Questions for NuScale VOYGR Reactor Certification: When Will It Be Done? And then, Will It Be Safe?[1]

By Arjun Makhijani and M. V. Ramana

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Of the designs currently planned for deployment, the 77-megawatt NuScale pressurized water reactor design (named VOYGR) is the farthest along of all small modular reactor (SMR) designs in terms of US Nuclear Regulatory Commission (NRC) certification. But the road forward is unclear; it is likely to be delayed even more than it already has because of questions about the design's safety. The saga of NuScale is one more signal that an SMR boom is going to be a long time coming, if ever.

On November 15, 2022 the NRC staff sent a letter to NuScale regarding its review of "preapplication documents." [i] The letter had 99 "significant" observations raising a variety of concerns. Of these, 11 concerns relating to accidents and reactor transients were completely redacted from the public document. In addition, there were six "challenging and/or significant issues" that could affect acceptance of the certification application and/or "be focus areas for…safety review." Two of the six involved a critical component for safety and operation – the steam generator. One involved the material of which reactor vessel and/or containment will be made. Another was about modeling loss-of coolant accidents, the mechanism that led to Three Mile Island and Fukushima, the most severe light water reactor accidents thus far.

Despite the serious and numerous deficiencies identified by the NRC in mid-November 2022, NuScale went ahead with its announced plan to submit a Standard Design Approval (SDA) Application by the end of 2022 – surely not enough time to fill the essential gaps. And indeed, even as it has begun to review some materials, the NRC staff has again called out deficiencies in the application materials and called on NuScale to provide more information before the application can be formally docketed and the certification process begun (https://www.nrc.gov/docs/ML2305/ML23058A160.pdf p. 3, italics added):

> Please note, however, that the staff's determination to commence this partial review of portions of the application does not signify a determination that the NRC staff will accept the SDA application for docketing and does not preclude the staff from requesting further information during its review of the SDA application. In addition, the staff notes that its commencement of this partial review is undertaken at the applicant's risk, in that *there is no assurance that the SDA application will be accepted for docketing and review or, if the application is accepted, that it will be approved upon completion of the staff's review*.

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[1] This article is about an ongoing process of the review of the NuScale reactor design by the Nuclear Regulatory Commission and its staff. There have been many twists and turns since the application for a reactor, smaller than the one now proposed, was filed in 2016. Those continue; what remains constant are serious safety concerns and cost increases. This article is current as of April 8, 2023 in terms of the review of NRC documents that are publicly available regarding certification. The NRC comments in 2023, after NuScale filed its Standard Design Approval (SDA) Application at the end of December 2022, do not mention all six "challenging" issues raised in the November 15 pre-application review letter. Presumably they will be reviewed and formally commented on before the SDA Application is formally docketed.

Some background and history can clarify the depth and breadth of the NuScale's problems. Nuclear plants in the United States have traditionally been licensed using a two-step process. But since 1989, they can also utilize a "combined license that provides a construction permit and an operating license with conditions for plant operation".[ii] Before obtaining a combined license, utilities or nuclear reactor vendors might also apply for a "design certification (DC) or standard design approval (SDA)" both of which are generic approvals without reference to a specific site for construction.[iii]

There are two key differences between a DC and an SDA. The DC requires approval by the Commission whereas the approval only requires the staff to sign off.[iv] Further, the DC "is considered a final regulatory decision and is not subject to additional review unless substantial new evidence is discovered" whereas an approval is "a quasi-final regulatory decision" with the regulatory staff being "instructed to avoid additional reviews absent new evidence".[v] This means that any issues that are resolved during the design certification rulemaking cannot be brought up later at the combined license stage.

NuScale started engaging with the NRC in April 2008 when it submitted its first formal pre-application project.[vi] Until at least 2010, NuScale stated that it expected to submit a design certification application for a 45 MW-electric reactor design to the NRC in 2012.[vii] NuScale later revised its design to have a slightly higher output of 50 MW; it submitted this larger version for certification to the NRC on December 31, 2016. The NRC granted a standard design approval (SDA) for the 50 MW design in September 2020.[viii]

But even before the Commission could evaluate the staff approval, NuScale announced that it was modifying the design once more to further increase the power output by 20 percent to 60 MW of electricity.[ix] Two years later, NuScale announced another power increase, this time to 77 MW.[x] NuScale's design, evidently, does not seem to be a stable one, constantly increasing its power rating. NuScale's website currently (February 2023) does not even mention that the 50 MW design is on offer (https://www.nuscalepower.com/en/products viewed on 2023-02-26); yet the Commission granted this version design certification, effective February 2023.[xi]

In January 2022, NuScale announced that it was "pursuing a new SDA [Standard Design Approval] for a plant comprised of six integrated pressurized water reactors that can generate 250 MWt (77 MWe) per module.…The SDA application is currently underway and the submittal of the application is planned for the fourth calendar year quarter of 2022".[xii] In January 2023, NuScale submitted a SDA application to the NRC for the 77 MW design.[xiii] The announcement did not mention anything about pursuing design certification of the 77 MW version. In effect, the over 50 percent increase in power has restarted the whole standard design approval and certification process.

As part of the renewed process, NuScale gave the NRC staff access to its materials and asked for a "preapplication" review. The staff clarified that the preapplication review was "not part of the NRC's official acceptance review process" but was just to understand if there were "any significant issues or information gaps between the draft application and the technical content required to be included in the final application submitted to the NRC".[xiv]

The NRC staff was asked to review the documents in NuScale's own electronic reading room; the material was not turned over to the NRC or made public. Keeping the documents in corporate hands prevents the public from getting them under the Freedom of Information Act. Thus, the public, including the present authors, cannot review the underlying NuScale materials. Nonetheless, the assessment, made by the NRC staff in its November 15, 2022 letter and the prior 50 MW documentation together are revealing; they provide a troubling picture.

I. Problems with NuScale's 50 MW design

The final rule from NRC identified "three issues as not resolved".[xv] The NRC stated that it had insufficient information "regarding (1) the shielding wall design in certain areas of the plant, (2) the potential for containment leakage from the combustible gas monitoring system, and (3) the ability of the steam generator tubes to maintain structural and leakage integrity during density wave oscillations in the secondary fluid system". Below, we elaborate on the third issue which we see as especially relevant to the 50 MW design and even more to the 77 MW version.

i. Steam generators

A major concern that emerged during the 50 MW design certification process was the stability of the steam generator;[xvi] it was identified in a March 2020 letter from the NRC's Advisory Committee on Reactor Safeguards (ACRS).[xvii] The ACRS letter warned that the "design and performance of the steam generators have not yet been sufficiently validated".[xviii] No commercial nuclear power plant uses the steam generator design proposed by NuScale; the Advisory Committee pointed out that it "introduces different failure modes".

The NRC concurred with the ACRS's findings, reiterating the ACRS's conclusion that the "design and performance of the steam generators have not yet been sufficiently validated because of uncertainties associated with unstable density wave oscillations (DWO) on the steam generator secondary side".[xix]

The integrity of the steam generator is a significant safety concern. In operating pressurized water reactors, the primary (reactor) water is pumped through a mass of tubes bent into a U-shape; it never boils. The secondary water flows vertically past these tubes and boils, with the steam gathering at the top to be sent to power the turbine-generator set where the electricity is produced. (A simplified diagram at the NRC website can help visualize this process: https://www.nrc.gov/reading-rm/basic-ref/students/animated-pwr.html) The steam generator is outside the reactor vessel but inside the secondary containment. It is not easy to replace the massive component; but it can be done and has been done in many pressurized water reactors.

The NuScale design is different. As part of its "passive design", the primary water circulates vertically upward from the reactor to the steam generator, which is inside the reactor vessel. The secondary water circulates in helical tubes, where it boils upon picking up heat as the primary water flows past the tubes. Two issues, arising from the design, were central to withholding approval of the steam generator. The first was premature wear of the steam generator tubes. The second, related, issue concerned vibrations called "density wave oscillations." Water circulation and vigorous boiling inside helical tube subjects the tubes to different mechanical forces than current pressurized water reactor designs.[xx] These have been extensively studied because "thermally induced oscillations of the flow rate and system pressure are undesirable"; such oscillations "can cause mechanical vibrations, thermal fatigue, problems of system control, and in extreme circumstances disturb the heat transfer" characteristics of the system.[xxi]

As noted, the NRC reiterated concerns expressed by ACRS and was even more specific about the "uncertainties associated with unstable density wave oscillations (DWO) on the steam generator secondary side".[xxii] Yet, the NRC staff stated that further analysis or testing results to "demonstrate the design and performance of the steam generators" could be included as part of the application for the license to construct and operate the reactor,[xxiii] even though '[s]ome uncertainty will remain until a NuScale Power Module is built and operated".[xxiv]

In punting on the steam generator issue, the NRC also ignored the advice of an ACRS member, Dr. Vesna Dimitrijevic, who is an expert in probabilistic risk assessment. She also agreed with the ACRS steam generator analysis but, on that very basis, she dissented from the decision to certify the reactor before steam-generator-related issues were settled. She wrote that "the steam generator integrity is *too significant of a safety issue* to not have received finality in the NuScale design certification" (our emphasis).[xxv]

II. Problems with NuScale's Preapplication for the 77 MW design

As noted above, in the November 2022 communication, NRC identified 99 "significant" observations and six "challenging and/or significant issues" that would have to be addressed for the safety review. We highlight some of them in this brief report.

ii. Removed information

An overall NRC finding was that NuScale appears to "have removed information needed to support a reasonable assurance of public health and safety determination" in its application materials. The NRC communication did not describe the removed materials in detail; it did imply it might be related to the large increase in power output by stating that the removal "may" have been related to "the "optimization" effort for the Standard Design Approval (SDA) application….".[xxvi]

iii. Severe accident evaluation

A specific concern identified by the NRC is that the increase in power impacts accident evaluation: The staff stated that "power uprate to 250 MWth from 160 MWth [i.e., to 77 MW electric from 50 MW electric] and other design changes is expected to impact all stages of the Severe Accident Evaluation, from identified accident sequences, derived source terms, and radiological consequence analyses". Yet, the staff noted, it "appears [that] all…'Severe Accident Progression', analyses remain unchanged" in NuScale preapplication documents.[xxvii] This is clearly one of the places where the "new elements" mentioned by NuScale in January 2022 should have been added. Because of the 50 percent increase in power, accident consequences would be expected to increase. Thus, leaving the accident analysis "unchanged" seems unjustified. Was NuScale's intent to check if the NRC staff actually read the documents? If so, the good news for the public is that the answer appears to be "yes."

iv. Steam generators

Despite the lapse of over two years since the steam generator concerns were expressed—and the clear dissent regarding granting certification to the 50 MW reactor design—the NRC has again identified "Comprehensive Vibration Assessment Plan and Steam Generator Tube Support" and "Density Wave Oscillation Analysis" as challenges for the 77 MW NuScale design.[xxviii] In other words, NuScale has apparently not made much progress in the last two years towards addressing one of the fundamental safety concerns with its design. Because it is inside the reactor vessel, replacing the NuScale steam generator, if it fails, will involve cutting open the reactor vessel, with the potential risks of greater damage to the vessel as well as outer structures. Also complicating the picture is the fact that the reactors would be underwater – locating them in a pool is part of the design.

This is not merely a theoretical concern. The Crystal River Unit 3 nuclear plant had to be shut down as a result of an attempt to replace the steam generators. This replacement required that a large hole "be made in the containment structure".[xxix] After the replacement of the steam generators, those in charge tried to restore the containment structure, which was observed to have been damaged. According to the NRC, the "licensee attempted to repair the damage, but later decided to decommission the reactor".[xxx]

Steam generator replacements at the units 2 and 3 of the San Onofre Nuclear Generating Station offer and object lesson closer to the concerns with the NuScale design. Although they had been replaced at a cost of hundreds of millions of dollars,[xxxi] the new steam generators experienced leaks and rapid, excessive wear within two years. Eight tubes showed wear of more than 70%, including one assessed at 100% wear.[xxxii] Pointing to the need to protect public "health and safety" as well as the environment, the NRC put the plant on heightened regulatory review:

> to address unexpected degradation of tubes in the newly installed steam generators after approximately 1.7 and 1 effective full power years of operation, respectively. The purpose of this special oversight was to assess the licensee's evaluation of the cause(s) of *unexpected tube degradation*, and verify that the licensee's corrective actions were appropriate to ensure the integrity of the steam generator' and to protect the health and safety of the public and the environment.[xxxiii]

Eventually the utility owners of the plant decided in June 2013 to shut it down permanently because the various costs associated with the prolonged shutdown, leaks and repairs were deemed too high to make the plant operational again at full power.[xxxiv]

The challenge in the case of NuScale is much greater. Steam generators are both essential to operating the plant—a steam turbine is necessary to drive the electric generator—and to safety, since it keeps the radioactive water in the primary reactor loop separate from the rest of the plant and the environment. Therefore, in addition to safety concerns, the financial implications of such a major repair might well be fatal to the economics of a NuScale plant. It is entirely possible that, if the steam generator fails, the reactor might have to be shut down permanently, the equivalent of having to junk a car because it is too costly and difficult to replace a failed transmission.

Compared to 2020, there is even more reason to be concerned now; the challenges with the steam generator have likely increased with the large increase in power output.

NuScale also proposes a higher burnup of the nuclear fuel to an average 45 gigawatt-days thermal per metric ton of uranium (GWdth/tU), up from around 35 GWdth/tU for the earlier design.[xxxv] The burnup represents the amount of thermal energy that the reactor produces on average per unit of uranium fuel; the greater the burnup, the higher the concentration of radioactivity in the core. The higher radionuclide inventory in the reactor and in the spent fuel pool is a central reason for carrying out a new accident analysis. If there is a loss-of-coolant accident the residual heat in the reactor core will be higher, enabling faster deterioration of conditions. This is likely an additional reason for the NRC staff to raise the loss-of-coolant accident analysis as a "significant issue" that may affect the acceptance of the design approval application and/or be a focus of a safety review. A loss-of-coolant accident is arguably the most important safety concern for light water reactors and thus a major focus of regulatory review in any case. NuScale staff are surely aware that the increase in burnup and steam throughput require a new analysis of loss-of-coolant accidents (among other things).

The concerns about steam generator-related safety issues have not abated after NuScale submitted its application for Standard Design Approval at the end of 2022. The NRC staff then carried out a first stage review to check whether the information provided was sufficient to formally docket the application and begin the formal SDA review process. In March 2023, the NRC staff informed NuScale (ref: https://www.nrc.gov/docs/ML2305/ML23058A160.pdf) that the documentation it had provided was "missing sufficient information in the following areas":

- "Scope of the methodology for calculating DWO [Density Wave Oscillations] and the full applicability range, conditions, and figures of merit;

- “Testing that was performed including test results and test data;
- “Comparisons of test data to the analysis models and justification for the applicability of the models for evaluation of the SDAA design; and
- “Evaluations of the effect of DWO on safety system performance during all operating conditions including normal operation, LOCAs, [Loss of Coolant Accidents], Non-LOCAs, and extended passive cooling.”

This is an impressive list; the issue of density wave oscillations and the safety of the helical steam generators continue to fester. If anything, the NRC staff’s rationale for the additional information reinforces prior concerns (ibid., pdf p, 5):

> DWOs or other instability phenomena can lead to a disruption in the flow of coolant through the steam generators and may challenge steam generator tube integrity. These may have adverse impacts on fission product barriers which could result in a release of radioactive material and potential offsite doses.

The NRC has given NuScale until September 2023 to submit the information it has requested from NuScale (ibid. p. 2) The evaluation of its completeness and suitability of the entire application to be formally docketed will follow submittal of the documents.

Why did NuScale not provide the requisite new elements to the NRC in its preapplication review or even in its formal submittal of the SDA? Was there a hope that somehow the NRC would accept incomplete documentation on critical issues and docket the application, so the company could present the public with evidence of progress on certification? Are the increasing financial pressures on NuScale creating a rush to file an application to raise more funds from the public and convince prospective customers to stick with its design?

III. Challenges with the NuScale project in Idaho

The first NuScale project is proposed to be constructed in Idaho with electricity to be purchased by Utah Associated Municipal Power Systems (UAMPS). In a nod to the inability to find enough takers for the power, UAMPS has officially reduced the plant size “from 12 NuScale Power Modules to 6 modules”,[xxxvi] which together will produce 462 MW (gross) of electricity. Each of the six modules is to generate 77 MW, instead of the prior 50 MW, presumably to take advantage of economies of scale. In part because eight municipalities withdrew from the project in October 2020, ahead of one of the scheduled “off-ramps”,[xxxvii] the total subscription for the UAMPS project, measured in terms of signed power sales contracts, amounted to just 101 MW as of October 2021.[xxxviii]

The withdrawals from the project were partly a result of successive cost escalations, which by 2020 had resulted in a project cost estimate of $6.1 billion for a 720 MW, twelve module design.[xxxix] Following the withdrawals, UAMPS modified its plan to only include six modules, each of 77 MW. But when evaluated in terms of cost per unit of generation capacity, that did not fix the cost problem: according to a November 2021 article by the CEO of UAMPS, the “actual all-in estimated cost of the six module/462 MWe project, including financing, inflationary costs, etc., is $5.32 billion”.[xl] Since then, the costs of the UAMPS project have gone up substantially.[xli]

On January 2, 2023, UAMPS released a set of “talking points” that provided a new cost estimate: from the $5.32 billion, the project is now estimated to cost an eye-popping $9.3 billion for just 462 MW of power capacity.[xlii] In per kilowatt terms, that estimate for the UAMPS project is around 250% more than the initial per kilowatt cost for the Vogtle project in Georgia, which consists of two AP1000 reactors capable of generating 1250 MW each (gross capacity), at a comparable stage – that is, when it was still on paper. The Vogtle cost has since exploded from $14 billion to over $30 billion as the reactors near completion.[xliii] A similar fate may await the UAMPS project if and when construction starts. After all, nuclear reactors have routinely exceeded initial cost estimates. One historical survey found that 175 out of 180 nuclear construction projects had experienced cost increases and delays. Cost escalations averaged 117 percent; and construction took 64 percent longer on average than projected.[xliv] And the cost of the UAMPS project will likely further increase prior to start of construction, especially if NuScale has to modify its design to address the safety issues identified by ACRS and NRC.

Even before the recent escalation in costs, NuScale has been struggling to raise investment capital. Its key investor, Fluor, has been systematically trying to reduce its equity stake in NuScale and has ceased to invest in it; as a result, NuScale is looking for other investors.[xlv] As early as 2019, a senior Credit Suisse analyst wrote to investors recommending that Fluor could reduce "underperforming investments," including its NuScale small modular nuclear reactor startup "which is long overdue, in our opinion".[xlvi] The NuScale holding is a very small part of Fluor, which is a large, multi-billion dollar multinational construction and engineering firm.

As of 2021, the total investment in NuScale has been over $1.1. billion, including around $400 million from the Department of Energy (DOE).[xlvii] The DOE has supported NuScale through competitive and non-competitive awards, most prominently a $226 million award from 2014-18 and an ongoing $263 million award for 2020-24. In 2020, DOE also awarded $1.355 billion for the UAMPS NuScale project to be used by 2030.[xlviii] The Government Accountability Office (GAO) has criticized the lack of oversight of these awards; as of September 2022, when the GAO published its report, DOE's Office of Nuclear Energy were still "developing their oversight plans".[xlix]

Despite this handsome support from the DOE, NuScale is clearly in need of much more funding. Specifically, NuScale has created a special purpose acquisition company (SPAC) as a way to obtain public money.[l] In April 2022, two Japanese companies, Japan NuScale Innovation and Japan Bank for International Corp., purchased a part of Fluor's equity in NuScale for $110 million.[li] Fluor, however, "remains the majority owner in NuScale".[lii] NuScale's stock price (Symbol: SMR) has been stagnant around $10 per share. Capital woes may well be part of NuScale's rush to get in a certification application.

Prior cost increases were likely a factor in NuScale's decision to increase the size of the reactor from 50 MW to 77 MW, with the attendant certification headaches and delays, and in the decision to increase the targeted burnup of the fuel: higher burnup reduces the average refueling outage time. But those efforts at economy have had a cost: reanalysis of the outstanding operational safety issues as well as the consequences of accidents – both of which are made more complex by the increased power.

IV. Conclusion

Anyone looking at NuScale's website, might well think that the 77 MW VOGR is ready to go:

> VOYGR™ SMR plants are powered by our innovative NuScale Power Module™, the first and only small modular reactor (SMR) to receive design approval from the U.S. Nuclear Regulatory Commission (NRC).
> (https://www.nuscalepower.com/en/products/voygr-smr-plants _

In fact, the 77-MW VOYGR has not received standard design approval, much less full Commission certification. On the contrary, it has received a letter from the NRC staff with 99 "significant" observations and six major challenges. These problems need real-world analysis, design, and most important, real-world testing to be resolved. Premature wear of the steam generators and their potential failure were not analyzed properly and insufficiently tested even for the 50 MW design. The hurdles are even higher with the 77-MW version.

Specifically, the testing of the steam generators was under conditions that did not adequately represent reactor operation. The ACRS noted that the onsite instabilities were studied by "reducing the flow in small steps until unstable oscillations developed…." It noted the difference with real operational conditions as follows:

> Actual oscillations may be larger than those observed in these tests. Differences between these scaled experiments and the actual design of the steam generator introduce uncertainty about the applicability of the data. Historically in two-phase flow experiments, small configuration differences have resulted in behavior observed in experiments that were not observed in the actual reactor. Thus, some uncertainty will remain until a NuScale Power Module is built and operated.[liii]

The ACRS also noted the related analytical weaknesses in regard to NuScale's analysis of accidents. It stated that the modeled accident, which postulated the rupture of a single tube, "may not be the limiting event. This also suggests that the estimate of containment bypass under such conditions may be underestimated in the probabilistic risk assessment".[liv]

One would hope that this time around, the NRC staff will insist that the issues related to wear of the tubes, steam generator instability, and limiting accident be thoroughly addressed *before standard design approval*. This is more important now, since the potential consequences have intensified with the increase in power from 50 MW to 77 MW. Will the NRC staff take the dissent of its own probabilistic risk assessment expert on the ACRS to heart this time before giving standard design approval? And if it does not, will the Commission do so?

Both the NRC staff and the Commission postponed essential safety concerns, including those with the steam generator in giving the green light to the 50 MW design. But simplification of certification should not compromise safety. Will the NRC do a careful and thorough job this time before granting certification to the 77 MW version? How long will approval take if it does so? Our best answer is that it will not be anytime soon.

The pressures to unveil the age of SMRs are great. Will the NRC bend to them? Or will it step back from its posture in the 50-MW NuScale certification process of treating those who invest in the first NuScale plant, who commit to purchasing its power, who work in it, and who live near it as neighbors as unwitting test subjects in the cause of promoting SMRs?

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