REACTOR CANNOT EXPLODE LIKE A NUCLEAR BOMB

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Summary:

In the debate over nuclear reactor safety, there is a recurring question - "can it explode?" Under this question lies a very real fear of nuclear weapon explosions. The anti-nuclear activist has only to transform the question to "when it explodes..." to use this fear in gaining support. It is the purpose of this note to explain the fundamentals of explosions and to point out the similarities and differences between various types of explosions. It is not a technical note and is not scientifically precise except in its qualitative comparisons. These comparisons are, however, correct to the best of my understanding; they support what is one of the few categorical statements made in the Nuclear Safety scientific literature, "a reactor cannot explode like a nuclear bomb."

Still valid after Chernobyl – noted on July 7, 1988

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1 INTRODUCTION

Nuclear power reactors are built to produce electricity. Electricity is one of the many components necessary to support our way of life; its cost and availability have a strong influence on the world's economic health. The electricity from CANDU reactors is cheaper than from fossil-fuelled boilers, and the long-term availability of fuel (uranium) is well established. The safety record of power reactors is excellent even by the very stringent standards that are applied. The final element of the power system, waste disposal, is under development with every indication that the necessary isolation from the environment can be achieved.

It is fair to ask "why the big fuss?" Why is it that some individuals and groups are violently opposed to use of nuclear power at any time for any reason? How have anti-nuclear groups brought the introduction of nuclear plants in several countries to a halt, even in the face of high costs and environmental damage that result from producing electricity by other means? The driving force, in my opinion, is fear. Fear of the unknown, fear of ionizing radiation, fear of terrorist attacks, and fear of reactor explosions all have been used effectively in the campaign against nuclear power. Such fears have the potential of turning a democratic society against any unfamiliar idea; these fears can be dispelled only by knowledge.

This paper addresses the particular fear of reactor explosions. This is a case where association induces fear; that is, "nuclear reactor" sounds like "nuclear weapon" so that "nuclear reactor accident" becomes like "bomb explosion". Pictures of huge mushroom clouds are juxtaposed with discussion of nuclear reactor safety, and fear of reactors is the result. There is no quick and easy way to dispel such fears; fears induced by a one-minute television spot might need hours of careful explanation before an individual can overcome them. It is important to try.

2 FUNDAMENTALS OF EXPLOSIONS

What is an explosion? How is it produced? What differences are there in various types of explosions? What effects do they have? Using a familiar example, lightning can show the fundamentals of explosions. In the following sections several other examples are given to illustrate the characteristics of different types of explosions. These are used, finally, in a discussion of the largest possible reactor accident to explain its fundamental characteristics and behaviour.

Lightning is produced following buildup of a high voltage between the earth and atmosphere. Extremely large electrical currents flow through a small tube of ionized air. The resistance of the air gives the same effect as electrical resistance in a wire - the air is heated. Due to the high electrical current the tube of air is heated very rapidly and starts to expand. As it expands it pushes surrounding air molecules out of the way. When the expanding gas exceeds the speed of sound in air a "shock wave" is formed (in much the same way as an aircraft moving faster than the speed of sound produces a shock wave that we know as a sonic "boom"). Near the position of the lightning bolt the shock wave can move at many times the speed of sound, but as it moves its energy is transferred into the air it passes through, so it becomes weaker. Eventually it changes to an ordinary sound wave travelling at the sound speed in air.

We are all familiar with this type of explosion. When a lightning bolt strikes a long distance away we see a flash first (because light travels so much faster than sound waves) then, after an interval, we hear a rumble that is the sound wave that follows the initial shock wave. This is a complicated wave because of the many reflections, which occur as it passes over the earth from the lightning bolt to our ears. If we are much closer to the lightning strike the effects are different. The flash is followed very quickly by a loud "bang", which we hear as the shock wave passes. Rumbles after this bang come from sound wave reflections off the earth. If the air is very still and the strike is close, we can feel a wind after the bang; the air expanding away from the position of the lightning bolt produces this. (After a very close lightning strike, few people are cool enough to notice this small wind).

This is the essence of an explosion. Energy must be released into a small space very fast; the gas in that space must expand quickly enough (faster than the speed of sound) so that a shock wave can be formed. The shock pressure, and so the amount of damage the shock wave can do, increases with the speed of expansion. The speed, in turn, increases with the temperature of the gas being heated. Higher peak temperature is reached when the material is heated more quickly, because there is less time for heat losses to act in reducing the temperature.

3 THOUGHT-EXPERIMENTS

The following series of experiments is arranged to introduce the different characteristics of explosions so the power reactor situation can be clarified. A thought-experiment is one that is defined by words. It need not be possible to do the experiment, but when the experimental results are described the behaviour that is used to prove a point must be physically correct.

3.1 Steam-boiler Experiment

This is a closed tank of water with very strong walls. It has a heat source, but is perfectly insulated so no heat can be lost. It is connected to a large but empty balloon through a valve. The pipes have no resistance to flow.

As experiment l(a), leave the valve open and add heat to the water. As the water starts to boil the balloon expands. Eventually all of the water is boiled off and the balloon becomes very large.

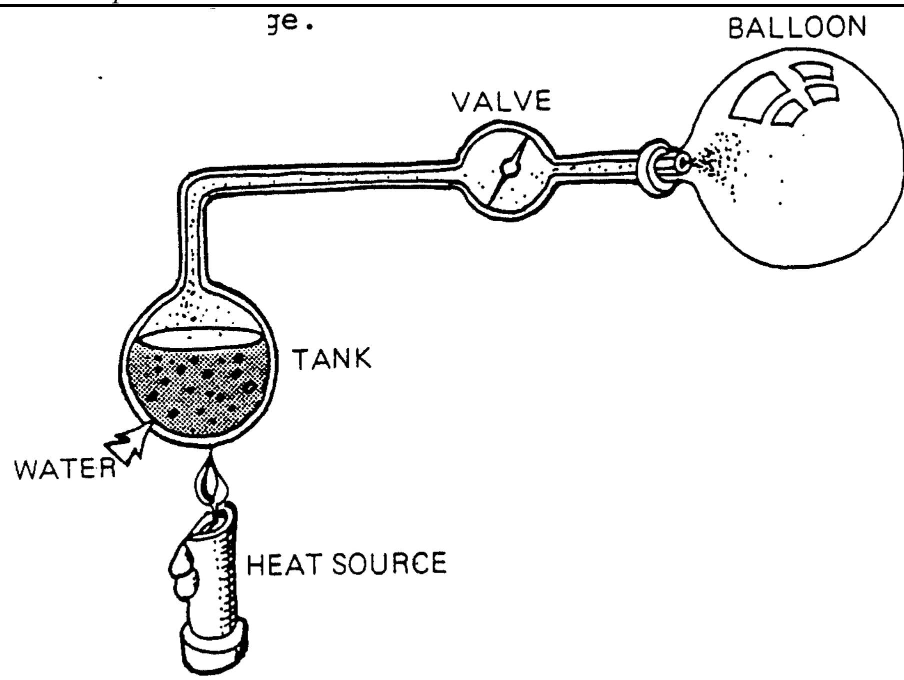

Figure 1 Steam-boiler experiment

Now redo the experiment with the valve closed. This is experiment l(b). Leave the flame on for the same amount of time as was needed to boil all of the water with the valve open. (Since the can is extremely strong, this is possible). Now open the valve suddenly. The balloon expands very rapidly. Standing at a distance from the balloon, you (the observer) feel a shock wave (a "bang") then a wind as the expanding balloon forces the surrounding air out of the way. It is an explosion, characterized by rapid release of thermal energy that was stored in the heated tank.

The balloon finally stops moving at about the same diameter as before, but the effects are different.

3.2 Open-dish Experiment

In this experiment, 2(a), the same amount of water is boiled as in the steam-boiler experiment. The steam expands into the surrounding air, and the time taken to boil all the water is the same as in experiment 1, because the flame is the same size.

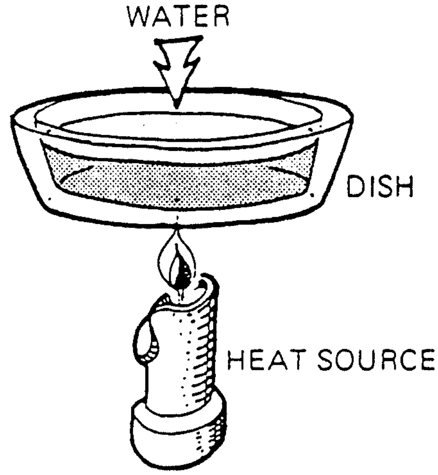

Figure 2 Open-dish experiment

Can we make an explosion in this case? Let us increase the heating rate by making the flame bigger. The steam expansion rate increases as the heating rate increases, and we approach the conditions of experiment l(b). The problem is that the boiling water-steam mixture starts to move away from the flame, so it does not get heated.

Now change the heating method. In experiment 2(b) throw very hot molten metal into the dish. Choose the amount and temperature of the metal so that the total heat content is the same as in experiment l(b). Under correct conditions we can produce a "vapour explosion". The molten metal breaks up into very fine particles dispersed in the water. Because of the large surface area of contact between these fine particles and the water, steam is produced very rapidly and a shock wave is formed. The observer at a distance again hears a bang (the shock wave) and feels a wind as the steam expands. An explosion has been produced. At the end of the experiment all the water is gone and the metal is cool. If the observer listens closely, what he hears is "bang -whoosh". This is because only a small amount of the original energy in the molten metal goes into producing the bang. Most of it goes into boiling the remaining water at a comparatively slow rate.

Vapour explosions occur occasionally in foundries when molten metal is dropped into a water pond, or when water is added accidentally to a furnace containing molten metal. The size of the explosion is limited by the size and geometry of the metal slug and the pond. It also depends strongly on initial temperatures, particle sizes, heat conductivity, and purity of the water. The fraction of the heat energy in the metal that can be converted to explosion energy is very low, and the shock wave produced is much weaker than is typical of a dynamite explosion as discussed below. This is best illustrated by the fact that casualties in aluminum-water foundry explosions are due to burns from the metal, not concussions from the shock wave. Vapour explosions are discussed in more detail in experiment 6.

3.3 The Dynamite Experiment

In experiment 3(a), dynamite is lit with an ordinary flame and burns completely. The burned gases expand in much the same way as the steam in the water-boiler and open-dish experiments, l(a) and 2(a).

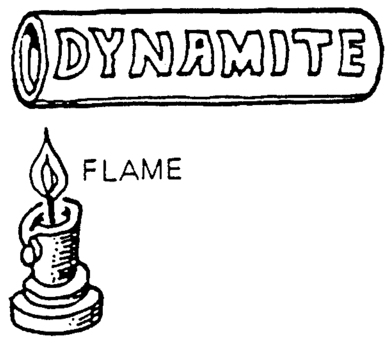

Figure 3 The dynamite experiment

The dynamite can be burned in another way in experiment 3(b). If it is hit very hard (with a hammer or a high-pressure shock wave from a detonator) a chemical reaction occurs which is similar to burning, but is extremely rapid. The rapid burning, which is called detonation, increases the shock wave -pressure and it travels through the dynamite very quickly. The burned gases then expand rapidly; the observer first sees a flash, then hears a "bang" and feels a wind. The expanded gas finally reaches about the same volume as before, but the effect is very different. The shock wave is responsible for most of the damage from chemical explosions.

The effect of the explosion increases as the amount of dynamite is increased. The largest explosions have been of a few hundred tons of TNT (tri-nitro toluene) at one time; say 30 large truckloads. This is very large compared with the largest explosions that can be produced in the open dish experiment, because stored energy in the explosive chemicals is released quickly and high temperatures are reached in a very short time.

3.4 The Fission Bomb Experiment

Experiment 4 is a much larger "thought experiment". Here, we see a picture of a fission bomb exploding. It is a sphere about the size of a soccer ball.

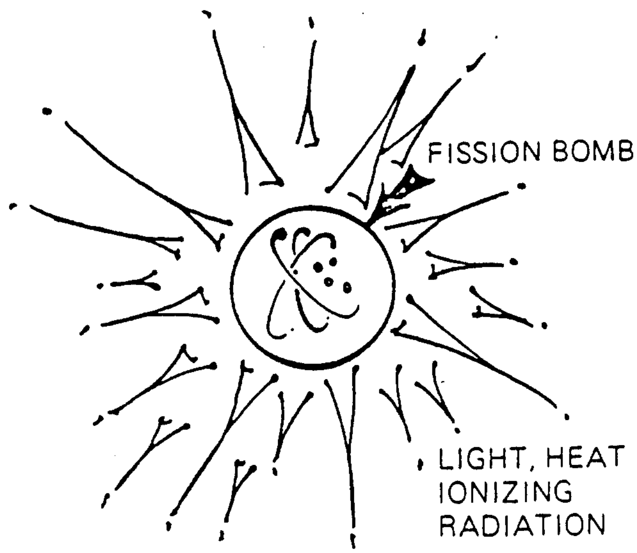

Figure 4 The fission bomb experiment

The energy being added to this sphere comes from splitting uranium or plutonium atoms (a "nuclear" reaction instead of a "chemical" reaction as in the dynamite experiment).

Because the addition of energy starts as soon as the bomb is put together, it must be stored in parts. If it is put together slowly it simply melts and comes apart. When it does this, the fission process stops immediately and no explosion is produced. As the material is put together more and more rapidly, more and more fission energy is added before it comes apart again, but still no "bang" can be heard. In fact, using a chemical explosion before a nuclear “bang” can be produced must put the parts together. If very special sets of conditions are met, then the material will look like a soccer ball, but only for a few millionths of a second after the chemical explosion. During this time all of the nuclear energy is added. The ball then starts to expand and the energy addition stops.

The largest explosion size that has been produced is about 200 times larger than in the dynamite experiment, 3(b). This is equivalent to about 6000 truckloads of TNT. When such a large amount of energy is added to a small amount of material it reaches an extremely high temperature, and so exerts a high pressure on the air around it. An intense, high-velocity shock wave is formed. The distant observer feels a bang, then a wind.

However, because of the extremely high explosion temperatures he first feels a heat pulse on his skin and sees an extremely bright light. This radiation travels much farther than the neutron and gamma radiation from the reaction itself. If the observer is close enough to receive lethal doses of neutron and gamma radiation he will likely be killed anyway by the extreme heat and blast.

3.5 The Zero-Power Reactor Experiment

This is a simple version of a CANDU reactor. Figure 5 depicts a tank of heavy water with natural-uranium rods spaced uniformly through it.

[Note: this text presumes a basic knowledge of fission reactors. This knowledge can be obtained from any one of several public sources.]

Before the experiment it has neutron-absorbing control rods in it, so the chain reaction cannot start.

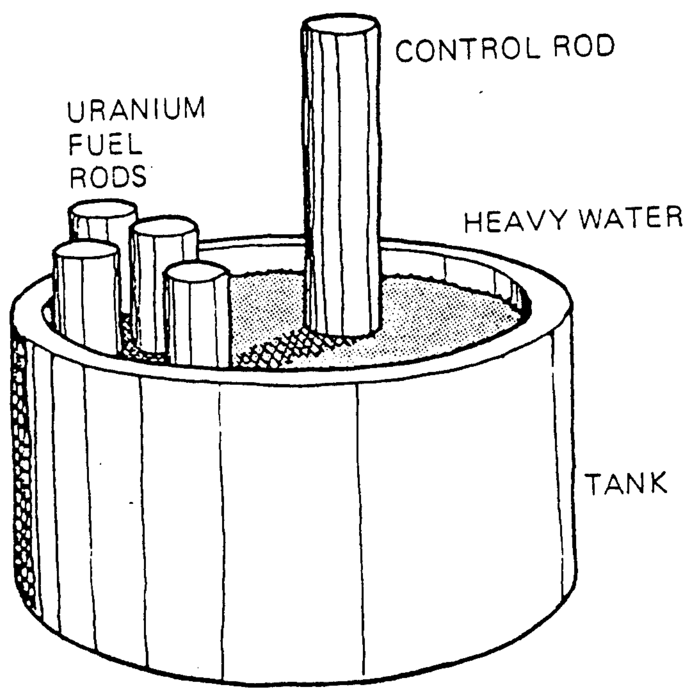

Figure 5 The zero-power reactor experiment

To start this experiment we pull out the control rods as fast as possible. If we have arranged materials correctly the fission rate rises quite rapidly and the fuel rods heat up. If we have deliberately placed an insulating gap between the rods and the heavy water, we might be able to melt the rods and then mix the molten mass with the water. The reactor behaviour after this is "like" experiment 2(b), in which molten metal was dropped into cold water. If any interaction occurs, it behaves like a vapour explosion, not like a nuclear weapon explosion. Such reactor safety experiments have been conducted in several different countries; all of these confirm that nuclear explosions cannot occur in reactor configurations. Other experiments have shown that these ingredients do not normally produce a vapour explosion, and that such explosions are eliminated completely if the water is slightly pressurized.

The implications from the above are interesting and important. A vapour explosion is unlikely in a pressurized water reactor (high pressure moderator), and hence core meltdown is possible in that system. The CANDU reactor, on the other hand, has a low-pressure moderator in which vapour explosions may occur. However, the fuel is widely dispersed in CANDU – an important fact, as will be seen in Section 7.

3.6 The CANDU Power Reactor Experiment

A CANDU power reactor looks very much like the zero-power reactor shown in experiment 5, except that the fuel is kept hot - the purpose of the reactor is to make medium-pressure steam by boiling water at a steady rate. This figure is a simple diagram of a CANDU power reactor. The fuel heat is removed by flowing water. Because this water is hot it must be enclosed in high-pressure piping to keep it from boiling. The heat is transported in this cooling water to a steam generator, where steam is produced to spin the electricity generator.

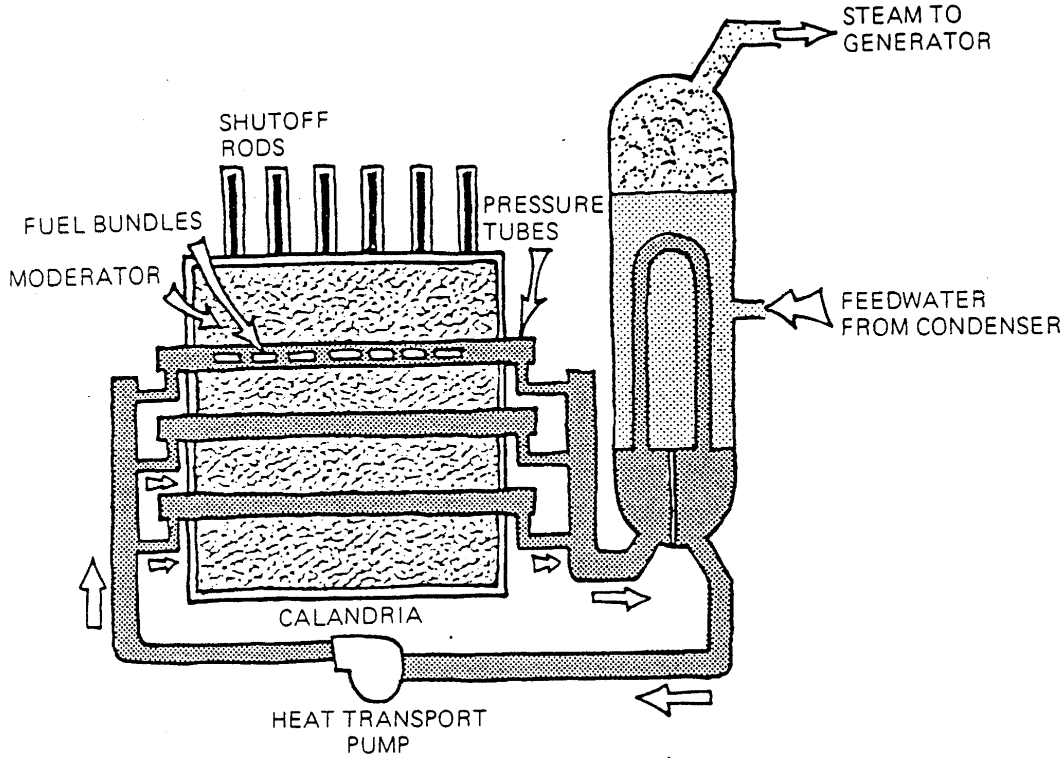

Figure 6 The CANDU power reactor experiment

By comparison with the zero-power reactor experiment, in this case by design of the control rods it is impossible to withdraw them rapidly.

For our experiment, the most rapid rate of increase in power can be achieved by breaking the heavy-water coolant piping. The safety shutdown systems are, of course, designed to enter the reactor and shut off the chain reaction if this happens. Either of these two independent systems will immediately shut off the reactor. Because we started the experiment by breaking a large pipe containing hot high-pressure water, steam from this break expands into the surrounding air, as in the water-boiler experiment, l(b). However, a massive concrete building called the containment system completely surrounds the reactor. It is designed for such accident conditions and easily contains the steam (plus any radioactive material contained in the steam). The containment system includes a cold-water spray that is started automatically by the steam pressure. This water condenses the steam and drops the pressure. Inside containment, conditions are "like" the water-boiler experiment; however, the observer outside feels no explosion. (Some containment systems also include a building from which most of the air has been pumped. Valves, also opened by steam pressure, connect this vacuum building to the main part of the containment and further reduce its internal pressure.)

Returning to our experiment, we now have a problem in trying to cause an explosion.

The chance of neither shutoff system working is less than one in a million each time we break a pipe. (The operating staff carries out regular tests to ensure that this statement remains true). If even one shutoff system works we cannot produce an explosion of any kind. We will have to try the experiment about a million times before we have a chance to find out what happens next.

Being persistent, we carry on with the experiment. Let us say (remembering that this is a thought experiment) that on the 337,264th try, we break a large pipe and neither shutoff system works. The reactor power goes up to the point where some of the fuel in the channels melts; this fuel goes through the pressure tubes and mixes with the moderator water. Steam layers are formed around the molten fuel particles in much the same way as in the open-dish experiment; the steam reaches high pressure and expands rapidly. When it expands it makes a steam bubble in the reactor that immediately stops the chain reaction.

This will be an explosion much the same as in the open-dish experiment, 2(b). The size of the explosion depends on the amount of fuel that mixes with moderator water and the time at which this happens.

If we repeat the explosion experiment many times (remembering that, on the average, we will have to attempt it about one million times for each successful explosion), we find that the energy released in all the successful experiments has a minimum, a maximum, and some distribution between these two limits. The minimum energy release is near zero. Since we are interested in explosions, let us look at the largest release.

It is a vapour (steam) explosion, i.e., a rapid boiling process in which steam is formed sufficiently fast to produce a shock wave. When high temperature fuel material enters the water, it is initially separated from the water by a thin vapour film. In this state, the hot material breaks into a large number of small particles. If and when the explosion is initiated, heat can be rapidly transferred because of the large surface area. However, steam explosions are notoriously inefficient compared to chemical explosives such as TNT. For example, a typical molten aluminum-water explosion might produce a shock wave of 100-200 pounds per square inch (psi) as opposed to 100,000-200,000 psi for a solid chemical explosive. As discussed earlier, this is demonstrated by the fact that casualties in foundry accidents are generally the result of severe burns from the molten metal that is sprayed by the explosion and not by concussions from the shock wave, as is the case with chemical explosives. Such foundry experiences have shown that the "blast" damage is generally confined to sheet metal walls and roofs, which is also indicative of the comparative weakness of shock waves produced by a steam explosion.

This inefficiency is generally the result of two limitations: (1) a vapour explosion is a random event and (2) it is a boiling process. In the first case, the molten material is poured into the water and the materials intermix in a film boiling state, but the intermixing of the two materials is not optimum as is the case for solid chemical explosives where the constituents can be finely premixed as cold powders. Consequently, the explosion itself generally tends to blow the two liquids apart and stop the heat transfer.

With regard to the second limitation, a steam explosion is a violent boiling event. As the pressure is increased, the boiling processes become more quiescent. Therefore, the initial heat transfer and pressure increases (shock wave) tend to inhibit further heat transfer and the process is somewhat self-limiting. This behaviour with pressure has been tested and verified by many different experiments.

Once the reactor tank fills with steam bubbles surrounding hot fuel particles, the chain reaction shuts off and rapid heat transfer stops. All of these effects mean that the highest kinetic energy which can be produced is equivalent to explosion of about one ton of TNT (less than one truckload), with the most likely event being typical of a couple of pounds of TNT. Compared with the dynamite explosion in experiment 3(b) this is a "slow" explosion, mainly because of the much lower temperatures in this case. Low temperature means low shock pressure; most of the energy is transferred quite slowly to the water surrounding the reactor. Compared with the nuclear weapon explosion in experiment 4, this largest energy release is extremely small. Using a different model for comparing the two, the reactor explosion is weak because the vapour pressure becomes high while the energy density is still low. The vapour pressure forces the reactor apart and stops further increase in the energy density.

Returning to our explosion experiment, water surrounding the steam bubbles is driven outward, perhaps bulging the reactor tank, and even allowing some water to escape past seals, bearings, etc. The water sprays outward like a jet and hits the containment building walls. These are massive reinforced concrete, so their weight and resiliency stops the water and any other missiles. The pressure rise that follows may result in some radioactive material leakage from the containment. The distant observer would see nothing. No bang. No wind. No explosion.

Compared with the effects of the nuclear weapon experiment, this worst reactor explosion is rather mild. Considering that the occurence frequency is less than once in a million years when the large pipe is broken deliberately, what is the chance when the piping is designed not to break? The answer is less than one in a billion. This is a frequency in which we can expect one such event in a time about as long as the time since our moon was formed. The chance is much less than the chance of a person being struck by lightning. It is about the same as the chance of a person being killed by a meteorite. It is unlikely.

3.7 A Pressure Vessel Experiment

Some pressurized water reactors are different from CANDU in that all the fuel is located in a single large steel vessel – called the Pressure Vessel. The difference is important.

In this case we wish to repeat the experiments conducted in Part 6, paragraph 5, where fuel melting in some channels leads directly to fuel channel failure and mixing of fuel with water. This mixing might lead to a vapour explosion – but due to the limited amount of molten fuel (at that particular instant of time) this is a "mini-explosion". Expansion away from the explosion point relieves pressure, into the reactor containment building. More "mini-explosions" occur as other channels fail. But, the important fact is that these explosions (pressure relief events) are spaced out over time. The time spacing might be only a few milliseconds, but it is sufficient to limit the size of the shock wave to a low level. The result is "like" a chain of firecracker explosions. The figure depicts a simple version of this experiment, the lighting of a package of old-fashioned firecrackers. The total energy released may be quite large (there are many small explosions) but the time separation between them means that the overall effect of the explosions is quite small.

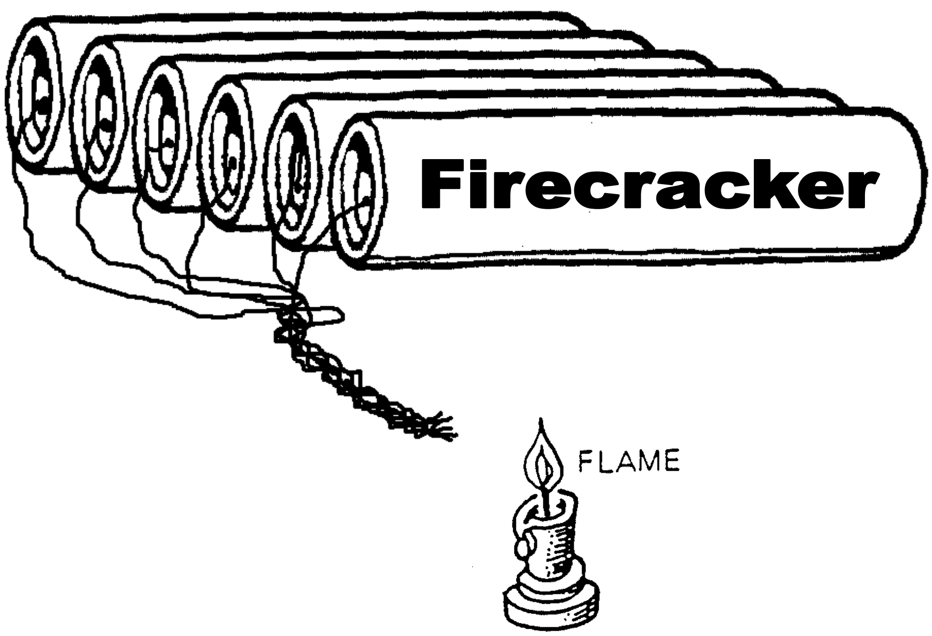

Figure 7 A pressure vessel experiment

Now, imagine the same experiment done inside a pressure vessel, experiment 7(b). This is equivalent to placing the firecracker package inside a strong, sealed vessel before lighting the fuse. Though the same amount of energy may be released in both cases, in this experiment the pressure inside the vessel increases steadily over time until some or all of the firecrackers have exploded. It is easy to imagine a combination of conditions in which the total energy released is sufficient to burst the sealed vessel. Recalling that the pressure vessel initially was filled with hot, high-pressure water, made hotter and brought to a much higher pressure by the energy added by fuel and coolant mixing, the resulting vessel burst produces a large explosion. In effect, the time-distributed fuel-coolant mixing reactions are “synchronized” by the pressure vessel. When the vessel fails all of the firecrackers’ energy, plus the initial stored energy of the pressurized water, is released at one instant of time.

Because of this major-accident possibility, reactors based on this principle have incorporated safety-related design rules such as the requirement that any increase in fuel temperature must result in a decrease in heat production (i.e. a negative prompt power coefficient). This requirement is necessary (but not in itself sufficient) to assure protection of the containment building from failure. Other safety systems are provided that will protect against human injury. The strict design limit on power coefficient is appropriate for a reactor with a pressure vessel, but is not necessary for a CANDU reactor that has no such large vessel.

4 CONCLUSION

A series of thought-experiments has been devised to explain the physics behind the categorical statement "a reactor cannot explode like a nuclear bomb". The explanation, though lengthy, cannot satisfy scientific requirements of precision and completeness. It would require a much more detailed description including actual experimental evidence to support the case from basic knowledge. Such a scientific paper would use many references to previous work for background facts.

What would be the impact of such a treatise? The majority of people would neither read it nor care about its accuracy. On the other hand, the “one-minute TV spot” which associates nuclear reactors with nuclear weapon explosions frightens many people. This short paper gives my best understanding of the actual differences between weapon effects and the worst possible reactor accident, hopefully in a way that can be read and understood by most people. Public discussion of energy options is vital to Canada at this time. It is important that this discussion be based on understanding rather than fear.

Can a reactor explode like a nuclear bomb? No, it cannot.