HIGHLY RELIABLE NUCLEAR POWER FOR MISSION-CRITICAL APPLICATIONS

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Abstract *– Some energy consumers require power on a 24/7/365 basis with a high level of certainty, including defense installations, isolated communities and some industrial processes. For these customers, interruptions in electricity or heat can mean substantial financial loss or even the loss of lives. In the absence of grid-scale energy storage, a high level of power reliability can only be accomplished through the robustness and redundancy of power generators. The NuScale small modular reactor design is well suited to provide highly reliable power because of several features related to both the nuclear steam supply system and the overall plant design. In analogy to RAID (redundant array of independent disks) systems used to provide highly reliable data storage, a NuScale plant can assure sustained power generation by virtue of its redundant array of integral reactors (RAIR).This paper describes the NuScale RAIR plant features and summarizes the results of a rigorous analysis of RAIR reliability as a function of power, or conversely, the RAIR plant output power as a function of power reliability. The analysis utilized MATLAB and included probability distributions for the frequency and duration of module outages due to planned and unplanned events. The study also evaluated the impact of implementing turbine bypass rather than cold shutdown and using one or more modules to supply house loads in the case of loss of offsite power. Reliability results are presented for a 12-module RAIR plant with and without turbine bypass during a loss of offsite power enabled, and different possible connections to the offsite power distribution grid and dedicated service loads. Results indicate that a very high level of reliability can be achieved at relatively high power output levels, especially when turbine bypass is enabled in the 12-module plant, coupled with a direct connection to a dedicated service load.*

I. INTRODUCTION

While many energy customers can tolerate minor fluctuations or interruptions in power, others require power on a 24/7/365 basis with a high level of certainty. These types of customers include defense installations, isolated communities, some industrial processes, major computer systems and other mission-critical applications. For these customers, interruptions in electricity or heat can mean substantial financial loss or even the loss of life. In the absence of grid-scale energy storage, a high level of power reliability can only be accomplished through the robustness and redundancy of power generators.

The NuScale small modular reactor design currently under development in the United States is well suited to provide highly reliable power because of several features related to both the nuclear steam supply system and the overall plant design. First, the NuScale power module utilizes an integral pressured water reactor (iPWR) configuration that yields a simplified and highly robust design of the individual modules (Ref. 1). Second, the multi-module nature of a NuScale plant, which can contain up to 12 separate modules and power conversion systems operating independently, allows the plant to provide some level of power on a continuous basis even when individual modules are taken offline for refueling or maintenance. Modules can also be returned to service one at a time to match the demand of the offsite grid in 50 MWe increments to help black start the grid when power is ready to be restored. Finally, the plant can be designed so one or more modules can provide house load in the case of a loss of offsite power.

In analogy to redundant array of independent disks (RAID) systems used to provide highly reliable data storage, the NuScale plant can assure sustained power generation by virtue of its redundant array of integral reactors (RAIR). In the case of RAID data storage, identical data is written simultaneously in multiple locations, thus trading storage capacity for reliability. By placing this data on multiple disks, there is inherent security in the system that the information can be retrieved when desired. Individual disks can even be "hot swapped," meaning the disk can be replaced while the storage system is operating without loss of data. The design of the NuScale plant is similar to a RAID. A NuScale plant is an array of 12 reactors, each operating in a similar and independent fashion to achieve an identical mission: power generation. Due to this redundancy in design, modules can be hot swapped, i.e. they can be removed from operation for refueling or maintenance while the other modules continue to produce power. Therefore, power output from a NuScale power plant can be assured at varying confidence levels, albeit at a reduced total power level, throughout the lifetime of the plant.

II. NUSCALE DESIGN OVERVIEW

The NuScale SMR plant is an innovative design that builds on sixty years of world-wide experience with the commercial application of pressurized water reactor (PWR) technology. The design incorporates several features that reduce complexity, improve safety, enhance operability, and reduce costs. From the outset, the top level design goals for the NuScale plant have been to achieve a high level of safety and asset protection while providing an affordable approach to nuclear power that gives the plant owner the maximum flexibility in plant application while allowing for standardized and simplified construction, operation and maintenance to improve safety and lower lifecycle costs.

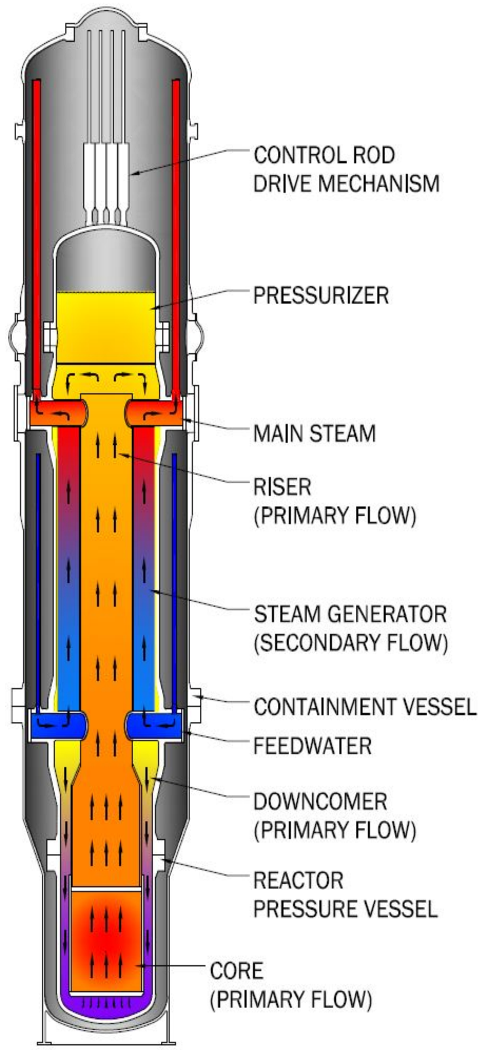
The fundamental building block of the NuScale plant is the NuScale power module. The power module consists of a small 160 MWt reactor core housed with other primary system components in an integral reactor pressure vessel and surrounded by a steel containment pressure vessel, which is immersed in a large pool of water. Several power modules (as many as 12) are co-located in the same pool to comprise a single plant. Dedicated turbine/generator systems provide a gross electrical power of 50 MWe for each module.

A diagram of the NuScale power module is shown in Fig. 1. The reactor vessel is approximately 17.7 m (58 ft) tall and 3.0 m (10 ft) in diameter. The integral vessel contains the nuclear core consisting of 37 fuel assemblies and 16 control rod clusters. Above the core is a central hot riser tube, a pair of helical coil steam generators surrounding the hot riser tube, and an internal pressurizer.

Also shown in the Fig. 1 are the primary and secondary coolant flow paths. Primary reactor coolant is circulated upward through the reactor core and the heated water is transported upward through the hot riser tube. The coolant flow is turned downward at the pressurizer plate and flows over the shell side of the steam generator, where it is cooled by conduction of heat to the secondary coolant via the steam generators and continues to flow downward until its direction is again reversed at the lower reactor vessel head and turned upward back into the core.

The coolant circulation is maintained entirely by natural buoyancy forces of the lower density heated water exiting the reactor core and the higher density cooled water exiting the steam generator annulus. On the secondary side, feedwater is pumped into the steam generator tubes where it boils to generate superheated steam, which is circulated to a dedicated turbine-generator system. Low pressure steam exiting the turbine is condensed and recirculated to the feedwater system. The entire nuclear steam supply system is enclosed in a steel containment vessel that is approximately 23.2 m (76 ft) tall and 4.6 m (15 ft) in diameter. The small volume, high design pressure containment vessel is a unique feature of the NuScale design and contributes significantly to the large safety margins and overall resilience of the plant. Multiple modules are placed in a single large pool contained within an aircraft-resistant reactor building. A cut-away, top-down view of a 12-module reactor plant is shown in Fig. 2. Not shown in the figure are the 12 turbine/generator systems that are located in two turbine buildings immediately adjacent to the reactor building.

Fig. 1. Schematic of a NuScale power module.



The NuScale power modules are located below grade in a large common pool of water. The reactor pool provides passive containment cooling and decay heat removal. Specifically, the pool provides an assured heat sink with a capacity to absorb the entire decay heat produced by up to 12 fully mature cores for greater than 30 days. After 30 days, air cooling of the 12 NuScale power modules is sufficient to avoid fuel damage. The pool also helps to reduce and delay fission product releases in the unlikely event of fuel failure and provides radiation shielding outside containment to reduce operational exposure. Finally, the below grade pool provides enhanced physical security by adding additional challenges to fuel access.

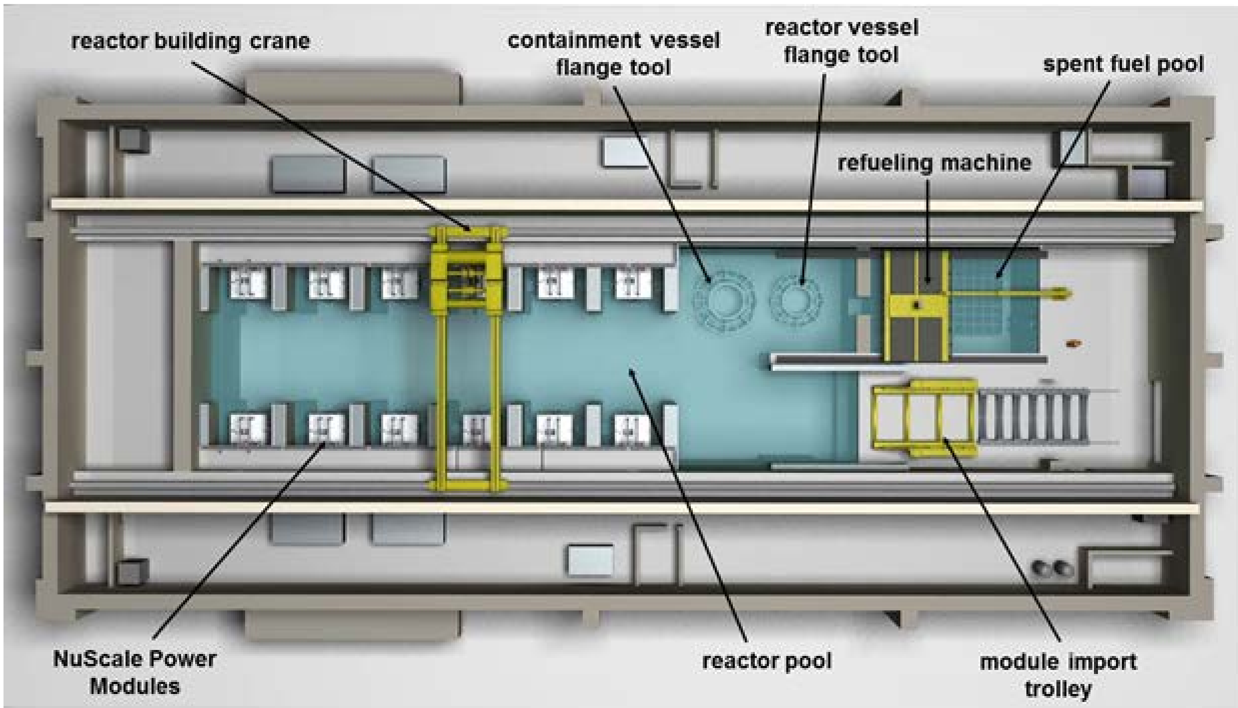


Fig. 2. Top view of reactor building for 12-module NuScale plant.

There are several key features of the NuScale plant that collectively distinguish it from the many other SMRs being developed today and contribute to its simplicity and flexibility.

- *Compact size.* The nuclear steam supply system, including containment, can be entirely prefabricated off site and shipped by rail, truck or barge to the site. This reduces construction time due to parallel fabrication considerations and reduces overall schedule uncertainty due to the reduced amount of on-site construction activities.
- *Natural circulation cooling.* Natural circulation operation and integral design eliminates pumps, pipes, and valves in the primary system and hence the maintenance and potential failures associated with those components, while also reducing house load.
- *Triple Crown of Safety.* The NuScale plant, with its innovative design is able to safely shut down and self-cool with no operator action, no AC or DC power, and no additional water for an unlimited period of time.
- *Dedicated power trains.* Because each power module, including the power conversion system, is independent of other modules, each module can be shut down while other modules continue to operate. This feature allows for continuous plant output and greatly enhances the overall reliability of output power.

III. ANALYSIS APPROACH AND ASSUMPTIONS

To assure a certain level of power output from a NuScale RAIR, an analysis of plant availability considering a number of plant "upsets" is performed. Results from this analysis are used to predict a highly reliable level of power which can be consistently output from a NuScale power plant. The methodology utilized in this analysis is discussed further below

To determine the power output level which can be assured by a NuScale plant, the Matrix Laboratory (MATLAB) programming language was used to simulate fifty thousand 60 year NuScale plant lifetimes. The plant was simulated on a daily basis (i.e. a time step of one day) with a variety of plant upsets included in the analysis. These upsets include the following:

- *Refueling outages.* Each module is refueled every 24 months at which time the module is taken offline for a nominal 10 days to accomplish refueling and inspection activities. It is expected that in a 12-module plant, there will be a refueling outage for one module every 2 months.
- *Short term outages.* Short term outages are initiated by an unplanned reactor trip but do not require the module to be opened to be serviced. During short term outages the module remains in the reactor bay and multiple modules can be repaired

simultaneously. Secondary system upsets are included in this type of outage.

- *Long term outages.* Long term outages are caused by failure of components internal to the module and the module must be opened in order to conduct repairs. There is one disassembly tool in a NuScale plant, so only a single module can be refueled or repaired at one time.
- *Two module outages.* Short term outages can occur for two modules simultaneously due to a loss of an AC bus for example. In these cases, the two modules can be taken offline and returned to service simultaneously.
- *Six module outages.* While many systems are independent among modules, some systems such as the circulating water system that provides cooling to the feedwater system condensers are common to six modules. In these cases, six modules are taken offline and repaired simultaneously, followed by a staggered restart.
- *12 module outages.* Twelve module outages can occur due to a failure of equipment that is common to all 12 modules other than loss of offsite power, which is handled separately. In these cases, twelve modules are taken offline and repaired simultaneously, followed by a staggered restart.
- *Loss of offsite power.* A loss of offsite power affects the whole plant simultaneously. The modules are suspended from their current state and placed into a LOOP state. Only refueling can be triggered during a LOOP. Once power is restored, the modules are brought online in a staggered fashion, one module at a time. Following LOOP recovery, the modules are returned to their previous states. If refueling is triggered during a LOOP and the module was in a down state prior to LOOP initiation, the module is returned to the down state and placed in refueling following recovery from the down state. Otherwise, the module is placed directly into the refueling state.

The study was performed in three major steps. The first analysis consisted of determining the performance of a single module. The second analysis involved determining the availability of all 12 modules as a function of power and assuming that all modules were completely independent. The final analysis considered the impacts of shared systems that can cause 2, 6 or 12 modules to sustain an outage simultaneously. In all cases, it was assumed that the output of a module was either 100% (50 MWe) or zero.

A module has five states: operating (up), refueling, down and closed (closed), down and open (open), or down due to a loss-of-offsite-power (LOOP). In the closed state, the module is not operating, but can be repaired without being opened. In the open state, the module is not operating and must be opened to be repaired. At a NuScale plant, a module is refueled once every two years, and the module is out of service for approximately 10 days. For a 12-module plant, refueling will occur every two months. Following refueling, the module is returned to full power. The remaining transition rates from up to closed, open, or LOOP were determined from a probabilistic risk assessment analysis, using modified initiating event frequencies from Initiating Event Rates at U.S. Nuclear Power Plants 1998-2013 (Ref. 2) to represent the systems in the NuScale design. The initiating event frequencies used are shown in Table I. The error factor shown in Table I is a measure of uncertainty in a lognormal distribution, and is taken as the ratio of the 95th percentile value of the distribution to the median value of the distribution (Ref. 3).

Table I. Initiating Event Frequencies

Initiator Description	Frequency (mcyr^{-1})	Error Factor
CVCS LOCA Inside Containment - Charging Line	2.60E-04	5.57
CVCS LOCA Outside Containment - Charging Line	3.00E-04	6.86
CVCS LOCA Outside Containment - Letdown Line	2.56E-04	13.18
Spurious Opening of an ECCS Valve	1.00E-05	3.11
Loss of DC Power	8.86E-05	33.44
Loss of Offsite Power	3.2E-02	3.46
Steam Generator Tube Failure	1.30E-03	3.40
LOCA Inside Containment	1.62E-03	1.78
Secondary Side Line Break	1.10E-02	3.62
Loss of Power Conversion System (PCS)	1.81E-01	1.10
Transient with PCS Available	1.16	1.04

To determine the frequency that the module transitions from up to closed, three initiating event frequencies were summed together: loss of DC power, loss of power conversion system, and transient with power conversion system available. These initiating events were judged to not require the module to be opened for repair. For example, the DC batteries and busses are located external to the module as well as the secondary systems such as the feedwater and condensate system. The frequency of transitioning from up to closed is then estimated using a lognormal distribution with a mean of 1.34 transitions per module critical year, or 3.672E-03 transitions per module critical day, with an error factor of 1.04.

The remaining initiating events in Table I contribute to the frequency with which a module transitions from up to open. Recovery from these events was judged to be difficult and causing damage to critical equipment internal to the module. The resulting frequency of transitioning from up to open is estimated using a lognormal distribution with a mean of 1.47E-02 transitions per module critical year, or 4.037E-05 transitions per module critical day, and an error factor of 2.47. Lastly, the LOOP initiating event frequency is the same as listed in Table I, which is 3.20E-02 transitions per plant critical year, or 8.761E-05 per plant critical day, with an error factor of 4.51.

If the module is in the refueling, closed, open, or LOOP states, it must remain in that state for a certain number of days depending on the state, before transitioning from that state. For the refueling, closed, or open states, the module returns to full power after module recovery. In the LOOP state, the module is returned to its previous state which is not necessarily the up state. For example, if a module is in the open state with 10 days of recovery time remaining when a LOOP is initiated, then that module is returned to the open state with 10 days of recovery remaining following a return of power to the grid. To determine the number of days required to recover from the closed or open state, reactor operating data for the United States from 2005 through 2014 were used (Ref.4). Values ranging from 1 to 25 days were used for the duration of a closed state event and 26 to 363 for an open state event. This data, which is derived from the existing fleet of large reactors, is expected to be conservative for a NuScale plant due to the fewer number of systems in a NuScale module. The actual value used for a specific module history was selected randomly using a probability distribution determined as the frequency of a downtime lasting some number of days divided by the total number of downtime occurrences for that module state (open or closed). For example, if there were 10 total short term downtimes reported between 2005-2014 and 5 of those had a duration of 1 day, then the probability of a 1 day downtime is estimated at 50%.

The recovery time for a LOOP was estimated using the NRC's Analysis of Loss-of-Offsite-Power Events 1998-2013 (Ref. 5). Data for weather related LOOP recovery time was used because this was the most limiting case. The length of recovery time was determined using equation 4 of Ref. 5. The minimum recovery time was determined to be 24 hours (1 day) based on the recovery times for plant-centered, switchyard-centered, and grid-related LOOPs.

In this study, a 12-module NuScale power plant was simulated for the expected full plant lifetime of 60 years using MATLAB 2015b. In each Monte Carlo simulation, module objects are created within a plant object and each day of the year is simulated for 21,915 days (60 years including leap days). Transitions from full power are actuated with probabilistic triggers in daily timesteps and then a module is forced into that state for some number of days before repair or refueling is complete. This simulation assumes that the plant was operating at steady state, full power conditions prior to the initiation of the simulation. In reality, the modules will come online in a staggered fashion, with each module being brought online as it is installed in the plant. Since this analysis is considering a 12 module plant, the plant is not considered to have 12 modules until the 12^{th} module is installed and brought online.

Two different NuScale plant and electricity grid configurations are considered, and two different plant responses to a LOOP are considered. Plant connections to the power grid are modeled as (1) the plant is connected to the large electrical distribution grid (macrogrid) or (2) the plant is connected to the macrogrid and the plant also has a direct connection to a dedicated service load (microgrid). In configuration 2, the assured power generated by the NuScale plant is delivered to the microgrid and the excess power is sold to utilities for use on the macrogrid. When a LOOP occurs in configuration 2, the modules supplying power to the microgrid remain in operation, while the remaining modules are critical but bypass the turbine generators and dump steam directly to the condensers until the macrogrid returns to service. The plant responses to a LOOP are modeled as (1) all 12 modules are placed in cold shutdown and brought back online with a staggered restart following the macrogrid return to service, and (2) one module supplies power to the NuScale plant house loads while the remaining modules remain critical and are placed in turbine generator bypass for the duration of the LOOP.

Three scenarios were analyzed:

- *Case 1*. The NuScale plant is connected to the macrogrid, does not contain a connection to a microgrid, and the modules are all placed in cold shutdown during a LOOP.
- *Case 2*. The NuScale plant is connected to the macrogrid, does not contain a connection to a microgrid, and one module supplies plant house loads while the remaining modules are critical and placed in turbine bypass during a LOOP.
- *Case 3*. The NuScale plant is connected to both the macrogrid and a microgrid, and during a LOOP modules supplying electricity to the microgrid continue to do so while the remaining modules are critical and placed in turbine bypass.

Multiple module outages due to outages of shared secondary systems are captured in the 2, 6, and 12 module outage states, which remove from operation the indicated number of modules simultaneously. Each of these initiators is assumed to occur with a frequency of 1E-2 per year based on engineering judgement. The modules then restart in a staggered fashion with a 2 day offset between modules, similar to LOOP recovery.

In this analysis, it is assumed that more than one module can be repaired in the closed state simultaneously. Since there is only one crane, disassembly tool, and refueling area, it is assumed that only one module can be opened at any one time, and the remaining modules that must be opened for repair must wait until there is an open spot to be refueled/repaired. For Case 1, the LOOP is assumed to remove the first module from service for 1 to 3 days with an extra 2 days for each additional module. For Case 2, the LOOP is assumed to remove all 12 modules from service for 1 to 3 days after which time all 12 modules are immediately returned to service. In Cases 1 and 2, the modules are not considered to be available to supply power during a LOOP. To determine the power level that can be assured with 99.99% availability to a dedicated service load, the modules in Case 3 are still considered available during a LOOP, as they are available to supply power to the dedicated service load on the microgrid if needed, even though they are most likely in turbine bypass. Uncertainty in initiating event frequencies and in recovery time is considered in this analysis.

IV. RESULTS

The plant was simulated for 50,000 lifetimes for each of the 3 cases. Two types of results were calculated: the capacity factor of the plant and the availability of electrical output at each plant power level. The capacity factor was determined as the ratio of the total electric power output by the plant to the maximum possible electric power that could be output by the plant over 60 years. The maximum likelihood estimate (MLE) of a NuScale plant capacity factor for Case 1 was determined to be 96.57% with a standard deviation of 0.30%. The corresponding 5 and 95 percentiles were 96.01% and 96.97%, respectively. The MLE of a NuScale plant capacity factor for Case 2 was determined to be 96.67% with a standard deviation of 0.27%. The corresponding 5 and 95 percentiles were 96.17% and 97.02%, respectively. The MLE of a NuScale plant capacity factor for Case 3 was determined to be 96.68% with a standard deviation of 0.27%. The corresponding 5 and 95 percentiles are 96.18% and 97.03%, respectively. The capacity factor is larger by approximately 0.1% when the modules are placed in turbine bypass rather than .placed in cold shutdown in response to a LOOP. The small difference in capacity factor is due to the small number of LOOPs that occur over the 60 years of plant operation. Although the predicted capacity factor in Case 2 and Case 3 are higher than in Case 1, the MLE for each case is within one standard deviation of the others and the MLEs should therefore be considered equivalent.

The results for a 12-module plant are given in Table II, which lists the MLE for the number of modules operating simultaneously for each of the 3 cases. The result of 67.22% availability of 12 modules for Case 1 does not correspond to a capacity factor of 67.22%, as seen above. This is because while the plant is operating at 100% output 67.22% of the time, the plant is also operating at 92% output 26.98% of the time and 86% output 4.64% of the time and so on.

As shown in Table II, the plant spends the majority of the time with all 12 modules operating, with the amount of time spent with fewer modules operational declining drastically as the number of modules in operation decreases. The plant rarely falls below 8 modules in operation. The time spent with 7 or fewer modules in operation is due almost solely to LOOP events. When the consequence of a LOOP is reduced, as in Case 2 and Case 3, the time spent with 7 or fewer modules in operation is due to failures of shared systems. Occasions with 5 modules simultaneously removed from operation due to refueling, closed, or open outages occurs on the order of a few days over the entire 60 year lifespan of the plant.

Table II. Percentage of time the plant operates with indicated number of modules producing power

Number of Modules	Case 1 MLE	Case 2 MLE	Case 3 MLE
12	67.22	67.35	67.36
11	26.98	27.01	27.01
10	4.64	4.63	4.63
9	0.69	0.68	0.68
8	0.19	0.17	0.17
7	0.09	0.07	0.07
6	0.05	0.03	0.03
5	0.03	0.01	0.01
4	0.02	0.01	0.01
3	0.02	0.01	0.01
2	0.02	0.01	0.01
1	0.02	0.01	0.01
0	0.03	0.02	0.01

The MLEs for the probabilities that at least the indicated power level is available are presented in Table III for Case 1, where the modules are placed in cold shutdown in response to a LOOP and the plant is connected to the macrogrid. The probability that at least 450 MWe is generated is 99% with at least 9 modules operating. The probability of achieving power at the 99.9% level drops to 200 MWe. By placing the modules in cold shutdown in response to a LOOP, a probability of 99.97% is the highest level achievable, with LOOP events being the limiting factor accounting for nearly 0.2% of the overall plant operational time. Permitting the modules to enter turbine bypass in Case 2 rather than cold shutdown leads to minor changes the power reliability, as expected. The fraction of the time that the plant operates with a specific number of modules generating power is not significantly different from Case 1. However, by lowering the consequence of LOOP events, the likelihood of power generation from the plant increases, as shown in Table IV. For Case 2, 99.0% reliability is achieved at 500 MWe, 99.9% reliability is achieved at 350 MWe, and 99.99% reliability is not achieved; however, 99.98% is the highest level achievable at 100 MWe. When a microgrid connection to a dedicated service load is available, where power may still be supplied when the macrogrid is unavailable, a power output reliability of 99.99% can be achieved as shown in Table V. For Case 3, 99.0% reliability is achieved at 500 MWe, 99.9% reliability is achieved at 350 MWe, and 99.99% is achievable at 100 MWe. A comparison of the three cases is shown in Fig. 3.

Table III. Probability that at least the indicated power is available for Case 1

Power	MLE	Std Dev	5%	95%
600	67.22	1.21	65.10	69.05
550	94.19	1.09	92.19	95.70
500	98.83	0.66	97.53	99.58
450	99.52	0.42	98.68	99.94
400	99.72	0.28	99.17	99.98
350	99.80	0.20	99.43	99.99
300	99.85	0.16	99.57	100.00
250	99.88	0.13	99.65	100.00
200	99.90	0.10	99.72	100.00
150	99.93	0.08	99.79	100.00
100	99.95	0.05	99.85	100.00
50	99.97	0.03	99.92	100.00
0	100.00	0.00	100.00	100.00

Table IV. Probability that at least the indicated number of modules are in operation for Case 2

Power	MLE	Std Dev	5%	95%
600	67.35	1.21	65.22	69.17
550	94.37	1.07	92.40	95.83
500	99.00	0.62	97.78	99.64
450	99.68	0.36	98.91	99.97
400	99.85	0.20	99.46	100.00
350	99.92	0.11	99.77	100.00
300	99.95	0.06	99.85	100.00
250	99.96	0.04	99.89	100.00
200	99.97	0.04	99.90	100.00
150	99.97	0.03	99.92	100.00
100	99.98	0.02	99.94	100.00
50	99.98	0.02	99.95	100.00
0	100.00	0.00	100.00	100.00

Table V. Probability that at least the indicated power is available for Case 3

Power	MLE	Std Dev	5%	95%
600	67.36	1.21	65.23	69.19
550	94.37	1.07	92.39	95.84
500	99.01	0.62	97.76	99.65
450	99.68	0.36	98.91	99.98
400	99.86	0.20	99.46	100.00
350	99.93	0.11	99.79	100.00
300	99.96	0.06	99.87	100.00
250	99.97	0.04	99.90	100.00
200	99.98	0.03	99.92	100.00
150	99.98	0.02	99.95	100.00
100	99.99	0.01	99.96	100.00
50	99.99	0.01	99.98	100.00
0	100.00	0.00	100.00	100.00

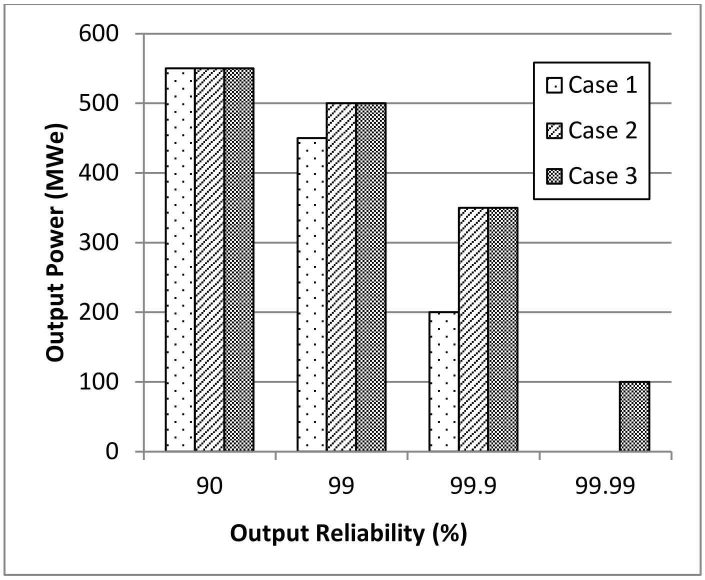


Fig. 3. Comparison of power reliability for all cases analyzed.

V. SUMMARY AND CONCLUSIONS

In this study, the reliability of a NuScale plant at different power levels was determined and the effect of multi-module outages and cold shutdown versus turbine bypass on plant availability were studied. Different plant responses to a LOOP had an insignificant effect on single plant capacity factor. However, the plant configuration to the macrogrid and micrograds coupled with the plant response to a LOOP has a visible effect on power output reliability. By placing the modules in cold shutdown in response to a LOOP, a gross plant output of 200 MWe is assured at a reliability of 99.9%. In contrast, by placing the modules in turbine bypass, a gross plant output of 350 MWe is assured at a reliability of 99.9%. The higher level of reliability of 99.99% can be assured at 100 MWe if the NuScale plant has a microgrid connection to a dedicated service load. Specific insights include:

- The capacity factor of a NuScale plant is approximately 96.6%, regardless of the plant connection to power distribution grids and internal plant response to a LOOP.
- At the 12-module plant level where modules are placed in cold shutdown in response to a LOOP, the highest level of power reliability achievable is 99.9% corresponding to a power level of 200 MWe. The potential occurrence of LOOP events precludes achieving a higher level of reliability.
- When modules are placed in turbine bypass in response to a LOOP, a total plant power level of 350 MWe with a likelihood of 99.9% can be achieved.
- When a NuScale plant is connected directly to a dedicated service load on a microgrid in addition to the macrogrid, a total plant power level of 100 MWe with a likelihood of 99.99% can be achieved.
- **In contrast to traditional plants, which cannot assure power at any level, power output can be assured at a NuScale plant at approximately 50% of total plant capacity at 99.9% reliability and 17% of total plant capacity at 99.99% reliability.**

The study substantiates the importance of module redundancy in achieving power generation at high levels of reliability as required by many mission-critical customers. The NuScale design using highly robust power modules and a multi-module plant design that can incorporate up to 12 modules is uniquely positioned to provide clean, abundant and highly reliable power to those customers.

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