Towards Resilience to Nuclear Accidents: Financing Nuclear Liabilities via Catastrophe Risk Bonds

Article · May 2016

DOI: 10.1115/1.4033518

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ABSTRACT

In light of the 2011 Fukushima disaster, recent discussion has focused on finding the best nuclear storage options, maximizing the oversight power of global institutions and strengthening safety measures. In addition to these, the development of dependable liability coverage that can be tapped in an emergency is also needed and should be considered thoughtfully. To succeed, financing is essential using special purpose instruments from the global bond market which is as big as US\$175 *trillion. Thus, in this paper, for the very first time, a two-coverage type trigger nuclear catastrophe (N-CAT) risk bond for potentially supplementing the covering of US commercial nuclear power plants beyond the coverage per the Price Anderson Act as amended, and potentially other plants worldwide is proposed and designed. The N-CAT peril is categorized by three risk layers: incident, accident and major accident. The pricing formula is derived by using a semi-Markovian dependence structure in continuous time. A numerical application illustrates the main findings of the paper.*

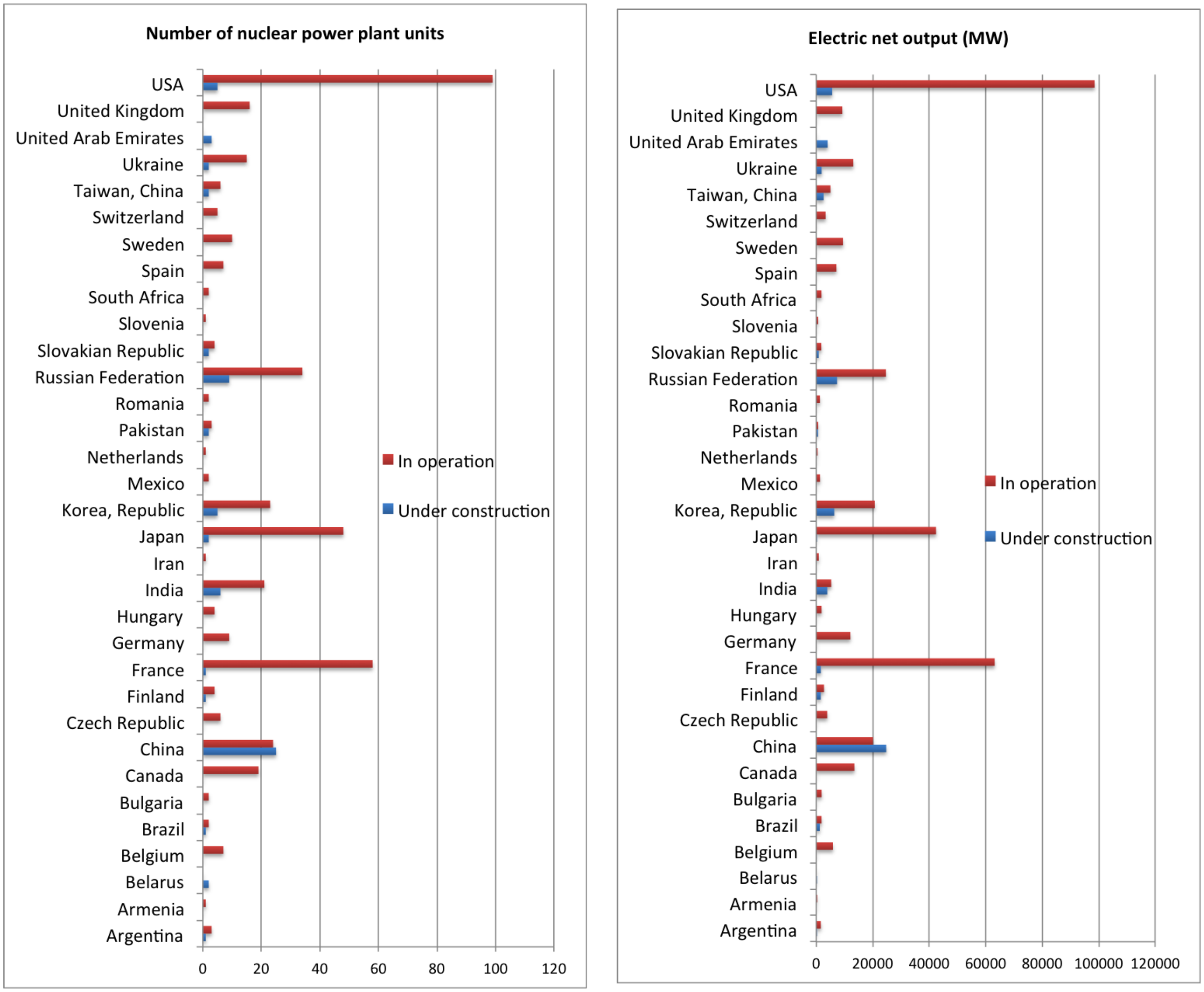
Keyword*: Nuclear power risk, catastrophe risk bonds, global market, liability, special purpose vehicle, two-coverage type trigger, semi-Markov environment.*

1 Introduction

1.1 Nuclear Power Risk

With a nuclear renaissance underway, the worldwide inventory of nuclear power plant (NPP) units is expected to increase from 439 to 508 [1] with corresponding increases in net electric outputs as shown in Figure 1. Without accounting for the variation in nuclear technology, regulatory regimes, operators' experience and NPP units' ages, the worldwide probability of a catastrophic nuclear accident can be estimated as significantly greater than, by orders of magnitude, the levels provided by the Presidential Commission on Catastrophic Nuclear Accidents in 1990. The Fukushima and Chernobyl disasters of 2011 and 1986, respectively, provide empirical evidence for such levels. The underlying computations are approximate to allow for using simple multiplication to account for the increase in unit-years. Such computations yield acceptable accuracy for small probabilities; however as the probabilities increase, the use of stochastic processes would become necessary in order to enhance the numerical accuracy and maintain the axiomatic requirements of probability theory [2]. These computations show catastrophic nuclear accidents would approach inevitability based on current practices, and growth in number of units and their ages as demonstrated in Figure 2. The curves in Figure 2 are based on the Presidential Commission on Catastrophic

Nuclear Accidents of 1990 updated by the increase in NPP units, and are not updated to account for accidents occurred afterwards, such as the Fukushima and Chernobyl disasters.



(a) Number of plant units

(b) Electric net output

Fig. 1: Nuclear power plant units worldwide, in operation and under construction, as of March 10, 2015 [1]

1.2 Nuclear Liability Conventions and Liability Limitation Regimes

Most countries with commercial nuclear programs adhere to one of the international conventions and concurrently have their own legislative regimes for nuclear liability, [3] and [4]. The national regimes implement the conventions' principles, and impose the financial security requirements that vary from country to country. The thirty four countries that possess NPPs can be grouped as follows, [5]:

1. The first group includes those countries that are parties to one or more of the conventions, and which have their own legislative regimes. Prominent examples are France, Germany, Spain and the United Kingdom, all of which are parties to the Paris Convention (PC) and Revised Paris Protocol (RPC, not yet in force); and the Argentina and Romania, both of which are parties to the Vienna Convention (VC) and Revised Vienna Convention (RVC). Parties of the Brussels Supplementary Convention (BSC) must also be parties to the PC and Revised Brussels Supplementary Convention (RBSC, not yet in force), for example Finland, France and Germany. Since 1988, parties to the Joint Protocol (JP) are treated as if they are parties to both the VC and the PC. Seventeen countries have signed the Convention on Supplementary Compensation for Nuclear Damage (CSC), including Czech Republic, Canada, Romania, Ukraine and India, but most

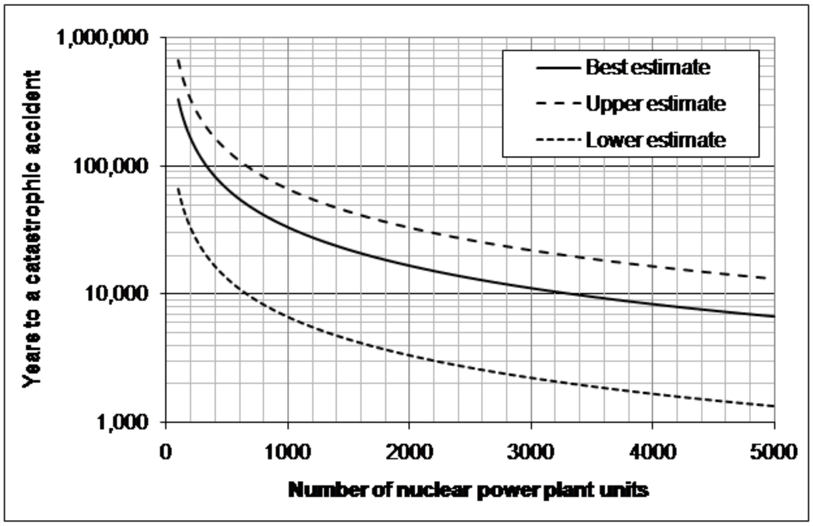


Fig. 2: Time to a catastrophic nuclear accident as a function of the number of nuclear power plant units worldwide

have not yet ratified it. In November 2014 Japan passed legislation to ratify the CSC. In total, twenty two countries belong to this group and are party to one of the conventions.

2. The second group includes those countries that are not parties to the conventions, but which have their own legislative regimes. Prominent examples are USA, Canada, Japan and Republic of Korea (South Korea). These countries impose strict liability on their nuclear installation operators. So they conform with the channeling requirements of the Paris and Vienna Conventions, despite not being parties to those conventions. In total, ten countries belong to this group.
3. The final group of countries neither being parties to the conventions nor having their own legislative regimes. Although these countries are relatively few, China is the most prominent example that has issued directives stating its position on nuclear liability, but has not yet developed a specific regime. China's nuclear liability directives were issued in 1986 as an interim measure in connection with the French-designed Daya Bay nuclear power plant. It contains most of the elements of the international nuclear liability conventions, e.g., channeling of absolute nuclear liability to the plant operator and exclusive court jurisdiction. Other countries in this group include Pakistan, with 2 NPPs. Pakistan is neither members of any international convention nor have any national legislation.

Table 2 provides a summary of the convention and membership by country.

In addition, the US enacted a nuclear liability regime - the Price Anderson Act - to manage the risk of a nuclear accident in 1957. It has created a favorable climate for the nuclear American industry and provides US$13.6 billion in cover without cost to the public or government and without fault needing to be proven. The Act was amended over the years. Someone could arguably demonstrate that the US government is providing subsidies since the coverage is far less than the potential loss, [3, 6, 5].

In this paper, we presented so far exposures from the perspectives of the public, operators and government; however, what does all this mean for a designer, builder, or supplier? If the products or services are provided to a nuclear installation in a country subject to the PC or VC, the supplier likely does not need nuclear liability insurance. The supplier should not be held liable for damages resulting from a nuclear incident. Liability should be channeled to the facility operator.

The two exposures [5] for suppliers are: have nuclear legislation with legally channels liability to the facility operator, and have cross-border liability. These exposures might necessitate suppliers to purchase their own insurance. The decision whether to purchase insurance often reflects how risk averse a supplier and its risk-management philosophy. The [4] makes available a foreign Supplier's and Transporter's policy (called S&T policy) for this purpose that indemnifies the insured for third-party bodily injury or property damage resulting from the nuclear energy hazard, which is defined as the radioactive, toxic, explosive or other hazardous properties of nuclear material. The policy is continuous from inception until cancelation or termination, at which time the insured has ten years to report claims for damages that took place during the policy period. The policy's current maximum limit of liability is US$50 million available in all insured countries except Japan, Mexico, South Africa, Spain and Sweden, where the available limit is US$15 million because of reinsurance commitments. The policy excludes several countries for various reasons, most notably the United States, Canada, China, India and Russia. Other exclusions worth noting are: worker's compensation and employer's liability; contractual liability, other than a warranty of materials, parts or equipment; bodily injury or property damage arising out of any nuclear weapon, or resulting from nuclear material used for military purposes; bodily injury or property damage arising out of war or a terrorist act or any radioactive isotope; bodily injury or property damage with respect to which any government indemnity or avail insurance; property

Table 1: Nuclear power countries and liability conventions to which they are party, [5].

Countries	Conventions party to	Countries	Conventions party to
Argentina	VC; RVC; CSC	Lithuania	VC; JP; (CSC signed)
Armenia	VC;	Mexico	VC
Belgium	PC; BSC; RPC; RBSC	Netherlands	PC; BSC; JP; RPC; RBSC
Brazil	VC	Pakistan	
Bulgaria	VC; JP	Romania	VC; JP; RVC; CSC
Canada	(CSC signed)	Russia	VC
China		Slovakia	VC; JP
Czech Republic	VC; JP; (CSC signed)	Slovenia	PC; BSC; JP; RPC; RBSC
Finland	PC; BSC; JP; RPC; RBSC	South Africa	
France	PC; BSC; RPC; RBSC	Spain	PC; BSC; RPC; RBSC
Germany	PC; BSC; JP; RPC; RBSC	Sweden	PC; BSC; JP; RPC; RBSC
Hungary	VC; JP	Switzerland	PC; RPC; BSC; RBSC
India	(CSC signed)*	Taiwan (State)	
Iran		Ukraine	VC; JP; (CSC signed)
Japan	CSC	UAE	RVC; CSC
Kazakhstan	RVC	United Kingdom	PC; BSC; RPC; RBSC
Korea		United States	CSC

PC = Paris Convention (PC). RPC = 2004 Revised Paris Protocol. Not yet in force.

BSC = Brussels Supplementary Convention. RBSC = 2004 Revised Brussels Supplementary Convention. Not yet in force.

VC = Vienna Convention. RVC = Revised Vienna Convention.

JP = 1988 Joint Protocol.

CSC = Convention on Supplementary Compensation for Nuclear Damage (CSC), in force from 15 April 2015.

* India has not ratified CSC, and it is not clear whether their domestic liability law conforms with the requirements of the convention.

damage, including business interruption and loss of use, to any nuclear facility or to any property at the facility, arising out of nuclear material at the facility.

Assessing the adequacy of liability coverage requires examining the consequences of historic and postulated nuclear accidents. Most notable nuclear accidents in the civil power sector include: the 1979 Three Mile Island in which the containment remained intact and resulted in 1993 US$1 billion dollar cleaning-up cost performed over 14 years; and the 1986 Chernobyl disaster in the former Soviet Union resulting in 56 lives lost, over 4000 people with long-term effects, and US$15 billion of direct loss. It is estimated that the damages could accumulate to US$305 billion for Ukraine and US$261 billion for Belarus in the thirty years following the Chernobyl accident. Various estimates of the total damage could be caused by accidents at nuclear power plants range from US$110 billion to as much as US$7 trillion [7, 8].

1.3 Catastrophe (CAT) Risk Bonds and Nuclear CAT Risk Bonds

Losses and recovery costs from catastrophic accidents are typically covered by a combination of utility companies, special insurance programs and/or governments. For example losses from the 2011 Fukushima disaster were covered primarily by the government of Japan. Resources for this purpose are often inadequate, and require a cash reserve that could be challenging to maintain. In emerging markets with nonexistent or immature legal regimes, liability could lead to international tensions and potentially wars particularly in cases of cross-border exposures. Using a catastrophic accident rate of 10^{-6} per year, 500 policies, and loss per accident of US$5 trillion, and price of a policy for the breakeven point can be computed to be US$10,000 per year. Obviously, an insurance model of this type would not sustain itself and would bankrupt upon the occurrence of the first catastrophic accident within the life of the present NNP population.

Two requirements are necessary for achieving adequate nuclear liability coverage. The first requirement of having an efficient and cost-effective system. The second requirement is to have a system that has adequate financial depth to fulfill claims. To succeed, financing is essential using special purpose instruments from the global market. Figure 3 provides an estimate of 2012 the global outstanding bonds and loans to be US$175 Trillion out of the total US$225 Trillion of capital stock (outstanding bonds, loans and equity) with stocks at US$50 Trillion. Despising 2008 financial crisis, global bonds and loans market is increasing consistently over the past twenty years from US$45 Trillion in 1990. In this paper, for the very first time, a catastrophe risk bond for financing nuclear liability is proposed based on a concept conceived by [9]. The model is fashioned after the *catastrophe* (CAT) bond financial products, and similarly tied to the global bond market.

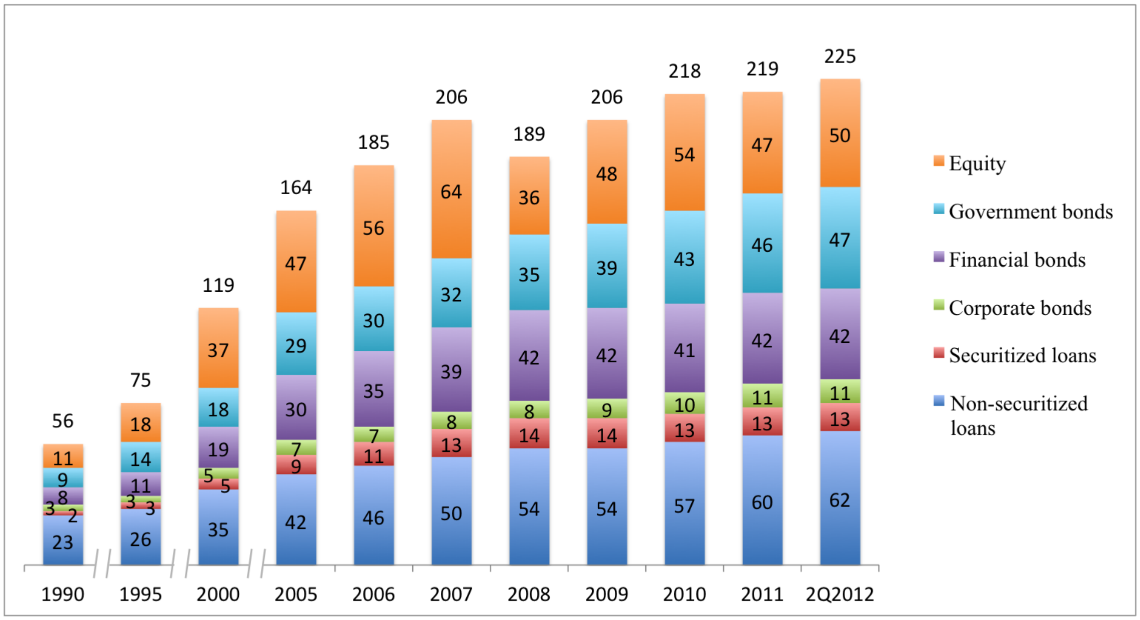


Fig. 3: Global stock of debt and equity outstanding, US$ Trillion, end of period, constant 2011 exchange rates, [10].

CAT risk bonds (or Act-of God bonds) are born for these extreme events and sharing the risk to another level - global financial market, which is the only pool of cash large enough to underwrite such losses lies in capital markets the collection of big investors like pension funds, hedge funds and sovereign wealth funds that normally invest in stocks and bonds. It directly transfers the financial consequences of catastrophe events to capital markets in contract to cover the possible huge liabilities through traditional reinsurance providers or governmental budgets. The first experimental transaction was completed in the mid-1990s after the Hurricane Andrew and Northridge earthquake with insurance losses of US$15.5 billion and US$12.5 billion, respectively, by a number of specialized catastrophe-oriented insurance and reinsurance companies in USA, such as AIG, Hannover Re, St. Paul Re, and USAA, see [11]. Catastrophe bond market reached historical best record at US$7 billion in 2007 compared with US$2 billion placed during 2005, despite the financial crisis in 2008 and 2009. Then, issuers raised approximately US$7 billion worth of new catastrophe bonds in 2013 [12, 13].

The CAT risk bonds are inherently risky, non-indemnity-based multi period deals that pay a regular coupon to investors at end of each period and a final principal payment at the maturity date if no predetermined catastrophic events have occurred. A major catastrophic event in the secured region before the CAT risk bond maturity date leads to full or partial loss of the capital. For bearing catastrophe risk, CAT risk bonds compensate a floating coupon of LIBOR plus a premium at rate between 2% and 20%, [14, 11]. In the literature, CAT risk bonds can be categorized into five basic trigger types: indemnity, industry index, modeled loss indices, parametric indices and hybrid triggers [15, 16]. Issuers do not directly issue the CAT risk bond, but use special purpose vehicle (SPV) for this transaction. SPV can be interpreted as a focused insurer whose only purpose it is to write one insurance contract. The existence of SPV minimizes the cost of raising and holding capital and increases the confidence of the insurer that the fund will be available when needed. Furthermore, sufficient high endowment of the SPV eliminates the counterparty risk. Finally, the feature of correlation of the traditional stock market allows CAT bonds investors to still gain in a bad economic circumstance. CAT risk bonds reduce barriers to entry and increase the contestability of the reinsurance market [17].

In the global financial market, nuclear CAT risk bonds are nonexistent, which specifically are designed for covering losses from nuclear disasters, like 2011 Fukushima disaster. Expanding the use of nuclear power, particularly in emerging markets, could contribute towards addressing global climate change and sustainability concerns. This expansion can be facilitated by nuclear CAT risk bonds covering nuclear related perils. It shifts the liability to the market and helps this sector to grow through increased participation of various service and product providers. The presentence of catastrophe risks requires an incomplete markets framework to evaluate the CAT risk bond price, because the catastrophe risks cannot be replicated by a portfolio of primitive securities, see Cox and Pedersen [18]. In [18], Cox and Pedersen are used a time-repeatable representative agent utility. Their approach is based on a model of the term structure of interest rates and a probability structure for catastrophe risks assuming that the agent uses the utility function to make choices about consumption streams. Finally, their theoretical structure and interesting findings have been applied to price the Morgan Stanley, Winterthur, USAA and Winterthur-style risk bonds. Zimbidis *et al.* [19] adopted the Cox and Pedersen [18] framework for pricing a Greek bond for Earthquakes using equilibrium pricing theory with dynamic interest rates. Extensions involving a multi financial and catastrophe risks framework were investigated by Shao *et al.*, [20], with applications to a structured multi-period coupon earthquakes CAT risk bond. Lee and Yu [21] additionally introduced default risk, moral hazard, and basis risk with stochastic interest rate. Shao [22] constructed a model using a Markov-dependent environment as an extension of the approach of [23] and employ the dependence between the claims sizes and the claim inter-arrival times.

Previous literature focused on one type of coverage (either per-occurrence or annual aggregate). In this paper a nuclear perils focused CAT risk bond with multi coverage type is proposed. An example of two-coverage type CAT risk bond is Residential Reinsurance 2012 Ltd. on behalf of USAA, which provide per-occurrence coverage for the all perils and also provides coverage on an annual aggregate basis.

2 Modelling N-CAT Risk Bond

According to the International Nuclear Event Scale (INES) [24], events are classified on the Scale at 7 levels which can be categorized by three risk layers: *incident* (level 1 to 3), *accident* (level 4 to 6) and *major accident* (level 7). Figure 4 provides example risk perils for each layer. In this paper, a nuclear CAT risk bond, termed N-CAT risk bonds, covered all nuclear power plants (104 operating reactors) in US which triggers are determined by the losses due to each peril is modelled. An incident is defined to include, for instance, strike, failures in safety provisions and lost or stolen highly radioactive sealed source, where the event with insignificant off-site impact and affordable in-site impact. An accident includes the release of radioactive material, cost of fitting a core machine, etc, which has severe in-site and off-site impact. A major accident is defined to include nuclear reactor core failure with widespread health and environmental effects, such as 2011 Fukushima disaster with total economic losses to US$210 billion.

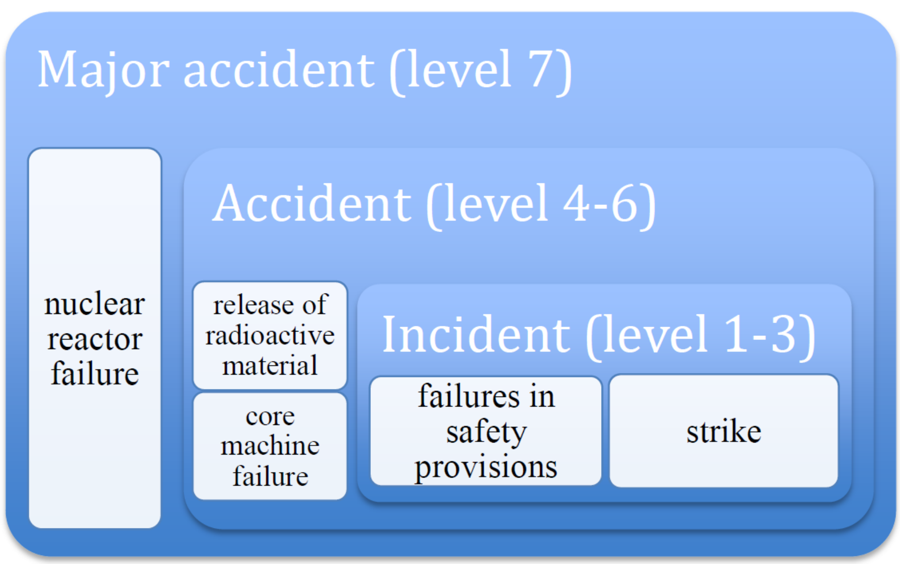


Fig. 4: The nuclear power risks

2.1 Modelling Assumptions

N-CAT bond is priced under the following assumptions: (i) there exists an arbitrage-free investment market with equivalent martingale measure, (ii) financial market behaves independently with the occurrence of catastrophes, and (iii) the replicability of interest rate changes by existing financial instruments[1].

Let $0 < T < \infty$ be the maturity date of the continuous time trading interval $[0,T]$. The market uncertainty is defined on a filtered probability space $(\Omega, \mathcal{F}, (\mathcal{F}_t)_{t\in[0,T]}, \mathbb{P})$, where $\mathcal{F}_t$ is an increasing family of σ-algebras given by $\mathcal{F}_t \subset \mathcal{F}$, for $t \in [0,T]$. All stochastic processes and random variables are defined with respect to probability measure $\mathbb{P}$.

2.2 Valuation Theory

The presence of catastrophic risks which are uncorrelated with the underlying financial risks leads to an incomplete market framework. For valuation purposes, assume that under the risk-neutral pricing measure $\mathbb{Q}$, events that depend on financial risks are independent of catastrophic events. Under this assumption (assumption ii), [18] proved that for any random variable X that depends only on catastrophe risk variables,

$$E^{\mathbb{Q}}[X] = E^{\mathbb{P}}[X]. \tag{1}$$

In an arbitrage free market (assumption i), at any time t, a contingent claim with payoff $\{P(T) : T > t\}$ at time T can be priced by the fundamental theorem of asset pricing [25], and the value of this claim is

$$V(t) = \mathbb{E}^{\mathbb{Q}}(e^{-\int_t^T r(s)ds} P(T)|\mathcal{F}_t), \tag{2}$$

where $\mathbb{E}^{\mathbb{Q}}$ is an equivalent expectation under the probability measure $\mathbb{Q}$, and $\{r(t) : t \in [0,T]\}$ is the spot interest rate process with selected dynamic, as discussed below.

2.3 Interest Rate Process

In this paper, the spot interest rate dynamic is assumed to be a Cox, Ingersol and Ross (CIR)[2] model [28]. The short-rate dynamics under the risk-neutral measure $\mathbb{Q}$ can be expressed as follows,

$$dr(t) = k(\theta - r(t))dt + \sigma\sqrt{r(t)}dW(t), \tag{3}$$

where $\{W(t) : t \in [0,T]\}$ is a standard Brownian motion, and $r(0), k, \theta$ and σ are positive constants. [27] assume a constant $\lambda_r(t)$ which represents the market price of risk, and price a pure-discount T-bond at time t by the following equalities:

$$B_{CIR}(t,T) = A(t,T)e^{-B(t,T)r(t)}, \tag{4}$$

where

$$A(t,T) = \left[\frac{2\gamma e^{(k+\lambda_r+\gamma)(T-t)/2}}{2\gamma + (k+\lambda_r+\gamma)(e^{(T-t)h} - 1)}\right]^{\frac{2k\theta}{\sigma^2}}, \tag{5}$$

$$B(t,T) = \left[\frac{2(e^{(T-t)\gamma} - 1)}{2\gamma + (k+\lambda_r+\gamma)(e^{(T-t)\gamma} - 1)}\right], \tag{6}$$

$$\gamma = \sqrt{(k+\lambda_r)^2 + 2\sigma^2}. \tag{7}$$

[1]These are some classical, however not too restrictive assumptions made by several other authors in the literature of CAT risk bonds; see, for instance, Cox and Pedersen [18], Zimbidis et al. [19], Shao et al. [20] and the references therein. Particularly, the assumption (ii), under which the financial and CAT markets are independent, simplifies the mathematical calculation of CAT-linked securities prices. These different assumptions are formulated in terms of filtrations that are independent but gather the full information needed. Now, practically speaking, the implementation of the dependency might be considered in the hypothetical extreme scenario that the catastrophic event is so big that it might affect the global economy. Perhaps, a severe nuclear accident, which is the motivation of the present paper, might create unpleasant macroeconomic side effects in the global markets. Obviously, the dependency between the two types of financial and catastrophic risks requires more advanced mathematical techniques, and it will be considered in a sequel paper.

[2]Nowak and Romaniuk [26] compared the CAT bond prices under the assumption of spot interest rate described by Vasicek, Hull-White and CIR model. However, the pricing process which affected by the interest rate dynamics is not the main focus of this paper. Thus, the paper employed the most popular model – CIR model – as an example. Readers can refer to [27] for more information on interest rate dynamics.

2.4 Aggregate Claims Process

As for the CAT bonds payment structure, CAT bonds investors receive premiums (or coupons) if trigger has not been pulled. This paper utilizes an insurance indemnity, two-coverage type trigger: per-occurrence trigger and aggregate loss trigger.

The aggregate loss process is modelled as a compound distribution process, which is characterized by the frequency (claim number process) and the severity (claim amounts process) of catastrophic events, (see [22]). As an extension of [22], a perturbed (absorbing) state model is introduced in order to model the per-occurrence trigger. In this model, time before the next claim depends on the state where the system stays, and the system stops (N-CAT bond contract is terminated) when it has jumped to the perturbed state.

The model considers a semi-Markovian dependence structure in continuous time, where the process $\{J_n, n \geq 0\}$ represents the successive type of claims or environment states take their values in $J = \{0,1,2,3,4\}$. For notation convenience, denote $J' = \{1,2,3,4\}$, therefore, $J = \{0\} + J'$. Here states J' called work of the system which refers to the minor and intermediate risks, and state 0 is the failure of the system (perturbed state) and refer to the nuclear reactor failure risk in this case. Figure 5 shows the possible states changes of the system that contrasted in this paper. The transition matrix $\mathbf{P}(= p_{ij}, i, j \in J)$ can be written as

$$\mathbf{P} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ p_{10} & p_{11} & p_{12} & p_{13} & p_{14} \\ p_{20} & p_{21} & p_{22} & p_{23} & p_{24} \\ p_{30} & p_{31} & p_{32} & p_{33} & p_{34} \\ p_{40} & p_{41} & p_{42} & p_{43} & p_{44} \end{pmatrix}, \tag{8}$$

where $\sum_{j=0}^{4} p_{ij} = 1, i \in J$. To interpret this N-CAT bond more properly, if a incident or accident level loss occurs, N-CAT bond stays in the period of work of the system (state i, where $i \in J'$), the probability to have a state j ($j \in J$) kind risk is p_{ij}. If a state 0 major accident loss occurs, CAT bond will expire immediately, i.e. the system will stay in the state 0.

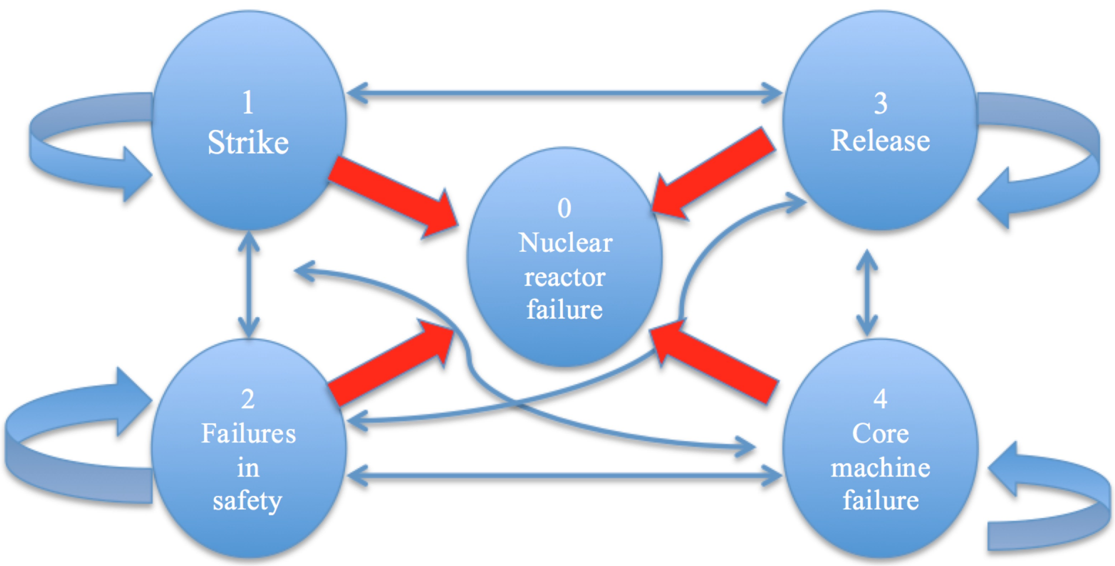


Fig. 5: Possible states changes of the system

Define $\{X_n, n \geq 1\}$ to be a sequence of successive claim sizes from all 104 NPPs in US, $X_0 = 0$ a.s. and $X_n > 0, \forall n$, and $\{T_n, n \in \mathbb{N}^+\}$ is the epoch time of the n^{th} claim. Suppose that $0 < T_1 < T_2 < \ldots < T_n < T_{n+1} < \ldots$, $T_0 = U_0 = 0$ a.s., and $U_n = T_n - T_{n-1}$ ($n \in \mathbb{N}^+$) denotes the sojourn time in state J_{n-1}. Suppose that the trivariate process $\{(J_n, U_n, X_n); n \geq 0\}$ is a semi-Markovian dependency process defined by the following matrix $\mathbf{Q}(= Q_{ij}, i, j \in J)$,

$$Q_{ij}(t,x) = \mathbb{P}(J_n = j, U_n \leq t, X_n \leq x | (J_k, U_k, X_k), k = 1,2,...,n-1, J_{n-1} = i), \tag{9}$$

where the process of successive claims $\{J_n\}$ is an irreducible homogeneous continuous time Markov chain with state space J and transition matrix $\mathbf{P}(=p_{ij})$, where $\lim_{t\to\infty,x\to\infty} Q_{ij}(t,x) = p_{ij}, i,j \in J$. An explanation of the special case in terms of US N-CAT bonds will be given in the end of this subsection.

Assuming that the random variable $J_n, n \geq 0$ and the two-dimensional random variable $(U_n, X_n), n \geq 1$ are conditionally independent, then

$$G_{ij}(t,x) = \mathbb{P}(U_n \leq t, X_n \leq x | J_0, ..., J_{n-1} = i, J_n = j) = \begin{cases} Q_{ij}(t,x)/p_{ij}, \text{ for } p_{ij} > 0, \\ \mathbb{1}\{t \geq 0\}\mathbb{1}\{x \geq 0\}, \text{ for } p_{ij} = 0, \end{cases} \tag{10}$$

where $\mathbb{1}\{\cdot\}$ represents an indicator function. The random variable $J_n, n \geq 0$ is conditionally dependent on the random variable $U_n, n \geq 1$ and also conditionally dependent on the random variable $X_n, n \geq 1$. Denote

$$G_{ij}(t,\infty) = \mathbb{P}(U_n \leq t | J_0, ..., J_{n-1} = i, J_n = j), \tag{11}$$
$$G_{ij}(\infty,x) = \mathbb{P}(X_n \leq x | J_0, ..., J_{n-1} = i, J_n = j), \tag{12}$$

and obtain the following equations by suppressing the condition J_n,

$$H_i(t,x) = \mathbb{P}(U_n \leq t, X_n \leq x | J_0, ..., J_{n-1} = i) = \sum_{j=0}^{4} p_{ij} G_{ij}(t,x), \tag{13}$$
$$H_i(t,\infty) = \mathbb{P}(U_n \leq t | J_0, ..., J_{n-1} = i), \tag{14}$$
$$H_i(\infty,x) = \mathbb{P}(X_n \leq x | J_0, ..., J_{n-1} = i). \tag{15}$$

Assuming that the sequences $\{U_n, n \geq 1\}$, $\{X_n, n \geq 1\}$ are conditionally independent and given the sequence $\{J_n, n \geq 0\}$, then

$$G_{ij}(t,x) = G_{ij}(t,\infty) G_{ij}(\infty,x), \forall t,x \in \mathbb{R}, \forall i,j \in J. \tag{16}$$

Thus, the semi-Markov kernel $\mathbf{Q}$ can be expressed as

$$Q_{ij}(t,x) = p_{ij} G_{ij}(t,\infty) G_{ij}(\infty,x), \forall t,x \in \mathbb{R}, \forall i,j \in J. \tag{17}$$

Define the claim number process $\{N(t) : t \in [0,T]\}$ $(N(0) = 0)$, which describes the number of claims in 104 NPPs which are insured in US. The claim sizes $\{X_k : k \in \mathbb{N}^+\}$, which are independent of the process $\{N(t) : t \in [0,T]\}$. Then, the aggregate loss process $\{L(t) : t \in [0,T]\}$ is modelled by a compound Poisson process, as follows:

$$L(t) = \sum_{k=1}^{N(t)} X_k, \tag{18}$$

with the convention that $L(t) = 0$ when $N(t) = 0$. And $J_{N(t)}$ is the state where last claim stays. Let L_n be the successive total claims amount after the arrival of the nth claim, which is defined as:

$$L_n = \sum_{k=1}^{n} X_k, \forall n \geq 1. \tag{19}$$

Then, the joint probability of the process $\{(J_n, T_n, L_n); n \geq 0\}$ can be denoted as

$$\mathbb{P}[J_n = j, T_n \leq t, L_n \leq x | J_0 = i] = Q_{ij}^{*n}(t,x), \tag{20}$$
$$\mathbb{P}[J_n = 0, T_n \leq t, L_{n-1} \leq x | J_0 = i] = Q_{i0}^{*n}(t,x), \tag{21}$$

where $i,j \in J'$. This n-fold convolution matrix $\mathbf{Q}^{(n)}(=Q_{ij}^{(n)}, i,j \in J)$ can be valued recursively by the following two parts: (where $i,j \in J'$)

$$Q_{ij}^{*0}(t,x) = \delta_{ij}(t,x)L_0 = \begin{cases} (1-G_{ij}(0,\infty))(1-G_{ij}(\infty,0)), \text{ if } i=j, \\ 0, \text{ elsewhere,} \end{cases} \tag{22}$$

$$Q_{ij}^{*1}(t,x) = Q_{ij}(t,x), \quad \dots \tag{23}$$

$$Q_{ij}^{*n}(t,x) = \sum_{l=1}^{4} \int_0^t \int_0^x Q_{lj}^{*(n-1)}(t-t',x-x')dQ_{il}(t',x'). \tag{24}$$

and

$$Q_{i0}^{*0}(t,x) = 0, \tag{25}$$

$$Q_{i0}^{*1}(t,x) = Q_{i0}(t,x) = G_{i0}(t,\infty)p_{i0}, \quad \dots \tag{26}$$

$$\begin{aligned} Q_{i0}^{*n}(t,x) &= \mathbb{P}[J_n = 0, J_{n-1} = J', \dots, J_1 = J', L_{n-1} \leq x, T_n \leq t | J_0 = i] \\ &= \sum_{l=1}^{4} \int_0^t \mathbb{Q}_{il}^{*(n-1)}(t-t',x)d(G_{l0}(t',\infty)p_{l0}). \end{aligned} \tag{27}$$

Moreover, suppose that there exist a sequence of unique probabilities $(\Pi_1,\Pi_2,\Pi_3,\Pi_4)$ (here we assume $\Pi_0 = 0$, a.s.), which represents the starting probability distribution for the embedded Markov Chain $\{J_n; n \geq 0\}$, $\Pi_1+\Pi_2+\Pi_3+\Pi_4 = 1$ and $\Pi_1,\Pi_2,\Pi_3,\Pi_4 \in [0,1]$.

The following probabilities are essential for the purposes of pricing N-CAT bond. At time t, for the predetermined threshold level D ($D \geq 0$), it derives that

$$\begin{aligned} F_1(t,D) &= \mathbb{P}(L(t) \leq D, J_{N(t)} \neq 0) \\ &= \sum_{i=1}^{4} \sum_{j=1}^{4} \Pi_i \sum_{n=0}^{\infty} \int_0^t (1-H_j(t-t',\infty))dQ_{ij}^{*n}(t',D), \end{aligned} \tag{28}$$

$$F_2(t,D) = \mathbb{P}(J_{N(t)} = 0) = \sum_{i=1}^{4} \Pi_i \sum_{n=1}^{\infty} Q_{i0}^{*n}(t,D), \tag{29}$$

$$F_3(t,D) = \mathbb{P}(L(t) > D, J_{N(t)} \neq 0) = 1 - F_1(t,D) - F_2(t,D). \tag{30}$$

In particular, a special case of this US N-CAT bond is SM'/SM model, which can be structured as $(i \in J', j \in J)$:

1. The inter-arrival time distribution only depends on the current state, and is given by matrix $G_{ij}(t,\infty) = \mathbb{P}_i(U_k \leq t)$.
2. Claim size distribution is given by $G_{ij}(\infty,x) = \mathbb{P}_j(X_k \leq x)$.

That is, the process changes its state at every claim instance based on the transition matrix $\mathbf{P}$, with the claim size distribution depend on the future state . While the arrival time before the next catastrophic claim U_k depends on the severity of the current event X_k, for all $k = 0,1,2,\dots$.

2.5 Pricing model for the CAT bonds

Defining a hypothetical zero coupon N-CAT bond at the maturity date T with face value Z, the price of the N-CAT risk bond is given to be the following payoffs structure:

1. If at expiring time T, $L(T) \geq D$ ($D \geq 0$) and $J_k \neq 0$ ($\forall k$), that is total loss greater than predefined level and no major accident occurs priority to T, bond holder will loss part of their capital and receive $p_1 Z$;
2. If a major accident (state 0 event) ($J_k = 0$) occurs before the expiry date T, N-CAT bond expire immediately and bond holder will receive partial of their principle $p_2 Z$ (normally, $0 < p_2 < p_1$);
3. Otherwise bond holder will receive Z.

Formally, the payoff function described above is given mathematically by

$$P_{CAT} = \begin{cases} Z, \text{ for } L(T) \leq D \text{ and } J_{N(t)} \neq 0, \\ p_1 Z, \text{ for } L(T) > D \text{ and } J_{N(t)} \neq 0, \\ p_2 Z, J_{N(t)} = 0. \end{cases} \tag{31}$$

Zero-coupon N-CAT bond prices at time t paying principal Z at time to maturity T is given in following Theorem 2.1.

Theorem 2.1. *Let $V(t)$ be the value of T-maturity zero-coupon CAT bond under the risk-neutral measure $\mathbb{Q}$ at time t with payoffs function P_{CAT} Eq.* (31)*. Then,*

$$V(t) = B_{CIR}(t,T)Z[p_1 + (1-p_1)F_1(T-t,D) + (p_2-p_1)F_2(T-t,D)], \tag{32}$$

where $F_1(T-t,D)$ and $F_2(T-t,D')$ represent the probabilities given in Eq. (28) *and Eq.* (29)*, respectively, and pure discounted bond price $B_{CIR}(t,T)$ with CIR interest rate model is given by Eq.* (4)–(7)*.*

Proof. Cox and Pedersen [18] suggested that the payoff function is independent of the financial risks variable (interest rate) under the risk-neutral measure $\mathbb{Q}$. Then we have

$$V(t) = \mathbb{E}^{\mathbb{Q}}(e^{-\int_t^T r_s ds} P_{CAT}(T)|\mathcal{F}_t) = \mathbb{E}^{\mathbb{Q}}(e^{-\int_t^T r_s ds}|\mathcal{F}_t)\mathbb{E}^{\mathbb{Q}}(P_{CAT}(T)|\mathcal{F}_t). \tag{33}$$

Using the result of the zero-coupon bond price with the CIR interest rate model (see [27]), we have $\mathbb{E}^{\mathbb{Q}}(e^{-\int_t^T r_s ds}) = B_{CIR}(t,T)$. The above equation can be written as

$$B_{CIR}(t,T)\mathbb{E}^{\mathbb{P}}(P_{CAT}(T)|\mathcal{F}_t). \tag{34}$$

Simply apply the payoffs function and rearrange the formula, the value of N-CAT bond price can be formulated as

$$\begin{aligned}V(t) =& B_{CIR}(t,T)\mathbb{E}^{\mathbb{P}}(Z\mathbb{1}\{L(T) \le D, J_{N(t)} \neq 0\} + p_1 Z\mathbb{1}\{L(T) > D, J_{N(t)} \neq 0\} \\ & + p_2 Z\mathbb{1}\{J_{N(t)} = 0\}|\mathcal{F}_t) \\ =& B_{CIR}(t,T)(Z\mathbb{P}(L(T) \le D, J_{N(t)} \neq 0) + p_1 Z\mathbb{P}(L(T) > D, J_{N(t)} \neq 0) \\ & + p_2 Z\mathbb{P}(J_{N(t)} = 0)) \\ =& B_{CIR}(t,T)(ZF_1(T,D) + p_1 F_3(T,D) + p_2 F_2(T,D)) \\ =& B_{CIR}(t,T)Z[p_1 + (1-p_1)F_1(T-t,D) + (p_2-p_1)F_2(T-t,D)] \\ =& B_{CIR}(t,T)Z[p_1 + (1-p_1)\sum_{i=1}^{4}\sum_{j=1}^{4}\Pi_i \sum_{n=0}^{\infty}\int_0^T (1-H(T-t',\infty))dQ_{ij}^{*n}(t',D) \\ & + (p_2-p_1)\sum_{i=1}^{4}\Pi_i\sum_{n=1}^{\infty} Q_{i0}^{*n}(T,D)].\end{aligned} \tag{35}$$

3 Numerical Example of N-CAT Risk Bond

In this section, a numerical example illustrates the applicability of the theoretical model which has been presented previously. Due to data limitations, the following assumptions need to be made.

For the US N-CAT bond SM'/SM model, the inter-arrival time distribution is assumed to be a Poisson process with parameter λ_i, and it can be given by matrix $\mathbf{G}(t,\infty)(= G_{ij}(t,\infty), i \in J', j \in J)$,

$$G_{ij}(t,\infty) = \begin{cases} 0, \, t < 0 \\ 1 - e^{-\lambda_i t}, \, t \ge 0. \end{cases} \tag{36}$$

Furthermore, arbitrarily assume that $\lambda_i = 10,\ 30,\ 5,\ 20$, for $i = 1,\ 2,\ 3,\ 4$, respectively. An interpretation of this can be: if an event occurs (termed to be either strike, failures in safety provisions, release of radioactive or core machine failure), the time before the next event follows an exponential distribution with parameter λ_i. The claim size distribution is assumed to follow a lognormal distribution with mean μ_j and variance σ_j, $(i \in J', j \in J)$,

$$G_{ij}(\infty,x) = \frac{1}{x\sigma_j\sqrt{2\pi}}\exp\left(-\frac{(lnx-\mu_j)^2}{2\sigma_j^2}\right). \tag{37}$$

Further assume that $\mu_j = 2,\ 1,\ 2.5,\ 3$ and $\sigma_j = 1,\ 0.8,\ 1.5,\ 1.2$, for $j = 1,\ 2,\ 3,\ 4$, respectively. Due to the property of the catastrophe events, the loss cost by each type of the peril is a heavy tailed distribution. In this case study, it is also assumed that core machine failure tends to cause more losses, while failure in safety provisions causes less losses. Moreover that the transition matrix $\mathbf{P}(= p_{ij})$ is given by

$$\mathbf{P} = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 \\ 0.003 & 0.397 & 0.3 & 0.2 & 0.1 \\ 0.004 & 0.4 & 0.096 & 0.3 & 0.2 \\ 0.001 & 0.4 & 0.4 & 0.199 & 0.1 \\ 0.001 & 0.2 & 0.2 & 0.5 & 0.098 \end{pmatrix}, \tag{38}$$

and the stationary distribution $(\Pi_1,\ \Pi_2,\ \Pi_3,\ \Pi_4) = (0.3476325,\ 0.2609975,\ 0.2642861,\ 0.1264328)$. Here, p_{i0} $(i \in J')$ is very small because the probability of having nuclear reactor failure is very rare. The first row $(p_{0j}, j \in J)$ are zero because if a major accident (state 0 event, nuclear reactor failure) occurs, the system stops and the N-CAT bond expires immediately. $p_{11} = 0.397$ means that the probability of having a strike after a strike is 0.397, and $p_{12} = 0.3$ means that the probability of failures in safety provisions after a strike is 0.3, and so on.

Generate $N = 100,000$ simulations and obtain the $T = [0.5,\ 2]$ years maturity zero-coupon N-CAT bond prices with face amount of US\$1,000 in Monte-Carlo simulations. For the payoff function (31), it is assumed that $p_1 = 0.5$ when the aggregate loss $L(T)$ exceeded the threshold level $D = [100,\ 1600]$ in million US\$, and $p_2 = 0.25$.

In this case study, same data set as [22] (3-month maturity US monthly Treasury bill data (1994–2013)) is fitted for interest rate model. Thurs, both the initial short-term interest rate r_0 and the long-term mean interest rate θ were 2.04% annually, the mean-reverting force $k = 0.0984$, and the volatility parameter $\sigma = 4.77\%$. Furthermore, it is assumed that the market price of risk λ_r is a constant -0.01.

Table 2 and Figure 6 illustrate the value of N-CAT bond for the payoff functions (31) with the CAT threshold level D and time to maturity T under the stochastic interest rate assumptions, where the loss distribution follows the lognormal distribution and the intensity of the claims is a Poisson distribution. For example, a N-CAT bond buyer need to pay US\$781.16 now in order to buy this N-CAT bond with face value US\$1,000 which will mature in six months and with threshold level US\$100 million. With fixed threshold level US\$100 million, the bond value decreases from US\$781.16 to US\$455.31 for the maturity time from half year to 2 years. This is a quicker rate for threshold level US\$1,600 million, with the bond value decreasing from US\$948.42 to US\$855.32. For fixed time to maturity, the N-CAT bond value increases when the threshold level increases (from US\$100 million to US\$1,600 million.), and with a quicker rate for longer maturity time (from US\$781.16 to US\$948.42 for $T = 0.5$ and US\$455.31 to US\$855.32 for $T = 2$.)

Table 2: Vaule of N-CAT bonds with face value US\$1,000 for time to the maturity ($T = 0.5,\ 1,\ 1.5,\ 2$, years) and threshold level ($D = 100,\ 600,\ 1000,\ 1600$ in million US\$).

N-CAT value (V, US\$)		Time to maturity (T, years)			
		0.5	1	1.5	2
Threshold (D, US\$ millions)	100	781.16	603.19	500.64	455.31
	600	942.38	905.84	853.43	792.51
	1000	947.09	919.22	881.91	843.62
	1600	948.42	922.55	888.49	855.32

Obviously, the value of the N-CAT (V) decreases in relation with the maturity time (T). Moreover, with higher predetermined threshold levels (D), the N-CAT bond value (V) increases accordingly. Although change of D won't affect the probability of having a major accident claim, the probability of total losses higher than the threshold level deceases.

4 Conclusion and future research

In this paper, for the very first time, a two-coverage type trigger nuclear catastrophe (N-CAT) bond is proposed for financing nuclear liability, which can be categorized by three risk layers: major accident, accident and incident. In the Global

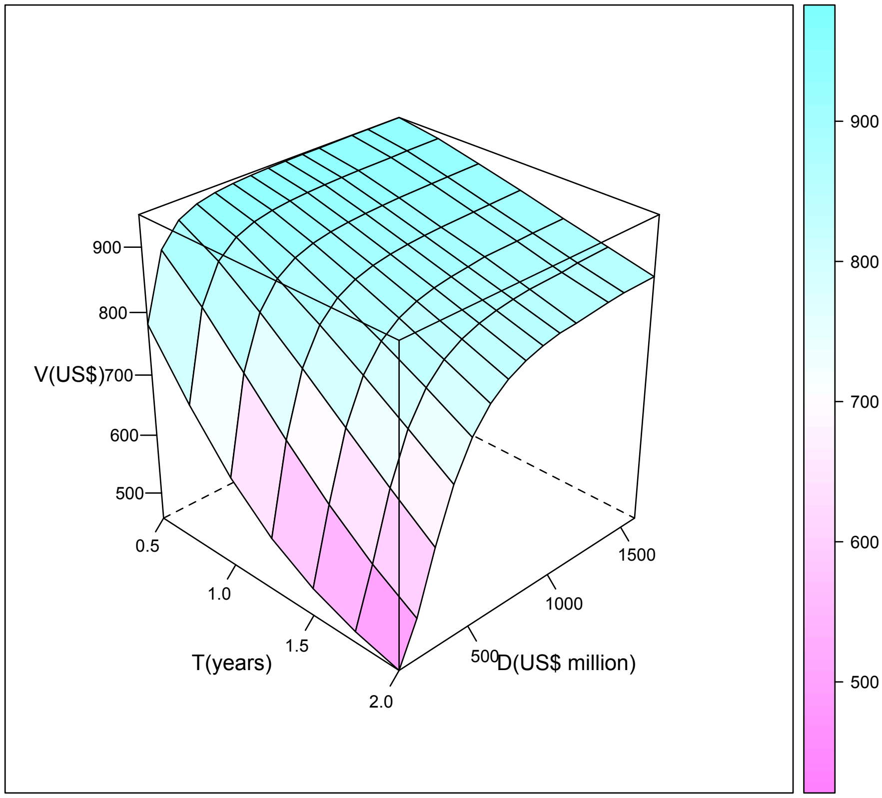


Fig. 6: Vaule of N-CAT bonds (z-coordinate axes) under the lognormal, the NHPP and stochastic interest rates assumptions. Here, time to the maturity (T) decreases by the left axes and threshold level (D) increases by the right axes. With fixed threshold level US$100 million, bond value decreases from US$781.16 to US$455.31 for the maturity time from half year to 2 years. This is a quicker rate for threshold level US$$1,600$ million, with bond value decreases from US$948.42 to US$855.32. For fixed time to maturity, N-CAT bond vaule increases when threshold level increases (from US$100 million to US$$1,600$ million.), and with a quicker rate for longer maturity time (form US$781.16 to US$948.42 for $T = 0.5$ and US$455.31 to US$855.32 for $T = 2$.)

CAT risk bond market, a similar trigger type of a total size of US$400 million has been proposed recently by Residential Reinsurance 2012 Ltd. (Series 2012-2)[3] for covering U.S. hurricane, U.S. earthquake, U.S. severe thunderstorm, U.S. winter storm and California wildfire. After the 2011 Fukushima disaster, the development of dependable liability coverage that can be tapped in an emergency is of significant importance in the many countries with significant number of NPPs. For instance, with 104 operating reactors, the U.S. has a total of about US$12 billion in coverage (as of 2011) [29] before congressional authorization for additional funding estimating the damage due to a catastrophic accident from US$110 billion to as much as US$7 trillion.

In this study, value of N-CAT bond is formulated under assumptions of a no-arbitrage market, independently of the financial risks and catastrophe risks, and the possibility of replicated interest rate changes with existing financial instruments. Under the risk-neutral pricing measure, the pricing formula is derived by using a semi-Markov dependent structure in continuous time where the claim inter-arrival times are dependent on the claim sizes together with CIR interest rate model and two-coverage type payoff functions. Numerical experiments utilized Monte Carlo simulations by assuming the distributions and parameters. The values of the N-CAT bonds are obtained under the lognormal, the NHPP and stochastic interest rates assumptions for different threshold levels (D) and time to the maturities (T). The numerical analysis shows that the CAT bond prices decreased as the threshold level decreased, as the time to maturity increased.

Always a challenging aspect is the estimation of the parameters involved in the model as the collection of historical data for losses due to catastrophic events in commercial NPPs is rather limited, which makes the accuracy of the pricing method

[3] See Artemis 2012, Residential Reinsurance 2012 Ltd. (Series 2012-2)
`http://www.artemis.bm/deal_directory/residential-reinsurance-2012-ltd-series-2012-2/`.

even more challenging. Although we solved the problem of two-coverage type N-CAT bond, the analysis of the impact of N-CAT risk bonds-specific variables on premiums is also a very interesting question, and particularly considering complexity in terms of the number of insured peril types or regions. Finally, it is useful to investigate how the future nuclear disasters (especially in emerging markets, like China and India) and financial crises might affect N-CAT bond premiums and demand.

Acknowledgements: The authors would like to acknowledge the gracious support of this work through the EPSRC and ESRC Centre for Doctoral Training on Quantification and Management of Risk and Uncertainty in Complex Systems and Environment (EP/L015927/1). The first author acknowledges the financial support of the national Security Analysis Department at the Applied Physics Lab of the Johns Hopkins University during his sabbatical leave from the University of Maryland, College Park.

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