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SAFETY OBJECTIVES AND DESIGN CRITERIA FOR THE NHR-200

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Abstract

The construction of a nuclear district heating reactor (NHR) demonstration plant with a thermal power of 200 MW has been decided for the northeast of China. To facilitate the design and licensability a set of design criteria were developed for the NHR, based on existing general criteria for NPP but amended with regard to the unique features of NHR-200. Some key points are discussed in this paper.

1. GENERAL SAFETY REQUIREMENT

For a nuclear district heating reactor (NHR) it is necessary to locate it near the user due to the necessary way of heat transport (hot water or low pressure steam). This means that a NHR is surrounded by a populous area. Using evacuation as an essential element in the ultimate protection of the public can thus become impractical. The safety for a NHR has to be ensured with its excellent inherent features and passive safety. In all credible accidents the radioactive release from a heating reactor has to be reduced to such low levels that off-site emergency actions, including sheltering, evacuation, relocation and field decontamination will be not necessary. In the Technical Report on "The Design of Nuclear Heating Plant" [1] issued by the Chinese National Nuclear Safety Administration (NNSA) it is stated explicitly that no off-site emergency actions such as sheltering, evacuation etc. are allowed for a NHR. In other words, the maximum accident should be no more serious than a level 4 event by the International Nuclear Event Scale. For a typical site in northern China a maximum individual dose of 5 mSv will result from an activity release of 4.7×10^{13} Bq I-131 equivalent via a stack of 50m height. It is indicated that a release of 3.7×10^{13} Bq I-131 can be the limitation for the maximum credible accident.

It is a fact that the existing reactors have become much safer due to various measures, with backfitting and upgrading, especially learning from TMI and Chernobyl accidents. Also, there is a trend that future plants will be, or will have to be, better in terms of CDF than the best of the existing ones, to be achieved by evolutionary design or/and innovative improvements. For convenience, the following figures of CDF can give an idea of what safety has been achieved and of what is the target for the next generation of NPP.

	CDF (1/reactor•year)
The best of the existing NPP	10^{-4}-10^{-5}
The NPP coming on-line by the year 2000 or later	10^{-5}-10^{-6}
The innovative designs	$<10^{-7}$

For a NHR, the safety requirement in terms of CDF has reached the top of the safety target if a figure of much less than 10^{-7} of CDF is achieved.

On the other hand, there is a serious challenge to the economy for a NHR. The capacity of a NHR can not be as big as that of NPP due to the limitations of heat transport. The economic thermal power is in the rang of 200-500MWt. Moreover, the load factor is also much lower than that of a normal NPP.

It is obvious that to meet the safety requirements, and to lower the capital investment are the major concerns in the design of a NHR. The only solution is to have a design with inherent safety characteristics and passive safety as much as possible instead of the complex engineering safety features. In addition, the high end-user efficiency of district heat application instead of electricity generation with low end-user efficiency is also a key point to improve the economy for a NHR.

2. DESIGN CRITERIA

The design criteria for conventional nuclear power plants already exist. Most of them are suitable for the NHR, but some of them have to be modified due to more stringent safety requirements and unusual design approaches. In order to have a design basis and to enable the safety regulatory body (NNSA) to evaluate systematically the design of the NHR-200, a set of design criteria for NHR is being drawn up and reviewed by a team organized by NNSA. Since no large scale operational experience is available at this time, the design criteria are not a complete nor a official set of regulations. It will be issued as a technical document. Some of the major points of this criteria are discussed as follows.

(1) Operation categories

Usually 4 operation categories are classified for a conventional NPP. Among them Category III and IV are accident conditions. The accidents of Category IV are the most serious ones in the sense of DBA. But in recent years addressing beyond design basic accidents has been required by various regulatory bodies. The French H procedures are perhaps the most comprehensive ones.

In order to meet the enhanced safety requirements as well as the position of the Chinese regulatory body, an operation Category V is added beyond the 4 categories in our design criteria. Generally, the operation Category V is such an accident condition after a DBA (Category III or IV). Apart from the assumption of a single failure, there is an additional failure assumed to occur. Therefore, Category V consists of events with lower frequency than those for Category IV. The typical events are: loss of off-site power followed by an assumed failure to scram combined with a stuck open safety valve; break of reactor vessel in its lower part or pipe break of coolant purification system followed by failure of isolation due to failure of two isolation valves; intermediate loop break followed by failure of isolation. The deterministic analysis is conducted with realistic parameters. The measures for mitigation of such accidents should be reliable. But a grace period can be taken credit of. The acceptance criteria of this Category is that the release of radioactive substance into the environment is not allowed to disrupt normal life beyond the non-residential area (the plant).

The limiting doses for individuals of the population during each operational Category are much less than that for a conventional NPP. They are listed as follows:

Category I (Normal operation)	0.1 mSv/a
Category II (Anticipative operation events)	0.2 mSv/event
Category III (Rare accident)	1.0 mSv/event
Category IV (Limited accident)	5.0 mSv/event
Category V (Additional Operation Category)	5.0 mSv/event

(2) Thermohydraulic design criteria

In order to reduce the radioactive release from the fuel elements in case of an accident, the thermohydraulic design criteria for a NHR are more rigorous than those for conventional NPPs.

a. In respect to fuel element damage the differences between NPP and NHR are listed below:

	NPP	NHR
Category I and II	No additional fuel damage	No additional fuel damage
Category III	Fuel damage should be limited in a small part of all fuel elements	No additional fuel damage
Category IV	Fuel damage possibly occurs with a large amount of all fuel elements	Fuel damage should be limited to a small part of all fuel elements
Category V	NA	Small as above

b. Correspondingly the DNBR must stay above the limit value in operation Category I and II for conventional NPP, but also in Category III for the NHR. The same requirement for fuel temperature is that the maximum temperature at the center of the fuel element at the hot spot never reach the melting temperature in the operation Category I and II for conventional NPPs, but also in Category III for the NHR.

c. For conventional NPPs, the average temperature of the fuel clad at the hot spot has to be below the embittlement temperature of 1204°C in case of a LOCA. But for the NHR it is required that the reactor core is always covered by coolant in case of LOCAs. Thus the temperature will be far less than the above limit.

(3) Containment

As a final barrier against fission product release, a containment system is one of the important Engineered Safety Features (ESF) in a current nuclear power plant. It consists of a containment structure and several systems to maintain the integrity of contaminant during accident scenarios. This system is very expensive. Recently, along with the development of advanced nuclear power plant, especially for more innovative reactor designs, the concept of a containment is also getting development. For example, a vented confinement concept

[2] is provided for a small or middle size modular high temperature gas cooled reactor instead of the gas-tight pressurized containment for the current generation LWRs due to the exclusion of the possibility of a fission product release from coated particle fuel elements in case of an accident. Another example, for the Safe Integral Reactor (SIR) developed by the UK and the USA [3], the integrated arrangement of the primary coolant system makes it possible that the containment is a compact one.

Based upon the definition given by 10CFR50, the primary reactor containment means the structure or vessel that encloses the components of the reactor coolant pressure boundary, and serves as an essentially leak-tight barrier against the uncontrolled release of radioactivity to the environment. For the systems connected to the reactor vessel, the reactor coolant pressure boundary is up to and including the second isolating valve. Since the NHR-200 is an integrated arrangement of the primary coolant system, a small compact containment is adopted which meets the above definition. Moreover, this containment has the further important function that it ensures the reactor core being always covered by coolant in all pipe break accidents, even in the case of a small break in the lower part of the reactor vessel.

The reactor building serves as a secondary confinement. The main function of this structure is the protection against external events. It also provides a subatmospheric enclosure to collect the leakage from the compact containment during LOCA.

(4) Special credit for NHR-200

Since the safety systems adopted for the NHR-200 have many differences compared with those in normal NPPs, these differences have to be reflected regarding the requirements for the support systems. Some special credits are discussed as follows.

a) Emergency power system

For a NPP, apart from two independent off-site power supply connections, there is an emergency power system with two or three separate trains equipped with a quick-starting diesel unit for each to supply power to all redundant safety-related systems, such as ECCS, containment cooling and spray system, residual heat removal system and the related support systems in case of loss of off-site power. But for a NHR some safety-related systems, such as ECCS, containment cooling and spray systems are not necessary, and some safety-related systems, such as the shut down and residual heat removal systems are passive systems. Therefore, the emergency diesel generators are no more necessary. Nevertheless, there are two diesel generators in the design of NHR-200, but they are not classified as safety related. In order to enhance the reliability of stand-by power supply, one of these two diesel generators is classified as seismic Category 1.

b) Component cooling water (CCW)

In the design of NHR-200 the loads of CCW are cooling of coolant purification system, condenser of liquid waste treatment system, and cooling of the control rod drive system. Among them there are no safety-related systems, therefore, the CCW is classified as a non-safety related.

c) Heating, ventilation and air conditioning system (HVAC) for the control room

Since a large release of radioactive material into the reactor building is impossible under all credible circumstances, the HVAC is not classified as safety related.

3. SPECIAL RADIOLOGICAL PROTECTION ISSUES FOR NHR

Since a NHR has to be located near the user, some radiological protection issues which are different from the case of NPPs have to be investigated. They are discussed as follows.

1) Site criteria

The features of current site criteria for NPP shown by the American code 10 CFR100 are as following:

1) The evaluation is based on an assumption of a core melt accident.
2) In case of the maximum hypothetical accident, emergency actions, including sheltering, evacuation and field decontamination, are adopted in order to assure that no individual receives a whole body dose in excess of 0.25Sv which would result in acute injury. Also, the accumulative dose received by the population is limited to a reasonable value.
3) An exclusion area and a low population zone are necessary. Also, a distance from the reactor to population center has to be kept in order to meet the above requirement.

More than 6000 reactor-years of NPP operating experience with only two significant accident shows that the above principles are correct. NPPs are quite safe but core melt with subsequent release of appreciable quantities of fission products is still considered credible (The frequency of core melt is considered as 10^{-5} per reactor year) [4]. Preparation of an off-site emergency action including evacuation is necessary. A site for NPP should be far from population center, saying larger than 25 km.

For the NHR it is impossible to require a large area adjacent to the plant with sparse population or a site far from a city. It means that distance is not a protecting factor any longer. The actions of evacuation, relocation and field decontamination are no longer practical emergency measures to protect the population from over-exposure. The public is protected only by the safety features of the NHR. Safety is achieved by adopting more inherent safety features, they have been presented in many papers [5, 6]. The frequency of core melt for a NHR is much less than 10^{-7} per reactor-year [6, 7] which can be considered negligible in practice. In this way core melt is no longer considered as a design basis. The site criteria for NPPs can not be used in case of the NHR. For a NHR the recommended dose limit for the maximum design basic accident is 5 mSv without any emergency action.

Regarding high population, high utilization factor of land and the unit power of 200-500MW for one NHR, which is one magnitude smaller than that for a NPP, a non-residential zone of 250m in radius and a physical isolation zone of 2km in radius are proposed. During the lifetime of the NHR, development in the physical isolation zone should be restricted in terms of population and large scale public facilities. This physical isolation zone is only functioning as an isolation between the plant and the public to reduce the interference with each other during normal operation as well as during abnormal conditions.

2) Liquid effluents

For a NHR site it is better to have no restriction on liquid effluent release. In most cases, there is no suitable receiver of liquid effluent near a proposed site for a NHR.

Therefore, the principle of treatment and disposal of liquid waste for a NHR should be different from that for a NPP. For a NPP the distinguishing features are: large amounts of liquid waste (more than 10,000 m^3/a), a moderate degree of decontamination (depends on the amount of salt content, evaporation or demineralizing approaches that are used respectively; the target of decontamination is 10^{-8}-10^{-7}Ci/l). After treatment, the liquid effluent is mixed with circulating cooling water and released to a river or sea.

For a NHR the amount of liquid waste is much less than that for a NPP (300 m^3/a is expected). The proposed principle is increasing the decontamination factor (the target of concentration after treatment is 10^{-10}Ci/l), and then reusing the decontaminated water as much as possible. For the remains of usage it can be used as a make-up of plant cooling water or evaporated in a natural evaporative pond, even drained to a city sewage network.

3) *Protection against pollution of the heating grid*

Differing with a nuclear power plant, the NHR will be connected with the user through the heating grid. Therefore, protection against pollution of the heating grid is extremely important. In the design of the NHR, an intermediate loop is adopted to separate the heating grid from the radioactive primary loop. Moreover, the pressure of the intermediate loop is kept higher than that of the primary loop in all conditions, so that it ensures that leakages, if there are any, are always from the intermediate loop to the primary loop, never vice versa. In addition, pressure and radioactivity of the intermediate loop are monitored continuously. An isolating device is also installed in order to quickly isolate the intermediate loop from the primary loop in case of occurrence of a large leakage. These measures ensure that the contamination of the intermediate loop is very low. The pressure of the intermediate loop is also kept higher than that of the heating grid. This arrangement not only makes heating grid operation easier but also favors keeping the water quality of the intermediate loop.

The limits of radioactive concentrate are: 10 Bq/l for the intermediate loop; 0.37 Bq/l for the heating grid.

4. SUMMARY

Most of the design criteria for conventional NPPs are suitable for the NHR, but some of them have to be modified due to more stringent safety requirements and due to the unusual design approaches. A set of design criteria for the NHR has been drawn up for facilitating the development of NHRs in China. Meeting these criteria means that off-site emergency plans for protecting the population would not be necessary.

The evaluation of the design of the NHR-200 which meets the proposed design criteria shows that the design of NHR-200 has attractiveness both in safety characteristics and economy. The proposed design criteria have to be updated along with the accumulation of practical experience with NHRs.

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