From:	Per Peterson
To:	AdvancedRxDCComments Resource
Subject:	[External_Sender] Advanced Non-Light Water Reactor Design Criteria
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Attached please find a letter with my comments on the NRC's draft Advanced Non-Light Water Reactor Design Criteria.

I commend the NRC for its efforts to establish ARDC to guide the design and licensing efforts of Advanced Reactor developers.

Thank you for this opportunity to comment. I will appreciate confirmation that NRC has received my letter.

With best regards,

Per Peterson

UNIVERSITY OF CALIFORNIA, BERKELEY

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COLLEGE OF ENGINEERING
DEPARTMENT OF NUCLEAR ENGINEERING
PER F. PETERSON
TELEPHONE: (510) 643-7749
FAX: (510) 643-9685
EMAIL: peterson@nuc.berkeley.edu

BERKELEY, CALIFORNIA 94720-1730

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Re: ML16096A420 Public Comment Sought - Advanced Non-Light Water Reactor Design Criteria

Thank you for this opportunity to provide comments on the "Advanced Non-Light Water Reactor Design Criteria," ML16096A420. I am Per F. Peterson, a Professor of Nuclear Engineering and Director of the Nuclear Technology Innovation lab at the University of California, Berkeley. The research we perform in the NTI lab contributes to the development of advanced reactor technologies and assessment of their safety.

I endorse the Nuclear Regulatory Commission's effort to modify the existing light-water reactor (LWR) specific General Design Criteria (GDC) to develop Advanced Reactor Design Criteria (ARDC), including modular High Temperature Gas Reactor (mHTGR) and Sodium Fast Reactor (SFR) Design Criteria.

My comments relate to the ARDCs. Examples of advanced reactor technologies that might be licensed under the ARDCs include solid fueled Fluoride salt cooled High temperature Reactors (FHRs), liquid-fueled Molten Salt Reactors, and Lead cooled Fast Reactors (LFRs). We have performed extensive research to develop the scientific and technical basis to design and license FHRs, and in comments here, use the Mark 1 Pebble Bed FHR (Mk1 PB-FHR) as a reference case [1].

I have four primary comments and recommendations for modifications to the ARDCs, described below.

[1] C. Andreades, et al., "Technical Description of the 'Mark 1' Pebble-Bed Fluoride-Salt-Cooled High-Temperature Reactor (PB-FHR) Power Plant," Department of Nuclear Engineering, U.C. Berkeley, Report UCBTH-14-002, 2014.

Comments on ARDC 16, "Containment Design," and related ARDCs 38, 39, 40, 41, 42, 43, 50, 51, 52, 53, 54, 55, 56, 57 [2].

ARDC 16 relates to design criteria for reactor containment structures. As currently written ARDC 16 requires advanced reactors other than SFRs and mHTGRs comply with containment Design Criteria that is appropriate for water cooled reactors, that is, ARDC 16 is "Same as GDC."

I strongly recommend that ARDC 16 and the related ARDCs 38, 39, 40, 41, 42, 43, 50, 51, 52, 53, 54, 55, 56, 57 be modified to state,

> "*Same as GDC,* ***unless the mHTGR-DC or SFR-DC can be demonstrated to be more appropriately applied***."

Fundamentally, the characteristics of the coolants and fuels used in non-water-cooled advanced reactor designs are much more likely to share commonalities with mHTGRs or SFRs, rather than with LWRs. It is important that the ARDC design criteria envision that the most appropriate approach should be selected from among the light water, mHTGR, and SFR design criteria, rather than deterministically requiring all advanced reactors other than mHTGRs and SFRs use LWR criteria. Here I discuss the reasons why this is important.

The central safety issues for containment design involve the potential sources of energy that could pressurize or damage containment structures, and the quantities and physical forms of radioactive materials that could be mobilized during accidents.

LWRs have historically been required to have high-pressure, low leakage containment structures because water is a volatile liquid that can remove substantial amounts of heat when evaporated. LWR emergency core cooling systems are designed to inject abundant quantities of water to provide core cooling, and therefore heat removal from LWRs can generate large quantities of steam under accident conditions. Under the chemical conditions that exist during LWR severe accidents, when overheated and melted LWR fuel releases a substantial fraction of its cesium and iodine in the form of fine aerosol

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[2] E.g. For ARDC 38 "Containment heat removal," ARDC 39 "Inspection of containment heat removal system," ARDC 40 "Testing of containment heat removal system," ARDC 41 "Containment atmosphere cleanup," ARDC 42 "Inspection of containment atmosphere cleanup systems," ARDC 43 "Testing of containment atmosphere cleanup systems," ARDC 50 "Containment design basis," ARDC 51 "Fracture prevention of containment pressure boundary," ARDC 52 "Capability for containment leakage rate testing," ARDC 53 "Provisions for containment testing and inspection," ARDC 54 "Piping systems penetrating containment," ARDC 55 "Reactor coolant pressure boundary penetrating containment," ARDC 56 "Primary containment isolation," and ARDC 57 "Closed system isolation valves."

particles, which can be mobilized and transported by steam. To mitigate severe accident consequences, LWR containments must provide mechanisms to remove heat and fission-product aerosols from the containment, and to minimize leakage of this contaminated steam.

Non-water-cooled advanced reactors have coolants with very different characteristics from LWRs. SFR-DC 16 and mHTGR-DC 16 both correctly recognize and address the differences of sodium and of helium as coolants. For sodium cooled reactors, SFR-DC 16 recognizes that reactions of sodium with air or water, as well as hypothetical reactivity accidents caused by sodium voiding or boiling, could release significant energy inside the reactor containment structure, so SFR-DC 16 correctly requires "a high strength, low leakage, pressure retaining structure surrounding the reactor."

For modular helium cooled reactors, the fuel has very high thermal margins to damage and heat removal during accidents is performed by a reactor cavity cooling system, without the need for coolant to be present in the reactor (depressurized conduction cool down). Under a loss of coolant accident in a mHTGR, overall safety may be increased by allowing the finite volume of helium released to vent from the reactor building to reduce stored energy, and by providing a non-pressure-retaining "reactor functional containment, and associated systems consisting of a structure surrounding the reactor and its cooling system or multiple barriers internal and/or external to the reactor," as required by mHTGR-DC 16.

Most coolants that would be considered for advanced reactors, including FHRs, MSRs, and LFRs, will have characteristics much different from water. For this reason, GDC 16 is unlikely to be appropriate for most advanced reactors, and instead mHTGR-DC 16 or SFR-DC will be most appropriate.

As a specific example, the U.C. Berkeley Mk1 PB-FHR uses the same TRISO-based pebble fuel used in pebble-bed mHTGRs. The Mk1 coolant is flibe ($^{7}Li_2BeF_4$), a low-volatility, chemically stable coolant. Because flibe contains beryllium, the Mk1 reactor building ventilation system is designed to have similar air flow and filtering as would be used in a hot cell facility (the General Electric Vallecitos hot cell facility was used as a point of reference for the design). Because they use of the same type of fuel as mHTGRs, and a chemically stable coolant, the Mk1 PB-FHR and other FHRs may be most appropriately regulated by mHTGR-DC 16 and related DC, rather than the light water GDC 16.

For liquid-fueled MSRs, that use a chemically stable, low-volatility molten salt as a solvent for fuel, the closest analogy for containment safety would be the hot cells used for pyro-reprocessing where substantial inventories of heat generating fission products are dissolved in molten salt, as in the Fuel Conditioning Facility at Idaho National

Laboratory [3]. Hot cells can be considered to be examples of non-pressure-retaining, functional containment structures. Thus MSRs might be most appropriately regulated by mHTGR-DC 16 and related mHTGR-DCs.

The lead coolant of LFRs is chemically inert, reducing maximum pressures possible with air or steam ingress. LFRs may be most appropriately regulated by SFR-DC 16 and related SFR-DCs.

Absent a specific design, it is not possible to say whether GDC 16, mHTGR-DC 16, or SFR-DC 16 would be most appropriate to apply to a non-water-cooled advanced reactor. ARDC 16 and related ARDCs should recognize this fact, and not deterministically require that non-water-cooled reactors meet LWR design criteria when the NRC has determined that the Design Criteria for some non-water-cooled reactors (SFRs and mHTGRs) should be different.

Comments on ARDC 10, "Reactor Design."

ARDC 10 relates to design criteria for reactors, particularly their fuel and core systems.

I recommend that ARDC 10 be modified to state, "*Same as GDC,* ***unless the mHTGR-DC can be demonstrated to be more appropriately applied.***"

The Rationale for mHTGR-DC 10 states,

> "To ensure the SARRDL is not violated during an AOO, a normal operation radionuclide inventory limit must also be established (i.e., appropriate margin). The radionuclide activity circulating within the helium coolant boundary is continuously monitored such that the normal operation limits and SARRDL are not exceeded."

FHRs like the U.C. Berkley Mk1 PB-FHR use similar TRISO fuel as mHTGRs. In FHRs, key fission products that might be released from TRISO fuel during normal operation and AOOs (particularly cesium-137) form soluble fluorides that are retained in the salt coolant. FHRs will monitor this circulating activity, as do mHTGRs, and thus mHTGR DC 10 is more appropriate to apply to FHRs than GDC 10.

When one looks at liquid-fuel MSR designs, where the fuel is circulated through the reactor core and (in many designs) can be drained to tanks that provide effective criticality control and heat removal, the "specified acceptable fuel design limits" of GDC

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[3] A description of the FCF can be found at http://www4vip.inl.gov/research/fuel-conditioning-facility/

10 make less sense than the "specified acceptable fuel core radionuclide release design limits" of mHTGR-DC 10.

Comments on ARDC 17, "Electric Power Supply."

GDC 17 states, "Electric power from the transmission network to the onsite electric distribution system shall be supplied by two physically independent circuits…" The ARDC, SFR-DC, and mHTGR-DC retain this requirement.

I recommend that, in ARDC 17, SFR-DC 17, and mHTGR-DC 17, after the words "two physically independent circuits," a statement such as "***unless the design does not use safety-related AC power so a single off site circuit provides sufficient defense in depth***."

Most (or all) U.S. advanced reactors designs can be expected to implement passive safety systems, and thus to not require any safety-related AC power. In the case of the Westinghouse AP1000, and in its preliminary review of the NuScale plant design, the NRC has concluded that due to their use of passive safety systems these plant designs can be exempted from the requirement for a second, alternate off site power supply.

> "Furthermore, the NRC staff believes that given considerations for defense-in-depth, one offsite power circuit meeting the requirements of GDC 17 should be available." (ML15222A323).

To provide clarity to advanced reactor developers, ARDC 17, SFR-DC 17, and mHTGR-DC 17 should be modified to be consistent with NRC's treatment of LWRs that use passive safety systems and that do not require safety-related AC power supply, and thus to allow a single off-site power supply if appropriate.

Comments on ARDC 34, "Residual heat removal," and ARDC 35, "Emergency Core Cooling."

ARDC 34 and 35 do not clearly describe key design principles for advanced reactor decay heat removal.

When one develops event trees for heat removal following shutdown of reactors, one concludes that one needs at least two independent systems to perform the heat removal function, just as ARDC 26 requires two independent systems for reactivity control. While one of these systems can be non-safety-related, the combination of two independent systems (at least one safety related) is necessary for the probability of complete loss of heat removal to be considered to be a beyond design basis event.

It is highly desirable that at least one of these residual heat removal systems use passive equipment that is (1) located inside the reactors external-event shield structures where it is well protected from external events and unauthorized access, (2) that is designed to function without external sources of power and active heat sink, and (3) that is activated by removing external power, instrument air, and instrumentation and control, as is the typical design for reactor reactivity control systems (where scram is initiated by removing electrical power from drive mechanisms).

This best practice is illustrated in the design of the Passive Core Cooling System in the Westinghouse AP1000, where safe shutdown can be achieved even under station blackout conditions due to the

> "location of passive core cooling systems inside containment and their design to 'fail safe' upon loss of power, loss of Instrumentation and Control (I&C), and loss of instrument air." [4]

The safety and security of nuclear plants can be enhanced and simplified if the primary goal of plant safety systems and operators is to disconnect sources of power to achieve safety shutdown, rather than to connect sources of power. This has long been the major design principal for reactivity control, and is preferable for decay heat removal as well.

But there exists a major design issue for decay heat removal, which is not captured by ARDC 34 and 35. To assure that decay heat removal has sufficient redundancy and diversity, the decay heat removal systems in reactors will always have enough total heat removal capability to make **overcooling** an anticipated operational occurrence, and thus to require the capability to control or shut off decay heat removal systems, and to add supplemental heating for reactors that have coolants that freeze above room temperature.

Whatever methods are used to control overcooling **must be** assessed for their potential to inadvertently (or for physical and cyber security, deliberately) cause overheating. The early damage to fuel at Fukushima Daiichi Unit 1 was caused by operator actions to isolate the reactor's isolation condenser to control overcooling, and the operator's inability to reopen the AC-powered valve inside containment after the tsunami struck.

I recommend that ARDC 34 and 35 be modified to require that all advanced reactors have at least two independent systems to remove residual heat, at least one of which should be safety related. I also recommend that at least one of these systems be designed so it does not require external power to function, uses passive equipment which is effectively protected from external events and has long delay times for unauthorized

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[4] I.B. Ezelarab and T.A. Kindred, "AP1000® Beyond Design Basis Mitigating Strategies," Proceedings of the 2016 International Congress on Advances in Nuclear Power Plants, ICAPP 2016, San Francisco, CA, April 17-20, 2016.

access, and is activated by disconnecting external sources of power, instrument air, and/or instrumentation and control. Finally, I recommend that methods used to control overcooling be considered early in the design process, and that the risk of inadvertent operation be considered in design and in the development of probabilistic risk assessment models.

Summary

In summary, I commend the Nuclear Regulatory Commission and the Department of Energy for their proactive effort to create guidance for advanced reactor developers, to reduce uncertainty for how license applications for innovative reactor designs will be evaluated. This important exercise proves that anticipatory research and development of regulatory guidance can be effective in reducing first-mover barriers. I am confident that the value of this work will become apparent when the NRC begins its first pre-application interactions with companies bringing new designs for review under the new ARDC, mHTGR-DC, and SFR-DC.

Sincerely yours,

Per F. Peterson
Nuclear Technology Innovation lab
William and Jean McCallum Floyd
Endowed Chair
Professor of Nuclear Engineering