I. Introduction

Nuclear power plants produce extremely large amounts of radioactive substances as a by-product of operation — substances which emit harmful nuclear radiation and which must be absolutely confined to containers and prevented from escaping into the biosphere (the human environment), in order to avoid exposing humans and other life to high levels of radiation and the high risk of cancer and other diseases that would result. These substances are considered as nuclear waste that must be safely disposed of, except possibly the by-product plutonium, which is a nuclear fuel material that can be further used, but which is also a highly toxic radioactive substance. Even if plutonium were used to fuel nuclear power plants, however, a substantial residue of it would still remain in the waste material, thereby adding to the waste's toxicity. It was originally intended to dispose of high level radioactive waste by placing it deep underground, for isolation from the biosphere in special facilities called "geologic repositories". However, there presently exist no such facilities for permanently and safely disposing of nuclear waste; nor is there any assurance that such facilities will exist in the next twenty years, or ever will exist, due to technical problems of assuring isolation of the waste for the hundreds and tens of thousands of years that will be required for the material to decay to safe levels of radiation. As a consequence, high-level radioactive waste and plutonium is dangerously accumulating in storage pits at nuclear power plants and other places in the form of spent fuel rods (to be described shortly). These "spent fuel storage pits", though each is enclosed in a building, are creating an

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extremely serious hazard to the public health and safety, because they can suffer accidents in which most of the radioactive substances, chiefly, Strontium-90, Cesium-137, and Plutonium, could conceivably be severely heated, vaporized, and released (vented) into the atmosphere as smoke, through explosion or other means, to cause geographically widespread radioactive fallout contamination, death, cancer disease, and genetic mutations in future generations. Specifically, an accident involving one spent fuel storage pit could potentially result in ruining agriculture over a land area of the size of one half of the land east of the Mississippi River (500,000 square miles) for over a hundred years, due to the release and fallout of Strontium-90 radioactivity—— a calcium-like substance that would enter the food chain through plant uptake and settle in human bone tissue to cause bone cancer. The fallout of Cesium-137 would also severely contaminate agricultural land; and in addition it would create severe X-Ray-like radiation levels above contaminated ground, covering about 250,000 square miles for over a hundred years. Finally, the buildup of plutonium, which besides being radioactive is also an atomic bomb material, creates the possibility of nuclear explosions occurring in a storage pit during an accident, which would disperse plutonium into the environment. Plutonium dust is an extremely toxic radioactive substance which causes lung and bone cancer and which lasts for thousands of years before decaying to harmless levels. A release of a fraction of the plutonium from a spent fuel storage pit would have the potential for causing permanent abandonment of a land area ~~the~~ size of 150,000 square miles, which equals Illinois, Indiana, Ohio, and half of Pennsylvania, combined. Clearly, it is extremely important that the accident hazards of spent fuel storage pits be thoroughly evaluated. There will be hundreds of such storage pits scattered throughout the country. Already, there are about seventy-five. It should be noted that a "nuclear disaster" is reported to have occurred in the Soviet Union in which about one hundred million of curies of Sr-90 and Cs-137 had been released and had fallen out over a land area covering a lake basin. This figure was estimated on the basis of contamination data published in scientific journals of the Soviet Union as analyzed by a Russian scientist. The figure is comparable to the Sr-90 and Cs-137 content of a spent fuel storage pool, and makes it all the more important to evaluate the accident hazards.

The source of the radioactive waste hazard is the nuclear reactor, which is the heart of a nuclear power plant. The reactor is a steel vessel containing a mass of nuclear fuel, called the reactor core, which undergoes an atomic reaction to produce heat (nuclear energy) for generating steam and eventually electricity. This atomic reaction also produces the radioactivity as a by-product, which builds up within the fuel material (uranium dioxide). The fuel is in the form of rods, which are sealed zirconium-alloy metal tubes containing solid uranium dioxide pellets and which are about a half inch in diameter and twelve feet long. The zirconium tube is called the fuel rod cladding, which acts to protect the uranium oxide from erosion by the reactor coolant flow and also to prevent the radioactivity from seeping out of the fuel rod. For handling convenience the fuel rods are bound together in separate bundles, called fuel assemblies, each containing about 250 rods. Typically, a reactor core consists of a closely packed array of about 200 fuel rod assemblies totalling 50,000 fuel rods.* The fuel rods are not destroyed by the atomic reaction, but instead maintain their mechanical form throughout their service in the reactor. (The zirconium cladding is designed to remain intact.) When the fuel rods become exhausted — depleted beyond efficient use — they are removed from the reactor and stored to await disposal. Thereafter, the fuel rods are called <u>spent fuel rods</u>, which are extremely radioactive, due to the maximum buildup of the radioactive by-products within the uranium dioxide. Typically, about 65 spent fuel assemblies (over 16,000 spent fuel rods) are removed annually from a reactor for refueling.

The spent fuel rods are stored under water in steel-lined, water-filled, concrete basins, called spent fuel storage pits or pools, located next to the reactor. (Hereafter, we shall refer to them as storage pools.) Underwater storage is ncessary for cooling purposes, because the radioactivity within the spent fuel rods generates heat, which must be dissipated in order to prevent the rods from overheating and releasing its radioactive materials by vaporization. (The nuclear radiation emitted by the radio-

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* These figures apply to "pressurized water reactors." For "boiling water reactors" — the other type of nuclear power reactor in use — the fuel rod/assembly data are somewhat different, but the principles are the same.

activity is energy, which ends up as heat generated within the spent fuel material, since the spent fuel absorbs most of its own radiation when it is bundled or packed together. The water in a spent fuel storage pool also acts to absorb the nuclear radiation which escapes the spent fuel and, thus, to shield the plant workers from the intense radiation.) The water in the pool effectively cools the spent fuel rods by efficiently absorbing the heat; but the water, too, must be cooled by a circulation cooling system, which discharges the heat to the outside environment, or else the water would heat up and boil away. However, the radioactivity decays with the passage of time — that is, the levels of radiation and heat generation decreases with time — such that after a period of six months in the storage pool the spent fuel can be removed in lead-shielded, water-cooled shipping casks and transported to a waste disposal facility without excessive radiation levels and heat generation rates that would otherwise make portable shielding and cooling systems impractical. Furthermore, shipping casks containing new spent fuel (no decay) would certainly be unsafe for transport, since an accident enroute which causes a loss-of-cooling would more likely lead to excessive spent fuel heatup and, presumably, a heavy radioactivity release and, hence, a major public disaster.

Hence, nuclear power plants are equipped with spent fuel storage pools, to provide interim storage of spent fuel assemblies while they "cool down" to heat generation and radiation levels that are low enough to permit relatively safe shipment away from the reactor site for disposal. (The heat generated by the radioactivity in spent fuel will hereafter be called decay heat, which is its common name, to associate it with the decay of the radioactivity.) The spent fuel storage pools, therefore, were designed on the assumption that spent fuel assemblies would be removed from the pool after the six month cooling-off period and, consequently, would not accumulate in the pool. With an annual refueling discharge of about 65 spent fuel assemblies or /3 of a reacto co, then, the spent fuel storage pools at nuclear power plants were expected to contain at most one third of a core load of spent fuel (two thirds for a pool which services two reactors). In addition, the pools were also designed to store a whole core, if it should be necessary to remove it from the reactor in an emergency, making a total storage rack capacity of 1 1/3 core loadings of fuel assemblies (1 2/3 cores for two-reactor pools).

However, because of the lack of waste disposal facilities, the industry with government approval is replacing the storage racks in the pools with new racks designed to permit close packing of the spent fuel assemblies and, therefore, storage of much more spent fuel in each storage pool. Also, it is planned to store the spent fuel on a long term basis (decades). It may even turn out that the densely packed storage pools will be the permanent repositories for the radioactive waste. Specifically, plans call for packing sixteen to eighteen times more spent fuel into the storage pools than was originally intended to be stored — up to 2112 spent fuel assemblies in the Zion nuclear station pool, for example, compared to 130 assemblies as originally intended. This will amount to over half a million spent fuel rods in one pool. In terms of radioactivity the Zion pool will contain at its planned new storage racks capacity 75 million curies of Strontium-90 radioactivity. (A curie is a unit of radioactivity.) For reference, the Federal Radiation Council has recommended that 0.1 micro-curie of Strontium-90 be used as a health limit for Strontium-90 ingestion, or one tenth of one millionth of a curie. For a more concrete comparison, the Atomic Energy Commission report *Theoretical Possibilities and Consequences of Major Accidents in Large[*] Nuclear Power Plants* (WASH-740; March, 1957) calculates, using a considerably greater health limit for Strontium-90, that a vaporous release of 150,000 curies of Strontium-90 from a reactor accident could potentially result in agricultural restrictions on 150,000 square miles of land, which equals Illinois, Indiana, Ohio, and half of Pennsylvania. *The Zion spent fuel storage pool will contain 500 times more Strontium-90 than this WASH-740 release value.* Moreover, there presently exists two spent fuel storage pools which are not reactor site pools for storing new spent fuel but rather they are separate, independent storage facilities designed to receive aged spent fuel (six months radioactive decay or longer). The Federal Government anticipates six such independent storage facilities by the year 2000 to store the overflow of spent fuel from several hundred reactor-sited spent storage pools. It is planned to store even greater amounts of spent fuel in these independent storage pools. For example, the General Electric Co.'s independent storage pool at Morris, Illinois, is to store 1850 tonnes of spent fuel, containing 120 million curies of

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[*] Today's plants are about seven times power rating assumed in the WASH-740 analysis, and will contain 3.7 million curies of Strontium-90, or 25 times the WASH-740 release assumption.

Strontium-90, which is 800 times the WASH-740 release value. The magnitudes of the buildup of Cesium-137 and Plutonium will be extremely large as well, as has been quantified at the outset. These magnitudes, including the figure of 75 million curies of Strontium-90 to be stored in the Zion reactors' pool, are derived in Appendix 1. It should be noted that both Strontium-90 and Cesium-137 decay slowly and plutonium extremely slowly, which explains their long-term contamination effects.*

We now turn to the matter of the accident hazards of storage pools——accidents by which the radioactivity could escape into the Environment.

As before mentioned, the spent fuel rods must be stored in water for cooling purposes — to remove the decay heat and thereby prevent the rods from overheating. Any accident resulting in a loss of water in a spent fuel storage pool would, therefore, lead to spent fuel heatup with potentially disastrous consequences, as will be shown in this analysis. The <u>loss-of-water accident</u> is the basic accident hazard of spent fuel storage pools and is, therefore, the focus of our analysis.

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*The rate of radioactive decay is measured by the amount of time it takes for the radioactivity — level of radiation — to decrease to one half of an earlier level. This decay time is called the "half life."

To illustrate, if the level were 32 curies to start with, then in a succession of half-life time periods, the level would decrease as follows: 32, 16, 8, 4, 2, 1, 0.5, 0.25, etc. Strontium-90 and Cesium-137 have half-lives of 29 and 30 years, respectively, and plutonium has half-lives ranging from a few thousand to 24,000 years, depending on the specific "isotope" of plutonium.

In a loss-of-water accident there would exist only two means of decay heat dissipation: cooling by natural convection air flow through the spent fuel rod assemblies and thermal radiation (radient heat) emanating from the extremities of the spent fuel assemblies. However, as will be shown in this analysis, these heat dissipation mechanisms are not sufficient to prevent severe spent fuel heat up. Furthermore, the heat-up potential is aggravated by closely packing spent fuel assemblies in the storage pools, which is now happening due to the spent fuel buildup problem. Close packing impedes natural convection air flows and thermal radiation heat dissipation. It will be shown in this analysis report that the spent fuel heat-up potential in a loss-of-water accident is such that the zirconium fuel rod cladding would catch on fire, starting first in new spent fuel assemblies and spreading to engulf the entire load of spent fuel in the pool, and thereby greatly adding to the heat generation in the spent fuel. (The zirconium could ignite at 900°C.) Molten zirconium metal could then form and run down and freeze in the air inlet passages of the spent fuel assemblies to plug up these passages and thereby starve the fuel assemblies of any air cooling, which would further worsen the spent fuel heatup. Under such conditions, it can be calculated that the vaporization and release of nearly all of the Strontium-90 and Cesium-137 radioactivity from the spent fuel rods is conceivable. The spent fuel building would heat up like an oven, and the internal air pressure due to air heating could burst open the building or its vent valves to allow the escape of the radioactivity. Or, zirconium and hydrogen explosions are possible, due to the presence of residual water which could chemically react violently with zirconium to produce explosions and also hydrogen, which, too, could detonate. Such explosions could conceivably burst the storage pool building as well, besides compacting the fuel rods and thus causing them to heat up even further, due to added restrictions to the flow of air for cooling.

It is conceivable, too, that spent fuel — particularly, the uranium dioxide — could melt (at 5000°F) and thus form a liquid pool of molten fuel within a frozen shell or crust of uranium dioxide and steel and zirconium. Under this condition, it is conceivable that the plutonium in the molten uranium dioxide could separate and stratify in such a pool — or at least a mass of fuel material could form which is rich in plutonium — and create as a result a nuclear fuel mass capable of generating the same kind of atomic reaction which takes place in an atomic bomb — a runaway reaction which could produce a strong nuclear explosion that would increase the dispersal of the radioactivity, into the environment, especially the plutonium. Plutonium might not escape heated solid fuel rods as readily as Strontium-90 and Cesium-137; and so pulverization or vaporization of the fuel may be required, as in a nuclear explosion, before a large amount of it (plutonium) could be released into the atmosphere. (This nuclear explosion possibility is similar to the mechanism which has been speculated to have caused the "nuclear disaster" in the Soviet Union, namely, a concentration of plutonium in a nuclear waste burial trench.) Such are the courses a loss-of-water accident could conceivably take. The possibilities must be thoroughly investigated.

Finally, it appears that such loss-of-water accidents are possible in independent storage pools, which would store only aged spent fuel. Although the decay heat in aged spent fuel is much less that new spent fuel, there still exists the potential for severe heatup, zirconium fire, and so forth, as will be shown.

The question arises: what incidents could cause a loss of water in the storage pool, and how likely are such incidents? There are several possibilities which need to be investigated; namely, cask drop, earthquake, sabotage, cooling system breakdown, a "criticality" accident, and a reactor accident. It is possible that the heavy spent fuel shipping cask could fall from its crane into the storage pool and break the floor of the storage pool, causing rapid drainage of the pool. Earthquakes and saboteur's bomb are additional possibilities for breaking open the storage pool walls and causing rapid drainage. Another possibility is a breakdown in the pool water cooling system, which would result in the pool water heating up and boiling dry due to the decay heat of the spent fuel; but this would be a relatively slow process, requiring three weeks or so. Still another possibility is an occurrence of a nuclear "criticality," which is the name of the main atomic reaction which nuclear fuel undergoes in a nuclear reactor when producing high power. Criticality can occur in a spent fuel storage pool if fuel is removed from the reactor without full usage for some emergency reason and is stored in the pool without adequate provisions to prevent criticality. Partially used fuel is more potent than spent fuel. However, the question arises whether it is possible for a mass of spent fuel rods to undergo criticality, as they are much depleted of fuel (though they still contain about one half of the original amount of nuclear fuel). A criticality is to be prevented in a spent fuel storage pool by the placement of special "neutron absorbing" material sheets placed between the spent fuel assemblies. (See *The Accident Hazards of Nuclear Power Plants* for a description of the criticality phenomenon and nuclear runaway accident possibilities involving criticality.) However, it is possible that a few of the sheets could be missing and a criticality accident occur as a result. Conceivably, such a criticality accident could generate enough heat to overwhelm the cooling system and boil the pool dry. The criticality accident has been stated to have such a possible consequence, but no analysis of it evidently exists.

The U. S. Nuclear Regulatory Commission (NRC) and the nuclear industry undoubtedly believe that the likelihood or probability of such incidents occurring can be made acceptably low. For instance, special pads can be installed on the pool floor to cushion the fall of a cask; but whether such pads are in fact going to be installed remains to be determined. The pool ~~pad~~ can be designed to withstand a given size earthquake (it seems that a nuclear plant is never designed for the worst possible earthquake, however, but only the worst size that is considered likely). Sabotage can be made difficult by plant security measures. And, three weeks may seem like a long enough time to repair a failed cooling system to avert a boil-off of the pool water; and, besides, water can always be added in a makeshift way to replenish water which boils off and thereby gain more time for repairs. But, nevertheless, such accidents are possible; for a pool and its equipment could possible be wrongly constructed or installed, or the safety measures could contain design flaws which lie undiscovered due to no inadequate experimental verification or confirmation of the design.

It should be noted that once the zirconium cladding of the fuel rods reaches high temperatures, any attempt to cool the spent fuel by injecting water back into the pool could, instead of quenching the spent fuel, merely hasten its heatup, because water reacts chemically with heated zirconium to produce heat and possible explosions. Moreover, conceivably, the intense heat in the spent fuel could cause some or all of the criticality-prevention sheets between the spent fuel assemblies to meltdown, leaving the fuel to generate a powerful criticality—that is, a high power nuclear reaction—which could prevent reflooding, and even result in explosions.

It is not possible to demonstrate the reliability of accident preventive measures or to foresee all possibilities for rapid drainage (Could the foundation of the pool be eroded?); but rather one can only make a judgment on whether the pool design, the pool foundation, and the safety measures are adequate, which will be a subjective judgment. However, in order to adequately assess the overall risk to the public, one must analyze the loss-of-water accident to determine the potential consequences, for surely the magnitude of the potential consequences has a crucial bearing on whether the risk is acceptable. But regardless, there is one possible cause of a loss-of-water in the storage pool which is highly likely, that being a <u>severe</u>

reactor accident. A reactor explosion accident would release such heavy amounts of radioactivity that the radiation levels in the vicinity of the reactor and its storage pool would be so great that the reactor plant personnel would surely flee, leaving the storage pool cooling system unattended. Excessive radiation levels could, potentially, persist for months; so that once the cooling system broke down, the pool could boil dry before emergency crews could reach the pool and re-establish cooling (assuming such crews could be raised). For one class of nuclear power reactors — specifically "boiling water" reactors — the storage pool is located above the reactor, so that a reactor explosion could presumably damage the pool and cause it to drain rapidly. The other class of reactors — pressurized water reactors, such as Zion — have their storage pools located in separate "auxiliary" buildings connected to the reactor building.

There are a great many — virtually innumerable — reactor accident possibilities that could end in explosion without warning and cause severe releases of radioactivity that would force evacuation of the reactor site, including the spent fuel storage pool or pools. For analysis of the reactor accident potentials, see this author's treatise *The Accident Hazards of Nuclear Power Plants*, University of Massachusetts Press, 1976, and his related works which are enumerated in reference no. 1 at the end of this present report.

Nuclear power reactors are high pressure/ high temperature systems with potentials for severe "runaways" in the power level of the reactor core or system ruptures such that they are always on the verge of rapid, uncontrollable core heatups and explosion. It takes a very great amount of highly detailed, careful attention and inspection throughout the entire course of making a reactor and other reactor plant systems, operating the plant, and maintaining it, in order to prevent explosion accidents, leaving very little or no room for human carelessness. In the opinion of this author, the vast range of reactor accident possibilities and their possible causes, and the instances of equipment failures, near-accident incidents, and reactor accidents that have already occurred indicate that severe reactor explosion accidents are _likely_ to occur, or we must assume so.* Reactor accidents, therefore, are the likely events to cause the spent fuel storage pool to lose its water and then erupt.

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* It is noted that this report was written a week before the Three Mile Island reactor accident in Pennsylvania.

The potential disastrous consequences of a *reactor accident* alone--excluding a spent fuel pool eruption--are extremely severe. For example: (1) agricultural restrictions for several years over an area equal to half of the land east of the Mississippi River could be required, and agriculture could be ruined over an area the size of Ohio for over a hundred years, due to strontium-90 release and fallout alone; (2) severe living restrictions over 120,000 square miles and evacuation of several thousands of square miles for a year and possibly longer (assuming no plutonium release); and (3) death and disease due to unavoidable radiation exposures affecting a million people: for example, a possible million cancer deaths. (See this author's treatise *Accident Hazards* and his essay *To the Congress of the United States, a Petition Calling for a Full Review and Investigation of the Hazards of Nuclear Power Plants and Radioactive Waste Disposal*, May 20, 1978) From these figures, and especially the land area figure for evacuation, which is a straight forward extrapolation of WASH-740 figures to apply to today's larger reactors, we can appreciate why the reactor/storage pool personnel would abandon the reactor site in the event of a severe reactor accident. Furthermore, there is an advanced reactor under vigorous development known as the *fast neutron breeder reactor*, which has accident potentials of *nuclear explosions*, which could release, say two tons of plutonium, as well as the other radioactivities, with the potential consequence of permanent abandonment of 150,000 square miles due to the lung cancer hazard of plutonium dust fallout. (See *Accident Hazards* and *Petition to Congress*). Such reactors could be considered to be more prone to accident and would be more devastating to the reactor site. We may expect that fast neutron breeder reactors would be built on the site of water-cooled reactors and their spent fuel storage pools; so that a breeder reactor accident too could effect a spent fuel pool loss of water accident. Therefore, reactor accident hazards must be thoroughly evaluated in order to assess the risks of spent fuel storage pool accidents. Unfortunately, the Federal Government has not evaluated the severe reactor accident possibilities, and has refused to investigate them for either their likelihood or their potential consequences in its licensing hearings; so that the public has not been informed by their Government of the full seriousness of the reactor accident hazards, except by this author's analysis and related works and those of other critics (see *Petition to Congress*).

The purpose of this report, however, is not to analyze the reactor accident hazards, but rather to analyze the spent fuel pool loss-of-water possibility for its potential consequences. (However, the potential radiation levels around a reactor site due to a postulated reactor accident will be evaluated to justify the assumption that plant personnel would have to evacuate the site and thus leave the spent fuel pool unattended.) The spent fuel storage pool loss-of-water accident must be evaluated for its potential harmful consequences because a storage pool will contain up to 20 times more Sr-90 and Cs-137 than the reactor and 16 times more plutonium--and thus a storage pool loss-of-water event, should it be caused by a reactor accident, would have the potential for greatly compounding the harmful consequences of a reactor accident.*

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* Thus, this present report is a supplement to my treatise *The Accident Hazards of Nuclear Power Plants*. It is noted that the treatise does not consider the storage pool accident due to an oversight. At the time the treatise was prepared, spent fuel accumulation in the storage pools was not anticipated. Furthermore, it was assumed that the storage of only one third of a core of spent fuel in a non-compact arrangement would not present a serious heat up hazard in the event of a loss-of-water in the storage pool; but this assumption was unfounded and incorrect, as we shall see later.

Also, since a loss-of-water accident is a possibility having a number of possible causes, even without the prior occurrence of a reactor accident, it needs to be evaluated for its consequences, in order to wisely assess the overall risks.

Unfortunately, the Government and the nuclear industry have issued no adequate analysis of the loss-of-water accident in spent fuel storage pools. Only three reports have been issued concerning the subject:

(1) The U. S. Nuclear Regulatory Commission's *Draft Generic Environmental Impact Statement on Handling and Storage of Spent Light Water Power Reactor Fuel* (NUREG-0404, March 1978);

(2) The NRC's *Reactor Safety Study*, known as the Rasmussen Report, which contains a crude analysis of the loss-of-water accident in spent fuel storage pools, and which is the only *published* analysis.

(3) An analytical report by Sandia Laboratories of Albuquerque, New Mexico, titled "Spent Fuel Heat-up Following Loss of Water During Storage", by A. S. Benjamin, et al. (*Draft*, Sept 1978, SAND-77-1371).

As we shall see, only the Sandia report provides a useful analysis of the loss-of-water accident; although it is far from adequate. The Sandia report only *partially* analyzes the loss-of-water accident to determine whether spent fuel will seriously overheat, but the report does not analyze for the radioactivity release consequences. Furthermore, the analysis has several serious shortcomings which make the numerical results presented in the report unreliable, according to this author's review. This present report presents a critique of the Sandia Report, which is a basis for the present analysis. This critique is outlined below; but first let us dispose of the NRC's environmental impact report and the Rasmussen Report.

The NRC's environmental impact report totally ignores the loss-of-water accident possibility in reactor-sited spent fuel storage pools (despite the fact the National Environmental Policy Act requires a "detailed statement" of the "risks to health and safety"). The report only mentions that calculations were made of a loss-of-water accident occurring in special storage pool facilities located away from reactors in which only aged spent fuel was assumed to be stored. (Recall that the decay heat rate is less in aged spent fuel.) The NRC report asserts that the calculations show that loss-of-water would not result in a serious heat up of one year old spent fuel; but the report cites no details of the calculation nor any reference where the calculations can be found and examined for their validity. Moreover, a report of the Sandia Laboratory in Albuquerque contradicts the NRC's statement. In place of rigorous scientific analysis, the NRC report offers only vague, qualitative, and unsubstantiated assertions, such as: That the waste in spent fuel "represents little potential hazard to the health and safety of the public" (p. S-3); That the "underwater storage of aged spent fuels is an operation involving an extremely low risk of a catastrophic release of radioactivity" p. 4-13); And that "there is no mechanism available for the release of radioactive materials [from "aged spent fuels"] in significant quantities from the facility," either at a reactor site pool or away-from-reactor pool (p. 4-13). Surely, such assertions are not acceptable substitutes for rigorous, scientific analysis. It is important to note that the NRC's report introduces its section on accidents with the statement: "A range of potential accidents and natural phenomena events have been analyzed." Clearly, this statement does not assure that all possible spent fuel storage accident situations have been analyzed. (This problem of the Federal Government failing to issue full hazards analysis applies to nuclear reactors as well. See this author's Accident Hazards and Petition.)

The NRC's report of its Reactor Safety Study--known as the Rasmussen Report--addresses the possibility of a loss of water accident in spent fuel storage pools at reactor sites, and estimates that the potential resultant radioactivity release would be small relative to a reactor accident. However, the report was not based on any scientific analysis but rather on a number of unfounded assumptions (guesses), the effect of which was to force the estimated radioactivity release potential to be small. Firstly, the report considers only light storage of spent fuel--130 spent fuel rod assemblies: 65 new spent fuel assemblies and 65 aged spent fuel assemblies--and not a heavy buildup of spent fuel in the storage pool as is now planned, such as the figure of 2112 spent fuel assemblies planned for the Zion reactors pool. Secondly, the report assumes that a serious release of radioactivity from the spent fuel rods would occur only if the uranium dioxide of the spent fuel would heat up to its melting temperature (2800°C) and melt, and that only the new spent fuel--65 assemblies--would melt and, hence, release radioactivity. Thirdly, the report assumes that only 10% of the strontium-90 radioactivity in 65 new spent fuel assemblies would escape the spent fuel upon a meltdown by vaporization.

Fourthly, the report assumes that 99% of the strontium-90 that does escape the spent fuel would subsequently be absorbed in the filters of the air ventilation system of the spent fuel storage building; and the rest (1%) finally escapes into the atmosphere. The result of these assumptions is that the Rasmussen Report estimates that about 2000 curies of Sr-90 would be released to the atmosphere in a loss-of-water accident (This value is not stated in the Rasmussen Report but must be derived from the data given in that report. See appendix 1). This 2000 curies release value should be compared to the total of about 4.6 million curies of strontium-90 that would be present in the 130 spent fuel assemblies assumed in storage (a release fraction of about .05%), and compared to the potential release of 75 million curies of Sr-90 from a spent fuel storage pool (Zion) that is now possible because of the planned buildup of spent fuel. Recall that the WASH-740 report assumed a release of 150,000 curies of strontium-90 from a reactor; so the Rasmussen Report's estimate of 2000 curies is a relatively small release.

Let us now review the assumptions of the Rasmussen Report. The assumptions that a serious radioactivity release will occur only upon fuel melting and that only the new spent fuel would reach melting temperature are not based on any analysis but instead are simply arbitrary assumptions. For one thing, the report neglects the possibility of a zironium fire, which has been predicted to start when the spent fuel rods reach 900°C temperature. If new spent fuel can heat up to the melting temperature (2800°C), as the Rasmussen Report assumes, the possibility certainly would exist for the zirononium fuel rod cladding to ignite (at 900°C) and the fire to spread throughout the whole storage of spent fuel rods--not just confined to the new spent fuel region of the storage. (The plans now for close-packing of spent fuel rod assemblies in the storage pool would promote the spreading of a zironium fire.) Furthermore, the heat generation potential of a zironium fire would be enough to cause spent fuel to melt without the decay heat. It will be shown in the present analysis that a near full release of Sr-90 from the entire load of spent fuel (new and aged) in a storage pool is conceivable and certainly has not been ruled out as a possibility. It will be shown also that the spent fuel need not reach melting temperature for a large fractional release of Sr-90 (and Cs-137) to occur, but that a 1900°C level may suffice. The assumption of 99% absorption of the radioactivity released from the spent fuel by the ventilation filters is also a mere assumption. It is conceivable that the ventilation system will break down in the event of a loss of water accident. The high radiation levels from the exposed unshielded spent fuel and the high air temperatures within the building (the spent fuel building would heat up like an oven, to be shown) would presumably prevent maintanence of the ventilation system. Also, if a reactor accident occurred, the severe site contamination would force evacuation of the spent fuel storage facility, as before noted, leaving the ventilation system unattended. Furthermore, there is the possibility of air pressure rises in the pool building due to heating and confinement of the air that could rupture the building (if the building were sealed shut), or zirconium and hydrogen explosions could rupture the building, either of which could cause the radioactive vapors and smoke to vent directly to the atmosphere, by-passing the filters. The Rasmussen Report admits the possibility of the failure of the ventilation system, but considers this an unlikely event. However, such an estimate of the likelihood is merely a guess, since the loss-of-water accident was not scientifically analyzed for the course it could take (Zirconium explosions, for example). For the Rasmussen Report states that its estimates of the radioactivity release resulting from a loss-of-water accident were not based on any scientific analysis but instead only on "rough estimates", (in other words, guesses): Said the report: "Detailed analyses of radioactive release, retention and removal under the specific conditions of the accidents considered below have not been performed." (App. I, p. 95). Clearly, therefore, the Rasmussen Report's evaluation of the spent fuel pool accident hazards is useless.

The Sandia Report

The Sandia Report mentioned previously is an attempt to evaluate the loss-of-water accident scientifically by means of mathematical analysis, to avoid mere speculation. Inasmuch as no other analysis exists, the Sandia Report appears to be the basis for the NRC's evaluation of the spent fuel storage pool hazards with respect to the loss-of-water accident. Although the report itself has yet to be published, a preview of it has been published in the American Nuclear Society's Transactions (Nov. 1978) which asserts that the spent fuel would not seriously overheat in "most pool drainage accidents", provided that certain design modifications are made, which the article insinuates are practical, and, therefore, that the spent fuel storage accident hazards are not too serious. However, this insinuation is not supported by the yet-to-published draft report, as will be shown herein. Moreover, the Sandia's analysis is grossly inadequate and may be greatly under-predicting the spent fuel heatup potential.

Calculating the spent fuel heatup (temperature excursion) in a loss-of-water accident is a formidable mathematical problem. A mathematical theory of spent fuel heatup must account for the natural flow of heated air through two thousand spent fuel assemblies, containing a total of a half a million fuel rods (the air passes between the fuel rods). The decay heat is highly non-uniform throughout the load of spent fuel in a pool. The fuel rod temperatures affect the air flow and, vice versa, the air flow affects the temperatures. Also, a theory must account for the phenomenon of thermal radiation, which is the form of heat emission from a body other than convection currents of heated fluids (such as air) or heat conduction through a medium in contact with a body. Thermal radiation passes through space (air or vacuum) in the same manner as light, and is the source of heat transmission which a person feels standing next to an open fire. Heated spent fuel rods will give off thermal radiation and adjacent fuel rods, and pool walls will absorb this energy. Therefore, besides the process of air flows, thermal radiation is a process by which heat will diffuse through a spent fuel load and eventually escape the pool, and therefore must be accounted for in any theory.

The Ambient temperature inside the spent fuel building will greatly affect the spent fuel temperature heatup; so the rate of ventilation--purging the heated air with cold air from outside the building--is a very important factor. Other factors which will greatly affect the spent fuel heatup are the details of the storage rack design, the decay heat generation in each spent fuel assembly, which depends on the length of time since a batch of spent fuel had been producing power in the reactor and its power history in the reactor (this decay time is sometimes called the decay period); and the total amount of spent fuel in the pool. Storage rack designs vary according to the distance or spacing between spent fuel assemblies. Large spacings for non-compact storage tends to promote air flow cooling, whereas close spacing ("high density" racks) tends to inhibit air flow by constricting air passages between fuel assemblies. (Present plans use high density racks, in order to maximize the amount of spent fuel that can be stored in a pool.) The Sandia analysis was performed using a theory that was constructed to account for these various factors and processes. The results are presented in its report, which analyzes a variety of storage rack designs, pool designs, decay periods, and building ventilation rates, and other conditions.

The Sandia analysis predicts that the spent fuel heatup in a loss-of-pool-water accident can be severe enough to cause the zirconium fuel rod cladding to catch on fire--a self-sustaining fire, especially for medium-density and high-density storage rack designs. That is, the Sandia's heatup theory predicts that spent fuel rods, particularly the newer spent fuel and not so much the aged fuel, would heat up to a temperature of 900°C, at which point the theory predicts that the zirconium will begin to burn (react with air) to generate more heat. The report states that the fire would cause the zirconium cladding to melt (the melting temperature is 1857°C). However, the Sandia's analysis was not extended beyond zirconium ignition and melting to determine the full heatup potential of the spent fuel (including the potential for the fire to spread to the aged fuel) and the potential for radioactivity release. In other words, the Sandia report does not analyze the loss-of-water accidents through its entire course to determine the potential harmful consequences.

Instead, the report uses the zirconium ignition temperature as a temperature limit/safety criterion and merely evaluates different storage conditions to determine what set of circumstances would prevent the spent fuel assemblies from heating up to this temperature--circumstances which might then be designed into the storage facility (design modifications) to minimize the chance of a fire occurring and an uncontrolled spent fuel accident. Based on its analysis, the Sandia report describes several possible design modifications which theoretically could prevent the zirconium ignition temperature from being reached in a loss-of-water accident, except for a relatively brief period of time after a batch of spent fuel has been removed from the reactor and stored in the pool, during which the decay heat rate in that batch would still be high. This period is called the "critical decay time". However, for the high density storage rack design, which is the design being planned by the utilities and which is being judged acceptable by the NRC, the critical decay time, assuming the design modifications were adopted, would still be great: 80 days, as predicted by the Sandia heatup theory. Since refuelings occur annually, this means that a uncontrollable, catastrophic spent fuel heatup accident would still be possible for 22% of the time (80/365 = .22). In view of the potential consequences, the risk would surely not be acceptable.

Moreover, none of the described design modifications are apparently being impl~~a~~emented, and none may be even practical. Without the modifications, the Sandia theory would predict zirconium ignition in a critical decay time of 700 days, which would span the entire reactor operating/refueling cycle (1 year) and beyond. The most crucial of the possible modifications seems totally impractical. It would consist in modifying the spent fuel storage building to provide for a large door and a chimney which would be opened upon a loss-of-water accident to allow the heated air to escape the building, and cold air to be drawn into the building to replenish the discharged air, to achieve perfect ventilation. This would expose highly radioactive spent fuel directly to the outside environment, and would provide air to fan a zirconium fire, if a fire should start, and also provide a direct escape path into the atmosphere for radioactivity which may be released from the fuel. Thus, such a open door/chimney feature could not be judged a safety feature. Moreover, there could be no assurance that the door and chimney would be opened in the event of a severe reactor accident, when the plant personnel would be fleeing. The Sandia report also fails to analyze the spent fuel heatup for the cases of most interest, namely high-density storage with existing building ventilation capacities. When building ventilation is perfect--no recycling of heated air through the spent fuel--it may be that aged spent fuel (the bulk of the spent fuel in a full storage pool) could not heat up to zirconium ignition temperature due to its own decay heat and that the only way for it to seriously heat up is for a zirconium fire to start and spread from newer spent fuel. But if heated air is re-cycled through the fuel, due to imperfect ventilation, then it may be that the whole load of spent fuel could overheat rapidly and much more intensely. The heatup potential of spent fuel is hardly explored at all in the Sandia report for the case of imperfect ventilation; and those cases that are analyzed (medium density racks that promote air cooling) indicate that the heatup in high density spent fuel would indeed be intense, even if only well aged (well decayed heat generation rates) spent fuel were stored.

Moreover, the Sandia analysis assumes a relatively small storage load of spent fuel: about 338 fuel rod assemblies as compared to 2112 in the Zion pool. It will be shown that heat transmission from fuel rod to fuel rod (mainly thermal radiation) has a major effect on the spent fuel heatup; so that the size mass of spent fuel in a pool will affect the heatup: a larger mass would mean a higher peak temperature. In short, the Sandia analysis needs to be extended to cover all storage conditions and circumstances of interest.

The next major shortcoming of the Sandia analysis concerns the mathematical theory that was used. The theory is not adequately described; nor is the theory and its various assumptions demonstrated to be valid. The theory contains a major assumption that may force the spent fuel heatup temperatures to be grossly under-predicted.

Specifically, the theory assumes that the fuel rods within a given spent fuel assembly undergo identical temperature rises; that is, at any given height ~~in a spent fuel assembly~~ the temperatures of all of the fuel rods in a fuel assembly are assumed to be the same, and the temperature is assumed to be uniform across each fuel rod, again at a given height up the rod. It will be shown that air flow alone through the spent fuel assemblies is far from being a sufficient decay heat removal--heat dissipation--mechanism for any spent fuel storage conditions, including those cases for which the Sandia theory predicts temperature rises that do not reach the zirconium ignition temperature. In order for the Sandia theory to predict limited, less-than-900°C heatup temperatures, therefore, it must have predicted a strong diffusion of heat from hotter spent fuel assemblies to cooler, adjacent assemblies by the thermal radiation heat transfer mechanism. However, the assumption of uniform temperature across a spent fuel assembly contradicts the physical process of lateral heat diffusion. In order to create a lateral flow of heat, there must be a finite temperature difference between adjacent fuel rods and across each fuel rod. Such temperature differences for driving the lateral heat flow are due to the resistance to heat flow that will exist. By assuming a constant temperature across a fuel assembly, and only a temperature difference between assemblies, the Sandia theory artificially minimizes the resistance for lateral heat dissipation and, thereby, over-predicts such heat dissipation. According to a bounding calculation which accounts for such temperature differences ~~with~~ within fuel assemblies, the constant temperature assumption in the Sandia theory could be causing such gross under-predictions of the spent fuel heatup temperatures as to make the numerical results in the Sandia report useless. This theoretical problem will be treated in this report, It will be shown that it may not be possible to investigate the size of the error by rigorous calculations, because the mathematical problem may be ~~become~~ intractable. The Sandia analysis does include some assumptions which may introduce some conservatism in the predictions--tendencies to over-predict the heatup temperatures--but these may not be substantial, and may also be more than off-set by the above-mentioned source of error.

In addition, the Sandia theory suffers from a lack of essential experimental verification. The Sandia Report does compare the theory with some experimental results, but the experiments bare little resemblance to the spent fuel heatup accident conditions. The experiments consisted of two parallel heated plates at a constant, uniform temperature of 57°C between which flowed air by natural convection; whereas the spent fuel accident will involve air temperatures which rise greatly as the air flows up through a fuel assembly--up to 900°C temperatures--and, consequently, large changes in the physical properties of the air (density, and viscosity) and in the air velocity, which affects friction. Moreover, spent fuel heatup accidents will involve intense thermal radiation heat transmission, whereas the experiment relied on by Sandia involved essentially no thermal radiation heat transfer. It is well established that theory--especially concerning the flow of fluids involving heat transfer--requires rigorous experimental verification using exact experimental mockups of the systems to which the theory will be applied. This lack of experimental verification is doubly important because the Sandia theory predicts little margin between the predicted maximum temperature and the 900°C temperature limit for those spent fuel storage conditions which the report concludes would not result in a severe heatup in the event of a loss-of-water accident.

Finally, the Sandia report analyzes the spent fuel heatup potentials of loss-of-water accidents in independent, "away-from-reactor, spent fuel storage pools, which would contain only aged spent fuel. The report concludes that the spent fuel heatup might be limited in these pools, provided that the spent fuel is aged for at least two to four years, depending on storage rack design. However, this conclusion is of little practical importance, since practically all of the storage pools are and will continue to be reactor-connected pools, which will contain new spent fuel as well as aged spent fuel, and, therefore, will have severe heatup potentials. Furthermore, the Sandia report does not explore the full accident possibilities of independent storage pools. Specifically, the report considers an accident in which there was no ventilation of the building at all. A zirconium fire was predicted to occur; but the building room would become depleted of oxygen (consumed by the fire) and the fire extinguished itself before the zirconium would melt. The report fails to treat a partially ventilated situation, which would support a fire. Moreover, the Sandia report does not consider the consequences of trying to re-flood the pool after the spent fuel reaches and remains at a high temperature. Opening the building to gain entry could trigger a fire flare-up by allowing oxygen to enter, or the injection of water could initiate a violent zirconium-water reaction and explosion, which could conceivably rupture the building and trigger a massive fire and radioactivity release. Moreover, there is the possibility that Sandia's analysis grossly under-predicts the spent fuel heatup temperatures, as before discussed.

The preceding critique of the Sandia report applies to the report's analysis of spent fuel storage for "pressurized water reactors" (PWRs). The spent fuel storage pools for this class of reactors are located in an auxiliary building attached to the reactor building. For the class of reactors known as "boiling water reactors" (BWRs), the spent fuel storage pool is located inside the reactor building, and almost directly above the reactor. The preceding critique applies to Sandia's analysis of BWR spent fuel heatup as well; however, the following additional comments are necessary:

The Sandia report indicates that BWR storage has a much less spent fuel heatup potential than PWR storage in a loss-of-water accident, and that with simple modifications (no chimney feature), the BWR spent fuel could be virtually prevented from seriously overheating. However, the Sandia report neglects to analyze the "high-density" storage rack design which is apparently being adopted in BWRs. High density racks would mean greater air flow restriction and, consequently, greater heatup potentials. Also, there is no evidence that the storage modifications suggested in the Sandia report are being implimented; namely, removal of the channel ducts that normally house a BWR fuel assembly, and side holes in the spent fuel holders (discussed later in section). Furthermore, the BWR spent storage situation presents peculiar loss-of-water accident possibilities that require separate analysis: Being inside the reactor building, a reactor explosion accident could rupture the storage pool and cause rapid pool drainage. The heated steam air mixture from the reactor explosion (reactor coolant flashed to steam) would tend to promote spent fuel heatup as the steam-air mixture circulates through the spent fuel. The steam would tend to react with the zirconium fuel rod cladding, if it is still present in the reactor building in quantity when the spent fuel heats up to reaction temperatures. Also, it is conceivable that a portion of a molten reactor core expelled from the reactor by a reactor explosion and other debris of the explosion could fall into the spent fuel storage pool. The fallen debris could restrict the free flow of air from the tops of some of the spent fuel assemblies and result in greater heatup temperatures after the pool drains than would otherwise occur. In addition there is a question as to the physical condition of the pool after a severe reactor explosion. Could the pool not only be ruptured but be so damaged as to cause the spent fuel to fall into a pile with a configuration that could not be adequately cooled by natural air convection? It is emphasized that in the BWR case a reactor explosion accident would (presumably) rupture the reactor building and allow a direct path of escape of radioactivity into the atmosphere as well as supply air to sustain a zirconium fire. Therefore, the storage pool accidents in nuclear power plants must be distinguished between PWR and BWR reactor plants and each analyzed separately.

In short, the Sandia report needs to be critically reviewed; for it does not establish the full, true potential of spent fuel heatup during a loss-of-water accident. On the other hand, the report does indicate that zirconium fires are possible and thus shows the need for a full analysis of the accident hazards of spent fuel storage pools--of the course of an accident following the initiation of a zirconium fire--to determine the radioactivity release potential.

Purpose and Plan of Present Report

The purpose of the remainder of the present report is:

(1) to critically review the Sandia Report in more detail;

(2) to prove the above assertions concerning theoretical shortcomings of the Sandia analysis; and thus to show that the numerical heatup predictions in the Sandia report are not reliable and that a corrected mathematically theory may not be practical;

(3) to examine the experimental basis given in the Sandia report for Sandia's mathematical theory of spent fuel heatup and to show that it is wholly inadequate and that, therefore, Sandia's theory is experimentally unconfirmed;

(4) to demonstrate the possibility for nuclear explosions occurring in a spent fuel pool accident due to plutonium concentration during a possible meltdown of spent fuel; and

(5) to show that it is not practical to scientifically establish the radioactivity release potential of loss-of-water accidents in spent fuel storage pools; other than to assume a near-100%

release of strontium-90 and cesium-137 and possibly other radioactive substances, because full-scale experiments of loss-of-water in a large-scale storage pool filled to capacity with actual spent fuel would be needed--which is obviously impractical. Also, there is no escape from the risk of spent fuel storage pool accidents no matter how nuclear power is managed. Even if spent fuel were removed from the pool after a six month cooling period, the quantity of storage at reactor pools would still be great in terms of radioactivity, including strontium-90 and cesium-137--almost as much strontium-90 and cesium-137 as in the reactor core, or more so for pools which service two reactors. Since the decay heat level of new spent fuel is much greater than aged spent fuel, the time required for storage pool water to boil away in a loss-of-cooling malfunction is not significantly affected if aged spent fuel is not allowed to accumulate in the pool. If spent fuel were shipped to a chemical reprocessing pool for separation of usable fuel and the radioactive waste, there would be created the accident hazards of the spent fuel storage pools that would exist at the reprocessing plant for receiving six-month old spent fuel transported from reactors. Such pools would be full of relatively new spent fuel, unlike reactor pools, which would contain mostly aged fuel when full to capacity; and so reprocessing plant receiving pools would have much more severe spent fuel heatup potentials. Therefore, it is necessary to evaluate the hazards of spent fuel storage pools and the validity of the mathematical theory of analysis which Sandia is developing, no matter what plan of nuclear waste disposal.

The remainder of this report consists of the following chapters:

(1) A detailed description of spent fuel assemblies and their storage pools:

(2) An introductory mathematical analysis of spent fuel heatup assuming natural air convection only, to demonstrate the severe affect imperfect building ventilation has on the heatup of spent fuel, and to show the necessity of accounting for lateral heat transfer to between fuel assemblies, in order to then be able to show the shortcoming of the Sandia theory in this regard;

(3) A more detailed critical review of the Sandia Report;

(4) A chapter discussing the full course which a spent fuel loss-of-water accident could take after a zirconium fire starts;

(5) A chapter demonstrating mathematically the land contamination potential of a release of radioactivity;

(6) A chapter on information needs;

(7) A chapter on non-reactor sited pools; and

(8) A concluding chapter.

Appendix 1

Derivation of Strontium-90, Cesium-137, and Plutonium Quantities to be Stored in the Zion Pool

Type	Quantify Based on 25,000 MWD/MT burnup
Sr-90	6.4×10^4 curies/metric ton of uranium
Cs-137	8.3×10^4 ci/MTU
Plutonium	7.7 Kg/MTU

Source: NUREG-0404, p. G-11, and G-16. There are xkk 0.45 MT of uranium per fuel assembly and 2112 spent fuel assemblies to be stored in the Zion Pool. Thus, the Zion pool will contain 80.3×10^6 curies of strontium-90:

$$2112 \times .45 \times 6.4 \times 10^4 \times \frac{33,000}{25,000} = 80.3 \times 10^6 \text{ Ci},$$

or about 75 million curies of Sr-90, as there will be a slight decay (29 year half life) after 15 years buildup of spent fuel. The factor 33,000/25,000 xax accounts for the higher fuel burnup which is expected. The NUREG-0404 figure of 6.4×10^4 Ci/MTU applies to 25,000 MWD/MTU whereas 33,000 MWD/MTU burnup is expected. (MWD/MTU means megawatt-days per metric ton fz of uranium).

For Cs-137, $2112 \times .45 \times 8.3 \times 10^4 \times \frac{33000}{25000} = 104 \times 10^6$ Ci. That is, the Zion pool will contain 104 million curies of cesium-137.

The plutonium quantity would be:

$$2xx \quad 2112 \times .45 \times 7.7 \text{ Kg/MTU} \times \frac{33000}{25000} = 9.7 \times 10^3 \text{ Kg}.$$

or 9.7 metric tons of plutonium.

Appendix 2

Rasmussen Report's Implicit Strontium-90 xs Release Figure for a Spent Fuel Storage Pool Accident: 2000 curies.

The Rasmussen Report estimates that 1.98×10^6 curies of "alkaline earths" radioactivity escapes one third of a core load of spent fuel which x has aged for 60 days, and that 1% of this radioactivity escapes the building (Ras. Rpt., app. I, p. 103-104). Alkaline earths consists of Barium-140, strontium-89, and strontium-90, with half lives of 12.8 days, 50.5 days, and 29 years, respectively. The NRC's environmental impact statement for spent fuel (NUREG-0404) tabulates the quantities of these substances per metric ton of spent fuel. At time of discharge from the reactor (p. G-11):

Ba-140---- $1.72 \quad 10^6$ Ci/MTU
Sr-89 ---- 9.47×10^5 Ci/MTU
Sr-90 ---- 6.4×10^4 Ci/MTU.

The mass of fuel per assembly is .45 MTU (NUREG-0404, p. G-5); and one core contains 193 fuel assemblies; hence 1/3 of a core equals 65 assemblies. From these data one can calculate the release fraction of alkaline earths and then the xefx release quantity of strontium-90. We can compute the release fraction (F_r) implicitly assumed in the Rasmussen's estimate from the following equation for radioactive decay:

$$F_r \times .45 \times 65 \times \left[1.72\times10^6 e^{-\frac{\ln 2\cdot 60}{12.8}} + 9.47\times10^5 e^{-\frac{\ln 2\cdot 60}{50.5}} + 6.4\times10^4 e^{-\frac{\ln 2\cdot 60}{29\times 365}}\right. = 1.98\times10$$

Solving for F_r, $F_r = .12$, or roughly 10%. Therefore, the asumed xt assumed strontium-90 release from the storage pool building (assusmed a (assumed in the Ras. Report) is

$$6.4\times10^4\ Ci/MTU \times .45\ MT/ass'y \times 65\ ass'y \times 0.1 \times 0.01 = 1872\ Ci$$

or about 2000 curies.

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Multiply	*by*	*to obtain*
acres	43,560	square feet
acres	4047	square meters
acres	1.562×10^{-3}	square miles
acres	5645.38	square varas
acres	4840	square yards
amperes	1/10	abamperes
amperes	3×10^{9}	statamperes
atmospheres	76.0	cms. of mercury
atmospheres	29.92	inches of mercury
atmospheres	33.90	feet of water
atmospheres	10,333	kgs. per sq. meter
atmospheres	14.70	pounds per sq. inch
atmospheres	1.058	tons per sq. foot
British thermal units	0.2520	kilogram-calories
British thermal units	777.5	foot-pounds
British thermal units	3.927×10^{-4}	horse-power-hours
British thermal units	1054	joules
British thermal units	[illegible]7.5	kilogram-meters
British thermal units	2.928×10^{-4}	kilowatt-hours
B.t.u. per min.	12.96	foot-pounds per sec.
B.t.u. per min.	0.02356	horse-power
B.t.u. per min.	0.01757	kilowatts
B.t.u. per min.	17.57	watts
B.t.u. per sq. ft. per min.	0.1220	watts per sq. inch
bushels	1.244	cubic feet
bushels	2150	cubic inches
bushels	0.03524	cubic meters
bushels	4	pecks
bushels	64	pints (dry)
bushels	32	quarts (dry)
centimeters	0.3937	inches
centimeters	0.01	meters
centimeters	393.7	mils
centimeters	10	millimeters
centimeter-grams	980.7	centimeter-dynes
centimeter-grams	10^{-5}	meter-kilograms
centimeter-grams	7.233×10^{-5}	pound-feet
centimeters of mercury	0.01316	atmospheres
centimeters of mercury	0.4461	feet of water
centimeters of mercury	136.0	kgs. per sq. meter
centimeters of mercury	27.85	pounds per sq. foot
centimeters of mercury	0.1934	pounds per sq. inch
centimeters per second	1.969	feet per minute
centimeters per second	0.03281	feet per second
centimeters per second	0.036	kilometers per hour
centimeters per second	0.6	meters per minute
centimeters per second	0.02237	miles per hour
centimeters per second	3.728×10^{-4}	miles per minute
cubic centimeters	3.531×10^{-5}	cubic feet
cubic centimeters	6.102×10^{-2}	cubic inches
cubic centimeters	10^{-6}	cubic meters
cubic centimeters	1.308×10^{-6}	cubic yards
cubic centimeters	2.642×10^{-4}	gallons
cubic centimeters	10^{-3}	liters
cubic centimeters	2.113×10^{-3}	pints (liq.)
cubic centimeters	1.057x10	quarts (liq.)
cubic feet	62.43	pounds of water
cubic feet	2.832x10	cubic cms.
cubic feet	1728	cubic inches
cubic feet	0.02832	cubic meters
cubic feet	0.03704	cubic yards
cubic feet	7.481	gallons
cubic feet	28.32	liters
cubic feet	59.84	pints (liq.)
cubic feet	29.92	quarts (liq.)
cubic feet per minute	472.0	cubic cms. per sec.
cubic feet per minute	0.1247	gallons per sec.
cubic feet per minute	0.4720	liters per second
cubic feet per minute	62.4	lbs. of water per min.
cubic inches	16.39	cubic centimeters
cubic inches	5.787×10^{-4}	cubic feet
cubic inches	1.639×10^{-5}	cubic meters
cubic inches	2.143×10^{-5}	cubic yards
cubic inches	4.329×10^{-3}	gallons
cubic inches	1.639×10^{-2}	liters
cubic inches	0.03463	pints (liq.)
cubic inches	0.01732	quarts (liq.)
cubic yards	7.646×10^{5}	cubic centimeters
cubic yards	27	cubic feet
cubic yards	46,656	cubic inches
cubic yards	0.7646	cubic meters
cubic yards	202.0	gallons
cubic yards	764.6	liters
cubic yards	1616	pints (liq.)
cubic yards	807.9	quarts (liq.)
cubic yards per minute	0.45	cubic feet per sec.
cubic yards per minute	3.367	gallons per second
cubic yards per minute	12.74	liters per second
degrees (angle)	60	minutes
degrees (angle)	0.01745	radians
degrees (angle)	3600	seconds
dynes	1.020×10^{-3}	grams
dynes	7.233×10^{-5}	poundals
dynes	2.248×10^{-6}	pounds
ergs	9.486×10^{-11}	British thermal units
ergs	1	dyne-centimeters
ergs	7.376×10^{-8}	foot-pounds
ergs	1.020×10^{-3}	gram-centimeters
ergs	10^{-7}	joules
ergs	2.390×10^{-11}	kilogram-calories
ergs	1.020×10^{-8}	kilogram-meters
feet	30.48	centimeters
feet	12	inches
feet	0.3048	meters
feet	.36	varas
feet	1/3	yards
feet of water	0.02950	atmospheres
feet of water	0.8826	inches of mercury
feet of water	304.8	kgs. per sq. meter
feet of water	62.43	pounds per sq. ft.
feet of water	0.4335	pounds per sq. inch
foot-pounds	1.286×10^{-3}	British thermal units
foot-pounds	1.356×10^{7}	ergs
foot-pounds	5.050×10^{-7}	horse-power-hours
foot-pounds	1.356	joules
foot-pounds	3.241×10^{-4}	kilogram-calories
foot-pounds	0.1383	kilogram-meters
foot-pounds	3.766×10^{-7}	kilowatt-hours
foot-pounds per min.	1.286×10^{-3}	B.t. units per minute
foot-pounds per min.	0.01667	foot-pounds per sec.
foot-pounds per min.	3.030×10^{-5}	horse-power
foot-pounds per min.	3.241×10^{-4}	kg.-calories per min.
foot-pounds per min.	2.260×10^{-5}	kilowatts
foot-pounds per sec.	7.717×10^{-2}	B.t. units per minute
foot-pounds per sec.	1.818×10^{-3}	horse-power
foot-pounds per sec.	1.945×10^{-2}	kg-calories per min.
foot-pounds per sec.	1.356×10^{-3}	kilowatts
gallons	8.345	pounds of water
gallons	3785	cubic centimeters
gallons	0.1337	cubic feet
gallons	231	cubic inches
gallons	3.785×10^{-3}	cubic meters
gallons	4.951×10^{-3}	cubic yards
gallons	3.785	liters
gallons	8	pints (liq.)
gallons	4	quarts (liq.)
gallons per minute	2.228×10^{-3}	cubic ft. per second
gallons per minute	0.06308	liters per second
grains (troy)	1	grains (av.)
grains (troy)	0.06480	grams
grains (troy)	0.04167	pennyweights (troy)
grams	980.7	dynes
grams	15.43	grains (troy)
grams	10^{-3}	kilograms
grams	10^{3}	milligrams
grams	0.03527	ounces
grams	0.03215	ounces (troy)
grams	0.07093	poundals
grams	2.205×10^{-3}	pounds
horse-power	42.44	B.t. units per min.

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Multiply	*by*	*to obtain*	*Multiply*	*by*	*to obtain*
horse-power	33,000	foot-pounds per min.	miles per hour	1.6093	kilometers per hour
horse-power	550	foot-pounds per sec.	miles per hour	0.8684	knots
horse-power	1.014	horse-power (metric)	miles per hour	26.82	meters per minute
horse-power	10.70	kg.-calories per min.	miles per hour per sec.	44.70	cms. per sec. per sec.
horse-power	0.7457	kilowatts	miles per hour per sec.	1.467	ft. per sec. per sec.
horse-power	745.7	watts	miles per hour per sec.	1.6093	kms. per hr. per sec.
horse-power (boiler)	33,520	B.t.u. per hour	miles per hour per sec.	0.4470	M. per sec. per sec.
horse-power (boiler)	9.804	kilowatts	months	30.42	days
horse-power-hours	2547	British thermal units	months	730	hours
horse-power-hours	1.98×10^6	foot-pounds	months	43,800	minutes
horse-power-hours	2.584×10^6	joules	months	2.628×10^6	seconds
horse-power-hours	641.7	kilogram-calories	ounces	8	drams
horse-power-hours	2.737×10^5	kilogram-meters	ounces	437.5	grains
horse-power-hours	0.7457	kilowatt-hours	ounces	28.35	grams
inches	2.540	centimeters	ounces	.0625	pounds
inches	10^3	mils	ounces per square inch	0.0625	pounds per sq. inch
inches	.03	varas	pints (dry)	33.60	cubic inches
inches of mercury	0.03342	atmospheres	pints (liq.)	28.87	cubic inches
inches of mercury	1.133	feet of water	pounds	444.823	dynes
inches of mercury	345.3	kgs. per sq. meter	pounds	7000	grains
inches of mercury	70.73	pounds per sq. ft.	pounds	453.6	grams
inches of mercury	0.4912	pounds per sq. in.	pounds	16	ounces
inches of water	0.002458	atmospheres	pounds	32.17	poundals
inches of water	0.07355	inches of mercury	pounds of water	0.01602	cubic feet
inches of water	25.40	kgs. per sq. meter	pounds of water	27.68	cubic inches
inches of water	0.5781	ounces per sq. in.	pounds of water	0.1198	gallons
inches of water	5.204	pounds per sq. ft.	pounds of water per min.	2.669×10^{-4}	cubic feet per sec.
inches of water	0.03613	pounds per sq. in.	pounds per cubic foot	0.01602	grams per cubic cm.
kilograms	980,665	dynes	pounds per cubic foot	16.02	kgs. per cubic meter
kilograms	10^3	grams	pounds per cubic foot	5.787×10^{-4}	pounds per cubic in.
kilograms	70.93	poundals	pounds per cubic foot	5.456×10^{-9}	pounds per mil foot
kilograms	2.2046	pounds	pounds per square foot	0.01602	feet of water
kilograms	1.102×10^{-3}	tons (short)	pounds per square foot	4.882	kgs. per sq. meter
kilogram-calories	3.968	British thermal units	pounds per square foot	6.944×10^{-3}	pounds per sq. inch
kilogram-calories	3086	foot-pounds	pounds per square inch	0.06804	atmospheres
kilogram-calories	1.558×10^{-3}	horse-power-hours	pounds per square inch	2.307	feet of water
kilogram-calories	4183	joules	pounds per square inch	2.036	inches of mercury
kilogram-calories	426.6	kilogram-meters	pounds per square inch	703.1	kgs. per sq. meter
kilogram-calories	1.162×10^{-3}	kilowatt-hours	pounds per square inch	144	pounds per sq. foot
kg.-calories per min.	51.43	foot-pounds per sec.	quarts	32	fluid ounces
kg.-calories per min.	0.09351	horse-power	quarts (dry)	67.20	cubic inches
kg.-calories per min.	0.06972	kilowatts	quarts (liquid)	57.75	cubic inches
kilometers	10^5	centimeters	rods	16.5	feet
kilometers	3281	feet	square centimeters	1.973×10^5	circular mils
kilometers	10^3	meters	square centimeters	1.076×10^{-3}	square feet
kilometers	0.6214	miles	square centimeters	0.1550	square inches
kilometers	1093.6	yards	square centimeters	10^{-4}	square meters
kilowatts	56.92	B.t. units per min.	square centimeters	100	square millimeters
kilowatts	4.425×10^4	foot-pounds per min.	square feet	2.296×10^{-5}	acres
kilowatts	737.6	foot-pounds per sec.	square feet	929.0	square centimeters
kilowatts	1.341	horse-power	square feet	144	square inches
kilowatts	14.34	kg.-calories per min.	square feet	0.09290	square meters
kilowatts	10^3	watts	square feet	3.587×10^{-8}	square miles
kilowatt-hours	3415	British thermal units	square feet	.1296	square varas
kilowatt-hours	2.655×10^6	foot-pounds	square feet	1/9	square yards
kilowatt-hours	1.341	horse-power-hours	square inches	1.273×10^6	circular mils
kilowatt-hours	3.6×10^6	joules	square inches	6.452	square centimeters
kilowatt-hours	860.5	kilogram-calories	square inches	6.944×10^{-3}	square feet
kilowatt-hours	3.671×10^5	kilogram-meters	square inches	10^6	square mils
$\log^{10} N$	2.303	$\log_e N$ or $\ln N$	square inches	645.2	square millimeters
$\log^e N$ or $\ln N$	0.4343	$\log_{10} N$	square miles	640	acres
meters	100	centimeters	square miles	27.88×10^6	square feet
meters	3.2808	feet	square miles	2.590	square kilometers
meters	39.37	inches	square miles	3,613,040.45	square varas
meters	10^{-3}	kilometers	square miles	3.098×10^6	square yards
meters	10^3	millimeters	square yards	2.066×10^{-4}	acres
meters	1.0936	yards	square yards	9	square feet
miles	1.609×10^5	centimeters	square yards	0.8361	square meters
miles	5280	feet	square yards	3.228×10^{-7}	square miles
miles	1.6093	kilometers	square yards	1.1664	square varas
miles	1760	yards	temp. (degs. C.) + 17.8	1.8	temp. (degs. Fahr.)
miles	1900.8	varas	temp. (degs. F.) − 32	5/9	temp. (degs. Cent.)
miles per hour	44.70	centimeters per sec.	tons (long)	2240	pounds
miles per hour	88	feet per minute	tons (short)	2000	pounds
miles per hour	1.467	feet per second	yards	.9144	meters

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Multiply	*by*	*to obtain*
acres	43,560	square feet
acres	4047	square meters
acres	1.562×10^{-3}	square miles
acres	5645.38	square varas
acres	4840	square yards
amperes	1/10	abamperes
amperes	3×10^{9}	statamperes
atmospheres	76.0	cms. of mercury
atmospheres	29.92	inches of mercury
atmospheres	33.90	feet of water
atmospheres	10,333	kgs. per sq. meter
atmospheres	14.70	pounds per sq. inch
atmospheres	1.058	tons per sq. foot
British thermal units	0.2520	kilogram-calories
British thermal units	777.5	foot-pounds
British thermal units	3.927×10^{-4}	horse-power-hours
British thermal units	1054	joules
British thermal units	107.5	kilogram-meters
British thermal units	2.928×10^{-4}	kilowatt-hours
B.t.u. per min.	12.96	foot-pounds per sec.
B.t.u. per min.	0.02356	horse-power
B.t.u. per min.	0.01757	kilowatts
B.t.u. per min.	17.57	watts
B.t.u. per sq. ft. per min.	0.1220	watts per sq. inch
bushels	1.244	cubic feet
bushels	2150	cubic inches
bushels	0.03524	cubic meters
bushels	4	pecks
bushels	64	pints (dry)
bushels	32	quarts (dry)
centimeters	0.3937	inches
centimeters	0.01	meters
centimeters	393.7	mils
centimeters	10	millimeters
centimeter-grams	980.7	centimeter-dynes
centimeter-grams	10^{-5}	meter-kilograms
centimeter-grams	7.233×10^{-5}	pound-feet
centimeters of mercury	0.01316	atmospheres
centimeters of mercury	0.4461	feet of water
centimeters of mercury	136.0	kgs. per sq. meter
centimeters of mercury	27.85	pounds per sq. foot
centimeters of mercury	0.1934	pounds per sq. inch
centimeters per second	1.969	feet per minute
centimeters per second	0.03281	feet per second
centimeters per second	0.036	kilometers per hour
centimeters per second	0.6	meters per minute
centimeters per second	0.02237	miles per hour
centimeters per second	3.728×10^{-4}	miles per minute
cubic centimeters	3.531×10^{-5}	cubic feet
cubic centimeters	6.102×10^{-2}	cubic inches
cubic centimeters	10^{-6}	cubic meters
cubic centimeters	1.308×10^{-6}	cubic yards
cubic centimeters	2.642×10^{-4}	gallons
cubic centimeters	10^{-3}	liters
cubic centimeters	2.113×10^{-3}	pints (liq.)
cubic centimeters	1.057×10^{-3}	quarts (liq.)
cubic feet	62.43	pounds of water
cubic feet	2.832×10^{4}	cubic cms.
cubic feet	1728	cubic inches
cubic feet	0.02832	cubic meters
cubic feet	0.03704	cubic yards
cubic feet	7.481	gallons
cubic feet	28.32	liters
cubic feet	59.84	pints (liq.)
cubic feet	29.92	quarts (liq.)
cubic feet per minute	472.0	cubic cms. per sec.
cubic feet per minute	0.1247	gallons per sec.
cubic feet per minute	0.4720	liters per second
cubic feet per minute	62.4	lbs. of water per min.
cubic inches	16.39	cubic centimeters
cubic inches	5.787×10^{-4}	cubic feet
cubic inches	1.639×10^{-5}	cubic meters
cubic inches	2.143×10^{-5}	cubic yards
cubic inches	4.329×10^{-3}	gallons
cubic inches	1.639×10^{-2}	liters

Multiply	*by*	*to obtain*
cubic inches	0.03463	pints (liq.)
cubic inches	0.01732	quarts (liq.)
cubic yards	7.646×10^{5}	cubic centimeters
cubic yards	27	cubic feet
cubic yards	46,656	cubic inches
cubic yards	0.7646	cubic meters
cubic yards	202.0	gallons
cubic yards	764.6	liters
cubic yards	1616	pints (liq.)
cubic yards	807.9	quarts (liq.)
cubic yards per minute	0.45	cubic feet per sec.
cubic yards per minute	3.367	gallons per second
cubic yards per minute	12.74	liters per second
degrees (angle)	60	minutes
degrees (angle)	0.01745	radians
degrees (angle)	3600	seconds
dynes	1.020×10^{-3}	grams
dynes	7.233×10^{-5}	poundals
dynes	2.248×10^{-6}	pounds
ergs	9.486×10^{-11}	British thermal units
ergs	1	dyne-centimeters
ergs	7.376×10^{-8}	foot-pounds
ergs	1.020×10^{-3}	gram-centimeters
ergs	10^{-7}	joules
ergs	2.390×10^{-11}	kilogram-calories
ergs	1.020×10^{-8}	kilogram-meters
feet	30.48	centimeters
feet	12	inches
feet	0.3048	meters
feet	.36	varas
feet	1/3	yards
feet of water	0.02950	atmospheres
feet of water	0.8826	inches of mercury
feet of water	304.8	kgs. per sq. meter
feet of water	62.43	pounds per sq. ft.
feet of water	0.4335	pounds per sq. inch
foot-pounds	1.286×10^{-3}	British thermal units
foot-pounds	1.356×10^{7}	ergs
foot-pounds	5.050×10^{-7}	horse-power-hours
foot-pounds	1.356	joules
foot-pounds	3.241×10^{-4}	kilogram-calories
foot-pounds	0.1383	kilogram-meters
foot-pounds	3.766×10^{-7}	kilowatt-hours
foot-pounds per min.	1.286×10^{-3}	B.t. units per minute
foot-pounds per min.	0.01667	foot-pounds per sec.
foot-pounds per min.	3.030×10^{-5}	horse-power
foot-pounds per min.	3.241×10^{-4}	kg.-calories per min.
foot-pounds per min.	2.260×10^{-5}	kilowatts
foot-pounds per sec.	7.717×10^{-2}	B.t. units per minute
foot-pounds per sec.	1.818×10^{-3}	horse-power
foot-pounds per sec.	1.945×10^{-2}	kg-calories per min.
foot-pounds per sec.	1.356×10^{-3}	kilowatts
gallons	8.345	pounds of water
gallons	3785	cubic centimeters
gallons	0.1337	cubic feet
gallons	231	cubic inches
gallons	3.785×10^{-3}	cubic meters
gallons	4.951×10^{-3}	cubic yards
gallons	3.785	liters
gallons	8	pints (liq.)
gallons	4	quarts (liq.)
gallons per minute	2.228×10^{-3}	cubic ft. per second
gallons per minute	0.06308	liters per second
grains (troy)	1	grains (av.)
grains (troy)	0.06480	grams
grains (troy)	0.04167	pennyweights (troy)
grams	980.7	dynes
grams	15.43	grains (troy)
grams	10^{-3}	kilograms
grams	10^{3}	milligrams
grams	0.03527	ounces
grams	0.03215	ounces (troy)
grams	0.07093	poundals
grams	2.205×10^{-3}	pounds
horse-power	42.44	B.t. units per min.

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Multiply	*by*	*to obtain*	*Multiply*	*by*	*to obtain*
horse-power	33,000	foot-pounds per min.	miles per hour	1.6093	kilometers per hour
horse-power	550	foot-pounds per sec.	miles per hour	0.8684	knots
horse-power	1.014	horse-power (metric)	miles per hour	26.82	meters per minute
horse-power	10.70	kg.-calories per min.	miles per hour per sec.	44.70	cms. per sec. per sec.
horse-power	0.7457	kilowatts	miles per hour per sec.	1.467	ft. per sec. per sec.
horse-power	745.7	watts	miles per hour per sec.	1.6093	kms. per hr. per sec.
horse-power (boiler)	33,520	B.t.u. per hour	miles per hour per sec.	0.4470	M. per sec. per sec.
horse-power (boiler)	9.804	kilowatts	months	30.42	days
horse-power-hours	2547	British thermal units	months	730	hours
horse-power-hours	1.98×10^{6}	foot-pounds	months	43,800	minutes
horse-power-hours	2.684×10^{6}	joules	months	2.628×10^{6}	seconds
horse-power-hours	641.7	kilogram-calories	ounces	8	drams
horse-power-hours	2.737×10^{5}	kilogram-meters	ounces	437.5	grains
horse-power-hours	0.7457	kilowatt-hours	ounces	28.35	grams
inches	2.540	centimeters	ounces	.0625	pounds
inches	10^{3}	mils	ounces per square inch	0.0625	pounds per sq. inch
inches	.03	varas	pints (dry)	33.60	cubic inches
inches of mercury	0.03342	atmospheres	pints (liq.)	28.87	cubic inches
inches of mercury	1.133	feet of water	pounds	444,823	dynes
inches of mercury	345.3	kgs. per sq. meter	pounds	7000	grains
inches of mercury	70.73	pounds per sq. ft.	pounds	453.6	grams
inches of mercury	0.4912	pounds per sq. in.	pounds	16	ounces
inches of water	0.002458	atmospheres	pounds	32.17	poundals
inches of water	0.07355	inches of mercury	pounds of water	0.01602	cubic feet
inches of water	25.40	kgs. per sq. meter	pounds of water	27.68	cubic inches
inches of water	0.5781	ounces per sq. in.	pounds of water	0.1198	gallons
inches of water	5.204	pounds per sq. ft.	pounds of water per min.	2.669×10^{-4}	cubic feet per sec.
inches of water	0.03613	pounds per sq. in.	pounds per cubic foot	0.01602	grams per cubic cm.
kilograms	980,665	dynes	pounds per cubic foot	16.02	kgs. per cubic meter
kilograms	10^{3}	grams	pounds per cubic foot	5.787×10^{-4}	pounds per cubic in.
kilograms	70.93	poundals	pounds per cubic foot	5.456×10^{-9}	pounds per mil foot
kilograms	2.2046	pounds	pounds per square foot	0.01602	feet of water
kilograms	1.102×10^{-3}	tons (short)	pounds per square foot	4.882	kgs. per sq. meter
kilogram-calories	3.968	British thermal units	pounds per square foot	6.944×10^{-3}	pounds per sq. inch
kilogram-calories	3086	foot-pounds	pounds per square inch	0.06804	atmospheres
kilogram-calories	1.558×10^{-3}	horse-power-hours	pounds per square inch	2.307	feet of water
kilogram-calories	4183	joules	pounds per square inch	2.036	inches of mercury
kilogram-calories	426.6	kilogram-meters	pounds per square inch	703.1	kgs. per sq. meter
kilogram-calories	1.162×10^{-3}	kilowatt-hours	pounds per square inch	144	pounds per sq. foot
kg.-calories per min.	51.43	foot-pounds per sec.	quarts	32	fluid ounces
kg.-calories per min.	0.09351	horse-power	quarts (dry)	67.20	cubic inches
kg.-calories per min.	0.06972	kilowatts	quarts (liquid)	57.75	cubic inches
kilometers	10^{5}	centimeters	rods	16.5	feet
kilometers	3281	feet	square centimeters	1.973×10^{5}	circular mils
kilometers	10^{3}	meters	square centimeters	1.076×10^{-3}	square feet
kilometers	0.6214	miles	square centimeters	0.1550	square inches
kilometers	1093.6	yards	square centimeters	10^{-4}	square meters
kilowatts	56.92	B.t. units per min.	square centimeters	100	square millimeters
kilowatts	4.425×10^{4}	foot-pounds per min.	square feet	2.296×10^{-5}	acres
kilowatts	737.6	foot-pounds per sec.	square feet	929.0	square centimeters
kilowatts	1.341	horse-power	square feet	144	square inches
kilowatts	14.34	kg.-calories per min.	square feet	0.09290	square meters
kilowatts	10^{3}	watts	square feet	3.587×10^{-8}	square miles
kilowatt-hours	3415	British thermal units	square feet	.1296	square varas
kilowatt-hours	2.655×10^{6}	foot-pounds	square feet	1/9	square yards
kilowatt-hours	1.341	horse-power-hours	square inches	1.273×10^{6}	circular mils
kilowatt-hours	3.6×10^{6}	joules	square inches	6.452	square centimeters
kilowatt-hours	860.5	kilogram-calories	square inches	6.944×10^{-3}	square feet
kilowatt-hours	3.671×10^{5}	kilogram-meters	square inches	10^{6}	square mils
$\log^{10} N$	2.303	$\log_e N$ or $\ln N$	square inches	645.2	square millimeters
$\log^{e} N$ or $\ln N$	0.4343	$\log_{10} N$	square miles	640	acres
meters	100	centimeters	square miles	27.88×10^{6}	square feet
meters	3.2808	feet	square miles	2.590	square kilometers
meters	39.37	inches	square miles	3,613,040.45	square varas
meters	10^{-3}	kilometers	square miles	3.098×10^{6}	square yards
meters	10^{3}	millimeters	square yards	2.066×10^{-4}	acres
meters	1.0936	yards	square yards	9	square feet
miles	1.609×10^{5}	centimeters	square yards	0.8361	square meters
miles	5280	feet	square yards	3.228×10^{-7}	square miles
miles	1.6093	kilometers	square yards	1.1664	square varas
miles	1760	yards	temp. (degs. C.) +17.8	1.8	temp. (degs. Fahr.)
miles	1900.8	varas	temp. (degs. F.) −32	5/9	temp. (degs. Cent.)
miles per hour	44.70	centimeters per sec.	tons (long)	2240	pounds
miles per hour	88	feet per minute	tons (short)	2000	pounds
miles per hour	1.467	feet per second	yards	.9144	meters

F211

CONTENTIONS REGARDING THE ACCIDENT HAZARDS OF SPENT FUEL STORAGE AT THE SALEM NUCLEAR POWER PLANT SALEM, NEW JERSEY

BY:
RICHARD F. WEBB, Ph.D.
February 27, 1979

F11A

CONTENTS

1. INTRODUCTORY CONTENTION: THE LOSS-OF-WATER ACCIDENT

The utility operating the Salem Nuclear Power Station at Salem, New Jersey--Public Service Electric and Gas Company--(PSE&G)--is requesting a license from the United States Nuclear Regulatory Commission to store indefinitely up to 1170 highly radioactive, spent nuclear fuel rod assemblies in each of two spent fuel storage pools located at the reactor site. The Station consists of one operating nuclear power reactor and one under construction. Each spent fuel pool is housed in a separate fuel handling building which is located next to its respective reactor containment building. Originally, it was intended only to have in storage about 64 spent fuel assemblies at any one time in each pool, as the plan was to ship spent fuel away from the site for disposal after a brief, 150 day cooling-off period that allows the radioactivity and associated heat in the spent fuel to decay substantially. Now, however, PSE&G proposes to increase the storage capacity of each storage pool, by replacing the original design of the storage racks with a rack design which allows the spent fuel assemblies to be packed in the pool at a high density (compaction). The proposed increase in storage capacity would increase the amount of long-lived radioactivity to be stored in the pool eighteen-fold. Approval to increase the storage capacity is requested by PSE&G

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because there presently exists no nuclear waste disposal system for disposing of the spent fuel.

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With respect to the hazards of the proposed spent fuel storage increase, it is contended that:

(a) The proposed design changes to the spent fuel storage pools would greatly increase the nuclear accident hazards of the em Station with respect to the health and safety of the public.

(b) The proposed design changes would create many severe accident possibilities which would have the potential for extremely disastrous consequences. Such accidents would involve the loss-of-pool-water, hereafter denominated the loss-of-water accident.

(c) Both the PSE&G's Safety Analysis Report and the Nuclear Regulatory Commission's Safety Evaluation Report for the proposed design changes fail to analyze the loss-of-water accident.

(d) The potential consequences of loss-of-water accidents are so serious that the utility (PSE&G) and the Nuclear Regulatory Commission's staff must analyze them, and the Atomic Safety and Licensing Board (AS&LB) and the Commission itself must investigate and consider them for both their likelihood and potential harmful consequences, in order to enable the Nuclear Regulatory Commission, that is, the Commission, itself, to responsibly

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form an opinion as to whether the proposed spent fuel storage would be "inimical to the health and safety of the public" (referring to Section 103 of the Atomic Energy Act) and to responsibly inform the public of the full risks to health and safety.

F2J1

(e) The likelihood of a loss-of-water accident occurring is not remote or extremely low; but rather, the probability of occurrence is indeterminable. More specifically, it cannot be proven mathematically or statistically that the probability of such an accident occurring in the time period of the life of the plant or even a decade . . . is less than 100% or significantly less than 100%. There exists an indeterminable but extremely large number of possibilities for potentially or conceivably causing a loss-of-water accident in a storage pool. Furthermore, many incidents associated with nuclear power reactors of near-accidents, equipment malfunction accidents, and human error have occurred. These facts indicate that the probability of a loss-of-water accident is high, not low. Because of these facts, plus the fact that the probability of a loss-of-water accident is indeterminable and the fact of the extreme potential for harmful consequences of such an accident, make the proposed storage facility unsafe.

(f) The Nuclear Regulatory Commission's current practice of evaluating the risks of the worst or severe

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nuclear accident possibilities by considering only the likelihood of such accidents, and not evaluating and considering the potential harmful consequences, is not consistent with the well-established method of assessing accident risks, which is to consider both the likelihood and the consequences of accidents.

~~(g) Because of the extreme potential for harmful consequences of a loss-of-water accident~~ Dr. Webb to supply F1K

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2. PHYSICAL CONSEQUENCES OF A LOSS-OF-WATER ACCIDENT F1K

(a) The radioactivity in spent fuel generates heat which must be dissipated in order to prevent the spent fuel assemblies from overheating. For this reason and for radiation shielding purposes, the spent fuel assemblies are stored under water. The pool water serves to remove the heat of the radioactivity. The pool water in turn is cooled by water circulating cooling systems to prevent the pool from overheating and boiling dry. In a loss-of-water accident the spent fuel assemblies will heat up to a high temperature, because natural air convection and thermal radiation heat dissipation processes are insufficient to cool the spent fuel. The full potential for spent fuel heatup has yet to be predicted by a thermal/hydraulics analysis.

(b) Upper bound calculations exist which indicate that the potential may exist for the uranium dioxide in the spent fuel to heat up beyond its melting temperature of about 2800°C, even if all of the spent fuel were stored for ten years.

(c) Calculations exist~~s~~ which tend to set a mathematical lower bound of the spent fuel heatup potential; and these calculations indicate that as a <u>minimum</u> the zirconium (zircaloy) fuel rod cladding material will heat up to 900°C and catch on fire for spent fuel that has decayed (aged) for three years. These calculations were performed by Sandia Laboratory and are presented in a report titled "Spent Fuel Heatup Following Loss of Water During Storage" (SAND77-1371, Sept. 1978, draft), by A. S. Benjamin, et al.; hereafter called the Sandia Report. The Sandia Report does not calculate the fuel temperature rise beyond the point when the temperature is calculated to reach the zirconium fire ignition temperature, and subsequent zirconium clad melting (1857°C).

F1K

(d) A zirconium fire would generate substantial additional heat with the potential for melting away the cladding of the fuel rod and also melting the uranium oxide fuel or raising the fuel to its melting temperature of 2850°C (about).

(e) A zirconium fire which starts in relatively new spent fuel (say, three year storage or less), which would include 16% of the total planned storage or less, could conceivably spread to old spent fuel and thus engulf the whole load of spent fuel in the pool.

(f) Severe zirconium explosions are conceivable, due to zirconium-water reactions in conjunction with zirconium-air reactions.

(g) Hydrogen explosions are conceivable due to the hydrogen released in a zirconium-water reaction and its reacting with air.

(h) Since zirconium fuel clad melting is possible, it is conceivable that the air flow passages inside the spent fuel rod assemblies could become plugged due to the zirconium dioxide reaction product and due to molten zirconium running down toward cooler portions of the spent fuel and freezing there. Plugged air flow passages would greatly worsen the spent fuel heatup. Also, explosive zirconium-water reactions and hydrogen explosions could conceivably damage adjacent spent fuel so as to constrict air flows and thus worsen the spent fuel heatup in these assemblies as well.

F1L

(i) Strontium-90, Cesium-137 and Plutonium are the dominant radioactive substances in spent fuel from a public health risk standpoint. It is conceivable--meaning that it has not been ruled out scientifically--that a near 100% release of Strontium-90 and Cesium-137 radioactivity from the spent fuel into the atmosphere would occur in a spent fuel heatup excursion in a loss-of-water accident. For such a near-100% release to occur, the spent fuel need not necessarily reach melting temperature, but

F1LC

need only attain a level of only about 1900°C and maintain that temperature for a day or so. The Strontium-90 and Cesium-137 could then diffuse out of solid UO_2 fuel at such temperatures. This assumes that the fuel rods have lost their zirconium cladding upon meltdown of the zirconium but that the rods would maintain their rod shape because the UO_2 fuel pellets inside the fuel rods would have sintered together during reactor operation to form a long UO_2 rod capable of maintaining its shape. If the UO_2 rods should crumble, air cooling would be further impeded and lead to higher UO_2 temperatures and consequently a greater thermal potential for strontium and cesium diffusion out of the UO_2 fuel.

F1LP

(j) Calculations exist which indicate that the air inside spent fuel storage building would heat up and pressurize due to the heat of the spent fuel (the building would become like an oven). The air pressurization would burst open the building and thus allow the radioactive vapor and smoke to escape into the atmosphere. If the building vents were opened, the radioactive vapor and smoke could conceivably escape through these vents. Zirconium and hydrogen explosions could conceivably rupture the building as well, to allow the escape of radioactivity.

(k) No experimental data ~~on~~ or theoretical analyses exist on which to establish the potential for release

500 112

F1L

of plutonium in the spent fuel into the atmosphere in a loss-of-water accident. Steam explosions, hydrogen explosions, and zirconium explosions are conceivable mechanisms which could pulverize large quantities of spent fuel bearing plutonium and blow it into the outside environment, where the plutonium would then spread through the environment.

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(1) Calculations exist which indicate that the Salem spent fuel storage building could not be modified to eliminate the possibility of a zirconium fire occurring in a loss-of-water accident. The Sandia Report suggests the possibility of modifying the building to provide for an open chimney effect: a large hole in the ceiling and a large hole at the floor level of the building side wall, to allow perfect room air ventilation during a loss-of-water accident to expel the heated air exiting from the spent fuel assemblies. The holes or openings would be normally closed by large doors, which would be opened in a loss-of-water emergency to create the chimney effect. Such a chimney effect by expelling heated air, would tend to limit the spent fuel heatup temperatures, according to Sandia's analysis, but would not eliminate the possibility of a zirconium fire. Since such a chimney feature would not eliminate the possibility of a zirconium fire, a chimney could conceivably not have any mitigating effect F1

F1mC

at all; for the building openings would provide unlimited air (oxygen) to promote the spreading of the fire and would provide ready access of radioactive vapors and smoke to the outside atmosphere. Nor would the activation of the chimney (automatic or manual opening of its doors) be reliable in the case of a severe reactor accident which causes a spent fuel loss-of-water. A severe reactor accident can potentially cause such a high level of radiation in and around the site that the whole site operating crew could flee in panic, leaving the spent fuel pool and related safety and cooling systems unattended. Under such a panic situation, it would not be expected that the chimney doors, if incorporated into the building, would be opened.

F1N

(m) A reduction in the number of spent fuel assemblies stored in the pool could not eliminate the possibility of a zirconium fire occurring in a loss-of-water accident, nor preclude the possibility of a loss-of-water accident.

(n) Emergency efforts to cool the spent fuel following a loss of pool water could conceivably worsen the accident or otherwise have no mitigating effect. Spraying the overheated spent fuel with water (which would have to be done remotely, due to the heavy radiation emanating from the spent fuel) would cause zirconium-water reaction that could promote the ignition or spreading of a zirconium fire, or cause explosions. Moreover, the heatup of the spent fuel could conceivably cause the boral neutron absorbing material to meltdown, leaving a region of spent fuel without enough neutron absorption to prevent a criticality should the pool be reflooded. Furthermore, the heat of the spent fuel in a loss-of-water accident (and possible explosions) could conceivably damage the spent fuel to such a degree that the pool would continuously leak heavily, should the pool be reflooded, which would result in a heavy seepage of radioactivity into the ground and nearby waters.

(o) In order to evaluate the potential for radioactivity release in a spent fuel pool loss-of-water accident, a thermal analysis must be performed, of course. The only mathematical theory of spent fuel heatup which exists in a form for ready use (besides this author's theory) is the SFUEL computer code of the Sandia Laboratory, which is described in the above-mentioned Sandia Report. The Sandia Report analyzes the loss-of-water accident for a spent fuel storage pool which is close to the Salem design. However, the Sandia Report is not sufficient for evaluating the spent fuel heatup potential for Salem (nor any other spent fuel storage pool); and, furthermore, the SFUEL computer code is not sufficiently developed and verified to provide reliable heatup temperature prediction with reasonable accuracy. To elaborate: F10

F102

(1) The Sandia Report does not investigate the spent fuel temperature excursion beyond the ignition of the zirconium or zirconium melting.

(2) The Sandia Report does not analyze the high-density storage rack design for the ~~care~~ case of imperfect building ventilation, which is the case for all pressurized water reactor (PWR) storage pools, including Salem.

F10

(3) Sandia's mathematical theory (SFUEL) contains serious theoretical deficiencies which, based on independent scoping calculations, may be causing the code to be drastically underpredicting spent fuel heatup temperatures. Foremost are the assumptions in the SFUEL theory that the temperatures of the fuel rods in a given spent fuel rod assembly and at a given elevation are the same (uniform temperature distribution horizontally), and that the temperature distribution inside a fuel rod at any given elevation is also uniform.

(4) Sandia's mathematical theory is not adequately described in the Sandia Report, and requires a systematic checking to verify the

code ~~theqrily~~ theoretically, and calculationally.

(5) A reliable mathematical theory of spent fuel heatup may not be practical, due to computer limitations.

(6) Sandia's SFUEL theory has not been experimentally verified, contrary to the claim made in the Sandia Report that adequate experimental data exists to validate the SFUEL theory. There experiment relied on in the Sandia Report consisted of two heated plates held at a low, constant and uniform temperature cooled by natural air convection; whereas the situation in a spent fuel heatup accident is one of a highly variable temperature distribution and extreme air temperatures in a rod bundle configuaration. Moreover, thermal radiation heat transfer aided by thermal heat conduction, appear to be a crucial heat transfer processes in a spent fuel heatup, which were totally absent in the two-heated-plate experiment cited in the Sandia Report. To adequately account for thermal radiation interchange among, and heat dissipation from, spent fuel rods in a storage pool under a loss-of-water accident, it would be necessary to conduct

F 10G

an experiment which includes a large scale loading of simulated spent fuel (electrically heated) or actual spent fuel. Because the electrical resistance of electrical heater filaments is dependent on temperature, an adequate simulation of spent fuel heatup may not be possible with electrically heated rods; in which case it may not be possible to experimentally verify a mathematical theory of spent fuel heatup, because it would not be practical or safe to conduct such tests with spent nuclear fuel rods.

F 1

(7) In short, the Sandia Report must be critically evaluated.

(p) It would not be practical or safe to experimentally investigate the radioactivity release potential of a loss-of-water accident; particularly in the event of a zirconium fire, zirconium melting, explosion, or other severe process which causes significant changes in the fuel's physical condition, because the fuel temperature excursion and the interrelated radioactivity release would both depend on the physical condition of the fuel and on the size of the spent fuel mass undergoing a loss-of-water accident. Moreover, the behavior of the spent fuel may be a function of the prior aging of spent fuel

F1

in water and the physical history of the spent fuel when it was in the reactor, such as whether the fuel had undergone overheating in the reactor in an accident.

(q) It is not possible to accurately predict the course of a loss-of-water accident once the zirconium cladding becomes ignited. Instead, only mathematical upper bound estimates of the radioactivity release potential could be developed, which presently do not exist. A near--100% release of radioactive strontium and cesium is plausible, and could not be disproven.

(r) The Salem Safety Analysis for the proposed spent fuel storage supplies inadequate information on which to perform heatup calculations; for example, the pool and building dimensions are not given. F1PL

3. POTENTIAL HARMFUL CONSEQUENCES OF THE RADIOACTIVITY RELEASE FROM A LOSS-OF-WATER ACCIDENT

(a) Each spent fuel storage pool at Salem would contain at capacity forty-five million curies of Strontium--90 radioactivity and about the same amount of curies of Cesium-137. For comparison the United States Atomic Energy Commission's report Theoretical Possibilities and Consequences Of Major Accidents In Large[1] Nuclear Power Plants (WASH-740, March, 1957) calculates that the release of 0.15 million curies of Strontium-90 (150,000 curies) could cause agricultural restrictions over a land area equal

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[1] The size of the power reactor assumed in the WASH-740 Report is not "large" compared to present size plants. Specifically, WASH-740 assumes a 500 megawatt thermal (M Wt.) reactor whereas each Salem reactor has a rated pwer outputof about 3300 M Wt.

to 150,000 square miles, which is the size of New Jersey, New York, Connecticut, Massachusetts, Rhode Island, Vermont, New Hampshire, Maine, and half of Pennsylvania, combined. A loss-of-water accident in one Salem spent fuel storage pool could conceivably release nearly all of the forty-five million curies of Strontium-90, or three hundred times the WASH-740 assumed release quantity of Strontium-90.

Assuming that land which is contaminated more than fifty times the WASH-740 contamination limit for Strontium-90 would be ruined agriculturally, which is a prudent assumption and one which is consistent with the view taken in the WASH-740 Report (the WASH-740 Report asserts that Strontium-90 land contamination at ten times the Report's contamination limit would require prohibiting dairying for a very long time), ~~It~~ it can be calculated that a spent fuel pool loss-of-water accident which releases forty-five million curies of Strontium-90 (which cannot now be shown to be impossible) could result in ruining agriculturally a land area of the size of about one-third of the land East of the Mississippi River, or certainly the entire eastern seaborad of the United States and Canada, for a hundred years or more.

F19

F1

(b) The release of Cesium-137 radioactivity from the storage pool into the atmosphere could result in high levels of gamma radiation (intense xray-like radiation) emanating from the ground over an area equal to 150,000 square miles. The gamma radiation exposure to persons standing on the ground could potentially occur at a rate which exceeds by a factor of thirty-eight or more the health limit recommended by the United States Environmental Protection Agency of 25 millirems per year for total radiation exposure from emission of radioactivity due to nuclear power.

(c) No reliable estimates exist of the potential cancer and genetic harm that could result from a near full release of Strontium-90 and Cesium-137 (and other volatile radioactive materials) in a spent fuel loss-of-water accident. Such estimates are necessary and should be developed, in order that the spent fuel accident hazards can be fully evaluated. F19

(d) The contamination levels indicated in (a) and (b) above apply to the boundary of the fallout land area zones that are quantified in those sections. In the interior of the zones and closer to the plant, the contamination levels would be much worse.

(e) One spent fuel pool at Salem would contain the equivalent of thirty-nine tons of Plutonium-239 alpha-

F19

radioactivity. If dispersed uniformly, this amount of plutonium would have the potential for causing abandonment of about five million square miles of land, which is 1.5 times the total United States land area, including Alaska. No analysis exists which proves that an area of the size of New Jersey, say, would not require permanent abandonment due to a plutonium release in the event of a loss-of-water accident in one spent fuel storage pool.

(f) It is possible that a reactor accident at the Salem Station could induce loss-of-water accidents in both spent fuel storage pools, which would then double the above estimates of potential harmful consequences. F1RB

(g) Even if the spent fuel pool held a minimum of spent fuel--sixty-five fuel assemblies, or one-third of a core, as was the original intent--the potential consequences of a loss-of-water accident would still be extreme: for example, a land area of the size of Ohio, or five times the size of New Jersey, could be ruined agriculturally for a hundred years or more, due to Strontium-90 release alone.

4. POSSIBLE LOSS-OF-WATER ACCIDENTS: SPECIFIC POSSIBILITIES

A loss-of-water accident is possible, which can happen if the pool water cooling system should break down. A boil-off of the pool water is possible in such an event, F1R

which would take about four days to two weeks, based on the figure for the "maximum evaporation rate" (56 gallons per minute) given in the Nuclear Regulatory Commission's Safety Evaluation Report (p. 2-5). The most likely cause of a breakdown in the pool water cooling system is a severe <u>reactor accident</u> (see contention No. 7 below). A severe reactor accident could result in such heavy radiation levels at the reactor site that the storage pools would be abandoned. In that event the cooling system would have to be assumed to breakdown; and there would be no adequate assurance that makeup water could be supplied to the pool. Such a reactor accident must be assumed to be highly likely to occur (see contention No. 7).

There are other possibilities for causing a loss-of-pool-water accident through a breakdown in the pool water cooling system which must be given serious consideration. One such possibility is for the reactor plant to have to be permanently closed down due to a reactor accident, leaving only a very small crew to perpetually watch over the storage pool and maintain perpetual cooling. In this situation, a cooling breakdown could occur through negligence and not be corrected. Sabotage and acts of war are other possibilities.

5. CONCEIVABLE POSSIBILITIES FOR LOSS-OF-WATER ACCIDENTS

There are a number of conceivable possibilities F254 of accidents and sabotage which could result in a loss-of-water accident and which, therefore, must be evaluated for their likelihood <u>and</u> their potential for causing a loss-of-pool-water. They are:

(a) Spent Fuel Shipping Cask Drop.

It appears to be possible for the heavy shipping cask to fall from its crane into the storage pool. Such an incident should be evaluated for the potential for rupturing the pool and causing rapid drainage of the pool. A crane failure has already occurred over a spent fuel storage pool (Shippingport); and an incident of improper handling of a spent fuel pool cask has already occurred (Big Rock Point).

(b) Criticality.

Indications are that it is possible for a local criticality to occur in the storage pool (see contention No. 6 below). Such a criticality has yet to be evaluated for the course it could take; so no upper bound exists of its thermal and mechanical consequences. It may be possible that the fission heat generated by such a criticality could cause a rapid boil-off of the pool water, despite the pool water cooling system.

(c) Sabotage and Terrorism. F15

The possibilities for sabotage and acts of terrorism are very real. The use of explosives could destroy the cooling system, and the removal of a new spent fuel assembly out of the pool water would produce such high levels of radiation in the pool building that action to supply makeup water would be severely impeded. Also, explosives conceivably could be used to rupture the pool and thereby cause rapid drainage.

(d) Others.

Under this heading, earthquakes breaking open the pool and large airplane crashes should be considered.

6. CRITICALITY ACCIDENTS

A criticality accident in the spent fuel pool is a very real possibility. Possible causes are as follows:

(a) Missing boral plates in a local region of a storage rack, or boral plates with a deficient amount of Boron-10; and

(b) Underprediction of the effective neutron mulliptication factor (K_{eff}). Public Service Electric and Gas Company's Safety Analysis Report and the Nuclear Regulatory Commission's Safety Evaluation Report do not provide adequate information to assess the hazard of a criticality accident. For example, there is no indication that there would not occur any positive reactivity feedback effect during the fission power rise in a criticality situation. It is a valid concern that a criticality might lead to a rapid boil-off of the pool water. The radiation from such a high-power criticality could conceivably obstruct efforts to control the accident. In order to assess the criticality hazard, therefore, it is necessary that a

X

full analysis be made of ~~the~~ all possible courses ~~of~~ a criticality ~~be developed.~~ may take.

The benchmark critical experiments used by Public Service Electric and Gas Company to verify its mathematical theory for calculating (K_{eff}) are not adequate to verify the accuracy of the predicted (K_{eff}) factor. Those experiments should only be considered as a means to develop the theory for design purposes. In the final analysis, the loading of fuel assemblies into the racks will be the proof of the validity of the predictions of (K_{eff}). Therefore, it would be necessary to perform an experiment in which new fuel is placed in the storage racks under controlled insertion and neutron monitoring for criticality. This should be a practical confirmatory experiment. It is well-established that such an experiment is necessary. Also, consideration should be given to the question of whether local boiling in a number of spent fuel assemblies could cause an increase in (K_{eff}); that is, whether the fuel in the storage racks would be over-moderated. In this regard the above described experiment should investigate the effect of voids and water temperature.

(More)

(c) It is conceivable, too, that spent fuel — particularly, the uranium dioxide — could melt (at 5000°F) and thus form a liquid pool of molten fuel within a frozen shell or crust of uranium dioxide and steel and zirconium. Under this condition, it is conceivable that the plutonium in the molten uranium dioxide could separate and stratify in such a pool — or at least a mass of fuel material could form which is rich in plutonium — and create as a result a nuclear fuel mass capable of generating the same kind of atomic reaction which takes place in an atomic bomb — a runaway reaction which could produce a strong nuclear explosion that would increase the dispersal of the radioactivity, into the environment, especially the plutonium. Plutonium might not escape heated solid fuel rods as readily as Strontium-90 and Cesium-137; and so pulverization or vaporization of the fuel may be required, as in a nuclear explosion, before a large amount of it (plutonium) could be released into the atmosphere. (This nuclear explosion possibility is similar to the mechanism which has been speculated to have caused the "nuclear disaster" in the Soviet Union, namely, a concentration of plutonium in a nuclear waste burial trench.) S~~uch are the courses a loss-of-~~

X 7. REACTOR ACCIDENTS CAUSING ~~A~~ A SPENT FUEL POOL LOSS-OF-WATER INCIDENT Accident F 2

(a) Severe reactor accidents are the most likely cause of a loss-of-water incident in a spent fuel storage pool. A severe reactor accident could result in such heavy radioactive contamination in the area of the spent fuel storage pool and building that the entire operating crew would be forced to flee for their lives. Such high radiation levels would persist for months and thus would prevent emergency crews from returning to the spent fuel pool building to maintain the pool cooling system. In such an accident, it is likely that the cooling system would breakdown, due to a lack of maintenenace, which would lead to a rapid boil-off of the pool water. In addition, the spent fuel scorage pool for Unit No. 2 would suffer the same consequences. (Indeed, the Unit No. 2 reactor would likely be abandoned as well, setting in motion a train of events leading to a core meltdown and possible explosion in that reactor as well).

(b) there exists a great number--essentially an infinite number of severe reactor accident possibilities that could result in a loss-of-water incident in the spent fuel storage pool.

(c) Severe reactor accident possibilities have never been investigated and analyzed by the Nuclear Regulatory Commission and its Atomic Safety and Licensing Board for the potential consequences or the likelihood of such F1U accidents, except to a limited degree in the Nuclear Regulatory Commission's Reactor Safety Study (Rasmussen Report), which is not an adequate hazards' analysis to assess the reactor accident risks (see contention No. (f)(6) below). It is contended that it has not been ruled out by scientific concensus that the potential harmful consequences of a servere reactor accident causing radioactive contamination could be:

(1) 120,000 square miles of land requiring evacuation or living restrictions.

(2) A lethal range of seventy-five miles of a released radiation causing acute radiation disease.

(3) 500,000 square miles of land requiring agricultural restrictions due to the release and fallout over the land of Strontium-90 alone; and

(4) If the living and agricultural restrictions are relaxed substantially, about 100,000 to 500,000 additional cancer deaths could result. From the figures, it can be appreciated that there exists the potential for causing abandonment of the spent fuel storage pools in the event of a ~~reverse~~ severe reactor accident.

(d) The proposed increase in the storage of spent fuel in each storage pool from about 65 spent fuel assem- F1 blies to 1170 spent fuel assemblies, amounts to an eighteen- fold increase in the quantity of spent fuel and hence Strontium-90 and Cesium-137 radioactivity to be stored. Since the core of one reactor would contain about 3.7 million curies of Strontium-90 which, if released in a reactor accident, would have the potential for causing agricultural restrictions over 500,000 square miles, and since one storage pool would, by the proposed storage increase, contain forty-five million curies of Strontium-90, or twelve times more Strontium-90 than in the core of the reactor, which could conceivably be released into the atmosphere in a loss-of-water incident, it is imperative that the most likely causes of a loss-of-water incident in a storage pool, namely, severe reactor accident possibilities, be investigated. Severe reactor accident possibilities cannot be considered independent of spent fuel storage loss-of-water accidents. From a radiological health standpoint, and in view of the fact that Strontium-90, Cesium-137 and Plutonium are among the most biologically hazardous radioactive substances, if not the most hazardous, the proposed storage increase would so greatly increase the potential consequences of reactor accidents that the issue of the likelihood of severe reactor accidents must be thoroughly and completely investigated. (The proposed storage increase is like proposing the construction of twenty-four large power reactors from a radiological hazards standpoint, particularly with respect to Strontium-90, Cesium-137, and Plutonium release potentials).

(e) The Nuclear Regulatory Commission has announced on January 18, 1979 that it supports the "use of ~~probabilities~~ probabilistic risk assessment in regulatory decision making," in other words, the making and considering estimates of the numerical probability of severe reactor accidents. However, it is contended that the probability of a severe reactor accident occurring within the next twenty years or so which results in a loss-of-water ~~incident~~ accident in a storage pool, cannot be proven to be significantly less than 100%; and that, therefore, ~~probabilities~~ probabilistic risk assessment methods should not be used to assess the risks of the proposed storage increase. F1

It is contended that in order to safely judge the overall safety or hazards of the Salem reactors and associated storage pools, the applicants (utility) and their nuclear plant designers and supplier and/or the Nuclear Regulatory Commission must analyze and evaluate all known accident possibilities (such as multiple control rod ejection accidents, including chain reaction ruptures of control rod drive mechanism housings, loss-of-coolant accidents without SCRAM, ejection of a high reactivity worth control rod, F1✓

and power excursions with excess boron concentration in the coolant) for both their likelihood of occurrence and their potential consequences, and publish the entire analysis and evaluation (that is, without reduction or simplification), as well as a reduced, simplified summary. Furthermore, the Nuclear Regulatory Commission should accept and hear testimony from all parties on the adequacy of such an analysis and evaluation, and should accept general testimony as to the likelihood and consequences of all possible serious reactor accidents (that is, the ~~testimoany~~ testimony should not be limited to the scope of the applicant's present safety analyses or the analysis and evaluation called for above, but receive independent analysis as well), and should fully consider and fully weigh all of the testimony and analyses and evaluations as above described in forming its opinion on the application. The called for analysis and evaluation of all possible accident--their likelihood and consequences--should also include:

(1) A listing of all theoretical uncertainties with regard to the possibility for worse consequences than predicted and the combined effect of the uncertainties.

(2) An identification of all parts of the analyses which have not been experimentally

F1VE

verified.

(3) A detailed fault tree graph for each accident possibility and a graph of the chain of events and equipment failures and human errors for each accident possibility; and

(4) A compilation of all experiences of reactor equipment failures and human error related to each accident chain of events.

It is further contended that a severe reactor accident which would likely cause a loss-of-water ~~incident~~ accident in a spent fuel storage pool is likely to occur--that is, such an accident can reasonably be expected--based on the fact that there is seemingly an infinite number of such accident possibilities, and based on the large potential for human error and carelessness and other human failings, and on the experience record of equipment malfunctions, past reactor accidents, and near-accident incidents.

F2

(f) The following additional contentions regarding reactor accidents are offered:

(1) The theoretical predictions of the course of the reactor design basis accidents have not been adequately verified experimentally. The accidents of most concern are the loss-of-coolant accidents, the control rod ejection

F1WE

accident, coolant pump seizure, control rod withdrawal accident, and the anticipated transients without SCRAM (that is, without emergency fast shutdown of the fissioning). For examples of particulars, see The Accident Hazards Of Nuclear Power Plants by Richard E. Webb (University of Massachusetts, 1976), Chapter 4 and 9. The applicant's reactor safety analysis reports do not give adequate scientific reasons why full-scale reactor tests are not necessary, nor do the reports even address the question of the necessity of full-scale or even large--but-less-than-full-scale tests.

(2) The theoretical analyses of the design basis accidents have a number of theoretical and mathematical shortcomings. See examples in chapter four of The Accident Hazards of Nuclear Power Plants. F23

(3) The safety analysis reports submitted by the applicant do not justify the selection of the reactor design basis accidents relative to possible accidents which are more severe. F1

F1w

(4) The reactor design basis accidents are analyzed in the applicant's safety analysis report with the added assumption in some cases of a single additional failure of some component in the safety systems intended to control the accident. However, the applicant's and the Nuclear Regulatory Commission's analyses do not give adequate analysis and consideration of past reactor accidents and near-accident incidents, some or most of which occurred by and with multiple malfunctions and human error. This is further reason why the full analysis and evaluation of all accident possibilities--their likelihood and potential consequences--should be prepared and considered. The Nuclear Regulatory Commission's "single failure criterion" to judge accidents worse than the design basis accident as "incredible" is wholly inadequate to assure safety, and should not be a basis to deny the full investigation of all accident possibilities as called for above.

(5) The magnitude of the potential consequences discussed above requires that the Nuclear Regulatory Commission should require the analy- F1x

F1

sis and evaluation of the likelihood and potential consequences of all accident possibilities, as described by the above contentions, and should fully consider and fully weigh the said likelihood and consequences of all accident possibilities, and should fully consider and fully weigh the said likelihood and consequences in the light of the experience of past reactor malfunction (see Accident Hazards generally, and chapters 5 and 6, including the section on Probability of Accidents, pp. 96-98 and appendix 2, and the testimony by D. Bridenbaugh, et al., before the Joint Committee on Atomic Energy of the U. S. Congress, February 18, 1976, which suggest that the likelihood of such severe accidents is not remote and may be unacceptable). A sound, rational judgment of reactor safety is not possible without the full analysis and evaluation called for in the above contentions.

(6) The Nuclear Regulatory Commission relies on the before-mentioned Rasmussen Report and a review of that Report known as the Risk Assessment Review Group Report (Lewis Report) to judge that the risk to the public health F1

F2

and safety due to the accident possibilities which are more severe than the design basis accidents is acceptably low and that the more severe accidents need not be further considered. It is contended that the Rasmussen Report and the Lewis Report have fundamental shortcomings which preclude their being used to establish the level of risk of the said severe accident possibility. See Accident Hazards, chapter six and appendix one, and the reviews of the Rasmussen Report by the United States Environmental Protection Agency, dated August, 1975 and June, 1976 (EPA-520/3-75-012 and EPA-520/3-76-009), for discussions of some of the shortcomings. For example, the most severe class of reactor accidents, namely nuclear runaway, are not analyzed for their likelihood and consequences in either the Rasmussen report or the Lewis Report. (*)

Other shortcomings of the Rasmussen Report are: The report does not present the analysis of the probability of the severe accidents which the reports considered, such as transients-without-scram; rather the report merely gives the results of the analysis performed by the Rasmussen study group, by the use of simplified, "reduced" fault trees, for example. In one extremely important instance, at least, there is no fault tree given at all, specifically, for the accident involving the failure of the recirculation pump trip safety action during an "anticipated transient without scram" (though this is a boiling water reactor accident, there likely are instances for the pressurized water reactor in the report as well, for I recall no fault tree for coolant pump siezure and control rod ejection accidents). The public is being asked, therefore, to accept the results of the Rasmussen Report and the Lewis Report on faith. This prevents others from being able to adequately scrutinize the probability evaluation of the Rasmussen Report for its accuracy, completeness, and validity of assumptions (explicit and implicit), which are mostly subjective. Moreover, the simplified analysis presented in the Rasmussen Report contains symbols which are not defined adequately for purposes of examining the safety systems for their potential for, and the likelihood of, malfunction.

F1XK

Overall, it is contended that the applicant's and the Nuclear Regulatory Commission's safety analysis reports are not an adequate basis for assessing the safety of the proposed Salem pressureized water reactor and its storage pools, and that the Rasmussen Report and the Lewis Report are not an adequate supplement to answer the concerns of these contentions.

(7) The reliability of the SCRAM system to control accidents has not been adequately demonstrated. (SCRAM means the rapid insertion of the reactor control rods, which shuts down the atomic reaction). No backup SCRAM system exists. The applicant has not adequately demonstrated that a backup scram system is unnecessary, inasmuch as the pressure surge of anticipated transients without scram may be too high. F2Y

(8) The integrity of the reactor containment system under a design basis accident (loss-of-coolant) has not been adequately confirmed experimentally. Full-scale tests appear to be necessary.

(9) The appplicant's design basis accident for the containment system and the emergency F12

F12

core cooling system (ECCS) has not been shown to be the most likely form of a loss-of-coolant accident. Specifically, the applicant has not demonstrated that a loss-of-coolant accident will not more likely occur as a result of a strong pressure surge transient. Stronger coolant pressures would produce stronger forces on the various components of the containment systems. As for the ECCS, a stronger coolant pressure may be the result of a transient that produces a hotter core at the time of the coolant system rupture. The ECCS is not designed to control the higher pressure and hotter core (higher temperatures) of such a loss of coolant accident.*

X

(10) It is contended that there should be additional consideration of an earthquake producing a loss-of-coolant accident, inasmuch as a prototype reactor plant will not be proof tested by simulated earthquakes (due to obvious impracticality).

F1.

(11) It is contended that the spontaneous reactor vessel rupture type of accident and a vessel rupture due to pressure surges of anticipated transients without scram have

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* This point has been demonstrated by the recent Three Mile Island reactor accident.

F12

not been adequately demonstrated to be of negligible probability (to warrant their neglect in the reactor containment design). There is the question of no leak-before-break warning.

(12) The applicant's safety analysis has not given adequate consideration for the possibility, perhaps the likely possibility, that a severe reactor accident will occur as a result of unforseen causes or effects, as that seems to be the experience of accidents or near-accidents in nuclear power plants.

(13) The applicant's safety analyses have given inadequate consideration to the possibility of common-mode type failures in the coolant piping and the emergency core cooling system piping, especially the possibility for sequential failure of the latter due to the forces generated by the former.

F21

(14) the applicant has given inadequate consideration to the possibility of sabotage, for example, consideration should be given to the lack of provision for separate rooms and blast shielding in between, to separate backup safety systems, instrumentation, and cables

from primary equipment in rooms normally unattended, to minimize the likelihood of a saboteur's bomb knocking out primary and backup safety equipment at once. Also, a multiple control rod ejection accident could easily be caused by a saboteur's bomb.

(15) Amplification of the preceding contention along with supporting arguments and information are given in the following documents, which have never been disputed by the Nuclear Regulatory Commission:

a. *The Accident Hazards Of Nuclear Power Plants*, R. E. Webb.

b. Memorandum in support of the contention of the Coalition for Safe Energy in the construction permit hearings for the proposed Erie pressurized water reactor (Docket No. STN-50-580 and 581), dated September 26, 1977, which treats issues concerning the emergency core cooling system; specific possibilities of "anticipated transients without scram" and their likelihood; the need for full scale testing of analyses of certain accidents; kinds and causes of multiple control rod ejection accidents; power excursions with excessive boron concentration in the coolant; loss-of-coolant accidents without scram; and common mode failures in coolant piping and emergency core coolant piping in loss-of-coolant accidents.

c. Remarks by R. E. Webb before the Nuclear Regulatory Commission's Atomic Safety and Licensing Board on the said Erie proceeding, July 28, 1977, Transcript pages 81-176, defending his contention. F22K

d. Petition to Congress "Calling for a Full Review and Investigation of the Hazards of Nuclear Power Plants and Radioactive Waste Disposal," by R. E. Webb, May 20, 1978, including an appendix titled "Remarks on the Crucial Factor of the Surface Contamination Limits for Plutonium and Strontium-90."

8. PERMANENT SPENT FUEL REPOSITORY AT SALEM F21F

(a) It is contended that it is likely that the spent fuel from the Salem reactors will be stored permanently in the on-site storage pools--that the Salem reactor site will become a permanent repository for the high-level radioactive, spent fuel generated at the plant.

(b) There presently exists no geologic nuclear waste repository for disposing of the spent nuclear fuel; and no such repository is likely to be developed and demonstrated to be safe, or permitted to be built and operated.

(c) Off-site spent fuel storage pools which store only aged spent fuel assemblies (older than six months or a year) have catastrophic loss-of-water accident possibilities as well as the reactor site storage pools. Such off-site pools have yet to be evaluated fully for their spent fuel heatup and radioactivity release potential in loss-of-water accident. Furthermore, the theoretical deficiencies in Sandia's mathematical theory (SFUEL) for spent fuel heatup in a loss-of-water accident, which are discussed in contention no. 2.(o) above, may very well mean that the heatup predictions presented in the Sandia Report for off-site pools may be grossly in error in the unsafe direction. Therefore, off-site storage pools cannot be considered a safe alternative for storing Salem spent fuel; nor does it appear to be an economically viable alternative.

(d) Even if the spent fuel were not allowed to accumulate in the Salem pools, there will be at least sixty-five new spent fuel assemblies stored in each pool at any one time, which means that there would be about F22F

2.5 million curies of Strontium-90 in each storage pool (and a like amount of Cesium-137). Information recently developed about the loss-of-water accident hazards of spent fuel storage pools reveals that it is conceivable that the Strontium-90 and Cesium-137 could be released from the fuel into the outside atmosphere in such ~~which~~ an accident (even for open, low density storage racks). Thus, a loss-of-water accident in a single spent fuel pool could result in ruining agriculture,[6] over a land area equal to three times the size of New Jersey, among other disastrous consequences. The combined release of radioactivity from a reactor accident and two spent fuel storage pools (as a consequence of a reactor accident) would be about three times worse.

(e) The only way to avoid the risks of spent fuel storage, therefore, is to cease generating the radioactivity by closing down the station and terminating the construction of Unit II--that is, to revoke the reactor licenses.

(more)

9. Impracticality of Theoretical Analysis and Experimental Verification.

The preceding contentions describe a broad scope of theoretical analyses and experiments that would be necessary in order to fully evaluate the hazards of spent fuel storage (and reactor accidents). However, it is contended that it is not practical (humanly possible) to prepare the needed analyses nor to conduct the needed experiments; and, therefore, the full hazards could never be scientifically established, except by assuming the worst conceivable consequences--that is, a near full release of radioactivity from the storage pool.

10. ~~2~~ CONCLUSION

F22P

Spent fuel storage at Salem (and any other reactors) is unsafe because loss-of-water accidents are possible and because the potential harmful consequences are extreme. Closing down the reactor* is the only responsible course of action. This would eliminate the risk of reactor accidents, which itself is extremely grave.

* and all other nuclear power plants

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