The Safety Goals of the U.S. Nuclear Regulatory Commission

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In August 1986, after 6 years of effort, the U.S. Nuclear Regulatory Commission adopted a Policy Statement on safety goals for nuclear power reactors. The commission's qualitative goals state that (i) individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that they bear no significant additional risk to life and health, and (ii) societal risks to life and health from nuclear power should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks. The commission's safety goal Policy Statement also includes quantitative design objectives.

THE SAFETY PHILOSOPHY ESPOUSED BY THE U.S. NUCLEAR Regulatory Commission (NRC), and the U.S. Atomic Energy Commission (AEC) before it, has often been called "defense-in-depth." In judging that there was a reasonable assurance that a plant could be operated without undue risk to the public, the NRC did not directly address the question "How safe is safe enough?" for light water reactors (LWRs), nor did it quantify the residual risk that was implicitly being accepted. In fact, until the *Reactor Safety Study* was completed (*1*), a methodology did not exist with which to assess LWR safety in a quantitative fashion.

As early as 1967, Farmer suggested a quantitative safety criterion for nuclear reactors that related the acceptable accident occurrence rate to the associated release of radioactive material (*2*). Several more suggestions for safety goals were made during the 1970s [for example (*3–5*)]. A 1973 AEC report suggested that a frequency greater than 10^{-6} per reactor year for severe accidents that result in individual doses exceeding 25 roentgen-equivalent-man (rem) (about one-tenth of the threshold dose for early fatality) would be unacceptable (*3*).

For several years after the publication of the *Reactor Safety Study*, a controversial document, probabilistic risk assessment (PRA) remained primarily a research topic, little used by the regulatory part of the NRC staff. Shortly after the accident at Three Mile Island, Pennsylvania, in 1979, however, the NRC's Advisory Committee on Reactor Safeguards (ACRS) recommended that consideration be given to the establishment of quantitative safety goals for nuclear power reactors (*6*). The President's Commission on the Accident at Three Mile Island (*7*) and the NRC's Special Inquiry Group (*8*) both recommended that safety objectives and philosophy be better articulated and thoroughly aired before the public. In its response to the recommendations of the President's commission, the NRC stated that it was "prepared to move forward with an explicit policy statement on safety philosophy and the role of safety-cost tradeoffs in the NRC safety decisions" (*9*, p. 7023). However, the task of developing quantitative safety goals was just beginning.

The ACRS Preliminary Proposal

In the fall of 1979, the ACRS was asked by the NRC to develop an approach to quantitative safety goals. In October 1980 the ACRS proposed a trial approach, which was intended to serve as a focus of discussion and, as such, was expected to be only a first step in an iterative process (*10*).

The ACRS trial approach to risk management was a set of quantitative design objectives that were intended to reflect the following partially overlapping qualitative goals (*10–12*):

1) Future nuclear power plants should, if practical, present less risk to society than that from the principal competitor, coal-fired power plants.

2) The risk arising from the presence of one or more LWRs at a particular site to those individuals at greatest risk (that is, those living or working close to the reactor site) should be small enough that (i) it does not significantly increase their risk of death from accidents or cancer and (ii) questions of equity are addressed (that is, any imbalance between the increment of individual risk and direct benefit should be small enough that a conscious effort to balance the disparity is not required).

3) The safety-related design should be required to place emphasis both on the prevention of accidents that could lead to severe core damage or large-scale core melt and on the mitigation of accidents involving large-scale fuel melt. The probability of such an accident should be very low, and there should be a very low probability that an individual living near the plant would be killed, even if a large-scale core melt accident did occur.

4) Suitable additional design efforts should be made to reduce the risk below specified safety goals, with an as-low-as-reasonably-achievable (ALARA) cost-effectiveness criterion.

5) All LWR accident sources should be considered in evaluating the risks, and the safety goals should be compared against mean values with a prudent allowance for the presence of large uncertainties.

6) Incentives should be provided to reduce still further the likelihood of accidents involving large numbers of casualties, without unduly penalizing the technology or placing excessive costs on society.

Although the ACRS report discussed the loss of societal or regional resources, for example, an important aquifer or rich farmland, as a potentially important yardstick, no goals were proposed in this regard.

The proposed ACRS design objectives were as follows (*10*):

1) Limits should be placed on the frequency of occurrence of certain hazardous conditions ("hazard states") within the reactor.

2) Limits should be placed on the risk to an individual of early death or delayed death from cancer as a result of an accident.

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3) Limits should be placed on overall societal risk of early and delayed death.

4) An ALARA approach with a cost-effectiveness criterion that includes economic costs and places a dollar value on the prevention of a statistical, premature death should be used.

5) A small element of risk aversion applied to infrequent accidents involving large numbers of early deaths compared to a similar number of deaths caused by many accidents involving one or two deaths, that is, infrequent high-fatality accidents should be given more weight (*13*).

The quantitative design objectives are summarized in part in Tables 1 and 2. They were intended to be applicable to new reactors, not yet designed. The ACRS acknowledged that for existing plants, modifications in the quantitative limits would be appropriate.

Although plausibility arguments were given for some of the proposed numerical risk limits, the ACRS acknowledged that the values were primarily a matter of judgment and suggested that the NRC and the Congress must consider a wide range of political and economic factors, of which direct risk to the public health and safety is but one, in arriving at a judgment of levels of acceptable risk (*10*).

The ACRS was conscious of the large uncertainties inherent in risk assessment. Among other things, it pointed to the difficulties that would arise because of differing opinions among experts on risk, as well as the subjectivity of much of the PRA results. Thus, the ACRS expected that progress toward adoption and use of quantitative safety goals would be slow. It suggested that a special science court might be needed to make the ultimate technical decision if the meeting of safety goals became part of the licensing process.

The Atomic Industrial Forum Proposal

In May 1981 the Atomic Industrial Forum (AIF) proposed a framework for establishing and using quantitative safety goals to rationalize the regulatory process (*14*). Probabilistic risk assessments would be used as a basis for establishing the NRC's deterministic requirements for nuclear plants generically and would not be used as licensing conditions for individual plants, except when indicated by screening assessments for particular plants. Methods of PRA would be used to justify departures from deterministic requirements.

The proposal contains primary goals that place limits on individual and aggregated population mortality risk. Its secondary goals focus on the probability of large-scale fuel melt and on the cost-effectiveness of reducing population radiation exposures due to accidents. The AIF goals are summarized in Table 3.

The limit on societal risk was intended to make the risk from a large reactor less than or comparable to a small fraction of the normal background incidence of health effects. The cost-effectiveness criterion attempts to make the effectiveness of risk reduction at nuclear power plants roughly equivalent to that for other areas of public risk reduction. The fuel melt criterion was chosen to make the occurrence of a large reactor accident in the United States less than one per several decades.

Table 1. ACRS trial limits on occurrence of hazard states. Abbreviation: LSFM, large-scale fuel melt. [Adapted from (*12*), table 1, p. 185]

Hazard state	Goal level	Upper nonacceptance limit
Significant core damage*	$<3 \times 10^{-4}$ per reactor year	$<1 \times 10^{-3}$ per reactor year
LSFM†	$<1 \times 10^{-4}$ per reactor year	$<5 \times 10^{-5}$ per reactor year
Large-scale uncontrolled release‡	<0.01 per LSFM	<0.1 per LSFM

*More than 10% of noble gas inventory leaking into primary coolant. †More than 30% of oxide fuel becoming molten. ‡More than 10% of iodine inventory and 90% of noble gas released.

Table 2. ACRS trial limits on risks to most exposed individual. Abbreviation: LSFM, large-scale fuel melt. [Adapted from (*12*), table 2, p. 185]

Threat	Goal level	Nonacceptance limit
Overall risk		
Early death	$<1 \times 10^{-6}$ per site year	$<5 \times 10^{-6}$ per site year
Cancer death	$<5 \times 10^{-6}$ per site year	$<25 \times 10^{-5}$ per site year
Risk given LSFM		
Early death	<0.002 per LSFM	<0.01 per LSFM
Cancer death	<0.01 per LSFM	<0.05 per LSFM

Table 3. AIF proposed quantitative safety goals. Abbreviation: MWe, megawatt (electric). [Adapted from (*12*), table 4, p. 186]

Primary goals		Secondary goals	
Individual risk	Population risk	Cost-effectiveness criterion	Large-scale fuel melt
$<10^{-5}$ per year mortality risk	<1 fatality per year per 1000 MWe	$100 per man-rem	$<10^{-4}$ per reactor year

The AIF proposal leaves out any specific requirement for the effectiveness of accident-mitigation features, that is, the conditional ACRS requirements in Tables 1 and 2. This represents a major difference in philosophy between the AIF and ACRS trial proposals. Both proposals include an ALARA criterion, but the AIF proposal only uses a reduction in integrated man-rem exposure in assessing benefits and proposes the ALARA be used only in the evaluation of backfitting (that is, the requirement for additional safety measures in a plant that had already received a construction permit or operating license). The AIF proposal does not include any risk aversion to large accidents. Finally, the ACRS proposal requires that a specific risk analysis be made and maintained for each plant, whereas the AIF would depend primarily on generic or surrogate risk analyses.

NRC Proposal on Safety Goals

At the request of the NRC commissioners, the NRC staff worked on development of a formal policy on safety goals. Workshops were held during April and July 1981, and in February 1982 the commission issued for public comment a Policy Statement on safety goals for nuclear power plants (*9*).

The commission proposed to adopt two qualitative goals supported by provisional numerical guidelines. The qualitative goals were as follows:

1) Individual members of the public should be provided a level of protection from the consequences of nuclear power plant accidents such that no individual bears a significant additional risk to life and health.

2) Societal risks to life and health from nuclear power plant accidents should be as low as reasonably achievable and should be comparable to or less than the risks of generating electricity by viable competing technologies.

The commission then proposed several provisional numerical guidelines.

Individual and societal mortality risks. The risk to an individual or to the population in the vicinity of a nuclear power plant site of prompt fatalities that might result from reactor accidents should not exceed 0.1% of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed.

The risk to an individual or to the population in the area near a nuclear power plant site of cancer fatalities that might result from reactor accidents should not exceed 0.1% of the sum of cancer fatality risks resulting from all other causes.

In applying the numerical guideline for cancer fatalities as a population guideline, the commission proposed that the population considered subject to a significant risk be taken as the population within 50 miles of the plant site. Although this was identified as a societal risk guideline, it actually represented a guideline risk of cancer to an individual, averaged over people living a great distance from the plant. The risk of cancer to individuals living near the plant site boundary is 25 to 50 times as great as this average. This guideline permits greater societal risk for plants having larger surrounding population densities. Essentially all PRAs performed to date have found that the prompt fatality goal is the controlling factor on plant risk.

Cost-benefit guideline. The commission proposed a cost-benefit guideline for use in decisions on safety improvements that would reduce individual and societal risks below the levels specified in the first and second numerical guidelines in accordance with the ALARA principle.

The benefit of an incremental reduction of risk below the numerical guidelines for societal mortality risks should be compared with the associated costs on the basis of $1000 per man-rem of exposure averted.

If one assumes one or two fatal cancers per exposure to 10,000 man-rem, this guideline appears to place a value on averting a premature death of $5 million to $10 million. However, economic costs, particularly on-site costs, are not included in the cost-benefit guideline.

Plant performance guideline for large-scale core melt. The likelihood of a nuclear reactor accident that results in a large-scale core melt should normally be less than one in 10,000 per year of reactor operation.

All accident sources except for sabotage were to be identified in the quantitative calculations. The commission stated its intent that the goals and guidelines be used by the NRC staff in conjunction with PRAs and that these goals would not substitute for the NRC's reactor regulations. Rather, individual licensing decisions would continue to be based principally on compliance with the commission's regulations.

The proposed numerical cost-benefit guideline could be used during a trial period as one consideration in deciding whether corrective measures or safety improvements should be made in plants previously approved for construction or operation.

NRC Policy Statement on Safety Goals—1983

After receiving comments from the ACRS, the industry, and the public, the commission adopted on 14 March 1983 a safety Policy Statement for use during a 2-year evaluation period (*15*). Also adopted was a staff implementation plan for evaluation of the quantitative guidance over the 2-year period. The 1983 Policy Statement reflected more the recommendations of industry than those of the ACRS.

Qualitative goals. The two qualitative safety goals were changed in only one significant way. The second goal now omitted the statement that risks "should be as-low-as-reasonably-achievable."

Quantitative design objectives (QDOs). The previous "provisional numerical guidelines" were now termed "quantitative design objectives." The principal change from 1982 was in the cost-benefit guideline, which was now restricted to decisions about whether to backfit plants that did not meet the safety goals, but not to measure possible safety improvements if the safety goals were met.

Implementation. The commission said that the basic impediment to the adoption of regulations that require risks to the public be below certain quantitative limits, as exemplified by the quantitative design objective for large-scale core melt, is that the techniques for developing quantitative risk estimates are complex and have substantial associated uncertainties. Thus a serious question was whether, for a specific nuclear power plant, the achievement of a regulatory-imposed quantitative risk goal could be verified with a sufficient degree of confidence. For this reason, the commission decided that, during the evaluation period, implementation of the Policy Statement should be limited to such uses as examining proposed and existing regulatory requirements, establishing research priorities, resolving generic issues, and defining the relative importance of issues as they arose.

The safety goals were not to be used in the licensing process or to be interpreted as requiring the performance of PRAs by applicants or licensees.

Evaluation of Safety Goal Policy

As part of the 2-year evaluation of the safety goal Policy Statement of 14 March 1983, a retrospective comparison of selected generic regulatory actions to the 1983 safety goals was made (*16*). The decisions taken were in general consistent with the decisions that would be suggested by the safety goals. However, Riggs and Sege (*16*) noted that this judgment is contingent on how the safety goals are applied, how the quantitative uncertainties are viewed, and how relevant factors outside the safety goals are applied.

A task force of relatively senior NRC staff members was established to review the safety goals themselves, and they made several recommendations for significant changes, including the following (*17*):

1) The quantitative design objective concerning the societal health risk of cancer should be averaged over the population within a 10-mile radius of the site, rather than the 50-mile radius chosen in the 1983 goals. This change would make the objective more restrictive since risk of cancer decreases with the distance from the plant.

2) The core melt criterion should receive key consideration in the regulatory implementation of the safety goals.

3) For core melt accidents, the averted on-site radiological and economic costs should be considered a benefit in the cost-benefit guideline.

In large part, the recommendations for upgrading the status of the core melt frequency QDO and for including averted on-site economic costs arose from two factors: (i) About 20 PRAs of varying quality and comprehensiveness had been performed for specific reactors by early 1985. A sizable fraction yielded core melt frequencies considerably larger than 10^{-4} reactor year. (ii) When consequence calculations were performed in these PRAs, they usually met the quantitative health and safety QDOs. The statistical prediction of total (societal) man-rem exposure was relatively small, and only changes in operations or new design features having very modest costs would yield cost-benefit ratios smaller than one, with $1000 per man-rem-averted as the only benefit. This factor made it difficult to accomplish reductions in overall core melt frequency.

Furthermore, the commission was in the process of adopting a new rule on backfitting that placed primary responsibility on the

NRC staff for justifying any proposed safety improvements made by using cost-benefit analysis (*18*).

The recommendation of the task force with regard to the inclusion of averted on-site costs in cost-benefit calculations (or steps equivalent in their effect) was followed by strong suggestions by two top-level office directors in favor of reducing the core melt frequency to 10^{-4} or less per reactor year (*19, 20*). The ACRS did not give support to any specific formula for cost-benefit calculations. Rather, in July 1985 the ACRS stated, "We believe that the Commission should state that a mean core melt frequency of not more than 10^{-4} per reactor year is an NRC objective for all but a few, small, existing nuclear power plants, and that, keeping in mind the considerable uncertainties, prudence and judgment will tend to take priority over benefit-cost analysis in working toward this goal" (*21*, p. 2). The ACRS also continued to press for a containment performance criterion and stated that "the Policy Statement may not give sufficient emphasis to defense-in-depth and may place too much emphasis on benefit-cost analysis."

In April 1986 the ACRS recommended a new guideline "that the chance of a very large release of radioactive materials to the environment should be less than 10^{-6} per reactor year" (*22*, p. 2). Within the commission itself, Commissioners Fred Bernthal and James Asselstine had been working toward a policy that held that the chance of a core melt accident should be very low during the lifetime of existing U.S. reactors and the chance of a large release should be still more remote.

The accident occurred at Chernobyl Nuclear Unit No. 4 on 26 April 1986. This accident may have influenced the commissioners to adopt a more conservative stance on safety goals.

NRC Final Policy Statement on Safety Goals—1986

On 4 August 1986, the NRC published a final Policy Statement on safety goals. Agreement on the statement was reached under the aegis of retiring Chairman Nunzio Palladino in late June, but the statement was signed by Lando W. Zech, Jr., the new chairman. Commissioners Asselstine, Bernthal, and Thomas Roberts concurred, but the first two voiced additional views (*23*).

The commission determined that the qualitative safety goals would remain unchanged from its March 1983 revised policy statement. Thus, the commission's two safety goals are (i) Individual members of the public should be provided a level of protection from the consequences of nuclear power plant operation such that individuals bear no significant additional risk to life and health. (ii) Societal risks to life and health from nuclear power plant operation should be comparable to or less than the risks of generating electricity by viable competing technologies and should not be a significant addition to other societal risks.

The safety goal Policy Statement also said the following (*23*, p. 28045):

> Severe core damage accidents can lead to more serious accidents with the potential for life-threatening offsite release of radiation, for evacuation of members of the public, and for contamination of public property. Apart from their health and safety consequences, severe core damage accidents can erode public confidence in the safety of nuclear power and can lead to further instability and unpredictability for the industry. In order to avoid these adverse consequences, the Commission intends to continue to pursue a regulatory program that has as its objective providing reasonable assurance, while giving appropriate consideration to the uncertainties involved, that a severe core damage accident will not occur at a U.S. nuclear power plant.

This statement represented a major change from the 1982–83 draft Policy Statements. Furthermore, of the previous QDOs, the commission retained only the two which quantified early and latent cancer mortality risks, that is, that these risks should not exceed 0.1% of the normal background accident or cancer mortality risk. The cancer risk was to be averaged over the population within a 10-mile radius of the plant, as recommended by the NRC staff task force. The quantitative objective on core melt frequency and the quantitative cost-benefit criterion were omitted from the Policy Statement.

Guidelines for Regulatory Implementation

Regarding the regulatory implementation, the commission stated the following (*23*, p. 28047):

> The Commission approves use of the qualitative safety goals, including use of the quantitative health effects objectives in the regulatory decision-making process. The Commission recognizes that the safety goals can provide a useful tool by which the adequacy of regulations or regulatory decisions regarding changes to the regulations can be judged. Likewise, the safety goals could be of benefit in the much more difficult task of assessing whether existing plants, designed, constructed, and operated to comply with past and current regulations, conform adequately with the intent of the safety goal policy.
>
> However, in order to do this, the staff will require specific guidelines to use as a basis for determining whether a level of safety ascribed to a plant is consistent with the safety goal policy. As a separate matter, the Commission intends to review and approve guidance to the staff regarding such determinations. It is currently envisioned that this guidance would address matters such as plant performance guidelines, indicators for operational performance, and guidelines for conduct of cost-benefit analyses. This guidance would be derived from additional studies conducted by the staff and result in recommendations to the Commission. The guidance would be based on the following general performance guideline which is proposed by the Commission for further staff examination.
>
> Consistent with the traditional defense-in-depth approach and the accident mitigation philosophy requiring reliable performance of containment systems, the overall mean frequency of a large release of radioactive materials to the environment from a reactor accident should be less than 1 in 1,000,000 per year of reactor operation.

This guideline, which was proposed for staff examination, was new and represented a major change from the 1982–83 policy statements.

On the Uses of PRA in the Regulatory Process

During the first few years after the publication of the *Reactor Safety Study* (*1*), PRA was confined primarily to the research wing of the NRC. First, truncated evaluations were made by NRC contractors for several reactors. These were followed by several improved PRAs, still limited in scope. About 1980, a considerable number of industry-sponsored PRAs were performed for various reasons. Some were done at the request of the NRC; others were done at the initiative of industry.

Before 1979–80, the application of PRA methodology by the NRC Regulatory Staff to safety issues was quite infrequent. After the accident at Three Mile Island reactor 2, use of the methodology grew very rapidly, and both utility companies and the NRC staff used PRA results in presenting arguments for their positions on safety issues.

The NRC's Special Proceeding for the Indian Point (IP) 2 and 3 reactors (located 40 miles north of New York City) represents the first and only time that review of a full-scale PRA became the principal object of an Atomic Safety and Licensing Board (ASLB) hearing.

On 17 September 1979, after the accident at Three Mile Island, the Union of Concerned Scientists (UCS) petitioned the NRC to suspend operation of IP 2 and 3 until certain issues were resolved.

On 11 February 1980, the NRC's director of regulation denied that part of the UCS petition requesting that operation of IP 2 and 3 be suspended. The director's decision relied on the existence and interim recommendations of an NRC task force to review IP 2 and 3 and Zion (Illinois) 1 and 2 reactors. The purpose of the task force was to determine what measures should be implemented to reduce the probability of a severe accident or its consequences. [The original risk estimates for IP 2 were based on analysis data from the Surry, Virginia, pressurized water reactor (PWR) that were applied to Indian Point. For these estimates, the task force raised the power, assumed the same core melt frequencies and radioactivity releases as at Surry, and then computed consequences, which were much higher, at the more populated IP site.] In June 1980 a second task force concluded that although the high population density near IP increased risk, the design features reduced risk by a comparable factor.

On 8 January 1981, the commission issued a Memorandum and Order establishing the issues to be addressed at the ASLB hearing (*24*). While the ASLB was asked to develop information and provide recommendations, the final decision was reserved by the commission for itself.

In the original PRA, the IP 2 unit was estimated to have a relatively large risk contribution to core melt and public risk from seismic events, hurricane winds, and fire. "Fixes" were proposed immediately by the licensee, and the core melt and risk values reported at the ASLB hearing were those based on the assumption that the fixes had been implemented. The estimated core melt frequency was still about 4×10^{-4} per reactor year for both IP 2 and IP 3, according to the staff. This was neither a median nor a mean estimate, so it could not be gauged statistically.

Several other specific possible safety improvements were evaluated by the NRC staff, using cost-benefit analysis, including a filtered, vented containment. The staff testimony was to the effect that, within large uncertainties, no improvements of major significance exhibited a cost-benefit ratio less than one, and they recommended against requiring any such improvement at that time. The staff did recommend that the IP units implement a reliability assurance program.

The commission itself judged that the relatively minor safety improvements recommended by the ASLB were not needed. The commission also did not support the recommendation of the NRC staff that a reliability assurance program be required.

Foreign Safety Goals

Among the leading foreign countries using LWRs in the Western world, only France has announced a quantitative safety goal, namely, that the design basis for a PWR should be that the global probability (probability due to all causes) for unacceptable radiological consequences is not higher than 10^{-6} per reactor year. In addition, if a family of adverse events (such as the crashes of all types of airplanes) is capable of causing unacceptable radiological events at a probability of 10^{-7} per reactor year, it should be taken into account. However, the licensee (in this case, Electricité de France) does not need to demonstrate having met the safety objectives.

In connection with the proposed Sizewell B PWR reactor in the United Kingdom, the Central Electricity Generating Board proposed similar design safety guidelines that have been accepted by the Nuclear Installations Inspectorate as reliability targets for licensing design.

Italy has announced the goal for future LWRs of 10^{-5} per reactor year for serious core degradation, with each sequence target being <10% of the total. Demonstration of compliance with the target criteria does not include man-made or natural external events.

Conclusions

The NRC has adopted a group of policy positions on safety goals (*23*), backfitting (*18*), and severe accidents (*25*) that may prove to be incompatible with one another. Reducing the core melt frequency or the frequency of a large release of radioactive material to the environment may involve expenditures that do not fit the cost-benefit procedures of the backfitting rule.

In my opinion, France and the Federal Republic of Germany have adopted safety design requirements that are considerably more stringent than those currently in use in the United States. It seems doubtful that the current NRC will be in favor of most such safety improvements, either under the backfitting rule or under the developing implementation guidelines for safety goal policy.

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