Nuclear accident in Fukushima-I nuclear power plant: Critical Analysis

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Abstract

The Fukushima nuclear power plant was struck by a magnitude 9.0 earthquake, followed by a magnitude 9.1 tsunami in the early afternoon of March 11, 2011. These two events crippled a significant part of the protection systems of the boiling water reactors in the power plant, resulting in a meltdown in multiple units. This work examines the background and sequence of events experienced in the Fukushima-I nuclear power plant and, in particular, the consequences of the long duration station blackout that disabled the emergency cooling systems of the reactors. To verify the importance of cooling and containment, it was estimated, for unit 1: (i) the core residual heat power at different times after the shutdown; (ii) the residual heat power in the spent fuel ponds; (iii) the core inventory at different times after the shutdown; (iv) the time that it takes to evaporate water in an unattended spent fuel pond; (v) the effective dose evolution until 30 m away from a molten reactor core in different media. The radioactive releases from the meltdown were less than 10% of the ones from the Chernobyl accident and were mostly a consequence of the hydrogen explosions in the buildings of units 1, 3 and 4. Even though radiation levels rose due to these releases, it is expected that the incidence of diseases caused by the extra radiation exposure stay below detection. The Fukushima-I nuclear accident shook the public trust on the nuclear industry and its future plans. It showed flaws that need to be fixed in the future in the regulation, preparation measures and management of nuclear accidents and on the national (Japanese) and international communication and cooperation.

Keywords: Fukushima-I, nuclear safety, (severe nuclear) accident, (boiling water) reactor

1. Introduction

Nuclear industry has grown a lot through the years. Learning from nuclear accidents, i.e., investigating their background, causes and consequences, enables the industry to learn with its mistakes and improve itself.

A severe nuclear accident is considered an extraordinary event due to its large consequences both in the involved facility (and workers) and general population (health, lifestyle, etc.).

The severe accident that occurred on the 11th of March of 2011 in Fukushima-I (Fukushima Dai-ichi) nuclear power plant, operated by Tokyo Electric Power Plant (TEPCO), had a huge impact in the nuclear safety history. There, for the first time, there were accidents in three reactors of the same plant, at the same time, in conditions never experienced before.

2. The Fukushima-I nuclear power plant

Fukushima-I nuclear power plant (see Figure 1) was equipped with 6 boiling water reactors (BWR) in 6 different units. Table 1 summarizes the characteristics of the different reactors in Fukushima-I.

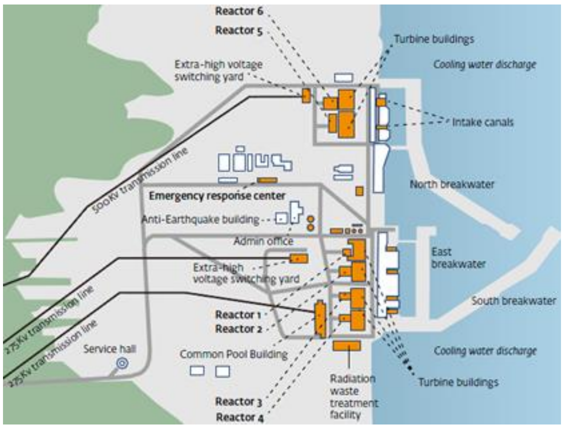

Figure 1: Fukushima-I nuclear power plant [1]

Table 1: Fukushima-I reactors [2]

Unit		Power (MWe)	Construction
1	BWR3	439	1970
2	BWR4	760	1973
3			1974
4			1978
5			1977
6	BWR5	1067	1979

The BWR is a light water reactor (LWR) that uses water as coolant and moderator. All the fuel of the reactor, enriched uranium, in this case, make the reactor core which is kept inside the reactor pressure vessel (RPV). This is contained by the reactor building (R/B) that is connected to the turbine building (T/B) which houses, among others, the turbine, generator and condenser (shown in Figure 2).

3. Nuclear Safety

The basic principle of nuclear safety is to ensure that nuclear reactors don't damage public and/or individual health plus protect the nuclear power plant and its workers. Safety culture is intrinsic to nuclear safety. The safety culture was developed since the beginning of nuclear industry so it would be inherent to the operation of every nuclear power plant.

A nuclear accident may have consequences that affect the general public. Therefore, nuclear industry is highly regulated by the countries that deal with nuclear power. The International Atomic Energy Agency (IAEA) promotes nuclear safety around the world and provides guidelines regarding nuclear industry that must be followed.

A normally operating nuclear power plant is considered safe with incidents occurring at a low frequency rate. To measure this and interpret results from probabilistic safety assessments (PSA), there are two indicators used worldwide:

- Core Damage Frequency (CDF) – 10^{-6} to 10^{-4}/year; Japan: 10^{-4}/reactor·year
- Large (Early) Release Frequency (L(E)RF) – Japan: 10^{-5}/reactor·year

The International Nuclear Events Scale (INES) classifies the severity of nuclear events in a logarithmic scale. Each of Fukushima-I events alone are classified as level 5. However, altogether are considered as level 7. Since level 7 is the last level of this scale and is an open level, even if Fukushima-I accident was 10 times smaller than Chernobyl accident, they both are classified as level 7.

The design of a nuclear power plant is made so the probability of an accident occurring is the lowest possible. For that, each plant has a safety design basis. For a light water reactor (LWR) this design is made to prevent a loss of coolant accident (LOCA), defined as the design basis accident (DBA). The designed system to fight the DBA is the Emergency Core Cooling System (ECCS).

To assure that all operation proceedings occur, there's a lot of variety and redundancy in the systems and equipment. This is related to the defense in depth approach, integrated in the design of nuclear power plants for more than 50 years. This approach is based of 4 consecutive barriers that prevent radioactive releases. Each barrier is protected by several independent levels.

The public risk associated to nuclear accidents was first approached by Farmer in 1975 [4]. There weren't so many severe nuclear accidents during nuclear industry history, however it still doesn't inspire trust among the general public. On the other hand, car accidents happen every day, but people trust this industry. The situation with nuclear accidents is similar to the one with plane crashes: although accidents are rare, their consequences might be extraordinary and that raises a lot of insecurity among the general public.

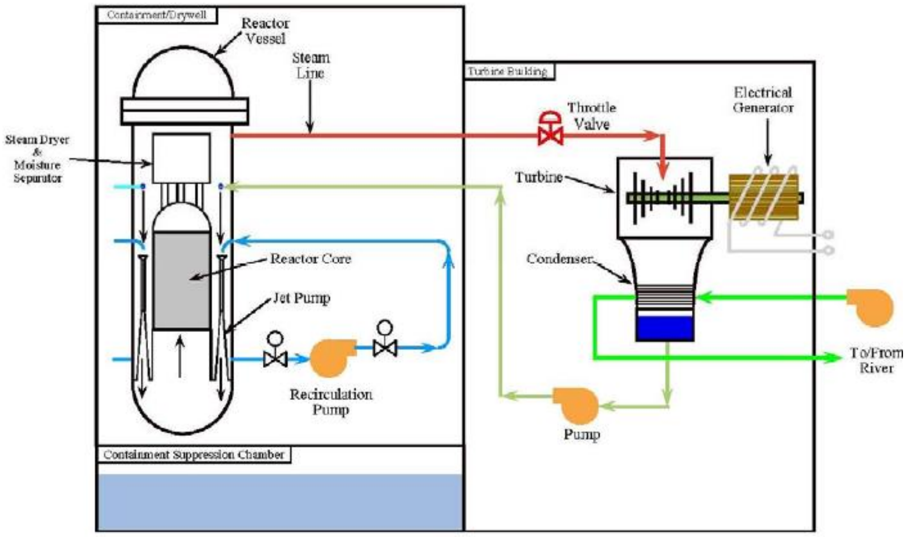

Figure 2: Layout of a BWR and its buildings, R/B (on the left) and T/B (on the right) [3]

4. The Accident

4.1 Accident Preparations in Fukushima-I

Fukushima-I nuclear power plant was built during the 1960s and the 1970s [2].

Throughout the years, TEPCO made efforts to improve the safety of their nuclear power plants and its own safety culture so it could respond the best way possible to a nuclear accident [2].

Since Japan is in a seismically active zone, there had to be earthquake and tsunami assessments to design the Fukushima-I nuclear power plant. Instead of doing a deterministic earthquake assessment, it was made a probabilistic one. This caused that the design wasn't made to endure on the worst conditions possible.

Since it was built, the plant was constantly updated with new safety measures. On the time of the nuclear accident, the plant was prepared to withstand ground movements until 270 Gals (by the essential facilities for the plant safety) and a maximum run-up height of O.P. +6.1 m [2]. As it will be shown later, this run-up height wasn't enough to bear the tsunami on the 11th of March of 2011. The unpreparedness for the tsunami was due to the lack of regulations regarding tsunamis. This happens because tsunamis weren't considered a serious threat to nuclear power plants till Fukushima-I accident. All studies suggesting big tsunamis striking the plant were always rejected as they were considered irrelevant and/or inconclusive.

All regulations were respected by TEPCO while designing and operating Fukushima-I [2]. However, a long duration station blackout (SBO) was never proposed, either by TEPCO itself or by a regulatory entity, as a possible accident scenario so the plant wasn't prepared for it when it happened on the 11th of March of 2011 [2].

4.2 Description

Tohuku earthquake stroke the plant at 2:46 pm on the 11th of March of 2011. At that time, only units 1 to 3 were in operation since units 4 to 6 were under regular maintenance. The earthquake had a magnitude of 9.0 in Richter's scale and had epicenter just 178 km from Fukushima.

As soon the earthquake was felt, all operating reactors went under automatic shutdown as planned. Since the grid power was cut with the earthquake, the emergency diesel generators (EGDs), 2 in each unit, started automatically.

All measures and operations took place as planned until the tsunami arrived.

Tohuku earthquake consequent tsunami arrived to the plant at 3:30 pm that day. The tsunami had a magnitude of 9.1 and it's estimated that arrived to

Fukushima-I with 13.1 m height (more than two times the height the plant was prepared to withstand).

The plant conditions deteriorated with the tsunami arrival. All EDGs, except one in unit 6 that was air cooled, stopped. This prevented all monitoring and cooling systems from working. Since there wasn't also external power available, Fukushima-I went under a long duration SBO, situation never occurred in nuclear industry. Also, when the tsunami stroke the plant, almost all facilities and surroundings got flooded, as shown in Figure 3.

Although the earthquake was slightly over of what the plant was design to withstand, it was the tsunami the cause of the nuclear accident.

The management and information disclosure of the accident was hard. There wasn't much technology available, the facilities and equipment were damaged and there was lack of cooperation and transparency between the several entities involved. The lack of technological conditions demanded a unified response by all entities involved.

Figure 3: Flooding in Fukushima-I caused by Tohuku earthquake consequent tsunami [2]

4.2.1 Hydrogen Explosions

On the 12th of March of 2011 unit 1 R/B suffered an explosion. This was followed by two other Hydrogen explosions in units 3 and 4 on the 14th and 15th of March, respectively. Since there's no evidence of unit 4 core damage, the origin of the Hydrogen in its R/B is thought to be one leaked into the building from unit 3 venting. This questions the design of the plant since a problem in a unit may harm an adjacent one (also happened with unit 2 that was damaged due to units 1 and 3 explosions).

The most probable origin of the Hydrogen is thought to be the Zirconium oxidation:

$$Zr + 2H_2O \rightarrow ZrO_2 + 2H_2 \quad (4.2.1.1)$$

The Zirconium is the main component of Zircaloy, cladding of the fuel. The reaction (4.2.1.1) is exothermic (1560 cal/g(Zr)=6.5 kJ/g(Zr) [5]) and accelerated by high temperatures. This can be easily perceived by drawing the curve (see Figure 4) of Zirconium oxidation rate:

$$R = 13.9e^{\frac{-1.47eV}{kT}} p^{1/6} \left(\frac{g}{cm^2 s}\right) \text{ [6] } (4.2.1.2),$$

where k is the Boltzmann constant, $k = 8.617 \times 10^{-5}\ eV/K$.

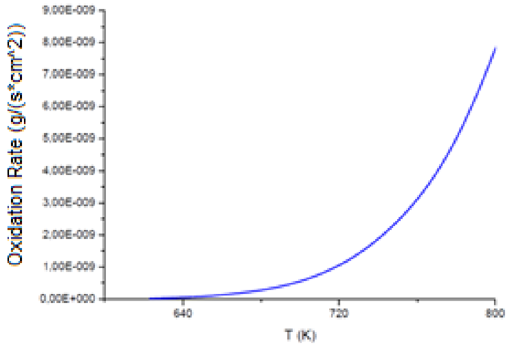

Figure 4: Exponential growth of Zirconium oxidation rate with temperature at p=1 atm, described by equation (4.2.1.2)

It's considered that the high temperatures experienced in Fukushima-I due to the lack of cooling systems, for a long period of time, allowed the Zirconium oxidation and accelerated the combustion of the Hydrogen, produced by the same oxidation reaction.

Although the plant was prepared to deal with Hydrogen production (Hydrogen recombiners, venting system, inert atmosphere, etc.), it wasn't predicted that the Hydrogen leaked from the pressure containment vessel (PCV) to the R/B, where there were no ways of eliminating the Hydrogen. Also, the station wasn't equipped with passive autocatalytic recombiners (PARs) that work even under a SBO.

5. Residual Heat Power

After the shutdown of a reactor, its main source of heat becomes the decay of the fission products.

Once under SBO, all cooling systems of the plant became inoperable and it wasn't possible to remove any of the residual heat being produced.

So it could be understood the importance of cooling systems to remove the residual heat being produced, there were made several calculations:

i. Residual heat power in unit 1
ii. Residual heat power in unit 1 SFP
iii. Evaporation time of a 1000 m^3 SFP

5.1 Residual Heat Power in Unit 1

The residual heat power produced in unit 1, after the shutdown, was estimated by 5 different methods. For all of them, it was assumed that the reactor was operating for a complete fuel cycle (58.5 months – 12 months operation and stops of 3.5 months for renewal of ¼ of the fuel).

Unit 1 core was composed by ^{235}U, 3.5 %, and ^{238}U, 96.5%.

The first 3 methods used are simple empirical formulas that depend on the burnup and decay times in question. These 3 methods are summarized in [7] and written below:

1) $\frac{P}{P_0} = 0.066\left[\tau_{elapsed}^{-0.2} - (\tau_{elapsed} + \tau_s)^{-0.2}\right]$ (5.1.1)

2) $\frac{P}{P_0} = 0.1\left[(\tau_{elapsed} + 10)^{-0.2} - (\tau_{elapsed} + \tau_s + 10)^{-0.2} + 0.87(\tau_{elapsed} + \tau_s + 2 \times 10^7)^{-0.2} - 0.87(\tau_{elapsed} + 2 \times 10^7)^{-0.2}\right]$ (5.1.2)

3) $\frac{P}{P_0} = 5 \times 10^{-3} a\left[\tau_{elapsed}^{-b} - (\tau_{elapsed} + \tau_s)^{-b}\right], in\ this\ case: a = 27.43\ e\ b = 0.292$ (5.1.3),

where P_0 is the thermal operating power of the reactor,1380 MWt, and τ_s the time the reactor had been operating (58.5 months).

Figure 5 shows the dependence of the residual heat power on the burnup time. It can be understood that the residual heat powers with longer burnup times are not so different than the ones with smaller burnup times.

Other method used was the American Nuclear Standard (ANS)-5.1.-2005, summarized in [8]. This was developed as a C++ program where the residual heat power was calculated until 9 months after the shutdown.

For the last method, it was used the software Origen 2.2 where it's also taken into account the contribution of activation products and actinides to the residual heat power. The results are shown in Figure 6.

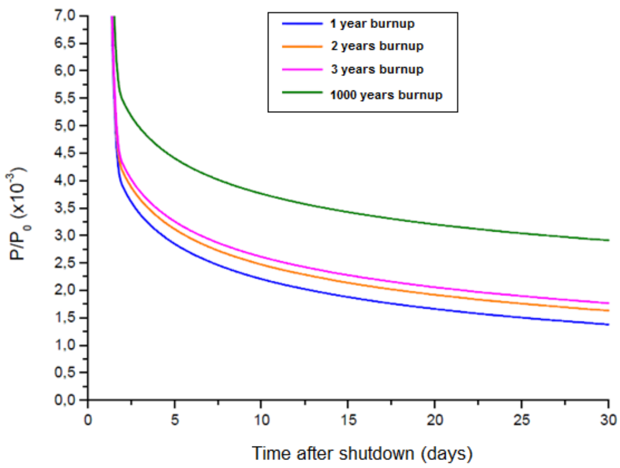

Figure 5: Dependence of decay heat power with the burnup time. Calculations made using the method of equation (5.1.1). The 1000 years burnup is not physically realistic, it illustrates an infinite burnup time

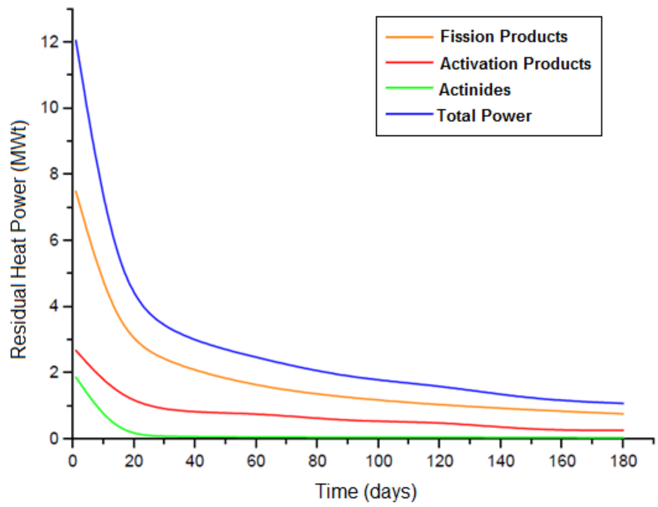

Figure 6: Decay heat power results generated by Origen 2.2. Different contributions and total power

In Figure 7 there are shown the results for the 5 different methods used until 9 months after the shutdown of the reactor.

According to results released by TEPCO in November of 2011 [9], 1 day after the shutdown, the residual heat power was around 6 MWt, value supported by the calculations made in the present work.

Analyzing all the 5 methods used, it can be understood that during the first moments after the shutdown, the residual heat power is always less than 10% of the operating power of the reactor. After, the residual heat power decreases exponentially, i.e., after 9 months of the shutdown, the residual heat power is certainly less than 1% of the 1380 MWt of the operation of the reactor. Therefore, it can be concluded that first moments after the shutdown are critical for the core cooling since it's released a great quantity of residual heat that will contribute for the water evaporation, exposing the core that may lead to a meltdown and hydrogen production.

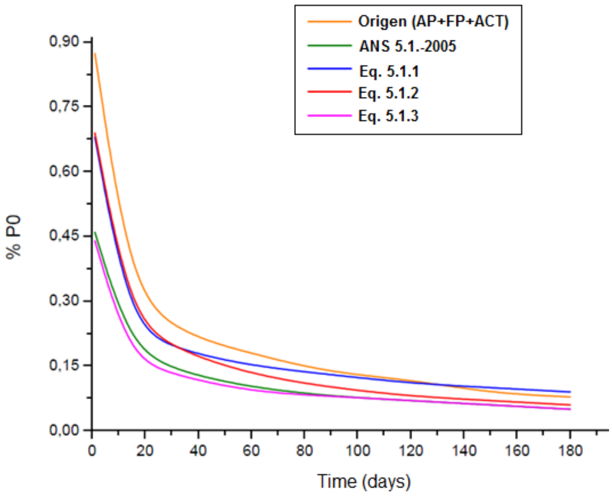

Figure 7: Results of the calculations for the decay heat power in unit 1 until 9 months after the shutdown by 5 different methods

TEPCO estimates that the core of unit 1 was exposed at 6:10 pm of the day of the accident [2]. It's also estimated that the damage in the core of unit 3 started 44h after the accident and of unit 2, after 77h [2].

5.2 Residual Heat Power in unit 1 SFP

According to [10], the spent fuel pool (SFP) of unit 1 had the distribution of fuel elements (FE) showed in Table 2, each FE having a weight of 0.17 tHM.

Table 2: Number of FE in SFP of unit 1 with their respective storage time [10]

Time Storage (years)	0	0.5	1.5	2.5	3.5
#FE	0	133	133	26	0

Using the method given by the equation (5.1.3) and the ANS-5.1.-2005 for the contribution of the FE for the overall residual hear power, it was calculated that at the time of the accident the SFP of unit 1 had a power of 28 MWt, i.e., 2% of the operating thermal power unit 1 reactor.

5.3 Evaporation of a 1000 m^3 SFP

Since a SFP can contain more fuel than a reactor core and has almost no containment measures, in case of the cooling systems fail (as it happened in Fukushima-I accident), the evaporation of a SFP can be more problematic than the uncovering of a reactor core.

To illustrate this problem, it was calculated the evaporation of a 1000 m^3 SFP till the top of the active fuel (TAF) stored, considered to be 4 m, storing ¼ of the fuel of unit 1.

Considering that the pool was, before the cooling fail, at 25 °C, it's needed around 3.14 TJ to saturate the 1000 m^3 of water.

Using a conservative approach and the method given by equation (5.1.3), it was calculated how long it would take for the 600 m^3 in question to evaporate, depending on how long the fuel was stored in the pool. These results are showed in Figure 8. For example, if the fuel was only stored for a day, it would take around 3 days and 16 hours for the water to evaporate. However, if the fuel was stored already for 1.5 years, the 600 m^3 would take 1.54 years to evaporate, revealing an almost liner relation for longer storage periods of time.

6. Radioactive Releases

Some isotopes existent in a nuclear power plant affect badly the ecosystems. This constitutes the main problem of the radioactivity being released to the environment.

The radioactive releases of Fukushima-I nuclear accident were mainly due to the Hydrogen explosions of the R/B of units 1, 3 and 4. Leaks and venting operations (controlled or not) also contributed to the releases.

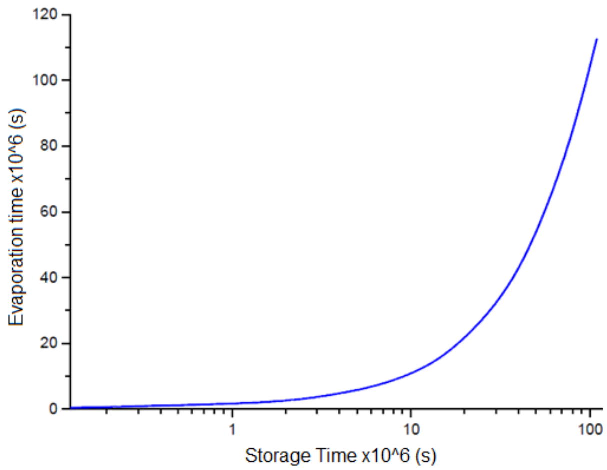

Figure 8: Evaporation time for a 1000 m3 SFP till the TAF depending on the storage time of the fuel that it contains (1/4 of unit 1's fuel)

6.1 Isotopes Inventory

In order to understand the results of the amount of radioactivity released to the environment, it was generated (using the Origen 2.2 software) the inventory of unit 1 core on several moments after its shutdown. The total activity of the core until 9 months after the shutdown is shown in Figure 9.

As it's illustrated in Figure 10, the short living isotopes (like ^{131}I) dominate the activity total during the first few months after the shutdown, after the ones having longer half-lives (like ^{137}Cs) dominate.

Based on the Origen 2.2 results of the isotopes activities and the fuel quantities in the cores and SFPs in Fukushima-I according to [10], it was estimated a total inventory for Fukushima-I for the isotopes: ^{131}I, ^{137}Cs, ^{238}Pu and ^{239}Pu. The total inventory for these isotopes calculated in this work agrees with the one calculated in [10], as it can be seen in Table 3. The differences between the results are due to different assumptions inherent of each work like quantity of impurities, duration of the reactors operation, etc.

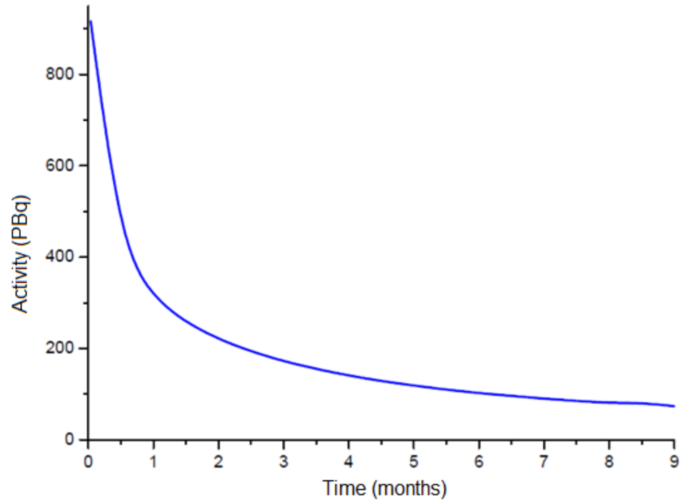

Figure 9: Unit 1 core total activity throughout the 9 months after its shutdown

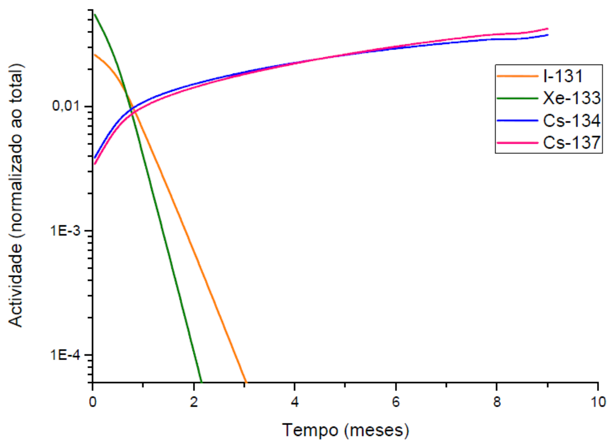

Figure 10: Evolution of the activity of the isotopes ^{131}I, ^{133}Xe, ^{134}Cs and ^{137}Cs, throughout the 9 months after unit 1 core shutdown

Table 3: Total Inventory in Fukushima-I estimated of some isotopes

	A_{total} (Bq) of [10]	A_{total} (Bq)
^{131}I	1.186×10^{19}	1.25×10^{19}
^{137}Cs	2.988×10^{18}	2.27×10^{18}
^{238}Pu	7.917×10^{16}	3.80×10^{16}
^{239}Pu	8.367×10^{15}	7.98×10^{15}

6.2 Effective Doses, Unit 1

From the activities of the different isotopes of unit 1 for different moments after the shutdown previously calculated, was estimated, using the Microshield software, the evolution of the effective doses depending of the medium and distance from the core, For that, it was assumed that the core had a spherical shape when melted with a density of 6.5 kgm^{-3} [11] and 68 tHM and 27 ton of Zircaloy.

Figure 11 shows the evolution of the effective dose rate until 30 m of the reactor's core 1 day after the shutdown in different mediums. Figure 12 shows the evolution of the effective dose rate on air on different moments after the shutdown until 30 m of the core. As expected, both plots show that the furthest from the core, the lower the dose.

From Figure 11 it can be concluded that the concrete is the most effective medium for containment. Water is a good option for the short term storage, as it is in a SFP, since every meter the dose decreases 4 times in magnitude. However, it can also be seen that in the air, even 30 m from the core, the dose is still very high, accentuating the importance of containment.

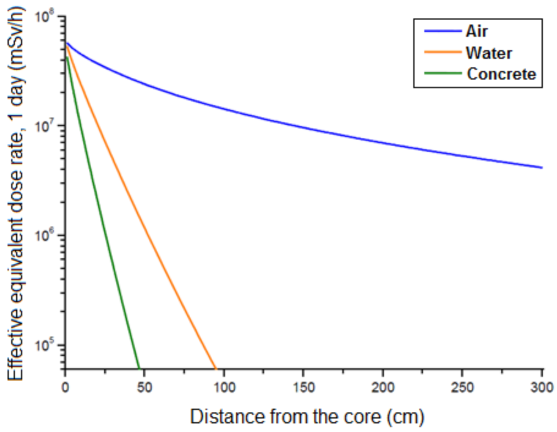

Figure 11: Evolution of the dose of unit 1 core, 1 day after the shutdown, in diferent mediums

6.3 Evacuation

The evacuation order was given regarding that the population wouldn't be exposed to more than 20 mSv/year [12], causing an evacuation zone with a 30 km radium from Fukushima-I nuclear power plant [9].

More than 160 000 people were evacuated. The evacuation caused around 1 200 disaster related deaths (DRDs), mainly due to psychosomatic stress and the fall of medical infrastructures [12]. With such a high number of DRDs, the evacuation parameters should be reevaluated.

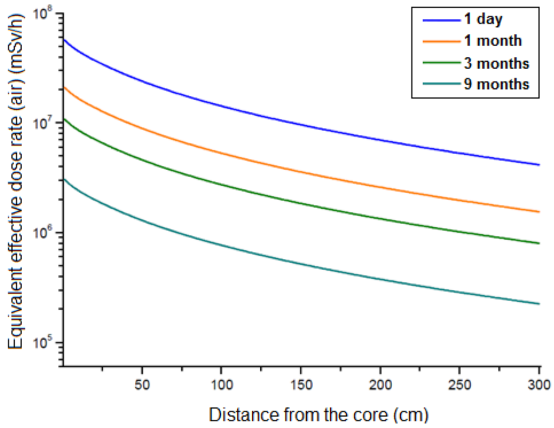

Figure 12: Evolution through the air of the dose until 30 m from the core in different moments after the shutdown

6.4 Radiation Exposure

In Figure 13 is showed the radiation doses in Fukushima area after 1 year of the accident.

The exposure to radiation was only significant in the region of Fukushima. None of the releases was compared to the ones caused by Chernobyl accident. One day after the accident, TEPCO estimated that the releases from units 1 and 3 together corresponded to 10% of the radioactive releases from Chernobyl accident [13].

It's believed that the diseases caused by the extra exposure caused by Fukushima nuclear accident will remain below the detectable parameters.

7. Conclusions

The nuclear accident in Fukushima-I nuclear power plant, classified as level 7 in INES scale, was caused by the consequent tsunami of Tohuku earthquake, for which the plant wasn't prepared for. With the arrival of the tsunami, the facilities were flooded, a lot of equipment was destroyed and the plant entered under a state of long duration SBO.

It was estimated, by 5 different methods, the residual heat produced in unit 1 core till 9 months after the shutdown. From the results, it's possible to conclude that the first few moments after the shutdown are crucial, since the lack of cooling may easily lead to a core meltdown, as it happened. The same thinking can be made for a SFP. A SFP can store more fuel than a reactor core therefore, its cooling is also very important, as also shown in this work, since the fuel can be easily exposed.

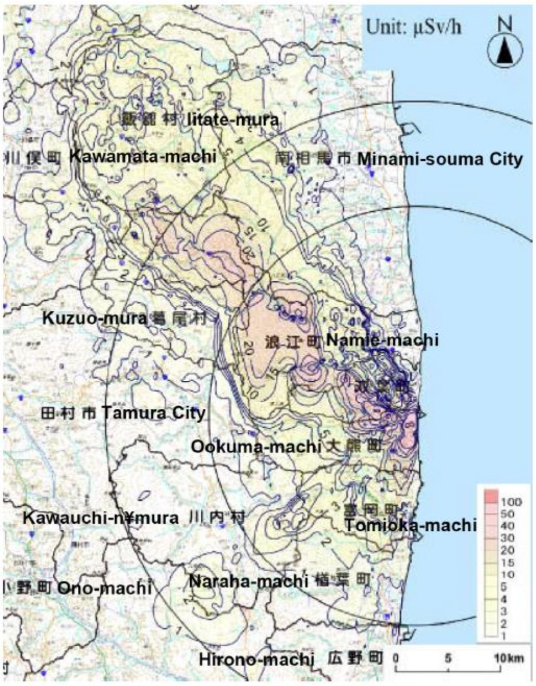

Figure 13: Radiation doses in Fukushima 1 year after the accident [12]

The hydrogen explosions (R/B of units 1, 3 and 4) were the main carrier of the radioactive releases to the environment. The most probable cause of the Hydrogen production was the Zirconium oxidation, main constituent of Zircaloy, present in the fuel cladding. Although the plant was prepared to prevent Hydrogen explosions, the measures weren't present in the R/B, where the Hydrogen leaked to in this accident and leading to the explosions.

It was calculated the evolution of the radiation dose in unit 1 reactor for different mediums and different moments after the shutdown till 30 m from the core. From the results, it can be seen how radiation can easily spread out in case there's lack of containment.

The evacuation order was given so the population wasn't exposed to more than 20 mSv/year, which was estimated to be around 2×10^{-8}% of the effective dose of unit 1 core one day after the shutdown. The evacuation zone was up till 30 km radius from the plant and affected 160 000 people, causing around 1 200 DRDs. The bad management of the evacuation and the high number of DRDs question the evacuation criteria used.

The radioactive releases weren't compared to the ones due to Chernobyl accident. It's believed that the diseases due to extra exposure caused by this accident will remain below detection levels.

The accident management and information disclosure was affected by the lack of cooperation and transparency between the several entities involved. It was seen that Japan wasn't ready to receive international help.

Although TEPCO admits its fault of the accident, it's considered that the Nuclear and Industry Safety Agency (of Japan) (NISA) failed with its responsibility of managing a nuclear crisis.

Fukushima-I nuclear accident shook the public trust in nuclear industry. Therefore, this accident will have consequence of the present operations in nuclear power plants (e.g. evaluate if second generation reactors should still operate) and future plans for the industry. All lessons learned with the accident will be applied to the industry so nuclear reactors may operate the safest way possible.

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