DEVELOPING DELIBERATE REACTIVITY INSERTION SOURCE TERMS FOR REGULATORY APPLICATIONS

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ABSTRACT

The Nuclear Regulatory Commission (NRC) is developing alternative physical protection requirements for new nuclear power reactors as part of its effort to "risk-inform" its licensing and oversight processes to address the enhanced safety and security characteristics that some assert the next generation of reactors will exhibit. These alternatives include a "limited scope" rule to provide a mechanism for exempting new reactor licensees from certain requirements that apply to the operating fleet, such as maintaining a minimum number of armed responders capable of preventing a design basis threat (DBT) adversary from causing radiological sabotage of the reactor(s). In parallel, the Part 53 rule under development would allow any new reactor to be entirely exempt from the requirement to protect against the DBT. To qualify for the exemptions in either case, applicants would have to provide analyses to demonstrate that postulated security-initiated events would not lead to exceeding certain dose limits to members of the public. NRC has not yet finalized the process for determining specific events to be analyzed. However, for certain reactor applications, it may be necessary to show that even adversaries with full access to the reactor could not "break" it by any available means prior to being neutralized by a local law enforcement response. Depending on reactor and facility design, sabotage attacks that cause rapid reactivity insertions may be plausible and could pose challenges to meeting dose limits. However, assessing the consequences of such events will be difficult because they cannot be experimentally validated today in real-world integral tests. Fortunately, an experimental database of transient tests resulting in core damage and radionuclide release exists from early programs such as BORAX and SPERT at the National Reactor Testing Station and the nuclear rocket and ramjet tests at the Nevada Test Site. However, in most of those tests the cores were unirradiated before the transients, which would not generally be the case for a sabotage attack on a power reactor. This paper will provide some observations about how the historical data may be able to inform sabotage analyses for regulatory applications.

“RISK-INFORMING” NEW REACTOR LICENSING

Based on unproven assumptions that new reactor designs will have improved safety compared to the current LWR fleet, the NRC is pursuing “risk-informed, performance-based” approaches for licensing. The agency’s underlying assumptions can be summarized as follows:

> “The new designs typically have lower probabilities of severe accidents because of their smaller source terms or innovative safety features, which will result in lower impacts to public health and safety from any radiological emergency, as compared to large LWRs.”[1]

Because of this perception, the NRC is considering, or has in some cases already implemented, changes to regulatory requirements or guidance that would provide pathways for

- Allowing reactor siting in densely populated urban areas, contrary to long-standing guidance;
- Allowing the absence of a physical, low-leakage containment structure by taking credit for other safety features ("functional containment")
- Allowing licensees to forego any off-site radiological emergency planning (with site boundaries nominally as close as 300 meters from the reactor);
- Allowing for the absence of safety-related backup electrical power;
- Fewer or less qualified operators (or even no operators).

SABOTAGE VS. ACCIDENTS

In addition to "risk-informing" safety requirements, the NRC is also seeking to weaken security requirements for new reactors based on the same presumptions of inherently greater safety, and hence reduced vulnerability to sabotage, compared to large LWRs:

> "… many of the advanced reactor designs have smaller power outputs and correspondingly smaller inventory of fission products available for potential release … and may include attributes that could result in smaller and slower releases … following the loss of certain safety functions."[2]

The NRC is pursuing these changes both through a "limited-scope" security rule for advanced reactors [3] and the more expansive revisions contained in the proposed Part 53 rulemaking, which could apply to any new reactor.

However, even if it were true *a priori* that SMRs or non-LWRs have intrinsic design features that would make them safer than large LWRs, this does not necessarily translate into lower risks to the public from a terrorist attack. First, as is the case with large LWRs, terrorists could cause severe outcomes that would be considered very low probability if left to chance. For example, the entirety of a small core—which could weigh only a few hundred kilograms—could be dispersed by a large truck bomb containing thousands of kilograms of high explosive, creating an improvised dirty bomb. Such an event would be very unlikely to occur from an accident. Also, passive heat removal systems could be disabled by sabotaging the ultimate heat sink or otherwise interfering with the passive heat transfer mechanisms. For example, a preliminary analysis shows that changing the orientation of the heat pipes in a microreactor by turning it upside down can cause a ten-fold increase in the reactor power.[4]

And even SMRs or microreactors with much smaller source terms than large LWRs would not necessarily pose lower radiological risks to the public. Those risks will also depend on the extent to which the regulatory relief the NRC is proposing would allow for reductions in defense-in-depth features such as a robust containment, potentially exposing the public to higher doses from a core damage event than a similar event at a large reactor licensed under the current rules. A reactor with a core inventory 100 times less than a large LWR might pose a comparable risk if located in an urban area with no exclusion zone and no containment. Moreover, the NRC's current draft final rule and guidance for developing mechanistic source terms for emergency planning zone size determination does not require consideration of sabotage attacks in developing the "spectrum of accidents" that applicants would need to consider. This could potentially allow for reactors to be exempt from off-site radiological emergency planning based on considering only accident source terms, even if credible sabotage scenarios could result in larger source terms and more severe consequences.

This is illustrated by a recent NRC study that evaluated doses to the public from accidents at a 2 megawatt-electric heat pipe microreactor.[5] The calculations indicated that near-term whole-body doses off-site accumulated in a 4-day period were comfortably below the Environmental Protection Agency (EPA) 1-5 rem trigger values for evacuation. However, the analysis found that radionuclide releases from the fuel were reduced by a factor of 1000 by the presence of a building the size of a large boiling-water reactor, which is not typically included in a microreactor design. But even if it were, a deliberate breach of the building could lead to far larger releases to the environment, which would increase doses to the extent that off-site protective actions would be necessary at least several kilometers away.

Another class of sabotage scenarios that could lead to enhanced offsite releases are reactivity excursions, which could be carried out by an insider at the controls (which could even be at a remote location), or by an external cyberattack. (Fully digital instrumentation and control systems are likely to be standard equipment for any new reactor, which is not the case for the operating fleet.) Depending on the reactor design, the reactor protection system, and the fuel properties, a rapid power increase could lead to vaporization and explosive disassembly of a large fraction of the core. And again, depending on the system, an adversary might be able to substantially increase the fission product inventory in the core if it can be sustainably operated at a higher power level before it explodes. This may be plausible for reactors that are designed for operation in a derated condition at a low power level to allow long core lives without refueling. Thus the nameplate power rating of a small reactor might not be a reliable indicator of the radiological hazard it could pose under such scenarios. Also, reactors with long-life cores would require significant excess reactivity at the beginning of cycle, which could potentially facilitate a large reactivity insertion at low fuel burnups.

REDEFINING RADIOLOGICAL SABOTAGE

In the post-9/11 revision to 10 CFR 73.55, NRC defined radiological sabotage at a nuclear power plant as “significant core damage” and “spent fuel sabotage. These are the objectives of the design basis threat adversary that physical protection programs must be designed to prevent. As currently defined, an adversary attack is considered successful if either of these goals is achieved, whether or not there is a significant off-site radiological release.

But the limited-scope rule presented in SECY-22-0072 would narrow the definition of radiological sabotage (for SMRs and non-LWRs) to only include sabotage resulting in “a significant release of radionuclides,” where “significant” would be defined in terms of the 25-rem dose limit used in the evaluation of design-basis accidents in 10 CFR §50.34 and §52.79. Under this more restrictive definition, site security plans would not have to prevent a “postulated security-related event” from causing core or spent fuel damage, provided that the resulting off-site releases were limited (through mitigative actions or by virtue of a smaller source term) and the 25-rem threshold was not exceeded. If licensees can meet the dose criterion, they would not be required to have armed response forces.

Going beyond the limited-scope rule, the current draft of Part 53, the so-called “risk-informed, technology-inclusive” licensing rules for commercial reactors that the NRC is developing, would exempt licensees from the requirements to protect their reactors from the radiological sabotage

DBT, and to maintain rigorous cybersecurity and access authorization procedures, if the dose criterion is not exceeded in the event of a "design basis threat initiated event involving the loss of engineered systems for decay heat removal and possible breaches in physical structures..."[6]

SABOTAGE SOURCE TERM

To be able to use these new rules, applicants will have to develop credible source terms for "security-related" or "design basis threat initiated" events. Although analytical work can play a role in supporting development of such source terms, ultimately, experimental data would be needed to validate them. This will be particularly important for reactors using novel fuels and other materials for which there may be little or no data on their response to extreme events, including explosive loadings. However, to carry out such testing under realistic conditions, using actual reactors, is not a viable option today.

Fortunately, experimental data does exist to support development of source terms for deliberately induced rapid reactivity transients. These include the BORAX-I (1954), SNAPTRAN (1964,1966), and Kiwi-TNT (1965) tests, which were performed in an era with significantly weaker norms of radiological and environmental protection.[7]

KIWI-TNT

The Kiwi reactor series, with nominal power ratings up to 900 MW-thermal, were the first prototypes developed for the ROVER nuclear rocket engine program. The core weighed around 1 tonne (800 kg graphite, 181 kg HEU), and was contained in a pressure vessel but lacked any other shielding or containment. The fuel has been described as "extremely refractory" (coated uranium carbide), as it was designed for normal operating temperatures greater than 2000°C. (This is far higher than the maximum temperature of 1600°C that TRISO fuel, which is used in high-temperature gas-cooled reactors and some microreactors, can withstand without significant degradation.)

On January 12, 1965, a test called Kiwi-TNT was carried out at the Nevada Test Site. A deliberate prompt reactivity insertion was induced by rapidly rotating the beryllium drums that were used for reactivity control to their most reactive position.[8] The purpose of the test was to measure the environmental effects of a nuclear rocket launch accident. (This may have been what occurred at Nyonoksa in Russia in August 2019.) The core was unirradiated, so there was no initial fission product inventory. All fission products were generated during the brief period of supercriticality, during which time 3.1×10^{20} fissions occurred, releasing 9000 MJ (an energy equivalent to 2.2 tonnes of TNT, or a moderately sized vehicle bomb). A violent explosion occurred which vaporized a fraction of the core, caused significant graphite oxidation, burst the pressure vessel, and dispersed core fragments as far as 2,000 feet away. It was later determined to have most resembled the deflagration and detonation of around 300 pounds of black powder (100 to 150 pounds of TNT-equivalent).[9] Thus most of the explosive energy went into vaporization of the core.

It was estimated that 5-20 percent of the "extremely refractory" core vaporized, and 67 percent of the fission products generated were released.[10] Thus, a substantial fraction of the volatile and semi-volatile fission products were released from the portion of the core that was not vaporized. Based on the number of fissions, one can estimate that around 20 megacuries (MCi) of total gross beta activity was present after 5 minutes, decreasing to 1 MCi after 1 hour. The radioactive iodine content of the plume 90 minutes after the transient was estimated to be 540 Ci I-131 and 63 Ci I-133.[11]

Because the point of the test was to study the radiological dispersion of the explosion, there was an extensive monitoring effort both on- and off-site, and the plume was tracked. Based on dosimetry readings, whole-body doses from direct exposure and cloud passage only (that is, excluding groundshine) were measured as

- > 1,000 rad out to about 300 feet (90 meters)
- 1,000 to 100 rad to 750 feet (230 meters)
- > 3 rad to 2,000 feet (600 meters)
- > 1 mrad to 64,000 feet (19.5 km).

The radioactive plume was detected as far away as Los Angeles (> 200 miles).

Although the consequences of this event were significant and wide-ranging, they do not appear to have triggered the 25 rem threshold for "security-related" events beyond a few hundred meters from the reactor. However even a small microreactor (5 MW-thermal) would have a greater fission product inventory than the Kiwi-TNT core after a short period of operation: 9000 MJ of fission energy would accumulate in 30 minutes. Thus the potential fission product release during a rapid reactivity transient at a microreactor could be considerably greater than what occurred during the Kiwi-TNT test.

For example, the NRC heat pipe microreactor study calculated core inventories of 0.125 MCi of I-131, over 200 times the Kiwi-TNT release, and 0.28 MCi of I-133, over 4,000 times the Kiwi-TNT release.[12] By scaling the downwind doses measured from Kiwi-TNT, the thyroid doses to adults from plume passage would be over one hundred times greater, or on the order of one rem at 10 miles downwind at the plume centerline. Corresponding doses to children could be 5-10 times higher, which could well exceed the EPA Protective Action Guide of 5 rem for thyroid exposure to children, warranting potassium iodide prophylaxis as far as 10 miles away. This illustrates that even microreactors may have difficulty qualifying for an exemption from off-site emergency planning requirements if such sabotage source terms are included in the consequence analysis.

Similar analyses could be carried out for whole-body doses, although it would be more complicated, as a much larger group of fission products contribute to whole-body dose.

In this example, the core inventories from at-power operation greatly exceed the fission product inventory generated by additional fission during the transient. However, as discussed above, adversaries with access to the reactor controls may be able to boost the inventory by a significant factor before blowing up the reactor. Although the event analyzed in the NRC microreactor study was in fact a reactivity transient, it did not take into account the additional generation of fission products.

CONCLUSIONS

The NRC rulemakings that would weaken security for advanced reactors are based on unrealistic expectations of their invulnerability to terrorist attacks. Sabotage source terms must include all credible scenarios for core damage, including induced reactivity transients, and should address the potential for boosting core fission product inventory.

Given the uncertainties in new reactor designs and security-initiated event progression, the NRC should suspend these rulemakings pending development of credible sabotage source terms, and continue to require all power reactors to have onsite armed response forces capable of interdicting and neutralizing the DBT adversary, as well as retaining rigorous access authorization and insider mitigation program requirements.

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