EXISTING METHODOLOGIES IN THE DESIGN AND ANALYSIS OF OFFSHORE FLOATING NUCLEAR POWER PLANTS

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SUMMARY

The paper presents a comprehensive state-of-the-art on the design and analysis of Floating Nuclear Power Plants (FNPs). The recent accelerated growth of the offshore oil industry has considerably increased the confidence in the offshore FNP concept, in view of the vast potential for the transposition of available technology. The main advantages of FNPs are: (1) unlimited supply of the cooling water, (2) isolation of thermal, noise and radioactive pollution, (3) elimination of the need for large areas of unoccupied lands usually required for safety precaution, and (4) financial savings by using standardised design and production line approach.

The topics covered in this paper are:

Offshore Concept Evaluation. — (i) Comparison of the various offshore concepts, namely, artificial islands, jack-up type, floating-deep, floating-shallow and sea bed, including evaluation based on cost, environmental impact, feasibility, plant vulnerability and nuclear safety; (ii) Acceptability of the offshore floating-deep plant as the most suitable concept.

Siting Considerations. — (i) Factors influencing site selection with some reference to the economic, ergonomic and environmental constraints; (ii) Study of bearing capacity, slope stability and settlement, liquefaction potential and scouring behaviour of the sea-bed.

Design Considerations. — (i) Conceptual design of the main components of the FNP; (ii) Calculation of wind, wave, current, ice, earthquake, and tornado forces; (iii) Determination of dynamic positioning forces acting on the floating platform; (iii) Design of (a) the floating platform for combinations of dead, imposed and environmental loadings, (b) bottom fixed and floating breakwaters, and (c) the mooring system; (iv) Construction and installation procedures.

Analysis. — (i) Analytical procedures for static and dynamic analysis of semi-submersibles applicable to FNPs; (ii) Stability criteria for (a) the floating platform (intact and damage stability) and (b) the breakwater; (iii) foundation analysis.

Miscellaneous Considerations

(i) Fatigue and crack propagation: (a) Fatigue analysis of steel components subjected to long-term wave loading and dynamic amplification of wave-induced response, (b) Crack propagation in offshore concrete applications;

(ii) Model Studies and experimental investigation: (a) Scaling of the model; (b) Three dimensional model studies to evaluate platform motion to environmental loads, mooring strut forces etc.;

(iii) Seismic instrumentation: (a) Need for seismic instrumentation, (b) Types of seismic instruments and locations of installation;

(iv) Noise and vibration level considerations: (a) Allowable noise level specifications for work areas, control rooms and accommodation areas; (b) Methods of noise and vibration control;

(v) Safety: (a) General safety requirements; (b) Risk and reliability analysis of offshore structural systems applicable to FNPs.

A detailed bibliography is presented to indicate the immediate need for further research in the areas of (i) dynamic analysis using improved mathematical modelling techniques incorporating water-structure interaction, and nonlinear effects of the supporting medium and the mooring system; (ii) safety analysis of FNPs to accident loadings.

1. INTRODUCTION

Ideal sites for nuclear power plants requiring large amounts of cooling water are the shorelines bordering estuaries, bays and oceans. The worsening trend in finding suitable land sites along the coast, and the growing concern of environmental impact on human population have considerably increased the interest in offshore siting. Offshore power plants have a number of significant advantages which have been listed by Orr and Dotson [1] as: (1) unlimited supply of cooling water, (2) considerable saving of time since site preparation can proceed while the construction of the plant is carried out at another location, (3) savings in certain costs (i) economy in transmission due to siting in close proximity to power demand areas, (ii) reduction in effort required for licensing by regulatory agencies due to the standardised design and production line approach to fabrication, and (iii) possibility of locating multiple identical units at one site, (4) elimination of thermal and noise pollution and contamination of drinking water with low levels of radioactivity, (5) avoidance of the need for extensive areas of unoccupied lands required to meet safety precautions, (6) lessening of the danger from tsunamis, and (7) cushioning against earthquakes. An additional advantage, not generally indicated in the literature, is the hybridisation of power generation and desalination concepts with flexibility to move the plant to power/water shortage locations. Some of the disadvantages in offshore siting are: (1) expensive undersea power transmission cables, (2) higher operational and construction costs since men and material have to be transferred to and from shore, (3) possible contamination of the marine ecological system, and (4) increased susceptibility to certain man-made and natural accidents.

The paper describes briefly the evaluation of the different offshore concepts and presents the state-of-the-art of existing methodologies for the design and analysis of floating nuclear plants (FNPs).

2. CONCEPT EVALUATION

Evaluation factors include cost, environmental impact, feasibility, plant vulnerability and nuclear safety. Table I presents the overall acceptability values of different concepts based on relative weighted values assigned to each factor by a panel of experts. The evaluation indicates the offshore floating deep plant to be the most favorable of the offshore concepts. Various configurations suggested for floating deep plant are shown in Fig. 1. Schmidt [4] has pointed out that the study conducted by Westinghouse has proven the technical and economic feasibility of offshore siting of nuclear power plants. The location and configuration of the first of its kind, the Atlantic Generating Station (AGS), is shown in Fig. 2.

3. SITING CONSIDERATIONS

3.1 Site Selection

The principal issues in the site selection of FNPs are containment isolation, safety systems, seismic resistance, thermal effects, and most significantly the environmental impact. The basic factors which influence the site selection of a nuclear power plant were given by Kèhmemuyi and Nichols [5], and some unique factors related to the site selection of FNPs are listed in a report of the U.S. Atomic Energy Commission [6].

Singh and Fischer [7] described a step-by-step procedure for the site selection of FNP's on the basis of the available information. Alternatives to offshore siting, such as near-shore, riverine and onshore siting studied by Bonsak [8], indicate that the choice of the siting should be based on adaptability to the particular environment.

The major requirements of a FNP site are:

- (1) location within 3 mile limits from the shoreline,
- (2) minimum of 40 feet depth of water to prevent contact between the plant and the ocean bottom,
- (3) maximum of 100 feet for economical construction of the breakwater,
- (4) sufficiently far from shipping lines,
- (5) a near inlet to provide a safe harbor for service vessels during adverse weather,
- (6) adequate compactness and strength of subsoil to support the breakwater, and
- (7) proximity to potential land-based switching station sites for economic transmission of line routing.

3.2 Site Investigation

Once the site is selected, it should be investigated for its accessibility. Adequate port and marine facilities must be available during any weather conditions for easy access to the site. A few of the procedures to be followed are:

- (1) determination of the elevation at an offshore site using available surveying techniques - Dette et al. [9],
- (2) subsoil sampling using (a) vibratory-cone penetrating test-Fischer et al. [10], (b) static cone penetration test - Arita et al. [11], (c) constant velocity penetration test - Dayal and Allen [12], (d) wire-line sampling test - McClelland [13], and (e) remote-vane shear testing - Doyle et al. [14].

4. DESIGN CONSIDERATIONS

The load history and environmental conditions experienced by the offshore structures are random and complex involving a great variety of design loads and the structural response to these loadings is complex. Table II lists different aspects of structural behavior outlined by Røren and Furnes [15]. Two design principles, namely, (i) the probabilistic method, and (ii) the limit state method are also discussed in Ref. 15.

The design aspects of the main components of the FNP are described below:

4.1 Floating Platform

The floating platform and the integrated power plant structure must be designed to withstand the most severe waves that may be encountered during tow, and the motions and stresses encountered at the permanent site should not result in catastrophic failures. The major considerations in the design of the platform are listed in Ref. 3.

The various loads and loading combinations to be considered in the design of the FNP platform and the allowable stresses in each design condition have been presented in detail by Dotson and Orr [16]. The design forces to be considered in the FNP construction were described by Fischer et al. [17].

4.2 Breakwater

In the passive type no energy is produced to induce wave attenuation. The incident wave energy is either absorbed or reflected or both. In contrast, the special geometry of the active type facilitates wave attenuation by producing and injecting kinetic energy into the breakwater system.

A conventional bottom fixed breakwater, passive type, is desirable for shallow water sites. The concept, configuration and design aspects of a protective breakwater for the AGS have been described by Kehnemuyi [18].

Protection to deep sea constructions by means of conventional breakwaters will be very uneconomical. This problem can be overcome by the floating breakwater concept outlined by Colvin [19]. The different kinds of floating breakwaters proposed are:

- i) scarp structure - Candle [20],
- ii) seabreaker floating breakwater - Hasler [21],
- iii) Harris-designed breakwater - Harris [22],
- iv) plastic floating breakwater - Yamashita and Nakayama [23], and
- v) passive collision protection system - Easterling [24].

Recent developments and the problems related to the usage of floating breakwaters have been reviewed by Adey [25].

4.3 Mooring Systems

The type of mooring system required depends on the maximum site condition - predicted wave, wind and water level combinations. The loads which affect the design of mooring systems should take into account: (i) tornado pressures, (ii) wind, wave and hurricane induced motions in the plant, (iii) seismicity from the basin bottom and feedback from the plant, and (iv) accidents due to aircraft or missile or ship collision. Investigations carried out by Harlow, Harris and Kehnemuyi [26] have shown the feasibility of an axial strut mooring system to protect the AGS. An alternative to the mooring system is the dynamic positioning of floating structures.

4.4 Intake Structure

The problems associated with the design of submerged in-take structures for recirculating systems to cool nuclear power plants are complex and cannot be solved analytically. Hence, experimental studies are very important to validate the design. Design considerations for an offshore intake tower, based on testings of inflow conditions using dyes have been presented by Rudovsky [27]. The design against liquefaction for the underwater pipeline, which is a part of the cooling system, has been described by Christian et al. [28].

4.5 Transmission Lines

A review of the design, manufacture and laying of submarine power transmission cables, related to the linking of FNP's to the mainland has been presented by Morello, Taralli and McConnell [29]. Some of the design and application features of insulated cables have been described by Nelson and Daly [30].

4.5 Construction and Installation

The rules, regulations and recommendations for the design and construction of offshore structures have been formulated by various authorities, namely, Det Norske Veritas [31], Bureau Veritas [32], Federation Internationale De La Precontrainte [33], Department of Energy, London [34], the American Petroleum Institute [35], and the American Society of Civil Engineers [36].

Construction of a floating breakwater and a floating platform made of reinforced concrete caissons have been studied by Won [37] for offshore resource development. The design criteria for steel offshore structures based on environmental conditions and loads, and the material and welding problems during fabrication and installation have been described by Wintermark [38].

4.6 Problem Areas

In a recent workshop on FNP's, Road and Gaither [39] identified the problem areas in the order of priority, and listed the solution approaches suggested by the participants. Some areas of immediate research for improvements in design are: (i) evaluation of the probabilities of failure due to aircraft and missile impact, ship collision hazards, and extreme environmental loading conditions to specify the safe shutdown conditions, (ii) improved mathematical model techniques to evaluate the design specifications for environmental loads, (iii) improved dynamic analysis, including water-structure interaction, to account for the added water mass and hydrodynamic damping, and the nonlinear effects of the supporting medium and the mooring system, (iv) verification of the analytical and design procedures by model testing, (v) establishing safe methods for management of nuclear waste, (vi) selection of corrosion-resistant materials of construction, and (vii) effects of sloshing of the water, confined within the breakwater, due to external wind and earthquake forces.

The additional areas that need to be investigated are:

- i) Stability criteria, ii) Fatigue and impact, and iii) Foundation behavior including scouring and liquefaction.

5. ENVIRONMENTAL LOAD EVALUATION

5.1 Wind Forces

Once the wind conditions are determined based on available meteorological data, the wind loads can be predicted using the procedure described by Aquirre and Boyce [40]. For design purposes, the wind forces normal to flat surfaces can be calculated using any one of the empirical formulas given in Refs. 31 to 35.

5.2 Wave Forces

The main steps in determining wave forces are selection of (i) the design wave amplitude and period, (ii) an appropriate theory to compute velocities and accelerations of the water particles within the wave, (iii) drag and inertia coefficients, and (iv) a suitable theory for wave force calculations.

The design wave, the height of which may be exceeded once in 100 years, is predicted by extrapolation of typical one year wave data. Different wave theories have been developed to find the velocities and accelerations of the water particles in the wave, but the range of validity of these theories cannot be precisely described. One criterion suggested by Bretschneider [41] is the value, HL^2/h^3 , where H is the wave height, L is the wave length, and h is the water depth, which enables a choice between sinusoidal, cnoidal and solitary wave theories. In problems where drag force is very important, a higher order theory has to be used. For large platform structures, where drag is predominant, first order theory is probably sufficient.

The wave force components acting on a floating semi-submersible platform can be calculated using the formula given by Bratteland, Leviseth, and Torset [42]. The long term statistics of wave loading of typical members has been described by Tickell, Burrows, and Holmes [43]. An analytical model for predicting wave impact loads on floating platforms has been developed by Giannotti [44]. Wave uplift forces on horizontal decks subjected to periodic breaking and nonbreaking waves were investigated by Elghamry [45]. Three-dimensional diffraction theory has been used by Løken and Olsen [46] to determine the wave loading on fixed and floating large volume structures. Computer programs were developed by Nørdenstorm [47] and Løken [48] to determine wave induced motions and loads on ships and other floating structures. Kokkinowrachos and Wilchens [49] used implied diffraction theory, based on potential flow, to determine the wave forces on large floating structures.

5.3 Current Forces

Current forces cause siltation, erosion of the sea bed, and significant drag loading. Similar to the design wind speed, design current speed has to be determined from measurements by using the method of Otto [50]. Drag and lift forces due to currents can be determined using the formulas given by Remery [51].

5.4 Ice Forces

Reviews and assessments of various analytical approaches and design formulas, available field records from full scale structures, and laboratory investigations for ice impact forces have been presented in a number of papers; the most recent ones are those of Neill [52], Reddy, Cheema, Swamidas and Halder [53], and Swamidas, Reddy and Purcell [54]. Ice force response spectra developed by Reddy, Cheema and Swamidas [55] will aid in the possibility of specifying code requirements for ice pressures in terms of frequency dependence. The stochastic concept, described in Ref. 54, coupled with the power spectral density analysis in Ref. 53, and spectrum broadening procedures outlined by Sundararajan and Reddy [56] will aid significantly in understanding ice-structure interaction behavior, and in formulating guidelines for ice pressures on floating platforms.

In certain regions, like the Grand Banks area off Newfoundland, the ice hazard is augmented by the threat of icebergs. Methods for protection by enclosing the offshore structure by energy absorbing fending systems have been described by Blenkarn and Knapp [57].

5.5 Earthquake Forces

Earthquake effects on a floating platform are reduced significantly due to the decoupling effect of the water medium. However, this does not apply to bottom fixed breakwaters and mooring lines. Depending on the type of mooring, horizontal movements due to an earthquake may have to be considered. For a floating platform, the seismic isolation is complete for horizontal accelerations, but less for vertical accelerations when the platform is in shallow waters. Heitner [58] proposes a compartmental cushion of air beneath the platform for additional isolation of vertical accelerations.

The mass to be used in the calculation of the earthquake forces should include the mass of the structure plus that of any fluid it contains, and the added mass of water accelerated by the structure. In addition, the design should also take into account the apparent mass and damping of the soil in the structure-water-soil interaction study.

Tsunami waves, with their violent forces and washout effects caused by the crustal deformations in the sea bottom due to seaquakes along the slope of the bed or a volcanic eruption underwater, can cause extensive damage to bottom fixed structures. Hence, care must be taken to protect the sites from such disasters.

5.6 Tornado Forces

Tornado effects on nuclear power plants have been studied by Doan [59]. The plant design should be based on a 'design tornado', the main characteristic values of which are (i) tangential speed = 300 mph, (ii) translation speed = 60 mph, and (iii) pressure drop = 3 psi in 3 secs.

Another source of damage, against which offshore nuclear plants have to be protected, is from tornado-generated missiles which are aerodynamically lifted and propelled. The knowledge of missile velocities is required to assess the potential damage caused by these missiles. Lee [60] has developed a method based on centrifugal accelerations which gives a realistic peak missile ejection velocity. However, the tornado intensities over water are expected to be less than those on land.

6. STATIC AND DYNAMIC ANALYSES

6.1 Static Analysis

The platform should be checked as a beam on a 'standard wave' which is the design wave during tow. It must have adequate strength to support the plant in the 'worse-than-possible' loading conditions. A three-dimensional finite element analysis should be performed to determine member stresses for operating and design basis load combinations.

6.2 Dynamic Analysis

Since most of the environmental loads acting on FNPs are random in nature, they can be

described by statistical means, and the responses determined using deterministic and stochastic analyses described by Taylor [61]. In deterministic analysis, all the calculations are carried out in the time domain, whereas the frequency domain is used for stochastic analysis.

Similar to soil-structure interaction for land-based nuclear plants, fluid-structure interaction, in terms of added water mass and hydrodynamic damping, plays an important role in the dynamic analysis of FNPs. The dynamic analysis of floating bodies, incorporating hydrodynamic interaction, has been reported by various investigators, in particular, by Garrison [62], Lee [63], Kim et al. [64], and Gomez-Rivas [65].

The finite element method has been used by Johnson et al. [66] to determine the dynamic response of FNPs. The dynamic analysis of floating platform-mounted turbine generators has been carried out by Aneja [67].

The response of FNPs to artificially generated tornado forces has been determined by Arockiasamy, Reddy and Cheema [68].

A thick plate bending element on elastic foundation was used by Thangam Babu and Reddy [69] to find the frequencies of FNP platforms.

Arockiasamy, Reddy and Yen [70] studied the response of rubble mound breakwaters to wave and seismic forces by dynamic finite-element analysis. The response of a floating breakwater to ocean waves has been calculated by Wen and Shinozuka [71] assuming it to be a flat plate on an elastic medium.

Fluid-structure interaction studies, using the finite element technique, have been carried out for bottom-fixed structures by Liaw and Chopra [72], and for submerged structures by Zienkiewicz and Newton [73]. Extensive investigations of fluid-soil-structure interaction are needed for breakwaters and floating platforms.

6.3 Fatigue and Crack Propagation Analysis

Long-term wave loading and the dynamic amplification of wave-induced response necessitate the consideration of fatigue characteristics. Fatigue analysis carried out by Maddox and Wildenstein [74] uses the well-known Palmgren-Miner rule. Closed-form expressions have been derived by Nolte and Hansford [75] to determine the fatigue damage due to waves. The experimental investigation of Kochera et al. [76] on the fatigue properties of steel plates used for the tubular joints of offshore platforms suggest the difficulties of predicting the crack growth from assumed defects. Söding [77] has described a method of calculating the long term extreme loads and the fatigue life of marine structures. Estimation of fatigue life based on fatigue crack growth tests has been suggested by Dover [78].

The fatigue life of offshore concrete structures is often limited by the steel elements rather than the concrete. The American Concrete Institute Committee Report [79] states that if the stress range in straight deformed high-tensile steel reinforcement, imposed on a minimum stress level, does not exceed $0.4 f_y$ (f_y = the characteristic proof stress of the reinforcement, less than 140 N/mm^2), then the fatigue in the reinforcement is not critical for reinforced concrete members. In prestressed concrete, for nominal tensile stress in the prestressed tensile zone not exceeding $0.45 \sqrt{f_{cu}} \text{ N/mm}^2$, where f_{cu} is the characteristic

compressive cubic strength of the concrete in N/mm^2 , it may be assumed that fatigue in the prestressing steel is not critical.

Ref. 37 points out that cracking in the concrete should not be excessive as it would adversely affect the durability. The surface width of cracks of reinforced concrete should not exceed 0.3 mm; for those nearest to the reinforcement the limit is 0.004 times the nominal cover.

7. MODEL STUDIES AND EXPERIMENTAL INVESTIGATION

The relative wind, current and wave effects have been estimated by Remery [80] using model tests to evaluate the validity of neglecting the wind and current loading.

Three-dimensional model testing has been carried out by Dean et al. [81] to evaluate platform motion, mooring strut forces, wave forces, and other design aspects of FNPs. The 1:196 and 1:64 models were scaled according to the Froude law since inertia and gravity are the predominant forces. The results reveal that platform motions determined from small scale models are larger than those from large scale model tests. The theoretical analysis of the motions induced on an instrumented 100 feet square barge by irregular waves was checked by Muga [82] with the measurements on (i) a prototype platform and (ii) laboratory model excited by unidirectional random surface gravity waves. An experimental determination of hydrodynamic forces and moments on floating nuclear power plants was reported by Nelson [83].

8. OTHER CONSIDERATIONS

8.1 Stability Criteria

The criteria for 'intact' and damage stability for floating structures are essentially the same as those used for ships. Bearing in mind the considerable differences in the configuration of a ship and a floating platform, and the dynamic nature of the problem, the true safety margins have to be evaluated by systematic model testing in waves and the formulation of associated analytical procedures.

The weights on board of the platform should be distributed in a favorable manner to ensure adequate stability under normal operational conditions. Inclining tests of the platform have to be carried out to make sure the weight and center of gravity are actually within the design limits. In order to ensure platform strength and stability for various operating conditions, immersion marks should be made for maximum, minimum and fixed drought conditions. The barge motion is most critical during the removal and replacement of fuel elements. The pitch and roll angle should not exceed ± 2 minutes (Ref. 3) during fuel handling. Adequate stability systems must be provided to limit the barge motion with the allowable limits.

For a floating platform, the initial metacentric height, taking into account the free surface correction, should not be less than 0.3 m (Ref. 32) for any loading condition. Breakwater stability considerations have been described by Fischer and Lu [84].

8.2 Foundation Analysis

The foundations for breakwater and mooring lines necessitate investigations of the seabed for bearing capacity, slope stability and settlement, scouring and liquefaction potential.

Empirical relations for sit-on-bottom structures have been developed by Ninomiya and Tagaya [85] and their experimental results show the hemispherical shape to be the best bottom profile of the structure effective against scouring. The pattern of scour around circular cylinders fixed at the sea bottom was investigated by Breusers [86], and model tests indicated that 90% of the tidal scouring occurs within a period of days or weeks. The protective medium against scour should be a flexible one composed of stone filters, mattresses, nylon clothes, etc. Liquefaction becomes a serious problem only when it causes ground failure. The kinds of ground failure associated with liquefaction are described by Youd [87].

8.3 Noise and Vibration Level Considerations

The reasons for the difference in allowable noise and vibration level specifications for offshore and onshore plants have been listed by Melling and Davies [88]. In general, there are three area classifications with corresponding noise specifications, namely, i) Work Areas: Allowable noise level - 90dBA, ii) Control Rooms: Allowable noise level - 60dBA, and iii) Accommodation Areas: Allowable noise level - 45 dBA.

8.4 Safety Considerations

An overview of the safety requirements, risk analysis and reliability concerning offshore installations has been outlined by Abrahamson [89]. The nuclear safety of FNPs has been evaluated by Okubo and Pritchard [90].

One typical plant accident, unique to FNPs, is the penetration of the hull structure by missiles generated by turbine failure which could result in partial flooding or adverse orientation of the plant. Also, flooding could result from surges, tsunamis, and wind generated wave activities existing in the offshore environment. Noble [91] discussed the determination of the probable maximum still water flood levels at offshore sites. It was noted that the shutdown of the plant during a postulated sinking emergency is a design basis requirement. Transportation of nuclear fuel and solid wastes to and from the offshore plant poses a transport accident risk which may release radioactivity in the environment.

A reliability engineering approach similar to that outlined by Moses [92], must be used to assure safety against major accidents resulting from seismic ground motions, tsunamis, collision of large ships, missiles, aircraft and rockets etc.

8.5 Waste Heat Dissipation

Using a diffusion model, the distribution of the temperature increase of the adjacent water due to the heat water discharge from FNP has been analysed by Adams, Almquist, Ingraham and Stolzenback [93]. A model to predict the temperature distribution due to horizontal surface discharge has been developed by Pritchard [94]. A correlation study has been carried out by North and Adams [95] to evaluate the areas of influence due to thermal discharges of FNPs of different capacities.

8.6 Influence on Marine Biology

The effect of FNPs on marine fisheries has been discussed by Burrell [96], and a

detailed study of the thermal effects on marine biology has been described by Soule [97].

8.7 Instrumentation

The problems associated with instrumentation of offshore structures has been detailed by Nicholson [98]. Various types of instruments used for offshore structures, and the techniques of automatic recording and processing of data have been presented by Geminder and Pomonik [99]. An instrumentation program to provide the environmental data and the response of offshore structures was discussed by Ohmart, Gratz and Mallery [100].

Modifications needed to adapt the instrumentation of fixed offshore structures to floating platforms have been discussed by Ruhe and Griffin [101].

8.8 Corrosion Control

The design of a cathodic protection system for corrosion control of the FNP has been discussed by Lehmann and Kyle [102].

8.9 Radiation

The effects of large radiation exposure on marine biological systems has been analysed by Templeton et al. [103]. Aten [104] estimated the maximum permissible radionuclides release in sea water using the specific activity method. An underwater instrumentation system to measure radioactive components in marine sediments was described by Noakes et al. [105].

8.10 Legal Aspects

The extension of the Price-Anderson act protection to FNPs has been reported by Wilk and Bockrath [106]; a detailed study of the legal and regulatory aspects of FNPs was presented by MacVey [107].

9. CONCLUSION

A state-of-the-art for the analysis and design of FNPs has been presented and the problem areas identified. Though present design experience is limited, there is a vast potential for the transposition of available technology in the oil exploration and ship building industries to the FNP concept. An interesting extension of this concept is the offshore nuclear energy center proposed by Diclemente [108], involving multiple plant units and fuel fabrication and reprocessing facilities.

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TABLE 1. CONCEPT TOTAL ACCEPTABILITY VALUES [2]

Concept Number	Titles	Acceptability Values
2	Aboveground-Inland	0.779
5	Aboveground-Floating Lagoon	0.761
3	Aboveground-Hillside	0.756
4	Aboveground-Low Profile	0.674
1	Aboveground-Coastal	0.657
12	Offshore-Floating, Deep	0.649
9	Underground-Nonmassive, Poorly Cemented Materials	0.642
15	Offshore-Artificial Island	0.637
11	Offshore-Floating, Shallow	0.636
17	Offshore-Tuned Sphere	0.617
7	Underground-Massive Sedimentary Rock	0.603
16	Offshore-Natural Island	0.581
14	Offshore-Undersea	0.549
6	Underground-Massive Igneous Rock	0.540
8	Underground-Unconsolidated Materials, Beach	0.522
13	Offshore-Seabed	0.502
10	Underground-Massive Rock, Faulted	0.494

TABLE 2. BEHAVIOR OF OFFSHORE STRUCTURES - MAIN ITEMS TO BE CONSIDERED [15]

Static Behavior	Dynamic Behavior	Enduring Behavior
System characteristics	Dynamic structure/	Changes of structure/
Stresses and Forces	foundation model.	foundation system during
Displacements	Dynamic stresses and	lifetime.
Foundation reactions	displacements.	Foundation long term
Structural performance	Dynamic load factors	settlements.
during accidental loads	Damping of soil/structure	Cumulated fatigue stress
or mishaps.	systems.	Damages
Stress redistributions,	Vibrations of members	Fatigue cracking
cracking, etc.	Long term stress	Durability
	responses.	Maintenance and repairs
		General serviceability
		and structural fitness
		as regards intended use.

Fig. 1. Different Configurations of FNP Platforms [3].

Fig. 2. Features and Location of Atlantic Generating Station [79].