FINAL REPORT

Flexible Siting Criteria and Staff Minimization for Micro-Reactors

NEUP Project Number 20-19042
Work Package ID NU-20-MA-MIT_-030205-01
Project start date: 10/1/2020
Project end date: 9/30/2022

Submitted by:
Jacopo Buongiorno, PI
Professor, Nuclear Science and Engineering

Massachusetts Institute of Technology
Cambridge, MA

November 15, 2022

PROJECT DESCRIPTION AND FINDINGS

The economic potential of micro-reactors is vast and underestimated. Commonly-emphasized applications include niche markets such as remote communities, mines and military bases. However, micro-reactors could be used as flexible energy generators also for larger markets, such as mobile and containerized agriculture and manufacturing facilities, district heating, micro-grids for data centers, sea ports, airports and hospitals. The implication is that micro-reactors may have to be deployed also in non-remote locations. Successful implementation of micro-reactors needs a navigable and predictable licensing process, technology-appropriate siting restrictions, risk-informed emergency and safety requirements, and practical operating and maintenance requirements. The primary goal of this project was to develop siting criteria that are tailored to micro-reactors deployable in densely-populated areas, e.g., urban environments.

To achieve that goal, we compared the characteristics of the MIT research reactor (MITR) with those of leading micro-reactor concepts (e.g., eVinci, USNC, Aurora), and evaluated whether and how the MITR design basis (e.g., inherent safety features, engineered safety systems, source term, emergency planning and emergency operating procedures) and associated regulations may be applicable to these new micro-reactors as well. What makes MITR a unique analogue in this context is its small power rating (6 MWt) and physical size, mode of operations (24/7 with a somewhat more commercial flavor than typical university reactors), and especially its urban location. Of course significant differences exist, such as mission (power production vs. research) and the reactor design itself. Leveraging the MITR experience, this project was able to generate criteria that will allow micro-reactors to realize their full economic potential as flexible heat and electricity generators for a diverse portfolio of applications in non-remote locations. As such, the outcome of this project might encourage investment in and use of micro-reactors.

A second goal of the project was to conceptualize a model of operations for micro-reactors that would minimize the staffing requirements, and thus reduce the cost of electricity and heat generated by these systems. Here too our approach was to systematically review the MITR experience and requirements, as well as survey the innovations in autonomous control technologies and monitoring (e.g., advanced sensors, drones, robotics, AI) that would permit a dramatic reduction in staffing at future micro-reactor installations.

The scope of work was expanded after the start date to include also an evaluation of micro-reactor security, using the so-called consequence-based analysis, and the development of a methodology to perform dynamic risk assessment for micro-reactors, using system theory and modeling and simulation.

The main findings of this project are as follows:

1) Developed scaled micro-reactor siting criteria and requirements to reflect those of research reactors specifically for deployment in densely populated urban environments. In doing so, we found that the main difference between a commercial micro-reactor and a research reactor is simply the end destination of their products, which should not warrant a substantially different regulatory treatment of the two classes of reactors. Thus, adoption of the so-called Non-Power User Facility (NPUF) rule and Advanced Reactor Generic Environmental Impact Statement (ANR GEIS) is recommended.

2) Developed an optimal licensing path for micro-reactors under the existing 10 CFR Part 50 and 10 CFR Part 52 frameworks with integration and leveraging of the NPUF rule and ANR GEIS. See Figures 1 and 2.

3) Quantified the staffing needs for operations and maintenance for four classes of micro-reactors and compared them with various non-nuclear power facilities (i.e., small aero-derivative gas turbines, and transportable supercritical CO2 power units). The analysis shows that with proper use of automation and remote monitoring, the staffing required onsite can be kept at a fairly low level, e.g., order of 1 FTE, but significant offsite staffing is still required for monitoring and servicing the micro-reactors. See Table I.

4) Identified the worst-case radiological consequences of a situation in which a hostile force gains control of a micro-reactor facility and deliberately damages it. This consequence-based security analysis allowed to quantify the size of the site boundary that is required to meet the radiation dose limits for various micro-reactors. See Figure 3.

5) Developed a risk-informed methodology that embeds (i) System-Theoretic Accident Model and Processes (STAMP) principles to guide a qualitative exploration of the system threats and hazards, (ii) Modeling and Simulation (M&S) to investigate the system dynamic behavior during accidental scenarios, and (iii) the Goal-Tree Success-Tree Master Logic Diagram framework to assess risk quantitatively. The integration of these three elements allows for a systematic identification of the risks and a dynamic (time-dependent) assessment of the risk profile.

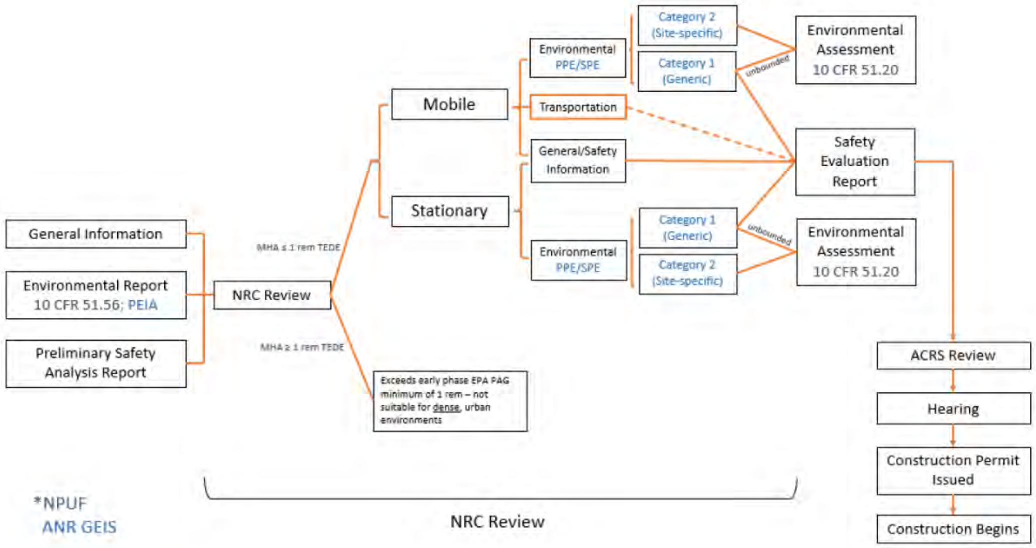
6) Demonstrated this methodology for a micro-reactor design with heat pipes, showing the ability to quantify the time-dependent probability density function for key safety variables (e.g., peak cladding temperature, moderator temperature) and their margin to postulated limits. See Figure 4.

The details of the analyses and findings have been documented in the milestone reports and will not be repeated here.

The membership of the project team, the advisory board and the external collaborators are reported in Appendix A.

A synopsis of the project’s scope and work flow is shown in Appendix B.

The dissemination plan, including publications and briefings, is reported in Appendix C.



h

Figure 1. Modified Part 50 for Licensing Micro-Reactors as NPUFs in Dense Urban Environments

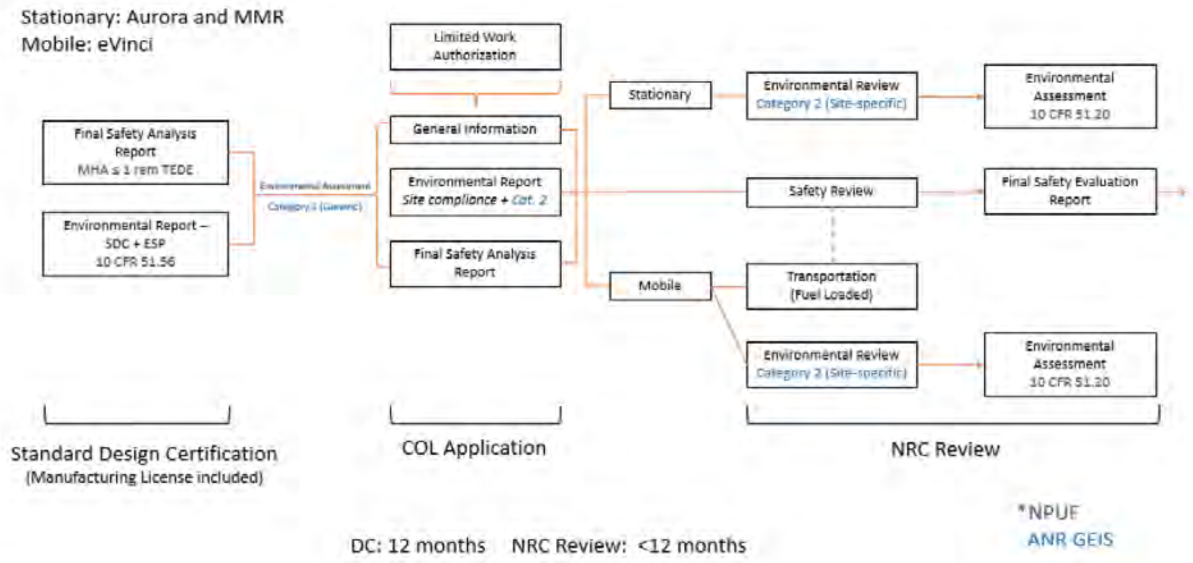


Figure 2. Modified Part 52 for Licensing Micro-Reactors as NPUFs in Dense Urban Environments.

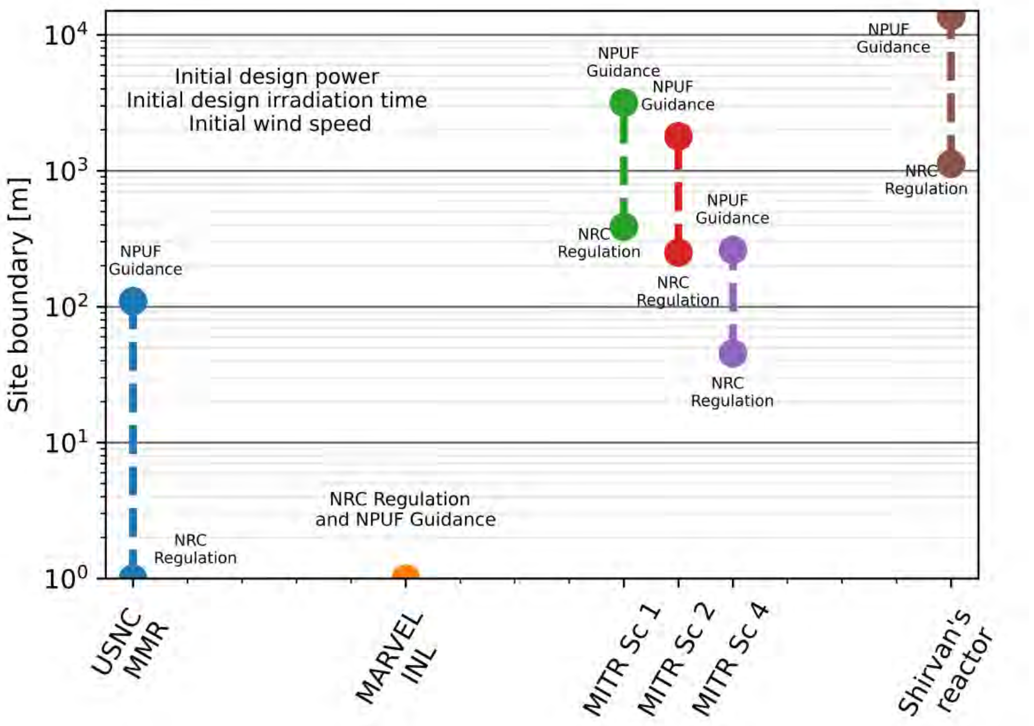


Figure 3. Site boundary required to meet the radiation dose limits for various nuclear reactor designs.

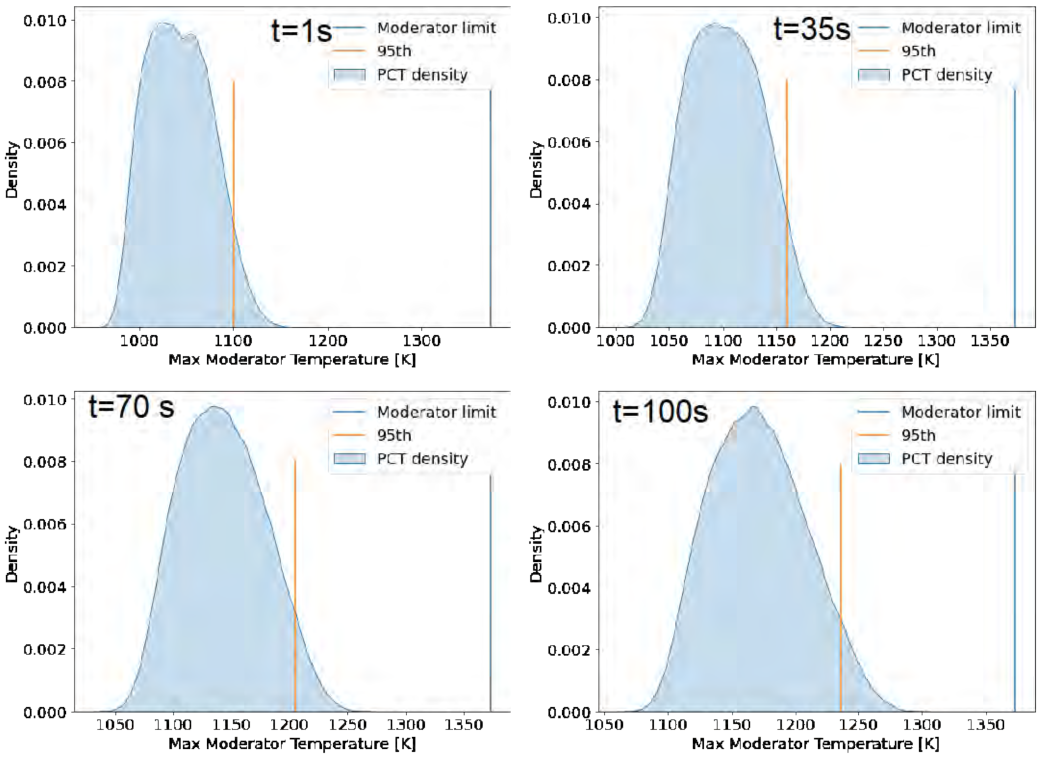


Figure 4. Probability density function of the maximum moderator temperature for scram time delays of 1 s, 35 s, 70 s and 100 s. PCT = Peak Cladding Temperature.

Table I. Summary of the maintenance workers and plant operators staffing required for various nuclear and non-nuclear power facilities.

Category	Description	MIT research reactor	Gas V16 2.4 MWe	Gas aero-derivative 1.5 MWe	sCO2 power unit	eVinci	Holos	Aurora	MMR
Maintenance – total	Total h of maintenance per year [h]	738	195	92	277	367	388	552	613
Maintenance – onsite, nuclear specific	Total h of onsite nuclear maintenance per year * FTEs [h]	557	0	0	0	118	143	118	143
Maintenance – onsite, non-specific	Total h of onsite non-specific maintenance per year * FTEs [h]	559	354	100	277	506	501	689	729
Maintenance – offsite, nuclear specific	Total h of offsite nuclear maintenance per year * FTEs [h]	0	0	0	0	44	46	44	46
Maintenance – offsite, non-specific	Total h of onsite non-specific maintenance per year * FTEs [h]	0	18	44	0	44	44	0	0
Maintenance – total	Average FTEs for maintenance during 1 year	0.35	0.23	0.09	0.17	0.44	0.46	0.53	0.57
Operation	Average FTEs for operations during 1 year	16	0.63	0.63	0.63	0.63	0.63	0.63	0.63
Total	TOT	16.35	0.86	0.71	0.80	1.07	1.08	1.16	1.20
Total	Per MWe	-	0.36	0.48		0.21	0.08	0.77	0.24

APPENDIX A

THE PROJECT TEAM


Isabel Naranjo
(grad)


Edward Garcia
(grad)


Carmen Sleight
(grad)


Lucy Nester
(UG)


Emile Gateau
(visiting gstudent)


Leanne Galanek
(UG)


Jacopo Buongiorno
(PI, NSE)


Edward Lau
(NRL)


Sara Hauptman
(NRL)


Neil Todreas
(NSE)


Federico Antonello
(postdoc)

THE ADVISORY COMMITTEE


Michael Corradini
(U-Wisconsin)


Matthew Smith
(Westinghouse)


James Kinsey
(INL, Coastal Technical Services)

EXTERNAL COLLABORATORS


Enrico Zio
(POLIMI)

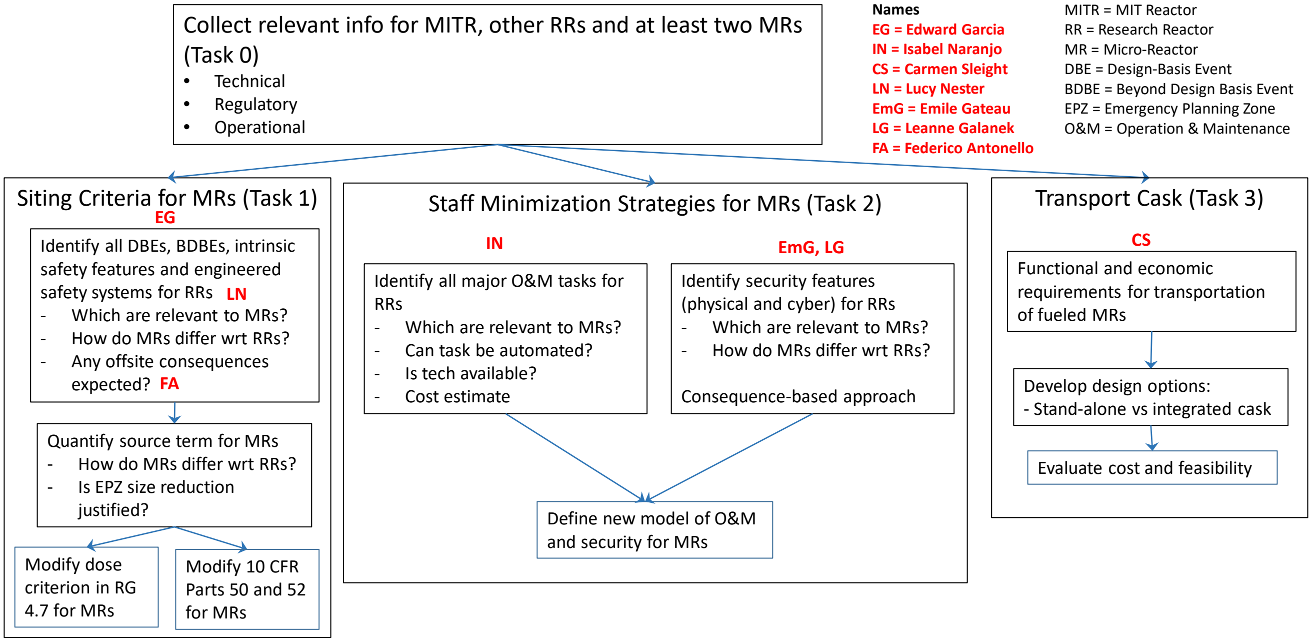

Piyush Sabharwall
(INL)

APPENDIX B

PROJECT SCOPE OF WORK

Student and Postdoc Names
EG = Edward Garcia
IN = Isabel Naranjo
CS = Carmen Sleight
LN = Lucy Nester
EmG = Emile Gateau
LG = Leanne Galanek
FA = Federico Antonello

Legend
MITR = MIT Reactor
RR = Research Reactor
MR = Micro-Reactor
DBE = Design-Basis Event
BDBE = Beyond Design Basis Event
EPZ = Emergency Planning Zone
O&M = Operation & Maintenance



Collect relevant info for MITR, other RRs and at least two MRs (Task 0)

- Technical
- Regulatory
- Operational

Siting Criteria for MRs (Task 1)
EG

Identify all DBEs, BDBEs, intrinsic safety features and engineered safety systems for RRs **LN**
- Which are relevant to MRs?
- How do MRs differ wrt RRs?
- Any offsite consequences expected? **FA**

Quantify source term for MRs
- How do MRs differ wrt RRs?
- Is EPZ size reduction justified?

Modify dose criterion in RG 4.7 for MRs

Modify 10 CFR Parts 50 and 52 for MRs

Staff Minimization Strategies for MRs (Task 2)

IN

Identify all major O&M tasks for RRs
- Which are relevant to MRs?
- Can task be automated?
- Is tech available?
- Cost estimate

EmG, LG

Identify security features (physical and cyber) for RRs
- Which are relevant to MRs?
- How do MRs differ wrt RRs?

Consequence-based approach

Define new model of O&M and security for MRs

Transport Cask (Task 3)

CS

Functional and economic requirements for transportation of fueled MRs

Develop design options:
- Stand-alone vs integrated cask

Evaluate cost and feasibility

APPENDIX C

Dissemination of the project findings has taken place primarily through publications (papers and student theses) and briefings of key stakeholders, as outlined below.

Papers:

- F. Antonello, J. Buongiorno, E. Zio, “Advanced Safety Assessment of Nuclear Batteries”, submitted to *Nuc Eng Des*, Sep 2022.
- F. Antonello, J. Buongiorno, E. Zio, “A Methodology to Perform Dynamic Risk Assessment Using System Theory and Modeling and Simulation”, *Reliability Engineering & System Safety*, 228, 108769, 2022.
- E. Garcia, L. Nester, J. Buongiorno, “Scaling Siting Criteria and Alternative Licensing Pathways for Micro-Reactors”, Proc. of ANS Meeting, June 12-16, Anaheim CA, 2022.
- Naranjo de Candido, J. Buongiorno, “Staffing minimization for micro-reactors”, Proc. of ANS Meeting, June 12-16, Anaheim CA, 2022.
- 2 journal papers in preparation based on E. Garcia’s and I. Naranjo de Candido’s work.
- 1 conference paper in preparation based on E. Gateau’s work.

Thesis dissertations:

- E. Garcia, “Scaling siting criteria and identifying alternative licensing pathways for micro-reactors within the existing regulatory framework”, M.S. Thesis, October 2022
- Naranjo de Candido, “Staff minimization strategy for micro-reactors”, M.S. Thesis, November 2022
- E. Gateau, “Consequence-based Security for Micro-Reactors”, M.S. Thesis, August 2022
- L. Galanek, “Physical Security Requirements for Micro-Reactors”, B.S. Thesis, May 2021

Briefings to:

- Micro-reactor program leadership at INL, August 2022
- Micro-reactor principals at the NRC, August 2022
- Micro-reactor group at NEI, August 2022
- eVinci group at Westinghouse Electric Company, August 2022