have some lead blocks 50 mm thick. How many would you need to block the beam?

The radiation field has to be reduced from 200 mGy/h or 200,000 μGy/h to 50 μGy/h, which corresponds to a factor of 200,000/50 = 4000.

We know that 2 HVLs will reduce the field by a factor of 4, and another 10 HVLs will reduce that by a factor of 1000, so we'll need 12 HVLs. Figure 6.9 tells us that the HVL for 1 MeV gammas is 8 mm of lead. Therefore we'll need 12 x 8 mm, or 96 mm. It seems that two 50 mm lead blocks should do it.

What you'd do is get three lead blocks from Stores, shove them over the hole, and then measure the field again to make sure that they had taken care of the problem.

You could rework this problem for steel sheet (use the HVL for iron) in case Stores are fresh out of lead blocks. A few copies of this book would do the job as well. See, it is useful.

It is very important that you appreciate that although these arithmetic exercises may be quite interesting, they are only meant to give you a clue as to how effective shielding can be. In practical work situations, you should **never** base your radiation protection plans on shielding calculations alone, but you should **always** measure the radiation field after the shielding has been put in position.

GAMMA BUILD-UP

The HVL values given so far apply only to narrow beams as shown in Figure 6.10, and where the number of HVLs is not too large.

In practice, we are more likely to come across gamma radiation that is not in the form of a narrow beam, but that is spreading out in all directions as shown in Fig. 6.11
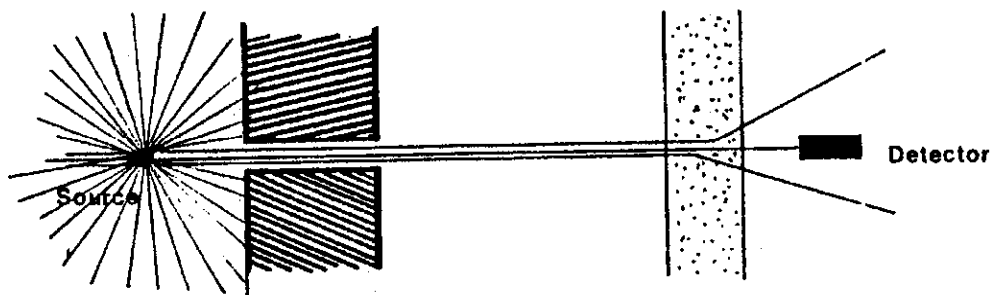
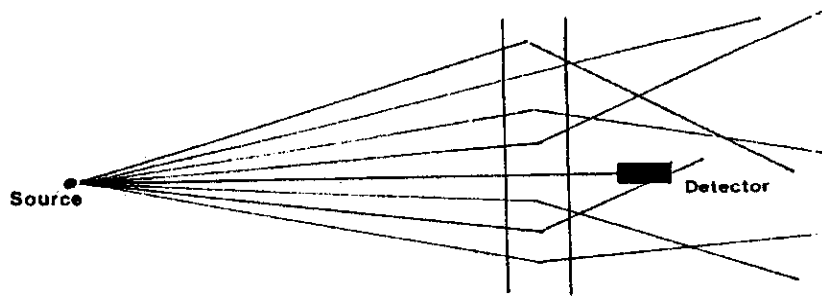

Fig. 6.10. Narrow Beam Absorption

Fig. 6.11. Broad Beam Absorption

In this case 3 HVLs would not reduce the field by a factor of 8, but rather less. The reason is that some photons that would have missed the detector if there had been no shielding are now scattered inside the shield (Compton effect) to interact with the detector. In other words, the gamma field will be greater than you would expect. The thicker the shield, the greater will be the chance of these scattering effects. It is possible to work out what the extra field will be — such calculations are normally done by people who have nothing better to do. In practice, you would just keep on adding to the shielding until your instrument measured a radiation field that you considered to be OK.

Some jobs require the use of temporary shielding while work is being done. You must ask yourself whether the extra dose you will absorb while you grunt the shield into position and then remove it again is going to be off-set by the reduction in absorbed dose caused by the shielding. If the job is a long job, temporary shielding will be worthwhile, but for a short job it may not be.

What else could you do to try to reduce your dose?

NEUTRON SHIELDING

Neutron shielding is a very complicated subject. We won't say very much about it, since I don't know much about it myself.

Fast neutrons must be slowed down before they are readily captured. Fast neutrons may be slowed down by two kinds of interactions:

1)   Inelastic scattering of neutrons with heavy elements (especially iron). This interaction predominates for neutron energies greater than 1 MeV.

2)   Elastic scattering with light nuclei such as hydrogen.

The resulting slower neutrons are captured by nuclei in the shielding material via an (n, γ) reaction. Therefore gamma radiation will be produced as a result of the capture process and additional shielding must be added to absorb the gamma rays produced.

Water, paraffin, masonite and polyethylene contain a high proportion of hydrogen and are therefore effective in slowing down neutrons. A thickness of 250 mm of water or paraffin will reduce the fast neutron dose rate by a factor greater than 10. Concrete retains some water permanently, and is therefore very useful as a neutron absorber.

Practical neutron shields usually consist of light materials to slow the neutrons down, followed by heavy materials to absorb the slow neutrons and the capture gammas. Such shields can be arranged in the form of a thick sandwich of alternating layers of steel and masonite.

PERMANENT SHIELDING

So far, we have discussed how temporary shielding (lead bricks and lead blankets) can be used to reduce the radiation field, but we haven't said anything about permanently installed shielding.

During the design of a nuclear generating station, it becomes clear which equipment will produce high radiation fields once the station operates. Efforts are made to calculate the radiation fields, both at power and during shutdown, so that appropriate shielding can be designed and installed during construction of the station.

REACTOR SHIELDING

First of all, let us pay a tribute to the early workers in radiation, because if they hadn't discovered the harmful effects of radiation before we knew how to build reactors, a lot of people would no longer be around.

An operating reactor at power emits so much neutron and gamma radiation, that you would receive a lethal dose in less than one second if you stood beside it! A thick shield is required to absorb this tremendous amount of radiation, and to reduce it to levels we can live with. This shield is called the **Biological Shield.**

Historically, (NPD, Douglas Point, Pickering A) such shields have been made of heavy concrete with a thickness of just over 2 m. The concrete would be exposed to huge heat stresses: the effect of thermal radiation from the reactor and the effect of absorbing neutron and gamma radiation. To avoid these heat stresses, which would dry out and crack the concrete, **Thermal Shields** were required. These were designed to absorb the thermal radiation and most of the gamma radiation. Cooling pipes embedded in the concrete took care of the rest. (Remember: 5 HVLs will absorb 97% of the gamma energy and hence 97% of all the heat produced by it).

The approach taken at Bruce G.S. and at Point Lepreau was to combine the thermal shielding with the biological shielding. The result is a water filled, steel lined concrete vault (Fig. 6.12). The water provides the shielding, and is circulated through heat exchangers to keep it cool. Ordinary concrete with no embedded cooling pipes is then adequate for the calandria vault walls.

Shielding is sometimes classified as **operational or shutdown shielding.** An operational shield provides adequate shielding at all power levels, whereas a shutdown shield is adequate only during shutdown.
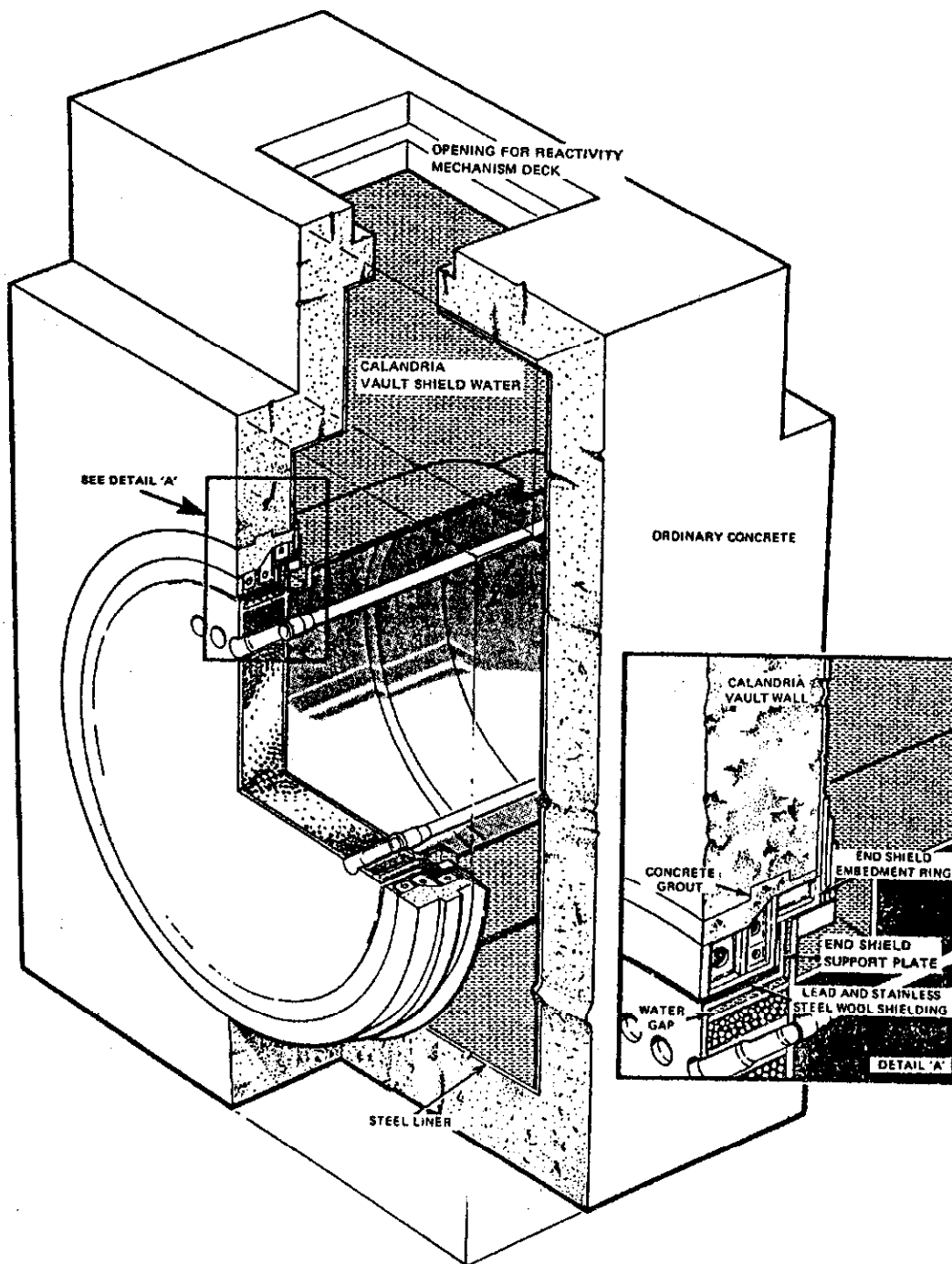
Fig. 6.12. Reactor Vault Shielding

For example, the Reactivity Mechanism Deck on top of the reactor needs to be accessible at all times. Its shielding is an **operational shield**: it was designed to reduce the gamma field to about 40 μGy/h on the R.M. Deck at full power. What we get is 20-50 μGy/h gamma and around 100 μSv/h neutrons. This is quite a good agreement, because it is very difficult to predict the fields accurately, even with detailed and complex shielding calculations.

On the other hand, the shielding in the ends of the calandria is **shutdown shielding** only. At full power, fields in the Fuelling Machine Vaults are around 150 mGy/h gamma and 200

mSv/h neutrons. One day after the shutdown, the fields have dropped to about 1 mGy/h (gamma only) at one metre from the reactor face. The shielding consists of 10 mm diameter carbon steel balls in the end shield. These are cooled by the same end shield cooling system that cools the water in the vault tank. The fuel channels themselves are shielded by a shield plug at the ends of each channel. If a shield plug is removed (for fuel channel maintenance), an intense beam of up to 500 mGy/h will shine out of the fuel channel.

OTHER PERMANENT SHIELDING

There are numerous locations in the Reactor and Service Buildings, which are permanently shielded. Some examples are the Boilers, the Spent Fuel Bays, Spent Resin Storage Tanks, and Filters and Ion Exchange Columns of various purification systems. The water in the Spent Fuel Discharge, Reception and Storage Bays is considered to be permanent shielding. For this reason, steps are taken in design and operation to make sure that these bays cannot be emptied.

If you want to have a bad nightmare, dream about putting the plug back in when the bay water drains out!

SHIELDING PENETRATIONS

Pipes to and from equipment located behind shield walls must pass through the shield at some point or other. The opening through the shield provides a path through which radiation may stream. Such ducts should have one or more bends in them to eliminate the straight-through path. Then radiation will be scattered several times before it can leave the duct. So you'll appreciate that provision of these bends reduces the emerging radiation field significantly. This situation is much better than a straight line path through which radiation can stream in a concentrated beam. Radioactive equipment which must be accessible can be shielded by an "access labyrinth", which is a sort of concrete maze.

From what has been said above, you've probably realized that input to minimizing radiation hazards was much more effective in the design stage at Point Lepreau than it would be now. This is pretty well true of any project, nuclear or otherwise, and I would like to digress for a moment and introduce you to Access Control via the "Safety Precedence Sequence".

SAFETY PRECEDENCE SEQUENCE

The following sequence indicates, in order of decreasing effectiveness, what you can do to minimize hazards:

1. Eliminate the hazard
2. Minimize the hazard
3. Install physical barriers
4. Install warning devices
5. Minimize human error potential
6. Establish procedures
7. Train, motivate and supervise personnel
8. Accept the hazard as it exists

Let us look at this sequence with respect to the hazards of gamma radiation at Point Lepreau.

1. Eliminate the Hazards

The only way to eliminate the gamma radiation hazards of Point Lepreau is not to have built it in the first place. If you want to have nuclear power, you can't eliminate the hazards completely.

2. Minimize the Hazards

You can certainly do this by suitable use of shielding. The intent was to design the plant so that the gamma fields in all routinely accessible areas would be less than 25 μGy/h. For some areas, the shielding requirements would have been excessive or impractical, and access to such areas has to be restricted.

3. Install Physical Barriers

Barriers which physically prevent people entering hazardous areas are very effective, e.g., locked doors. The Access Control System at Point Lepreau is based on this Physical Barriers approach and we'll deal with it in the remainder of this chapter.

4. Install Warning Devices

Warning devices are not as effective as physical barriers, because some morons will ignore them. We have an electronic warning system, which alarms when exposed to high gamma fields, and it will be described in the next chapter.

5. Minimize Human Error Potential

Whatever methods you use to control the hazard should be chosen so that the chances of human error are minimized. Make it easy for people to do it right, and make it hard for them to do it wrong. If you still don't know what I mean, take a look at the control panel for the Equipment Airlock next time you're there.

6. Establish Procedures

Procedures for controlling the hazard should be established, written down and followed. Again, to be effective, the procedures should be designed with the people, equipment and work environment in mind: if you ask people to do things in an awkward way, they tend not to do them.

7. Personnel

This means selecting suitable people to do the work, training them, motivating them and supervising them.

8. Accept the Residual Hazards

This just means you and management should clearly understand what remaining hazards you've chosen to accept after you've done all the other things.

The Safety Precedence Sequence will tell you that this training course (will it ever end?) is one of the least effective of all our techniques for controlling hazards. Eliminating hazards is better than training people to avoid them. However, if you follow the Radiation Protection Procedures at all times, you should never have a problem.

This brings us back to item 7 — if you don't understand the procedures (training), or the need for them (motivation), you won't have much incentive for following them. Physical barriers and warning devices are there to stop you and warn you in case you haven't followed the procedures — or if the procedures are inadequate or wrong, which would be our fault, not yours. With this background in mind, let us now turn to Access Control.

ACCESS CONTROL

Access to the station is restricted to qualified personnel (training) and people escorted by them (supervision). Areas in the station are either "accessible at all times" or "access controlled". Those that are accessible at all times have residual radiation hazards that are so low that they pose no problem. Access Controlled Areas often have high residual hazards, require Shift Supervisor approval before you can enter them (procedures), and are equipped with locks and interlocks (physical barriers) and alarming gamma monitoring systems (warning devices).

ACCESS CONTROL SYSTEM

The Access Control System controls entry to Access Controlled Areas by physical barriers, warning devices and procedures. In the section to follow we'll describe the physical barriers. The next chapter will introduce you to the warning devices and how they are tied into the physical barriers, and in the Applications Course you will be taught the procedures that you have to follow.

The Access Control System consists of three subsystems defined as:

Subsystem A (conditioned by reactor power level)
Subsystem B (conditioned by Fuelling Machine status)
Subsystem C (controlled by the Shift Supervisor).

Doors to A and B areas can only be opened with a special key of a weird shape. All A and B keys are locked in Panel 15 in the Main Control Room, and cannot be removed until special conditions have been met.

Subsystem A

Access to A areas is conditioned by reactor power. If reactor power is greater than 2% of full power, the keys are locked in Panel 15 in the Main Control Room. An A key can be removed at less than 2% power, but an interlock with the Reactor Regulating System then inhibits power increases beyond 2%. This remains in effect until the key is reinserted in Panel 15. There are only two A areas at Point Lepreau: the East and West Fuelling Machine Vaults.

Subsystem B

Access to B areas is determined by the status of the Fuelling Machines (F/M). Areas are the Spent Fuel Discharge Room, the F/M Maintenance Locks and both F/M Vaults. For the S/F Discharge Room, the only condition that has to be met before its key can be removed from Panel 15 is that the ball valves (through which spent fuel passes into the room) must be closed. Access to the F/M Maintenance Locks requires the shielding doors separating them from the F/M Vaults to be closed, and the door seals to be inflated. This will reduce the field to acceptable levels, even at full power.

Finally, access to both F/M Vaults is also B conditioned, because again the shielding doors and seals must be inflated. This guarantees that the fuelling machines will not be in the F/M Vaults. Note that the F/M Vaults are conditioned by A and B, whereas the other B areas are conditioned by B alone.

Subsystem C

C Areas are of lower hazards. The keys are under the control of the Shift Supervisor. At present, we have only two C Areas; all of the Boiler Room is one, and the Moderator Enclosure is the other.

Note that the only way to get to the Moderator Enclosure is through the F/M Vault access points, so it (the Moderator Enclosure) really has A+B+C control on it. The C access was added in 1984 as an extra measure of control.

NOTES ON ACCESS CONTROL

Although the procedures will be left until later, here's an overview of how Access is controlled to A, B and C areas:

* Any access to locked A or B areas requires a Work Permit signed by the Shift Supervisor. If it is already unlocked (during shutdown maintenance work, for example), it may be treated as any other free access area in the station. Of course, you should still heed any signs placed at the entrance to, and within the area.

* Entry to a locked A or B area under access hazard conditions requires that the door be left open and guarded to prevent unauthorized entry.

* Entry to a locked C area does not require a Work Permit (unless the Shift Supervisor thinks otherwise). The access door can be left unguarded while work is in progress, but it must be locked on completion.

* An override key which allows any key to be removed under any condition is under the control of the Shift Supervisor. This is used very rarely, maybe three or four times a year, to enter Access Controlled Areas for a few minutes to make a quick fix to some failed gizmo.

* Removal of a B key requires consultation with the Fuel Handling Group (e.g., there may be spent fuel in the machines).

* When access control is to be restored, the person locking the door must check thoroughly that nobody remains inside, and that the area is clean and tidy. This is particularly important in the F/M Vaults and Maintenance Locks.

* Exit is possible from inside even when the door is locked. The only exception is the S/F Discharge Room - here the large shielding door at the entrance should be padlocked open and tagged to ensure that nobody closes it by mistake.

* In the Main Control Room, audible and visual alarms come in whenever an A or B key is removed from Panel 15, and whenever an A or B door is opened.

SUMMARY

The four methods of radiation dose control for external sources are Time, Decay, Distance and Shielding.

Radiation fields from a source will be reduced to less than 1% for every seven half-lives the source is allowed to decay.

For "point" gamma sources, the field drops in proportion to the square of the distance from the source. For "line" gamma sources, the field drops in proportion to the distance from the source, and for large plane gamma sources it doesn't change much at all as you move away.

No shielding is needed for alpha radiation. Beta sources are usually completely shielded by the systems containing them, and a beta hazard will exist only when these systems are opened. Personal or protective clothing provides little beta shielding. Gamma shielding is best with high density, high Z materials. Effective neutron shields have a high hydrogen content (to slow the neutrons down) and incorporate gamma shields as well (to absorb the neutrons and the resulting capture gammas).

Never rely on shielding calculations alone — always make radiation measurements after temporary shielding is installed.

The Access Control System consists of physical barriers, warning devices and procedural controls, and is designed to prevent entry to areas with high external radiation hazards. The system is conditioned by reactor power (subsystem A) and/or fuelling machine status (subsystem B), or neither (subsystem C).
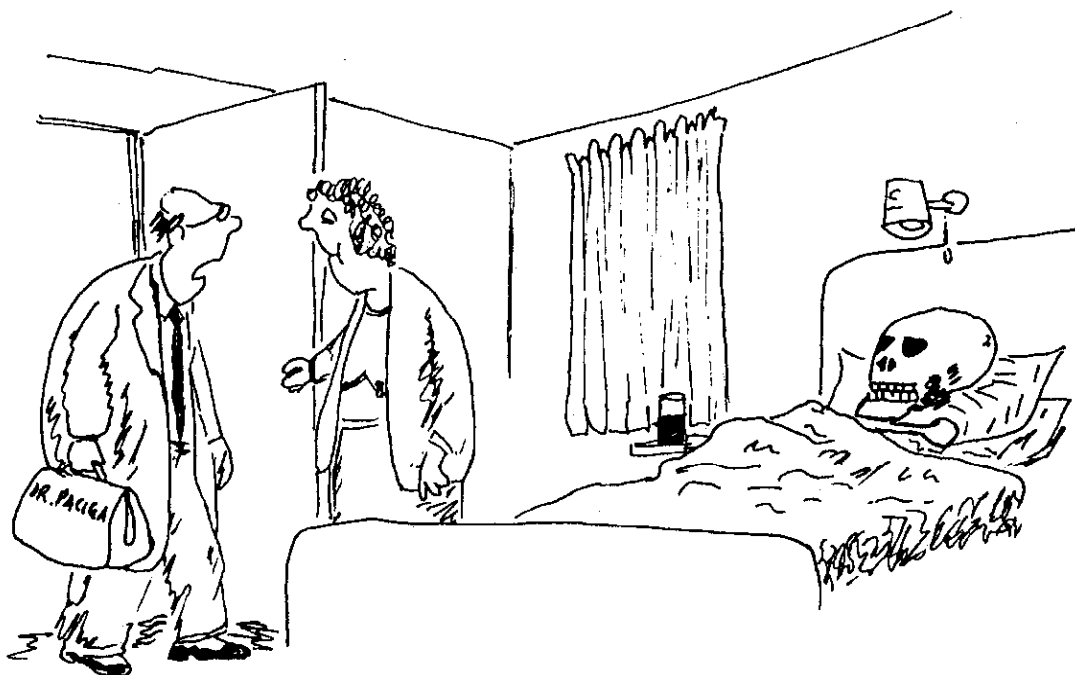
"I wish you'd called me earlier, Mrs. Oaten."

PROBLEMS

1. What is the difference between internal and external radiation?

2. Describe four ways in which external radiation exposure can be decreased.

3. You are going to work in a gamma field of 1 mGy/h for 45 minutes. There are also neutrons of 0.6 mSv/h. What deep dose will you get? If you are only allowed 1 mSv for the job, how long could you work?

4. You are going to work for 20 minutes in an area where the gamma radiation field is decaying with a half-life of 3 hours. If it is 300 mGy/h now, how long will you have to wait to reduce your dose to just less than 1 mSv?

5. The radiation field coming from a small purification system strainer was measured to be 3 mGy/h 1 metre below the strainer. You have to work for an hour on a catwalk 3 m above the strainer. What will the field be there — assuming that it is all due to the strainer?

6. Suppose a piece of broken fuel was accidentally lifted out of the water in the Spent Fuel Receiving Bay and Joe Cretin was exposed to the piece of fuel for 5 minutes, facing it and 0.5 m from it, before he realized the danger. A quick gamma survey about half an hour later measured the gamma field at 2 m to be 4.0 Gy/h. Joe's TLD was read out shortly after, and indicated 4780 mSv deep dose, 9420 mSv shallow dose.

    (a) Is the deep dose result consistent with the facts given? Why?
    (b) How do you explain the shallow dose?
    (c) Assuming that the TLD deep dose estimate is the best we have, what are Joe's chances of survival? Hint: by estimating the dose to his back, try to get an average whole-body dose assessment.
    (d) What are the short-term and long-term consequences of this exposure?

7. You and your buddy worked for half an hour near a point source of gamma radiation. You were about twice as far away from the source as your buddy. On leaving the area, your DRD indicated 1 mGy and your buddy's was off-scale (greater than 5 mGy). Give as many reasons as you can that would explain why his DRD was off-scale (I can think of nine).

8. We have a Cs-137 gamma source at Mactaquac for irradiating calibration TLDs. We want to expose a number of TLDs to 1, 10, 100 and 400 mGy. The source is at the centre of a table 1 m in diameter. If the radiation field is 0.2 mGy/minute at 50 cm from the source when it is in the exposed position, at what distance from the source should we put the TLDs so that we can expose all of them at once for 2 hours? (We don't actually do it this way, because the TLDs closer to the source would act as shielding for those further away).

9. A gamma source used for radiography sits in a cylindrical shielded container of lead. The wall thickness is 20 cm, and a gamma field of 10 μGy/h above background can be detected on the outside wall. If the HVL of lead is 11 mm, what field would you expect at the same distance from the source if it were removed from its container?

10. A small beta source used in our lab for calibrating beta survey meters produces a measured dose rate of 90 mGy/h at 50 cm. Using this information, we calculate an approximate dose of 2.25 Gy/h at 10 cm. Is this calculated dose rate accurate, too high or too low? Explain.
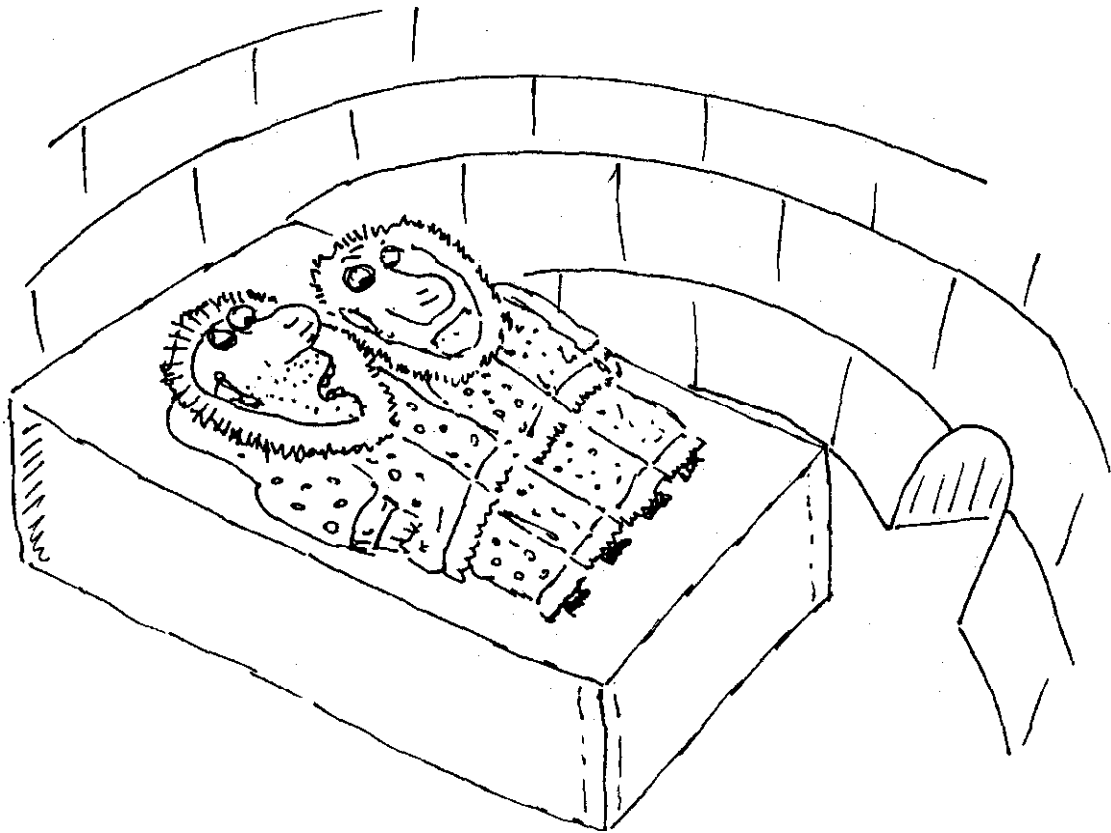
"I think these water beds are vastly overrated."