INTRODUCTION

During the past three decades, major advances have improved our understanding of earthquake hazards worldwide. While the ability to estimate the potential intensity and characteristics of site-specific motion has improved, tremendous uncertainty exists in such predictions. Thus, engineers have sought technologies and design approaches minimizing the effect of these uncertainties on the safety and overall performance of critical facilities. Over the previous 30 years, one of the principal approaches used to mitigate seismic risk is seismic isolation.

Seismic isolation is not a new concept. In 1909, a medical doctor produced the first patent for a rudimentary isolation system that consisted of a layer of sand, mica, or talc between a structure and its foundation. Since that time, this technology has developed and matured with advancements in materials.

The advent of modern seismic isolation technology is considered to have started in the mid-1960s, when the New Zealand Department of Scientific and Industrial Research devised a new form of isolation device based on alternating layers of rubber or other elastomeric sheets and steel shim plates vulcanized together to act as a unit. The introduction of steel shims answered a major problem with rudimentary elastomeric isolators which suffered from bulging under vertical loading. This form of seismic isolation was first applied in Macedonia during the late 1960s, when these isolation devices were installed between a school building and its supporting foundation.

Since that time, the use of seismic isolation has increased gradually around the world. Nonetheless, seismic isolation has found only limited application to date in the construction of nuclear power facilities. With increasing public concern for seismic safety in general and research findings that indicate that seismic hazards may be larger than expected in...
many parts of the world, it is reasonable for the nuclear power
industry to consider the wider use of seismic isolation in the
design of new nuclear power plants (NPPs) and related fa-
cilities. At the same time, it would be prudent to consider
more fully the potential benefits, costs, and impediments as-
associated with widespread use of seismic in the nuclear indus-
try; to identify actions needed for more realistic cost-benefit
assessment; and to refine the technology for specific applica-
tion to NPPs and related facilities. This study attempts to
systematically address these issues, which is mainly focusing
on base isolation.

2 | OVERARCHING ADVANTAGES
AND DISADVANTAGES

The primary advantages and disadvantages of seismic isola-
tion are summarized in this section.

2.1 | Advantages of seismic isolation

Some of the primary advantages identified for using seismic
isolation include:

2.1.1 | Improves seismic performance

Seismic isolation provides an effective and cost-effective
means of limiting the forces that can be transmitted to the
supported structure by horizontal components of ground
shaking. When the superstructure has adequate stiffness and
strength, drifts and accelerations in the superstructure can
be reduced by factors of 5 or more when compared with a
fixed-base system.3 Because of smaller earthquake demands
on structures, systems, and components, safety margins can
be increased and/or construction costs can be reduced.

2.1.2 | Favorably viewed by public

Seismic isolation is viewed by the public, regulatory, and
government officials, and the engineering community as a
new technology that is capable of increasing seismic safety
margins.4

2.1.3 | Speeds resumption of service

Seismic isolation will likely allow more rapid resumption of
normal power production following moderate to major earth-
quakes. In conjunction with appropriate instrumentation sys-
tems, the substantially lowered demands on the superstructure
should permit rapid resumption of power generation. The
resumption of revenue generation would be a tangible ben-
efit that should be considered in cost/benefit analyses. For
large seismic events, higher demands and disruption of other
ancillary facilities needed to generate and distribute power
may delay the resumption of power generation unless con-
sistent protective actions are taken.

2.1.4 | Expands use of proven standard
plant designs

Seismic isolation can leverage the benefit of existing, proven
standard plant designs. This will result in cost savings by
eliminating the need for a redesign of all the components of
a unit, but it also enables the use of details for which con-
siderable experience and confidence already exist. Through
the use of seismic isolation, standard plant designs can be
extended for use in regions of more intense ground shaking
or for a broader range of ground motion characteristics. The
MCEER report 15-0008 particularizes some standardized
designs of seismically isolated nuclear reactors.5 With time,
the reduction in design forces in seismically isolated standard
plants may allow simplifications of design methods and con-
struction details, resulting in further reduction in costs and
construction time.

2.1.5 | Facilitates adoption of innovative,
next-generation reactor designs

With the development of new reactor technologies and the
interest in small modular plant design concepts, seismic iso-
lation can facilitate the development of standardized designs
that can be applied to a broad range of seismic environments.
Many of these reactor designs have denser mass and lower
stiffness compare to traditional NPP designs. As such, seis-
mic isolation can facilitate their use in regions susceptible to
earthquake ground shaking.

A study was performed at the University of California
Berkeley titled, “Advanced Seismic Base Isolation Methods
for Modular Reactors.”6 The report focused on the develop-
ment of isolation of small modular reactors and addressed
some additional issues, including impact by aircraft on iso-
lated structures, torsional response due to mass and stiffness
eccentricities above the isolation plane, the location of the
isolation plane (at the top, middle, or bottom of the Small
Modular Reactor [SMR]), and so on. The conclusion of this
study was that, with certain limitations, seismic isolation is
applicable to small modular reactors in high seismic regions.

2.1.6 | Increases confidence in achieving
regulatory approval in the face of uncertainties
with seismic hazard

Seismic isolation can help reduce the uncertainty that confrons
tutilities in many parts of the world where seismic hazards are
currently being reassessed or not well defined. Improved defi-
nition of seismic hazard resulting from improved knowledge
of the underlying seismic source mechanisms and attenuation relationships during the design process or service life of a plant raises substantial uncertainties in the planning and design process. Seismic demands in seismically isolated NPPs are far less sensitive to changes in seismic hazard than a fixed-base structure. Changes in seismic hazard would have the most profound effect on the horizontal dimension of the seismic gap needed to permit operation of the isolation system. Thus, safety margin reserves can be achieved by providing initially installed isolators with a larger-than-needed displacement capacity. If mandated seismic hazards increase during a plant's service life, the isolation system may be adequate if the reserve displacement capacity is adequate, or the isolation system can be supplemented with additional viscous, friction, or yielding energy-dissipation devices. In some cases, it may be advantageous to exchange bearings with ones having improved characteristics for the new hazard. While careful study is needed to make such upgrades, the ability to change the mechanical characteristics of the isolation system is a significant benefit. Changes in seismic hazard during the design of a fixed-base plant normally trigger major design changes for nearly all components of the facility; changes in seismic hazard during a plant's life might necessitate widespread upgrades to systems, structures, and components that are undesirable from a technical and economical perspective.

2.1.7 | Increases confidence in plant performance

Seismic isolation can be used by regulatory agencies to realize a more risk-based assessment of the performance of NPPs. That is, seismic isolators are manufactured under high-quality conditions and tested to ensure compliance with design documents. During earthquakes, systems, structures, and components in an isolated plant would be expected to remain well within the elastic range. As such, analysis models developed for isolated NPPs can be calibrated to test results for the bearings actually used in the structure. Consequently, high confidence is expected in analysis results obtained for seismically isolated structures. On the other hand, fixed-base systems depend on the stiffness, strength, and hysteretic characteristics of a multitude of structural elements and their connections and of the components and their attachments to the structure. The potential variability in these properties due to the intrinsic mechanical behavior and uncertainty in material properties and workmanship lead to the need to use high factors of safety to achieve the desired confidence in performance.

2.1.8 | Can improve overall post earthquake operability and safety of a plant

Consideration should be given to seismic isolation of other structures at a NPP site to facilitate overall operability of the facility following a major seismic event. In most cases, isolation is considered only for the nuclear steam supply system, but benefits may ensue from isolation of the turbine generation system and balance of plant. As evidenced by the experience of Japanese utilities during the 2011 East Japan Earthquake, seismic isolation of emergency operations, administration, and other buildings at a nuclear power station can be of substantial benefit following an earthquake.

2.2 | Disadvantages of seismic isolation

Some of the primary, overarching difficulties commonly cited for the seismic isolation of NPPs include:

2.2.1 | Limited experience with isolated NPPs subject to earthquakes

Real-world experience with seismically isolated NPPs located in regions of major earthquake ground shaking is limited.

- No NPPs have been isolated in regions susceptible to moderate-to-high levels of ground shaking.
- None of the isolated NPPs constructed to date have been subjected to major ground shaking.
- Few large-scale tests of systems resembling NPPs have been done to demonstrate dynamic behavior of isolators, isolated structures, and systems and components within an isolated plant.

2.2.2 | Regulatory uncertainty

Uncertainty exists regarding how regulatory agencies will view seismic isolation.

- There has been a positive response by the Nuclear Regulatory Commission (NRC) in developing NUREG/CR-7253 document related to the application of seismic isolation to NPPs and similar efforts elsewhere.7
- Initial applicants will have some guidance on specific issues to be raised in a licensing review, but the actual level of detail and issues that may come up in the review of an application is uncertain. The level of effort and time needed may be greater than for a regular fixed-base plant designed for larger earthquakes.
- There may be a tendency for regulators and reviewers to be more conservative in reviewing and approving new technology, even if it is likely to perform better than conventional approaches. Thus, full justification and validation of the particular isolation approach to be used is needed.
2.2.3 | Umbilicals designed for larger displacements

Concern is typically raised regarding the behavior of umbilical connections that cross the seismic gap. For instance, design and performance goals for items such as pressurized piping lines, control and monitoring electrical conduits, and so on need to be carefully studied. The in-service and earthquake behavior of swivel or gimbal connections in pipes needs to be carefully considered, as does the feasibility of hard serpentine piping layouts.

2.2.4 | Education and training needed

Engineers and contractors working on nuclear power facilities as well as regulators and the public are generally unfamiliar with seismic isolation.

- This may lead to resistance to change.
- Design and construction teams may require additional in-house education and training. Appropriate short courses, seminars, and workshops may be desirable to increase the understanding of isolation within the nuclear industry and regulatory agencies.

2.2.5 | Cost premium may be needed for improved performance

The initial cost of a seismically isolated NPP may increase. There will be extra cost in the design and construction of the base mat for the structure and the seismic vault, and related costs of detailing the seismic gap and providing umbilical components with adequate displacement capacity. However, these costs need to be weighed against (a) the cost and reliability of modifying the standard plant design to withstand larger earthquake hazards, and (b) the costs associated with potentially minor but disruptive widespread damages in a fixed-base plant and the effects of downtime on revenue generation. Thus, it is recommended that cost/benefit studies be carried out that consider comparable performance goals and cover the full life cycle of a plant.

2.2.6 | Concern for what happens if the displacement capacity of an isolation system is exceeded

While related issues are equally relevant for fixed-base structures, issues are raised about the response of seismically isolated structures in the event of a larger-than-expected seismic event. The special concern with an isolated system is the possible abrupt change in behavior that might occur prior to and after the isolation system reaches its ultimate displacement capacity. Thus, concern centers around the effects of a hard stop on the response of the supported structure, systems, components, and equipment. A simple solution is to make the displacement capacity large enough so that the probability of encountering a hard stop is highly unlikely. However, for friction sliding systems without re-centering capabilities, the total displacement that needs to be considered includes incremental displacements caused by the main shock and several aftershocks. Another approach is to design supplemental energy dissipation systems to control the deceleration of the isolation system in a manner that would not generate transient forces that would endanger the supported facility. Iiba et al8 developed a displacement restraint device that can be categorized as a bumper. The device is made of 16 pieces of rubber. The load-carrying capacity increases with the rise of lateral displacement. And Mazuka et al9 carried out a series of numerical analyses to investigate the reduction in excessive displacement in an isolated building by various types of passive dampers.

2.2.7 | Response of isolated systems to other hazards

Clearly, seismic isolation systems need to be designed to respond adequately in windstorms, floods, and other natural disasters. In some cases, regulatory agencies are requesting information about hazards not associated with natural hazards. Thus, issues related to the effect of a blast, an airplane collision, and so on are raised. These issues can be addressed using sound engineering principles, but only limited investigation of these topics has been done for seismically isolated NPPs to date.

Fixed-base plants share some of these issues and potential solutions. For example, constructing lighter pressurized water reactor (PWR) and boiling water reactor (BWR) plants and small modular reactors in below-grade configurations is useful for both isolated and nonisolated facilities when considering the effects of an airplane collision. Also, efforts to protect the seismic vault from infiltration of groundwater and inundation by flood or tsunami are needed. For instance, one unexpected area of concern for the isolation system at the Koeberg NPP arose immediately after construction was completed. Groundwater infiltration into the seismic vault was detected. This problem was resolved by a series of waterproofing measures applied to the construction joints in the retaining walls and lower raft.10

3 | IMPACT OF SEISMIC ISOLATION ON COST AND SCHEDULE

In assessing the application of seismic isolation to NPPs and related facilities, careful consideration is needed on the
implications related to the overall planning, design, construction operation, maintenance, and decommissioning of a plant, including impacts on cost and schedule. While a full comparative economic evaluation of a seismically isolated plant is beyond the scope of this paper, some of the key differences between seismically isolated and fixed-base facilities are examined below.

3.1 Some special uncertainties

Some overall uncertainties exist in making comparisons of likely impacts of a conventional fixed-base design approach vs a strategy based on seismic isolation (see Table 1). For instance, in the United States, the NRC is moving rapidly toward implementation of a quantitative performance-based, risk-informed approach for assessment of plant safety.11 As a result, utilities seeking approval for new NPPs may face far different requirements in the near future than in the past. While this may be especially true for seismically isolated facilities, where explicit consideration of nonlinear behavior needs to be accounted for, greater reliance on detailed nonlinear analysis may potentially be required for isolated plants subjected to beyond-design-basis events.

A second common source of uncertainty is the nature of seismic hazards in regions where NPPs might be constructed in the near term. Reassessment of seismic source mechanisms and attenuation relations will likely result in dramatic changes in design earthquakes for some locations. While the likely peak ground acceleration (PGA) or other seismic intensity measures will have a common effect on both isolated and fixed-base structures, the shape of the response spectrum will have a distinct effect on the relative advantage of isolated and fixed-base systems. That is, increases in pseudo-acceleration in the high-frequency range may have an important effect on fixed-base plants, but isolated plants may be the most sensitive to increases in the low-frequency range of a spectrum. Additionally, it is a matter of relating these changes to the floor level responses as well. Changes in these spectra can place equipment in previously well designed acceleration ranges back into regions of acceleration sensitivity.

A third common source of uncertainty is with respect to public acceptance of the construction of new NPPs. This is especially true following the 2011 East Japan Earthquake. However, with a more rigorous, performance-based, risk-informed evaluation approach, improved characterization of earthquake hazards, and other factors, this problem may be resolved. Some may view seismic isolation of nuclear facilities as a new and unproven technology and be resistant to its use. However, the majority may view it as a newly mature technology that, if adequately substantiated by analysis and testing, can improve seismic performance and safety margins.

Special uncertainties are associated with seismically isolated facilities. Typically, “first-of-a-kind” approaches will result in longer schedules (and thus costs) associated with decision making. Tasks that may have an uncertain impact on schedule and cost include:

- Establishing standards, guidelines, and regulations;
- Settling on specific licensing procedures and processes where these differ from those for fixed-base plants;
- Identifying specific specifications and procurement requirements;
- Conducting tests and analyses necessary to substantiate confidence in plant safety and performance; and
- Training engineers and plant operators.

To mitigate this, and as noted previously, the NRC is moving rapidly forward on the development of a NUREG document to provide near-term guidance regarding their specific expectations for considering seismically isolated NPPs. Also, ASCE 4 (Seismic Analysis of Safety-Related Nuclear Structures and Commentary) was updated in 2016, including sections related to seismic isolation. These documents, in conjunction with ASCE 43 (Seismic Design Criteria for Structures, Systems, and Components in Nuclear Facilities) and other design standards, should provide a reliable basis for consideration of the seismic isolation of NPPs.12,13 In addition, International Atomic Energy Agency (IAEA) and Japanese and European regulatory agencies are also moving toward updating documents to promote consideration of the seismic isolation of nuclear facilities.

While seismic isolation is a mature technology and has been applied to various types of complex infrastructure and industrial facilities, the limited experience with the construction of isolated nuclear facilities and power stations along with the manufacturing of isolation systems and special features such as umbilical elements may lead many to believe there will be unexpected complications and delays. However,
this is not expected and can be mitigated by design engineers studying previous projects such as those at the International Thermonuclear Experimental Reactor (ITER) and the Jules Horowitz Reactor (JHR) nuclear projects in France and large industrial and civil projects related to liquefied natural gas (LNG) tanks, offshore platforms, and so on.

The procurement process for isolators can be a time-intensive part of the process. Given the necessity of prototype testing, the manufacturing timeline will be dictated based on the tested performance. As a result, this places the isolators on a critical path given the location of their installation in the structural system. Thus, this process should begin as early as possible in schematic design, and schedules should incorporate slack time to absorb potential design and manufacturing difficulties. It is not expected that this will be a critical issue if manufacturers are selected that have extensive experience with isolators with similar load and displacement capacities and other performance expectations for the plant under design. This is especially true where seismic demands do not stretch the bounds of current technology.

### 3.2 | Cost and scheduling issues

The basic elements entering into the calculation of nuclear power generation costs include capital/investment costs, operation and maintenance costs, and nuclear fuel cycle costs. In the case of nuclear power, IAEA (2007) indicates that capital/investment costs represent approximately 60% of the total nuclear generation cost, whereas operations/maintenance and nuclear fuel cycle costs represent about 20% each. Thus, seismic isolation is likely to affect the capital/investment costs the most and, to a much lesser extent, operations and maintenance costs.

In the following discussion, the focus will be on items that increase or decrease the costs of isolated plants compared to otherwise similar plants that are fixed base. For this comparison, the situation is used where an existing standard PWR or BWR that has been licensed for an area of modest seismic hazard is to be adapted to a location with a modestly higher (150%) design earthquake. The subsequent sections are based on this premise, and no more emphasis will be placed on it. Clearly, more specific details about the plant design, seismic hazard, and local soil conditions are necessary to do this comparison in detail. However, this discussion will highlight the basic issues involved in such a comparison. Many of the underlying issues pertain to other types of facilities, such as small modular plants, and seismic hazards (large design earthquakes, or special ground motion characteristics). However, these would require more specific understanding of the underlying situation.
3.3 | Project stages

This discussion will examine the five stages that according to IAEA (2007) characterize an overall NPP project: Stage 1: Preproject planning; Stage 2: Project decision making; Stage 3: Plant engineering and construction; Stage 4: Plant operation; and Stage 5: Plant decommissioning. Discussion will include a review of the underlying technical issues involved and their potential impacts on cost and schedule.

These stages examined are illustrated in Figure 1.14 The following discussion follows the basic project stages outlined by IAEA (2007). Highlights of this discussion are itemized in Tables 2 and 3.

3.3.1 | Stage 1: Preproject planning

The activities performed during the preproject stage are typically nonengineering in nature. For example, they involve examining the plant's role in the regional energy supply, determining cost and financial feasibility in terms of the market for energy and production costs, establishing various organizational and management structures, assessing public and regulatory acceptance, and identifying key consultants and partners.

Typically, selection of seismic isolation is not expected to have a large impact on this stage, other than potentially increasing public acceptance in regions of significant seismic hazard and reducing life-cycle costs as well as the set of consultants evaluated for the project. Planning studies and discussions regarding the use of seismic isolation may extend the duration of this phase, especially for early adopters. However, such detailed studies might be done in Stage 2. Nonetheless, all such schedule extensions are likely to reduce significantly once these initial cost and technical studies have been undertaken for a few plants.

3.3.2 | Stage 2: Project decision making

The activities performed during the project decision-making stage are again mainly nonengineering in nature and are related to more detailed financial studies, formalizing management systems, establishing work plans for achieving regulatory approval, obtaining financing, and establishing contracts with key consultants.

Site selection and evaluation is typically done at this stage. The selection of the site may have a significant bearing on the relative feasibility and cost of an isolated or fixed-base plant, depending on the general intensity of the design earthquake and the shape of the response spectra associated with alternative sites. This is not likely to extend the technical investigations needed or increase costs, but deliberations related to selecting a fixed-base or isolated solution may increase the duration of this stage. Again, such delays are likely to diminish when more experience is gained by the industry.

3.3.3 | Stage 3: Plant engineering and construction

The activities performed during the plant design and construction stage according to IAEA (2007) are:

- Overall project management.
- Establishing and implementing plant safety objectives.
- Project engineering.
- Plant licensing process including the preparation of the plant safety report and providing for safeguards and physical protection.
- Procurement and expediting equipment and material.
- Manufacturing of equipment and components.
- Plant construction.
- Plant commissioning and acceptance.

The decision to use seismic isolation will have a minor but important impact on the first two bullet items in the list of activities to be performed during the plant design and construction stage according to IAEA (2007): overall project management and establishing and implementing plant safety objectives. In terms of overall planning, new operations associated with designing, procurement, quality assurance testing, installation, and acceptance of isolation systems and umbilical elements need to be integrated into the overall engineering and construction planning process. Isolation of the nuclear steam supply system (NSSS) and other facilities at the plant may become an integral aspect of the plant safety objectives and plans.

Project engineering

For project engineering, the major impact expected is on budget and schedule. However, this is true for both a fixed-base plant and a seismically isolated one. For the fixed-base plant, considering the scenario mentioned above where an existing standard plant is to be adapted to a site with a higher design basis ground motion (GMRS), nearly all systems, structures, and components, including architectural and nonstructural features not directly related to plant nuclear operations, may need to be redesigned. For the seismically isolated structure, it is likely that the intensity of shaking can be increased significantly before plant redesign is necessary due to the system's ability to perform for a range of seismic conditions. In this way, proven designs incorporated in the existing standard plant can be reused once the adequacy of their performance is confirmed by analysis.

This is not always possible, however. For example, situations where the systems, structures, and components and
## TABLE 2  Impact of fixed-base and seismically isolated approaches to adapting a standard plant to a larger design earthquake

| Item                  | Conventional fixed-base plant                                           | Seismically isolated plant                      |
|-----------------------|--------------------------------------------------------------------------|-------------------------------------------------|
|                       | Impact on schedule | Impact on cost | Comment                                                                 | Impact on schedule | Impact on cost | Comment                                                                 |
| 1 Preproject Planning Activities | Significant | Significant | Generally, the higher seismic demands on the plant will necessitate small or large changes to nearly all elements throughout a plant. Thus, the scale of changes is large and requires careful coordination. | Minor              | Negligible     | In ideal conditions where seismic forces above the isolation plane are smaller or at the level of the standard plant design, changes are localized in and near the isolation plane to accommodate the isolators and changes to umbilical elements. |
| 2 Project Decision Making | Negligible | Negligible | Higher intensity shaking may trigger a need for soil improvement and modestly larger excavation to accommodate thicker mats and wall structures, if needed. | Moderate            | Moderate       | Because of the addition of the seismic vault and extra mat, substantially more excavation/shoring may be necessary. |
| 3A Design | Significant | Significant | For higher intensity motions than considered in the initial standard plant, nearly all systems, structures, and components, including features that are not safety related, will need to be assessed and redesigned for the higher demands. This will use standard practices, but it may require requalification of features and major changes in some items. | Significant         | Moderate       | Considerable efforts are needed because this is a first-of-a-kind project. Increased efforts are associated with selecting the location and configuration of the isolation plane and seismic gap, identifying the bearing type and prequalifying manufacturers, conducting prototype and quality assurance (QA) tests, conducting nonlinear analyses, etc. |
| 3B Construction | Significant | Significant | See Table 1.                                                      | Moderate            | Moderate       | See Table 1.                                                      |
| 4 Plant Operation | Negligible | Negligible | Periodic visual inspection of bearings. Mechanical testing is optional. | Minor              | Minor          |                                                                 |
| 4A Post Earthquake Activities | Significant | Significant | Since all elements are called upon to carry major loads, detailed inspection is required. Extensive repair of items (doors, windows, plumbing, ceilings, etc.) is expected. Substantial loss of revenue is possible due to shutdown of the reactor for inspections and repair. | Moderate            | Moderate       | For moderate to design-level events, it is anticipated that only modest inspections would be required. Instrumentation and decision support (analysis tools set up in advance will assist in this). For beyond-design-level events, more thorough inspection and review are needed. |
| 5 Plant Decommissioning | Minor | Minor | Larger and stronger components will require greater effort to demolish. | Minor              | Minor          | There is an extra base slab to demolish. |
other aspects of an isolated plant may need to be redesigned include:

- Items sensitive to low-frequency input energy. For instance, fuel storage pools, long span piping runs, and other features may have low frequencies that are not excited in a fixed-base structure, but they may be in resonance with the frequency of the isolation system (e.g., between 0.2 Hz and 0.5 Hz).
- Items vulnerable to vertical components of seismic excitation. Often systems have high factors of safety in the vertical direction due to load combinations that do not include seismic loading and load conditions necessary to insure their protection during shipping and installation. However, isolators like those presented previously do not prevent vertical seismic forces from being transmitted directly into the structure, and some may, in fact, amplify vertical response within the structure. Thus, the sensitivity of SSC items to vertical components of motion should be carefully assessed. In some cases, extra braces or local forms of vertical isolation can be provided for the vulnerable items.
- Some isolation systems that continually strengthen as displacements increase and others that may stiffen when the bearing is subjected to especially large displacement demands. Such systems may experience larger force, acceleration, and drift demands compared to the design basis in case of larger-than-design-basis events. As such, portions of the plant above and below the isolation plane may need to be strengthened or designed with a safety factor. This can be avoided by selecting isolation systems that do not exhibit this behavior or by modifying the characteristics of the bearings to avoid the situation.
- In some cases, engineering analysis may show that the candidate isolation system selected does not have sufficient displacement capacity for the design basis GMRS (or for any beyond design basis event that is considered). In such cases, a completely new system, integrating the physical design of the plant, umbilical components and isolation system, may be warranted. While this redesign may involve some considerable expense, it is expected to be less expensive than designing a fixed-base plant for the same performance at these excitation levels.

Although there may be considerable effort and staff required related to the engineering of an isolated or fixed-base NPP, IAEA (2007) indicates that that engineering makes up about 10% of the cost of a plant that has no first-of-a-kind issues. Thus, to the extent that isolation systems can reuse many of the features of an existing standard plant design, the impact of using seismic isolation should not have an excessive impact on costs compared to using a fixed-base approach.

Schematic design

The schematic design phase is particularly critical for an isolated facility. In addition to examining issues related to plant configuration and the position of the seismic gap, various characteristics of the isolation system should be investigated. As noted previously, different isolation systems have many common traits. However, there are differences among them—some isolators more easily accommodate heavy loads at large displacements, others may be better at controlling the amplitude of floor spectra in particular frequency ranges, and others may better resist certain types of earthquakes (e.g., long duration excitations, near-fault excitations, etc.). Thus, care is needed to identify the characteristics of the isolators and supplemental damping devices.

Studies are needed to assess the tradeoffs between fewer bearings that carry heavier loads vs an increased number of smaller bearings. A smaller number of bearings may reduce the costs associated with bearing installation, but this will result in longer spans on the upper and lower mats of the isolation vault, thereby possibly increasing their thickness in order to control deflections and vibrations. Larger bearings cost more than smaller ones and require additional man power in the placement process. Having too many bearings reduces the ability to easily access and maintain bearings in the seismic vault and increases the number and cost of isolator pedestals and attachments. Thus, design studies are needed to identify the optimal number of bearings.

Some bearings are more sensitive to mass and stiffness eccentricities in the superstructure, and the arrangement of bearings needs to be studied to avoid excessive torsional response of the superstructure. Alternatively, bearings that do not exhibit this behavior or supplemental energy-dissipation devices can be investigated to control torsional response. The impacts of the properties of isolation system on torsional response are discussed in MCEER report 15-0008. Additionally, depending on the response of the structure, the necessity for tension capacity of exterior bearings needs to be accounted for. This requires a more specialized material affecting cost and potentially schedule due to additional testing.

Similar attention is needed with regard to the design of piping and other umbilical elements that cross over the seismic gap. Typically, isolators involve a trade-off between imposing higher loads and accelerations on the isolated portion of the structure and imposing higher lateral displacements on the isolation bearings. Although it is possible to reduce the lateral displacement of the bearings to enable the use of isolators available from a broader range of suppliers and to permit solid serpentine piping loops, it is at the expense of higher accelerations and forces in the superstructure. Thus, these tradeoffs and their effects on cost and safety need to be carefully considered. Beyond the connections, there is
TABLE 3  Impact of fixed-base and seismically isolated approaches on construction cost and schedule

| Item          | Conventional fixed-base plant | Impact on schedule | Impact on cost | Comment                                                                                                                                   |
|---------------|--------------------------------|--------------------|----------------|------------------------------------------------------------------------------------------------------------------------------------------|
| 1  General Requirements | Significant | Significant | Generally, the higher seismic demands on the plant will necessitate large or small changes to nearly all elements throughout a plant. Thus, the scale of changes is large, and requires careful coordination. |
| 2  Site Work | Negligible | Negligible | Higher intensity shaking may trigger a need for soil improvement and modestly larger excavation to accommodate thicker mats and wall structures, if needed. |
| 3  Reinforced Concrete | Significant | Significant | Higher seismic demands are expected throughout the plant, necessitating higher strength concrete, additional reinforcing steel, and/or thicker members. |
| 4  Masonry | Minor | Minor | Any masonry elements (nonstructural walls) will need to be designed for higher forces and drifts developed in the structure. |
| 5  Metals | Higher seismic demands are expected throughout the plant, necessitating stronger and/or stiffer misc. metal components expected to carry significant seismic loads. |
| 6  Wood and Plastics | Negligible | Negligible | Minor enhancements may be needed if seismic loads or movement affects the attachment of elements to the structure. |
| 7  Thermal and Moisture | Negligible | Negligible | Minor changes may be needed to accommodate seismic forces or movements. |
| 8  Doors and Windows | Negligible | Negligible | Minor enhancements may be needed if seismic loads or movement affects the attachment of elements to the structure. |
| 9  Finishes | Negligible | Negligible | Minor enhancements may be needed if seismic loads or movement affects the attachment of elements to the structure. |
| 10 Specialties | Unknown | Unknown | The ability of the reactor and related specialty items to withstand higher seismic demands is beyond the scope of this report. |
| 11 Equipment | Significant | Significant | Higher demands may trigger the need to re-qualify equipment. Equipment and attachments may have to be enhanced. |
| 12 Furnishings | Negligible | Negligible | |
| 13 Special Construction | Significant | Significant | Higher demands may necessitate special construction methods, such as augmented composite construction, reinforcement of wall penetrations, use of fiber-reinforced concrete to mitigate cracking, etc. Special construction related to the containment vessel, large-diameter piping, and related systems will need to be designed to accommodate high-level accelerations. |
| 14 Conveying Systems | Significant | Significant | Cranes, elevators, and material-handling equipment will need to be enhanced to accommodate higher intensity shaking throughout the plant. |
| 15 Mechanical | Significant | Significant | Heating, Ventilation, and Air Conditioning (HVAC), piping, and other mechanical systems may be subject to significantly larger accelerations and displacements, and they may require redesign and enhancement. |
| 16 Electrical | Significant | Significant | Higher acceleration demands throughout the plant may require requalification or other types of bearings are proprietary and covered by patents, whereas other patents have expired and the bearings are |
| Item                  | Impact on schedule | Impact on cost | Comment                                                                                                                                 |
|-----------------------|--------------------|----------------|------------------------------------------------------------------------------------------------------------------------------------------|
| Conventional fixed-  | Minor              | Negligible     | In ideal conditions where seismic forces above the isolation plane are smaller or at the level of the standard plant design, changes are localized in and near the isolation plane to accommodate the isolators and changes to umbilical elements. |
| base plant            | Moderate           | Moderate       | Because of the addition of the seismic vault and extra mat, substantially more excavation/shoring may be necessary.                         |
| Equipment and         | Minor              | Moderate       | An extra reinforced concrete mat and numerous pedestals are required to support the isolation system. Walls for below-grade portions of the structure are taller than for a typical NPP and must be designed as retaining walls. The remainder of the plant would be expected to need the same or a smaller amount of concrete than the standard plant design. |
| attachments           | Negligible         | Negligible     | Design forces and drifts will likely be less.                                                                                             |
| NA                    | Minor              | Negligible     | Various metal support parts are needed to provide support for isolators or to provide displacement restraints. Piping and other umbilical supports may need to be enhanced at the seismic gap. |
| Specialties           | NA                 | NA             | Possible reduction in the size of members or attachments may be possible if seismic forces are reduced significantly.                    |
| Conveying systems     | Moderate           | Moderate       | Depending on environmental conditions and other hazards, such as flooding, special attention may be required in the design of covers for the seismic gap exposed to the exterior of the structure. |
| Furnishings           | Negligible         | Negligible     | Seismic demands on these elements will likely be reduced significantly.                                                                    |
| Equipment             | Minor              | Moderate       | Various architectural elements may be needed around the seismic gap to avoid damage.                                                       |
| Masonry               | Significant        | Minor          | Costs are associated with the prequalification of vendors, testing of prototype bearings, and QA testing of production bearings. Similar costs associated with any supplemental energy dissipation devices, or any hard stops or displacement restraining systems. |
| Reinforced concrete   | Significant        | Negligible     | Seismic demands are expected to be reduced. Potential savings are expected. Items that are sensitive to low-frequency excitations may need requalification. |
| Wood and plastics     | Negligible         | Negligible     | Seismic demands are expected to be reduced. Potential savings are expected. Items that are sensitive to low-frequency excitations may need requalification. |
| Doors and Windows     | Negligible         | Negligible     | Seismic demands are expected to be reduced. Potential savings are expected. Items that are sensitive to low-frequency excitations may need requalification. |
| General requirements  | Significant        | Minor          | To the extent that the accelerations and drifts in the isolated portion of the plant can be reduced or capped at the level considered in the design of the standard plant, there will be no impact from special construction. Special attention will be needed near the interface between the isolated and nonisolated portions of the structure. There may be significant extra costs associated with accommodating mechanical services (high-pressure steam lines, etc.) across the seismic gap. |
| Doors and Windows     | Negligible         | Minor          | Seismic demands are expected to be reduced. Potential savings are expected. Hydraulic and other types of elevators may need to be redesigned if they cross into the isolation plan. A freight elevator to the seismic vault or a crane will be needed to access the seismic vault in case isolators need replacing or repair. |
| Masonry               | Significant        | Minor          | Horizontal components of acceleration and displacements are expected to be reduced. Some enhancement or local isolation may be needed in the vertical direction. New HVAC systems are needed for the seismic vault. Items in nonisolated portions of the plant may need enhancement. The potential exists for net overall savings. |
| Specialties           | Negligible         | Minor          | There may be minor extra costs associated with accommodating electrical services across the seismic gap. Depending on the isolation system used, amplified vertical accelerations may require special attention. Lighting and electrical service will be needed for the seismic vault area. Items in the nonisolated portions of the plant may need enhancement. The potential exists for net overall savings. |

Available from a variety of suppliers. It is typical to conduct prototype tests to characterize the hysteretic behavior of bearings and their properties under a range of loading and environmental conditions expected over the life of the structure. However, this alone does not attest to the quality of manufacturing. In most, but not all, building projects in the United States, quality assurance testing is performed on all bearings. This is a good practice but is left to the discretion of the designer of record.
In general, it is good to prequalify suppliers before bidding or initiating procurement. In some projects, inexperienced or other suppliers have had difficulty in making a large number of bearings that consistently meet project specifications or are durable. In some cases, more reputable manufacturers test every single bearing produced while others have a less stringent quality assurance process. Thus, it is common for projects to prequalify vendors, examine their record of successful projects and internal quality controls, and conduct research on related documentation. This is intended to identify high-quality suppliers and prevent surprises during quality assurance testing that could lead to delays in project schedules and add associated costs. Currently, in the United States, there are no specifications for qualifying suppliers of isolation devices or for manufacturing of isolation systems. However, one recent publication has initiated discussion of this very issue with a general overview of what requirements clients should be requiring of any isolated project.\textsuperscript{16}

Seismic analysis
As noted, with the exception of low-damping rubber bearings (LDRBs) used in combination with linear viscous dampers, seismically isolated structures are explicitly nonlinear in their dynamic response characteristics. While equivalent linear analysis may be useful and realistic for preliminary design, the NRC has indicated in the NUREG/CR-7253 guide on seismically isolated NPPs\textsuperscript{7} that nonlinear time-history analysis methods will be required. There is currently limited, but growing experience with this analysis approach in the nuclear industry. Thus, extra time and costs will be associated with these analyses. Some of this will be associated with verifying that the results obtained are of sufficient accuracy for use in licensing.

Acceptance criteria
While acceptance criteria for structures may be moderately straightforward to establish for an isolated structure, some components and systems may need to be reassessed if the fragility curves applicable to them were not developed sufficiently to extend into the low-frequency range. It may be that high-frequency components of floor spectra are greatly reduced or no higher than in a fixed-base facility, but they may be larger than considered in the design of the initial standard plant in the low-frequency range.

Quality assurance program
For buildings, details of a quality assurance (QA) program are left to the engineer of record. In many cases, all bearings are tested, and in others, only a fraction. In some countries other than the United States, QA tests involved sampling of only the materials used in the bearings, and they do not involve tests of the actual bearings. Where bearings are physically tested as part of a QA program, engineers specify the maximum displacement capacity of the bearings, some stipulate the design-earthquake-level displacement, and others use different displacements. As with prototype testing, different displacement rates are specified, ranging from slow to real-time testing. Thus, a QA program needs to be established based on project performance requirements.

It should be noted that most manufacturers can make only a few isolators a day (5-10) and that for a facility requiring many isolators, prototype testing, manufacturer testing, and QA testing may take as much as a year or more. Since the bearings are among the first items to be installed, decisions on the type and properties of isolators need to be made early in the design process.

Preparation of safety analysis reports
It is likely that the first several applicants will need to devote more time and effort for preparing the preliminary and final safety analysis reports than for conventional fixed base plants.

Plant construction
In terms of construction impacts, there may be relatively few changes in an isolated NPP. For a fixed-base structure where seismic demands are appreciably higher, there may be cases where various aspects of the reactor and other systems and components need to be redesigned and strengthened. These can have a major impact on schedule and cost.

It is expected that a new NPP constructed in a seismic area should be heavily instrumented. This will help identify issues following a ground shaking. It is important for an isolated plant to confirm that the isolation system operated as intended and to be able to quantify the demands (displacements, forces, etc.) that were made on the bearings. The impacts on schedule and cost would be the same for both types of plants.

To facilitate comparison of fixed-base and isolated approaches for constructing NPPs, Table 3 examines possible impacts related to general requirements, site work, reinforced concrete, masonry, metals, wood and plastics, thermal and moisture, doors and windows, finishes, specialties, equipment, furnishings, special construction, conveying systems, mechanical features, and electrical features.

For an isolated plant, significant impacts on schedule and cost are related to constructing the seismic vault/gap, installing the isolation system, and detailing umbilicals and egress features that cross over the seismic gap.

Seismic vault and gap
The increased height of the plant due to the seismic vault and the extra mat will require extra excavation at the site to keep other features at the same elevation relative to the ground surface. The extra mat increases the time and cost required for reinforced concrete, but it is relatively simple to construct.
Additionally, the increase in depth is not expected to be a significant change from existing vaults present in fixed base plants. In spite of the excellent consistency of properties after several decades, Electricité de France (EDF) and others have strongly recommended that the design of seismically isolated NPPs be done in such a way to facilitate replacement of isolators if necessary. The mats and mechanical, electrical, and plumbing features in the seismic vault need to be designed in anticipation of removing and replacing bearings. This is possible by predesigning shoring points. Alternatively, and likely preferable in seismically isolated NPPs, the mats can be designed so that the bearing can be removed without shoring the mat. This latter approach would be a reserve safety feature in the case where a bearing failed. However, the cost implications of this approach should be carefully assessed.

Where the plant is to be embedded significantly as suggested above, the retaining walls around the perimeter are cantilevered from the bottom mat, rather than being supported against the structure. They need to be larger to resist the soil and seismic loading or will use tiebacks. If the retaining wall is to be used as a safety stop for the isolation system, it may need to be designed to accommodate the desired mechanical behavior if impact occurs. Due to the likely placement of other structures near the moat (e.g., the auxiliary or turbine building), it is more likely that any safety-related ultimate displacement restraint system would be inboard of the seismic gap.

The isolators are generally supported on pedestals. For isolated nuclear and industrial facilities, pedestals are typically tall enough to allow workers and equipment (forklifts) to freely operate in the seismic vault. This is to facilitate inspection of the isolators and their removal and replacement if needed. In building structures, pedestals are often quite short, due to building height restrictions and cost considerations.

Heating and ventilation is needed in the seismic vault for the benefit of workers and to minimize differential temperature gradients in the building. In addition, lighting and power is needed to facilitate bearing inspection and replacement.

The seismic gap needs to be finished to eliminate falling hazards for personnel. Typically, for building systems, a sliding or pop-up cover is placed over the gap around the perimeter of the isolated superstructure. This is installed for the safety of personnel and as an environmental seal. In the case of NPPs, it is likely that explicit precautions are needed to prevent flooding of the seismic vault in the event of local or area flood hazards.

**Procuring and installing isolators**

Seismic isolators are a known expense for the isolated plant. The cost will depend on a variety of factors, including the type, size, and number of bearings, the amount of prototype and quality assurance testing, warranties provided, service agreements, and the competitive nature of the procurement process. As noted before, the isolators are likely on the critical path for the project construction, so efforts are needed to avoid delays in ordering and delivering the bearings and other parts of the isolation assembly.

Because the bearings are part of the vertical load-carrying system, they may be considered nonredundant and need to be fire protected. In the building industry, fire protection requirements vary greatly, but various methods of fire protection (fire rate jackets, nonstructural fire rated furring, etc.) are often used. These enclosures can make periodic visual inspection difficult. In many cases, either engineers successfully argue that there is little fuel in the vicinity of isolators so that fire protection is not needed or fire sprinklers are used.

In some projects, it is common to purchase a few spare isolation bearings. These have several potential uses. The first is that they can be used to replace a bearing that is unintentionally damaged (fire, water leakage, etc.). In a building employing a few bearings where one or a few might be damaged due to random defects or where local demands on a few bearings could be large (due to a combination of bidirectional bending and torsion as well as axial loading), such a strategy is prudent.

In the case of an NPP, where there are likely hundreds of bearings and high QA is mandated, having only a few bearings on hand following a larger-than-design-level event likely leads to a false sense of security. In such cases, a high confidence of avoiding catastrophic failure of the bearings is needed. Tests have demonstrated that many types of bearing can continue to function quite adequately following the rupture of rubber or metal components.

The second use of extra bearings is to use them as part of a test program to examine possible changes in bearing properties with time. These tests can be done by removing a load-bearing isolator. This process would include shoring, removing, substituting a temporary bearing, testing, and replacing the bearing in the system. Since this process is expensive and it subjects a bearing supporting the structure to large inelastic deformations, it is increasingly common to simply place extra bearings in the seismic vault so that they have the same environmental exposure as the bearings in the plant. These bearings would be prestressed to apply a load similar to that imposed on the bearings under the plant. For example, Figure 2 shows some of the spare neoprene (elastomer) pads that are stored in situ for testing at the Cruas nuclear power plant. Some of the samples are prestressed to mimic the stresses acting on the bearings at the plant. This synthetic neoprene used is now known to stiffen with age, changing the properties of the isolation system with time, and is no longer in widespread use today.

Thus, if a test program with 10-year intervals is selected, the prestressed bearing is moved from the vault to the test lab, and tests are performed to identify any changes in properties. The tested bearing can be restressed and returned to the seismic vault for retesting in another 10 years. In some cases, a new bearing for each test has been desirable, so that for a
plant with an expected life of 60 years, five extra bearings of each size used are required for such tests. Twice that number is required if two bearings are to be tested each decade and so on. Consequently, a testing program will necessitate extra cost for the spare bearings and test program.

### 3.3.4 | Stage 4: Plant operation

The activities that take place over the expected plant life (40-60 years) have the largest cumulative impact on the overall costs of power production. Once constructed, a plant should be as maintenance-free as possible. Thus, a goal of engineers designing a seismically isolated NPP is to minimize any added maintenance activities and costs during normal operations and following seismic events.

**Maintenance during normal operations**

For the scenario considered here, incremental maintenance issues will largely be associated with the isolation bearings themselves and the umbilical connections between the isolated and nonisolated portions of the plant. As noted above, most isolation manufacturers recommend periodic visual inspection of bearings to make sure that water leaks or other moisture problems have not occurred, leading to corrosion of the metallic parts of a bearing (generally stainless steel galvanized or covered with zinc-based paints), or that they have not suffered other accidental damage. As noted previously, some owners request similar testing of bearings either that have been removed from the structure or that have been stored under load in the seismic vault. This can be facilitated by preplanning the means of removing bearings from the seismic vault, providing adequate work space between the bearings and the ceiling to permit a fork lift or other similar vehicle to operate in the seismic vault and a freight elevator or crane to enable bearings and equipment to be moved in and out of the seismic vault.

As noted previously, umbilicals crossing the seismic gap, especially piping systems that include gimbal or bellow connections, may require considerable maintenance. These details need to be carefully investigated to avoid regular plant shutdowns for maintenance of these piping and other umbilical systems.

**Activities following a seismic event**

It is expected that for small and moderate earthquakes up to the design level and perhaps beyond that an isolated plant will suffer little damage. In conjunction with a good instrumentation plan and decision support system, it is likely that the plant can be returned to operation quite soon after any mandatory shutdown, inspection, and requalification. Even if a fixed-base plant behaves exceptionally well in such events in terms of the safety-critical structures, systems, and components (SSC), the disruption to other components in the plant will likely hamper recovery and resumption of normal plant operations. The lower forces, displacements, and accelerations within the isolated nuclear island will likely reduce the consequence of the earthquake shaking. However, special attention would need to be placed on inspecting the bearings and isolation system, umbilicals and access portals. Thus, properly designed and detailed isolated NPPs are likely expected to minimize loss of revenue due to post earthquake shutdowns.

Isolation bearings are generally designed to be capable of withstanding several beyond-design-level events. As such, there is likely no need to replace bearings. If spare bearings are available, existing bearings can be removed and replaced by the spares, and selected bearings that went through the earthquake can be tested to confirm that they retain adequate capacity to withstand future aftershocks and new earthquakes.

### 3.3.5 | Stage 5: Plant decommissioning

It is expected that a fixed-base and isolated NPP designed for higher seismic loads would have marginally higher demolition costs. This is due to the larger and stronger SSCs in the fixed-base case and the addition of the extra mat and seismic moat detailing for the isolated case.

### 4 | OTHER TECHNICAL ISSUES

#### 4.1 | Performance and design criteria

In terms of project engineering, substantial effort is needed that is associated with establishing the performance and design criteria for the plant, including nonsafety-related features. The NRC is expected to provide specific guidance on their expectations for design features, along with ASCE 4 and ASCE 43, providing adequate guidance when used in conjunction with other standards.

With regard to performance criteria, as noted following the recent earthquakes in Japan, disruption of nonsafety-critical...
aspects of a plant severely hampered plant operations. As such, it may be possible and desirable to take advantage of isolation to not only protect the immediate nuclear island but the auxiliary structures deemed crucial to continued operation.

### 4.2 Configuration of isolation system

Another key aspect of the engineering design is identifying the plant layout, that is, the location of the isolation plane and seismic gaps. While the isolation layer is normally at the base of a structure, as shown in Figure 3, giving rise to the term base isolation, other isolation planes are routinely selected, giving rise to the more generic term seismic isolation. For example, several small modular plant designs place the isolation plane near the elevation of the center of mass of the plant to minimize the tendency of the plant to pitch or roll on the bearings. This is illustrated in Figure 4. As noted, there are differences in opinion on whether the NSSS should be isolated alone or whether it should be isolated on both a single platform and conjoined isolated platforms along with the auxiliary/turbine structures. This impacts the design of the high-pressure steam piping and umbilicals that would need to cross over the seismic gap impacting maintenance and safety issues. By integrating the turbine and NSSS on a common isolated platform, it may be possible to mitigate these issues.

### 4.3 Prototype investigations

With the increased use of seismic isolation, many manufacturers have compiled a good record of achieving consistent behavior for common-size bearings. Thus, the issue of avoiding the need for prototype tests where sufficient data exist has been raised. However, for the initial application of seismic isolation to NPPs, the size, load capacity, and performance criteria are likely far different from prior solutions. Thus, performance-oriented test protocols need to be developed, as well as standards for quality control, quality assurance, and documentation.

As noted previously, it is common in major civil and nuclear-related projects to require a variety of tests to characterize stiffness and strength in the vertical loading direction; to characterize the bearing under horizontal cycles of motion representative of the design earthquake under different (and perhaps varying axial load intensity) and varying displacement velocities; and to characterize bearing stability in the maximum displaced configuration, simulated wear/durability tests, accelerated aging tests, and other tests as relevant. Sufficient tests need to be carried out to develop a statistical basis for predicting upper- and lower-bound characteristics for the mechanical properties of the bearings. Specific prototype test methods are expounded in MCEER report 15-0006.19 These statistics are needed for the NRC’s emphasis on performance-based, risk-informed assessment methods.

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**FIGURE 3** Typical approach of applying seismic isolation at the base

**FIGURE 4** Schematic illustration of isolators installed near the center of mass of a plant
4.4 | Four aspects of the nonlinear modeling

- The first is related to the modeling of the superstructure. This is likely expected to remain elastic. However, because of trends in analysis and increased concern for coupled vertical and horizontal response, it is expected that high-fidelity finite element models may be needed. These raise other practical challenges in identifying member, connection, and other properties and in the computational effort needed to carry out the simulations.

- The second aspect is modeling the isolators. Many isolators at low- and design-level events are likely to be modeled well with elements available in many commercial and research computer software. However, the behavior of bearings as they approach their limits under beyond-design-basis events or under high levels of vertical excitation is not so well characterized, and development and verification efforts are needed to match prototype test results.

- The third area of modeling uncertainty relates to the modeling of soil. Although equivalent elastic models have been regularly used, these have been questioned in some recent NRC documents when the level of excitation is large as in beyond-design-basis events. These motions may not be large in some parts of the world, however. Additionally, work on soil-structure-interaction (SSI) of isolated facilities is a current area of research with very little data available for model validation.

- Finally, the interface between the soil and foundation is likely nonlinear, with gaps opening and closing and with sliding occurring parallel to the foundation walls. All these are quite complex and necessitate careful consideration, adding time and cost to a project. However, it is likely that as the intensity of shaking associated with the GMRS increases, these modeling and analysis issues will likely be similar for fixed-base and isolated facilities.

4.5 | Umbilical, egress, and safety issues at the seismic gap

The seismic gap requires various types of construction not used in a fixed-base plant. The most challenging of these issues is related to high-pressure piping systems. Where displacements are modest, serpentine hard loops are possible. Movements of more than 1 m (39.4 in) have been achieved for large-diameter solid piping systems for LNG tanks. Gimbals, bellows, and other swivel-type piping connections are possible, but they introduce possible regular maintenance and postearthquake repair issues. Either way, the cost of piping systems at this location is higher than for a fixed-base plant. Lower pressure, normal-temperature piping is generally handled by a flexible hose, and electrical cables are dealt with using coiled and draped wires (with adequate flexible protection from wear). Special arrangements are needed for crossings into the isolated portions from adjacent structures and the exterior of the structure. Since current isolators do not move very much in the vertical direction, it is possible to hide the seismic gap by means of a step to accommodate a change in elevation from the isolated to nonisolated portion of the plant. However, for access by wheelchair or for carts used to transport materials within the plant, a step is not possible. Some type of tapered ramp is frequently used that is allowed to slide during an earthquake over an unobstructed portion of floor on the lower side of the gap. Where the elevation on both sides of the gap must be the same height, a variety of thin sliding sheets or pop-up covers are available. These may be damaged and may hamper access following an earthquake, so special care is needed in their design.

- There may be some need to modify elevator designs to accommodate the seismic vault. In cases where hydraulic elevators are used and the hydraulic system is embedded in a vault below grade, the elevator needs to be converted to a traction system where the elevator is hung from above by cables.

- Careful consideration is needed to ensure adequate clearances all around the seismic gap and in the seismic vault to ensure that the motion of the isolated superstructure is unimpeded. This is often an issue related to mechanical, electrical, and plumbing features, and architectural features where consultants may not adequately understand the movement of the structure during an earthquake.

5 | SOME RESEARCH AND DEVELOPMENT NEEDS

In addition to the general and project-related issues identified above, several more technical issues should be considered during the planning, design, and construction process, during operations, and following a major seismic event. These will likely necessitate focused technical development or research. Some of them may have been resolved and typically addressed in general isolated buildings, but still need further exploration in isolated NPPs due to their particularity and importance.

5.1 | Careful study of benefits for seismic isolation

In the planning, design, and construction process, several benefits are likely for seismic isolation. These need careful study in an actual design.

- The substantially reduced base shears developed by an isolated structure can result in an opportunity to reduce
the size or complexity of structural elements, systems, and components (or to increase margins). In addition, it may result in reduced costs for resisting base shears in site preparation and foundation construction.

- Many technical issues have been investigated and solutions found for the seismic isolation of other critical civil infrastructure facilities. These include piping systems that cross-over seismic gaps in LNG tanks, access and gap detailing issues in various types of structures, and so on. Clearly, it is necessary to learn and benefit from these experiences, but careful consideration needs to be given to the special features of NPPs and the high level of confidence that is expected.

5.2 New concerns in the planning, design, and construction process

Some new concerns that likely need to be addressed in the planning, design, and construction process include:

- There are many types of isolation systems and combinations of isolation systems, and each has its particular advantages and disadvantages. Similarly, there are trade-offs in the selection design parameters for a particular type of isolation system. For example, one type of isolator or set of parameters may result in low forces, accelerations, and drifts in the portions of the structure above the isolation plane, but rather high isolator displacements. Another type of isolator system or set of parameters may have less displacement of the isolation system, but higher design forces for the supported structure and components. Thus, a balance needs to be identified. This may be easier for the case where an existing standard plant design is to be used.

- Three-dimensional (3D) isolation has made some progress recently. In Japan, a number of important development studies have been completed related to 3D isolation of nuclear facilities. Three promising ideas for 3D isolation were examined by the Japanese Fast Breeder Reactors (FBR) project, that is, “Rolling Seal Type Air Spring,” “Hydraulic 3D Isolation System,” and “Cable Reinforced Air Spring.”

Shimizu Corporation, in conjunction with Kozo Keikaku Engineering, Inc., has extended the basic ideas from these 3D isolation projects and applied it to an actual three-story reinforced concrete apartment building in Tokyo. The 3D isolation system installed in the building performed as expected in the 2011 East Japan Earthquake. However, 3D isolation technology is not yet mature. Therefore, how to reduce the vertical seismic response of the isolated NPPs and the impact of 3D seismic action on design of isolated NPPs need to be carefully studied.

- Nonlinear 3D finite element analyses are different from traditional elastic simplified methods used in the nuclear power industry. Expertise in this area is not generally available across all segments of the industry. Development work may be needed to improve modeling of isolation and energy-dissipation devices, soils, reinforced concrete, structural damping, and mechanical equipment/piping systems.

- Seismically isolated standard plant designs should be carefully evaluated to assess the true range of seismic ground motions that they are able to resist. For instance, isolation may not be as effective for sites on soft soil or where long-period, near-fault acceleration pulses may occur. Recent concern has been raised about the vibration of long-period structures of all types when subjected to surface waves arriving from distant earthquake fault ruptures. Thus, while standard response spectrum definitions for design basis events is useful for design and siting, careful evaluation of the performance of isolated NPPs to a full range of earthquake ground motion time-history characteristics is needed to develop full confidence in isolation to achieve targeted performance goals.

- Given the importance of NPPs, careful consideration is needed to confirm the expected reduction in design forces on mechanical and other equipment attached to the structural elements. In particular, the effect of vertical accelerations and of local modes contributing to high-frequency vibrations in isolated structures needs to be investigated. The need and approach for providing supplemental seismic isolation of special components and equipment should be investigated to assess potential benefits.

- It is necessary to design the isolation system to achieve acceptable probabilities of failure. The MCEER report 15-0006 partially addresses this issue for nuclear structures through evaluating and calculating the annual frequency of unacceptable performance of the isolation system, which can be an important basis for design. The MCEER report 18-0004 presents evaluation on structural collapse, including collapse capacity, collapse margin ratio, median collapse spectral acceleration, etc., which is based on FEMA P695.

- Generally, manufacturers of isolation bearings provide specifications for the installation of their devices. These range from tolerances on alignment in the horizontal and vertical direction, how level they are, and the method for attaching them to adjacent structural elements. These need to be assessed in view of the special requirements of NPPs.

- While many components of an NPP have long delivery times and need to be procured early in the design process, many are installed later in the construction process. Seismic isolators need to be installed relatively early in the construction process, and they take considerable time to manufacture, considering the size and number required for a typical NPP and the necessary quality assurance and control procedures. Thus, attention is needed early in the
design process to qualify bearing vendors and to order bearings in order to ensure their arrival on site at the appropriate time.

- Ordering extra bearings for testing or to be used as replacement bearings following unintended accidents or earthquakes should be considered. The large number of bearings needed if replacement of bearings is required following an earthquake might suggest that other actions might be taken to prevent damage to bearings under beyond-design-level events during the initial design process.

- Some topics related to the use of protective systems in nuclear structures are not yet completely addressed and/or characterized, such as: isolation systems for surface mounted and deeply embedded nuclear facilities; verified and validated models of nonlinear soil-structure-fluid systems; isolation of advanced reactors which explicitly considered the fluid-structure interaction and soil-structure interaction.\textsuperscript{25}

5.3 Considerations during normal operations

Some considerations during normal operations that require consideration include:

- Questions regarding the need to regularly inspect, maintain, test, and possibly replace components of the isolation system are commonly raised. Most isolation vendors stipulate periodic visual inspection to ensure that unexpected environmental conditions have not occurred that adversely affect the bearings. Most isolation systems have no required maintenance. A requirement to test bearings periodically during the service life is not universally required, given the increased number and age of isolated structures. However, this may be prudent and should be carefully considered for NPPs. In many situations, extra bearings are located in the seismic vault and prestressed to replicate the axial loads on the bearings. These are then used for testing to avoid the complication and cost of removing and reinstalling bearings used to support the NPP.

- Issues related to regular inspection also extend to items that cross the seismic gap.

- Where possible and needed, effects of longevity and reliability of seismic isolation hardware should be studied. Performance-based component tests are needed to characterize bearings, energy-dissipation devices and other components for a wide range of loading conditions, ranging from in-service conditions, small earthquake excitations, design-basis events, beyond-design-basis events, to ultimate failure. These should be conducted at realistic loading rates using full-size devices. Effects of exposure to radiation and elevated temperatures should be identified. Research and development efforts are needed to develop, verify, and validate numerical models based on these component tests. ASCE/SEI 7-16 attempts to formalize these procedures.\textsuperscript{26}

- An area for potential research is the effects of radiation exposure on the lifetime performance of bearings.\textsuperscript{25} Given the limited use of isolation in nuclear facilities, there is not a significant amount of data comparing against material properties at time of installation. The Cruas and Koeberg NPPs are the only plants that have been isolated for several decades. Based on observations and tests from the Cruas plant,\textsuperscript{4} there has been a slight increase in the stiffness of the material over the past 30 years. However, it is unclear if this increase was expedited due to radiation exposure (although limited) or consistent with expected material changes for any elastomeric bearing. As a result, this does raise the question whether pendulum bearings made of steel and a proprietary coating would be preferable to an elastomeric bearing.

5.4 Considerations Following a Seismic Incident

Some special considerations following a seismic incident include:

- Many types of isolators are expected to suffer visually apparent signs of their response to an earthquake. These may range from flaking of paint, to wrinkling of rubber covers on elastomeric bearings, to residue of the composite liner material used in friction bearings. Thus, documents to assist those inspecting isolators following an earthquake are needed to distinguish acceptable from unacceptable forms of behavior. Without this, some expected and benign types of behavior may cause unwarranted concern following an earthquake.

- A good system for automatic monitoring the response of the isolation system and supported structure during an earthquake is essential for seismically isolated NPPs. Without this, there is no way to tell the maximum displacements of the system, the number of cycles of loading, and so on. This information can be used to judge the remaining life of the bearing and its ability to withstand expected aftershocks. It is expected that most isolation systems in use today can withstand many repetitions of the design-level event. As such, instrumentation can help assess any need to replace a bearing following an earthquake.

- Given the desire to resume production of electricity as quickly as possible following a seismic event that triggers a shutdown of a plant, it would be desirable to extend any instrumentation scheme to include items of the plant that could help confirm the absence of damage and identify locations where damage might have occurred.

- Some isolation systems may not perfectly re-center following an earthquake. It appears for most of these systems that aftershock motions tend to reduce the residual
displacements with time. Practical criteria regarding the acceptable level of residual displacement and guidelines covering methods for reducing any unacceptable residual displacements need to be devised.

6 CONCLUSIONS

Overall, the use of isolation for NPPs offers a number of significant advantages. First, by extending the use of a standard plant design, the effort and costs are reduced compared to designing unique site-specific structures. In addition, although the isolation layer is costly, this is compensated for by the decrease in the cost of the earthquake protection needed within the plant unit itself and greater overall seismic safety margins. Overall, seismic isolation provides a very effective and promising means of improving the safety and performance of NPPs under strong seismic shaking.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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