Tree of scenarios for the 2011 accident at the first power unit of the Fukushima-1 nuclear power plant

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Abstract. This paper presents a tree of scenarios for the development of an accident at the first power unit of the Fukushima-1 nuclear power plant in a transfer form. This model allows us to evaluate the probabilistic safety indicators of the power unit, as well as to visualize all possible scenarios for the development of the 2011 accident.

1. Introduction
Today, the nuclear power industry is paying more and more attention to the issue of safe operation of reactor installations [1, 2]. During the design process, planned replacement of reactor plant equipment, or periodically during operation, a safety justification report is issued or reissued for each unit, including a probabilistic safety analysis, which assesses the safety of this unit of a nuclear power plant.

This paper presents only a small part of the probabilistic safety analysis, namely, the conservative construction of the event tree for the first power unit of the Fukushima-1 nuclear power plant, under the complex external impact of an earthquake and tsunami. In other words, building a model based on one initial event, under one normal operation mode (at power), for one location of nuclear materials (reactor core).

2. Methods
When constructing a tree of scenarios for the development of an accident in a transfer form, the complex external impact of an earthquake and tsunami was taken as the initial event. The construction used a conservative approach to building a tree, focused on estimating the probabilistic indicators of a large outlier as a result of an accident.

The final events of the scenario are:

1) safe state of the reactor plant (SafS) – a state in which subsequent failures are extremely unlikely to occur, leading to disruption of normal operation and a large release;

2) singular state of the reactor plant (SinS) – a state in which there is no shutdown of the reactor, but the removal of heat from the core continues, so this state can last extremely long time, and, if subsequent failures or errors occur, instantly lead to a large release;

3) large discharge (LD) and large discharge through the ventilation pipe (LDttVP) – states in which the system has a sharp increase in the main parameters (temperature, pressure, and power), active vaporisation, boiling of the coolant, followed by melting of the fuel and the flow of a vapour-zirconium reaction, as a result of which hydrogen is formed in the protective shell. At the same time, with increasing temperature, the rate of this reaction increases. If the protective shell is vented in a timely manner, hydrogen with radioactive vapour is released through the ventilation pipe, which reduces the concentration of hydrogen and pressure in the protective shell and thereby maintains its integrity. If
ventilation is not carried out, the container flanges start to melt due to high temperatures, the protective shell is depressurized and the hydrogen explosion occurs with the release of radioactive substances outside the reactor installation.

When evaluating the total probability indicators, a singular state, a state with a large outlier, and a large outlier through the vent pipe are taken as an unfavourable outcome. Each of them in one way or another leads to damage to nuclear fuel (melting of fuel rods) and, subsequently, to the release of radioactive materials outside the sealed shell of the reactor plant.

3. Results

The transfer event tree is shown in Figures 1-9.

The estimated total probability indicators of the occurrence of a large release from various scenarios of the accident development at the first power unit are presented in Table 1.

| Events                                           | Total probability of implementation |
|--------------------------------------------------|------------------------------------|
| Explosion, large discharge                       | 7.10222039E-8                     |
| Large discharge                                   | 4.0240304E-11                     |
| Large discharge through the ventilation pipe      | 2.0028068E-7                      |
| Singular state of the reactor plant               | 2.0504996E-12                     |
| Total dangerous condition                         | 2.7135E-7                        |
| Safe state of the reactor plant                   | 0.99999972865                     |
| Total for all outcomes                            | 1                                 |

Figure 1. The event tree. Branch 0.
Figure 2. The event tree. Branches 1.1 and 2.1.
Figure 3. The event tree. Branches 1.2 and 2.2.
Figure 4. The event tree. Branches 1.3 and 2.3.
Figure 5. The event tree. Branches 1.4 and 2.4.
Figure 6. The event tree. Branch 3.1.
Figure 7. The event tree. Branch 3.2.

The event tree:

- **Failure of the emergency protection system**
  - Sensor Failure
  - Damage to the boric acid supply system
    - The lack of core isolation condenser
      - Damage to the core by steam to the reactor by imported means
    - The reactor contour formed by the core

- **Active vaporization**
  - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
    - A hydrogen explosion LD
    - Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
      - A hydrogen explosion LD
    - Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD
      - Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
        - A hydrogen explosion LD
        - Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD
          - Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
            - A hydrogen explosion LD
            - Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD
              - Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
                - A hydrogen explosion LD

The probability of the implementation of branch 3.2 events:

- The input of boric acid - the removal of residual heat through the isolation condenser contour 6.94437E-11
- Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP 2.459972E-13
- Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
  - A hydrogen explosion LD 3E-19
- Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
  - A hydrogen explosion LD 2.459972E-13
- Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD 5E-18
- Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP 9.999888E-17
- Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
  - A hydrogen explosion LD 12E-22
- Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDTYP
  - A hydrogen explosion LD 9.999888E-17
- Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD 1.2E-22
- Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD 2E-21
Figure 8. The event tree. Branch 3.3.

| Damage to the basic and supply contour | Isolation condenser contour damage | The lack of recharging isolation Condenser | The failure of the valves Discharge steam to the reactor by imported means | Damage to the ventilation contour |
|--------------------------------------|-----------------------------------|-------------------------------------------|-------------------------------------------------|--------------------------------|
| 3.3                                   |                                   |                                           |                                                 | The probability of the implementation of branch 3.3 events |
| The lack of cool down - the steam through the isolation condenser contour SinS | 5.04898E-14                      |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDtVP | 2.549915E-16                     |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell - A hydrogen explosion LD | 3E-22                              |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDtVP | 2.549915E-16                     |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell - A hydrogen explosion LD | 3E-22                              |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD | 5.1E-21                            |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDtVP | 9.999888E-20                     |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell - A hydrogen explosion LD | 12E-25                             |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LDtVP | 9.999888E-20                     |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell - A hydrogen explosion LD | 12E-25                             |                                           |                                                 |                                             |
| Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD | 2E-24                              |                                           |                                                 |                                             |
| Sensor Failure | Isolation condenser contour damage | Containment core isolation | Containment core condenser | Water supply to the reactor by imported means | Damage to the ventilation contour | The probability of the implementation of branch 3.4 events |
|----------------|-----------------------------------|---------------------------|---------------------------|---------------------------------------------|---------------------------------|--------------------------------------------------------|
|                |                                   |                            |                            |                                             |                                 | Insertion of control rods - Residual tap heat through the isolation condenser contour SARS |
|                |                                   |                            |                            |                                             |                                 | 2.969988E-17                                              |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LD+VP |
|                |                                   |                            |                            |                                             |                                 | 1.499983E-19                                              |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LD+VP - A hydrogen explosion LD |
|                |                                   |                            |                            |                                             |                                 | 2E-25                                                  |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LD+VP - A hydrogen explosion LD |
|                |                                   |                            |                            |                                             |                                 | 1.499983E-19                                              |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD |
|                |                                   |                            |                            |                                             |                                 | 2E-25                                                  |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD |
|                |                                   |                            |                            |                                             |                                 | 3E-24                                                   |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LD+VP |
|                |                                   |                            |                            |                                             |                                 | 5.499933E-23                                              |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LD+VP - A hydrogen explosion LD |
|                |                                   |                            |                            |                                             |                                 | 7E-29                                                   |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled growth of temperature and pressure in the protective shell LD+VP - A hydrogen explosion LD |
|                |                                   |                            |                            |                                             |                                 | 5.999933E-23                                              |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD |
|                |                                   |                            |                            |                                             |                                 | 7E-29                                                   |
|                |                                   |                            |                            |                                             |                                 | Active vaporization - Uncontrolled increase in temperature and pressure in the reactor - Explosion LD |
|                |                                   |                            |                            |                                             |                                 | 1.2E-27                                                  |

**Figure 9.** The event tree. Branch 3.4.
4. Conclusion
The constructed model allowed us to estimate the total probability indicators of the occurrence of a large release from various scenarios of the accident development at the first power unit due to the complex external impact of an earthquake and tsunami.

The value of the total probability of a large release of $2.7 \times 10^{-7}$ is almost three times higher than the permissible limit, while, as mentioned earlier, this value is obtained only from one initial state and under one operating mode of the reactor. When preparing project documentation, such a value would be unacceptable and would require major changes in the system structure. Therefore, this type of reactor was subsequently improved.

The probability of an accident scenario at the first power unit in 2011 was also calculated [3], its value is $5 \times 10^{-17}$. As you can see, this is an extremely small value, since when building the model, it was assumed that the system was fully functioning according to the rules before the initial event occurred. For this reason, the accident at this power unit is unique, because the cause of the accident is an error made before the start of any impact [4].

References
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