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The Nuclear Renaissance

Innovation, Regulation, Sustainability -
Frameworks in a Changing Energy Landscape

Edited by Pavel Tsvetkov and Anna Erickson



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and Anna Erickson*

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<https://engineering.tamu.edu/nuclear/profiles/tsvetkov-pavel-v.html>

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Contents

Preface	IX
Section 1	
Fundamental Science	1
Chapter 1	3
Perspective Chapter: Water Radiolysis Control to Reduce Corrosion Risk <i>by Tomas Moucha, Adam Boura, Radim Petricek and Tomas Kracik</i>	
Section 2	
Technological Innovation	25
Chapter 2	27
Perspective Chapter: The Visual Cognition and Attention Allocation Principles in Nuclear Power Monitoring Operations <i>by Xiaoli Wu</i>	
Section 3	
Frameworks Necessary for Expansion	57
Chapter 3	59
Perspective Chapter: Advanced Reactor Decision-Making in the Trans-Science Setting <i>by Ernie Kee</i>	
Chapter 4	69
Perspective Chapter: Radiation Protection Plays the Key Role in Nuclear Power Expansions <i>by Hiromichi Fumoto</i>	
Section 4	
Applications as a Sustainable Resource	89
Chapter 5	91
Perspective Chapter: Use of Gamma Radiation in the Food Industry <i>by Nikolay Dolchinkov</i>	

Preface

The book draws on the broader global context to examine the overarching challenges and opportunities of nuclear energy technologies and their applications. It presents a comprehensive, multidisciplinary examination of nuclear technology's critical role in addressing escalating global energy demands and mitigating environmental challenges. As the world strives for responsible global development, nuclear power stands out for having lifecycle greenhouse gas emissions as low as those of wind and solar, while uniquely providing a continuous, stable baseload power. To fully realize this potential, the industry is undergoing a period of profound technological innovation. This includes the development of Generation IV systems - such as High Temperature Reactors (HTRs), Molten Salt Reactors (MSRs) and Fast Reactors (FRs) - which promise enhanced intrinsic safety, vastly improved resource utilization, and the ability to recycle and transmute long-lived radioactive waste. Concurrently, the deployment of Small Modular Reactors (SMRs) offers scalable, cost-effective, and flexible power generation that can easily complement intermittent renewable energy sources. Furthermore, the nuclear sector is rapidly integrating digital technologies, leveraging Artificial Intelligence (AI) to optimize reactor operations, including fuel loading and advanced monitoring.

Technological progress alone is insufficient. The expansion of nuclear power must navigate a shifting regulatory landscape, ensure rigorous spent fuel management (such as deep geological repositories), and confront the enduring trans-scientific challenge of public perception stemming from historical accidents. Beyond electricity generation, the book highlights the broader societal benefits of nuclear science, including its highly sustainable applications in agriculture, food safety, and industrial sterilization.

Let us introduce book chapters. The book begins with fundamental science, moves into technological innovations, discusses the frameworks necessary for expansion, and concludes with its applications as a sustainable resource. The first chapter focuses on the science of nuclear power and its practical fundamentals, such as radiolysis and corrosion control. At the foundational scientific level, the safety of a nuclear reactor relies heavily on the chemistry of its primary coolant. As coolant water passes through the reactor's active core, it undergoes significant irradiation, leading to water radiolysis. This process produces highly corrosive species, including hydrogen peroxide, nitric acid, and oxygen. To mitigate the corrosion of primary circuit pipes, hydrogen (or ammonia) is deliberately dosed into the coolant to trigger recombination reactions that suppress these corrosive molecules. Because mathematical models of these reactions often show discrepancies, the chapter details the development of a novel amperometric hydrogen sensor. This device provides precise, real-time measurements and features a fast response time, making it an effective early warning system for hydrogen leaks.

The second chapter focuses on optimizing human factors in intelligent control operations. Building upon reactor science, the chapter explores critical innovations in the “nerve center” of the nuclear plant: the main control room. Modern, intelligent display and control systems require operators to manage vast amounts of information across multiple screens and devices, leading to high cognitive workloads and the risk of visual fatigue or decision-making errors. The chapter analyzes visual cognition and attention allocation, identifying how operators process information through both bottom-up (stimulus-driven) and top-down (goal-driven) attentional mechanisms. By applying these cognitive models to optimize human-machine interfaces - such as improving device grouping and visual hierarchy - these innovations successfully reduce operator cognitive load, prevent attention disruption, and minimize perceptual bias during critical monitoring tasks.

The third chapter is centered on regulatory decision-making in a trans-science setting. For nuclear power to expand, it must navigate a shifting and highly complex regulatory landscape. The chapter evaluates the recent trend to accelerate the deployment of Advanced Commercial Nuclear Fission Reactors through Risk-Informed and Performance-Based licensing. This approach represents a trans-scientific challenge, as it replaces traditional, conservative bounding analyses (such as the Maximum Hypothetical Accident) with optimistic Probabilistic Risk Assessments (PRAs). The chapter asserts that because novel reactors lack historical accident data, relying too heavily on probabilistic models may prioritize deployment speed over proven safety. Comparing this to the Titanic’s inadequate lifeboat capacity, the chapter argues that safe expansion requires transparent risk disclosures and mechanism-based safety margins rather than idealized mathematical assumptions.

The fourth chapter connects radiation protection considerations and gaining public trust. Sustainable expansion requires deep societal support, which is frequently hindered by public fear. The chapter examines the history of radiation protection and the adoption of the Linear No-Threshold (LNT) hypothesis, which assumes no level of radiation exposure is entirely safe, thereby fueling public anxiety. By reviewing historical nuclear incidents - such as the Windscale reactor fire, the Palomares B-52 crash, the Rocky Flats fire, Chernobyl, and Fukushima- the text highlights the psychological consequences of this fear. The chapter demonstrates that securing public trust for nuclear expansion relies on swift, sincere communication and practical, graded approaches to environmental decontamination, rather than implementing stopgap measures driven by panic.

The fifth and final chapter looks beyond electricity generation to demonstrate how nuclear technology contributes to a sustainable future through industrial applications. A prominent example is the use of gamma radiation and ionizing radiation in the food industry. Serving as a method of cold sterilization, irradiation effectively destroys pathogenic microorganisms, bacteria, and insects without raising the food’s temperature or altering its taste, texture, and appearance. Governed by strict safety standards and the ALARA (As Low As Reasonably Achievable) principle, this process extends the shelf life of products such as spices, meats, and produce while ensuring safety. By significantly reducing global food waste, food irradiation stands as a highly sustainable and economically beneficial application of nuclear science.

As Editors of this book, we assert that opinions presented in the book chapters belong to chapter authors and chapter authors only. We assembled this collection of chapters driven by the intrinsic value of topics raised by rapidly expanding nuclear technology developments in anticipation of approaching commercial deployments. The concepts introduced by the chapter authors are of paramount importance for advancing Generation IV systems and Small Modular Reactors (SMRs). We encourage our readers to join us in this quest for sustainable nuclear energy solutions by reading our book. Thank you for your interest in nuclear technologies.

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Section 1

Fundamental Science

Chapter 1

Perspective Chapter: Water Radiolysis Control to Reduce Corrosion Risk

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Tomas Kracik*

Abstract

Primary coolant radiolysis, when the coolant passes through the reactor active zone, produces corrosive species such as hydrogen peroxide, oxygen, and nitric acid. To reduce the corrosion risk of primary circuit devices, a sufficiently low concentration of corrosive products should be maintained in the primary circuit. This can be achieved by dosing hydrogen into the primary coolant. Therefore, hydrogen concentration monitoring in the primary coolant is of considerable importance. Commercial hydrogen sensors are often based on principles that do not provide a hydrogen-selective signal, employing, for example, thermal conductivity. According to the statements from the nuclear power plant's experts, the signals of various sensors differ significantly. In an effort to improve the described situation, we are developing a type of hydrogen sensor, the principle of which and its development into a prototype will be described in the chapter.

Keywords: primary coolant, hydrogen concentration, reactor safety, corrosion control, sensor design

1. Introduction

In the context of this book's ideas about nuclear energy as an earth-friendly energy source, we present an overview of one branch of corrosion engineering applied in nuclear power plants to make them as safe as possible. Frankly speaking, there is a limited number of energy sources that can be considered as the earth-friendly and can simultaneously provide us with sufficient power, which mankind is accustomed to have at its disposal. Therefore, we are confident that a positive attitude toward nuclear energy extends far beyond the scope of this book.

In all industry branches, the safety criteria should belong to the key parameters in technology tuning, and especially in those where even a small defect can bring considerable danger, as it could be in the case of nuclear power plants. Monitoring and control of the chemistry of a nuclear reactor's primary circuit represent one of the important activities to prevent the safety risks connected with corrosion.

What is the primary circuit chemistry about? Primary coolant, usually water with additives, the most known of which the boric acid probably is, flows through the active zone along the reactor. The coolant undergoes massive irradiation (in the orders of 10^{20} photons per second, which corresponds to up to 10000 kGy/h) in the active zone, and a large number of radicals are produced in it. Due to their strong reactivities, the radicals, having very short lifetimes, intensively recombine into stable molecules, also producing corrosion-inducing species such as hydrogen peroxide, nitric acid, and oxygen.

2. Theoretical background

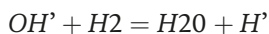
In an effort to reduce corrosion risks, recombination reactions have been studied for several decades. Christensen [1] and [2], e.g., studied the radiolysis of water containing boric acid. Later, [3] described the details of ammonia radiolysis, which also occurs in the primary coolant.

To illustrate the processes studied, we show several equations important from the perspective of primary circuit corrosion control. First, water molecules undergo radiolysis as follows.

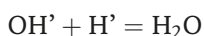
An excited water molecule produces a hydrogen molecule and an oxygen radical O'



Another radical from other water molecules, OH', produces a hydrogen radical, H'



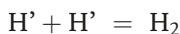
Consequently, radicals H' and OH' form water again



but other recombinations also occur:



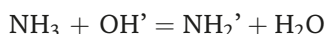
and



Especially, the corrosive hydrogen peroxide production belongs to the unwanted ones.

To get a better feeling of the complexity of the water radiolysis process, see **Table 1** (taken from Butarbutar et al. [4]), which shows even the simplified, reduced water chemistry scheme under irradiation.

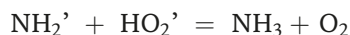
The other species added to the primary coolant react as well and produce corrosive species. For instance, ammonia undergoes reactions with the radicals produced from water molecules under irradiation (Kritski et al. [5] and Grachev et al. [3]):



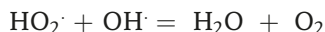
Reaction	$k (M^{-1} s^{-1})$	Reaction	$k (M^{-1} s^{-1})$
$H^{\bullet} + H^{\bullet} \rightarrow H_2$	5.2×10^9	$e_{aq}^{-} + e_{aq}^{-} \rightarrow H_2 + 2 OH^{-}$	7.3×10^8
$H^{\bullet} + \cdot OH \rightarrow H_2O$	1.6×10^{10}	$e_{aq}^{-} + H^{\bullet} \rightarrow H^{\bullet}$	2.1×10^{10}
$H^{\bullet} + H_2O_2 \rightarrow H_2O + \cdot OH$	3.6×10^7	$e_{aq}^{-} + O_2^{\bullet -} \rightarrow H_2O_2 + 2 OH^{-}$	1.3×10^{10}
$H^{\bullet} + e_{aq}^{-} \rightarrow H_2 + OH^{-}$	2.8×10^{10}	$e_{aq}^{-} + HO_2^{\bullet} \rightarrow O^{\bullet -} + OH^{-}$	3.51×10^9
$H^{\bullet} + OH^{-} \rightarrow H_2O + e_{aq}^{-}$	2.4×10^7	$e_{aq}^{-} + O^{\bullet -} \rightarrow 2 OH^{-}$	2.31×10^{10}
$H^{\bullet} + O_2 \rightarrow HO_2^{\bullet}$	1.3×10^{10}	$e_{aq}^{-} + H_2O \rightarrow H^{\bullet} + OH^{-}$	15.8
$H^{\bullet} + HO_2^{\bullet} \rightarrow H_2O_2$	1.1×10^{10}	$e_{aq}^{-} + O_2 \rightarrow O_2^{\bullet -}$	2.3×10^{10}
$H^{\bullet} + O_2^{\bullet -} \rightarrow HO_2^{\bullet}$	1.1×10^{10}	$e_{aq}^{-} + HO_2^{\bullet} \rightarrow HO_2^{\bullet}$	1.3×10^{10}
$H^{\bullet} + HO_2^{\bullet} \rightarrow \cdot OH + OH^{-}$	1.5×10^9	$e_{aq}^{-} + O(^3P) \rightarrow O^{\bullet -}$	2.0×10^{10}
$H^{\bullet} + O(^3P) \rightarrow \cdot OH$	2.0×10^{10}	$e_{aq}^{-} + O_3 \rightarrow O_3^{\bullet -}$	3.6×10^{10}
$H^{\bullet} + O^{\bullet -} \rightarrow OH^{-}$	2.0×10^{10}	$H^{\bullet} + O^{\bullet -} \rightarrow \cdot OH$	5.0×10^{10}
$H^{\bullet} + O_3 \rightarrow O_2 + \cdot OH$	3.7×10^{10}	$H^{\bullet} + O_2^{\bullet -} \rightarrow HO_2^{\bullet}$	5.0×10^{10}
$H^{\bullet} + O_3^{\bullet -} \rightarrow OH^{-} + O_2$	1.0×10^{10}	$H^{\bullet} + OH^{-} \rightarrow H_2O$	1.2×10^{11}
$\cdot OH + \cdot OH \rightarrow H_2O_2$	6.3×10^9	$H^{\bullet} + O_3^{\bullet -} \rightarrow \cdot OH + O_2$	9.0×10^{10}
$\cdot OH + H_2O_2 \rightarrow HO_2^{\bullet} + H_2O$	2.9×10^7	$H^{\bullet} + HO_2^{\bullet} \rightarrow H_2O_2$	5.0×10^{10}
$\cdot OH + H_2 \rightarrow H^{\bullet} + H_2O$	4.0×10^7	$OH^{-} + O(^3P) \rightarrow HO_2^{\bullet}$	4.2×10^8
$\cdot OH + e_{aq}^{-} \rightarrow OH^{-}$	3.6×10^{10}	$OH^{-} + HO_2^{\bullet} \rightarrow O_2^{\bullet -} + H_2O$	1.3×10^{10}
$\cdot OH + OH^{-} \rightarrow O^{\bullet -} + H_2O$	1.3×10^{10}	$O_2 + O^{\bullet -} \rightarrow O_3^{\bullet -}$	3.7×10^9
$\cdot OH + HO_2^{\bullet} \rightarrow O_2 + H_2O$	9.0×10^9	$O_2 + O(^3P) \rightarrow O_3$	4.0×10^9
$\cdot OH + O_2^{\bullet -} \rightarrow O_2 + OH^{-}$	1.1×10^{10}	$HO_2^{\bullet} + O_2^{\bullet -} \rightarrow HO_2^{\bullet} + O_2$	9.7×10^7
$\cdot OH + HO_2^{\bullet} \rightarrow HO_2^{\bullet} + OH^{-}$	8.3×10^9	$HO_2^{\bullet} + HO_2^{\bullet} \rightarrow H_2O_2 + O_2$	1.94×10^8
$\cdot OH + O(^3P) \rightarrow HO_2^{\bullet}$	2.02×10^{10}	$HO_2^{\bullet} + O(^3P) \rightarrow O_2 + \cdot OH$	2.02×10^{10}
$\cdot OH + O^{\bullet -} \rightarrow HO_2^{\bullet}$	1.0×10^9	$HO_2^{\bullet} + H_2O \rightarrow H^{\bullet} + O_2^{\bullet -}$	1.4×10^4
$\cdot OH + O_3^{\bullet -} \rightarrow O_2^{\bullet -} + HO_2^{\bullet}$	8.5×10^9	$O_2^{\bullet -} + O^{\bullet -} \rightarrow O_2 + 2 OH^{-}$	6.0×10^8
$\cdot OH + O_3 \rightarrow O_2 + HO_2^{\bullet}$	1.11×10^8	$O_2^{\bullet -} + H_2O \rightarrow HO_2^{\bullet} + OH^{-}$	0.155
$H_2O_2 + e_{aq}^{-} \rightarrow OH^{-} + \cdot OH$	1.1×10^{10}	$O_2^{\bullet -} + O_3 \rightarrow O_3^{\bullet -} + O_2$	1.5×10^9
$H_2O_2 + OH^{-} \rightarrow HO_2^{\bullet} + H_2O$	1.33×10^{10}	$HO_2^{\bullet} + H_2O \rightarrow H_2O_2 + OH^{-}$	1.27×10^6
$H_2O_2 + O(^3P) \rightarrow HO_2^{\bullet} + \cdot OH$	1.6×10^9	$HO_2^{\bullet} + O^{\bullet -} \rightarrow O_2^{\bullet -} + OH^{-}$	8.02×10^8
$H_2O_2 + O^{\bullet -} \rightarrow HO_2^{\bullet} + OH^{-}$	5.55×10^8	$HO_2^{\bullet} + O(^3P) \rightarrow O_2^{\bullet -} + \cdot OH$	5.3×10^9
$H_2 + O(^3P) \rightarrow H^{\bullet} + \cdot OH$	4.77×10^3	$O^{\bullet -} + O^{\bullet -} \rightarrow H_2O_2 + 2 OH^{-}$	1.0×10^8
$H_2 + O^{\bullet -} \rightarrow H^{\bullet} + OH^{-}$	1.3×10^8	$O^{\bullet -} + O_3^{\bullet -} \rightarrow 2 O_2^{\bullet -}$	7.0×10^8
$O(^3P) + O(^3P) \rightarrow O_2$	2.2×10^{10}	$O^{\bullet -} + H_2O \rightarrow \cdot OH + OH^{-}$	1.3×10^6
$O(^3P) + H_2O \rightarrow 2 \cdot OH$	1.9×10^3	$O_3^{\bullet -} + H_2O \rightarrow O^{\bullet -} + O_2$	46.5

Table 1.
Recombination reactions of radicals produced by water molecule radiolysis as described by Butarbutar et al. [1].

And the $NH_2^{\bullet}$ radical, reacting with $HO_2^{\bullet}$ formed from another water molecule, produces stable molecules of ammonia and other corrosive species – a molecule of oxygen:



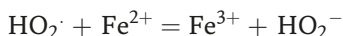
Similarly, recombination reactions of water itself, which involve the $\text{HO}_2^\cdot$, bring oxygen and hydrogen peroxide too:



For illustration, the recombination reactions of other species – ammonia and boric acid – present in the primary coolant, which are considered in mathematical simulations by [3], are given in **Table 2**.

Next to the expected reactions of corrosive species H_2O_2 and O_2 with primary circuit pipes made of stainless steel, the reaction of iron directly with the radicals in the irradiated water was also observed and described. For instance, [6] described it as follows in **Table 3**.

When the kinetic data from the literature are analyzed, multiple uncertainties in their quantification are observed. For example, Lundstrom et al. [6] paid effort in their article to the reaction.



When it was seen that reaching higher accuracy in its kinetics was significant to achieve reliable simulation results.

Similarly, [2] declared the uncertainty in the kinetics knowledge: “there is a need for more reliable rate constants for the reactions of $\text{H}_2 + \text{OH} \sim \text{H} + \text{H}_2\text{O}$ and $\text{e-aq} + \text{H} + \sim \text{H}$, which can be neglected at room temperature”.

There were several mathematical models published in the literature in the field, which described both pure water radiolysis as well as the recombination reactions of other species, such as nitrogen compounds (originating from ammonia, e.g.), boric acid, and metals from the primary circuit piping wall.

3. Mathematical modelling results

Pure water radiolysis was well described, for instance, by Sunaryo et al. [7], who presented the concentration-time profiles of many radicals obtained from their simulations. As can be seen in **Figure 1**, the reactions are fast, and the major part of concentration changes takes place in fractions of seconds, with a steady-state almost reached after one second.

It is worth noting that these concentration profiles were successfully obtained also by the computational module we developed in Fortran at our workplace – UCT Prague [8], and what is interesting about that is: we used the chemical equation series published by [1], and obtained exactly the same concentration profiles of water radicals as those shown in **Figure 1**. This meant that the pure water radiolysis was described well in the literature, as two independent sources provided the same simulation results.

When the radiolysis of a complete species series occurring in the primary coolant is described as successfully as that of pure water, the corrosion risks could be effectively predicted by simulations. [9] points to this approach, showing corrosion potentials obtained from the known concentrations of individual species in the primary coolant, see **Figure 2**.

No.	Reaction equation	$k_{25}, \text{L} \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$	$E_w, \text{kJ/mol}$
1	$\text{NH}_3 + \text{OH} \rightarrow \text{NH}_3 + \text{H}_2\text{O}$	9.7×10^3 [23]	11.4 [24]
2	$\text{NH}_3 + \text{H} \rightarrow \text{NH}_3$	10^{10} [14]	E_w
3	$\text{NH}_3 + e_{aq}^- \rightarrow \text{NH}_3 + \text{OH}^-$	10^{10} [14]	E_w
4	$\text{NH}_3 + \text{HO}_2 \rightarrow \text{NH}_3 + \text{O}_2$	10^{10} [25]	E_w
5	$\text{NH}_3 + \text{OH} \rightarrow \text{NH}_2\text{OH}$	9.5×10^9 [26]	E_w
6	$\text{NH}_3 + \text{H}_2\text{O}_2 \rightarrow \text{NHOH} + \text{H}_2\text{O}$	9.0×10^7 [26]	E_w
7	$\text{NH}_3 + \text{NO} \rightarrow \text{N}_2 + \text{H}_2\text{O}$	10^{8*}	E_w
8	$\text{NHOH} + \text{H} \rightarrow \text{NH}_2\text{OH}$	10^{8*}	E_w
9	$\text{NHOH} + e_{aq}^- \rightarrow \text{NH}_2\text{OH} + \text{OH}^-$	10^{8*}	E_w
10	$2\text{NHOH} \rightarrow \text{N}_2 + 2\text{H}_2\text{O}$	10^{6**} [14]	E_w
11	$\text{NHOH} + \text{HO}_2 \rightarrow \text{NH}_2\text{OH} + \text{O}_2$	10^{8*}	E_w
12	$\text{NO} + \text{OH} \rightarrow \text{HNO}_2$	2.0×10^{10} [27]	E_w
13	$\text{NH}_2\text{OH} + \text{OH} \rightarrow \text{NHOH} + \text{H}_2\text{O}$	9.5×10^9 [28]	E_w
14	$\text{NH}_2\text{OH} + e_{aq}^- \rightarrow \text{NH}_2 + \text{OH}^- + \text{H}_2\text{O}$	9.2×10^8 [28]	E_w
15	$\text{HNO}_2 + \text{H} \rightarrow \text{NO} + \text{H}_2\text{O}$	4.5×10^8 [29]	E_w
16	$\text{HNO}_2 + \text{NH}_2\text{OH} \rightarrow \text{N}_2\text{O} + 2\text{H}_2\text{O}$	10^{8*}	E_w
17	$\text{N}_2\text{O} + \text{H} \rightarrow \text{N}_2 + \text{OH}$	2.1×10^6 [30]	E_w
18	$\text{N}_2\text{O} + e_{aq}^- \rightarrow \text{N}_2 + \text{OH} + \text{OH}^-$	9.6×10^9 [31]	19.0 [31]
19	$2\text{NH}_3 \rightarrow \text{N}_2\text{H}_4$	2.2×10^9 [26]	0 [24]
20	$\text{NH}_3 + \text{H} \rightarrow \text{NH}_3^+ + e_{aq}^-$	6.7×10^5 [32]	E_w
21	$\text{NH}_3^+ + e_{aq}^- \rightarrow \text{NH}_3 + \text{H}$	1.5×10^6 [33]	20.0 [33]
22	$\text{NH}_3^+ + \text{OH}^- \rightarrow \text{NH}_3 + \text{H}_2\text{O}$	3.3×10^{10} [14]	20.0* [34]
23	$\text{NH}_3 + \text{H}_2\text{O} \rightarrow \text{NH}_3^+ + \text{OH}^-$	$9.7 \times 10^{1*}$ (sm. [34])	0.0 [34]
24	$\text{NH}_3 + \text{O}_2 \rightarrow \text{NO} + \text{H}_2\text{O}$	1.2×10^8 [35]	E_w
25	$\text{NH}_3^+ + \text{HO}_2^- \rightarrow \text{NH}_3 + \text{H}_2\text{O}_2$	10^{10*}	E_w
26	$\text{H}^+ + \text{NH}_3 \rightarrow \text{NH}_4^+ + \text{H}_2\text{O}$	4.3×10^{10} [22]	0*
27	$\text{NH}_4^+ + \text{H}_2\text{O} \rightarrow \text{H}^+ + \text{NH}_3$	0.45*	72.0*
28	$\text{N}_2\text{H}_4 + \text{OH} \rightarrow \text{N}_2\text{H}_3 + \text{H}_2\text{O}$	4.5×10^9 [8]	12.0 [8]
29	$\text{N}_2\text{H}_4 + \text{NH}_2 \rightarrow \text{N}_2\text{H}_3 + \text{NH}_3$	1.2×10^7 [10]	8.2 [10]
30	$2\text{N}_2\text{H}_3 \rightarrow \text{N}_2 + 2\text{NH}_3$	10^9 [8]	0 [8]
31	$\text{N}_2\text{H}_3 + \text{O}_2 \rightarrow \text{N}_2\text{H}_2 + \text{HO}_2$	3.8×10^8 [9]	5.6 [9]
32	$\text{N}_2\text{H}_4 + \text{HO}_2 \rightarrow \text{N}_2\text{H}_3 + \text{H}_2\text{O}_2$	7.0×10^6 ** [10]	E_w
33	$\text{N}_2\text{H}_2 + \text{H}_2\text{O}_2 \rightarrow \text{N}_2 + 2\text{H}_2\text{O}$	6.0×1^7 ** [10]	E_w
34	$2\text{N}_2\text{H}_2 \rightarrow \text{N}_2\text{H}_4 + \text{N}_2$	2.0×10^4 [10]	E_w
35	$\text{N}_2\text{H}_4 + \text{H} \rightarrow \text{H}_3 + \text{N}_2\text{H}_3$	3.0×1^4 ** [36]	8.36 [36]
36	$\text{N}_2\text{H}_4 + \text{H}_2\text{O} \rightarrow 2\text{NH}_3 + \text{H}_2\text{O}$	$1.8 \times 10^{-6*}$ [37]	58.5* [38]
37	$\text{OH}^* + \text{H}_2\text{O} \rightarrow \text{OH} + \text{H}_2\text{O}$	10^{5*}	E_w
38	$\text{OH}^* + \text{N}_2 \rightarrow \text{NH} + \text{NO}$	10^{10*}	E_w
39	$\text{NH} + \text{H}_2 \rightarrow \text{NH}_3$	10^{10*}	E_w
40	$\text{H}_2\text{BO}_3 + e_{aq}^- \rightarrow \text{H}_2\text{BO}_2^- + \text{H}$	5.0×10^3 [15]	E_w
41	$\text{H}_2\text{BO}_2^- + \text{H}^+ \rightarrow \text{H}_3\text{BO}_3 + \text{H}_2\text{O}$	7.25×10^{10} [34]	12.6 [34]
42	$\text{H}_2\text{BO}_3 + \text{OH} \rightarrow \text{H}_2\text{BO}_2^- + \text{H}_2\text{O}$	$2.0 \times 10^{6**}$ [15]	E_w
43	$\text{H}_2\text{BO}_3 + \text{NH}_2 \rightarrow \text{H}_2\text{BO}_2^- + \text{NH}_3$	$2.0 \times 10^{6*}$	E_w
44	$\text{H}_2\text{BO}_3 + \text{H} \rightarrow \text{H}_3\text{BO}_3$	10^{10*}	E_w
45	$\text{H}_2\text{BO}_3 + \text{HO}_2 \rightarrow \text{H}_2\text{BO}_2^- + \text{O}_2$	10^{8*}	E_w

Table 2.
 Reaction schemes of recombination reactions in primary coolant under irradiation for nitrogen species and boric acid. Taken from Grachev et al. [4].

$\text{Fe}^{2+} + \text{OH} \rightarrow \text{Fe}^{3+} + \text{OH}^-$
$\text{Fe}^{2+} + \text{e}_{\text{aq}}^- \rightarrow \text{Fe}^{3+} + \text{OH}^- + \text{H}^-$
$\text{Fe}^{3+} + \text{e}_{\text{aq}}^- \rightarrow \text{Fe}^{2+} + \text{H}_2\text{O}$
$\text{Fe}^{2+} + \text{H} \rightarrow \text{Fe}^{3+} + \text{H}^-$
$\text{Fe}^{3+} + \text{H} \rightarrow \text{Fe}^{2+} + \text{H}^+$
$\text{Fe}^{2+} + \text{O}_2^- \rightarrow \text{Fe}^{3+} + \text{O}_2^{2-}$
$\text{Fe}^{2+} + \text{HO}_2 \rightarrow \text{Fe}^{3+} + \text{HO}_2^-$
$\text{Fe}^{3+} + \text{O}_2^- \rightarrow \text{Fe}^{2+} + \text{O}_2$
$\text{Fe}^{2+} + \text{H}_2\text{O}_2 \rightarrow \text{Fe}^{3+} + \text{OH} + \text{OH}^-$
$\text{H}^- + \text{H}_2\text{O} \rightarrow \text{H}_2 + \text{OH}^-$
$\text{O}_2^{2-} + \text{H}_2\text{O} \rightarrow \text{HO}_2^- + \text{OH}^-$

$\text{Cu}^{2+} + \text{OH} \rightarrow \text{Cu}^{3+} + \text{OH}^-$
$\text{Cu}^{2+} + \text{HO}_2 \rightarrow \text{Cu}^+ + \text{H}^+ + \text{O}_2$

Table 3.

Iron and copper reactions during water radiolysis, as described by Lundstrom et al. [10].

When the complete series of the species occurring in the primary coolant is considered, there exist, however, discrepancies between the results of various researchers concerning the reaction rate constants and, in addition, other important parameters, such as G-values, the yield of the species per unit of irradiation power. For instance, [10] mentions discrepancies in hydrogen G-values in various liquid compositions (water and sulphuric acid). As we will see further, the concentration of hydrogen is one of the key parameters in corrosion risk control.

Even if the kinetic data, as well as the G-values, show discrepancies when extracted from various literature sources, some qualitative conclusions are unequivocal. For example, the finding reported, e.g., by [1], that an increase in hydrogen concentration dissolved in primary coolant mitigates the corrosion risk: “When $[\text{H}_2]$ is increased from 5 to 50 Ncm³/kg, the concentration of oxidants is reduced by about 35%”. It is well known that hydrogen can be supplied into the primary coolant not only in the form of H_2 directly but also in the form of ammonia NH_3 or hydrazine N_2H_4 . And, really, to suppress the corrosive species production, the hydrogen, in one of its forms mentioned above, is usually dosed into the primary circuits of nuclear power plants around the world.

In the case of a successful description of the complete chemical system in the primary coolant, the concentration of the components of interest obtained from the simulation could be used to safely control nuclear reactor performance – remember **Figure 2**. Unfortunately, in the case of the kinetics description of other species next to pure water, significant disagreement among the data of various researchers exists. To illustrate this, see the following example.

In an effort to describe complete primary coolant radiolysis, we extended our mathematical model of pure water (based on Christensen’s data, as mentioned above) by incorporating data for nitrogen species and boric acid (based on Grachev [3]). Using literature data on chemical kinetics and G-values, we built the mathematical model and predicted hydrogen, oxygen, and hydrogen peroxide

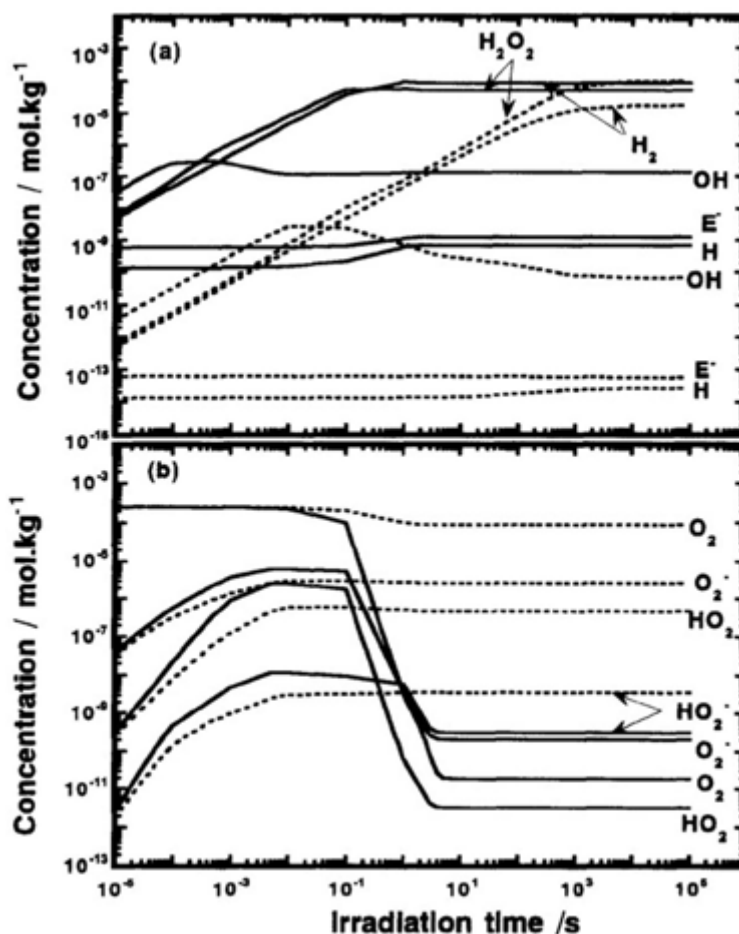


Figure 1.
 Water radiolysis time development for various irradiation rates (3600 Gy/h for dotted line and 36,000 kGy/h for full line). Taken from Sunaryo et al. [8].

concentrations, which can be controlled by ammonia dosage. Our findings confirmed literature statements about qualitative agreement in trends, but our quantitative parameters differed significantly from those in the literature. We illustrate these results in **Figures 3** and **4**, which describe the dependency of corrosive species on ammonia dosage, determining the hydrogen concentration in the primary coolant.

In **Figure 3**, we can see the results of our computation with the minimum in hydrogen concentration at an ammonia initial concentration of 2 mg/L (corresponding to an H₂ concentration of about 4.5 Nml/L). Compare it with the results in [5] in **Figure 4**, where the minimum in hydrogen concentration occurs as well.

We can see significant quantitative differences both in the NH₃ dosage concentration itself and in the hydrogen concentration, where its minimum occurs.

Even if there exist some agreements about the trends in primary coolant chemistry, the quantification data, however, show significant differences. It is, therefore, of significant importance to directly determine the concentrations of key components by process measurement using precise devices.

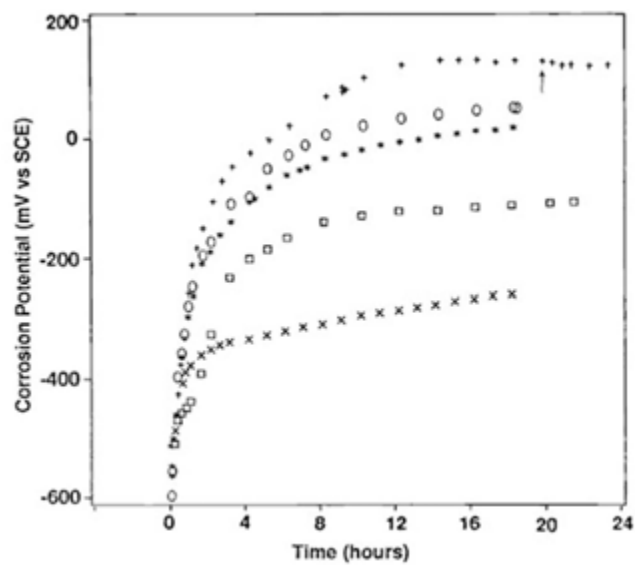


Figure 2. Corrosion potential on fuel rods surface in a nuclear reactor. Higher values correspond with higher irradiation rates in the range from 0 (“x” symbols) to 280Gy/h(“+” symbols), taken from Christensen et al. [3].

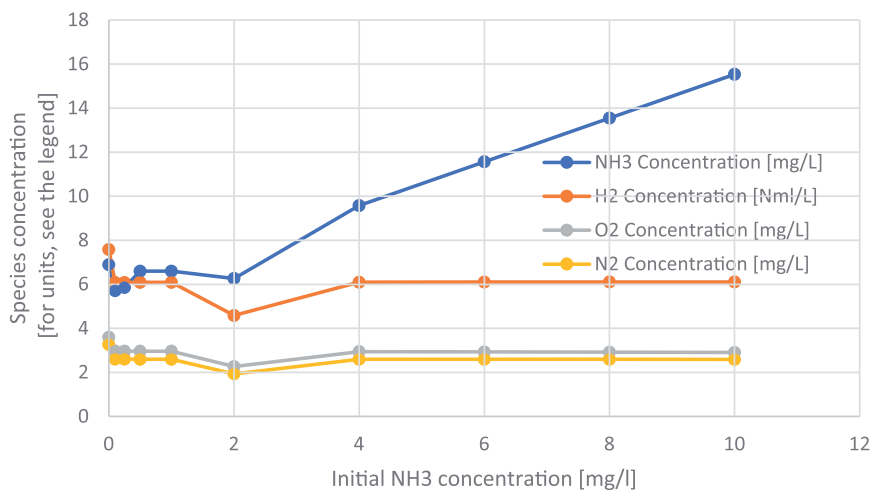


Figure 3. Concentrations of several species depending on the ammonia concentration in primary coolant, calculated for this work using our radiolysis model developed at UCT Prague.

4. Process measurement

The measurement of oxygen concentration is usually well managed; we can easily find the offerings of many manufacturers, whose devices provide fairly precise data, such as Hach, Orbisphere, Swan, Ingold, Hamilton, etc. Our workplace, the Mass Transfer Laboratory at UCT Prague, also developed a similar device, the “Oxymeter

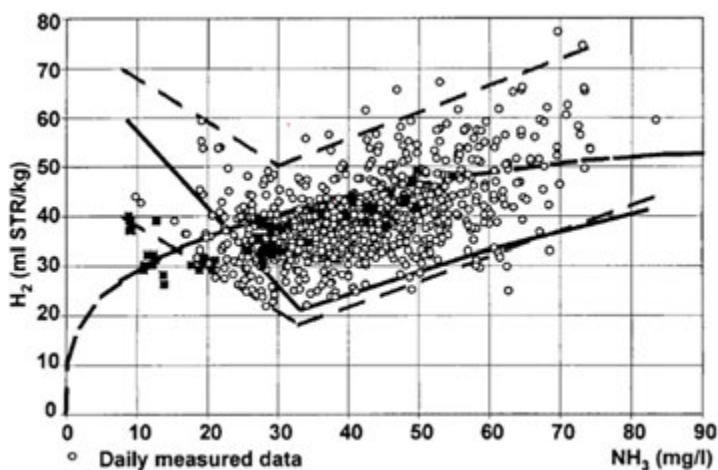


Figure 4.
 Hydrogen concentration in primary coolant in dependency on the ammonia concentration. Calculated by [5] using several mathematical models – all the lines (dashed and full) and compared with several NPPs' measured data – all the symbols (circles and squares).

LOC”, which was commercially distributed by the Asset company to nuclear power plants Dukovany, Temelin and Jaslovske Bohunice in 1990's. At our workplace, the whole book was even written about oxygen measurement using membrane-covered sensors [11].

In the field of hydrogen concentration measurement, there are, however, significantly more limited options. Compared to the amount of oxygen concentration measurement devices, for hydrogen, there are only a fraction of offered devices. And, in addition, according to the technicians in Czech nuclear power plants Temelin and Dukovany, there are larger scatters in the data of various hydrogen concentration measuring devices. Therefore, there is a lot of work in front of hydrogen sensor producers, to whom we also count our Mass Transfer Lab team at UCT Prague.

To show the reader how the oxygen and hydrogen concentrations can be measured in nuclear power plants, we will briefly describe the history of hydrogen sensor development at our workplace.

The principle of the sensor is the amperometric measurement. This means the measurement of electric current at a constant polarization voltage applied to the electrodes of the sensor. **Figure 5** shows the schematic construction of the sensor, which includes two electrodes in the electrolyte and a membrane positioned between the electrolyte and the measured environment. The figure also illustrates the process of hydrogen diffusion to the electrode through the membrane and electrolyte layer. At the anode, hydrogen molecules are consumed through an electrochemical reaction, producing H^+ ions. The hydrogen concentration gradient from the environment, which has a hydrogen concentration (partial pressure) p_{H_2} , creates a driving force for hydrogen diffusion. When the anode surface activity is sufficient, the hydrogen concentration on it becomes negligible, practically zero. In such a case, the hydrogen diffusion driving force is directly proportional to the hydrogen concentration in front of the membrane, as well as the hydrogen diffusional flow to the anode, and consequently, the electric current. Based on this physical principle, the sensor produces a signal directly proportional to the hydrogen concentration in

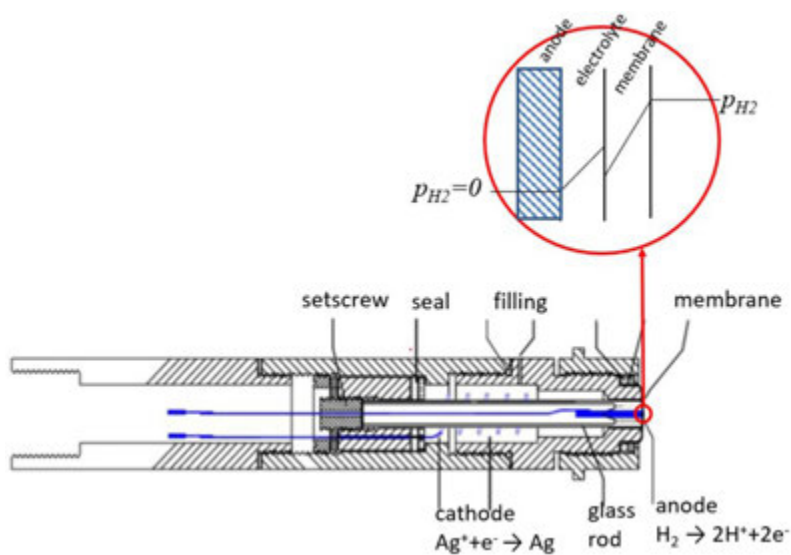


Figure 5.
The scheme of the hydrogen sensor and a detailed description of the sensor tip with the membrane, electrolyte layer, and anode.



Figure 6.
The inner part of the sensor, with a glass rod containing a platinum anode and a silver cathode wrapped around the glass rod.

the measured environment. One issue that arises here is the need to maintain the anode activity at a sufficiently high level to ensure a linear sensor signal, even at the highest hydrogen concentration expected in the measured environment.

Figure 6 shows the real geometry of the inner part of the sensor, with a platinum anode welded into a glass rod and a silver cathode wrapped around the rod, and



Figure 7.
The hydrogen sensor with the membrane-covered platinum anode in the geometric configuration used for the measurement in primary circuit sampling channel in the NPP Dukovany. A thermometer is also visible.

Figure 7 shows the entire sensor assembly with a stainless steel tip used in the sampling channel of the primary circuit.

The first issue after assembling the sensor is to determine the optimum polarization voltage, which should be applied to the electrodes to achieve the most stable signal. The values of the hydrogen sensor signal, obtained at various polarization voltages and after reaching a steady-state at each value, are shown in **Figure 8**.

We can see the plateau with an almost constant signal between 0.2 and 0.4 volt, so in this range will probably lie the optimum setting for process measurement.

The linearity of the signal probe is a further issue, which can provide evidence that the activity of the platinum anode surface is sufficiently high. **Figure 9** shows the results of the tests, which employed three easily available values of hydrogen concentrations: zero in the air, atmospheric pressure (about 100 kPa) of pure hydrogen flowing through the measuring cell to the atmosphere, and an increased pressure of about 115 kPa obtained by introducing hydrogen output from the cell to a manostat containing approximately 1.5 m of water.

The linearity of all five sensors tested showed that the preparation of platinum electrode surfaces resulted in a sufficiently high activity to consume all the hydrogen transported through the sensor's membrane.

When a new electrode surface is prepared, various compounds are formed there, called PtOx, for instance. To obtain a long-term stable hydrogen sensor, it is good practice to let the electrodes mature. The initial period of new electrodes' life is shown in **Figure 10**.

We can see that it is desirable to take at least a three-week period before the hydrogen sensor is installed in an industrial application. After all these initial activities, we can finally measure the hydrogen concentration under process conditions. **Figure 11** shows our first attempts to record hydrogen concentration at atmospheric pressure. Comparing the atmospheric pressure trends with those of the

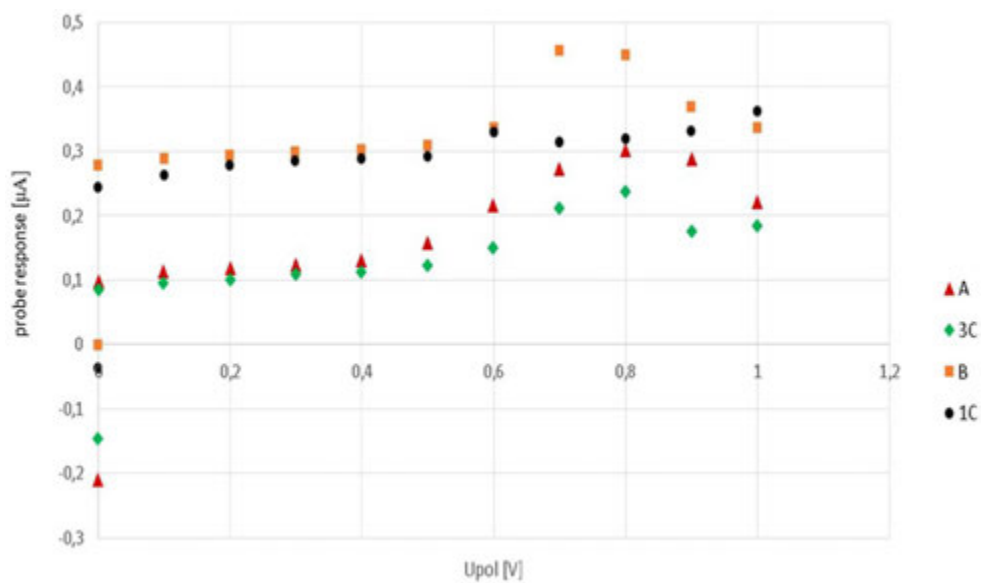


Figure 8.
Polarograms of several hydrogen probes made to determine the voltage plateau suitable for amperometric hydrogen concentration determination.

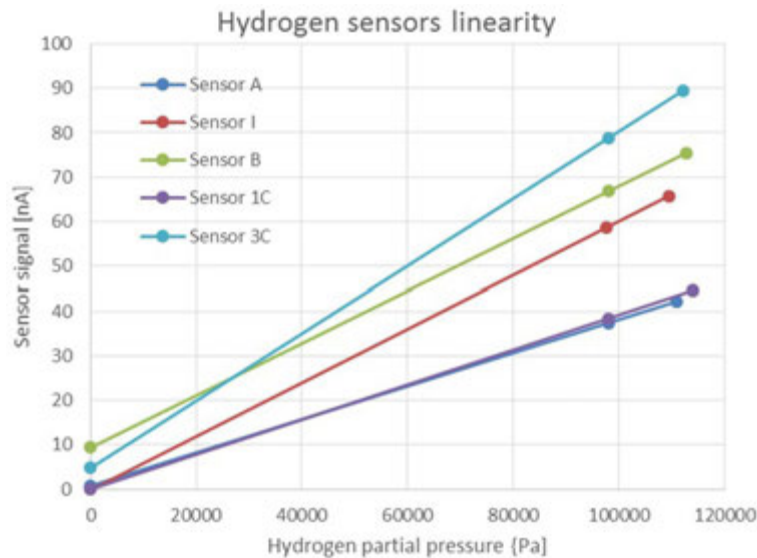


Figure 9.
Signal linearity tests for several hydrogen sensors prepared in mass transfer.

sensor signal, we observe fairly high sensitivity of the sensor to small changes in hydrogen total pressure when the output of the measuring cell is opened to the atmosphere.

Believing we had in hand the sensor, which was sufficiently stable and sensitive, we arranged the first measurement under process conditions in the primary circuit sampling channel at the NPP Dukovany. We performed one week of continual

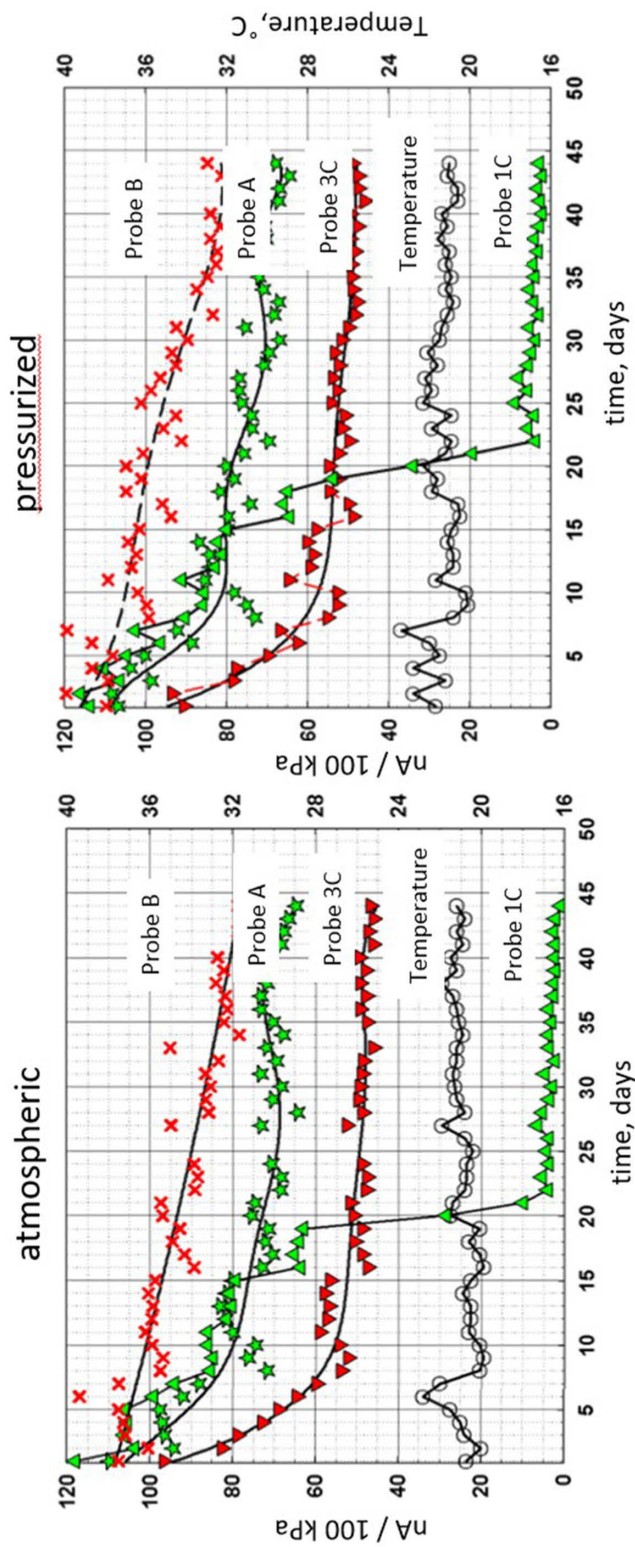


Figure 10.
Initial parts of hydrogen sensors signal-time profiles after sensor's preparation, which is called electrodes maturing.

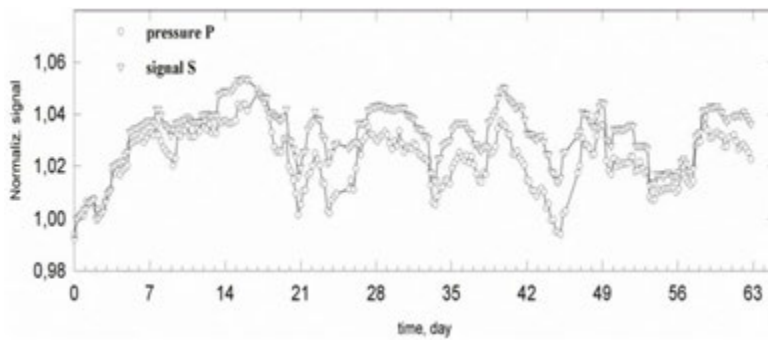


Figure 11.

First longer-term signal profile at laboratory conditions. Signals and pressures are normalized by their initial values to easily identify percentage changes.

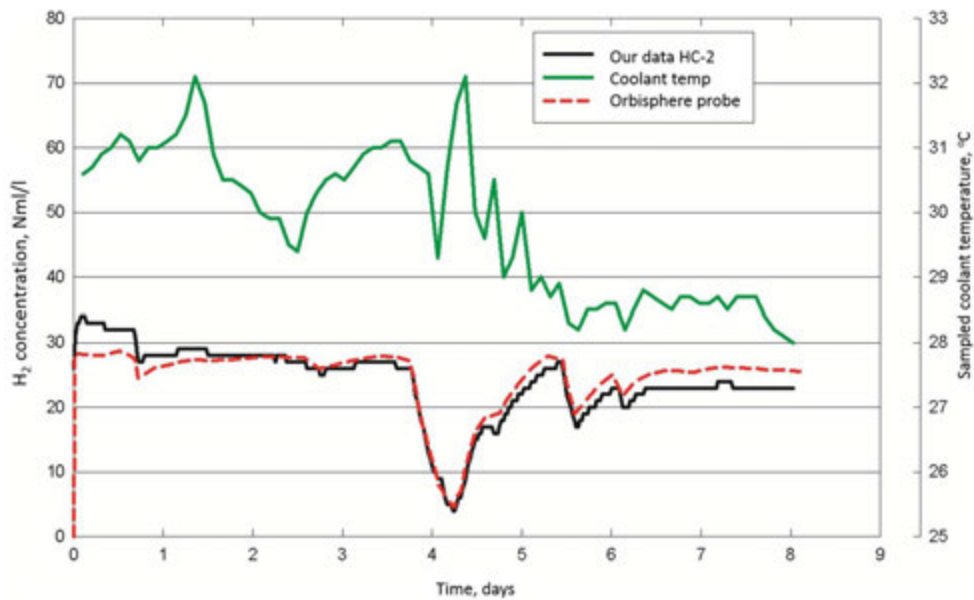


Figure 12.

First process measurement in the primary circuit's sampling channel in NPP dukovany.

measurement and found a significant decrease in the signal sensitivity, as you can see in **Figure 12**. Within one week, the signal decreased by about 1/3 with respect to the values measured by the standard Orbisphere device (compare 33 vs. 28 Nm/l at the beginning of the measurement, when our sensor showed a hydrogen concentration 5 Nm/l higher, and 23 vs. 26 Nm/l at the end, when our sensor showed a hydrogen concentration 3 Nm/l lower).

After finding that the signal decreases significantly in a short time period, we focused on the electrodes' surface preparation to prolong the sensor's life-time. Usually, the electrodes in amperometry are considered to be fairly refreshed by short-term changes in polarization voltage. In the case of the hydrogen sensor, we,

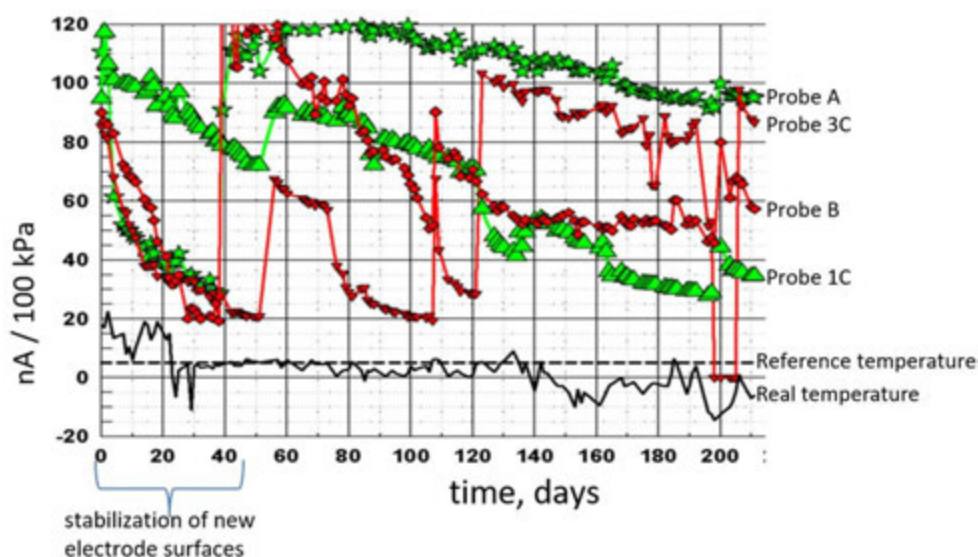


Figure 13. Testing of different techniques of electrode surface preparation effects on (i) signal sensitivity and (ii) long-term stability: polarization voltage changes, electrochemical processes.

however, found that the electrochemical treatment of electrodes was necessary to achieve higher long-term sensitivity, while the change in polarization voltage caused significant electrode refreshment for only several days. The signals of hydrogen sensors during the tests of the refreshment possibilities are shown in **Figure 13**.

To explain the signal profiles in **Figure 13**, the description of the test situation follows.

40th day – electrode surface renewal (electrochemical) in the probe B $\gg$ rapid signal increase,

55th day – refresh of all the sensors using polarization voltage change

73rd day – poisoning of the 3C electrode by H_2S (often occurring in petrochemistry) and subsequent attempt to refresh the surface (108th day) using polarization voltage change, and after that by electrochemical surface renewal (122nd day).

On the 3C probe signal, we can see the difference between the attempt to refresh the electrode activity by polarization voltage change and the real, long-term effective refreshment achieved through electrochemical processes using several acid solutions.

After a broad study of literature and experimental tests on the behavior of hydrogen sensor electrodes using various methods of surface preparation, we achieved significantly better stability. This can be seen from the following results of testing the “new generation” probes.

First, the long-term stability under laboratory conditions was tested for 220 days, as shown in **Figure 14**. In addition to the long period of fairly stable signals, we can also observe a rapid increase in signals during the last several days, when verification polarograms of all probes were performed, and the polarization voltage was changed in the range of 0 to 1V every day.

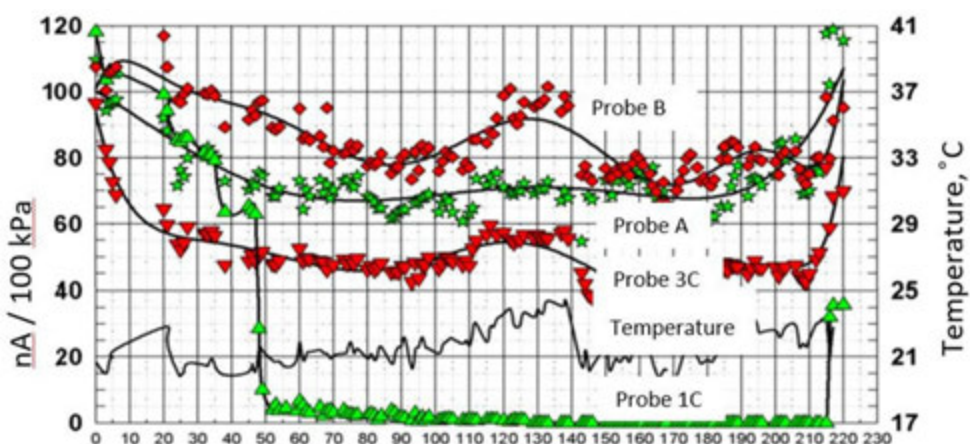


Figure 14.
Results of a long-term stability testing of four sensors. The signal increase at the end of the record was caused by polarization changes when the polarograms were performed.

Because the diffusivity and solubility of hydrogen in the sensor's membrane are significantly temperature-dependent, the temperature dependence of the probe signal is significant too. Therefore, we determined the average value of the parameter we entitled "membrane activation energy, E " and using an Arrhenius-shaped equation, as shown in **Figure 15**. Even if the data smoothing is not perfect when a single average value of activation energy, E , was used for all probes, we can see a substantial improvement.

This finding of remaining data noise indicates that the membrane used to cover the sensor's anode is not of a quite homogeneous structure, and each anode is covered by a membrane piece with slightly different diffusivity and solubility of

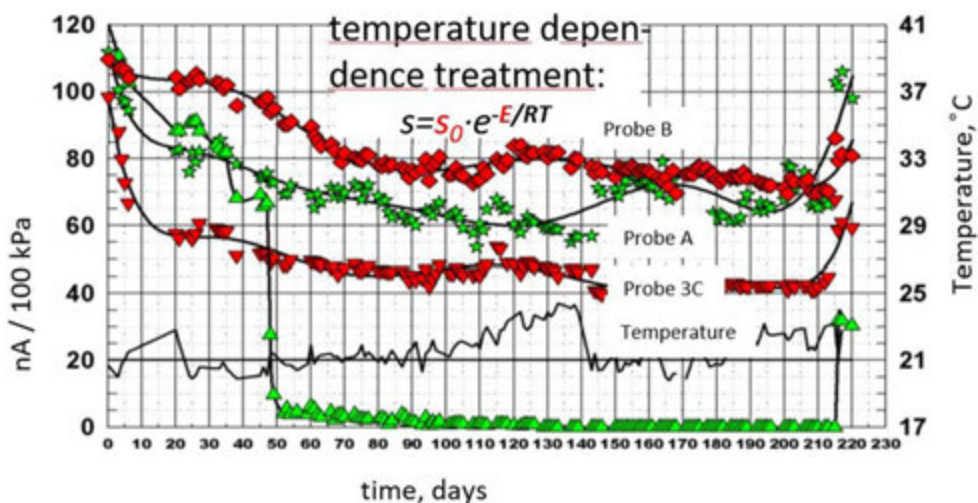


Figure 15.
Long-term signals of four hydrogen sensors tested. The signals are partly smoothed by temperature correction using a single, averaged membrane activation energy for all the sensors.

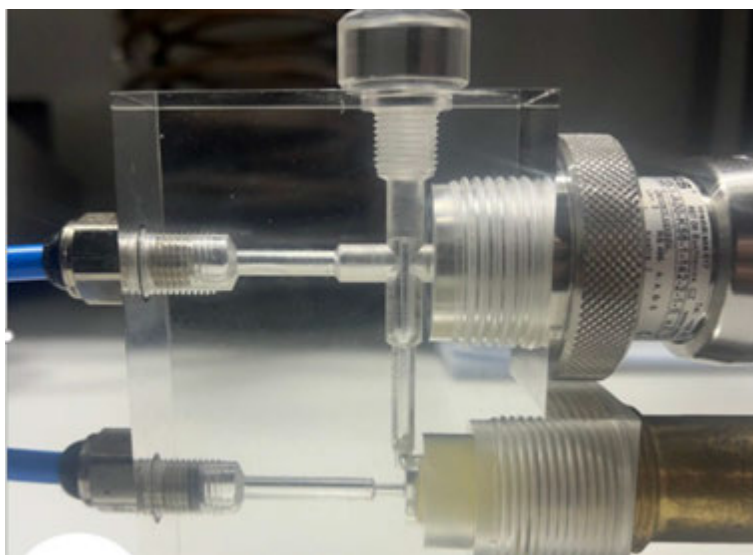


Figure 16.
Measuring cell: the liquid input enters from the left and flows against the hydrogen sensor located at the bottom of the figure. At the top, we can see the manometer and the liquid output.

hydrogen. Further, the thickness of the membrane depends on the degree of its stretching during the probe preparation, which, of course, is not strictly constant in the manufacturing process. This results in the need to determine the membrane activation energy for each hydrogen sensor separately.

After the laboratory tests, we started further measurements in the nuclear power plant. It is also worth noting that when the amperometric probe is used, which consumes hydrogen in front of its membrane, it is necessary to ensure a sufficient fluid flow along the membrane to eliminate the risk of a hydrogen concentration decrease near the membrane surface. Otherwise, the sensor would provide undervalued data. On the other hand, the sampling stream represents a kind of leakage of primary circuit coolant, so its flow should be as low as possible. To cope with these contradictory requirements, we use the measuring cell, where the sampled liquid enters the sensor tip space, directing to the center of the membrane covering the anode, as shown in **Figure 16**.

The process measurement in the NPP Dukovany resulted in the sensor signal-time profile shown in **Figure 17**.

As well as in the area of mathematical modeling, the uncertainties in the dissolved hydrogen concentration measurement occur too.

Mathematical modeling brought the agreement in trends, for example *kritski v. G., Bobro v ju. G., Vasil Yev v. N., Berezina I G., Shmantsar O. P., RODIONOVJU.A.*

Figure 17 shows the decrease in the sensor signal, which is fundamentally slighter compared to the first measurement shown in **Figure 12**. The average sensor sensitivity decrease was about 5% per week now, which was great when compared to the decrease by 1/3, i.e., by 33%, during one week of the first process measurement. This sensitivity trend could be acceptable for long-term process measurements when automatic recalibration is involved.

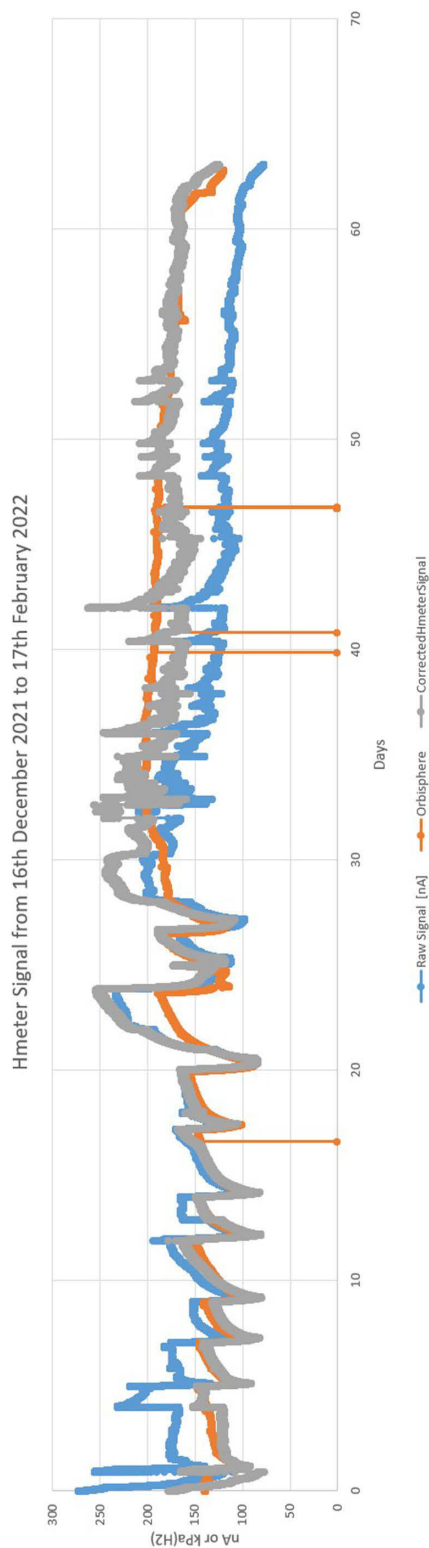


Figure 17.
63-day-record of hydrogen sensor signal in the sampling channel of the primary circuit at NPP dukovany.

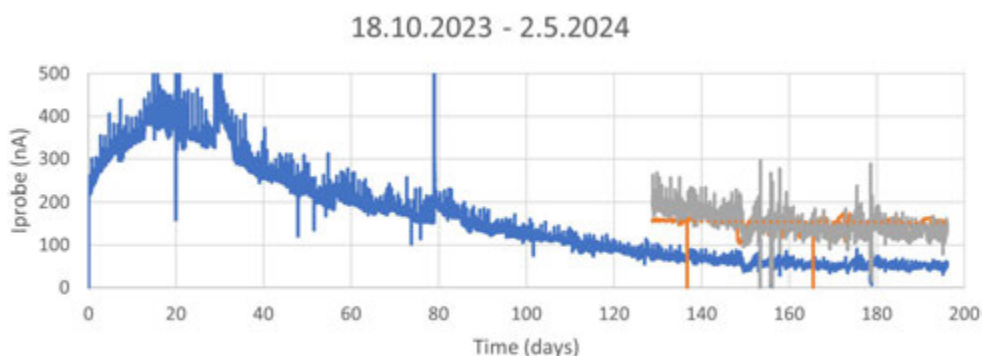


Figure 18.
 The record of a long-term signal development of the hydrogen sensor prototype developed by the Mass Transfer Lab at UCT Prague.

After further improvement of the electrode surfaces, we installed a new probe to the primary circuit of the NPP Dukovany and obtained more than half a year's record of hydrogen concentration, as shown in **Figure 18**.

After the initial period, we can see a relatively stable sensor signal, and, when the recalibration was performed, we reached fairly good agreement with the standard sensor signal, as seen in the period from the 130th day in **Figure 18**.

What is also worth noting, in the frame of the data presented here, is that the newly prepared sensor gives a much faster response (time constant usually lower than 10 seconds) than contemporary devices used in NPPs, which show time constants in several minutes. It is also evident in **Figure 12**, where we compare many local changes in the new sensor signal in contrary to the standard measurement device signal, which is rather monotonous over longer time periods. This feature makes the new sensor a viable option to be considered for use in an early warning system when hydrogen concentration increases in an unwanted space.

5. Conclusions

We followed the idea of improving NPP's safety by contributing to a better analysis of nuclear reactor primary circuit behavior. Within the framework of this idea, we investigated the possibilities of mathematically simulating the situation, i.e., quantifying chemical processes in the primary coolant irradiated as it flows through the active zone of a nuclear reactor. Upon obtaining results that showed only a qualitative agreement with the trends in individual species concentrations in the primary circuit, when various literature sources were employed, we concluded that mathematical simulation alone is not sufficient. To reliably control the primary circuit chemistry, and thus minimize the corrosion risk, it is necessary to directly measure the concentration of key species. Hydrogen, the presence of which suppresses the production rate of corrosive molecules like H_2O_2 and O_2 , certainly belongs to these key species. Since information from the nuclear industry indicates that there are not many reliable devices on the market for determining the concentration of hydrogen in the primary circuit, we have described our long journey of developing the hydrogen sensor into its current prototype form. In addition, faster response times of the new sensor were achieved, enabling it to also be used in an early warning system in case of hydrogen leakage.

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Section 2

Technological Innovation

Perspective Chapter: The Visual Cognition and Attention Allocation Principles in Nuclear Power Monitoring Operations

Xiaoli Wu

Abstract

In the monitoring tasks within the nuclear power plant control room, operators engage in human-machine interactions across multiple screens and equipment groups during task execution. They face challenges such as ambiguous information hierarchy between screens and equipment, spatial perception barriers, and difficulties in adapting and coordinating interaction methods. These issues are highly likely to lead to visual cognitive problems, such as perceptual bias and attention disruption. This study aims to explore the visual attention-capture mechanism in cross-screen and cross-equipment group interactions, propose an experimental paradigm for visual attention capture in nuclear power monitoring operations, and reveal the principles of operator attention capture in hybrid display work scenarios. The research clarifies how operators screen key information through visual attention during monitoring tasks and optimizes human-computer interface design and task process arrangements accordingly. Furthermore, by constructing a perceptual span prediction framework and a cognitive bias effect paradigm for operator visual interaction, this study establishes principles for information function allocation in monitoring operations, which can accurately describe visual behavior and cognitive mechanisms in such tasks. Overall, operators' cross-screen interaction is a complex and dynamically evolving cognitive process involving the coordination of multiple cognitive elements, such as memory, thinking, and visual search. It is recommended that future designs focus on the salience of information presentation, consistency in screen layout, and relevance of task-related information to enhance the safety and reliability of cross-screen interaction.

Keywords: nuclear power monitoring, cross-screen/cross-device interaction, visual cognition, attention capture, visual interaction principles

1. Introduction

The intelligent nuclear power display and control system is a typical complex information system [1]. The human brain is no longer able to handle the large amount of information within it. The main control room is the “nerve center” of the nuclear

power display and control system and is also a typical multiscreen scene [2]. The advancement of nuclear power intelligent technology has intensified the human factors challenges of the main control room, especially in cross-screen interaction [1]. The most common human-computer interaction behavior in the nuclear power main control room is cross-screen information search activities, which occur across different screens or paper documents [3]. As shown in **Figure 1**, in the key information center, the operator needs to manage information distributed across the visual display unit (VDU), large display panel (LDP), and paper documents. The cognitive process of the operator's cross-screen interaction behavior not only involves the processing and transmission of information but also deeply reflects the operator's cognitive strategy and behavior pattern in a specific task environment, which can lead to cognitive overload risks, including visual fatigue, attention distraction, and decision-making errors.

2. Visual cognitive process of cross-screen task operation

2.1 Operator's cognitive process

The nuclear power display and control system is a human-machine interactive system monitored and controlled by the operator. The operator's control of the nuclear power plant can be divided into four stages: "monitoring/detection-status assessment-response plan-execution" [4]. These four stages constitute a complete control cycle and reflect the core workflow of the operator in the nuclear power display and control system. In the "monitoring/detection" stage, the operator monitors the operating parameters and status information through the display interface to promptly identify abnormalities or potential risks; in the "status assessment" stage, the current operating conditions are analyzed based on the monitoring information, the nature and impact of the abnormality are determined, and a basis for subsequent decision-making is provided; in the "response plan" stage, a response plan is formulated based on the evaluation results; and finally, in the "execution" stage, control is implemented through the system according to the plan's operating steps. According to NUREG/CR-6633[4], during the monitoring phase, operators mainly obtain information from the distributed control system, with vision as the main source (accounting for 80–90%), followed by hearing (5–10%), and the rest obtained through smell, taste, and touch. Therefore, this study focuses on the relevant mechanisms of visual attention.

In the intelligent nuclear power display and control system, the numerous information sources require the operator's senses (especially the visual information channel) to adapt to frequent cross-screen interaction scenarios. Human-computer interaction in different task scenarios involves various nuclear power display and control systems and tasks. Different task modes have distinct requirements for human-computer interface information configuration, information feedback, and interactive operations [5]. The operator primarily obtains the dynamic nuclear power plant information in the monitoring interface through the visual channel and performs attention allocation and cognitive processing. Multiple screens in the main control room workstation simultaneously present physical visual information to the operator, but the operator's attention resources and visual channel processing capabilities for information are limited [6], making it easy for the

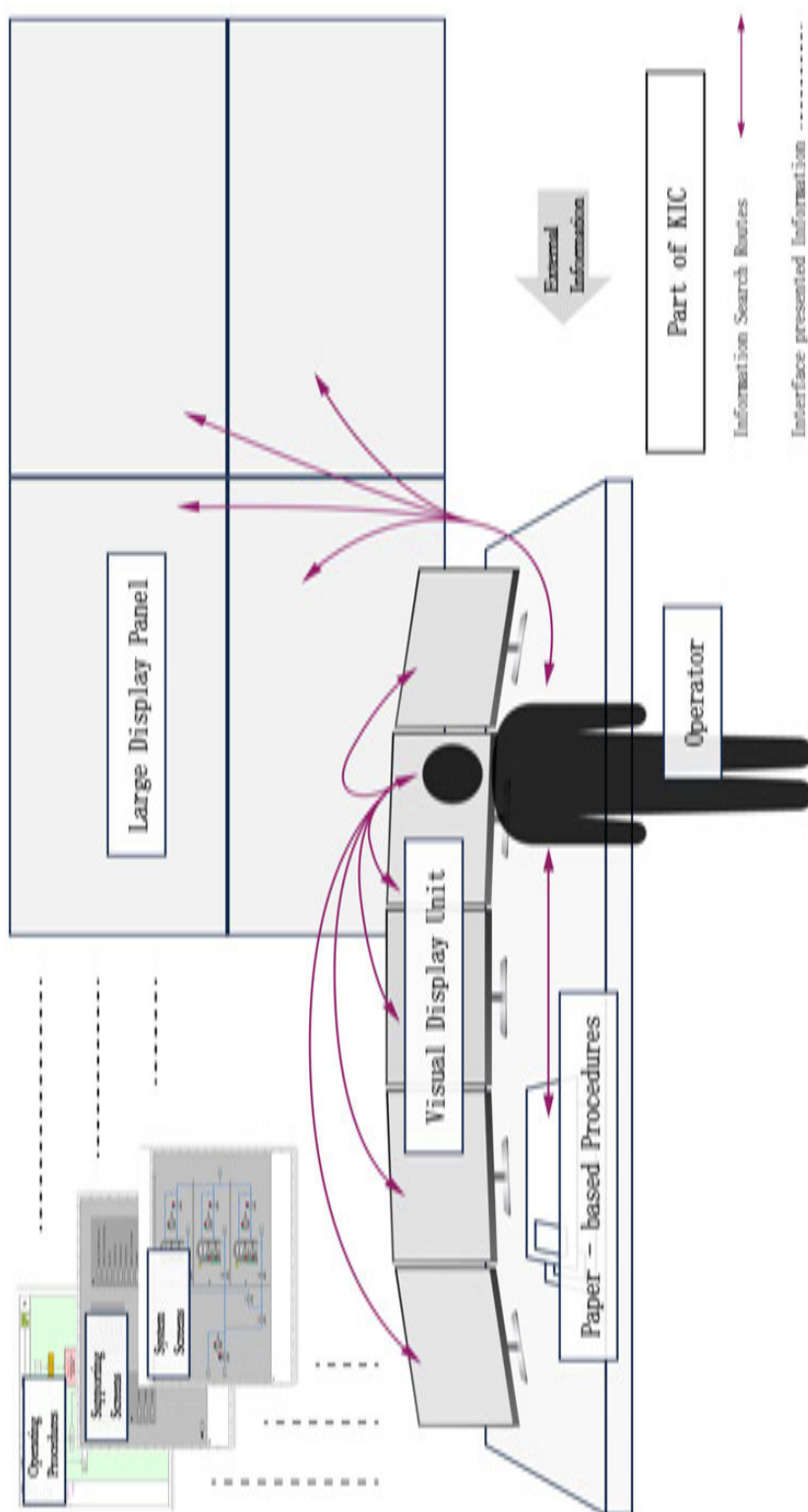


Figure 1.
The cross-screen information search activity.

operator to make mistakes during cross-screen interaction. Therefore, cross-screen/cross-device information presentation needs to consider the degree of visual attention capture of different element features. Through attention screening, information that is not related to the current task is suppressed, and some relevant information is selected to enter the visual processing channel for processing [7], enabling the operator to easily browse and understand complex information.

2.2 Attention-capture principle

In recent years, researchers have often used eye-tracking technology to record gaze points to help designers determine the important information that needs to be highlighted on the interface, thereby guiding the user's attention [8–10]. Users have a certain attention bias on the interface. Researchers have constructed various attention-capture mechanism models to organize information into a visual hierarchy, allowing users to quickly understand and process information.

Nikolic et al. [11] conducted an experiment to explore the effectiveness of visual starting points in capturing attention when they were placed in several different display backgrounds with varying colors and dynamics. The results showed that other display conditions demonstrated that dynamics affected performance more strongly than color similarity between the target and the background. Imbert et al. [12] evaluated the ability of five air traffic control notification designs to attract attention during ongoing supervision tasks and their impact on the main task. Intrusive designs impaired the performance of the main task. Owens et al. [13] explored the effects of sudden local changes and element prominence on the interface on the attention-capture mechanism. Ruthruff et al. [14] verified through experiments that interface information prominence has the advantage of attention capture due to its saliency and pointed out that static colors can only attract attention when they are relevant to the task. Stolte et al. [15] conducted an experiment to explore whether abnormal flicker frequency, a kind of motion vision, would have an attention-capture effect. The results showed that abnormal flicker frequency would cause an attention-capture effect and also exhibit the phenomenon of return inhibition. Wang Qiuzhen et al. [16] used eye-tracking technology to study the visual trajectory of users when facing complex website interactive interfaces and thus studied the mapping relationship between cognitive load and visual attention. Wu Xiaoli [17] proposed the error mechanism and corresponding cognitive principles of users in complex information system interfaces. Li Jing [18] explored the influence of shape features in human-computer interfaces on attention-capture ability, believing that it would guide and restrict attention capture. Experiments have shown that increasing the difference between shape features and their attributes will make the target shape easier to capture attention.

Since the information received by the human visual system far exceeds the processing capacity of the brain, the attention selection mechanism is crucial. In the bottom-up processing process, exogenous stimuli (such as salient or emergent features) often automatically capture attention and interfere with goal-oriented behavior. This phenomenon of capturing attention is called attention capture [19]. Domestic scholar Chu Hengqing pointed out that although attention capture is an automatic process, it can be regulated by endogenous attention, which manifests as inhibition or facilitation [20]. When the task requires high attention concentration (such as joint search), irrelevant stimuli are less likely to trigger attention capture;

while in a state of relaxed attention, interfering stimuli are more likely to attract attention. In addition, attention capture is also affected by task strategy. Stimuli that meet the task set are more likely to capture attention, regardless of whether they are targets or distractors. There are two main views on the current research on attention capture: Scholars represented by Theeuwes emphasize stimulus-driven attention capture and believe that salience itself can trigger attention shifts [19, 21]; while scholars such as Folk emphasize top-down control and believe that only stimuli that match the task goals can trigger attention capture [22, 23].

2.3 Attentional capture mechanism in the operator's cognitive process

During the operation in the main control room, the operator needs to deploy multiple information processing resources, such as attention, reasoning ability, and memory, to complete the main task being performed and the secondary task of monitoring and browsing the information system, as shown in **Figure 2**. Attention resources play an important role in the above cognitive process [24]. Zhang Li et al. [2] established the visual attention mechanism and cognitive mechanism of the operator's monitoring process and the cognitive process of the state assessment process.

During task cognition activities, the information on the display and control interface continuously captures the operator's attention through stimulus-driven or purpose-driven methods [25, 26]. Stimulus-driven attention arises from the physical salience of information and often appears in secondary task monitoring, while purpose-driven attention stems from task requirements such as procedure execution, status assessment, or response planning, guiding attention to focus on key information. These two driving mechanisms correspond to the "bottom-up" and "top-down" attention pathways [27], respectively, throughout the operator's entire cognitive process. Visual attention has an important influence on cognitive behavior in intelligent nuclear power display and control systems. Therefore, the introduction of an attention-capture mechanism helps to optimize the presentation of interface information and improve the recognizability and integration efficiency of key information, thereby enhancing interface usability and supporting operators in completing tasks efficiently.

3. Visual cognition process of operators' cross-screen interaction behaviors

3.1 Research on visual search monitoring cross-screen interactive behavior

Establishing a user behavior model is an important way to understand the behavior patterns and habits of users in cross-screen interaction. María Lozano et al. [28], Wu Dan, and Liang Shaobo [29] built relevant search behavior models based on grounded theory and selected more device types to collect more types of user data. Based on the data description, they explored the underlying causes and analyzed the personalized differences in user behavior. Wang Xiwei et al. [30] focused on the user transfer behavior of social media and built a theoretical model based on the expectation confirmation theory, immersion theory, and information system success model, focusing on whether and to what extent each factor would affect the user

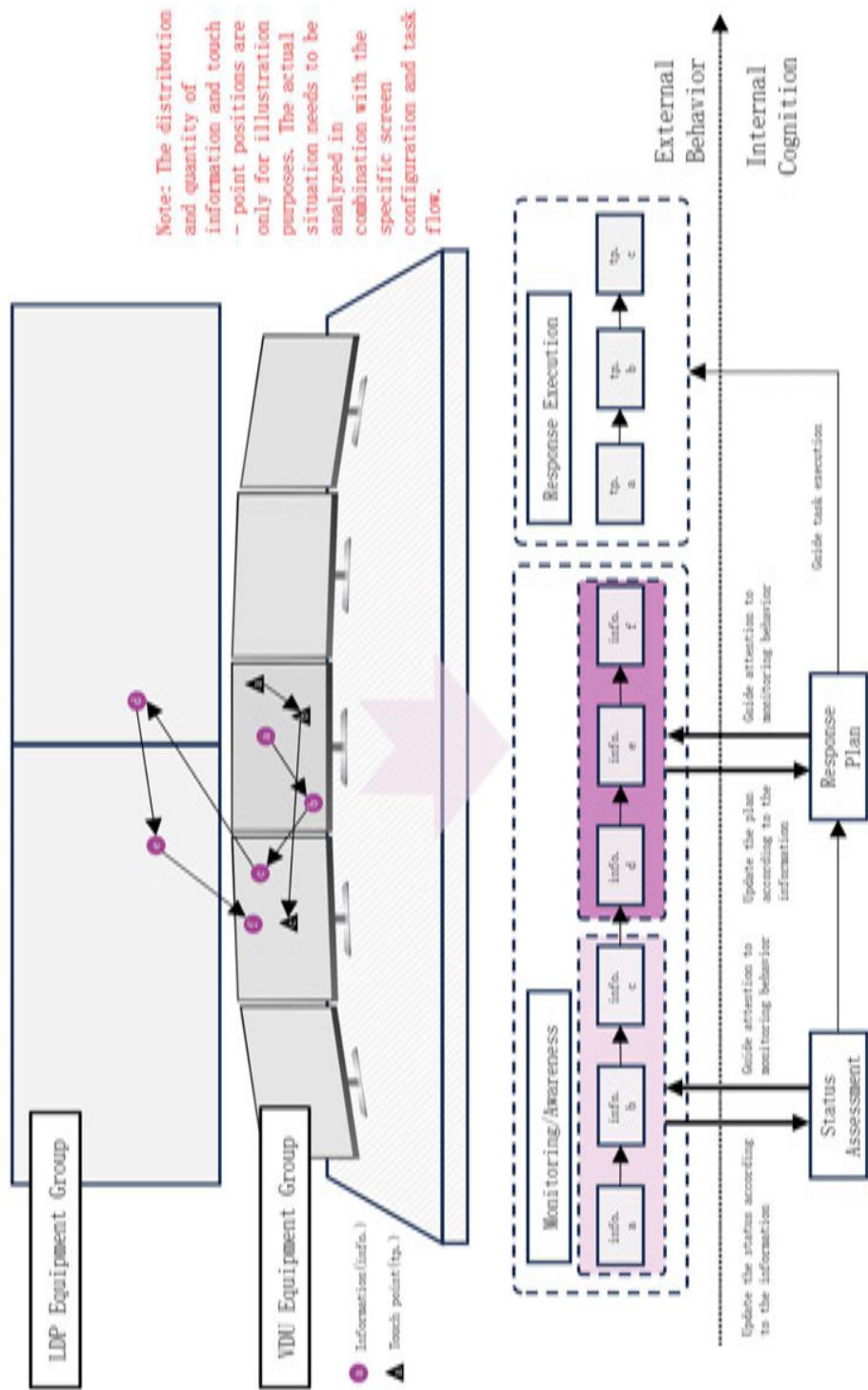


Figure 2.
Visual search area and cognitive process during operator cross-screen interaction.

transfer behavior. The goal of cross-screen interaction is to provide a good user experience and satisfaction. Due to the differences in operating systems, screen sizes, and input methods between different devices, developers need to spend more effort to adapt and optimize applications to ensure a good experience on different devices [31]. Dong-Hee Shin et al. [32] used neural networks to analyze user behavior on multiscreen services to predict user experience satisfaction and prioritize factors that affect user intention. Chen Yadan et al. [33] studied the correspondence between user experience elements and mental models based on the characteristics of multiscreen interaction and its influencing factors and proposed a method of seeking commonalities at the microlevel and emphasizing usage scenarios at the macrolevel to build a consistent multiscreen interaction experience.

3.2 Cross-screen/cross-device interaction

Cross-screen, as the name implies, means “crossing the screen.” Crossing is not limited to a single screen but can refer to multiple devices of the same type or different types of devices [34]. This concept is often considered as one with concepts such as multiscreen, cross-device, and multidevice.

Cross-screen interaction is a way of transmitting and interacting with information and functions through multiple screens or devices [35]. Cross-screen interaction is widely used in daily office environments, entertainment and leisure [36], education and learning [33], and even in production and manufacturing [37], national defense and military [38], and other fields. Domestic and foreign researchers focus more on the cross-screen interaction behavior mechanism from the perspective of the mobile Internet environment, and research on complex information systems is relatively scarce.

The nuclear power main control room is the “nerve center” of the nuclear power display and control system and is also a typical multiscreen interaction scenario. Operators interact with multiple VDUs, LDPs, and other equipment groups, so the interaction between screens can be divided into same-screen interaction and cross-screen interaction [39]. Cross-screen interaction can be further divided into cross-screen interaction within the same device group and cross-screen interaction across device groups [34], as shown in **Figure 3**.

3.3 Visual search and cognitive processes of operators interacting across screens

Visual search refers to the process by which a person or animal finds a specific target through a series of gazes, scans, and information processing. Visual search involves two basic processes: The first stage is called “scanning,” and the second stage is called “searching.” First, all display locations are processed in parallel to extract a limited amount of information. Then, the visual field is limited to the location of interest, and more complex processing is performed to extract additional information.

The operator’s behavior of searching and locating target information in the main control room environment can be referred to as information search or visual search. The primary media for operators to obtain nuclear power plant information from the main control room through visual channels are the operator workstation, the large LDP screen in front of the main control room, and a small number of paper documents. Based on the needs for nuclear power plant status tracking, warning,

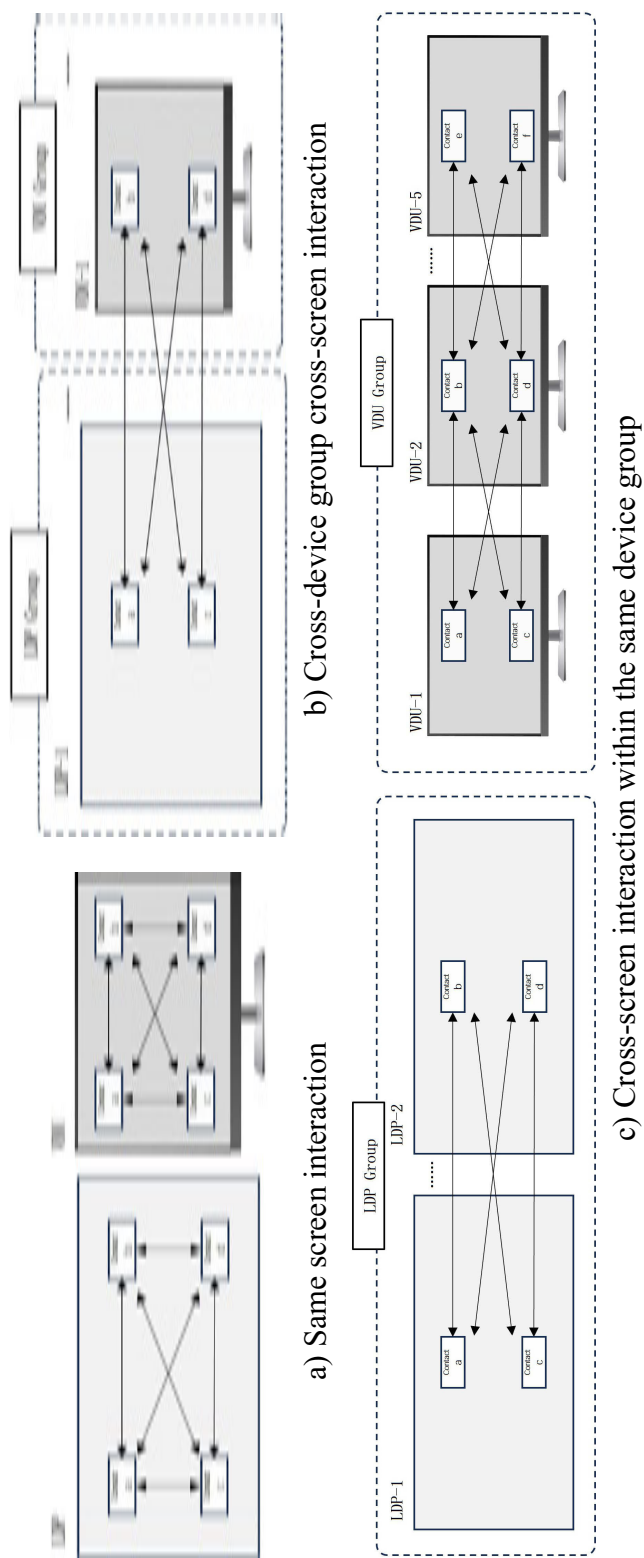


Figure 3.
Nuclear power display and control: same screen/cross-screen interactive scenarios.

and control information, operators must search for and locate target information in the operator workstation VDU and the front LDP screen. Therefore, monitoring transfer can be roughly divided into three stages: determining monitoring targets, target information search, and target information location [40]. The target information search area or path is mainly concentrated in the operator workstation's multiple VDUs, the multiple LDP screens in front, and paper documents.

At the beginning of task execution, the operator quickly scans each display screen through visual attention to obtain preliminary task information. This process relies on intuitive reaction and quick judgment and is the initial stage of cognition. Cross-screen interaction is particularly critical in this process. Whether switching screens within the same device group or between different groups, the purpose is to obtain more detailed information to update the system status and adjust the response plan. This requires the operator to have strong spatial cognition, information association ability, and understanding of the functional differences of the equipment. Throughout the interaction process, the operator's cognitive state gradually develops from initial perception to in-depth analysis and comprehensive decision-making, and the cognitive process continues to change dynamically. In addition to goal-driven attention capture, the physical salience of interface information may also trigger visual attention transfer. Cognitive elements such as visual attention, memory, and thinking work together to support the effective execution of cross-screen interaction.

4. Operator cross-screen interaction behavior model based on an attention-capture mechanism

The cross-screen interactive behavior of operators in the nuclear power display and control system is a complex and sophisticated cognitive process, involving cognitive strategies and behavioral patterns in information processing and task environments. In order to deeply understand this behavior, this section constructs a cross-screen interactive behavior model based on the attention-capture mechanism, as shown in **Figure 4**, which integrates the interactive relationship between information elements and screen configurations [41].

In a multiscreen information environment, operators need to filter key information through the cognitive system and switch across screens. The attention-capture mechanism plays a core role in this process, which can be divided into two modes: bottom-up stimulus-driven and top-down purpose-driven. In the bottom-up mode, significant or urgent information (such as alarms or parameter changes) automatically attracts the operator's attention and prompts them to respond quickly. Its efficiency depends on the physical properties and perception threshold of the information, but excessive stimulation may also lead to distraction and affect the decision-making effect. In the top-down mode, the operator actively focuses on key information and switches purposefully between different screens based on task goals, experience, and knowledge structure, continuously updating the mental model until the operation feedback is completed. Individual status, task context, and attention resources interact with each other and jointly shape cross-screen behavior. In actual operation, these two attention mechanisms do not exist in isolation but are dynamically intertwined and synergistically act on the operator's cognition and decision-making process.

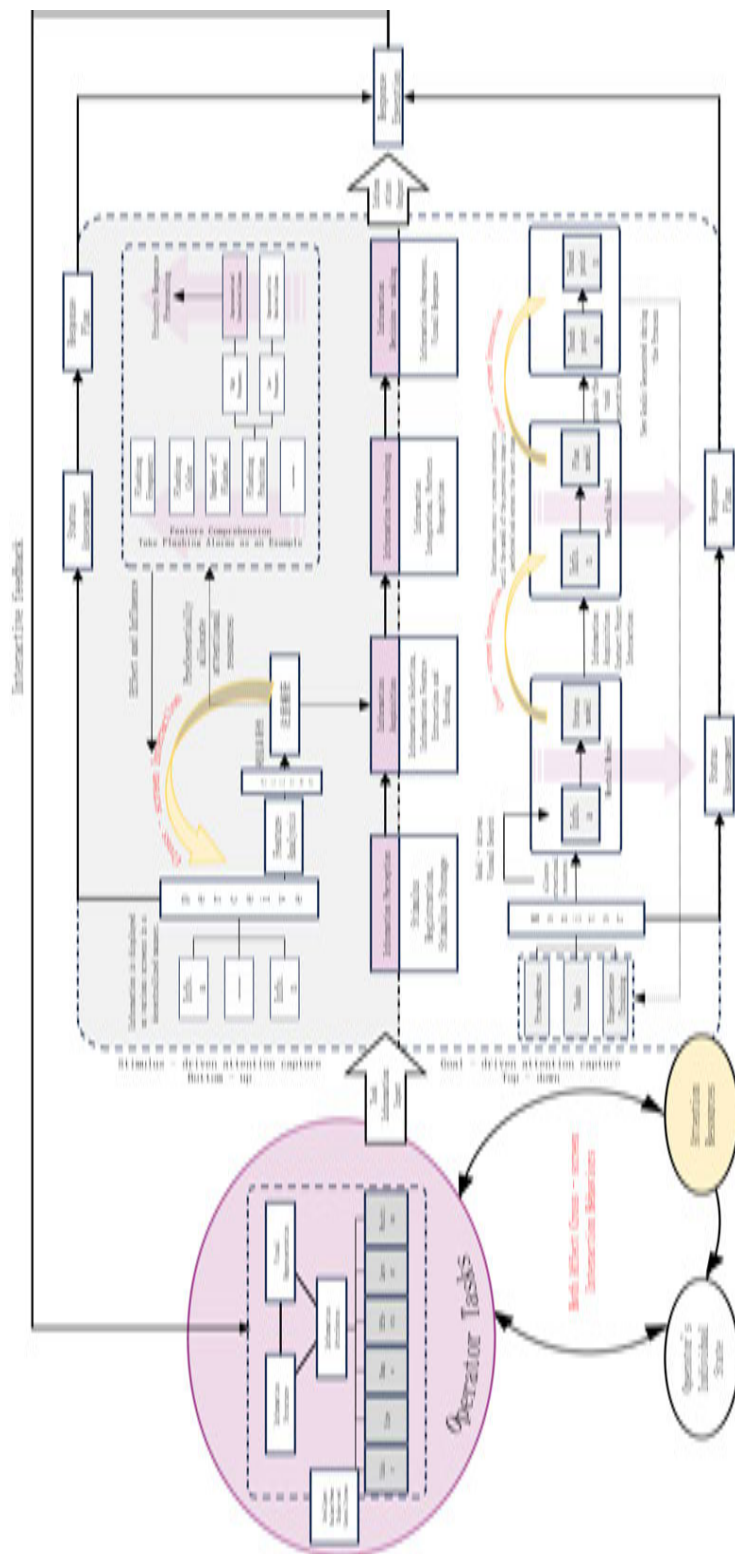


Figure 4. Operator cross-screen interaction behavior model based on the attention-capture mechanism.

5. Cross-screen/cross-device interactive attention-capture experiment

5.1 Cross-screen/cross-device interactive attention-capture experimental paradigm

Based on the operator cross-screen interaction behavior model of the attention-capture mechanism, a behavioral experimental paradigm for studying the operator's attention-capture effect in cross-screen interaction scenarios is proposed, as shown in **Figure 5**.

5.1.1 Experimental purpose

The experimental purpose of this paradigm should be to systematically collect and evaluate various indicators related to attention capture in cross-screen scenarios (such as typical task scenarios of intelligent nuclear power display and control systems) and to conduct in-depth research on the influence of information factors, task factors, and scenario factors on the cross-screen interaction behavior of subjects from the perspective of stimulus-driven/goal-driven attention-capture mechanisms.

5.1.2 Experimental variables

It is recommended that researchers closely combine the specific task context and the type of attention-capture effect on cross-screen interaction within the context when setting experimental variables. The cross-screen interactive attention-capture experiment needs to build a framework around the three factors of context, information, and task:

- (1) Contextual factors: As a prerequisite for the experiment, it is necessary to clarify the screen category configuration, the device/screen layout relationship, and the information presentation method, and to ensure at least dual-screen interaction to evaluate the impact of the scene on attention capture.
- (2) Information factors: Focus on the visual attributes (layout, color, size, etc.) of interface elements (text, images, etc.), and its design needs to balance task requirements and visual appeal (there is a sufficient research foundation).
- (3) Task factors: Guide user behavior and attention allocation through task difficulty, relevance, sequence, and specific requirements (such as time limits and accuracy). It is necessary to combine the scene and information characteristics for comprehensive design and to examine the interaction effect of multiple factors.

5.1.3 Experimental tasks

The experimental tasks require the subjects to interact with different screens, such as transferring stimuli from one screen to another. The experimental tasks should be designed based on experimental factors. They can be simple visual search tasks or combined with other psychological experimental paradigms.

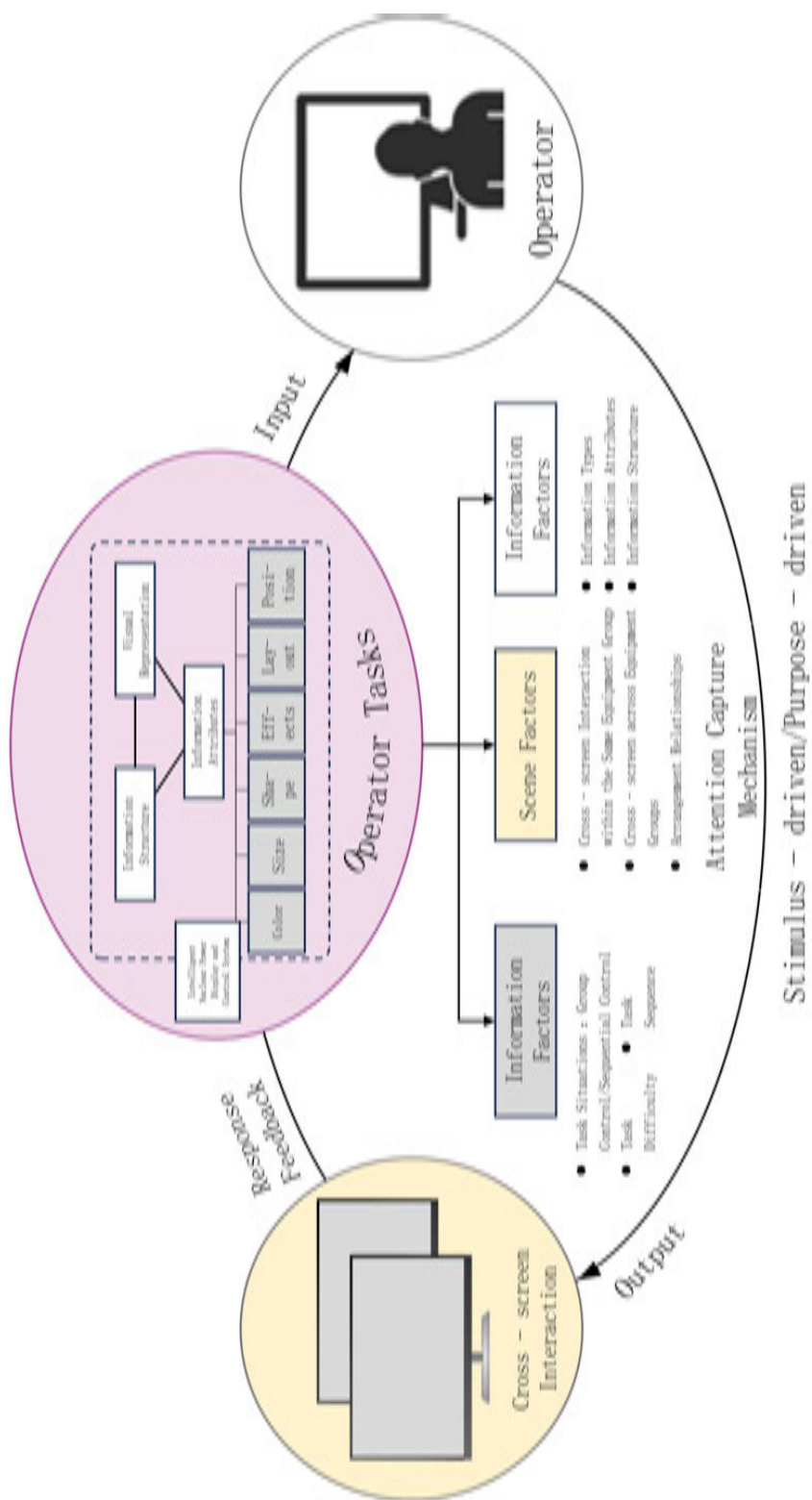


Figure 5. Cross-screen interactive attention-capture paradigm under typical tasks of intelligent nuclear power.

5.1.4 Experimental methods and selection of indicators

In the cross-screen interactive attention-capture experiment, the appropriate choice of experimental methods and the precise selection of indicators are crucial to the accuracy and reliability of the results. Common methods include behavioral data collection and analysis, eye movement technology, and EEG technology. Behavioral data mainly record the number of clicks, reaction time, task completion rate, etc.; eye movement technology reflects visual attention by tracking indicators such as gaze point, gaze time, and pupil changes; EEG technology reveals the neural mechanism of attention capture by recording event-related potentials. Research should be combined with specific task situations, using the above-mentioned cross-screen interactive attention-capture experimental paradigm to evaluate the effectiveness of cross-screen interaction from the perspective of the attention mechanism.

5.2 Experiment 1: Alert information highlighting and cross-screen interaction experiment

5.2.1 Experimental purpose

This experiment adopted a cross-screen interactive attention-capture experimental paradigm; inserted fault alarm information into the abnormal diagnosis process of group control tasks; designed two experimental variables, cross-screen interaction (scenario factor) and fault alarm (information factor); conducted behavioral response and eye movement experiments, collected reaction time, accuracy, and eye movement indicators; and analyzed the impact of the stimulus-driven attention-capture mechanism on cross-screen behavior in the alarm information perception task in the intelligent nuclear power display and control system.

5.2.2 Equipment and participants

A prototype built in Figma was tested across five identical computers using Python scripts (PyAutoGUI, Pynput) for event tracking. Eye movements were recorded with Tobii Glasses 2. Twelve experienced nuclear interface designers (aged 29–44, avg. 35.75 years; work experience 4–18 years) participated. All had corrected vision above 1.0 and no color blindness. Participants viewed five VDU screens (2,880 × 1,800 px) placed in a row at a 55–60 cm distance, as shown in **Figure 6**.

5.2.3 Experimental results

- (1) Behavioral indicator data: Analysis of behavioral results revealed that both the number of cross-screens and the alarm level significantly affected reaction time ($p < 0.001$), while the direction of screen shift, number of alarms, and their position had no significant effect. Accuracy remained unaffected across all conditions. Regression analysis indicated that reaction time increased proportionally with the number of screen transitions, suggesting that attention-capture efficiency declined as visual demands increased. In contrast, high-level alarms significantly reduced response times, confirming their enhanced salience in guiding attention.

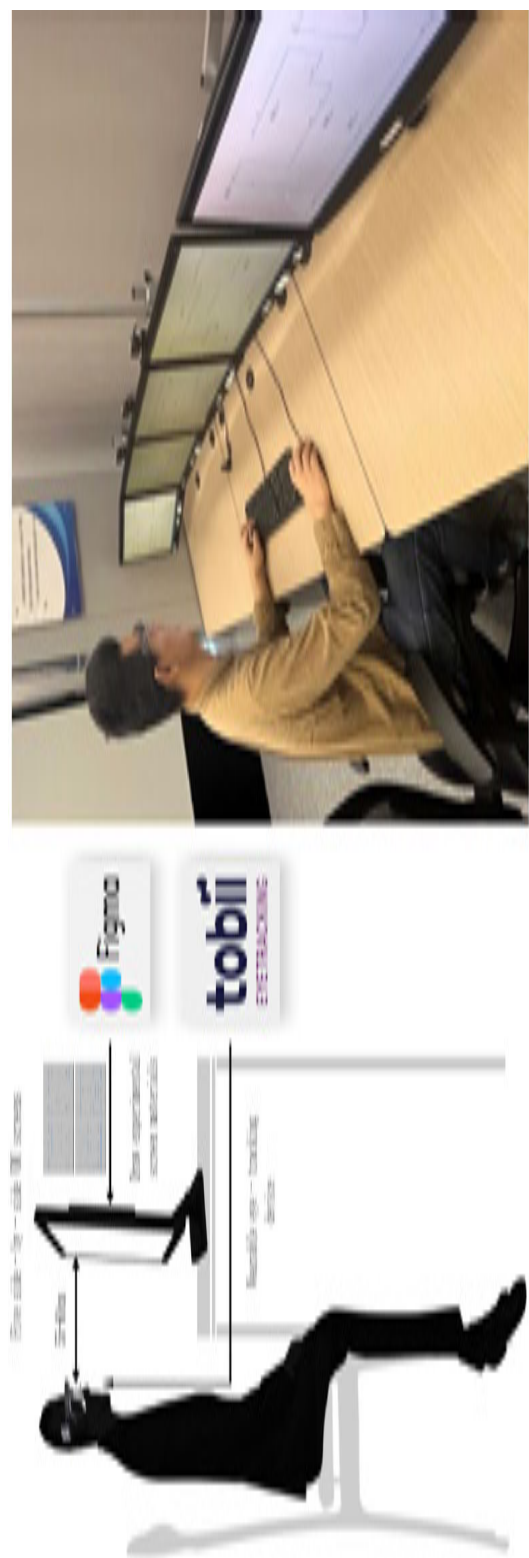


Figure 6.
Same device (VDU-VDU) group experiment scenario.

- (2) Eye movement indicator data: After preprocessing with I-VT filtering and outlier removal, they showed that an increased number of screen transitions significantly raised the number of saccades, although it did not affect fixation duration, fixation count, or pupil diameter. High-level alarms notably increased both saccades and fixations, whereas an increased number of alarms reduced fixation count and duration, implying distraction due to excessive visual stimuli. Regression models supported these findings, showing that screen transitions led to more frequent saccades ($\beta = + 4.772$), indicating cognitive distraction, while high-level alarms reduced saccade frequency ($\beta = - 5.558$), suggesting more efficient target detection.

As shown in **Figures 7 and 8**, further visualization indicated that reaction time increased in tandem with saccade count, regardless of alarm level. However, high-level alarms consistently resulted in shorter response times and fewer eye movements, confirming their advantage in capturing attention. When the number of screens exceeded the subject's visual span, participants had to shift their head or torso, resulting in decreased efficiency, more dispersed attention, and increased scanning effort. Likewise, multiple simultaneous alarms diluted attentional focus, leading to more frequent gaze switching and hindered in-depth processing of any single target – possibly due to perceptual similarity among alarm signals.

5.2.4 Experimental conclusion

- (1) Subfactor influence: The subfactors of cross-screen interaction and fault alarm significantly affect attention capture, which is reflected in the changes in reaction time, number of eye saccades, number of fixations, and duration, verifying the role of information and scene factors.
- (2) Limitation of the number of screens: The increase in the number of screens leads to frequent switching of viewing angles, which reduces the efficiency of attention capture; when the field of view is exceeded, the performance of cross-screen interaction is significantly limited, highlighting the importance of layout.
- (3) The role of alarm level: High-level alarms (such as high-frequency flashing) can quickly capture attention and improve emergency response speed, confirming the optimization effect of signal significance.
- (4) Interference from the number of alarms: When the number of alarms increases, the number and duration of fixations decrease, indicating that multiple alarms distract attention and weaken the processing depth of a single alarm.

5.3 Experiment 2: Breakpoint state evaluation to perform cross-screen interaction experiments

5.3.1 Experimental purpose

This experiment adopts the cross-screen interactive attention-capture paradigm, inserts the state evaluation task into the breakpoint confirmation stage of the

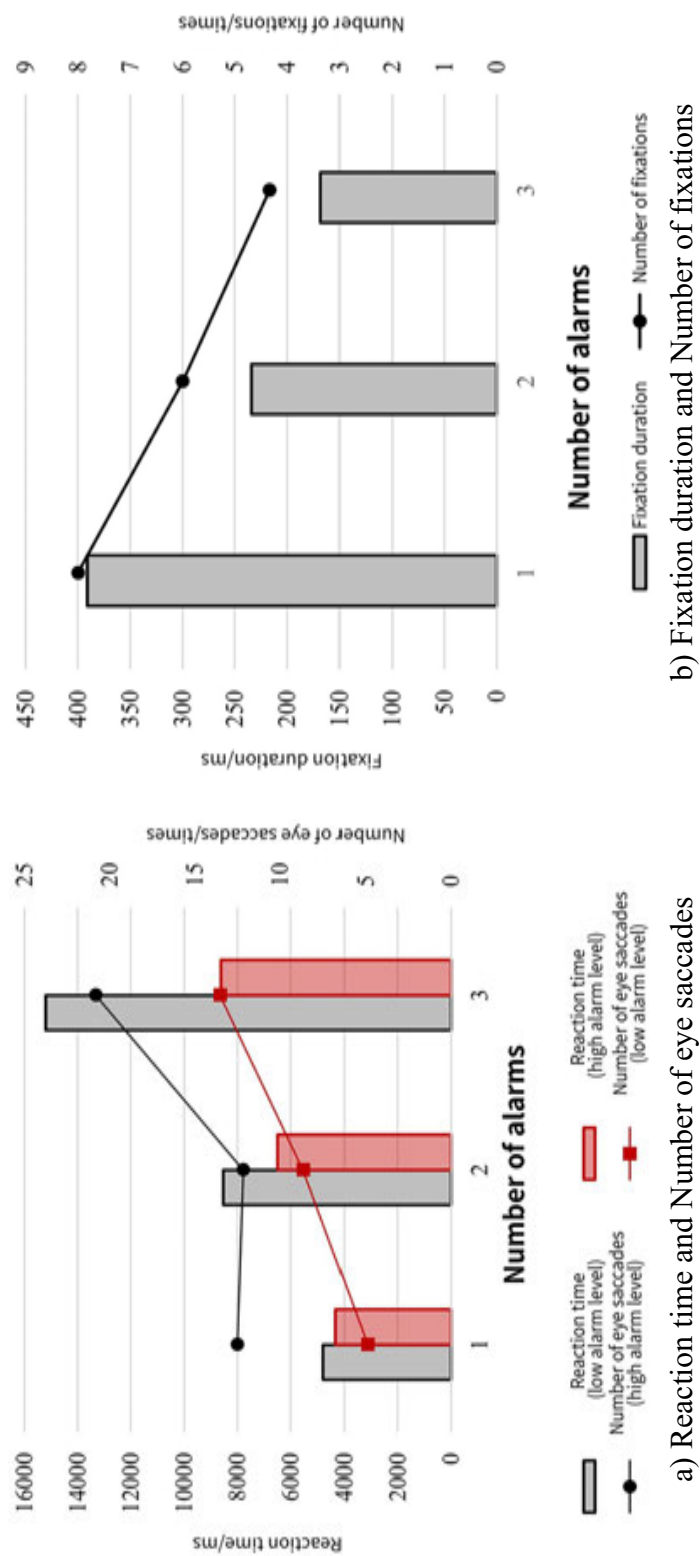


Figure 7. Reaction time, number of eye saccades, fixation duration, and number of fixations for high and low alarm levels at different screen span numbers.

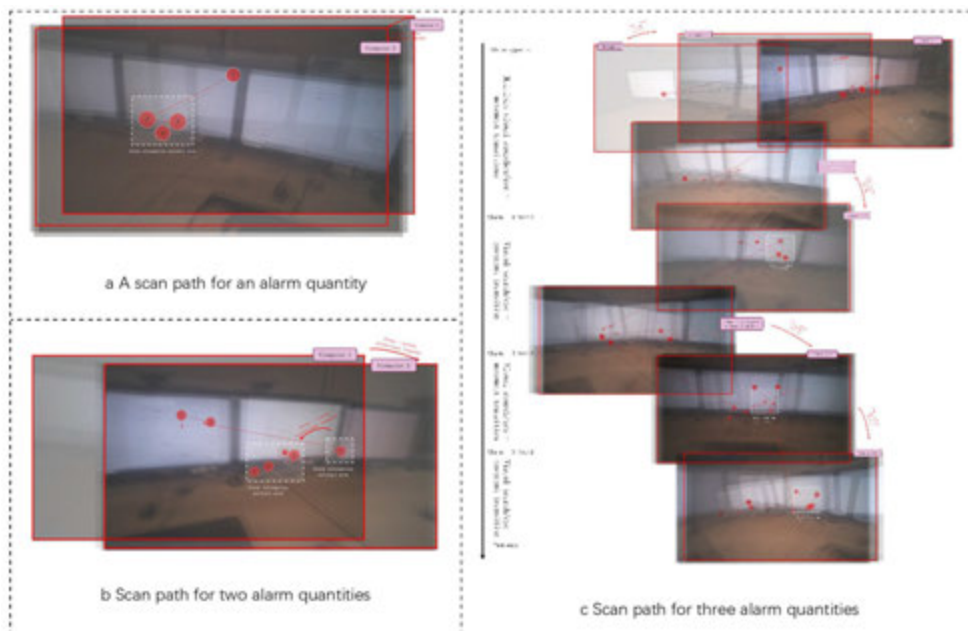


Figure 8.
 The scanning path of a typical subject under different alarm numbers at high alarm levels.

sequential control task, and simulates the cross-screen interactive situation. Variables are designed from two dimensions: information relevance (information factor) and task difficulty (task factor), and behavioral and eye movement experiments are carried out to collect reaction time, accuracy, and eye movement data, and analyze the impact of the purpose-driven attention-capture mechanism on the cross-screen behavior related to task state evaluation in the intelligent nuclear power display and control system.

5.3.2 Equipment and participants

The experimental prototype was developed using Figma, with keyboard and mouse event data recorded via Python. Tobii Glasses 2 was used for eye tracking. Sixteen practitioners experienced in nuclear power control interface design participated (mean age: 32.3 years; mean work experience: 7 years), all with corrected vision of 1.0 or above. The experiment was conducted on a 14-inch main screen (2880 × 1800) and a 65-inch external screen (3840 × 2160). Subjects sat 55–60 cm from the main screen and 180–200 cm from the extended screen.

5.3.3 Experimental results

- (1) Behavioral indicator data: Behavioral results from 16 valid participants (with 2.3% of extreme data excluded) showed that both information relevance and task load significantly influenced response time and accuracy. Specifically, information relevance affected all three behavioral metrics (RT, average RT, and accuracy), while task load impacted response time and accuracy but not

average RT. Their interaction significantly influenced both average RT and accuracy, indicating that the two factors jointly affect task performance.

- (2) Eye movement indicator data: Eye-tracking data from 14 participants (after excluding 7.7% of abnormal data) revealed that information relevance significantly affected the number of saccades, while task load influenced both fixation count and saccades. Their interaction also significantly affected these two indicators, though neither variable significantly impacted average fixation duration or pupil size. As task load increased, fixation and saccade counts also rose, especially under conditions of low information relevance. Notably, LDP screens with higher information relevance yielded shorter reaction times and fewer visual search behaviors, suggesting more efficient information encoding. However, when information relevance was low, participants spent more time fixating on the LDP screen and often switched attention to the VDU screen for spatial reference. This suggests a shift in attentional strategy, where users rely more on external layout cues when internal retrieval fails, reinforcing the role of goal-directed attention in enhancing search efficiency.

As shown in **Figure 9**, while high information relevance facilitated faster target identification, it also increased cross-screen attention shifts. Under high task loads, this did not necessarily improve accuracy, possibly due to attentional resource limitations. In contrast, under low relevance conditions, participants performed more exhaustive searches, but accuracy remained low. These results indicate that, although improved relevance enhances attentional engagement and speeds up search, its benefits are moderated by task difficulty and cognitive load.

5.3.4 Experimental conclusion

- (1) Both information relevance and task load significantly affect attention capture across devices, and their main effects and interactions are reflected in both behavioral and eye movement data.
- (2) Improving information relevance can shorten reaction time, especially under high load, which helps decision-making; but under low load, information overload may delay reaction.
- (3) Increased task load usually reduces accuracy, but high information relevance can alleviate the downward trend, indicating that it optimizes attention and memory processing.
- (4) High task load leads to more fixations and saccades; high relevance reduces the burden of visual search under medium load, while information overload causes attention distraction.
- (5) Under low information relevance, subjects search more frequently on the LDP screen, reflecting strategic attention shifting; although high relevance is generally beneficial, attention resources are limited, and excessive switching does not help improve performance and may even affect accuracy.

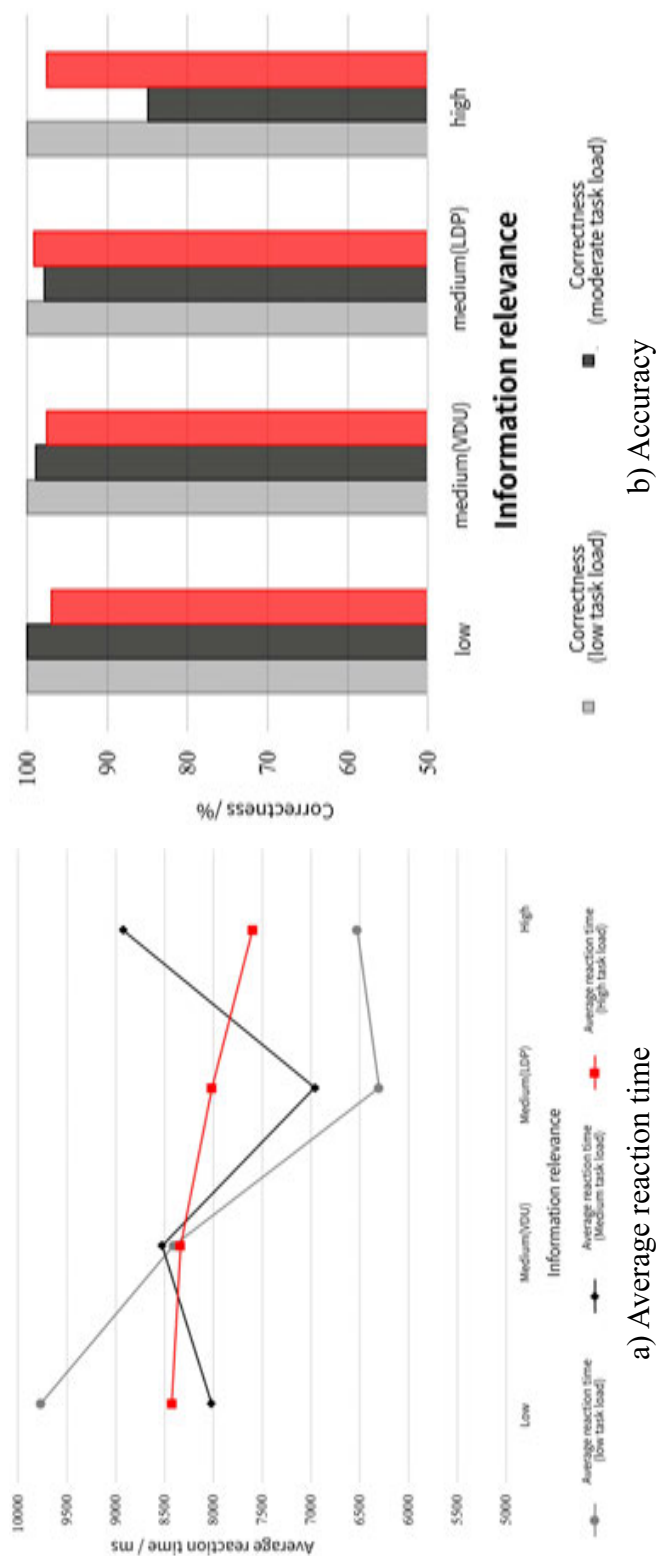


Figure 9.
Average reaction time and accuracy of subjects under each experimental condition.

5.4 Experiment 3: Double-target visual search experiment for the power image group

5.4.1 Experimental purpose

This experiment was designed to investigate how information layout and group structure affect attention allocation and visual search performance during monitoring operations in nuclear power control rooms. By simulating the device group interface in a highly integrated intelligent display and control system, a dual-target visual search task was conducted to evaluate the impact of different grouping strategies on cognitive load and user performance. The experiment focused on two core variables: device group structure (grouped vs. ungrouped) and target relevance (one-target vs. two-target conditions), with eye-tracking and behavioral data collected to examine the role of visual grouping in supporting efficient information retrieval.

5.4.2 Equipment and participants

The experimental interface was constructed using interface components and icons from an actual Hualong One nuclear power unit, presented on a 27-inch monitor (resolution: 1920 × 1080). Twenty participants (aged 21–32, average age 25.4) with relevant academic backgrounds and normal or corrected-to-normal vision completed the task in a controlled laboratory environment. Participants sat approximately 55 cm from the display, and their eye movements were recorded using a Tobii Pro Fusion eye tracker.

5.4.3 Experimental results

- (1) Behavioral indicator data: Behavioral data analysis showed that grouping had a significant effect on both search accuracy and response time. Participants responded faster and more accurately in the grouped condition, especially in the dual-target task. The interaction between grouping and the number of targets was also significant, indicating that grouping facilitated more efficient target recognition and reduced cognitive load under higher task demands, as shown in **Figure 10**.
- (2) Eye movement indicator data. Eye-tracking results further supported these findings. In grouped conditions, participants exhibited fewer fixations, shorter average fixation durations, and fewer saccades, suggesting more efficient visual search behavior. The heatmap data indicated that participants' attention was more narrowly distributed in the grouped condition, with faster convergence on target areas. In contrast, ungrouped conditions resulted in broader scan paths and more frequent switching between areas, reflecting higher search effort and reduced efficiency.

5.4.4 Experimental conclusion

The experiment suggests that device grouping significantly enhances attention capture and search performance in dual-target monitoring tasks. Grouping

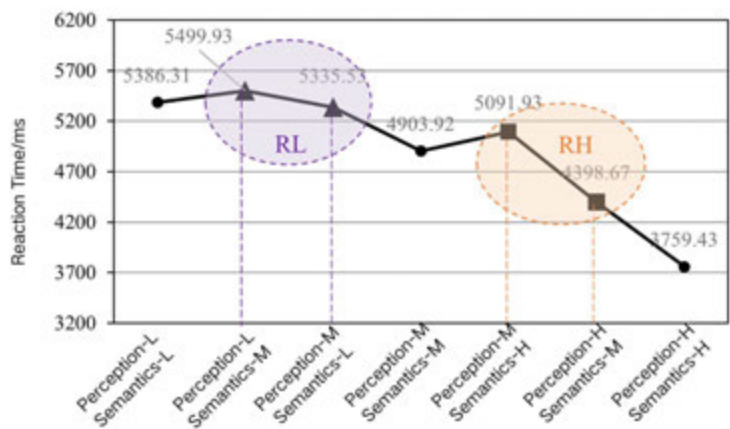


Figure 10.
Mean visual search reaction time under seven similarities of semantic groups.

provides spatial and semantic cues that support top-down attention strategies, reduce search uncertainty, and promote faster information processing. In the context of intelligent nuclear power display systems, optimizing interface layout through appropriate device grouping can substantially improve monitoring efficiency and reduce operator cognitive workload. This experiment thus highlights the importance of leveraging perceptual organization principles in control room interface design.

5.5 Cognitive similarity bias effect paradigm

Combining the above experimental conclusions with the similarity generation process [42] and the mapping model [43], we can outline the similarity bias effect paradigm under visual search, as shown in **Figure 11**: In a visual search scenario, if a person exhibits a similarity bias when perceiving and processing information about the search target and distractors, it can be classified into perceptual similarity bias and decoding similarity bias according to the cognitive process [44, 45].

6. Visual attention allocation and interactive behavior mechanisms in monitoring tasks

Based on the cross-screen interactive attention-capture experimental paradigm applied to typical tasks of intelligent display and control systems proposed in the previous article, and combined with methods such as eye-tracking and behavioral response analysis, a cross-screen/cross-device task operation interaction experiment was designed and implemented. Through data analysis, the influence of attention switching and task priority during multitask collaborative execution was determined, and a visual attention-capture mechanism model for cross-screen interactive behavior in monitoring operations was established.

Combining cognitive load theory with visual search theory, we observed the changes in attention allocation during the prominence of alarm information and breakpoint status evaluation, analyzed the distribution rules of visual attention, and examined the

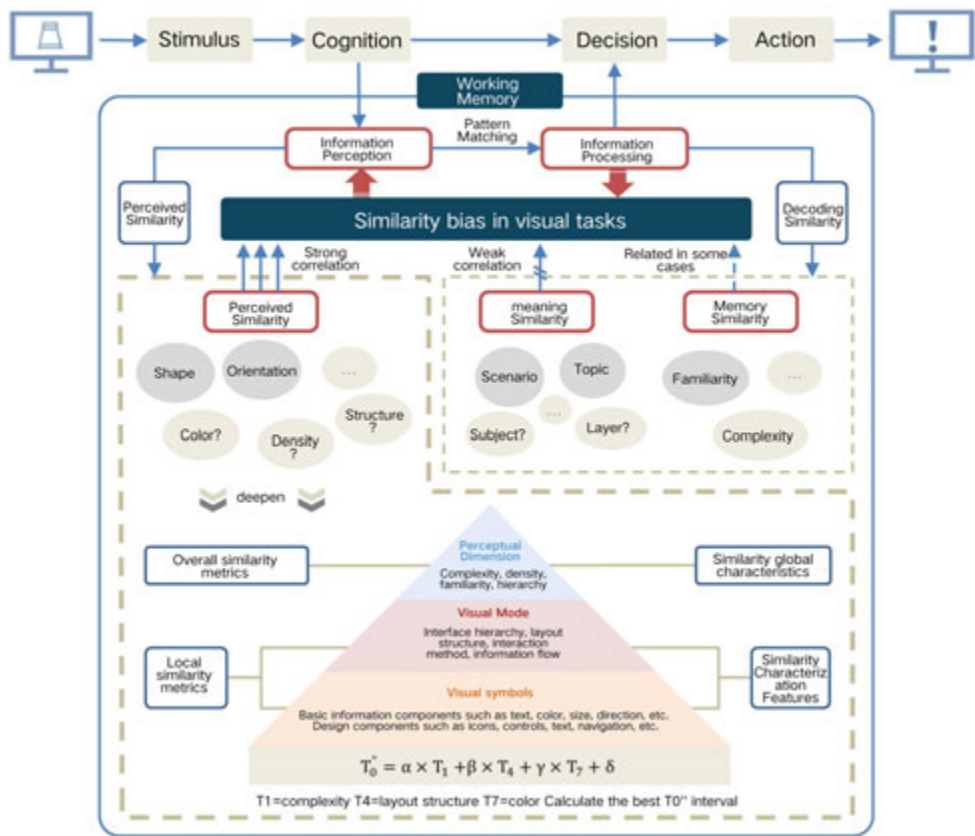


Figure 11.
Similarity bias effect paradigm in visual search.

influence of the attention-capture effect driven by subfactors of stimulation and cross-screen interaction behavior from the perspective of cross-screen interaction, as well as the influence of information relevance and task load on the attention-capture effect driven by purpose, revealing the intrinsic correlation between visual attention allocation and the operator's cross-screen interaction behavior in different operation task scenarios; collected and evaluated eye movement data and behavioral indicators related to attention capture in cross-screen scenarios, and conducted in-depth research on the influence of information factors, task factors, and scenario factors on the subjects' cross-screen interaction behavior from the perspective of stimulation-driven/goal-driven attention-capture mechanisms; and analyzed how operators moved their sights and adjusted their attention focus between different display terminals when working collaboratively on multiple display terminals (such as VDU, LDP, and BUP), and constructed the visual interaction behavior mechanism of operators in monitoring operations, as shown in **Figure 12**.

Combining the perceptual span theory [46] and the cognitive bias effect theory [47], the information presentation method is divided into three cognitive dimensions: perceptual similarity, semantic similarity, and memory similarity [48]. The influencing factors of display elements on cognitive behavior in cross-screen/cross-device tasks are proposed. A visual behavior cognitive model of

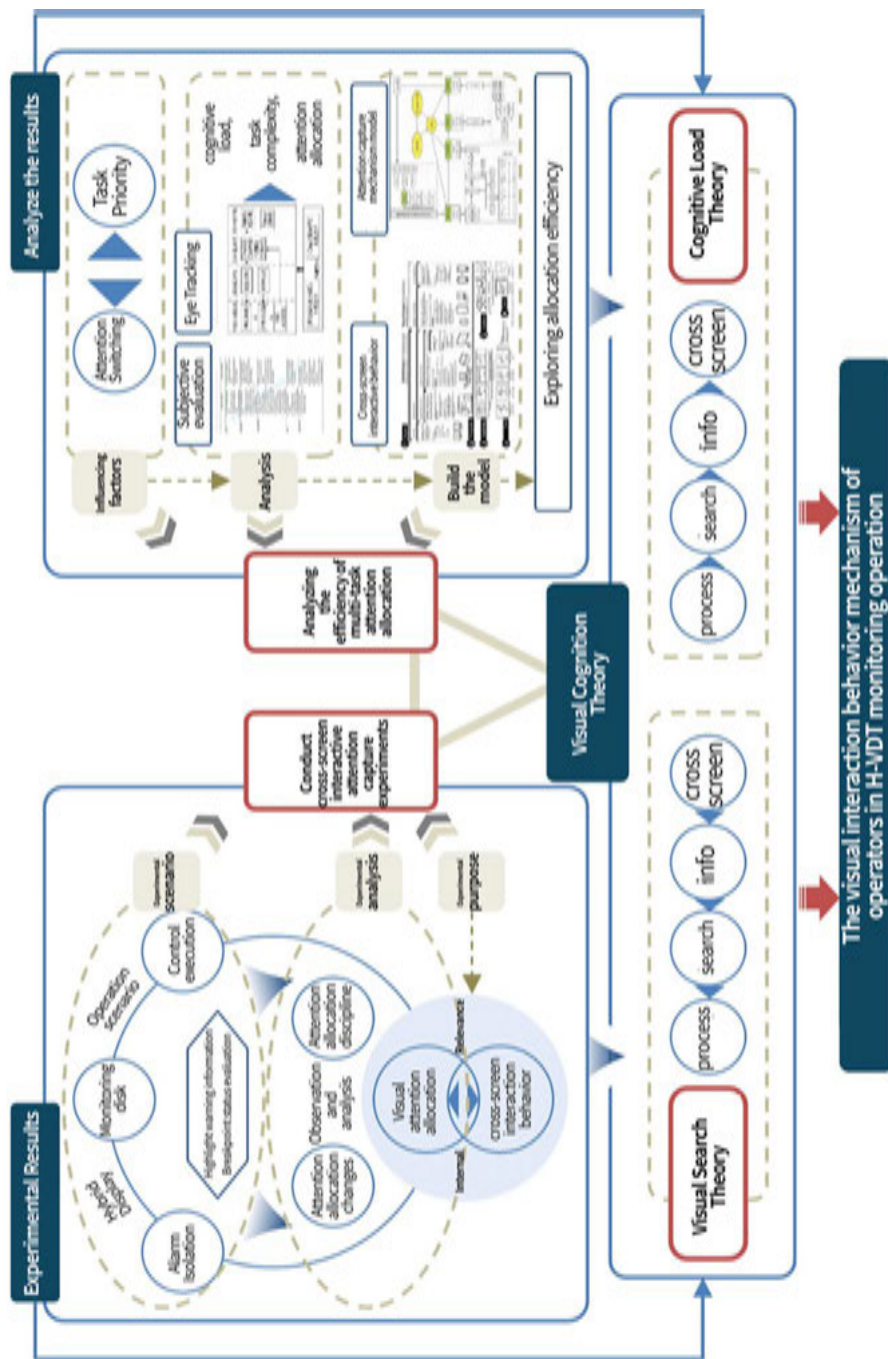


Figure 12.
Visual attention allocation and interactive behavior mechanisms in monitoring tasks.

endogenous associations of visual information display is constructed to form a set of visual behavior cognitive models, including “information graph group similarity model-visual threshold influencing factors-physiological index change indicators,” which can accurately describe the visual behavior and cognitive mechanism in H-VDT monitoring tasks, as shown in **Figure 13**.

7. Conclusions

This study focuses on the cross-screen interaction behavior mechanism of operators in the intelligent nuclear power display and control system, with an emphasis on visual cognition and attention allocation. The study reveals that, as a typical multiscreen human–computer interaction scenario, the nuclear power control room encounters challenges such as fuzzy information hierarchy, spatial perception barriers, and difficulty in adapting to the interaction mode during task execution, which can easily lead to risks such as distraction, perception bias, and decision-making errors. To address these issues: 1) the study constructed a cross-screen interaction behavior model based on the attention-capture mechanism and identified two key attention-driving mechanisms: bottom-up (stimulus-driven) and top-down (purpose-driven); 2) a set of cross-screen interaction attention-capture experimental paradigms suitable for nuclear power monitoring tasks was proposed, and through two typical task experiments – fault alarm salience perception task and breakpoint status assessment task – the study verified the significant influence of information salience and task goals on the attention-capture effect; 3) further combining cognitive load theory and visual search theory, a cross-screen interaction attention allocation and behavior mechanism model was proposed, which revealed how operators screen key information through visual attention during the execution of monitoring tasks and optimized the human–computer interface design and task process arrangement accordingly [49]; and 4) by combining the theory of perceptual breadth and the cognitive bias effect, a visual behavior cognitive model was developed. This model, which includes the “information graph group similarity model-visual threshold influencing factor-physiological index change,” can accurately describe the visual behavior and cognitive mechanism in monitoring tasks [50].

Overall, the operator’s cross-screen interaction behavior is a complex and dynamically changing cognitive process, involving the synergy of multiple cognitive elements (such as memory, thinking, and visual search). Attention resources are the key factor limiting the efficiency of cross-screen interaction. Visual search is driven by stimuli at first, but ultimately depends on task goal guidance. The research results provide theoretical support for the optimization of the nuclear power control room interface. It is recommended that future designs focus on the prominence of information presentation, the consistency of screen layout, and the relevance of task-oriented information, so as to improve the safety and reliability of cross-screen interaction.

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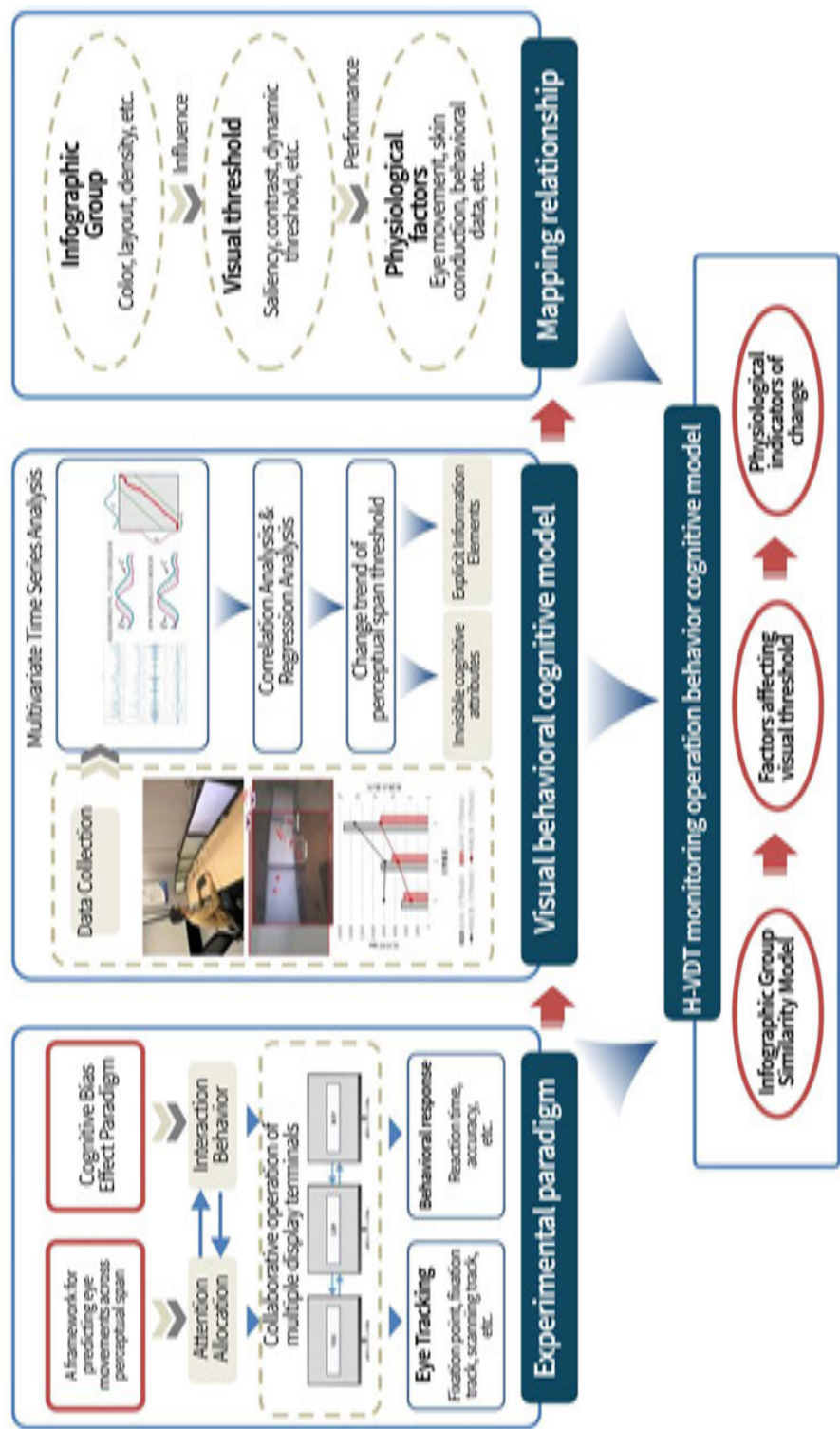


Figure 13.
A cognitive model of visual behavior in which visual information displays endogenous associations.

Notes/thanks/other declarations

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Section 3

Frameworks Necessary for Expansion

Perspective Chapter: Advanced Reactor Decision-Making in the Trans-Science Setting

Ernie Kee

Abstract

Nuclear power from fission is an inherently hazardous energy technology whose safety has historically been managed through rigorous engineering practices and conservative regulatory frameworks grounded in the Atomic Energy Act of 1954. Public and policy support for nuclear energy has fluctuated over the decades, often in response to high-profile accidents, waste concerns, and changing political priorities. More recently, support has grown due to nuclear energy's strong historical safety record and its potential role in mitigating climate change. This renewed interest has led to legislation – such as the Nuclear Energy Innovation and Modernization Act and the Accelerating Deployment of Versatile Advanced Nuclear for Clean Energy Act of 2024 – that directs the US Nuclear Regulatory Commission to modernize its licensing framework for Advanced Commercial Nuclear Fission Reactors (A-CNFRs). These reforms emphasize Risk-Informed and Performance-Based regulation intended to streamline deployment. This political shift in regulatory philosophy reflects a trans-scientific challenge. As defined by Alvin Weinberg, trans-scientific questions arise from science but cannot be answered by science alone. In the case of A-CNFRs, regulators must make safety decisions in the absence of operational experience and robust accident data, relying more heavily on optimistic probabilistic models that are poorly suited to novel technologies and cases where applicable data are sparse or nonexistent. This chapter examines the evolution of nuclear safety decision-making – as opposed to traditional safety engineering-based decision-making – critiques the assumptions underlying current risk-based methodologies, and argues that shifts away from traditional regulatory safeguards in favor of accelerated deployment increase the probability of reactor accidents. It calls for transparency in safety claims and advocates for a regulatory process that remains anchored in empirical defensibility and public trust.

Keywords: trans-science, safety margin (SM), regulation, PRA, probabilistic risk assessment

THE COMMISSIONER. Of course one sees the logic of it: if you can get a boat so built that she cannot sink, then you do not want any lifeboats at all.

THE ATTORNEY-GENERAL. No.

THE COMMISSIONER. But until you get that, one can always conceive that there may be an occasion when lifeboats for all the people on board are required.

British Wreck Commissioner's Inquiry into the Loss of the Titanic
Day 36 (Final arguments), 1912.

1. Introduction

At the time of its construction, the Titanic complied with lifeboat regulations, but only by exploiting a loophole that allowed fewer lifeboats than passengers. This decision was driven largely by profit considerations—upper-class cabins commanded premium fares, and their number was limited by lifeboat crowding. The owners believed the new Titanic design effectively eliminated the possibility of sinking, which influenced their decision on lifeboat capacity. The tragedy illustrates how inadequate regulatory oversight of design, when combined with economic incentives, can produce unexpected levels of losses. In much the same way, confidence in Advanced Commercial Nuclear Fission Reactor (A-CNFR) designs, including fuel often promoted as inherently safe against radioactive material release, has led to proposals for reduced safety margins, raising the question of how much protection against low-probability but high-consequence events society is willing to forgo.

The political and regulatory landscape surrounding nuclear power is evolving rapidly. Recent efforts to accelerate the deployment of Advanced Commercial Nuclear Fission Reactors (A-CNFRs) reflect a shift in decision-making logic—from one rooted in engineering conservatism and empirical safety data to one grounded in optimistic risk projections and political expediency. This chapter argues that such a shift increases the likelihood of protection system failure by prioritizing deployment speed over proven safety assurance.

The development of nuclear power sits at the intersection of science, politics, economics, and public perception. This convergence makes regulation particularly vulnerable to what Alvin Weinberg called trans-science—problems that emerge from scientific contexts but cannot be settled by scientific inquiry alone [1].

As early as the 1950s and 1960s, the scientific feasibility of safe, efficient, and proliferation-resistant reactors was demonstrated at institutions such as Oak Ridge National Laboratory (ORNL), where concepts such as molten salt reactors were successfully developed and operated [2]. Despite such technical achievements, the broader deployment of advanced reactor technologies stalled in the 1970s, as political, economic, and societal concerns began to override technical merit. Anti-nuclear sentiment grew—fueled by fears surrounding radioactive waste, reactor accidents, and weapons proliferation—and coincided with a broader erosion of public trust in government institutions. Regulatory agencies, including the US Nuclear Regulatory Commission (USNRC), successor to the Atomic Energy

Commission (AEC), responded by adopting more conservative regulatory frameworks. These measures were successful in lowering the probability of severe accidents but also significantly increased compliance costs and delayed project timelines. As a result, private investment pivoted toward alternative technologies.

Today, this landscape is shifting. Climate change, energy security, and geopolitical instability have brought nuclear power back to the forefront of policy discussions. Advanced reactor designs, once sidelined, are again under active development. Statutory mandates—including the Nuclear Energy Innovation and Modernization Act (NEIMA) and Accelerating Deployment of Versatile Energy Systems—are driving progress in this field.

Advanced Nuclear for Clean Energy Act of 2024 (ADVANCE) directs the USNRC to implement Risk-Informed and Performance-Based (RIPB) approaches to licensing in an effort to streamline deployment and reduce the cost of regulatory oversight.

Still, the process of regulating safety in nuclear power remains fundamentally trans-scientific. Regulators must make consequential decisions with limited empirical data on reactor accidents and considerable uncertainty about future system behavior. Hansson, in his contribution to the “Philosophy of Technology and Engineering Sciences,” introduces the concept of hypothetical retrospection, a normative framework for decision-making that seeks to ensure moral defensibility from the standpoint of future hindsight [3]. That is, one should contemplate alternative future outcomes as if they have already occurred and ask whether the present decision would remain ethically justifiable.

This notion complements Hansson’s broader epistemic critique of risk quantification. He emphasizes that the level of empirical evidence required to support a risk assertion grows with the rarity of the event, creating an “ethical gap” between what can be scientifically asserted and what the public expects. An assertion of a 10% failure probability may be defensible with modest data, but claiming a risk of 1 in 10,000—the public expectation for risk—demands vastly greater empirical support that cannot be obtained in practice [e.g., see Ref. [4]]. As such, extremely small risk assertions—often made in nuclear licensing—tend to outstrip the available evidence and enter the realm of trans-science. The gap between scientific capability and political risk tolerance, compounded by tensions between public welfare and commercial interests, continues to challenge effective oversight.

2. Bounding analyses

The concept of the maximum hypothetical accident (MHA) originated during the early development of reactor safety regulation. It served as a bounding scenario for evaluating siting and design adequacy, especially for research and test reactors.¹ The MHA typically assumed a total core meltdown with substantial release of radionuclides and no mitigating safety systems. Although it was not considered a likely event, it provided a conservative analytical basis for determining exclusion zones, containment requirements, and emergency response planning.

In contrast, contemporary regulatory reform—anchored by legislation such as NEIMA and ADVANCE—emphasizes RIPB approaches [4, 5]. These reforms encourage the USNRC to redefine its licensing framework by incorporating

⁶¹ See for example, WASH-740 available as ML20086S495 and NUREG-0879 available as ML20053C423 in the NRC Public Document Room (ADAMS) library.

optimistic analyses, such as probabilistic risk assessment (PRA), to limit regulatory oversight, which has been classically grounded in well-established safety engineering principles.²

Nevertheless, MHA-style bounding scenarios persist in discussions surrounding advanced reactor licensing, particularly for defining source terms and emergency planning zones. This persistence illustrates a core trans-scientific challenge: how to reconcile public assurance through conservative assumptions with scientifically-based analyses that would disclose actual system behavior.

Risk assessment is itself a trans-scientific activity. As argued by Hansson and Aven [6], it draws on scientific concepts and data but inevitably incorporates value judgments and assumptions that cannot be verified through empirical testing alone. When applied to A-CNFRs—where relevant accident data are scarce or nonexistent—these limitations become particularly pronounced. Two central realities must be acknowledged:

1. The risk of rare, high-consequence events in novel reactor designs cannot be precisely quantified in the absence of operational experience. Estimates must rely on expert judgment and modeling assumptions.
2. Managing risk is a dynamic control process that depends on the timely detection and mitigation of evolving hazards during operation.

Reactor licensing should be understood as a stochastic process unfolding over a facility's operational lifetime. A reactor may shut down due to a catastrophic failure or reach end-of-life through normal decommissioning. In this context, one practical regulatory requirement is to ensure that a high proportion of the probability mass for accident occurrence lies beyond the license expiration date. The decision to approve or reject a reactor design must, therefore, account for how protections are expected to perform over time—and whether those protections can maintain acceptable safety margins (SMs) throughout the licensed period of operation.

Both ADVANCE and NEIMA direct the USNRC to use RIPB licensing methodologies as a basis for evaluating SM. Unfortunately, the USNRC relies on the PRA methodology first developed by Rasmussen in the early 1970s, which fails to model the stochastic dynamics of an operating A-CNFR [7]. The USNRC has long recognized the need to manage operational dynamics by requiring root cause analysis and corrective actions that would help compensate for unexpected events that would otherwise erode SM in operating reactors.³

3. Protection decision-making under regulation

In a trans-scientific setting, regulatory decision-making about nuclear reactor deployment must weigh competing interests, incomplete data, and ethical responsibility under uncertainty. The final decision is not a purely technical one – it

⁶² See for example, Appendix A to 10 CFR 50.

³ See for example, Appendix B to 10 CFR 50.

is ultimately a political choice shaped by societal values and expressed through tradeoffs between cost, risk, and safety.

Regulatory oversight of protection systems does not—and cannot—guarantee accident avoidance. Instead, it seeks to manage risk within acceptable bounds, where acceptability is defined relative to perceived social welfare. In this context, each protection alternative carries with it a cost, an expected efficacy in preventing accidents, and the societal consequences of failure.

The selection of a given protection alternative thus depends on the decision-maker's utility function—an expression of how much weight is given to safety versus cost. Importantly, the probability of an accident under each alternative is not a fixed physical parameter but a composite function that embeds:

- The cost and technical features of the protection system.
- The regulatory constraints imposed.
- And the decision-maker's utility on accident tolerance.

This highlights a central feature of trans-scientific decision-making: *whose utility function is driving the choice?* A public-oriented utility function typically reflects low tolerance for accidents and favors more robust (and expensive) protections. An industry-oriented utility function, by contrast, is often more risk-neutral and may tolerate higher accident probabilities to reduce costs and accelerate deployment.

When political institutions shift decision-making power toward industry preferences, the resulting policy choices tend to externalize more risk onto the public. In such cases, risk-informed regulation becomes less about achieving safety and more about justifying a level of risk consistent with political or economic expediency. This fundamental tension—between safety as a public good and deployment as an economic goal—lies at the heart of the trans-scientific nature of nuclear regulatory policy.

4. Discussion

The regulatory landscape for advanced nuclear reactors is undergoing a profound shift. Legislation such as NEIMA and ADVANCE reflects a political will to reduce regulatory burdens in order to accelerate deployment. While this shift may serve economic and climate objectives, it risks eroding SMs if it leans on probabilistic models that are insufficiently supported by empirical evidence or robust mechanistic justification. The passengers on the *Titanic* were certainly unaware that there were not enough lifeboats for all on board; had they known, some might have changed their minds about going to sea. But when events began to unfold late at night on April 14, 1912; it was too late. Making clear that science cannot close the gap between what can be known and the level of protections expected by the public is an essential function of ethical decision-making.

The *Titanic*'s lifeboat shortfall is an apt metaphor for regulatory design: Safety must be guaranteed by *protections with capacity*, not by optimistic averages. In modern terms, RIPB decision-making must be anchored to *demonstrable protective performance* over relevant hazard ensembles, not to point estimates derived from

idealized assumptions. When uncertainty is high and data are sparse, guardrails should be placed on allowed operating envelopes *before* deployment, just as lifeboat capacity should be properly sized, numbered, and tested before leaving port.

PRA requires a calibrated probability law for the underlying state process. In PRA, the law is typically summarized through time-averaged frequencies, independence assumptions, and steady-state surrogates. Most of the assumptions made in PRAs ignore the actual operation of an A-CNFR that requires recognition of generative, state- and time-dependent rules—for example, wearout, maintenance/test interventions, available resources such as limited vs. infinite labor force, and hazard-induced fragility. The unrealistic assumptions made cause optimistic estimates of safety performance that should be disclosed in the public square, not masked in “scientific certainty.”

4.1 Utilitarianism, truthfulness, and risk disclosure

Utilitarianism (Bentham, Mill) evaluates policies by their aggregate consequences—maximizing expected social welfare. Under uncertainty, this reduces to maximizing expected utility across possible outcomes. *Kantian* ethics imposes side constraints rooted in respect for persons: duties such as truthfulness (do not lie) and the injunction to treat persons as ends, not mere means.

In risk regulation, utilitarian cost-benefit reasoning is most defensible when those who bear hazards are *adequately informed* about: (i) the risks and potential harms, (ii) the mechanisms by which harms may arise, and (iii) the limits of what is known (model structure, assumptions, data gaps, and unmodeled hazards; see the earlier discussion on the calibration of probability law). Informed publics can then consent, contest, or demand mitigation/compensation. Absent such disclosure, aggregate maximization risks shifting burdens onto the less informed, thereby violating fairness and autonomy.

The Kantian duty not to lie extends beyond literal falsehoods to *material omissions* that foreseeably mislead stakeholders about safety. For regulated protections, this entails a duty of candor about the calibration of the probability law, the evidential basis for parameters, and the range of credible hazard scenarios. This duty sets a nonnegotiable floor: certain protective capacities.

“Lifeboats” must not be traded away on the strength of optimistic averages.

Because many questions at the science-policy boundary are *trans-scientific*—answerable only by judgment plus values—RIPB frameworks should combine the following: (i) conservative, mechanism-based protection floors, (ii) mechanistic stress-testing across schedules and hazard ensembles, and (iii) transparent communication.

Of uncertainty, so that any remaining utilitarian aggregation proceeds with the public’s informed awareness. Utilitarian reasoning can help prioritize resources *once* transparency and protective floors are secured [8–10]. In his research on equitable risk-taking, Hansson arrives at a preliminary moral criterion for accepting risk – his Rule 5: “Exposure of a person to a risk is acceptable if and only if this exposure is part of an equitable social system of risk-taking that works to her advantage” [[11], p. 305–306]. He points out some unresolved clarifications; however, if risk quantification evaluation is to be the basis for downside outcomes, as in PRA, it is imperative that it be done with the best available methodology and carry with it honest disclosure of its limitations.

This chapter has shown that:

- RIPB licensing relies on PRA accident estimates that cannot be fully calibrated for new designs—the basis for risk assessments is speculative and highly sensitive to modeling assumptions.
- Conservative approaches, such as the MHA, offered a public assurance mechanism rooted in deterministic SMs.
- Replacing these margins with optimistic risk metrics creates a trans-scientific gap between policy decisions and engineering reality.

As Hansson and others have argued, claims of extreme safety—for example, one-in-ten-thousand risk estimates—require empirical evidence unavailable in “Discussion” section.

New reactor designs. Absent substantial empirical evidence, such claims can have profound effects on policies that are necessarily trans-scientific. Making them without transparent disclosure of their underlying assumptions and ethical bases may lead to questionable decision-making outcomes in the trans-science domain [11].

A useful perspective on the precautionary principle can be gained by comparing its application in two domains of energy policy: nuclear safety and greenhouse gas regulation. In nuclear regulation, the Linear No-Threshold (LNT) model for radiation risk has long served as a precautionary default—assuming that any dose of ionizing radiation carries some risk of harm, no matter how small. This assumption has guided stringent safety standards in reactor design, operation, and waste management. In climate policy, the 2009 EPA Greenhouse Gas Endangerment Finding played a parallel precautionary role by establishing that greenhouse gases endanger public health and welfare under the Clean Air Act. In July 2025, the EPA *proposed* rescinding that finding (and related vehicle GHG standards); the proposal both questions the scientific basis and argues that Section 202 addresses only local or regional harms, not global climate change. The proposal is pending and subject to litigation; if finalized, it would mark a departure from the prior precautionary stance [12–16].

If both nuclear safety policy (via LNT and USNRC regulatory policy) and climate policy (via regulation of CO₂ and other GHGs) have been shaped by precautionary reasoning, then changes in its application in one domain could have profound effects on the other. Relaxing precautionary constraints on fossil fuel emissions may reduce the perceived urgency for deploying A-CNFRs as a low-carbon alternative. Conversely, abandoning precaution in nuclear safety could accelerate A-CNFR deployment. In both cases, changes in the role of precaution within energy policy will likely impact future energy portfolios and the distribution of societal risks.

In the trans-scientific decision-making domain, transparency becomes paramount. Regulatory policy must be openly tied to the ethical basis used for decision-making—the public must be able to understand and evaluate the tradeoffs being made. Policymakers must critically examine the connections between implementing legislation and the regulatory enforcement policies that flow from them. Understanding such connections helps shape better decisions on energy technology deployments that would create different public exposures to risk [11].

To align with the public’s expectation of adequate protections, RIPB frameworks should: (i) require a minimum floor of design-basis protections independent of probabilistic claims and (ii) condition approvals on leading indicators and operational readiness tests that validate modeled mechanisms. These steps ensure that when the proverbial iceberg appears, the system’s *lifeboat capacity*—its engineered protections—is sized for the crowd we actually carry, not the one our averages imagined.

The ethical obligation is not to eliminate uncertainty—an impossible task—but to prevent uncertainty from silently reducing protections below what the public would judge acceptable if fully informed. That obligation motivates conservative design flaws, transparent communication of uncertainty, and PRA, for example, as a complement *to*, not a substitute *for*, calibrated probability law.

Abbreviations

A-CNFR	Advanced Commercial Nuclear Fission Reactor
ADVANCE	Accelerating Deployment of Versatile Advanced Nuclear for Clean Energy Act of 2024
AEA	Atomic Energy Act of 1954
AEC	Atomic Energy Commission
LNT	Linear No-Threshold
MHA	Maximum Hypothetical Accident
MPP	Marked Point Process
MSR	Molten Salt Reactor
NEIMA	Nuclear Energy Innovation and Modernization Act
ORNL	Oak Ridge National Laboratory
PRA	Probabilistic Risk Assessment
RIPB	Risk-Informed and Performance-Based
SM	Safety Margin
USNRC	US Nuclear Regulatory Commission

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Perspective Chapter: Radiation Protection Plays the Key Role in Nuclear Power Expansions

Hiromichi Fumoto

Abstract

This chapter reviews the history of radiation protection and how we satisfied the request for As Low As Reasonably Achievable (ALARA) exposure, as demanded by contemporary society, through the design of Nuclear Power Plants (NPPs), even when evaluating the design basis accident. Discussions will be extended to how those unexpected events of nuclear accidents can be applied to severe accidents. The argument refers to the birth of the linear no threshold (LNT) hypothesis, a brief explanation of our past experiences in understanding the consequences of radioactive substance releases to the environment after a nuclear accident, and the proper application of radiation protection principles. Scientific interpretation, in principle, is still needed in the expansion of nuclear power for essential societal support.

Keywords: nuclear energy, radiation protection, LNT hypothesis, nuclear reactor accident, environmental remedies, decontamination

1. Introduction

This chapter reviews the history of nuclear power development for civil purposes and how to accept nuclear energy as a part of our daily lives. Dr. Takashi Nagai, who submitted the first rescue report of Nagasaki atomic bomb victims, mentioned in his “Atomic Bomb Rescue and Relief Report” that peaceful uses of atomic energy are the only offering dedicated to the souls lost in the atomic bomb explosion in Japan [1]. Most scientists believe that the coming nuclear era shall be led by our wish to achieve the peaceful use of nuclear energy instead of nuclear war head production. However, in reality, scientists are facing antinuclear campaigns alerting the public to the risks of nuclear reactor accidents, which result in the release of huge amounts of radioactive substances. Attorneys in the USA have declared that the nuclear field is a source of lawsuits that provide them with jobs at a higher rate of success [2]. Scientists have become pilots carrying misfortunes in the boat of inviting devils. Atoms for peace need social support.

ICRP, the International Commission on Radiological Protection, delivered its first recommendation on X-ray and radium protection in 1934 [3]. The permissible dose

was chosen to be 0.2 fr/day (600 mSv/y), referring to 1/100 of the exposure required to induce erythema [4].

Similarly, Robley D. Evans, a US scientist, made great efforts to trace radium painters and those patients with radium injections to conclude that the maximum load of radium in the body is less than 10 Ci (3,700 Bq) [5].

Although those two levels of permissible doses and internal loads seem to be quite high in comparison to those adopted today, the important thing is that radiation control had already started in the 1930s, which shows the nuclear industry has been growing while moderately considering the negative effects of radiation in its usage of radioactive substances.

Consequently, in the development of the atomic bomb, the radiation effects on human bodies were thoroughly investigated. The Manhattan Project, which developed the first atomic bomb, confirmed the existence of a threshold in the radiation effects [6]. It was reported that the epidemic analysis showed that radiation effects had threshold levels in their biological effects [6].

However, Dr. Hermann Muller, who received the Nobel Prize for his contribution to the Manhattan Project, delivered his Nobel Prize lecture, indicating the danger of radiation to our health and explaining that biological cell mutation was proportional to cumulative radiation exposure, even in cases where the exposure was truly trivial. In other words, he concluded that no threshold was expected in the biological effect of ionizing radiation. In his Nobel Prize lecture, he used the figurative expression of mustard gas to describe the radiation effect on the human body and predicted that the expansion of nuclear energy for civil purposes would result in the tragedy of serious disasters witnessed by future generations [7].

His Nobel Prize lecture marked the inaugural date of the birth of the linear no threshold (LNT) hypothesis; however, recent research revealed that Dr. Herman Muller had received a report, which was to be published, stating that a threshold existed in the study of dragonfly exposure effects. Nevertheless, Dr. Muller delivered the speech supporting the LNT hypothesis [7].

Dr. Muller comes to the edge of the cliff, on the verge of descending to the valley bottom, admitting his failure in missing the threshold-supporting report, or rebalancing again from the dangerous situation by himself, reproducing facts to support his assumption of the LNT hypothesis. It was not clear how he obtained the research funds from the Rockefeller Foundation; however, he had managed to have his colleagues conduct research supporting his LNT hypothesis. Finally, Dr. Muller was able to lead the Biological Effects of Atomic Radiation (BEIR) committee of the Genetics Panel of the National Academy of Sciences, and ultimately, he managed to obtain the conclusion that the LNT hypothesis exists [6, 8].

We may often see the gradation of artificial exposures illustrated. **Figure 1** is one of the examples shown in UNSCEAR [9]. As you may see, the levels represent exposures during one incident or accident, since UNSCEAR mainly addresses atomic bomb exposures and nuclear accidents. For medical exposures, **Figure 2** shows the levels of radiation diagnosis and radiation therapy [9]. The gradation of exposures is shown not for the purpose of radiation protection but for understanding the actual numbers of exposures we receive. As a matter of fact, I believe that when scientists think about exposures, they tend to first envision radiation levels as illustrated in **Figures 1** and **2**. The numbers are sometimes higher

Dose bands used by UNSCEAR		
High dose	More than ~1 Gy	Severe radiation accidents (e.g. firemen at the Chernobyl accident)
Moderate dose	~100 mGy to ~1 Gy	Recovery operation workers after the Chernobyl accident
Low dose	~10 mGy to ~100 mGy	Multiple computer tomography (CT) scans
Very low dose	Less than ~10 mGy	Conventional radiography (i.e. without CT)

Figure 1.
Gradation of radiation levels illustrated in UNSCEAR [9].

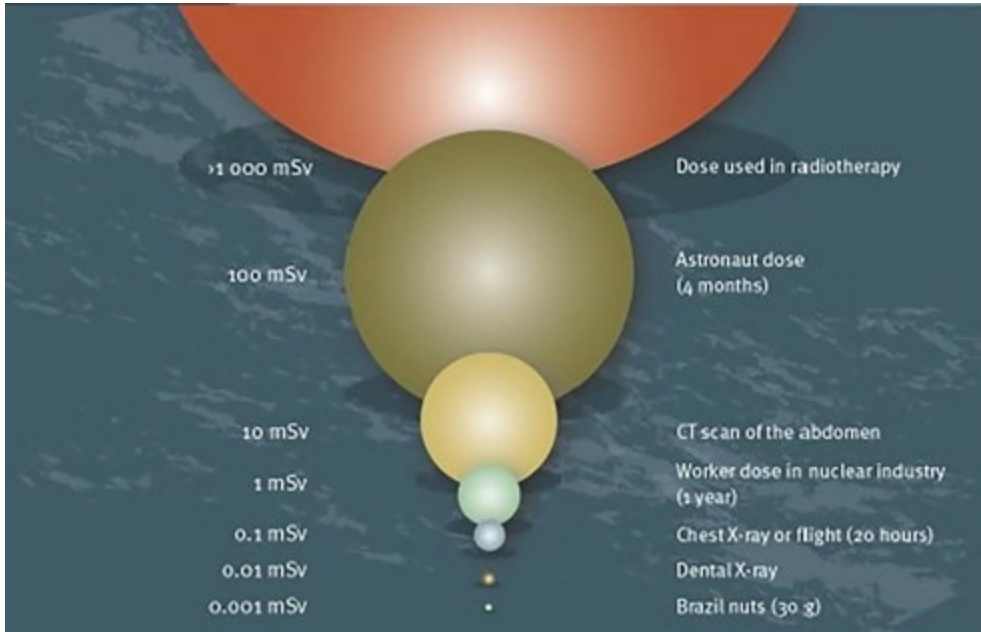


Figure 2.
Gradation of radiation levels, as illustrated in medical applications [9].

than our annual average exposure. Then the idea shifts to the field of radiation protection, where the exposure must be much lower than what is shown in **Figure 1**. This suggests how wide a range of safety margins is needed to interpret the rectification of radiation effects for the public. **Table 1** shows one of the examples of gradation for radiation protection. If the safety margin is further widened, it implicitly reflects the LNT hypothesis, which shows no thresholds or, in other words, no concept of trivial exposures introduced into the framework of radiation protection. These discussions have been made in the past.

DOSE LIMIT COMPARISON CHART				
Exposure limits	ICRP 26	ICRP60	ICRP103	Part 20
Occupational	50 mSv (5 rem)/yr (108) ²	20 mSv (2 rem)/yr, averaged over 5 years; 50 mSv (5 rem) in any single year; 100 mSv (10 rem) (total) in 5 years (166)	20 mSv (2 rem) per year, averaged over 5 years. 50 mSv (5 rem) in any single year. 100 mSv (10 rem) total over 5 years (183)	50 mSv (5 rem)/yr (§201,201(a)(1)(i))
Public	5 mSv (0.5 rem)/yr (119)	1 mSv (0.1 rem)/yr special circumstances of higher value, 5-year average: 1 mSv (0.1 mrem) (192)	1 mSv (0.1 rem)/yr, special circumstances of higher value, 5-year average 1 mSv(0.1 rem) (191)	1 mSv (0.1 rem)/yr, up to 5 mSv (500 rem)/yr, with prior NRC authorization (§201, 301(a), and (d))
Fetal (declared pregnant occupational workers)	15 mSv (15 rem) working condition B (116)	2 mSv (200 rem) to the surface of the abdomen for the remainder of pregnancy; limit intakes to 1/20 ALI (178)	1 mSv(100 rem) to the embryo/fetus (186)	5 mSv (0.5 rem) (§201, 208(a))

Table 1.
Gradation of radiation levels for the purpose of radiation protection [12].

As shown in **Figure 2**, the lowest threshold of radiation level for medical applications is 0.01 mSv, or 10 micro Sv. The levels of tens of micro Sv often referred to in nuclear industries in the application of exemption and clearance.

Through the discussion of exemptions and clearance in the 1980s, it is confirmed that there is trivial radioactivity. For example, trivial radioactivity was discussed by the IAEA in 1962 as 370 Bq/g for natural radioactive substances and 74 Bq/g for other radio nuclides [10]. However, there are no trivial exposures in this world. Thus, the ICRP recommended 10 micro Sv/year to be adopted for the exemption of radioactive waste from the control of radioactive substances [11]. It took more than 10 years to shift the practice of exempting radioactive waste from the basis of specific radioactivity concentrations to that of exposures.

If it were not true that the LNT hypothesis is adopted as a primary norm of radiation exposure control, trivial doses at more modest levels could be discussed, avoiding being stuck to the values of 10 micro Sv/year or several tens of micro Sv/year at most, as if to refuse 100 micro Sv/year. Thus, the LNT hypothesis influences our modern societies, guiding people not to choose nuclear energy.

Thus, nuclear industries have been showing their best efforts to demonstrate that their operations maintain levels of tens of micro Sv/year in their surrounding environment. Since the exposure we receive from the natural environment is about 2 mSv/year, although it differs from area to area, 10 micro Sv/year is not so easy to detect, as it is 1/200 of the annual exposure we receive. Thus, in most cases, the levels of tens of micro Sv are assessed based on specific radioactivity concentrations. This is something curious if we judge the consequences of radiation effects without definite measurement results.

For your reference, the radiation levels for workers under the conditions of radiation exposure are shown in **Table 1** [12].

The levels shown in **Table 1** are described with units of mSv/year, since those workers are controlled in terms of accumulated radiation exposure, monitored by dosimetry records. The dose limit has been prudently selected through discussions among experts, and those levels are called tolerable or acceptable dose levels.

Thus, nuclear industries have guidelines to protect their workers and the general public in their adjacent areas, and they design their plants to maintain those levels in their design-based accidents.

However, if an incredible or unexpected accident were to happen, causing a core melt down, its consequences could not be imagined, but at least very huge damage could be expected. The damage could be easily assessed, and private entities could not cover it by themselves.

Thus, clearing the industry's liabilities in the case of a severe nuclear accident, the Price–Anderson Nuclear Industries Indemnity Act (PA Act) was enacted in 1957 to foster the emerging nuclear industries [13]. Since a nuclear power plant accident could not be imagined, the state must confront the damage to the public. Payment of any damages above that liability limit would require congressional approval under special procedures outlined in the act, which does not specify the source of the funds. Avoiding an unlimited commitment to accidents while gaining support from the government, the 1960s and early 1970s witnessed an unprecedented boom in nuclear power plant orders. In 1979, the TMI-2 accident occurred, and the damage payment under the PA Act was accumulated to \$71 million, calculated in current US dollars [13]. Furthermore, an additional \$15.0 billion with secondary insurance (retrospective insurance) is prepared for public compensation at nuclear reactor sites [10]. These numbers seem to be sufficient; however, in 2011, the Fukushima accident revealed the damage payment by the government to be more than \$90 billion [10]. It is uncertain whether the Fukushima accident accelerated the PA Act's extension or not, but the PA Act has been extended through 2065 [13].

The hidden intention of the PA Act implementation is that any damages caused by a nuclear accident shall be recovered by government funds on the basis of unlimited liabilities. The PA Act, extended until 2065, shows a time span of more than 100 years of protecting nuclear industries by the government. One hundred years is long enough for an individual person; however, in our history, it could be considered an instance. We may recall that nuclear energy was first released in the form of an atomic bomb, and our society surely needs a certain period of time to understand the meaning of the invention of atomic energy in the history of human beings. To my understanding, 100 years would be the right period to trace back what we did and how we could adapt ourselves to live in a world of free utilization of nuclear energy.

In 1975, Rasmussen reported that the probabilities of nuclear plant failure were 60 times higher than expected [14, 15]. Prof. Yasumasa Togo quoted the report, saying that approaches by social sciences were needed for nuclear power to be accepted by societies [15].

Figure 3 shows the frequencies of natural events involving natural fatalities [14].

The author briefly reviewed the development of nuclear industries, focusing on radiation protection, and emphasized the need for further understanding of the effects of radiation on our health in the case of a severe accident, where facing core melt down is indispensable. Initially, discussions were based on the assumption of

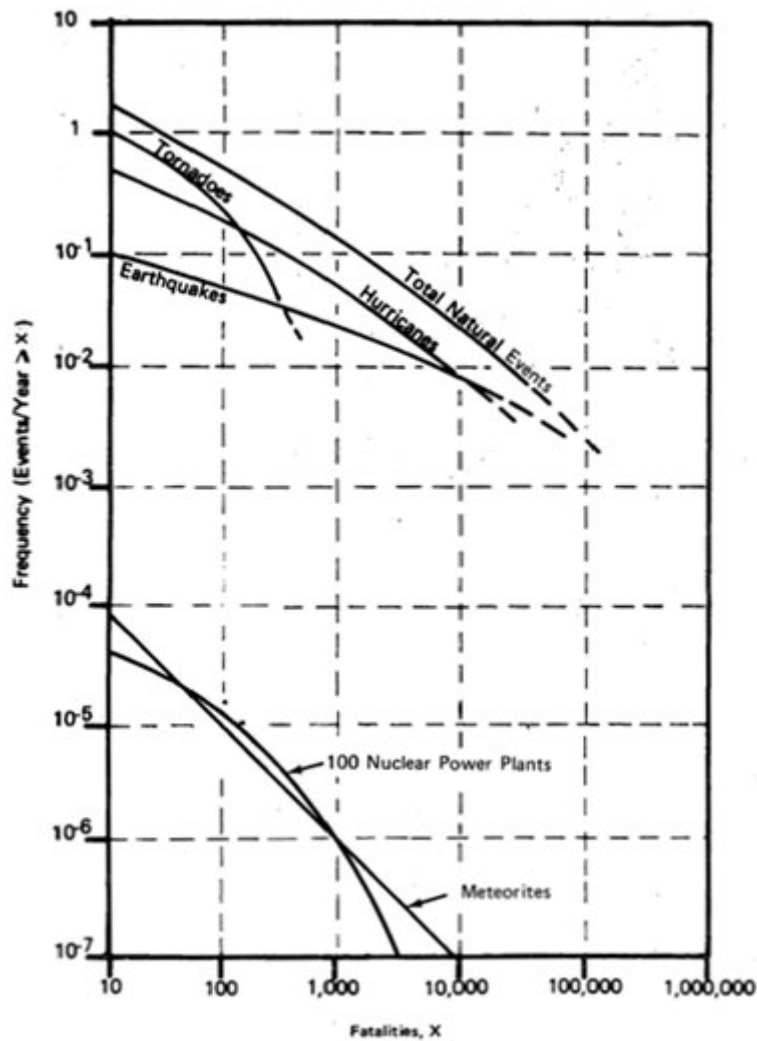


Figure 3.
The frequencies of natural events involving natural fatalities [14].

an incredibly severe accident; however, we have experienced such a severe accident within a remarkably short period of 70 years since the atomic bomb exposure.

The following sections address environmental contamination caused by radioactive substances resulting from nuclear accidents experienced in the past. Unexpectedly, the first release of radioactive substances over a wide area of daily life came from the crash of an atomic bomb carrier in Spain. In fact, the remedial plans applied to subsequent nuclear facility accidents were based on the experience of that crash, as discussed and implemented by the AEC and the Nuclear Energy Council of Spain. The lessons learned in the past should be revived in our contemporary society, offering wisdom on how to overcome incredible or unexpected nuclear accidents.

2. Windscale reactor accident in 1957

The Windscale reactor faced Wigner energy release in 1957, which resulted in the release of radioactive substances. This occurred on October 8, 1957; however, the UKAEA report was not made public until January, 1988 [16]. This is because the reactor releasing radioactive substances was a plutonium production reactor for military purposes. Nevertheless, whether the accident occurred in military reactors or civil reactors, radioactive substances would be released through the stack and fall into public areas within biosphere domains. Thus, a simple but thought-provoking dialogue between the local communities and the licensing bodies was witnessed. As is the case with reactor accidents, the standard counter measures in Windscale included the immediate cessation of milk delivery, which led the local community to notice that the reactor was experiencing trouble and that radioactive substances had been released. Scientists were calm in their analysis and would remain so. When they detected increased environmental radiation levels on the street, they compared the concentration with the annual limit of intake (ALI) to assess how dangerous the radiation levels were. The highest measured activity was recorded on Calder Farm Road at 23:00 on October 10, at levels approximately ten times higher than the ICRP limit for continuous lifetime breathing [16]. Although the level exceeded the ALI, scientists were not shaken by this fact, remaining composed in their nature. On the other hand, the milking prohibition was easily linked to concerns about the dangerous effects on the health conditions of dairy cattle. The local authority of the Ministry of Agriculture and Fisheries mistakenly announced that the thyroid of all livestock should be removed when they were slaughtered. To address this, the Ministry decided to send officials to attend the Lancashire Branch Special Meeting and succeeded in calming anxieties by demonstrating no fluctuation in radiation levels before and after the accident [16].

In the event of the Windscale reactor accident, the scientists observed levels more than ten times higher than the ICRP recommendations for continuous lifetime breathing on the street. However, they believed that the specific radioactivity concentration exceeding the annual intake was not a serious problem, and needless to say, they did not release the information to the public. Releasing every piece of information is not always useful and can simply cause public irritation for no reason.

Attention was extended to the government officials to correct the misunderstandings of local people and communities about radiation effects on the thyroids of their cattle.

What can be seen in their action as a lesson learned is that the counter measures must be swiftly implemented, and the scale of the disaster's consequences shall not be exaggerated.

Next, the details of the A-bomb carrier's crash to the ground in Spain will be discussed, followed by accidents in nuclear facilities.

3. Palomares B-52 collision accident in 1966

On July 17, 1966, a B-52 bomber carrying four atomic bombs collided with the refueling plane KC-137, and they fell to the ground, scattering plutonium on the ground [17]. Among the four thermonuclear weapons carried, two of them detonated, spreading plutonium over the villages [18].

On the day of the accident, the Joint Nuclear Accident Coordinating Center (JNACC, a joint commission of the DOD and AEC) was set up at Sandia Base (now Kirtland Air Force Base), New Mexico, and representatives of JNACC, the Los Alamos Scientific Laboratory, and Sandia Corporation were alerted and departed Albuquerque on the aircraft on January 17, 1966 [17]. It is clear that the scientists of nuclear energy development had the major task force in the course of planning environmental remedies at the site.

The detector of alpha radiation developed at that time was PAC-1S, despite the fact that they were facing a lot of troubles. Sorry for the poor resolution, but **Figure 4** shows the monitoring in rough terrain with PAC-1S [17].

The first action to be taken when a nuclear accident has happened is the same as that of today, namely, to survey the surface contamination levels. Then, areas are sorted out for further treatment [17].

On May 1, 1963, the Los Alamos Scientific Laboratory had already summarized the training manual of the Atomic Weapons Group, and Dr. Wright Langham, along with other representatives from the AEC, recommended the following treatment of the contaminated area to the Nuclear Energy Council, Spain (JEN) [17].

- a) All areas in which alpha counts per probe area are 100,000 CPM or above will be removed to a depth of at least 5–6 cm and buried in an appropriate pit that will not permit seepage into the water table.
- b) All areas with counts between 100,000 CPM and 7,000 CPM will have the present crops removed and buried. In all cases where the ground shows counts

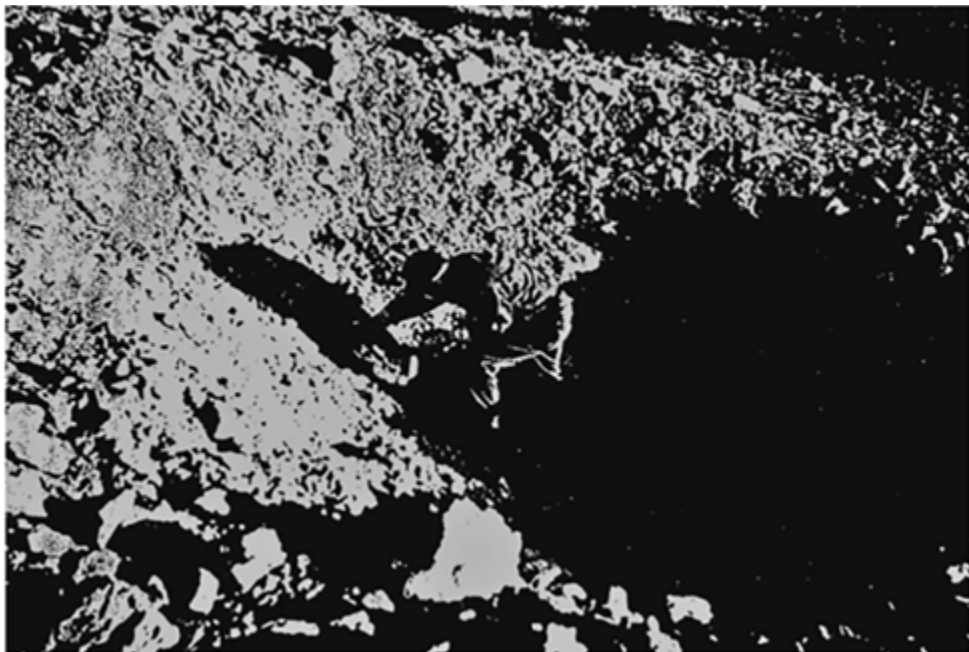


Figure 4.
Monitoring on rough terrain [17].

of 7,000 CPM to 100,000 CPM, the soil will be sprinkled with water and plowed to a depth of at least 10 cm. After it is plowed, it will be sprinkled again, and another monitoring survey will be conducted. Any spots that read above 7,000 CPM will be replowed and resprinkled until all readings are below the 7,000 CPM value.

- c) All areas reading between 500 CPM and 7,000 CPM will be sprinkled with water to leach and fix the activity in the soil, minimizing spreading by the wind. After sprinkling, the areas that read above 1,000 CPM will be resprinkled.

The PAC-1S counting rate was converted to the plutonium weight. The counting rate of 100,000 CPM was found to be equivalent to 770 micro-g/m². If we choose the specific radioactive concentration of 2.3×10⁹ (Bq/g) for ²³⁹Pu, the PAC-1S counting of 100,000 CPM comes to be equivalent to 177 Bq/cm².

Thus, converting the PAC-1S counting rate into the level of Bq/cm², the counter measure manual dated May 1, 1963 by Los Alamos Scientific Laboratory is summarized in **Table 2**. In this table, PAC-1S CPM is assumed to be proportional to specific radioactivity concentration, which must include the bias of over estimation in activity concentration for the lower range, since the background counting contribution would be the same as that for the higher range.

Table 2 summarizes the AEC report about the accident [17], and it is the perfect reflection of the graded approach later proposed by the ICRP for the radiation control of radon in mining [19]. Namely, counter measures shall be graded down or graded up depending on the nature of radiation, especially in terms of danger to our health. In principle, the ICRP can be regarded as a symbolic code of ethical values in radiation protection, and the Manual of the Atomic Weapons Group at Los Alamos National Laboratory showed no discrepancies with the ethical values described in the ICRP, written in later times [19].

Next, the specific surface radioactivity concentration of 0.9 Bq/cm² will be discussed. US Regulatory Guide 1.86 defines the termination of a nuclear reactor by the acceptable surface contamination levels [20]. It describes the maximum contamination levels of 300 dpm/100cm² for transuranium nuclides. 300 dpm/100cm² can be transformed to 0.05 Bq/cm², ² which suggests the contamination level in Palomares is 20 times higher than the termination level of nuclear reactors.

Specific surface contamination	Counter measures
>177 Bq/cm ²	Remove the surface soils to a depth of 5 to 6 cm and dispose of the contaminated soils in a pit that will not allow seepage into the water table.
177 Bq/cm ² >> 12.4 Bq/cm ²	Current crops removed, soils sprinkled and plowed to a depth of at least 10 cm. All spots showing >12.4 Bq/cm ² must be replowed and resprinkled to reduce levels below >12.4 Bq/cm ²
12.4 Bq/cm ² >> 0.9 Bq/cm ²	Sprinkled with water to leach and fix the activities in the soil, minimizing spreading by the wind. If >1.8 Bq/cm ² , resprinkled to reach 0.9 Bq/cm ²

Table 2.
Summary of the manual of the atomic weapons group summarized on May 1, 1963.

Since the contamination levels described in Regulatory 1.86 are for the unlimited release of nuclear reactor components, while those for the Palomares accident are for the soils and vegetation. In Palomares, 28 samples of beans, cabbage, etc., and 74 samples of tomatoes had been sent to Germany for radiation analysis and ensured that none of them exceeded permissible levels of contamination [17]. Through the on-site measurement of the sampled vegetables, it was proven that the specific radioactivity concentration of 0.9 Bq/cm² adopted in Palomares produces safe vegetables, and there is no need to refer to the nuclear reactor termination levels of less than 0.05 Bq/cm². The decision made at that time was quite reasonable.

Now we are back to the discussion between JNACC and JEN. JNACC shows the summary of the Manual of the Atomic Weapons Group to JEN. JEN agreed with the decontamination procedures; however, it was clear that more conservative conditions were requested by JEN, and the psychological depression and anger of local residents must be respected.

As no plutonium processing plant exists in Spain, no permissible criteria are established in Spain, nor even in the USA. The criteria are available only in plutonium handling facilities, and they are not applicable to this type of accident at all.

JNACC and JEN must set up criteria and initiate the clean up the contaminated area immediately. JNACC amended the Manual of the Atomic Weapons Group to propose its implementation at Palomares on February 2, 1966, as follows [17]:

- a) Select a place with adequate conditions to build a disposal pit where highly contaminated soil and products will be deposited.
- b) Build the pit with proper safety provisions for public health.
- c) Annual vegetable crops with a reading above 200 CPM will be removed to the disposal pit, buried, and decomposed in a short time.
- d) Fruit orchards will be carefully water-washed to remove all contamination.
- e) The ground areas treated, as indicated in paragraphs b) and d) above, will be remonitored
- f) After completion of the water-washing operation, and depending upon the level found at that time, one of the following three procedures will be observed:
 - Soil above 7,000 CPM will be removed and deposited in the disposal pit. Soil will be replaced to the extent to which it was removed and refertilized.
 - Soil areas between 7,000 and 700 CPM shall be wetted down, plowed, and remonitored for contamination. If the count does not decrease to less than 700 CPM, the soil will be treated again until less than 700 CPM is achieved.
 - Soil areas below 700 CPM will be soaked with the necessary water to bring contamination down to a very low level and remonitored for readings.

- g) All monitoring will be done with the PAC-1S.

Trial decontamination progress shown below has been reported, which would contribute to the acceptance of JEN [17]. Sincere work and effective performance say everything to obtain mutual understanding.

- a) On February 4, 1966, watering following plowing would not be a requirement, since plowing followed by rototilling reduced the surface count to nondetectable.
- b) On February 8, 1966, permit hauling of harvested crops having a count of 200 CPM or less to the river bed for burning.
- c) On February 10, 1966, raise the counts per minute on harvested crops, which could be burned, to 400 CPM.
- d) Negotiations conducted by the US Embassy and JUSMG-MAAG with their Spanish governmental counterparts during the week of February 14, 1966, having a surface contamination level of 60,000 CPM, would result in its removal from Spain. (Plowing to a depth of 8 inches on an experimental tract of 0.09 acres, which had a surface count of 40,000 CPM, followed by a second plowing to a depth of 4 inches, demonstrated that this procedure would maintain the surface contamination level at nondetectable.)
- e) On February 24, 1966, an agreement was reached with Lt. Colonel Santiago Norena (JEN) to permit the burial of the previously scraped and piled soil in Area 2 (with a surface count above 7,000 CPM but less than 60,000 CPM) in the pits that had been dug for the permanent burial of the highly contaminated dirt.

On February 28, 1966, difficulty was encountered in applying the original criteria to hilly, rocky, uncultivated areas, but the following agreement was reached on decontamination levels and methods:

- a) Follow-up cleanup requirements in the uncultivated land areas would be limited to Area 2. Earth would be removed from:
 - Hot spots, which showed counts of 60,000 CPM or above, would be included with that earth to be shipped from Spain.
 - Land surface showing counts in excess of 10,000 CPM would be washed, scarified, or dug up and raked.
 - Land surface showing surface counts of less than 10,000 CPM will be watered down where practical.
- b) The permissible level of contamination was accepted as 10,000 CPM.
- c) No work will be accomplished in Area 6.

Specific surface contamination	Counter measures
>106 Bq/cm ²	Scraped and removed from Spain
106 Bq/cm ² >> 1.2 Bq/cm ²	Water and plow
1.2 Bq/cm ² >	Water
17.7 Bq/cm ² >	Permissible where other measures cannot be applied

Table 3.

Summary of the JNACC JSN-agreed levels and counter measures on February 28, 1966 [12].

To clarify which radioactivity JNACC and JSN agreed with, **Table 3** summarizes the contamination levels of radioactivity and counter measures to be taken for each level, as reported in [17].

When **Table 3** is compared with **Table 2**, not only do the criteria levels contribute to giving psychological resilience to local residents, but it is also much simpler and gives a more familiar impression of the daily lives in their neighborhood.

It can be concluded that sincere communication with local people, swift conduct of surveys and trial decontamination, and the proposal of a long-range remedy program at the very early stage of an accident can solve the complicated problems involving radiation effects on human health.

4. Fire at Rocky Flats Plant

Rocky Flats Plant was processing plutonium metals to produce PIT, a nuclear weapon head component, but a fire involving a large amount of plutonium occurred on May11, 1969 [21]. During the course of a study on the offsite plutonium contamination from the fire, the Dow Chemical Company, which managed the operation of the Rocky Flats Plant, released the ²³⁹Pu accumulation map in 1970. In addition to the contamination mapping, the ²³⁹Pu release opportunities were reported to be one of the following [21].

- a) Fire at Rocky Flats Plant in September, 1957
- b) Pu-contaminated oil spill on the plant site, 1957
- c) Fire at Rocky Flats Plant on May11, 1969

Dow Chemical Company suggested that the oil spill would be the most probable cause of the release of the offsite plutonium contamination.

The map of the Dow Chemical Corporation shown is provided in **Figure 5**.

The highest contour level in **Figure 5** is 2,000 mCi/km², which is converted into 7.4 Bq/cm². This level is higher than 1.2 Bq/cm², which requires watering to reduce the concentration in Palomares. According to the report given by S. E. Poet and E. A. Martell, the measured activity concentrations of ²³⁹Pu fluctuate but are mostly less than 0.1 Bq/g, and contamination levels of 7.4 Bq/cm², cannot be expected, referring to S. E. Poet and E. A. Martell's data. **Figure 6** shows the results of measurement made by Philip W. Krey [22]



Figure 5.
Plutonium-239 accumulation in soils surrounding the Dow Chemical Company Rocky Flats plutonium plant [21].

Figure 5 Plutonium-239 measured concentration in soils surrounding the Rocky Flats plutonium plant. The heavy, irregular line reflects the isoconcentration contours of Rocky Flats plutonium in the soil, expressed as mCi/km^3 [22].

^{239}Pu survey, in this case, proved that the higher concentration of ^{239}Pu was not observed. The scientist did trustworthy work to fulfill his/her tasks and be accepted as a member of the local community to gain mutual understanding and trust.

5. TMI accident in 1979

As for the necessity of evacuation, the scientists and politicians had totally different views; sometimes, a wide discrepancy can be seen. In this section, evacuation is discussed. In general, politicians, like mayors or heads of local government, would like to have evacuation at the early stage of an accident.

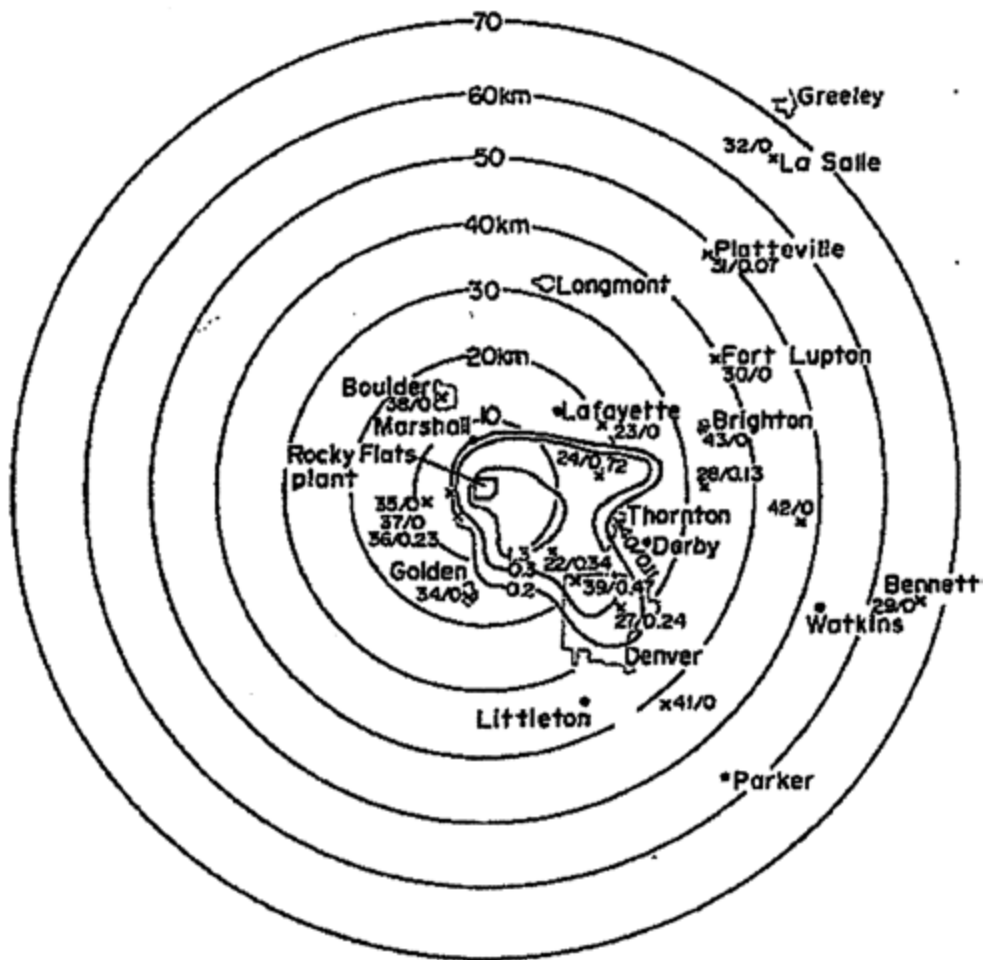


Figure 6.

Shows the measured plutonium concentration, other than the Dow Chemical Company. The highest contour is read at 1.3 mCi/km², which is more than 1,000 times smaller than that of the Dow Chemical Company indicated [22].

Nuclear power plants normally have a wide area of exclusion zone in the direct surroundings of the reactor, and outside of the exclusion zone is the low population zone. The concept of the zones is the same for each other, except for the time duration required to reach the permissible accumulated exposures in case of an accident. In case of an accident, if a person stays in the exclusion zone for two hours, they would receive the annual limit of exposure of 250 mSv, while in the low population zone, the exposure reaches 250 mSv in 30 days [23]. Although it depends on how high the release rate of radioactive substances is, under the conditions of a design base accident, people living in the low population zone have at least 30 days to prepare for their evacuation.

In the case of the TMI accident, the radioactive substances had fallen over the site due to the calm wind conditions, and none of the NRC scientists at the site felt any need for evacuation. Even if evacuation were ordered, they expected that the evacuation area would be limited to the down wind direction of wedge-shaped areas.

Contrary to the expectations of NRC staff at the site on March 31, 1979, the Governor announced advice for pregnant women and preschool aged children to leave the area within a five-mile radius of the Three Mile Island facility [16].

What we may think of it is that the fear of radiation effects always supersedes other conventional risks, damage, or inconvenience. The root cause of this psychological bias first comes from the atomic bomb victims but gradually expanded with media reports. It is not limited to the very last day of the ground zero survey of atomic bomb victims but also expanded to the TMI accident in Harrisburg. At the time of the TMI accident, “No more Harrisburg,” duplicating the phrase “No more Hiroshima,” was orchestrated with a film streaming of atomic bomb explosions on TVs in the USA. TV media would like to raise a sensational image by linking the TMI accident to the mushroom cloud growth caused by atomic bomb explosions [2].

This is truly a mirror image of social media’s role in our contemporary society. Experts in nuclear energy have been and will continue to be warriors on the front lines, facing the media. Our weapon is scientific knowledge, combined with proper ethical values, sincerity, and the belief in using nuclear energy for the betterment of our future. Science supports us through evaluation and assessment, and our belief in the correct path for nuclear energy usage will shape the future.

6. Chernobyl accident in 1986

The Chernobyl accident occurred in February 1986, and almost 40 years have passed. The accident caused disastrous effects in the surroundings; however, about six million people in Ukraine, Belarus, and Russia were living in areas officially designated as contaminated [24]. The threshold level was set at 37 kBq Cs/m², which can be converted into 3.7 Bq/cm². We may recall the Palomares lowest level of 1.2 Bq/cm², at which level only watering is required. Although in Palomares the nuclide is ²³⁹Pu with alpha decay, while in Chernobyl ¹³⁷Cs with gamma decay, the clearance levels of ²³⁹Pu and ¹³⁷Cs are the same at 0.1. We may see that Palomares and Chernobyl adopted a similar level of threshold for controlling radiation.

However, in Chernobyl, 270,000 people were living in 670 settlements where land surface activity levels exceeded 555 kBq ¹³⁷Cs/m², which may be converted into 55.5 Bq/cm². This level needs to be watered and plowed in the case of Palomares; thus, wide-scale remedial actions are needed.

Chernobyl is important in its epidemic research on wild life. Our assumption that mammals are more sensitive to radiation effects than others may be confirmed in the future. Radiation effects on ecology, including biological diversity, may be observed, although it may take more than 100 years.

Contrary to Palomares, Chernobyl cannot remediate the environment of the affected area since the scattered radionuclide amount is so huge, and a large area was contaminated. However hard it is, we need to monitor the radiation effects on ecologies, on wildlife, and also radionuclide migrations. This cannot be completed by one generation, and the scientific interest in radiation ecology shall be kept and transferred to the next generation.

7. Fukushima accident in 2011

Since evacuation programs were never planned or drilled in Japan, they had no choice but to rely on stopgap counter measures to address the Fukushima accident, without any thoughtful consideration of their future consequences.

For example, evacuation was ordered even for the elderly who needed intensive care [6]. The radius of the evacuation zone was initially 10 km, then expanded to 20 km. As was the case with TMI, a wedge-shaped evacuation zone toward the downwind direction could not be adopted.

Despite the emergency recommendation by ICRP, which indicates the highest residual band of doses at 20–100 mSv [25], the government of Japan set the limit dose as low as 1 mSv [6]. Thus, many residents cannot return home, contrary to the case of Chernobyl, where residents were allowed to return home even though their land was registered as a contaminated area.

Counter measures to decontamination were also stopgap means. Plow soils were not widely adopted; rather, collecting soils occurred even when the specific surface radiation dose rate was so low. A huge amount of very slightly contaminated soils was collected and is waiting for reuse. The amount of soils, along with other waste, is estimated to be about 15 million m³ [26].

One simple idea of avoiding extra exposure cannot be applied to the Fukushima accident. Instead, we must be more flexible and familiar with radiation to realize that we live in an environment surrounded by radiation. Proper understanding of ecologies under extra radiation control, currently being studied in Chernobyl, is also helpful in Fukushima.

Science always changes the cruise course, following the needs of human societies. How to overcome TMI, Chernobyl, and Fukushima accidents must be referred to our experiences to solve the release of radioactive substances in the case of an atomic bomber plane crash and other unexpected circumstances with our wisdom.

8. Conclusions

The author believes nuclear energy plays an important role in saving the globe. It is clear that we need time to understand the meaning of nuclear fission in taming it for the purpose of our happiness and welfare.

We did correct the bias regarding the negative harmful effects of radiation on our health, stating that radiation induces effects on our body even in trivial exposures; however, it is important to recall that radiation protection used to be only a concern among medical workers at first, and at that time, a much higher dose level was adopted as the safety standard.

Nowadays, the danger comes down to the general public, and the safety criteria for our health go down dramatically.

Nuclear industries follow the lowest levels of radiation in their routine work of energy production, although sometimes it is requested to maintain the same level even in incredible situations.

Recent retrofitting of existing thresholds in radiation effects is one of the favorable trends in the support of nuclear energy expansions.

Societies need time, sometimes centuries, to change their ideas of common sense. Currently, nuclear energy is categorized as a shady technology. People are

going back and forth, pronuclear and antinuclear. Only the scientists can say something.

Nuclear energy is said to be an area of interdisciplinary field, but in fact, it simply consists of theory and laboratory experiments, as is the case with other scientific approaches.

Nuclear energy was born in August, 1945, and ancestors have been passing away together with their knowledge, especially when they encountered the release of radioactive substances and how they could manage to obtain a reasonable understanding of radiation effects on the residents in their affected areas.

As the ICRP defined the dose limit to be applied to controlled situations and recommended it never be applied to uncontrolled situations when they first introduced the concept of dose limit [26], the dose limit is expected to be defined by the legal system, and the answers from radiation protection experts were full of wisdom.

I hope in somedays, the legal system gives way to the thoughtful recommendations given by radiation protection experts in the twentieth century.

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Section 4

Applications as a Sustainable Resource

Perspective Chapter: Use of Gamma Radiation in the Food Industry

Nikolay Dolchinkov

Abstract

“Irradiated food” is a topic that has generated much interest and discussion and represents the treatment of food and food products with gamma rays or other ionizing radiations. This technology is used to improve the safety and quality of food by destroying pathogenic microorganisms and extending the shelf life. Scientific research conducted over the past five decades has shown that irradiated foods are safe to eat and do not contain harmful products that could harm human health. The World Health Organization (WHO), the International Food Organization (IFO), and the International Atomic Energy Agency (IAEA) have confirmed these conclusions in their reports. Currently, over 170 industrial irradiation facilities are operating around the world, and they are used for various purposes, including medical sterilization and food processing. To date, there have been no accidents that have resulted in environmental or product contamination.

Keywords: food industry, gamma sources, gamma radiation, hazards, industrial applications, processing

1. Introduction

Irradiated food is food that has been treated with ionizing radiation, which is done to improve its quality, kill bacteria and microorganisms, and extend its shelf life [1]. Gamma and X-ray radiation, as well as accelerated electrons, which are part of ionizing radiation, are used in food processing. This technology became popular in the 1990s and is used to subsequently extend the shelf life, kill harmful microorganisms and parasites, and disrupt the germination of potatoes, onions, and other vegetables.

The irradiation process does not change the appearance, taste, or texture of the food [2].

Ionizing radiation is an excellent means of sterilization/disinfection, killing organisms without raising the temperature, so-called cold sterilization. It destroys bacterial endospores and vegetative cells, both eukaryotic and prokaryotic; but it is not always effective against viruses [3].

The mechanism of sterilization by ionizing radiation is related to the collision of ionizing radiation with particles that produce electrons (e^-) and other reactive

molecules such as hydroxyl radicals (-OH) and hydride radicals (H^+). Each of these reactive molecules is capable of degrading and modifying biopolymers such as DNA and protein [4]. DNA damage and enzyme degradation lead to the death of the irradiated cells.

Several sources of ionizing radiation are available, including X-ray machines, cathode ray tubes (electron beam radiation), and radioactive nuclides (gamma/X-ray sources) [5].

Storage processing is applied to various products to extend shelf life and improve safety. Here are some of the most commonly irradiated foods:

1. Spices and aromatic herbs are subjected to ionizing radiation to destroy microorganisms and insects.
2. Meat delicacies and poultry are processed to reduce the risk of pathogenic bacteria.
3. In grain products and starches, the development of insects is completely prevented [6].
4. In frozen foods, ionizing radiation helps to extend the shelf life and maintain quality.
5. In dried fruits and vegetables, with the effect of ionizing radiation, we strive to prevent the development of mold and insects.
6. In the processing of oilseeds, we achieve an improvement in safety and quality [7].

The coating of the storage has a wide application in different life, and the composition of “irradiated foods” should not be applied because this process is carried out under the control of specialists and is in accordance with the norms for storage and processing of the storage. Objective repositories have been the subject of scientific research for more than five decades worldwide, and the results have been discussed and summarized by experts from the World Health Organization, the International Food Organization, and the International Atomic Energy Agency in the reports in 1970, 1977, and 1981 of the Joint FAO/IAEA/WHO Expert Committee on Wholesomeness of irradiated food (WHO, 1980) [8].

2. Essence of the food “irradiation” process

2.1 Nature of ionizing radiation

Ionizing radiation is a type of radiation that has enough energy to ionize the atoms or molecules it passes through. This means that it can remove electrons from atoms, creating ions. Ionizing radiation includes alpha particles, beta particles, gamma rays, X-rays, and neutrons [8].

The main sources of ionizing radiation are radioactive materials, cosmic radiation, and artificial sources such as X-ray machines and nuclear reactors [9]. This radiation is used in a variety of fields, including medicine for diagnosis and treatment, the industry for quality control, and scientific research.

Exposure to ionizing radiation in one form or another can pose health risks. The main risks of ionizing radiation exposure include:

1. Acute radiation sickness occurs when high doses of radiation are given over a short period of time and can cause symptoms such as nausea, vomiting, fatigue, and hair loss.
2. Cancer is a serious disease that occurs in the body with prolonged exposure to low doses of ionizing radiation. This exposure increases the risk of developing various types of cancer, including leukemia and thyroid cancer.
3. Genetic damage occurs because ionizing radiation can cause mutations in DNA that can be passed on to subsequent generations in both humans and other living organisms.
4. Long-term exposure to radiation can lead to the development of cataracts.

It is important to take precautions when working with sources of ionizing radiation and to comply with established safety standards. When observing the conditions for working with ionizing radiation, the probability of illness is within the probability of illness from other diseases. It is also necessary to maintain constant medical supervision of those working with ionizing radiation and monitor the health status of those exposed to this type of radiation.

The ALARA system is a fundamental principle in radiation protection, which stands for “As Low As Reasonably Achievable.” This principle was formulated in 1954 by the International Commission on Radiological Protection (ICRP) with the aim of minimizing the harmful effects of ionizing radiation.

The main aspects of ALARA include:

Dose minimization: Keeping individual and collective doses of radiation as low as reasonably achievable, taking into account social and economic factors.

Optimization of protection: Using the best available technologies and practices to reduce radiation exposure.

Risk assessment: Continuously assessing and managing the risk of radiation exposure [10].

The ALARA principle is applied in various fields, including nuclear energy, medicine and industry, to ensure maximum protection of people and the environment, including the exposure of food to ionizing radiation.

2.2 Extending the shelf life of food products

Extending the shelf life and quality of food products is essential for several reasons:

1. A longer shelf life means that food remains edible for a longer period of time, which reduces the amount of food wasted. Improving the quality of food also leads to limiting food waste, which is a major problem in modern society.
2. A longer shelf life helps producers and retailers reduce losses and increase their profits. Consumers can also save money by using quality food and not having to throw away spoiled or unfit food. This also leads to economic benefits for producers, sellers, and buyers.

3. Extending the shelf life and quality of food ensures longer-lasting availability of food products, which is especially important in regions with limited access to fresh food.
4. By using different methods to extend the shelf life, such as refrigeration, freezing, and modified atmosphere packaging, the quality and safety of food products are preserved. This also leads to the consumption of better quality food throughout the shelf life.

Different methods are used to extend the shelf life of food products, each with its own advantages and disadvantages. Here are some of them:

1. Refrigeration and freezing. This method slows down the activity of microorganisms and enzymes that cause spoilage. Depending on the food product, different freezing techniques can be used. Each product, depending on the type of freezing, can have a different shelf life during which it retains its nutritional qualities. In a frozen state, products can be stored for even tens of years.
2. Modified atmosphere packaging (MAP). In this type of processing, the composition of the internal atmosphere of the package is changed to inhibit the growth of aerobic organisms [11]. It is used for specific foods where the growth of these microorganisms needs to be slowed down.
3. Preservatives and antioxidants. They are added to foods to prevent oxidation and the growth of microorganisms. They are widely used in the food industry and to preserve food at that stage of development of microorganisms, in which they are most useful.
4. Reduction of water activity. By drying or adding salt or sugar, the water available to microorganisms is reduced. This type is used for seasonal foods, which in this dried form can be preserved for other seasons, without undergoing heat treatment and retaining their nutritional qualities.
5. High-pressure processing (HPP). It uses high pressure to destroy pathogenic microorganisms. This processing method is used when there is a suspicion of the presence of dangerous microorganisms in food.
6. Ionizing radiation. It uses irradiation with ionizing radiation to destroy microorganisms and extend the shelf life [2].
7. All methods are used in practice to extend the shelf life or improve the quality of foods of plant and animal origin. Depending on the required results, the condition of the food, and its quantity, the most appropriate processing method is selected [3, 12].

2.3 Use of ionizing radiation for food processing

The use of ionizing radiation for food processing does not lead to changes in the appearance, shape, and temperature of the products; it mainly affects their

microbiological status and shelf life. It has been practically established that in technological processing regimes of the main food components (proteins, fats, and carbohydrates), they are resistant to the effects of radiation and do not change their structure. Irradiation mainly reduces the content of vitamins, with the most pronounced changes in the content of vitamins A, B1, B2, B3, B6, B12, folic acid, vitamins C, E, K, and polyunsaturated fatty acids [4, 13]. Based on experiments conducted in the last 50 years, it has been established that the influence of irradiation is no different from that of other treatments (thermal, freezing, chemical) applied to extend the shelf life of food products. Naturally occurring products, both in irradiated and in foods processed by other methods and technologies, are the so-called “free radicals.” The impact of free radicals on human health is among the issues on which there is still no generally accepted opinion, and research is ongoing. Many theories have emerged, but none of them have yet been fully proven.

A basic principle of radiation technologies for food processing is that they do not replace good agricultural, manufacturing, and hygienic practices. Irradiation is justified if it fulfills a technological requirement or is beneficial to the consumer [14].

Foods subjected to irradiation must be fit for consumption and comply with hygiene standards, nutritional standards and transport standards.

The sponsor of radiation treatment of food products must guarantee their quality before irradiation. He must also declare that the food has not been previously treated with ionizing radiation and chemical preparations for the same purpose.

The packaging of foods to be irradiated must be suitable for the purpose, that is, resistant to the effects of radiation. Recommended materials are polyethylene, polypropylene, paper, etc. It is advisable that the packaging has been tested in advance for the effects of the relevant radiation.

Each irradiation facility should develop a system of incoming documentation that provides information and guarantees about the microbial, nutritional, and hygienic status of the food received for irradiation [1, 15].

Food irradiation achieves the following technological goals and is used in the following cases:

1. Shelf-life extension—irradiation inactivates putrefactive microorganisms and allows for the extension of the storage time of products, preserving to a greater extent than the preservation process the natural texture, color, and smell of foods. The radiation treatment process does not require the addition of liquid, the natural juices of the foods are preserved, and the irradiation takes place in the final consumer packaging in a fresh or frozen state.
2. Sterilization—radiation-treated foods can be stored for years without the use of refrigeration equipment (as is the case with high-temperature sterilization of foods). In this way, food is prepared for special medical purposes, for military and space needs [16].
3. Delaying the ripening of fruits and vegetables and the germination of root crops—irradiation extends the shelf life and reduces losses.
4. Disinfection—radiation treatment of food is an alternative to chemical disinfection and fumigation of grain, dry products, herbs and spices, rice, beans, and lentils. It does not contaminate food with foreign chemicals.

5. Control of pathogenic microorganisms—irradiation prevents the occurrence of dangerous diseases caused by bacteria, parasites, and various microorganisms. Such are common ones such as microbial contamination in various types of raw meat and dangerous to humans.

The safety of irradiated foods has been the subject of scientific research for more than five decades throughout the world, and the results have been discussed and summarized by experts from the World Health Organization, the International Food Organization, and the International Atomic Energy Agency. No specific and unknown harmful products have been identified that arise only as a result of irradiation, as well as specific radiolysis products in concentrations that would harm human health. Another main conclusion is that irradiation does not pose an increased microbiological risk to human health and does not increase the viability of pathogenic microorganisms [6, 14].

The main questions that need to be answered are what are the advantages and disadvantages of using ionizing radiation in food processing [3, 15].

2.4 The advantages can be summarized mainly in the following areas

1. Efficiency. Ionizing radiation acts at the cellular level and destroys a wide range of pathogenic microorganisms, including bacteria, viruses, and parasites.
2. Quality preservation. Exposure to this type of radiation does not significantly change the taste, texture, and appearance of food. They retain these qualities and, as a result of the destruction of harmful microorganisms, retain these qualities for a significantly longer period.
3. Shelf-life extension. This method significantly extends the shelf life of food products.
4. Along with the advantages, there are also a number of disadvantages to processing with ionizing radiation, such as:
 1. Potential health risks. Although irradiated foods are safe to consume, there is public concern about possible long-term effects. This is a result of the two major accidents in Chernobyl and Fukushima, the lack of public awareness, and the spread of false information in the media and social networks [8, 17, 18].
 2. Reduction of nutritional value. It can lead to the loss of some vitamins and nutrients when irradiating foods with higher doses with a high presence of pathogenic organisms and potentially dangerous foods. Irradiation with higher doses is applied when food products come from contaminated areas, when there is a suspicion of contamination with dangerous microbes, viruses, bacteria or other microorganisms, so that the food can remain fit and not be thrown away.
 3. High costs. Irradiation installations and equipment are expensive and therefore this method is used for processing large quantities of food, mainly when imported from other countries where there is a risk of transferring dangerous microorganisms. The processes for processing with ionizing radiation are controlled and for each product the irradiation time is different, and the condition of the specific batch must also be taken into account.

When irradiating food, certain norms and rules must be observed, and all requirements for irradiated food are contained in the Codex Alimentary General Standard for Irradiated Food.

The general requirements can be formulated in the following general way:

1. For the radiation source—gamma rays, radioisotopes of Co-60, Cs-137, X-rays from electron accelerators with an energy of less than 5 MeV, electrons generated by electron accelerators operating up to 10 MeV energy level. These sources are recommended and all companies that use the method of processing food with ionizing radiation must comply with them.
2. For the absorbed dose—up to 10 kGy, except for “special purposes.” In special cases, this limit may be exceeded, but after the appropriate decision in compliance with the prescription of the relevant regulatory authorities.
3. For facilities and process control—requirement for licensing of facilities, personnel, reporting, including quantitative dosimetry, hygiene (CAC/RCP 1-1969, REV 3-1997), the Hazard Analysis and Critical Control Point (HACCP) system. All this is done after licensing by the relevant state regulatory body for the relevant country and in strict compliance with the standards for irradiation of production and personnel. Any deviation from the standards must be reported to the relevant state regulatory and supervisory bodies [19, 20].

The choice of irradiator is determined by the following factors:

1. method of movement of production;
2. dose limits for processing food products;
3. productivity;
4. reliability;
5. safety systems and
6. capital and operating costs.

Depending on the field of use, irradiators can be specialized or multipurpose.

Specialized ones are designed for irradiation of a finite number of products and are usually the final link in the production process. Multipurpose irradiators are used to irradiate various products at the request of external customers [1, 21].

All stages of irradiation must be strictly documented. Each irradiation facility must maintain an archive that reflects the results of measurements during commissioning of the facility and periodic testing, the parameters of each technological process and the calibration of the dosimetric system and other measuring instruments.

Each irradiated batch must receive an identification number by which its movement in the irradiation facility can be traced.

Each facility must issue a certificate for the food products irradiated in it, which must include:

1. the batch identification number;
2. the date/period/of irradiation;
3. the quantity of the batch;
4. the purpose of irradiation;
5. the limits of the measured dose during routine processing and
6. environmental conditions.

In order to achieve control of irradiated foods, a plan and procedure must be in place to ensure reliable separation of irradiated and non-irradiated products. This can be achieved by controlled one-way movement of products within the irradiation facility and, in particular, by separating storage areas for irradiated and non-irradiated foods [11, 22].

Irradiation facilities for radiation treatment of food must meet the requirements of good hygiene practices.

Personnel operating the radiation facilities must be appropriately qualified, trained and competent. In addition to specialized training for operating the irradiation facility provided by the facility supplier, training for the ability to work with sources of ionizing radiation conducted by licensed organizations, it is necessary for the personnel to undergo training from international or national competent authorities for radiation processing of food and methods, means and procedures of technological dosimetric control.

When processing food with ionizing radiation, technological requirements for the course of the process and activities after its completion must be observed. This includes the following activities:

1. Re-irradiation. Foods are not re-irradiated except in cases where the initial irradiation is of low dose, the initially irradiated ingredient is less than 5%, and the cumulative absorbed dose is below 10 kGy (except in “special cases”). For re-irradiation, an analysis and assessment of the initial irradiation must be made, and only after establishing the need for re-irradiation is it proceed.
2. Post-irradiation verification. This is actually a measurement of the irradiated dose and the results of the impact of ionizing radiation on foods. This is also an important part of the food processing process because at this stage the real values and effects of the irradiated foods are obtained.
3. Labeling. At this stage, the necessary information about the type of treatment and the dose to which the foods have been subjected must be placed on the food label.

Irradiation does not replace the need to apply the requirements for good manufacturing practices at all stages of food production. A basic requirement of this treatment is to only subject foods that arrive in a proven good hygienic condition, according to nationally accepted standards for good manufacturing practice [22].

Legislation on food irradiation is strictly regulated both at national and international levels. In Bulgaria, for example, the Ministry of Health and the National Center

for Radiobiology and Radiation Protection (NCRRP) are the main bodies that regulate this process. The European Union also has strict regulations that determine the conditions for authorizing food irradiation, permissible doses and labeling requirements. This process is legislatively regulated in many countries [1, 23].

The main aspects of the legislation in the field of using ionizing sources for food processing include:

1. Authorization of irradiation. Irradiation is permitted only for certain foods and under certain conditions. This is regulated in the legislation of the countries and enterprises operating in the territory of these countries must comply with local legislation
2. Licensing of facilities. Facilities that perform irradiation must be licensed by the relevant state regulatory authorities and are subject to strict control at all times and on any occasion by the state's controlling authorities. Control must be carried out not only on the occasion of a specific action, but continuously and without cause, and in case of violations, the licensing authority must be notified, and in case of major violations, even the license may be revoked.
3. Labeling. Irradiated foods must be clearly labeled to inform consumers. The label must indicate the type of irradiation, the radioisotope used and the radiation dose. By using a QR code on the label, significantly more information about the type of treatment and its results can be collected.
4. Although food irradiation has many advantages, there are also some risks and concerns, some of which are not fully proven, but they exist and cannot be dismissed, such as:
5. Loss of nutrients. Irradiation can lead to a reduction in the content of some vitamins and nutrients, similar to other processing methods such as heat treatment. This depends on the type of food product, the isotope used, the exposure time and the dose ingested. After each exposure to food products, follow-up control and analysis should be carried out.
6. Public concern. Although scientific studies show that irradiated foods are safe to eat, there is public concern about possible long-term effects. This is a result of the accidents in Chernobyl and Fukushima, the ignorance and lack of information of the population and the presence of false information in the media and social networks [14, 22]. Taken together, this leads to distrust in the information on the label and doubts about its reliability.
7. Potential chemical changes. Irradiation can cause chemical changes in foods that lead to the formation of new compounds, some of which may be harmful. This probability is different for each specific case and appropriate measurements and analysis must be made to prove it.

In the world, in order to improve quality and meet consumer requirements in many countries and with the permission of the competent health and safety authorities, more than 40 types of different foods are irradiated, including potatoes, onions and garlic; dry spices and their mixtures; herbs and teas; grains, flour and grain

products; beans, lentils and rice; fruits (fresh and dry); vegetables (fresh and dry); various types of meat and meat products; fish and fish products; seafood; enzymes, enzyme preparations and food supplements; nuts and coffee beans [21].

Food irradiation is applied in over 50 countries. The leaders in this regard are the USA, Canada, France, Japan, the Netherlands, Belgium, Russia, Italy and South Africa.

Bulgaria has long-standing traditions in the field of radiation technologies. Scientific research began in the 1970s, when various technological processes for food processing were developed and their safety was investigated. After the introduction of industrial irradiators in many food processing plants in Bulgaria, herbs, spices, teas, dried fruits and vegetables, food additives, dairy products, citrus fruits, and others are mainly processed [20].

Incidents in the processing of food with ionizing radiation are rare, as this process is strictly regulated and safety control is very high. However, there are cases of incidents related to improper handling of equipment or inadequate safety measures.

One of the famous incidents occurred in Mexico in 1983, when workers in a food irradiation plant were exposed to high doses of radiation due to malfunctioning equipment. Another case was registered in India in 2010, when improperly disposed radioactive materials led to the exposure of workers. There is also a known incident when a source was removed from a food plant in the town of Stamboliyski in Bulgaria, which had no consequences for the food and the personnel working on the premises of the plant.

These incidents highlight the importance of strict safety measures and proper training for personnel working with ionizing radiation.

2.5 Regulation of food irradiation with ionizing radiation

The irradiation of food with ionizing radiation is strictly regulated to ensure consumer safety and food quality and complies with the General Standard for Irradiated Foods, which is mandatory for all countries. Here are some of the main rules and requirements that are enshrined in this international document:

1. Irradiation permit. Irradiation of food is permitted only if there is a legitimate technological need and it does not pose a health risk to the consumer. The relevant enterprise must have a permit to use a system for irradiating food with ionizing radiation and all standards for the power of the source used, shielding of the premises, distance from other buildings and other requirements according to the relevant national and international legislation must be met.
2. Sources of ionizing radiation. Irradiation can only be carried out with certain sources such as gamma rays from the radionuclides cobalt-60 and cesium-137, X-rays and accelerated electrons. Accordingly, there must be a licensed worker who is entitled to work with these sources.
3. Maximum dose. The total average absorbed dose of ionizing radiation must not exceed 10 kGy for food products for the specified period. The standards for the exposure of personnel of different labor categories and people who are in the area of action of the source of ionizing radiation must also be observed. If necessary, the dose of irradiation of the product must be changed or personnel rotation must be carried out.

4. Labeling. Irradiated foods must be clearly labeled to inform consumers that they have been treated with ionizing radiation. The type of irradiation, the dose of irradiation and the results after irradiation must be indicated.
5. Control and licensing. Facilities that perform irradiation must be licensed by the relevant state regulatory authorities and are subject to strict control by the relevant regulatory authorities of the country where the enterprise operates. The controlling authorities have the right and obligation to carry out relevant inspections at any time and the management of the enterprise has no right to obstruct their activities. If violations are found, prescriptions are issued, the enterprise is fined, and even the license to work with ionizing radiation may be revoked.
6. Documentation. Foods subject to irradiation must be accompanied by a declaration from the person who provided the foods for irradiation, indicating the purpose and conditions of irradiation. After irradiation, measurements must be made and the results obtained must be entered in the appropriate document form. All results and data are stored for a certain period of time, which is specified in the relevant legislation.

These rules are created to ensure the safety and quality of irradiated foods, as well as to protect the health of consumers. They must be strictly observed and their implementation monitored at all levels [20, 23].

To ensure the quality of irradiation and the interests of consumers, a number of documents of the Codex Alimentarius Commission define the basic principles of licensing and control of food irradiation. In 1999, the European Parliament and the European Council issued directives on the radiation treatment of food and trade in it Directive 1999/2/EC of the European Parliament and of the European Council of 22.02.1999 on the approximation of the laws of the Member States relating to foods and food supplements treated with ionizing radiation. This Directive describes the rules for the production, import and trade of irradiated foods within the European Union, the cases of possible exceptions, as well as the procedure for introducing changes to Directive 1999/3/EC of the European Parliament and of the European Council of 22.02.1999 on the establishment of a common list of foods and food supplements treated with ionizing radiation. At the moment, the list contains dried aromatic herbs, spices and vegetable mixtures. Although according to the EU Directive 1999/2 this list was to be completed by the end of 2000, at present no other food products are permitted for radiation treatment [1, 24].

In connection with Bulgaria's accession to the EU, the legislation in the field of irradiated foods was harmonized in accordance with the EU Directives. The Food Act specifies the purposes for which irradiation may be used, and stipulates that food irradiation shall be carried out only by registered facilities. The Act describes the procedure and conditions for the registration of irradiators and for issuing permits for food irradiation. Regulation No. 6 "On the types of foods that may be treated with ionizing radiation and the conditions and procedure for their treatment" defines the types of foods that may be treated with ionizing radiation. The EU positive list has been adopted at this stage—dried aromatic herbs, spices and vegetable mixtures that may be treated up to a maximum average absorbed dose of 10 kGy.

The regulation describes the requirements for facilities, technological processes and procedures for dosimeters.

Trade in irradiated foods is permitted only if the label states that they have been subjected to radiation treatment, that is, it must contain the inscription “Treated with ionizing radiation” or “irradiated” [10].

Imports of irradiated foods are only allowed for foods on the positive list and provided they have been processed in EU-licensed facilities.

Each country is required to bring its national legislation into line with international standards, but some of the countries with the strictest rules on food irradiation are, for example:

1. The European Union has strict regulations on food irradiation, which include requirements for licensing facilities, maximum permissible doses and mandatory labeling of irradiated foods. The European Commission and the European Food Safety Authority (EFSA) ensure control and monitoring of compliance with these standards. Since 2000, more than 15 European Union directives have been issued on the irradiation of various types of foods of plant or animal origin with ionizing radiation.
2. In the United States, the Food and Drug Administration (FDA) and the Department of Agriculture (USDA) regulate food irradiation. They require rigorous safety and efficacy testing, as well as mandatory labeling of irradiated products.
3. The Canadian Food Inspection Agency (CFIA) regulates food irradiation and requires strict safety and labeling standards [22].
4. Food irradiation violations can have serious consequences for both producers and consumers, and therefore strict controls and high penalties are necessary. Here are some of the main consequences:
5. Health risks. Incorrect irradiation can lead to insufficient destruction of pathogenic microorganisms, which increases the risk of foodborne illness. At the other extreme, it can lead to the destruction of some vitamins and minerals and loss of nutritional value.
6. Legal sanctions: Violations of regulations can lead to fines, revocation of licenses and other legal actions against responsible individuals and companies. Therefore, strict compliance with the rules, continuous control and strict penalties are necessary.
7. Loss of trust. Consumers may lose confidence in the safety and quality of a company's products, which can lead to reduced sales and reputational damage. Fake news is also often used to damage the reputation of a company or to erase omissions and sanctions against a particular enterprise.
8. Economic losses. Incorrect irradiation can lead to the withdrawal of products from the market, which leads to significant financial losses for manufacturers. This can even lead to the bankruptcy of a company [25].

Strict regulations and controls are created to prevent these risks and ensure the safety of irradiated foods.

3. Conclusions

The use of the method of irradiating food with ionizing radiation has its advantages and disadvantages, which must be taken into account when making a decision. It is a progressive method and, subject to all work rules and labor discipline, leads to positive results. As with working with ionizing radiation in other areas, strict adherence to the rules is required here.

Based on the above, we can conclude that the method has a number of advantages, the most important of which are:

1. **Safety.** Irradiation effectively destroys pathogenic microorganisms, such as bacteria, viruses and parasites, which reduces the risk of foodborne diseases. At the same time, it preserves proteins, carbohydrates and proteins, but can lead to a slight loss of vitamins and minerals.
2. **Shelf life extension.** Irradiation can significantly extend the shelf life of food products by slowing down the processes of spoilage and decay. At the same time, it destroys a number of harmful microorganisms that are a prerequisite for the spoilage of plant and animal foods.
3. **Quality preservation.** Irradiation does not significantly change the taste, texture, or appearance of food. Food does not lose its nutritional value.
4. **Reduction of chemical treatments.** Irradiation can reduce the need for chemical preservatives and pesticides, which leave traces in food and can accumulate in the human body.

Along with the positive aspects, the disadvantages of this method should not be overlooked, some of which are:

- **Loss of nutrients.** Irradiation can lead to a decrease in the content of some vitamins and nutrients when irradiated with higher doses.
- **Public concern.** Although scientific studies show that irradiated foods are safe to consume, there is public concern about possible long-term effects. The main reason for this is the lack of information among the population and the frequent appearance of fake news or incorrect information in the media and social media.
- **High costs:** Irradiation facilities and equipment are expensive, which can increase costs for producers, but they are generally used in large quantities and facilities are used rationally and to their full potential.

The method of irradiating food with ionizing radiation can be useful and effective, especially when used to improve the safety and extend the shelf life of food products. However, it is important to comply with strict regulations and inform consumers about the process in order to minimize risks and address public concerns.

The future of food irradiation with ionizing radiation looks promising, and it is expected to play an important role in ensuring the safety and extending the shelf life of food products. Here are some of the key aspects:

1. With the development of technology and scientific research, food irradiation can be applied to an increasingly wide range of products and has expanded its scope. This includes not only traditional spices and meat products, but also new food categories, such as fresh fruits and vegetables. Many space foods are processed with ionizing radiation in order to extend their shelf life and preserve their beneficial ingredients.
2. Irradiation technologies are expected to continue to develop, which will lead to more efficient and economical processing methods. This may include new sources of ionizing radiation and improved control and monitoring systems. With the advent of modern technologies, the range of foods processed by this method will also expand.
3. As scientific evidence on the safety and effectiveness of irradiation increases, public confidence in this method can increase. This will be supported by transparent regulations and labeling that inform consumers about the process.
4. More and more countries are adopting and implementing food irradiation as a standard method to ensure safety and extend shelf life. In the future, not only will about 50 countries implement this method, but the number of countries using it will increase. This can lead to global harmonization of regulations and standards. By unifying the standards and norms of different countries, there is a move toward unification of the method and the same rules everywhere, which must be strictly followed.
5. Irradiation can be combined with other food processing methods, such as refrigeration, freezing and modified atmosphere packaging, to achieve maximum efficiency and safety. This is already used in the production of space food and feeding the military on critical missions. But this will expand the range of applications of the method of processing foods of plant and animal origin with ionizing radiation.

Research conducted so far in various laboratories and enterprises around the world shows that the effect of irradiation is related to the type of plant, storage conditions and the dose of irradiation. This requires, before being put into practice, preliminary studies to establish the optimal doses of irradiation for different varieties and the relationship between the method of storage and the result of irradiation with ionizing radiation.

Conflict of interest

The authors declare no conflict of interest.

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Edited by Pavel Tsvetkov and Anna Erickson

As global energy demands continue to escalate, nuclear power stands as a critical cornerstone of a sustainable future, providing continuous, reliable power that uniquely complements intermittent renewable energy sources. This edited volume offers a multidisciplinary examination of the industry's current transformation, exploring how cutting-edge technological advancements and strategic policy frameworks are defining the next era of global energy production. By expertly synthesizing the latest developments in advanced Generation IV reactor designs - such as High Temperature, Molten Salt, and Fast Reactors - with the rapid integration of Artificial Intelligence and digital transformations, this book maps the path toward achieving optimized performance, vastly enhanced intrinsic safety, and long-term operational resilience. Beyond the engineering technicalities, the text thoughtfully navigates the complex, shifting modern regulatory landscape and the enduring, trans-scientific challenge of fostering necessary public trust; it demonstrates how transparent risk disclosures, effective spent fuel management, and rigorous radiation protection protocols form the absolute foundation of successful, responsible expansion.

Furthermore, the work highlights the profound societal impact of nuclear science, showcasing highly sustainable applications that extend well beyond electricity generation into areas such as food safety, agriculture, and industrial sterilization. This book provides a distinct advantage to its readers by successfully bridging the gap between foundational nuclear science and the complex, practical, real-world requirements for rapid commercial deployment. Offering a holistic view of the intersection of innovative engineering systems and evolving global policies, this book serves as a resource for professionals and scholars alike seeking to understand the technical, regulatory, and environmental imperatives required to thrive in a rapidly changing energy landscape.

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