DESIGN AND SAFETY CONSIDERATIONS FOR THE 10 MW(t) MULTIPURPOSE TRIGA® REACTOR IN THAILAND

J. Razvi[1], J. M. Bolin, J. J. Saurwein, W. L. Whittemore
General Atomics[2]

S. Proongmuang
Office of Atomic Energy for Peace, Thailand[3]

ABSTRACT

General Atomics (GA) is constructing the Ongkharak Nuclear Research Center (ONRC) near Bangkok, Thailand for the Office of Atomic Energy for Peace. The ONRC complex includes the following:

- A multipurpose 10 MW(t) research reactor
- An Isotope Production Facility
- Centralized Radioactive Waste Processing and Storage Facilities.

The Center is being built 60-km northeast of Bangkok, with a 10 MW(t) TRIGA type research reactor as the centerpiece. Facilities are included for neutron transmutation doping of silicon, neutron capture therapy neutron beam research and for production of a variety of radioisotopes. The facility will also be utilized for applied research and technology development as well as training in reactor operations, conduct of experiments and in reactor physics.

The multipurpose, pool-type reactor will be fueled with high-density (45 wt%), low-enriched (19.7 wt%) uranium-erbium-zirconium-hydride (UErZrH) fuel rods, cooled and moderated by light water, and reflected by beryllium and heavy water. The general arrangement of the reactor and auxiliary pool structure allows irradiated targets to be transferred entirely under water from their irradiation locations to the hot cell, then pneumatically transferred to the adjacent Isotope Production Facility for processing.

The core configuration includes 4 x 4 array standard TRIGA fuel clusters, modified clusters to serve as fast-neutron irradiation facilities, control rods and an in-core Ir-192 production facility. The active core is reflected on two sides by beryllium and on the other two sides by D_2O. Additional irradiation facilities are also located in the beryllium reflector blocks and the D_2O reflector blanket. The fuel provides the fundamental safety feature of the ONRC reactor, and as a result of all the well-established accident-mitigating characteristics of the UErZrH fuel itself (large prompt negative temperature coefficient of reactivity, fission product retention and chemical stability), a containment structure is not required. Thus the reactor will be housed in a confinement building.

The basic design of the reactor, reactor structure, auxiliary systems, reactor instrumentation and control systems and other balance of plant systems have been completed and detailed design is underway. The Preliminary Safety Analysis Report (PSAR) has been completed and submitted to OAEP for approval and issuance of a Construction Permit. The PSAR has been reviewed by OAEP, its consultants as well as the IAEA. Fuel loading and commissioning is expected before the end of 2002.

This paper describes the basic design features of the new reactor, including key features of the reactor fuel, core and related structures. The results of reactor performance and safety analyses performed in support of the PSAR are described.

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[1] Presenting author
[2] 10240 Flanders Court, San Diego, CA 92121,USA
[3] Vibhavadi Rangsit Road, Chatuchak, Bangkok, 10900 Thailand

1. PROJECT SUMMARY

In June 1997, the Office of Atomic Energy for Peace (OAEP) awarded a turnkey contract to General Atomics (GA) to design, build and commission the Ongkharak Nuclear Research Center (ONRC) near Bangkok, Thailand. The ONRC research complex includes the following:

- the Reactor Island, consisting of a multipurpose 10 MW(t) TRIGA research reactor,
- the Isotope Production Facility (IPF) for the production of radioisotopes and radiopharmaceuticals, and
- the Centralized Waste Processing and Storage Facility.

The Center is being built in Nakhon Nayok Province, 60 km northeast of Bangkok. The centerpiece of the ONRC is a TRIGA research reactor. Facilities are included for production of radioisotopes for medicine, industry and agriculture, neutron transmutation doping (NTD) of silicon, boron neutron capture therapy (BNCT), neutron activation analysis (NAA), gemstone enhancement and neutron beam research. The facility will also be utilized for applied research and technology development as well as training in reactor operations, conduct of experiments and reactor physics.

2. REACTOR DESIGN FEATURES

The multipurpose, pool-type TRIGA reactor will be fueled with high-density, low-enriched (19.7 wt. %) uranium-erbium-zirconium-hydride (UErZrH) fuel with a rated thermal power output of 10 MW(t). Such high density LEU fuels, ranging in uranium content from 20 wt% to 45 wt% have been fully qualified under the auspices of the RERTR program, and have been in use in TRIGA reactors for nearly 20 years, at power levels ranging from 2 MW to 14 MW(t). They offer the same safety advantages of lower density UZrH fuels through a large prompt negative temperature coefficient of reactivity, chemical stability and large fission product retention characteristics. It is designed to be cooled and moderated by light water, and reflected by beryllium and heavy water (D_2O). The general arrangement of the reactor system is presented in Fig. 1 and consists of a 4-m diameter by 10-m deep main reactor pool, and an auxiliary pool connected to the main pool by a transfer canal. The reactor pool, transfer canal, and auxiliary pool are all lined with stainless steel and encased on all sides and below by a thick concrete biological shield. An isotope transfer hot cell is located at the edge of the auxiliary pool. The auxiliary pool also contains a spent fuel storage facility and provides the necessary shielding and cooling for safe storage of the spent fuel. The arrangement of the pools and isotope transfer hot cell allows irradiated targets to be transferred entirely under water from their irradiation locations in the main pool to the above pool hot cell. The targets are then transferred from the hot cell to the IPF either pneumatically via a tube between the two buildings or using a bottom-loading isotope transfer cask.

The Primary Coolant System consists of the primary coolant piping, primary coolant pumps, heat exchangers, an accessible delay tank with sufficient capacity for N-16 decay, and the pool water storage tank. The primary coolant flow exiting the core is held up in the delay tank to allow for radioactive decay of the N-16 and O-19 isotopes generated in the water as it passed through the core. Two 50% capacity primary coolant pumps operating in parallel circulate the coolant water through the system at a design flow rate of 363 liter/second. Anti-siphon devices in the upper portions of the primary coolant inlet and outlet pipes within the reactor pool prevent excessive reactor pool water from being siphoned from the reactor pool in the event of a break in the primary coolant loop. The Primary Coolant System rejects the heat from the core to the secondary coolant through a water-to-water, plate-type heat exchangers.

Although such an accident is not considered credible for the ONRC reactor, the reactor includes an Emergency Core Cooling System (ECCS) for defense-in-depth to ensure that the core remains covered with water in the event of a loss-of-coolant accident (LOCA) that causes the reactor pool to drain. The ECCS is a simple system that transfers water from the delay tank in the Primary Coolant System to the reactor structure to replace evaporative losses from the water retained within the structure.

A perspective view of the reactor pool is shown in Fig. 2 and consists of the reactor pool liner, the reactor structure, the beam tube protection grid, and the primary coolant piping within the reactor tank. The reactor structure contains the core, the core shroud, core support grid, core outlet plenum, neutron detector guide tubes, D_2O reflector tank, silicon doping facilities, BNCT port, and primary coolant discharge riser. The reactor assembly includes six beam tubes as shown in the core configuration (Fig. 3). Neutron beam experiments that will be performed include high resolution power diffractometry, small angle neutron scattering, neutron radiography, and prompt gamma neutron activation analysis. The NB4 beam tube is designed to perform medical therapy of patients using the BNCT technique.

The core configuration shown in Fig. 3 includes 29 standard TRIGA fuel clusters, a fast-neutron irradiation facility, 4 control rods and an in-core Ir-192 production facility, all of which are arranged in an approximately square array. The fuel rods in the fuel clusters are arranged in a 4 x 4 array (16 fuel rods per cluster). The active core is reflected on two sides by beryllium reflector blocks and on the other two sides by a D_2O reflector blanket. The Be reflector blocks have a central hole to accommodate irradiation experiments or to allow for coolant flow through the blocks. A position for an equipment rig for conducting irradiation damage experiments is also located in the reflector area. There are 3 pneumatic transfer (“rabbit”) systems for transfer of very short-lived radioisotopes. There are four vertical irradiation sites in the D_2O reflector for NTD of silicon.

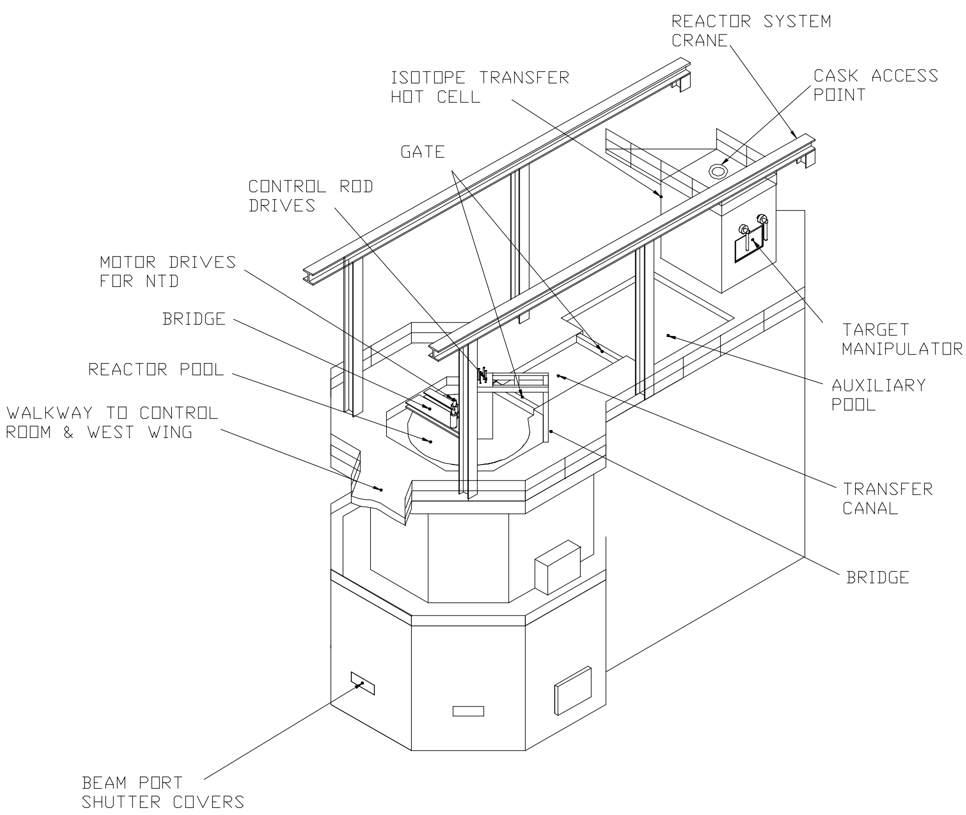

Figure 1. Perspective View of ONRC Reactor System

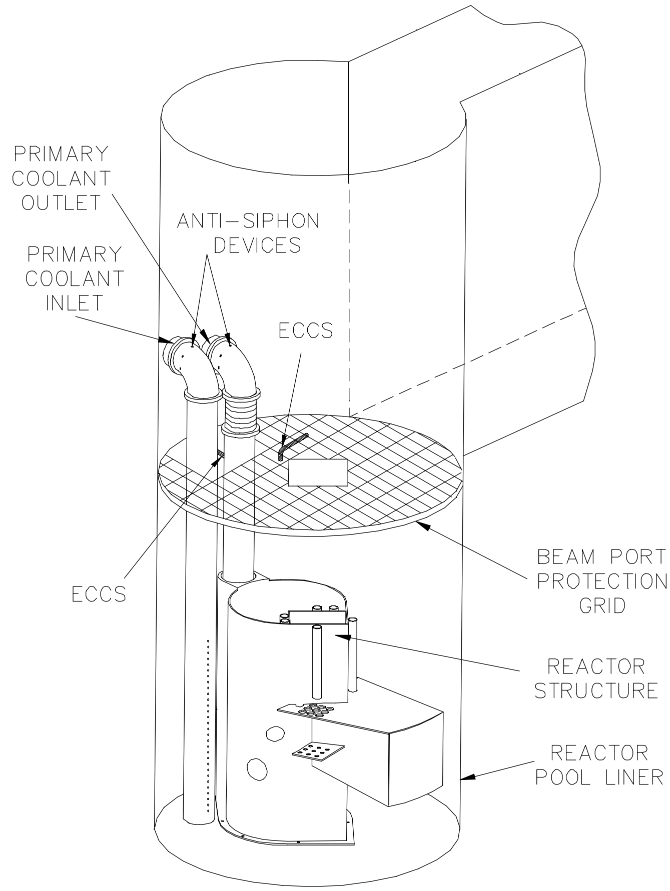

Figure 2. Perspective View of Reactor Pool

The nominal specifications of the TRIGA fuel rod design for a 16-rod cluster are presented in Table I. The fuel is a solid, homogeneous mixture of UErZrH alloy containing 45 wt. % uranium. The uranium is enriched to a nominal 19.7% U-235. The hydrogen-to-zirconium atom ratio is nominally 1.6. The contained fuel alloy "meats" in the fuel rod fit snugly within the Alloy 800H cladding. Erbium is included as a burnable poison, and also serves to enhance the prompt negative temperature coefficient of reactivity.

TABLE I. NOMINAL SPECIFICATION FOR FUEL RODS

Property	Nominal Design Value
Overall length	770 mm
Outside clad diameter	13.8 mm
Fuel outside diameter	13 mm
Fuel length	560 mm
Fuel composition	UErZrH
Uranium content	45 wt. %
Uranium-235 enrichment	19.7%
H/Zr ratio	1.6
Cladding material	Alloy 800H
Cladding thickness	0.4 mm
Erbium content (wt. %)	0.3% to 1.0%

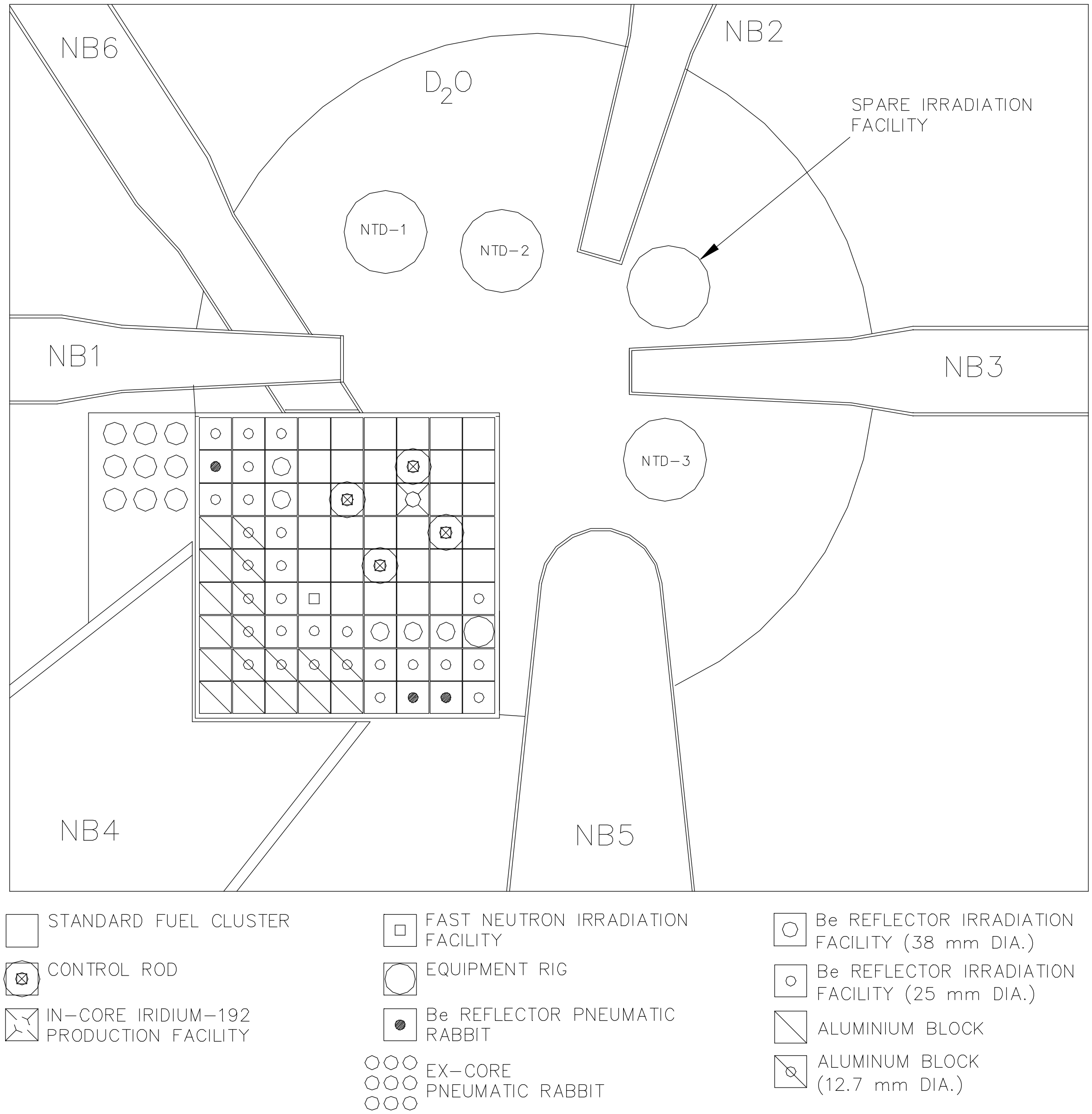

Figure 3. ONRC Reactor Core Configuration

TABLE II. ONRC REACTOR NEUTRON FLUX REQUIREMENTS

Location	Neutron Flux (neutrons/cm^2-s)
Beam Ports	>1 x 10^{13}
Fast Irradiation Facility	>1 x 10^{13}
Ir-192 Production Facility	>1 x 10^{14}
Epithermal In-Core Locations	>1 x 10^{13}
NTD Facility	>1.6 x 10^{13}

3. REACTOR PERFORMANCE

The flux requirements for the ONRC reactor are presented in Table II. The computer code MCNP-4A [1] was used to determine the calculated neutron flux values. The calculations show that the ONRC reactor design exceeds the OAEP requirements by at least 25%. As the core operates, the in-core thermal flux values increase slightly while the epithermal, fast, and out-of-core flux values remain about the same. In all cases, the neutron flux levels meet the design requirements established by OAEP. The NTD facilities meet the annual production requirement of 1000 Kg of doped silicon. Fifteen vertical irradiation sites, including two in-core locations, are available for radioisotope production. The design production capacity per year is expected to be as follows:

- I-131: 200 Ci (7.4 TBq);
- I-125: 2 Ci (0.07 TBq);
- Tc-99m: 800 Ci (30 TBq);
- P-32: 5 Ci (0.2 TBq);
- Ir-192: 10,000 Ci (370 TBq);
- Labeled compound: 0.1 Ci;
- Miscellaneous isotopes (Cr-51, Fe-59, K-42, etc.): > 10 Ci (0.4 TBq); and
- Radiopharmaceuticals (>10 types of Cold Kits): 5,000 Kits.

The fuel reload plan divides the fuel clusters into five groups with six clusters in each group. Burnup calculations show that the initial core can be operated to 4500 MWd at full power and without fuel shuffling before addition of reload fuel is required. For an equilibrium cycle discharge burnup of 50% of the initially contained U-235, each reload cycle will last about 195 effective full power days (EFPD) and the burnup lifetime of an equilibrium core of 29 standard fuel clusters and one partial fuel cluster (fast flux facility) will be about 975 EFPD. One group, or one-fifth of the core will be reloaded about once every year since the reactor is to be operated at full power about 210 days per year.

TABLE III. STEADY-STATE OPERATING PARAMETERS

Parameter (hot rod and channel)	Nominal Value
Coolant inlet temperature	37ºC
Coolant exit temperature	49ºC
Fluid velocity	4.8 m/s
Cladding outer surface temperature	136ºC
Cladding inner surface temperature	199ºC
Fuel surface temperature	306ºC
Fuel centerline temperature	613ºC
Maximum heat flux	2.12 MW/m^2
CHFR, nominal spacing	2.1

Results of steady-state thermal-hydraulic analysis of the ONRC TRIGA reactor are presented in Table III. The coolant flow rate through the fuel clusters is 315 liter/second at a design inlet temperature of 37ºC. The analysis examines both a nominal and hot channel. The hot channel is for the fuel cluster with the fuel rod having the highest localized power peaking factor (2.42) during the life of the reactor. The critical heat flux ratio (CHFR) is predicted using a correlation developed by Lund [2]. This correlation was developed from empirical data gathered from experiments conducted at Columbia University. The minimum CHFR is evaluated at the design rod separation of 2.54 mm and at the minimum separation distance corresponding to the maximum allowable bowing for the "bent rod" case.

4. SAFETY ANALYSIS

The UErZrH fuel is the fundamental safety feature of the ONRC reactor that is responsible for TRIGA reactors widely recognized safety and acceptance worldwide. The large, prompt negative temperature coefficient of reactivity, an intrinsic property of this fuel, acts to automatically and instantaneously limit reactor power increases resulting from inadvertent large positive reactivity insertions, thereby preventing loss of reactor control and damage to the fuel rods. The fuel matrix and cladding can tolerate high temperatures which further mitigates the effects of reactivity insertions and other transients. The demonstrated, excellent fission product retention capability of UErZrH fuel, retaining about 99.9% of its volatile fission products at temperatures of 650ºC even with the cladding removed, allows the fuel itself to be the primary fission product barrier (with the cladding as the secondary barrier), and therefore contributes to the superior safety characteristics of the ONRC TRIGA reactor [3]. As a result of the accident-mitigating characteristics of the fuel itself, a containment structure is unnecessary and the reactor will be housed in a confinement building.

The PSAR includes the analysis of several types of events:

Reactivity Transients. The most limiting reactivity transient is a rapid withdrawal within 0.3 s of an experiment worth 1.40% ($2.00) which would involve extreme human error or failure of administrative controls. The design of the reactor core provides for experiments having reactivity worth of up to 1.00% ($1.43); experiments having reactivity worth of up to 1.40% ($2.00) can be accommodated at the beginning of each fuel cycle when more reactivity is available. For this transient, the highest fuel temperatures are predicted to occur if the reactivity accident begins while the core is cold critical. The reactor power rapidly increases and reaches 11 MW after about 0.375 s which generates a scram signal causing the control rods to drop after a delay of about 0.025 s. The core power peaks at about 596 MW approximately 0.04 s after the control rods begin to fall. The peak fuel temperature during this transient is 889ºC and occurs about 0.07 s after the peak power is reached. This peak fuel temperature is well below the 1150ºC fuel temperature limit for TRIGA fuel for reactivity transients. The maximum rate of control rod travel is such that rapid withdrawal of all control rods as a bank is not considered the limiting reactivity transient that was analyzed.

Loss of Forced Cooling: A loss of forced cooling (LOFC) as a result of loss of electrical power which shuts down the primary coolant pumps is an anticipated operational occurrence for the ONRC reactor. The reactor is shut down automatically by a low-flow scram signal, and core decay heat removal transitions passively from forced convection to natural convection. An analysis was performed to verify the transition from forced cooling to natural convection cooling using the RELAP5/MOD3.2 computer code [4]. The fuel clusters with the highest power density are the first to transition from downward to upward flow. After about two hours, the flow in the coolest fuel clusters reverses from down-flow to up-flow so that there is up-flow in all fuel clusters. The maximum cladding temperature increases slightly from the steady-state temperature to about 135ºC. The cladding temperature then drops quickly to 107ºC. Cladding temperatures start to rise after about 10 seconds reaching a peak temperature of about 125ºC during the transition from downward flow to upward flow in the fuel cluster. The maximum cladding temperature then drops to about 80ºC one hour after the onset of the transient and stays below this temperature for the remainder of the LOFC.

Loss of Coolant Accident: A hypothetical loss-of-coolant accident (LOCA) was also analyzed and included in the PSAR. The LOCA analysis used the RELAP5/MOD3.2 computer code [4] to assess natural circulation cooling, boiling, and ECCS performance. The lowest level that the reactor can drain in a beam tube rupture accident followed by a failure of the corresponding beam port cover is just below the mid-plane of the active core. The decay heat from the core is transferred to the water retained by the reactor structure resulting in evaporative losses. Although the water level in the core shroud varies during the transient, the core remains covered by water. The analysis shows that the emergency supply of water provided by the ECCS is sufficient to replace the evaporative loss and keep the core covered by water.

5. PROJECT STATUS

The basic design of the Reactor Island and other balance-of-plant systems have been completed and detailed design is underway. The PSAR has been completed, and reviewed by OAEP and their consultants as well as IAEA experts, for issuance of a construction permit.. Fuel loading and commissioning is expected around the end of 2002.

6. REFERENCES

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