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ACRS WORKSHOP
Regulatory Challenges for Future Nuclear Power Plants
"Safety Goals for Future Nuclear Power Plants"

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This talk presents technology goals developed for Generation IV nuclear energy systems that can be made available to the market by 2030 or earlier. These goals are defined in the broad areas of sustainability, safety and reliability, and economics. Sustainability goals focus on fuel utilization, waste management, and proliferation resistance. Safety and reliability goals focus on safe and reliable operation, investment protection, and essentially eliminating the need for emergency response. Economics goals focus on competitive life cycle and energy production costs and financial risk.

The goals have three purposes: First, they define and guide the development and design of Generation IV systems. Second, they are challenging and will stimulate the search for innovative nuclear energy systems—both fuel cycles and reactor technologies. Third, they serve as the basis for developing criteria to assess and compare the systems in a technology roadmap.

The Generation IV technology goals derive from a set of guiding principles:

- Technology goals for Generation IV systems must be challenging and stimulate innovation.
- Generation IV systems must be responsive to energy needs worldwide.
- Generation IV concepts must define complete nuclear energy systems, not simply reactor technologies.
- All candidates should be evaluated against the goals on the basis of their benefits, costs, risks, and uncertainties, with no technologies excluded at the outset.

The Generation IV technology goals are intended to stretch the envelope of current technologies. Hence, the following caveats are important to note:

- The goals will guide the development of new nuclear energy systems. The objective of Generation IV systems is to meet as many goals as possible.
- The goals are not overly specific because the social, regulatory, economic, and technological conditions of 2030 and beyond are uncertain.
- The goals must not be construed as regulatory requirements.

Future designs will likely (but not necessarily) involve new fuel cycles and the capability to produce a broader range of energy products. For these reasons and to enhance the economic performance of electricity-only producing systems, I anticipate:

- New Fuel Materials
- Higher Burnups
- Longer Operating Cycles
- Higher Temperature Operation

These trends will be driven by the Sustainability (SU 1, 2, +3) and the Economic (EC 1+2) Goals.

Since these trends involve significant safety issues, all the goals should be considered as relevant contributors to the safety profile of future Generation IV energy systems.

Each of the eight goals is presented and the key issues debated and decided upon in their formulation will be discussed. The illumination of this debate is reflected in the Viewgraphs by highlighting the wording in the Goals Statements that best embodies the deliberations.

For the Sustainability Goals the following observations are relevant:

- Fuel cycle development offers the only way to address objectives of availability, waste management and nonproliferation in an integrated manner.

- Hence, for the US, R+D on fuel cycle options needs to be reinvigorated.

- The once -thru fuel cycle will likely be hard to beat considering that the objective of effective fuel utilization involves the following elements:

    - Economics (fuel cycle plus effect on O+M cost).

    - Nonproliferation concerns - challenge remains on cross-rating individual intrinsic and extrinsic barriers.

    - Environmental concerns - to what degree are externalities to be internalized in the nuclear fuel cycle and in other competing energy supply systems.

For the Economic Goals the following observations are relevant:

- Legitimate differing views exist on whether "clear" life-cycle cost advantage will be needed over the 30 year horizon for introduction of GENIV systems or whether breakeven will suffice because of recognition/credit for environmental benefits derived from nuclear systems.

- A judgement has been made that the history of deployment of nuclear systems has so raised the specter of risk and uncertainty of deployment cost that a "clear" advantage will be necessary to induce a commercial commitment to GENIV (or any nuclear system i.e. NTD) systems. Further, although allowable financial risk is limited by the need to achieve the life cycle cost advantage, the nuclear deployment history has also so raised the issues of risk & uncertainty of deployment that the separate and specific EC-2 Goal on "level of financial" risk was deemed necessary.

Anticipating enhanced interest in this audience in the three Safety and Reliability Goals, the text of the discussion which follows and supports each of these goals is also presented with the relevant wording similarly highlighted.

The latest statement of these Goals which was presented to NERAC on May 1, 2001 and subsequently accepted by DOE for final presentation to GIF is appended.

Conclusion:

Future reactors fall in three categories - those which are:

- Certified or derivatives of certified designs.
- Designed to a reasonable extent and based on available technology.
- In Conceptual form only with potential to most fully satisfy the GENIV goals.

My focus has been on goals for the third category.

It will be desirable to develop a range of design options in this third category to enable response to a range of possible market demands such as:

- cheap versus expensive uranium
- small versus large power ratings
- significant reduction of greenhouse emissions
- new fuel cycles to achieve a significant response to the sustainability goals

Considerable R+D activity will be required to achieve these goals among which fuels, materials, and coolant corrosion research are the most intensive and long term.

Consequently it is important that while an early dialogue between designers and regulators occur, the dialogue be framed to encourage & promote fundamental design directions which inherently promote safety. Development of a new regulatory process using risk-based principles is an important element of this dialogue. Interactions which frame the dialogue around the current regulatory framework can have the undesirable intent of discouraging the necessary and desirable exploration of technology and design alternatives.

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HOW TO MISCONSTRUE THIS TALK

I am not talking about:

- NRC Safety Goals - Quantitative Health Objectives - CDF and LERF.
- Suggested Regulatory Requirements for Future Power Plants.
- Soley about Future Power Reactors.
- Goals for Near Term Deployment* Plants (by 2010).

I am talking about:

- DOE and GIF Generation IV Technology Goals.
- Technology Goals formulated to
  - stimulate innovation.
  - suggest metrics for downselection which specifically are not to be construed as regulatory requirements.
- Nuclear Energy Systems Including
  - Fuel Cycles
- Goals for Systems to be Deployed from 2011 to 2030.

* Deployment: Manufacture, construction, and startup of certified plants ready to produce energy in their chosen market.

HOW TO MISCONSTRUE THE GOALS

- Assume that new nuclear energy systems must meet every new goal
  - Tradeoffs among goal parameters must be made for each design. Future markets may value different parameters.

    Desirable outcome is a spectrum of designs each best suiting different market conditions hence different goals.
  - Some goals presently appear unattainable (S+R 3).
  - Most goals are not overly specific because the social regulatory, economic and technological conditions of 2030 and beyond are uncertain.

HOW TO MISCONSTRUE THE GOALS (cont.)

- Assume that all safety considerations are encompassed in the Safety and Reliability Goal grouping (S+R 1, 2, +3)
  - Future designs will likely (but not necessarily) involve new fuel cycles and the capability to produce a broader range of energy products. For these reasons and to enhance the economic performance of electricity-only producing systems, I anticipate:
    - New Fuel Materials
    - Higher Burnups
    - Longer Operating Cycles
    - Higher Temperature Operation
  - These trends will be driven by the Sustainability (SÜ 1, 2, +3) and the Economic (EC 1+2) Goals.

SUSTAINABILITY

Sustainability is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely into the future.

Sustainability–1.

Generation IV nuclear energy systems including fuel cycles will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.

Sustainability–2.

Generation IV nuclear energy systems including fuel cycles will minimize and manage their nuclear waste and notably reduce the long term stewardship burden in the future, thereby improving protection for the public health and the environment.

Sustainability–3. **Generation IV nuclear energy systems including fuel cycles will increase the assurance that they are a very unattractive and least desirable route for diversion or theft of weapons-usable materials.**

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SAFETY AND RELIABILITY

Safety and reliability are essential priorities in the development and operation of nuclear energy systems.

Safety and Reliability –1.

Generation IV nuclear energy systems operations will excel in safety and reliability.

Safety and Reliability–2.

Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

Safety and Reliability–3.

Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

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Safety and Reliability –1. Generation IV nuclear energy systems operations will excel in safety and reliability.

This goal aims at increasing operational safety by reducing the number of events, equipment problems, and human performance issues that can initiate accidents or cause them to deteriorate into more severe accidents. It also aims at achieving increased nuclear energy systems reliability that will benefit their economics. Appropriate requirements and robust designs are needed to advance such operational objectives and to support the demonstration of safety that enhances public confidence.

During the last two decades, operating nuclear power plants have improved their safety levels significantly, as tracked by the World Association of Nuclear Power Operators (WANO). At the same time, design requirements have been developed to simplify their design, enhance their defense-in-depth in nuclear safety, and improve their constructability, operability, maintainability, and economics. Increased emphasis is being put on preventing abnormal events and on improving human performance by using advanced instrumentation and digital systems. Also, the demonstration of safety is being strengthened through prototype demonstration that is supported by validated analysis tools and testing, or by showing that the design relies on proven technology supported by ample analysis, testing, and research results. Radiation protection is being maintained over the total system lifetime by operating within the applicable standards and regulations. The concept of keeping radiation exposure as low as reasonably achievable (ALARA) is being successfully employed to lower radiation exposure.

Generation IV nuclear energy systems must continue to promote the highest levels of safety and reliability by adopting established principles and best practices developed by the industry and regulators to enhance public confidence, and by employing future technological advances. The continued and judicious pursuit of excellence in safety and reliability is important to improving economics.

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Safety and Reliability–2. Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.

This goal is vital to achieve investment protection for the owner/operators and to preserve the plant's ability to return to power. There has been a strong trend over the years to reduce the possibility of reactor core damage. Probabilistic risk assessment (PRA) identifies and helps prevent accident sequences that could result in core damage and off-site radiation releases and reduces the uncertainties associated with them. For example, the U.S. Advanced Light Water Reactor (ALWR) Utility Requirements Document requires the plant designer to demonstrate a core damage frequency of less than 10^{-5} per reactor year by PRA. This is a factor of about 10 lower in frequency by comparison to the previous generation of light water reactor energy systems. Additional means, such as passive features to provide cooling of the fuel and reducing the need for uninterrupted electrical power, have been valuable factors in establishing this trend. The evaluation of passive safety should be continued and passive safety features incorporated into Generation IV nuclear energy systems whenever appropriate.

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Safety and Reliability-3. Generation IV nuclear energy systems will eliminate the need for offsite emergency response.

The intent of this goal is, through design and application of advanced technology, to eliminate the need for offsite emergency response. Although its demonstration may eventually prove to be unachievable, this goal is intended to stimulate innovation, leading to the development of designs that could meet it. The strategy is to identify severe accidents that lead to offsite radioactive releases, and then to evaluate the effectiveness and impact on economics of design features that eliminate the need for offsite emergency response.

The need for offsite emergency response has been interpreted as a safety weakness by the public and especially by people living near nuclear facilities. Hence, for Generation IV systems a design effort focused on elimination of the need for offsite emergency response is warranted. This effort is in addition to actions which will be taken to reduce the likelihood and degree of core damage required by the previous goal.

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ECONOMICS

Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems.

Economics–1.

Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.

Economics–2.

Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

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CONCLUSIONS

- Future reactors fall in three categories - those which are:
  - Certified or derivatives of certified designs.
  - Designed to a reasonable extent and based on available technology.
  - In Conceptual form only with potential to most fully satisfy the GENIV goals.

  My focus has been on goals for the third category.

- It will be desirable to develop a range of design options in this third category to enable response to a range of marketing demands such as:
  - cheap versus expensive uranium.
  - small versus large power ratings.
  - significant reduction of greenhouse emissions.
  - new fuel cycles to achieve a significant response to the sustainability goals.

  Considerable R+D activity will be required to achieve these goals among which fuels, materials, and coolant corrosion research are the most intensive and long term.

- **Consequently it is important that while an early dialogue between designers and regulators occur, the dialogue be framed to encourage & promote fundamental design directions which inherently promote safety. Development of a new regulatory process using risk-based principles is an important element of this dialogue. Interactions which frame the dialogue around the current regulatory framework can have the undesirable intent of discouraging the necessary and desirable exploration of technology and design alternatives.**

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D. Powers, ACRS Member: One of the questions that comes to mind, especially after the previous speaker portrayed something of a crisis appearing, I wonder if in looking at these goals and looking at new systems that you compare the more modern or the existing plants against them to see if we really need all new concepts, and the 94 new concepts that were portrayed to us yesterday or, in fact, how well do the existing plants meet these various goals that you've laid out?

N. Todreas, MIT: The answer to that is on the metrics that we're going to develop to assess these new concepts. We've picked a standard, and the evaluation process will measure these new concepts against the standard. Is it better, much better, et cetera, worse, much worse, and the standard we picked is the advanced LWR with once through fuel cycle. The rest of your question asked me what's the answer going to be, and I don't know that yet.

D. Powers, ACRS Member: I find that a peculiar standard to pick because we don't have a whole lot of experience with advanced LWR. With existing machines, we have a lot of experience, and that experience, at least my friends at NEI certainly provide metrics that suggest that experience, is outstanding right now.

N. Todreas, MIT: I can see thinking about that, but if we're going to develop advanced systems, I would say from the vendor community and the development community, we've got ABWR experience to an extent, and we have some degree of real respect for what the designs have accomplished in the ALWR. As a minimum you'd include both, but I certainly wouldn't go back just to the operating reactors as the standard for the future. I wouldn't ignore the 15 years of ALWR development.

G. Wallis, ACRS Member: I think that while you're being innovative, you should not use -- you seem to be here really talking about core damage frequency, and that just may get you in a box, and I think to be innovative, get away from these terms of the past and be more general.

T. Kress, Chairman, Future Reactors Subcommittee: I think it is fission products we're worried about.

N. Todreas, MIT: That's a reasonable point. If you are saying that we ought to get away from terms of the past which will lock us into certain design directions and means of dialogue, that is really my whole message, too. If you're offering me a suggestion that says what I wrote doesn't go that way; I should go a different way, then I'd perfectly accept it.

J. Garrick, Chairman, ACNW: We have to be a little careful not to unduly focus on fission products because for many of the most important scenarios it is not the fission products that's driving the long-term performance of Yucca Mountain. It's mainly, technetium and Iodine 129 certainly are in there, but depending on the scenario and depending on how you look at it, Neptunium 237 is the principal driver.

And also, in most low level waste situations, you find that much to our surprise most of the low level waste is uranium contaminated. So, again, the fission products are not driving the long-term stewardship or management of a lot of the low level waste, but rather it's actinides. The same thing is true in WIPP for transuranic waste. Again, it's not fission products, but it's plutonium.

N. Todreas, MIT: But that also refers back to the sustainability goal. It really doesn't obviate the suggestion relative to Safety and Reliability (S&R) grouping 2 relative to core damage. I say that because what Garrick's comment really impacts on is the waste issue, not effectively the immediate release through core damage.

T. Kress, Chairman, Future Reactors Subcommittee: In particular, do you have some sort of criteria on what it would take to eliminate this need? And if so, does that criteria encompass some sort of measure of defense-in-depth also?

N. Todreas, MIT: That's how the ACRS ought to look at it. From the point of view of a regulator or a group advising a regulator. These are technology goals. These are goals we want to drive the designers into thinking about.

T. Kress, Chairman, Future Reactors Subcommittee: How would you know if you met that goal? That was my question. What is the measure that you're going to use to say, "Okay. The technology we have here meets that goal." Whether or not it actually comes about or not is another thing.

N. Todreas, MIT: The measure has got to be release of fission products or radioactivity of a certain amount past the boundary.

D. Powers, ACRS Member: I can always find a way to get fission products out. Any design you come up with I can find a mechanism to get the fission products out to the point that it violates some emergency planning guide.

E. Lyman, Nuclear Control Institute: There are a few goals that are really missing from this whole formulation. First of all, under sustainability you refer to one that minimizes, that a goal is minimizing and managing nuclear waste, but at the same time, you really should impose a requirement that the routine emissions from the entire fuel cycle, as well as, occupational exposures are also minimized because one of the concerns with fuel cycles that involve reprocessing are these additional routine emissions, and you have to balance whether the reduced risk in a repository is justified by increased short-term emission. So that's really something you have to keep to minimize at the same time or it doesn't make sense.

Second of all, under the financial goals issue, you didn't really dwell on the one that requires or suggests that the financial risks should be comparable to other energy projects, and I was wondering if in that context, you would also have a requirement then, that Price Anderson protection not be extended to Generation IV plants because other energy projects don't require that kind of protection.

N. Todreas, MIT: Yes, on the first point you brought up, the specifics of that have been recognized and will come up in Safety and Reliability group 1 because there we are talking about across the whole fuel cycle, and those routine emissions are picked up there. They could be picked up either place, but that's where they come up.

And on Price Anderson, we didn't get into the specific item within the structure of the goal that can be picked up and debated. It's been debated to some extent, but we didn't pin it down and resolve it specifically. I know that's coming up legislatively.

R. Barrett, NRC: My question relates to the methods that we use for estimating the likelihood of core damage and the likelihood of release of radioactivity.

If NEI is correct and we have 50,000 new megawatts of capacity out there, and those are modular reactors -- that's 500 cores, and in an environment like that you find yourself striving for lower and lower core damage frequencies, and as you do that, you begin to put more and more stress on the current methods of estimating core damage frequency, and you begin to get to the point where many people think you're beyond the capability and the limitations of the method and the ability to have a complete model.

In addition, as you move to different types of reactors, you find that you're depending less and less on highly reliable, redundant, and diverse systems and more and more on the intrinsic capability of the core itself to withstand these accidents, and to withstand them either indefinitely or for long periods of time. And, again, the methods that we have today really don't deal very well with this kind of intrinsic, passive capability.

So my question to you is the stated purpose of your effort is to stimulate innovation in the design of the reactors, and my question is: could you also complement that with trying to stimulate innovation in the methods that we use for analyzing the risk associated with these reactors?

N. Todreas, MIT: Yes, I would answer that two ways. First, it's a good suggestion and a fair suggestion. There's nothing implicit in my statement that precludes risk methods development -- what's going to come out of this fundamentally it is a spectrum of concepts to focus on, but much more than that, an R&D road map of activities to flesh out those concepts and the methods associated with the concept development is certainly part and parcel of that. So we could do that.

The other thing though that I'd say is if we were to develop the methods we're going to have to reduce core damage frequencies further to get a desired output. So that really leads you to say that if you go with concepts now that are clones or like -- I'm talking about 20, 30 years down the road -- existing concepts are like these, you're going to reach a point where the methods can only go so far based on the existing design approaches, and so that's a clarion call to change those approaches and go toward -- well, first, you go toward situations that avoid core melt, but that's very limited in a sense that what you really want to do is do what Dana Powers was talking about. It's not core melt. It's the fission products, and it's the radioactivity in the dose from that, and that's what you've got to get after. So I would say we certainly would accept and develop methods, but what we are trying to do is stimulate. I'm talking about real innovation, beyond that, to try to open up approaches that really change the playing field.

L. E. Hochreiter, Penn State University: It's not clear to me why in your conclusions you have to have small versus large power ratings. It seems like you're biasing yourself already towards a particular class of designs.

N. Todreas, MIT: Yes. Yesterday I presumed the whole layout of this program was announced or was explained as an international program with eight to nine countries now, and one of the goals of the program is to come up with design solutions or concepts that meet markets internationally, and there are some international markets. Also if you listen in the United States, too, depending on the grid size, there are some markets that have a priority toward low rated systems. And so you have some of those, and then you also have the traditional, if you talk about Asia, Japan, Korea, Taiwan, large systems. So inherent in the whole program, since it's looking at worldwide markets, we're going to have this dichotomy, these two parts, and no one reactor thrust or direction is going to meet them both. So you're going to have to come up with systems in both directions. Now, your point may be fine, but they're not going to be sellable in the United States or the industrialized world. That's fine, but we'll have a product for that. We just may not use the other product.

N. P. Kadambi, NRC: If I understand the rules by which the South Africans are trying to license their plant, one of their goals is that in the long term the concepts employed should be amenable for society to make a decision that higher levels of safety need to be obtained from these energy systems.

And therefore, one of their goals, as I read it, and if I should be corrected, I'd like somebody to point this out; one of their goals is the design should be amenable for society to demand higher levels of safety at some future time if we take, you know, these systems as operating for many decades.

Where does such a concept fit into the kinds of goals that you have articulated?

N. Todreas, MIT: Okay. On this let me give you a brief answer and ask for some help because I am not knowledgeable about a specific or the specific South African drive that you're talking about. I just haven't interacted with them specifically. I would say that even though these are general goals, we are going to have some kind of constraint because we're going to come up with a set of specific metrics that go with each of these goals. They're going to be as we go on a year or two -- there's going to be some numbers and some specificity here . So there's going to be a little bit of a lock-in with your desire to accommodate future societal wishes for enhanced safety. The way I interpret what you're saying is you come up with a design. Society decides they want more safety, and so this design has somehow got to be expandable or have margin or a way to capture more safety. That's how I understand it.

So I don't know the answer. These goals have been pushed in through a discussion with the so-called GIF countries, of which South Africa is a part, and we didn't get any effective comment back from them that's relevant to what you said. But if Andy Kadak or somebody else can speak specifically to that, that would help me.

J. Slabber, PBMR: In the South African concept, the baseline was to use existing technology as far as possible, existing technology that has been qualified and tested and proven to be acceptable for use in the PBMRs, and with a basis that the fuel is the central point of focus. And within that framework, we do the system design. Imbedded in the design is the requirement to be fulfilled that no reliance is placed on immediate operator action to bring the reactor to a safe state, and I again say, in inverted commas, inherent safety and small units, and usable for not only producing nuclear power, but also some other usable byproducts such as possibly desalination specific for South Africa.

N. Todreas, MIT: Can I build on that maybe in answer to his question? I would say with that focus and the ability, as you went to successive improvements in fuel fabrication and fuel reliability, you could actually enhance your safety profile if the key focus is fuel, and that would be an answer back to how you reflect the future, the fuel.

J. Slabber, PBMR: I think the objective of any new innovative system should be to improve, but there is a limit because it's also costly. So improvement, the improvement for public acceptance, improvement of safety, that at the boundary you do not have to shelter and evacuate. These are all factored in to provide a facility which is still affordable and reliable.