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UNITED STATES
NUCLEAR REGULATORY COMMISSION
ADVISORY COMMITTEE ON REACTOR SAFEGUARDS
WASHINGTON, D.C. 20555-0001

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MEMORANDUM TO: Apostolakis, Bonaca, Kress, Duraiswamy, Larkins, Lyons, Savio, Sorensen

MEMORANDUM #: AWC-102.2001

FROM: A. W. Cronenberg

SUBJECT: Work Scope: Reductions in Safety Margins for Re-Licensed Plants with Additional Separate Actions

Summary: This memo outlines a scope of effort related to the ACRS desire to explore potential "Reductions in Safety Margins" for aged plants, operated at ever higher power, longer fuel duty times, higher fuel burnups, reduced inspections, etc. The ACRS is specifically concerned that the agency has not investigated, to any great degree, the combined/synergistic impact of such separate licensing actions, as industry aggressively moves toward the goal of maximizing power generation and investment recovery from an aged population of nuclear power plants. This proposal is formulated as a ACRS Fellow project, to investigate this concern.

The primary goal of this investigation is to quantify, in some manner, potential reductions in safety margins stemming from individual licensing actions, such as license renewal, power uprate, burnup extension individually, and the total impact on safety margin due to the sum effect of such actions (synergistic impact on margins). It is anticipated that the end products will be a full-length Fellow Report on the subject, which is intended to support a White Paper or Letter to The Commission. Additionally, findings may be reported in the form of proceedings of a technical conference.

This memo briefly discusses the following:

A) Outlines the types of algorithms which might be developed to quantify safety margin reductions for separate actions, and the combined/synergistic impact on margin reduction

B) Estimation of the ACRS Fellow effort involved (FTE effort); 4-6 FTE man-months

Work Scope & Approach:

The goal of this investigation is to quantify, in a simplified manner, potential reductions in safety margins stemming from individual licensing actions, such as license renewal, power uprate, burnup extension individually, and the total impact on overall plant safety margin due to the sum effect of such actions (synergistic impact on margins). The study is not intended to be a full-scope investigation of the problem, rather it is intended to illustrative of how trends might be assessed from a limited investigation of some key elements impacting safety. The study will focus on safety margin reductions as dictated from deterministic considerations (e.g. pressure vessel design margin= rupture pressure - allowable pressure; Zry cladding ductility margin = Brittle ZrO_2 - 17% oxidation limit; etc) say for say power uprates and plant life extension, as well as margin reductions due to changes in Tech. Specs. and changes in operational conditions associated with such uprates or extensions. Results from prior PSA studies (e.g. NUREG-1150) will be employed to translate margin reductions into changes in CDF, LERF, QHO or some other matrix for safety implications. A few simple examples are given here, to illustrate how one might quantify the impact of a specific licensing action or design change on safety related margin(s).

As an example we cite the paper by Khatib-Rahbar [1], "*Risk-Impact of Reactor Power Upgrade for a BWR....*", where a reduction in safety margin was assessed based on an estimation of the reduced operator response time to a core uncovery event associated with a power uprate. It is of particular note that the algorithm they used to estimate margin reduction was quite simple, nevertheless it illustrates the point that some decrease in safety margin can be expected. They assumed that an increase in reactor power level would impact safety margin by an increase in the decay heat load and thus a reduction in time to core uncovery for a severe accident, assuming all other factors equal (same core coolant inventory, same decay heat removal capacity, etc. as with prior lower power level). Making use of the simple algorithm that the decay power and time to core uncovery (t_{uc}) is inversely proportional to core operating power (Q) to the 1.43 power, a reduction in time for uncovery (and thus time for operator remedial action) was estimated for the 15-% power increase proposed for the Swiss Leibstadt-BWR plant:

$$(t_{uc}) = \quad (1/Q)^{1.43} = (1/1.15 = 0.87)^{1.43} = 0.81$$

or a core uncovery time which was 19-% less for the 15-% power increase. From PSA models they deduced a corresponding increase the CDF by about 30-% for this reduction in uncovery time. They also note a similar power-dependence can be shown for containment failure time (due to containment over-pressurization) and thereby the time of fission product release to the environment.

One might also attempt to estimate the impact burnup increase on margins via an increase in fission product inventory and therefore source term estimates. Table A presents ORIGIN predictions [2] of after-heat power (i.e. decay power), which is a measure of fission product inventory. Two burnup conditions are shown, 33 GWD/t and 55 GWD/t, for similar initial enrichment (3.3-% U235) and irradiation history. Predictions are given for the decay power for both light elements and actinide decay products, as well as their sum. The salient point is that the decay power, and thus fission product inventory, is clearly higher for the 55 GWD/t case than for 33 GWD/t, which would manifest as a higher TIDE (Total Integrated Dose Equivalent) for site exclusion boundary calculations, or for that matter public exposure estimates. For comparison purposes we can see that for a 10 day cool-off period the 33 GWD/t case yields a decay value of about 0.619 E+4 (W/MT) versus 1.018 E+4 for the 55 GWD/t burnup case; thus a 64-% increase in decay power (or approximate fission product inventory) for a 67-% increase in burnup. Clearly there is an almost direct proportionality of an increase in decay heat and fission product inventory with burnup, which can be correlated to an increase in site worker or public exposure risk, all other factors being equal.

Table A: ORIGIN Predictions of Decay Power [2]

Cooling	3.3% ^{235}U, 33 GWD/MTU			3.3% ^{235}U, 55 GWD/MTU		
	Afterheat Power (W/MTU)			Afterheat Power (W/MTU)		
Time	Light Element	Actinide	Sum	Light Element	Actinide	Sum
10d	5.8755(+2)	5.6055(+3)	6.1931(+3)	7.4920(+2)	9.4328(+3)	1.0182(+4)
30d	5.1581(+2)	1.8079(+3)	2.3237(+3)	6.6379(+2)	4.9161(+3)	5.5799(+3)
60d	4.3205(+2)	1.5297(+3)	1.9618(+3)	5.6381(+2)	4.3434(+3)	4.9072(+3)
90d	3.6540(+2)	1.3711(+3)	1.7365(+3)	4.8433(+2)	3.9413(+3)	4.4256(+3)
120d	3.1252(+2)	1.2351(+3)	1.5476(+3)	4.2129(+2)	3.5913(+3)	4.0126(+3)
180d	2.3919(+2)	1.0105(+3)	1.2497(+3)	3.3374(+2)	3.0120(+3)	3.3457(+3)
365d	1.5390(+2)	5.9003(+2)	7.4393(+2)	2.3006(+2)	1.9226(+3)	2.1527(+3)
730d	1.2126(+2)	3.1492(+2)	4.3618(+2)	1.8547(+2)	1.1932(+3)	1.3787(+3)
1825d	7.9164(+1)	2.4980(+2)	3.2896(+2)	1.2164(+2)	9.5697(+2)	1.0786(+3)
10y	4.0343(+1)	2.6046(+2)	3.0080(+2)	6.2082(+1)	8.8603(+2)	9.4811(+2)

The impact of higher fuel burnup on safety margin might also be manifested via degradation of cladding mechanical properties due to the longer fuel duty time associated with extended burnups. For example let us assume a threshold dependence on Zircaloy cladding failure with burnup level, as implied from several in-pile test results [3,4] for Design Basis Reactivity Insertion Accidents (RIA). Such tests indicate RIA associated Zircaloy cladding failures due to loss of ductility via oxidation (Zr-Ox) and attendant hydrogen uptake. For illustrative purposes let us assume a threshold dependence, say at 40 GWD/t, with the following algorithm:

$$\text{Zr-Ox} = \{1 - [\text{X-Burnup}/40\ \text{GWD}]^{0.3}\}$$

Let us compare predictions at 50 GWD/t and 62 GWD/t (present NRC burnup limit) and compare them to the NRC allowable oxidation limits for Design Basis conditions (i.e. 17-% oxidation limit):

$$\text{Zr-Ox} = \{ 1 - [50/40 = 1.25]^{0.3} \} = 7\text{-\% oxidation}$$

$$\text{Zr-Ox} = \{ 1 - [62/40 = 1.55]^{0.3} \} = 14\text{-\% oxidation}$$

Although neither burnup violates the regulatory oxidation limit of 17-%, one might reasonably ascribe an increase in Zircaloy oxidation with an attendant loss of cladding ductility (let us say for example a linear dependence), which could translate to some increase in clad failure potential and thus a reduced safety margin.

Although such simple examples are used here for demonstrative purposes only; they nevertheless indicate the type of approaches that might be used to **Quantify**, in some manner, the impact of a specific licensing action (power uprate, fuel burnup increase, etc.) on safety margins. Simple statistical models might then be employed to estimate the synergistic (compound) effect of several licensing actions (i.e. power uprate + burnup increase + plant life extension).

In addition to the above approaches, Cronenberg [5] also presents examples, from a review of operational events (i.e. License Event Reports-LERs) for power uprated plants, of potential synergistic safety implications of uprates in conjunction with fuel life extensions to higher burnup and plant aging phenomena. Examples cited in that study include control rod insertion problems in high-burnup assemblies noted at the uprated Wolf Creek plant , as well as a feedwater pipe failure event via corrosion/erosion (aging) effect at the uprated Callaway-PWR plant. Also noted in that study was the vibrational fatigue failure in a re-circulation line at the uprated Susquehanna-BWR plant, where such failure was ascribed to the increased core flow rates associated with uprate. Operational experience can thus likewise serve as an indicator of increased event frequencies for plants having been approved for multiple actions (uprated power, higher burnup/longer fuel cycle, plant life extension, etc).

An examination of diminished margins between plant Administrative Limits and NRC imposed for Safety Limits also has bearing on implications for reduced safety margins. As discussed in a recent INPO report [6], continuing industry initiatives for plant optimization has almost universally resulted in a continuing trend of a reduction in available operating margin. In some cases Operational Events (LERs) occurred as a result of such initiatives. For example the Minimum Critical Power Ratio (MCPR) for BWRs is a safety (thermal) limit for BWRs and defined as the ratio of the calculated power for boiling transition divided by the actual fuel assembly operating power. It is common practice for BWRs to express the MCPR operating limit as a value of One and maintain an administrative limit less than 1. Figure A is an example of variations in the minimum critical power ratio for the Peach Bottom-2 plant over several fuel cycles. As shown the margin to the operating limit varies over the three fuel cycles due to a number of reasons. Some changes, such as core monitoring improvements and improved fuel designs actually increase the margin to the operating limit. However, other changes result in a reduced margin. Of particular note is the considerably higher MCPR for Cycle-11, which reflects the higher uprated thermal power approved for that fuel cycle at Peach Bottom-2, which also included fuel assemblies operated to higher burnups. The cumulative effect was a reduced MCPR margin, where the closer proximity to the operating limit caused greater difficulty for operators to remain within thermal limits during reactor maneuvering transients.

Another example of reduced margins from the INPO report concerns the Nuclear Enthalpy Rise Hot Channel Factor (HCF) for PWRs, which is defined as the ratio of the maximum enthalpy increase in the hot channel to the average enthalpy increase per channel. This is a thermal limit specified as part of the plant safety analyses for PWRs. Figure B illustrates the design HCF for Comanche Peak-1 and shows how operation closer to this limit (decrease in margin) occurred with the use of a higher-enrichment/higher-burnup core reloads used in later fuel cycles.

One other example includes an observation noted at the Limerick-BWR plants (units 1 and 2) where maximum thermal power limit (planer/across-the-core average) was exceeded during a startup with new extended life fuel (two-year cycle fuel), which necessitated changes to control rod withdrawal strategies. With past core reloads there had been minimal concern with the impact of certain control rod withdrawal sequences on the thermal limits. However, the same control rod banking sequence that was used for the longer duty fuel was not appropriate, and the reactor operators were unaware that closer proximity to the core thermal design limit would be reached. These reductions in operational margins and associated operational events (some of which fall under NRC requirements for event reporting as License Event Reports-LERs) also point to reductions in margins for various plant changes associated with industry efforts at nuclear plant optimization. Events related to reduced operating margins would likewise be investigated in the proposed study.

Such examples indicate how one might estimate, albeit in a crude manner, the impact of multiple changes in plant operational conditions on safety margins. It is anticipated that the end product of this investigation will be a Full Length Report and White Paper, which will focus on estimates of margin impact from several algorithms that can be reasonably justified. The intent will be to demonstrate trends from simple models rather than a full-scope study of the problem.

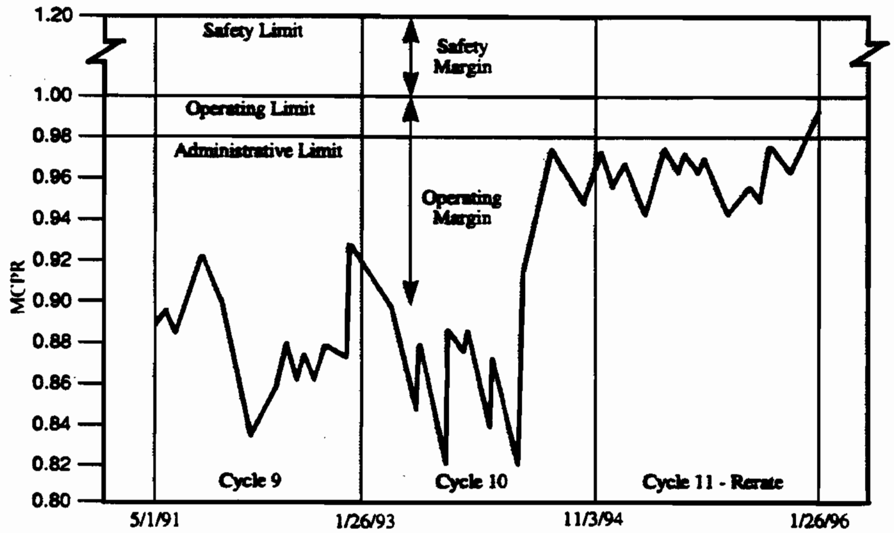

Figure A. Minimum Critical Power Ratio (MCPR) for Peach Bottom-2 (see INPO Report, Ref. 6).

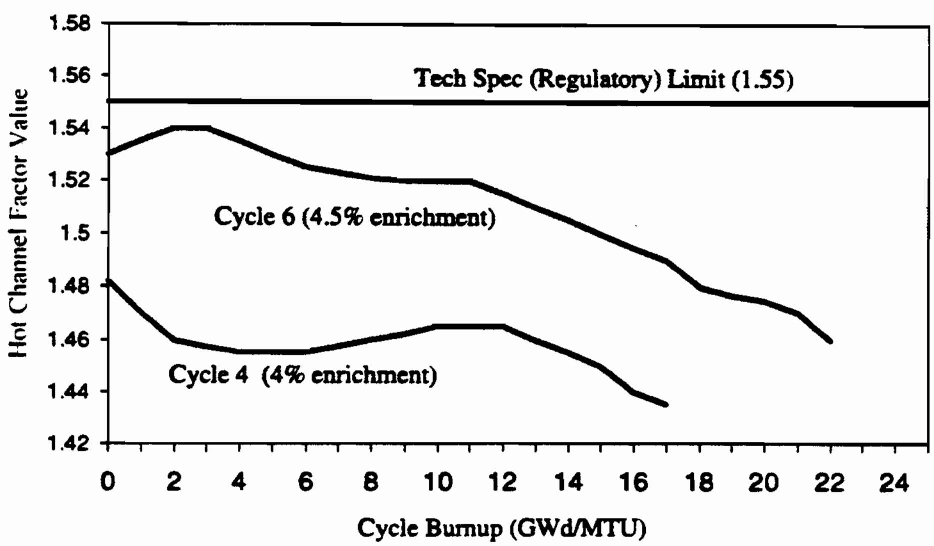

Figure B. Enthalpy Hot Channel Factor (HCF) for Comanche Peak-1 (see INPO Report, Ref. 6).

Estimate of Man-month Effort:

Based on an end-product of a Final Report of say 50-70 pages and a Conference White Paper, an FTE (Full Time Equivalent) 4 to 6 man-months is estimated. This estimate is based on prior Fellow projects of a similar nature summarized below (FTE estimate based on Table of Efforts documented in Fellow Quarterly Reports):

Project Description	FTE Man-months
Review of Spent Fuel Pool Heatup & Source term Issues for Shutdown Plants (Report)	4.5 man-months
Potential Synergistic Safety Issues for Power Uprates (Report, ANS Abstract)	5-6 man-months
Evaluation of Generic Safety Issues Program from Review of Licensee Operational Events Data (Report, ANS Abstract, Conf. Paper)	6 man-months
Multiple System Responses and Interaction: Treatment in IPEs/IPEEEs (Report, Conf. Paper)	6 man-months

The minimum effort of 4 FTE man-months assumes no additional Fellow commitments and minimal attendance at ACRS full and subcommittee meetings. The 6 FTE man-month effort assumes normal Fellow participation with ACRS staff and members.

References:

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2. J. C. Ryman, et al, *Fuel Inventory and Afterheat Power Studies of Uranium-Fueled PWR Fuel Assemblies Using SAS2 and ORIGIN-S",* NUREG/CR-2397, Oak Ridge Nat. Laboratory, (19824).
3. R. Meyer, *Summary of High Burnup Fuel Issuews and NRC's Plan of Action,* Proc. 24th Water Reactor Safety Mtg., NUREG/CP-0157, (1996).
4. F. Schmitz, C. Gonnier, and J. Papin, *Status of the CABRI Test Program: Recent Results and Future Activities,* Proc. 24th Water Reactor Safety Mtg., NUREG/CP-0157, (1996).
5. A. W. Cronenberg, *Potential Synergistic Safety Issues Related to Reactor Power Uprates,* Proc. Am. Nucl. Soc., San Diego, Ca (June 2000).
6. Institute of Nuclear Power Operations (INPO), *Design and Operating Considerations fro Reactor Cores,* INPO Significant Operating Experience Report, SOER: 96-2, (Nov.1996).