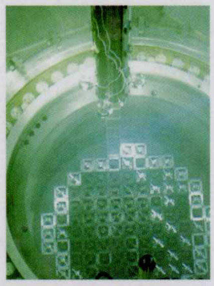
STRUCTURAL INTEGRITY IN NUCLEAR ENGINEERING

ISSI 2011



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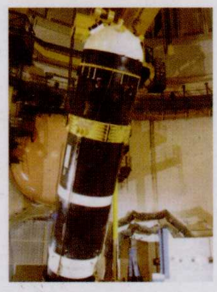

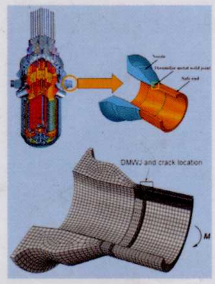

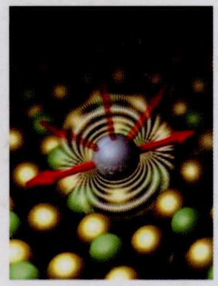

EAST CHINA UNIVERSITY OF SCIENCE AND TECHNOLOGY PRESS

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East China University of Science and Technology Press
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图书在版编目（CIP）数据
核工程结构完整性技术/涂善东等主编. —上海：华东理工大学出版社，2011.10
ISBN 978-7-5628-3153-2
I. ①核... II. ①涂... III. ①核工程—工程结构—文集 IV. ①TL34-53
中国版本图书馆 CIP 数据核字（2011）第 205386 号

核工程结构完整性技术

Structural Integrity in Nuclear Engineering

主　　编/涂善东 王正东 薛昌明
责任编辑/徐知今
责任校对/李　晔
封面设计/裘幼华
出版发行/华东理工大学出版社有限公司
社　址：上海市梅陇路 130 号，200237
电　话：（021）64250306（营销部）
传　真：（021）64252707
网　址：Press.ecust.edu.cn
印　　刷/上海展强印刷有限公司
开　　本/787mm×1092mm　1/16
印　　张/25.5
字　　数/867 千字
版　　次/2011 年 10 月第 1 版
印　　次/2011 年 10 月第 1 次
书　　号/ISBN 978-7-5628-3153-2/TB・43
定　　价/180.00 元
（本书如有印装质量问题，请到出版社营销部调换。）

Preface

This book presents the proceedings of the 2011 international symposium on structural integrity (ISSI2011), held in Hefei, China, on October 27-30, 2011. As the successor of Fracture Mechanics symposium series (from 2003 to 2009), ISSI series is devoted to promote the science and technology related to the structural integrity and encourage the exchange and cooperation among the universities, research institutions and industry sectors in China and abroad. The first symposium of the FM series was held in 2003 at East China University of Science and Technology, Shanghai. Since then, annual meetings have taken place at different cities in China, which includes 2004 in Huangshan, Anhui Province, 2005 in Zhengzhou, Henan Province, 2006 in Nanjing, Jiangsu Province, 2007 in Changsha, Hunan Province, 2008 in Hangzhou, Zhejiang Province, 2009 in Chengdu, Sichuan Province and 2010 again in Shanghai.

Nuclear power has been looked to as an alternative to coal power in China. The country has indicated the intention to raise the percentage of China's electricity produced by nuclear power from the current 1% to 6% by 2020. However, the recent accident at Fukushima Daiichi caused a worldwide concern of nuclear safety. Even though the accident was caused by extraordinary natural forces, it did challenge our conventional concept of structural integrity and safety of the nuclear plants. Once again the philosophy of structural integrity becomes one of the top urgent issues in the development of nuclear power industry.

Structural Integrity in Nuclear Engineering is hence set as the main theme of ISSI2011 though general issues in structural integrity are also discussed in the symposium. Various sessions are planned for presentations and discussions on theoretical aspects and practical applications in the area of structural integrity in nuclear engineering. It is necessary to highlight the other main intention of the Symposium, which is to provide an opportunity for national and international experts on structural integrity to come together to exchange state of the art research and experiences in order to build a net-work for future collaboration and regional dissemination on the subject.

The symposium (ISSI2011) is co-organized by member organizations of China Structural Integrity Consortium, including National Engineering Research Center of Pressure Vessels and Pipelines Safety Technology (Hefei General Machinery Research Institute), MOE Key Laboratory of Pressure Systems and Safety, East China University of Science and Technology, Nanjing University of Technology, Zhejiang University, Zhejiang University of Technology, Zhengzhou University, Changsha University of Science and Technology, Shandong University, Southwest Jiaotong University, Beihang University and co-sponsored by China Pressure Vessel Institution, China Materials Institution, National Natural Science Foundation of China, General Administration of Quality Supervision, Inspection and Quarantine of China.

On behalf of the organizing committee, we would like to thank the above co-organizers and co-sponsors who made ISSI2011 possible. We also wish to thank Professor George C. Sih and Professor Zhengdong Wang for their passion to the symposium and efforts made to ensure the success of the event. The financial support from the National High Technology Research and Development Program of China is gratefully acknowledged.

Xuedong Chen
Executive Chairman
Hefei General Machinery Research Institute

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Symposium Series Chairman
East China University of Science & Technology

October, 2011

Contents

Margin between safety and disaster concerned with nuclear power generation entities

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Abstract

The concern for nuclear power safety was initiated by the International Atomic Energy Agency (IAEA) about 12 years after World War II. Within the commercial arena alone, the safety issues connected with nuclear power generation of electricity are already enormous. They can involve the interactive changes of the combined effects of technical, ecological, economical, social, and political.

The heart of the nuclear power plant is the nuclear reactor that can be PWR, BWR, GMR (RBMK) and MSR. Safety operational regulations are presently concerned mostly with the PWR and BWR to which the US NRC coordinates with 14 other countries. As commendable as the tasks performed by the Nuclear Regulatory Commission (NRC) for the past 30 years and more, Codes & Standards (C&S) do age and amendments are necessary. This is especially true for those that require the support of hard core science and advanced technology. Advanced physical laws and computational schemes can enhance the C&S. The revision, validation, and revalidation of the NRC-ASME &III/XI codes, about 10 years ago under the VOCALIST program, however, have not lived up to their intention. The Elastic-Plastic Fracture Mechanics (EPFM) code as part of PVC (Pressure Vessel Code) lost credibility as the elastoplasticity-based *J*-Integral had no connection with the dislocation theories that were assumed to provide the theoretical mechanics foundation for elastoplasitictiy. This hope vanished after the NRC C&S codes were prematurely installed. The possible uses of multiple scaling were by passed, since the 1990s. Certainly, nuclear power safety will not wait for NRC to recognize Multiscale Fracture Mechanics (MFM). Particularly vulnerable are the use of commercial black box programs based on mono-scale parameters such as the *J*-, *C*- and *C**-Integral for characterizing inherently dual- or multiscale-damage processes that are referred to as Elastic & Plastic (E&P), Creep & Fatigue (C&F), and Stress Corrosion Cracking (SCC). Future code development connected with the Liquid Salt Very High Temperature Reactor (LS-VHTR) cannot afford to disregard the life expectancy of the critical components for each scale range from nano to macro. The *J*- and *C**-Integral are mono-scale by definition. Their replacement by the Generalized Crack Extension Energy (GCEE) *G* can be accomplished simply by altering the specimen thickness, and loading rate for a given material using Multiscale Fracture Mechanics (MFM). The suggested approach is heuristic since adjustments are needed to remove the ambiguities in applying the *J*- and *C**-Integral. The global (load) energy transferred to the *"crack tip"* had to be measured correctly. This required a knowledge that the *singularity point (absorbing-dissipating energy in tandem) can be assumed to characterize the phantom crack tip as inhaling and exhaling in breathing at the different spatial-temporal scales.* Keep in mind that not all of the input energy is absorbed. Some can be dissipated. This mass pulsation behavior is described in the theory of "Crack Tip Mechanics" (CTM). The pulsation energy model was necessary for determination of the multiscale crack tip location. A consistent interpretation of the fracture mechanics test data was thus made possible.

The mission of NRC envisioned by the Energy Reorganization Act (ERA) of 1974 was to oversee reactor safety and security, reactor licensing and renewal. While the choice of nuclear power plant (NNP) type is influenced by democracy, technocracy, and sciocracy, the rules governing nuclear safety, however, should follow hard core science and not decided by the expediency of the establishment. The Fukushima disaster has indeed pointed out the need to delineate these differences and to scrutinize the present system of administering and defining nuclear safety. Predicting the unpredictable stood out as a key issue. The need for a research operational group is apparent. It can be dubbed as "Think Tank for Nuclear Power Safety (TTNPS)" with the mission to translate theoretical concepts from formal economics and hard science into seemingly unquantifiable predictions. It is not unthinkable that *the un-expectable can be converted to the expectable.* Careful thought should be given to placing safety before cost or reducing cost at the expense of safety.

Keywords: Think tank; Structural integrity; Nuclear; Safety; Disaster; Beyond design; Climate change; Risk; Cost.

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1. Introduction

Foresight cannot compete with hindsight since the outcome will not be known until the time has been past. Engineering for the better part is based on experience accumulated from hindsight. Safety prevails until failure occurs. These definitions depend on the spatial-temporal scales at which the physical events take place. Hence, disaster is nothing more than the sudden and unexpected change of morphology and property of the physical system. In principle, nothing is really safe because changes occur for the electrons and the smaller particles that translate into uncertainties. These effects are transferable to the larger scales, even the initial causes are not sensitive to the sensory perceptions. As a rule, safety and disaster refer to the macro- and micro-scale, a *dual-scale* behavior. All real materials are multiscale [1,2] in behavior.

Depicted analytical fracture criteria in the NRC Codes and Standards (C&S) are restricted to the macro-scale [3]. Incompatibility of stress-strain solutions and failure estimation becomes eminent when the former being dual-scale is used with the latter being mono-scale. Contrived agreement between so called theory and test can only be regarded as fortuitous. Numerical solutions relies on adjusting the empirical parameters and the time steps until the results between tests and analyses agree [4,5]. Reproduction of existing solutions [5] belongs to hindsight calculation. *The conclusion is that the solution has already been pre-conceived by the analyst.* Such a procedure does not qualify for prediction. This differs from model simulation for extrapolating known results.

Admittedly, the safety of all structures and vehicles do not and cannot depend on design nor on laboratory tests. On site monitoring [6,7] and testing of operational data are necessary to mitigate disasters, if and only if the enforced codes and standards can properly identify the possible contingencies, especially those known to be critical [8]. Failure leading to the loss of coolant, hardware and software, should be double-checked frequently, even for situation "beyond design basis". This is especially true for older nuclear power plants where ecological changes can affect the aging of mechanical parts. Moreover, the credibility of the US Nuclear Regulatory Commission has been questioned in recent years [9]. The same applies to the issue of fracture toughness. It is not sufficient to just improve on Linear-Elastic Facture Mechanics (ELFM) using the valid K_{IC} as the fracture toughness, "a go and no-go" scenario. The replacement by the *J*-integral definition as recommended by the ASME Boiler and Pressure Vessel Code for Elastic-Plastic Fracture Mechanics (EPFM) [10], however, is a step backward for understanding nuclear safety. The intention of EPFM was to account for micro (plastic) in addition to macro (elastic) damage. But the *J*-integral is defined only for mono-scale, the macro case [3]. Applications of *J* to dual-scale situations have yielded "negative" energy release rate (ERR) [11,12], a physical impossibility. Use of CINT (Center for Integrated Nanotechnologies) command for *J*-Integral calculation of 3D model with ANSYS (Analysis Systems) have resulted strange results with negative values [9]. *J*-Integral calculation has led to "very different values of two adjacent nodes on the crack front from one contour to another, going up and down [9]. In an effort to correct for the crack-tip constraint, the VOCALIST methodology [13] used equally skeptical procedures for validation, since the combined use of elastoplasticity with *J*-Integral is problematic. Keep in mind that the continuum approach of plasticity has neglected the size effect by invoking the limit that the rate change of volume with surface for the continuum element approaches zero. *Two wrongs do not make a right.* The foregoing endorsement by the NRC C&S is jeopardizing the safety of the nuclear power generation plants. Fortunately, the recent three nuclear reactor disasters were caused by "Beyond Design Basis (BDB)" rather than the EPFM codes. The same comments apply to the mono-scale *C*- and C^*-Integral for characterizing high temperature creep, which is inherently a dual-scale, if not multiscale, physical process. Negative values of *C*- and C^*-Integral have been encountered regularly, but they were dismissed arbitrarily.

The mono-scale *J*- and C^*-Integral are presently adopted in the NRC C&S. They can be represented by the Generalized Crack Extension Energy (GCEE) *G* simply by altering the specimen thickness, and loading rate for a given material based on the concept of Multiscale Fracture Mechanics (MFM). The approach is heuristic in that adjustments are necessary to remove the ambiguities in the J- and C^*-Integral. The *singularity point (absorbing-dissipating energy in tandem) can characterize the crack tip as inhaling and exhaling in breathing at the different spatial-temporal scales.* A way is thus found for locating the crack tip that is needed for a consistent interpretation of the multiscale fracture mechanics test data. The foregoing concepts were developed from the work on Crack Tip Mechanics (CTM) [14].

2. Country specificity of nuclear power policy

Nuclear energy policies are country specific and they will not be unified by consensus. This can be evidenced by the March 2011 *Fukushima I nuclear accident*, after which time China, Germany, Switzerland, Israel, Malaysia, Thailand, United Kingdom, and the Philippines underwent reviewing their nuclear power programs. Germany has already decided to phase out nuclear power plants by 2022. A decision, of course, may be reversed when the opposing party wins the election. Indonesia and Vietnam still plan to build nuclear power plants. As of three years ago, China planned to increase nuclear power fourfold (70 Gw) by 2020, and up to 400 Gw by 2050. The Fukushima effect prompted China to announce that all nuclear plant approvals (but not those already approved) were being frozen until "full safety checks" of existing reactors are made, possibly a short lived delay. It is unlikely that the future plans of new reactors will change for China, South Korea, India, and Russia. On the other hand, countries such as Australia, Austria, Denmark, Greece, Ireland, Latvia, Lichtenstein, Luxembourg, Malta, Portugal, Israel, Malaysia, New Zealand, and Norway remain opposed to nuclear power.

2.1. "Beyond Design Basis"

The fear of past disasters will wear off in time, including that of Fukushima and those of the 1986 Chernobyl accident and the 1979 Three Miles Island (TMI) disaster. Meltdown of the reactor was dubbed as the "Chinese Syndrome". This is especially true when the rising fossil fuel prices coupled with new concerns about reducing greenhouse gas emissions will out weigh the risk for generating electricity from nuclear power, not to mention the increase in the world population. Public sentiment can and will change at times of economical crisis at the expense of nuclear safety, despite the obvious inadequacies of the NRC C&S. Hindsight excuses such as "Beyond Design Basis" cannot justify the disaster at Fukushima. Present nuclear safety rules are already known to have overlooked the risk that a single event may knock out electricity from the grid and from emergency generators [15]. The "unexpected" will continue to haunt nuclear power safety. New ways have to be found via hard science to convert the unexpected to the expected. All possibilities should be considered to mitigate nuclear disasters that can destroy a nation if not jeopardizing the earthly environment. Fig. 1 shows the extent of radioactivity measured in mR/hr, which stands for milli-Roentgens per hour, read on a Geiger counter.

2.2. Democratic implications of nuclear power safety

Public opinion can influence political policy under democracy in contrast to meritocracy/technocracy. This is particularly noticeable in the US nuclear industry after the 1979 Three Mile Island accident. It resulted in a major setback for the development of nuclear power generation with the cancellation or suspension of many orders, projects and nuclear construction. The hope for recovery heightened in mid-2007 when 16 license applications submitted to NRC were increased to 24, following a 30-year period in which few new reactors were built. In the same year of election, Barack Obama accused NRC of becoming *"captive of the industries that it regulates"*. Corporation and government are suspect of confiding in secrecy on nuclear matters, while released information are couched in jargons, incomprehensible to the public.

The recent Fukushima disaster though has far surpassed the destructive power of the Three Mile Island accident, the reaction of the US public is more reserved, despite the petition of the 45 groups [9] and individuals from across the nation to formally ask the US Nuclear Regulatory Commission (NRC) to immediately suspend all licensing and other activities at 21 proposed nuclear reactor projects in 15 states until the NRC completes a thorough post-Fukushima reactor crisis examination comparable to the process set up in the wake of the serious, though less severe, 1979 accident at Three Mile Island. The petitioners are also requesting the NRC to supplement its own investigation by establishing an independent commission. The global economical crisis will no doubt be a major factor in the final decision making process.

What should be kept in mind is that none of social/political commotions are doing any good to nuclear power safety, since it is not likely that the world economy can survive without the use of nuclear energy. Furthermore, it is evident by now that each of the three major disasters including TMI, Chernobyl, and Fukushima, were caused by "unexpected" event of one kind. Those expected by the NRC C&S of a long term nature have yet to be tested. Henceforth, the codes and standards for "Beyond Design Basis (BDB)" deserves separate attention from those of "Cause for Retirement (CFR)", the need of which will become apparent only when the nuclear power plants start to age.

As recent as 2011, the US congress released a report via the Government Accountability Office (GAO) that three-quarters of America's 65 nuclear plant sites have leaked radioactive tritium, a radioactive form of hydrogen. The US nuclear power plant operators have not figured out how to quickly detect leaks of radioactive water from aging pipes that snake underneath the sites and the leaks, often undetected for years. The leaks are not going to stop as reported by the congressional investigators. A photo released by NRC in 2011 can be found in Fig. 2. It illustrates a 10-gallon/minute leak of tritium. The leaks have contaminated residential drinking wells near at least three nuclear power plants. What should be recognized is that *the kind of Fukushima's meltdown could happen in the U.S. if a pipe that is supposed to carry water to cool a reactor's core fails*. There would be no warning if no one ever checks the integrity of the aging underground pipes. It is hardly sufficient to rely on the industry's Nuclear Energy Institute to urge frequent inspection with a goal of preventing and fixing leaks. What must be weighed is *the cost effectiveness of frequent inspection against "Cause for Retirement"*. Disasters are often the results of not reinforcing or relaxing the codes and standards instead of retiring the aging nuclear power plants. The world wide demand for the increase use of nuclear electricity will preoccupy the US government and industry to work closely on expedited approval for construction and new plant designs. Past experience, since the late 1990s, also reveals that the US nuclear policy will continue to sway with the public opinion and economical issues of selling and licensing nuclear power plants.

Nuclear power plant safety regulation will always play a catch-up game. This is to be expected. But to deceive and/or tell partial truth to misguide the public on nuclear safety issues cannot be condoned. The negligence to keep up with the scientific and technological findings over a period of 30 years is no excuse. This can be evidenced in the field of Fracture Mechanics that makes up the NRC C&S. The safety of the new plants should certainly be questioned with reference to amending many of the Fracture-Mecha-nics-based codes and standards to assure to assure more reliable ways of assuring nuclear reactor safety.

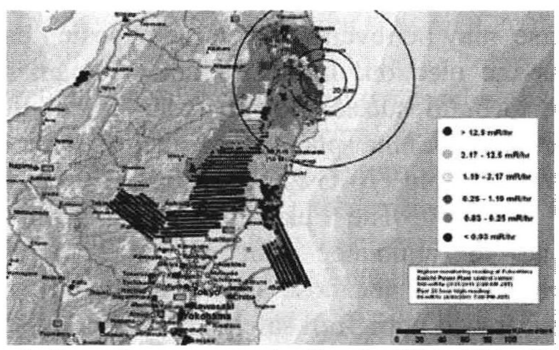

Fig. 1. Ground measurements of mr/hr 30Mar03Apr2011.

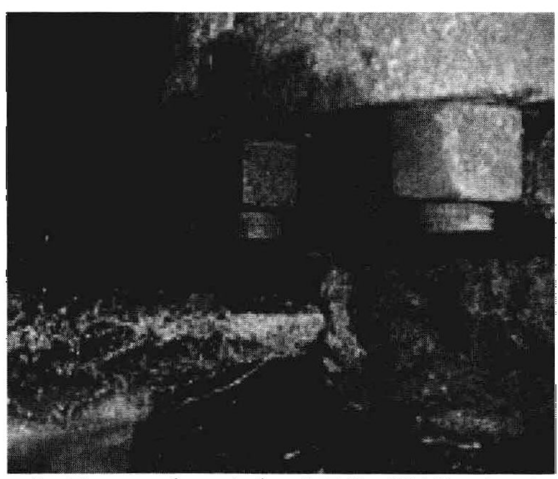

Fig. 2. Photo released by NRC (2011) showing a 10-gallon/minute leak of radioactive water.

2.3. Technocratic choice of nuclear power plant

A super economic power country such as China thrives on technocracy. The enormous appetite for green energy calls for the sustainable use of nuclear power with high efficiency and safety. Existing nuclear reactor technology from France, Canada, Russia, and USA (via Westinghouse AP100 owned by Toshiba), all of which are PWRs. China has 27 new reactors planned for construction and planned for 50 plants in the next several decades. The aim (3 yrs ago) is to generate 70 Gw by 2020, leveling off at 200 GW around 2040. Additional increase of the nuclear power electrical energy is contemplated at 400 Gw by 2050 and 1400 GW by 2100. The use of thorium fueled MSR (molten-salt reactor) has been advocated to be safer and more efficient than the PWR. The speculation, however, rests on a higher efficiency based on higher operating temperature of the MSR. This is a classical notion of the Carnot Cycle that does not hold for the nuclear reactor, the thermodynamic processes of which are neither isothermal nor adiabatic. For non-equilibrium and non-homogeneous thermodynamic systems, it is the proportion of the dissipation and available energy density, designated by $\mathcal{D}$ and $\mathcal{A}$, that determines the efficiency η [16]:

$$\eta = 1 - \frac{\mathcal{D}}{\Omega \mathcal{A}} \tag{1}$$

where Ω is a weighting parameter that specifies the nature of a particular component.

It is not obvious that a higher temperature & lower pressure system would have a higher efficiency than a higher pressure &lower temperature system. Energy depends on both the pressure and temperature. It is insufficient to speak only of temperature or pressure individually without qualifying the both of them. Trade off for a multi-variable system cannot be pre-assumed.

Shifting the PWR to MSR as a primary energy source for nuclear power was a crucial step from the past as outlined in Table 1. The operators CGNPC and CNNC stand, respectively, for China Guandong Nuclear Power Holding Co. Ltd. and China National Nuclear Corporation. They are responsible for operating the plants in the South and North. Other governing agencies are the China Atomic Energy Authority (CAEA); Chinese Academy of Sciences (CAS); China Institute of Atomic Energy (CIAE); and The Shanghai Nuclear Engineering. Research & Design Institute (SNERDI). Refer to Fig. 3 for the division of nuclear power plant (NPP) to the North and South. Tianwan I at Lianyungang city in Jiangsu province is a Russian AES-91 power plant (with two 1060 MW VVER reactors) constructed under a cooperation agreement between China and Russia.

China has recently unveiled the development of a thorium-fueled molten-salt nuclear reactor. It was announced at the annual Chinese Academy of Sciences (CAS) conference in Shanghai February 1, 2011 (*Wen Hui Bao* newspaper). CAS has made clear that China intends to *develop the technology alone and control the intellectual property around thorium for its own benefit.* Thorium is well-suited for use in molten-salt reactors, where nuclear reactions take place inside a fluid core rather than solid fuel rods such that the risk of meltdown is eliminated. Fluid fuel reactors have significantly different *safety* issues compared to solid fuel designs. One of the trade offs is the reduction for potential major reactor accidents for the increase of the potential for processing accidents. Molten salt operates at a lower pressure and higher temperature. The salts remove heat from the core more readily, reducing the requirement for pumping, piping, and size of the core. Reduced size of the reactor translates into less material to absorb neutrons. Inconel 600 alloy for the metal structure and piping has been operated using liquid sodium as a coolant (with a peak temperature of 860 °C) for 100 MW-hours over nine days in 1954. Preliminary researches were done on thorium and MSRs at Oak Ridge National Laboratory in the 1960s and 70s. The project was abandoned. In recent times, there is a revival of interest for very high temperature reactor using molten salt, namely MSR.

To reiterate, structural integrity issues for MSRs will differ from those of the PWRs. High-temperature low-pressure primary cooling loop will present a series of new problems concerned with SSC, C&F, and Elastoplasticity, unlike those for the PWRs. The mono-scale J-, C- and C^*-Integral are not applicable for multiscale cracking of the nuclear reactors.

Table 1. Operating PWRs.

Units	Province	(MW)	Type	Operator	Operation
Daya Bay 1&2	Guangdong	944	PWR	CGNPC	1994
Qinshan I	Zhejiang	279	PWR (CNP-300)	CNNC	April 1994
Qinshan II, 1-3	Zhejiang	610	PWR (CNP-600)	CNNC	2002, 2004, 2010
Qinshan III, 1&2	Zhejiang	665	PHWR (Candu 6)	CNNC	2002, 2003
Ling Ao I, 1&2	Guangdong	935	PWR	CGNPC	2002, 2003
Tianwan 1&2	Jiangsu	1000	PWR(VVER-1000)	CNNC	2007, 2007
Ling Ao II, 1&2	Guangdong	1037	PWR (CPR-1000)	CGNPC	2010, 2011
Total: 14 units		11,271			

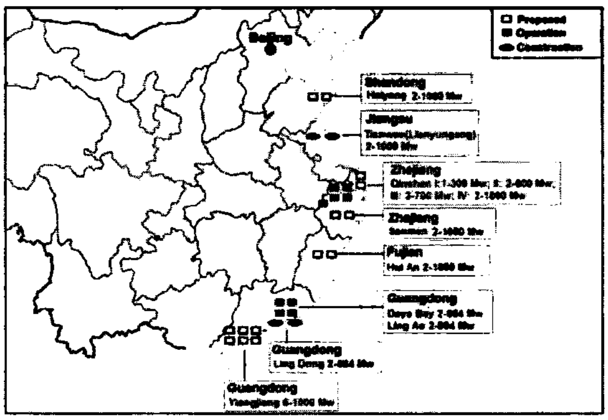

Fig. 3. Locations of present and future nuclear power plants in China.

2.4. Sociocratic approach to nuclear power generation

Successful domestic social, political, and economic environments will transform technocracy to sociocracy for maintaining national stability and prosperity. The tendency is to have more generalists studying philosophy, economics, law and social science. This calls for more general experts, similar to that of the West. Already recognized are the implications for *social, educational, gender, environmental and political issues* that are created by the impact of science and technological change. The spiral escalation of the economy and exponential increase in the need of green energy, demands a delicate balance that lies in the judicious deployment of nuclear power generation. There is no room for mediocracy in science and technology and less alone apparent contradictions and inconsistencies in safety issues. Duplication of already known mistakes is against the spirit of sociocracy. To this end, the US NRC C&S for the PWRs cannot be blindly copied for use in the MSRs. The new codes should stress the safe life expectancy of the nuclear power plant components by multiscaling since damage should cover neutron-irradiation (pico-nano), SCC and creep-fatigue (nano-micro) plastic-deformation (micro-macro). More refined scale divisions can be made via additional meso scales. The safe life of the plant by design t_{life} (say 40yrs) should be less than that of failure t_f (say 60yrs), however, defined and estimated for the different scale segments:

$$\sum_i^n t_i = t_1 + t_2 + \cdots + t_n = t_f > t_{life} \tag{2}$$

In this way, the damage at the different scales can be accounted for such that the desired distribution caused by the different physical mechanisms can be adjusted. That is t_1 can stand for pico-nano, t_2 for nano-micro and so on. Moreover, the principle of least variance [17] can be used to determine the reliability of the prediction for each of the scale range.

There is no useful purpose to add the corresponding $\mathcal{G}_s$ such as

$$\sum_i^n \mathcal{G}_i = \mathcal{G}_1 + \mathcal{G}_2 + \cdots + \mathcal{G}_n = \mathcal{G}_f \tag{3}$$

because they occur successively one after the other. The fact that

$$\mathcal{G}_{pi/na} > \mathcal{G}_{na/mi} > \mathcal{G}_{mi/ma} \tag{4}$$

implies that different energy is required to create a unit area of crack surface depending on the scale range in question. The material can have only one fracture toughness at a given scale or extended over a scale range as shown by Eq. (4).

A ductile material is no tougher than a brittle material because it also releases energy at the micro-scale. A duel-scale material may fail at a higher load at a later time than a mono-scale material. It is not just a matter of making the material tougher by altering its microstructure. Trade offs of the geometry, loading, and material properties must be considered.

Referring to Eq. (3), it is the terminal $\mathcal{G}_n$ that triggers global instability $\mathcal{G}_f$. The other $\mathcal{G}s$ simply reduce the energy that would otherwise be available to cause global crack instability. They behave as transitional functions that are connected from one scale range to another. Note that the $\mathcal{G}s$ given by $\mathcal{G}_1$, $\mathcal{G}_2$, *and* $\mathcal{G}_3$ can be made to stand for $\mathcal{G}_{pi/na}$, $\mathcal{G}_{na/mi}$, *and* $\mathcal{G}_{mi/ma}$, respectively. The idea is to design the multiscale material such that each segment of the time span can be controlled. Since the *J*-, *C*- and C^*-Integral parameters act as the intermediaters for finding the life time segments, they have to be positive definite. Negative *J* or C^* can yield negative time the is incomprehensible.

3. Multiscale fracture mechanics (MFM): Assessment of nuclear power safety

Micro structural defects, fabrication flaws, and fatigue cracks have been known to act as crack initiators locally and then spread globally into the nuclear vessel wall at large. The process is one of multiscaling. Stress Corrosion Cracking (SCC) aggravated by neutron irradiation can cause serious degradation of the reactor vessel wall form the nano to the macro scale. Nanocracks were a major concern to nuclear vessel integrity studies [18-20]. The field of "Crack-Tip Chemistry (CCC)" research was then recognized at the General Electric Global Research Center. Multiple scale cracking in relation to mesomechanics was emphasized [21-23] in the 1990s. Since then more than 13 International Symposiums have been held and numerous open literature publications have appeared. It is hard to believe that such a widely publicized field of Multiscale Fracture Mechanics can be overlooked by NRC.

ASME Section III/XI committee [5] has been concerned with estimating the fabrication flaws modeled as cracks for use in fracture mechanics structural integrity assessments. Finite element elastoplasticity or plasticity has been used in conjunction with the *J*-Integral fracture criterion. Among the calculations are *J*-Integral estimation methods developed by EPRI/GE and *J-T* (T stands for tearing) evaluation procedures. These results on Elastic-Plastic Fracture Mechanics (EPFM) of ASME Section XI Code were intended as improvement over the early ASME Section XI flaw evaluation procedures using LEFM. The expected improvement were a disappointment after discovering that "dislocations led to an euphoria lasting several decades and hope that theoretical mechanics of elastoplastic deformation of crystalline solids on the basis of dislocation theory could be created. These hopes have never come true. plastic flow could not be described by the theory of dislocations" [21]. The *J* and elastoplastic deformation theories lost their credibility after years of wasted efforts.

Returning to ELFM, which deals with the onset of macro-fracture from loading and crack geometry of the macroscopic specimen, remains as the pillar of fracture mechanics. The stress intensity factor (SIF) is related to the energy release rate (ERR) $\mathcal{G}$ that provides the physical interpretation of the energy required to create a unit of macro-crack surface extension. It must be distinguished from a unit of micro-crack surface and nano-crack surface [3]. Both the SIF and ERR are scale sensitive. Their definition in the context of ELFM holds only macroscopically.

When the specimen size (thickness) and or loading rate are reduced, the energy dissipated from the free surface come into play in addition to that in the bulk. In other words, *the bulk and surface effects now interact*. The state of affairs near the crack tip can be seriously disturbed giving rise to the creation of micro- as well as macro-crack surfaces. The fact that the original version of the *J*-Integral were identical to $\mathcal{G}$. is an indication that *J* is just another way of expressing the release rate without dissipative effects. It applies only to elastic deformation, although it can be non-linear (equivalent to the deformation theory of plasticity). Simply put, the *J*-Integral remained a macroscopic mono-scale parameter. Energy released microscopically are sensitive to material micro-structural morphology, and cannot be determined from the load/crack symmetry of the macroscopic specimen. Both the *J*-Integral and ERR assume Mode I macro-cracking only. This is why they can result in negative values [11,12] when micro-cracking and/or surface effects are not negligible [24,25]. Incidentally, the specific surface energy γ used in connection with the relation $\mathcal{G}_c = 2\gamma$ for a finite length crack refers strictly to the creation of macroscopic crack surface. Models named after "cohesive strength" can be equally confusing if their physical failure mechanisms are not identified with the atomic, microscopic, and macroscopic.

A reduction of specimen size and/or increase in temperature add another spatial-temporal scale range into the so called Creep Crack Growth (CCG) regime. A triple-scale situation calls for the attention of nanoscopic, microscopic and macroscopic effects. They can be important for the design of Very High Temperature Reactor (VHTR). The Liquid Salt Very High Temperature Reactor (LS-VHTR) is a possible candidate. Irradiation of neutrons on the reactor vessel wall may further need the consideration of picoscopic effects, a quadruple-scale situation. LS reactor components may have to operate for temperatures greater than 850°C [26]. As mentioned earlier, energy requirement calls for the combined effects of operating pressure and temperature. *Temperature alone is not sufficient to decide on the structural integrity of the material nor the efficiency of the operating system.* The present codes using C^* are far from adequate for VHTR. To start off with, they can yield negatives values.

The fact that the inadequate C&S based on J and C^* have done no harm up to now is because the recent nuclear disasters were all attributed to Beyond Design Basis (BDB), rather than the use of the codes. Incorrect interpretation of the reactor vessel wall test data based on the *J*-Integral [13] is the proof that the codes are irrelevant to the failure that they intend to address.

3.1. Interaction of bulk and surface (B&S) effects

By tradition, mechanics and physics have disregarded the interaction of bulk and surface effects by assuming that the bodies are either large or small such that the three dimensional model can be simplified to one or two dimensions. Surface and bulk properties have been treated separately. The simplification is inherent in almost all of the existing classical continuum mechanics theories. The two extremes correspond to having the rate change of volume with surface dV/dA to be very large such that the "bulk" dominate or dV/dA to be very small such that the "surface" dominate. In situations where dV/dA takes intermediate values, the classical approach starts to fumble with trade offs among the variations of geometry (B or dV/dA), loading (P or $\dot{u}$), and material properties (σ_{yd} & SED), where σ_{yd} and SED can be represented by a single trade-off relation, say S. Hence, the state (dV/dA, P, S) suffices to describe the geometry, loading and material. Their variations are expressible by three for each of the three parameters. This would require a minimum of 27 tests to construct a set of curves from which other possible combinations (dV/dA, P, S) can be obtained by interpolation. The details and examples can be found in [27]. The same scheme can be adopted by using the trade-off parameters in Table 2 to demonstrate the generality of Multiscale Fracture Mechanics (MFM) approach. The NRC C&S refer to endless test data for every conceivable situations. Instead, the two dimensional models of the ERR $\mathcal{G}$ for LEFM, the *J*-Integral for EPFM, and C^*-Integral for CCG can be combined into a single MFM model by judicious application of three of the parameters ($B, P, \dot{u}$) in Table 2. In this way, it is possible to *perform only 27 tests to construct a set of C&S for LEFM, EPFM, and CCG by interpolation for situations other than those tested.* The parameters B, P, and $\dot{u}$ can be set up to represent the geometry, loading, and material type while correcting for the B&S interaction effects, not treated in the classical approach.

The foregoing trade-offs have often been referred to as the "size effect" that arises from letting dV/dA of the continuum element to approach zero in the limit. The fact that $dV/dA \to 0$ are also invoked in the non-local theories (known as strain gradients and Cosserat), they give the false impression that the added length parameters to account for the dimensions introduced by the gradients are correcting for the size effect. These attempts are not valid on the basis of the First Principle.