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11. Division of Nuclear Policy, Human Resources and Cooperation

# Development of Risk Assessment Model for Nuclear Proliferation Scenario Based on the Nuclear Fuel Cycle

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FNC TECHNOLOGY CO., LTD.

# CONTENTS

- 1 Introduction
- 2 Methods
- 3 Analysis and Results
- 4 Conclusions and Future Works

# 1 Introduction

## Background & Objective

- **Export controls on strategic goods are being implemented in accordance with international treaties to prevent the proliferation of weapons of mass destruction such as nuclear weapons.**
  - **Trigger list items are designated according to the Nuclear Supply Group guidelines, and export controls are in place to prevent nuclear proliferation.**
- **Moreover, exports of nuclear material and technologies to various customer countries are expected to phenomenally increase inasmuch as the rapid growth of domestic competences in nuclear technology and nuclear industry.**
- **However, there is a high possibility that the current professional judgment of export license depends on the subjective judgment of the examiner as it contains many qualitative contents.**
- **Therefore, it is necessary to develop an export risk assessment system that can support export controls.**
- **It is carrying out the 'Development of Export Risk Assessment Program for Trigger Items' task.**

## Export Risk Assessment Model Overview

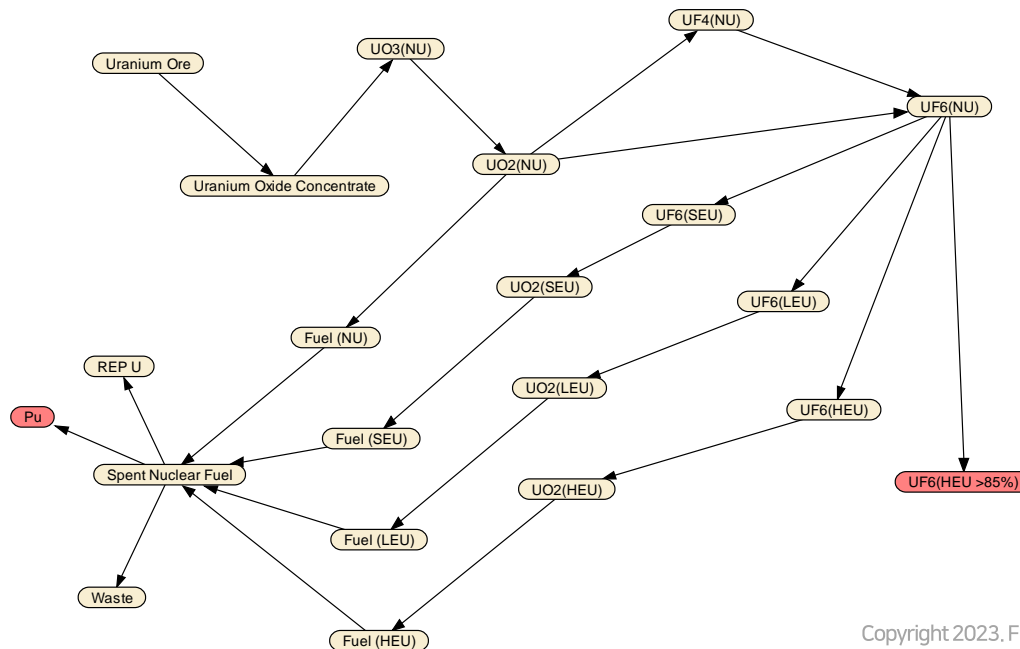
### Export Risk Assessment

Country credibility	Trader credibility	Item contribution																																																																																																																																																																
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 <b>Heungdeok 1-ro, Giheung-gu</b>          Yongin-si, Gyeonggi-do, 16954          Korea</p> </div> <div data-bbox="971 829 1228 878"> <p><b>Nuclear Core and T-H Design Analyses</b></p> </div> <div data-bbox="971 901 1228 949"> <p>FNC has a full range of experiences designing both commercial power reactor as well as experimental and research reactor.</p> </div>	
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➤ This study is about assessment of nuclear proliferation contribution of items.

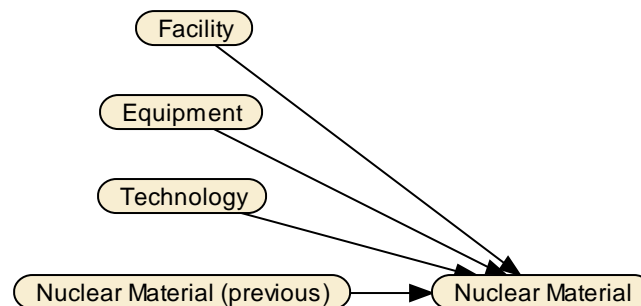
## Nuclear Fuel Cycle

- In order to create a proliferation scenario, it is necessary to understand the process by which nuclear materials are made into weapons-grade special nuclear materials.
  - The nuclear fuel cycle is an example of a nuclear materials production process.
- The nuclear fuel cycle represents the steps of nuclear material processing from mining to disposal.
  - Mining, milling, conversion, enrichment, fabrication, power generation, interim storage, reprocessing, and waste disposal are the primary processes.
- In order to focus on generating nuclear materials, the pathway was built around nuclear materials.



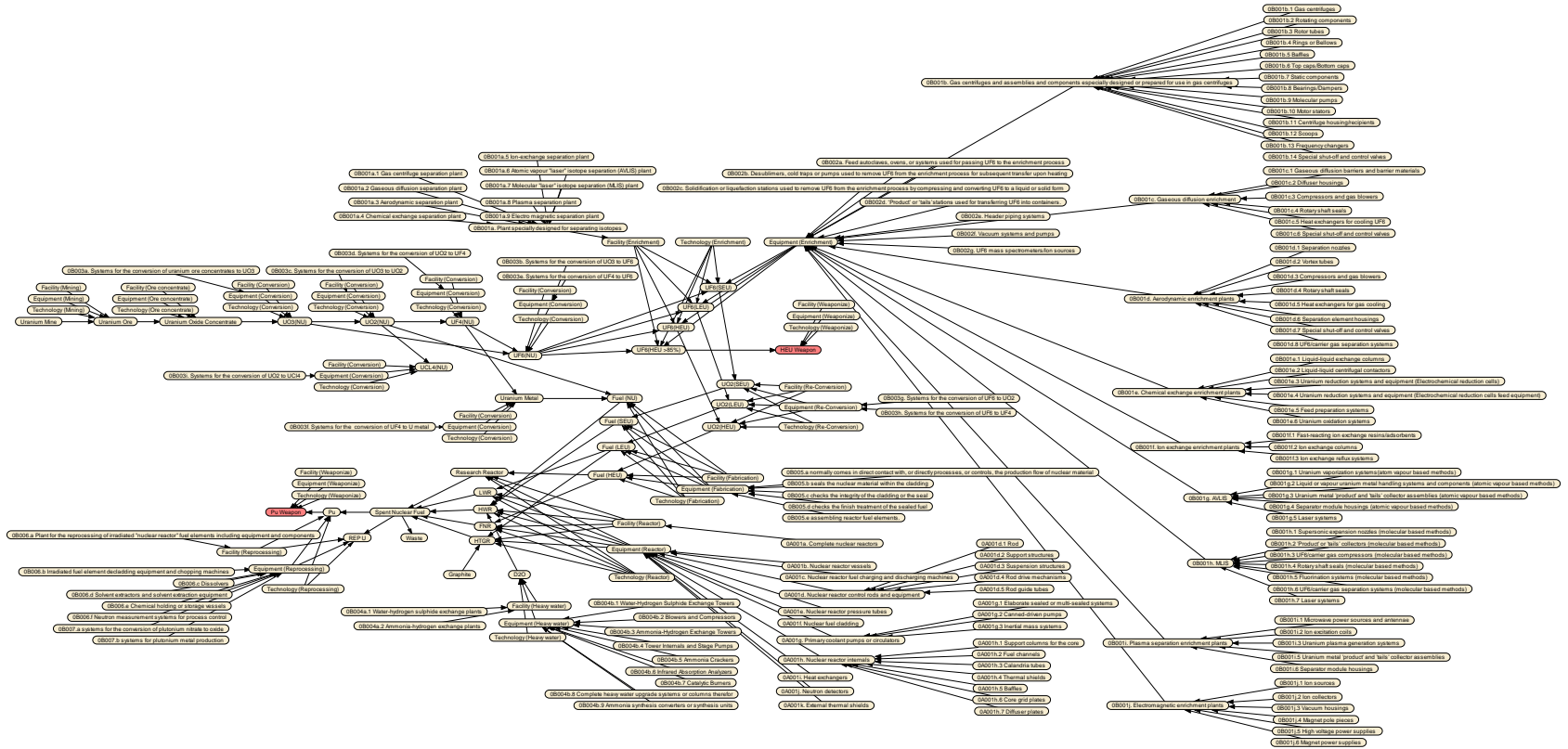
## Trigger List Items

- **Trigger list items are items subject to export control in accordance with the guidelines of the Nuclear Supply Group in order to prevent international nuclear proliferation.**
  - According to the control number, the trigger list items are classified into five categories.
    - OA: systems, equipment and components
    - OB: test, inspection and production equipment
    - OC: materials
    - OD: software
    - OE: technology
- **To assess the risk, a proliferation scenario was created by incorporating trigger list items into the nuclear fuel cycle.**
  - The control number-classified items were linked to facilities, technology, and equipment required for nuclear material production
  - Sub-items were constructed by linking them to upper-level items.



## Trigger List Items

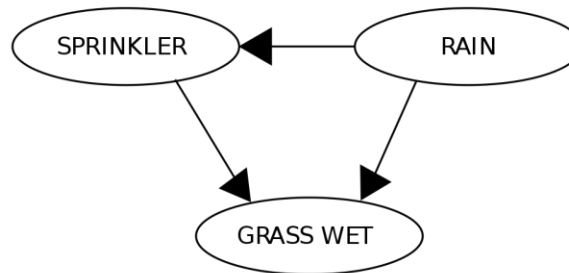
➤ A proliferation scenario was created by incorporating trigger list items.



## Bayesian Network

- A Bayesian network is a directed acyclic graphical model that can calculate the probability of another event occurring when a given event occurs through conditional probability.
- Bayesian network consists of nodes, arcs and conditional probability table.

RAIN	SPRINKLER	
	T	F
F	0.4	0.6
T	0.01	0.99



RAIN	T	F
	0.2	0.8

SPRINKLER	RAIN	GRASS WET	
		T	F
F	F	0.0	1.0
F	T	0.8	0.2
T	F	0.9	0.1
T	T	0.99	0.01

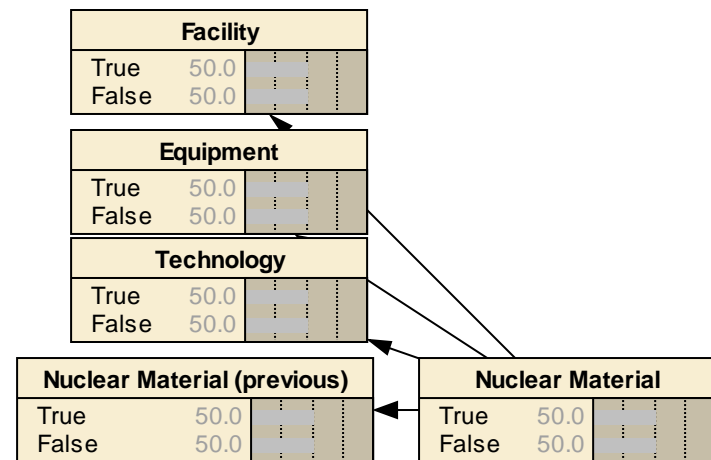
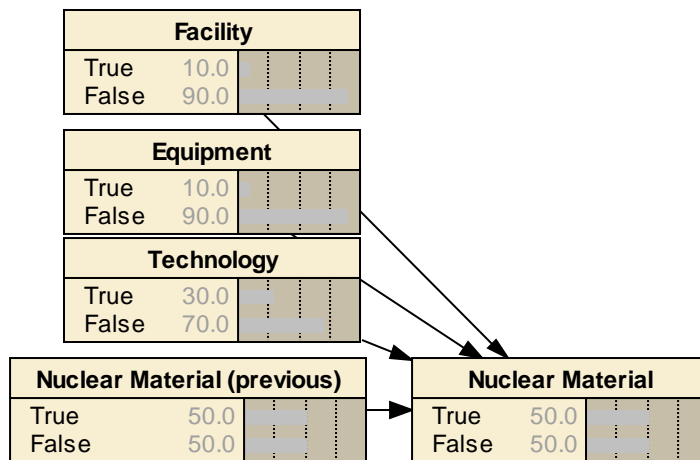
- Bayesian network can calculate posterior probabilities using Bayes' theorem

$$p(h|D) = \frac{p(D|h)p(h)}{p(D)}$$



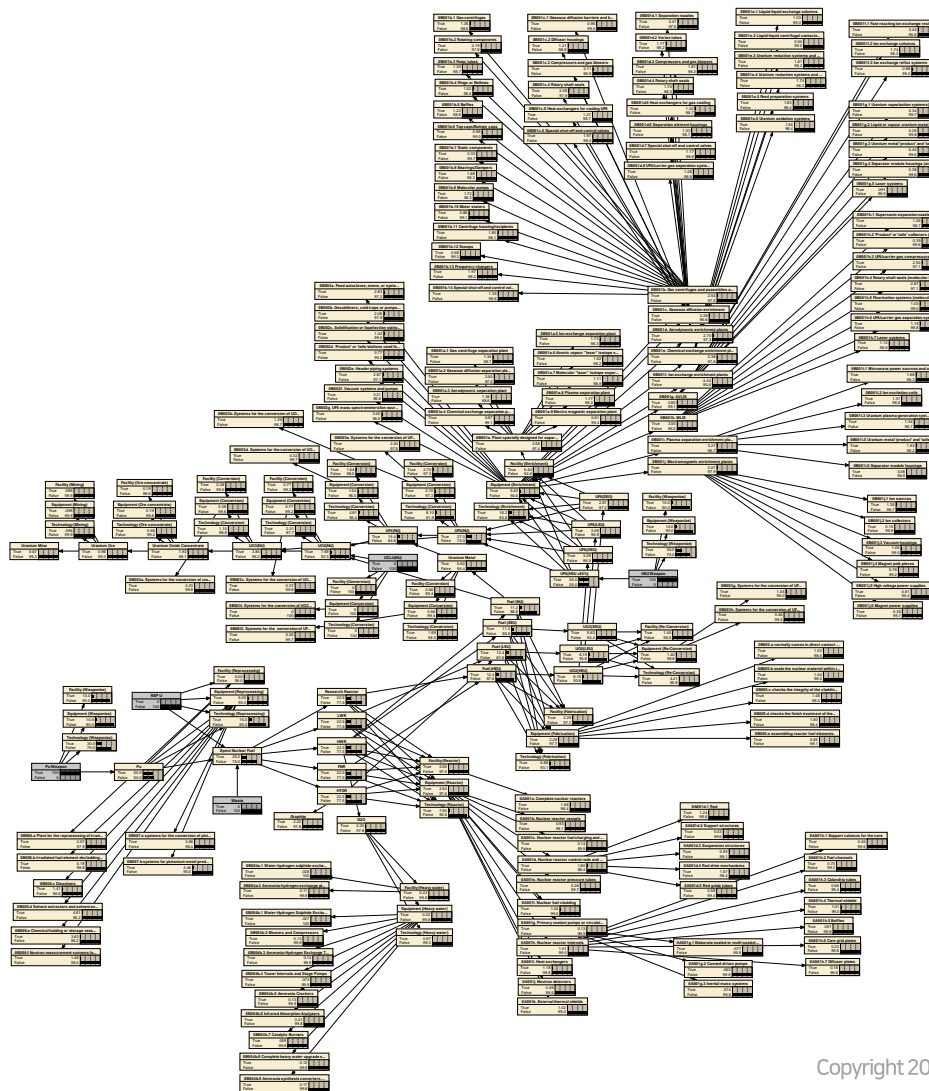
## Bayesian Network

- Bayesian network methodology was applied to evaluate the established proliferation scenario.
  - When proliferation occurs, the probability that another item spreads can be assessed as a risk.
  - When an event in the next path occurs, the probability of another event in the previous path must be obtained, so the Bayesian network was constructed in the opposite direction to the nuclear fuel cycle.
    - If configured in the forward direction, the probability of an event occurring in the next path can be obtained from the probability of an event occurring in the previous path.
    - If configured in the reverse direction, when an event in the next path occurs, the probability of an event in the previous path occurring can be obtained. (i.e. The contribution can be obtained.)
  - The number of cases was limited to true/false cases in which an event occurred or no event occurred.



## Bayesian Network

➤ A proliferation scenario of trigger list items established with Bayesian network.



## Conditional Probability

- To evaluate probabilities, conditional probabilities between linked items must be defined.
  - To calculate the probability in a Bayesian network, the conditional probability between the node and other connected nodes must be created, which can be written as a conditional probability table.
  - Since it is difficult to evaluate the impact of a specific trigger list item on other items, the value was tentatively set in this study.
    - The impact of nuclear materials, facilities, technology, and equipment on other nuclear materials in the following routes was set at 50%, 10%, 30%, and 10%, respectively.
    - When nuclear proliferation did not occur, it was set to 0%.
    - The detailed items' probabilities were chosen at randomly.

	Material	
	True	False
True	50	50
False	0	100

	Facility	
	True	False
True	10	90
False	0	100

	Technology	
	True	False
True	30	70
False	0	100

	Equipment	
	True	False
True	10	90
False	0	100

# 3 Analysis and Results

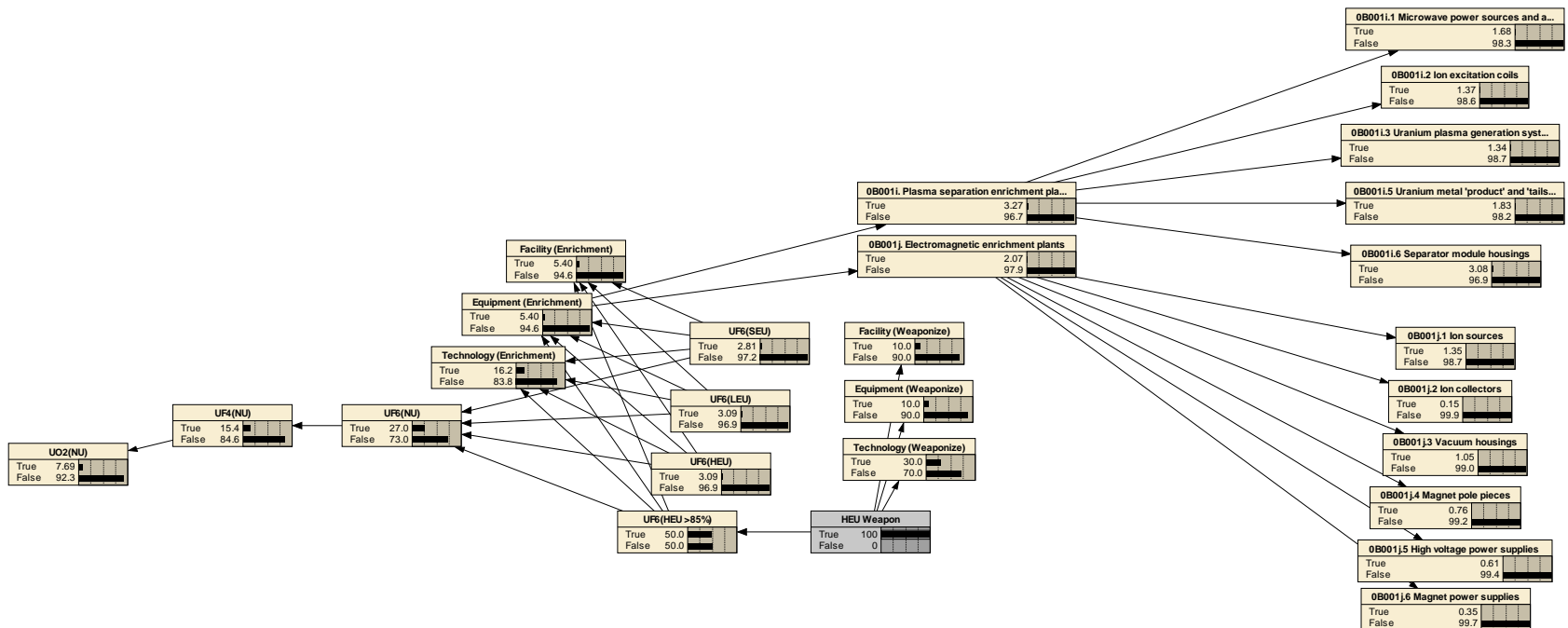
## Analysis & Results

### ➤ Evaluate the contribution of trigger list items.

- Netica, a commercial Bayesian network program, was used to calculate the risk assessment.
- The special nuclear material node was set to true to evaluate the risk of other trigger list items.

### ➤ Results:

- The risk of items on routes away from special nuclear materials came out low.
- However, even if the path was long, the risk increased when the conditional probability value was set high.



# 4 Conclusions and Future Works

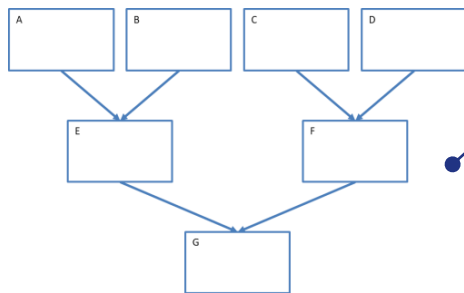
## Conclusions

- Evaluate the nuclear proliferation contribution of trigger list items using a Bayesian network.
- The results are unreliable because the contribution values are set arbitrarily.
  - Because the approximate value was entered as a qualitative judgment, it is possible to see the trend along the route, but it is difficult to trust the quantitative value.
  - Continuous updates are required through the experience of examiners or expert advice.
- Bayesian networks cannot create circular paths.
  - The nuclear fuel cycle has a circular path that is used as nuclear fuel again through reprocessing.
- Items in pathways directly connected to special nuclear material have high risk values.
  - UF6 (NU), which is directly connected to the production of highly enriched uranium, has a higher risk than other enriched UF6 (SEU), UF6 (LEU), and UF6 (HEU).
  - Even if it is not directly connected to the path, it is necessary to reflect the correlation for highly correlated items.

# 4 Conclusions and Future Works

## Future Works

- Bayesian network expansion to reflect uncertainty.
  - Consider undeclared nuclear material production, import, theft and so on.
  - Apply parameters according to technology or facilities owned by each country.
- Export risk assessment through random sampling using Monte Carlo method.



Create a scenario



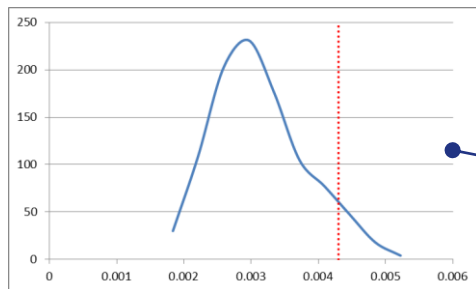
Enter probability value



Random sampling



Distribution of results



	TRUE				TRUE				TRUE				TRUE		
A	min		max	B	min		max	C	min		max	D	min		max
p(A)	1		1	p(B)	0.02		0.04	p(C)	0.015		0.055	p(D)	0.005		0.006
A	TRUE	0.3	0.7	E	TRUE	0.1	0.5	F	TRUE	0.3	0.7	G	TRUE	0.3	0.7
	TRUE	FALSE	0.1		FALSE	0.01	0.05		TRUE	FALSE	0.01		TRUE	FALSE	0.01
	FALSE	TRUE	0.02		TRUE	0.02	0.04		FALSE	TRUE	0.02		FALSE	TRUE	0.02
	FALSE	FALSE	0.001		FALSE	0.001	0.002		FALSE	FALSE	0.001		FALSE	FALSE	0.001

#	Range	A	Value	Result	Range	B	Value	Result	Range	C	Value	Result	Range	D	Value	Result	Range	E	Value	Result	Range	F	Value	Result	Range	G	Value	Result	
1		0.21340	TRUE	0.031178	0.295720	FALSE	0.0381018	0.868203	FALSE	0.003536	0.262401	FALSE	0.047496	0.74949	FALSE	0.001750	0.133053	FALSE	0.001341	0.447205	FALSE								
2		0.1642408	TRUE	0.032504	0.309827	FALSE	0.040818	0.908203	FALSE	0.009997	0.037821	FALSE	0.017272	0.388261	FALSE	0.00151	0.659191	FALSE	0.001774	0.488235	FALSE								
3		0.164526	TRUE	0.037929	0.147183	FALSE	0.017161	0.293623	FALSE	0.005862	0.633294	FALSE	0.030713	0.359505	FALSE	0.001404	0.919412	FALSE	0.001351	0.261063	FALSE								
4		0.089711	TRUE	0.038818	0.064644	FALSE	0.019329	0.000211	TRUE	0.030503	0.637180	FALSE	0.044077	0.734903	FALSE	0.002072	0.153535	FALSE	0.001168	0.309369	FALSE								
5		0.028181	TRUE	0.032188	0.157416	FALSE	0.028033	0.320774	FALSE	0.005023	0.293197	FALSE	0.011593	0.064772	FALSE	0.001593	0.686931	FALSE	0.001687	0.888165	FALSE								
6		0.1615351	TRUE	0.039962	0.908203	FALSE	0.022563	0.759247	FALSE	0.005468	0.872074	FALSE	0.016681	0.462747	FALSE	0.001698	0.547241	FALSE	0.001582	0.273289	FALSE								
7		0.180264	TRUE	0.029274	0.861132	FALSE	0.022464	0.298718	FALSE	0.005053	0.001108	FALSE	0.042883	0.02054	FALSE	0.001308	0.313868	FALSE	0.001864	0.447466	FALSE								
8		0.1487982	TRUE	0.037284	0.616256	FALSE	0.051118	0.844128	FALSE	0.0051	0.047578	FALSE	0.035916	0.751909	FALSE	0.001412	0.450088	FALSE	0.001485	0.474466	FALSE								
9		0.1819248	TRUE	0.038999	0.584616	FALSE	0.048132	0.934128	FALSE	0.00528	0.730888	FALSE	0.034113	0.252348	FALSE	0.001891	0.850553	FALSE	0.001832	0.048071	FALSE								
10		0.1440448	TRUE	0.023913	0.004096	FALSE	0.038755	0.007393	FALSE	0.005948	0.831428	FALSE	0.028768	0.188444	FALSE	0.001698	0.206044	FALSE	0.001138	0.909848	FALSE								
11		0.081193	TRUE	0.023106	0.553216	FALSE	0.026523	0.23505	FALSE	0.005127	0.699132	FALSE	0.048883	0.153007	FALSE	0.001718	0.629632	FALSE	0.001269	0.689819	FALSE								
12		0.1897	TRUE	0.031196	0.868024	FALSE	0.054118	0.504188	FALSE	0.005178	0.334787	FALSE	0.030652	0.458727	FALSE	0.001888	0.874826	FALSE	0.001392	0.032729	FALSE								
13		0.030383	TRUE	0.026208	0.252813	FALSE	0.032682	0.169051	FALSE	0.005395	0.334753	FALSE	0.011662	0.379503	FALSE	0.001298	0.621068	FALSE	0.001884	0.023441	FALSE								
14		0.138751	TRUE	0.033027	0.332754	FALSE	0.02314	0.831698	FALSE	0.005813	0.147442	FALSE	0.037038	0.936332	FALSE	0.001308	0.681113	FALSE	0.001292	0.038122	FALSE								
15		0.1968077	TRUE	0.020227	0.037335	FALSE	0.022172	0.031623	FALSE	0.005827	0.823158	FALSE	0.025598	0.025342	FALSE	0.001344	0.050233	FALSE	0.001644	0.823054	FALSE								
16		0.1409738	TRUE	0.029174	0.819178	FALSE	0.025068	0.038918	FALSE	0.005512	0.023307	FALSE	0.025473	0.569998	FALSE	0.001888	0.789778	FALSE	0.001157	0.328918	FALSE								
17		0.0284883	TRUE	0.030527	0.78983	FALSE	0.048447	0.9411918	FALSE	0.0059	0.708211	FALSE	0.016108	0.152444	FALSE	0.001341	0.162828	FALSE	0.001341	0.109904	FALSE								
18		0.1531178	TRUE	0.030514	0.157795	FALSE	0.042089	0.084318	FALSE	0.005654	0.509975	FALSE	0.027459	0.612517	FALSE	0.001902	0.919709	FALSE	0.001397	0.010852	FALSE								
19		0.0868821	TRUE	0.031384	0.030849	FALSE	0.031794	0.816263	FALSE	0.005818	0.796134	FALSE	0.535971	0.467909	TRUE	0.00143	0.567909	FALSE	0.002397	0.217751	FALSE								
20		0.1700873	TRUE	0.031969	0.253862	FALSE	0.051828	0.208561	FALSE	0.005017	0.961254	FALSE	0.018247	0.879093	FALSE	0.001252	0.132074	FALSE	0.001485	0.640793	FALSE								
21		0.1602628	TRUE	0.037719	0.277008	FALSE	0.019508	0.666003	FALSE	0.005093	0.755719	FALSE	0.034762	0.426984	FALSE	0.001998	0.814802	FALSE	0.001847	0.477229	FALSE								
22		0.1145777	TRUE	0.03145	0.770795	FALSE	0.054999	0.19095	FALSE	0.00576	0.78546	FALSE	0.045764	0.613729	FALSE	0.001601	0.814802	FALSE	0.001659	0.224398	FALSE								
23		0.080829	TRUE	0.03982	0.654665	FALSE	0.049919	0.068108	FALSE	0.00552	0.378012	FALSE	0.042187	0.482391	FALSE	0.001888	0.973998	FALSE	0.001888	0.848235	FALSE								
24		0.1644344	TRUE	0.029108	0.61113	FALSE	0.027592	0.978468	FALSE	0.005801	0.830825	FALSE	0.027473	0.969101	FALSE	0.001909	0.916952	FALSE	0.001298	0.277931	FALSE								
25		0.1499648	TRUE	0.024968	0.751209	FALSE	0.05143	0.801888	FALSE	0.005542	0.189183	FALSE	0.038683	0.877	FALSE	0.001847	0.242721	FALSE	0.001178	0.539679	FALSE								
26		0.1216953	TRUE	0.026661	0.89977	FALSE	0.022289	0.54881	FALSE	0.005232	0.320881	FALSE	0.005251	0.591825	FALSE	0.001847	0.483091	FALSE	0.001692	0.177799	FALSE								
27		0.1989583	TRUE	0.022263	0.732416	FALSE	0.038919	0.770748	FALSE	0.005017	0.291262	FALSE	0.024165	0.482031	FALSE	0.001503	0.764197	FALSE	0.001392	0.212944	FALSE								
28		0.1202181	TRUE	0.022286	0.177917	FALSE	0.048833	0.01578	FALSE	0.005886	0.688339	FALSE	0.022271	0.81184	FALSE	0.001422	0.179102	FALSE	0.001771	0.518903	FALSE								
29		0.189884	TRUE	0.03174	0.897834	FALSE	0.049816	0.264612	FALSE	0.005957	0.50684	FALSE	0.049522	0.882394	FALSE	0.001847	0.873084	FALSE	0.001927	0.914123	FALSE								
30		0.192358	TRUE	0.035578	0.468418	FALSE	0.047407	0.990643	FALSE	0.00552	0.659683	FALSE	0.019858	0.901784	FALSE	0.001378	0.568601	FALSE	0.001328	0.474687	FALSE								
31		0.1162918	TRUE	0.022677	0.290956	FALSE	0.037887	0.389323	FALSE	0.001742	0.710516	FALSE	0.018487	0.625281	FALSE	0.001808	0.173238	FALSE	0.001725	0.234462	FALSE								
32		0.1524558	TRUE	0.03647	0.878988	FALSE	0.051478	0.18111	FALSE	0.005925	0.704944	FALSE	0.005186	0.718957	FALSE	0.00113	0.859532	FALSE	0.001891	0.409198	FALSE								
33		0.1568138	TRUE	0.02584	0.558997	FALSE	0.036317	0.907534	FALSE	0.005778	0.493028	FALSE	0.044588	0.028088	FALSE	0.00102	0.196785	FALSE	0.001395	0.548488	FALSE								
34		0.179007	TRUE	0.034716	0.179204	FALSE	0.035824	0.300717	FALSE	0.005844	0.848288	FALSE	0.024199	0.101171	FALSE	0.001713	0.246881	FALSE	0.001485	0.271574	FALSE								
35		0.127799	TRUE	0.038211	0.060206	FALSE	0.039585	0.609781	FALSE	0.005682	0.764821	FALSE	0.029773	0.340893	FALSE	0.001927	0.498937	FALSE	0.001683	0.89951	FALSE								
36		0.188761	TRUE	0.026257	0.165446	FALSE	0.028603	0.078188	FALSE	0.00523	0.37116	FALSE	0.028191	0.048171	FALSE	0.001983	0.750313	FALSE	0.001485	0.185408	FALSE								
37		0.13198	TRUE	0.039507	0.237542	FALSE	0.039862	0.975342	FALSE	0.005943	0.395244	FALSE	0.046691	0.881633	FALSE	0.001989	0.12461	FALSE	0.001245	0.800718	FALSE								
38		0.1894431	TRUE	0.03821	0.821718	FALSE	0.03821	0.821718	FALSE	0.005943	0.395244	FALSE	0.04679	0.818003	FALSE	0.001989	0.12461	FALSE	0.001245	0.800718	FALSE								
39		0.167453	TRUE	0.035783	0.87345	FALSE	0.03784	0.25618	FALSE	0.005954	0.035512	FALSE	0.048209	0.614064	FALSE	0.00143	0.84238	FALSE	0.00145	0.76289	FALSE								
40		0.1669214	TRUE	0.038826	0.021678	TRUE	0.016123	0.453886	FALSE	0.005526	0.189852	FALSE	0.001977	0.519882	FALSE	0.001977	0.519882	FALSE	0.001977	0.805273	FALSE								

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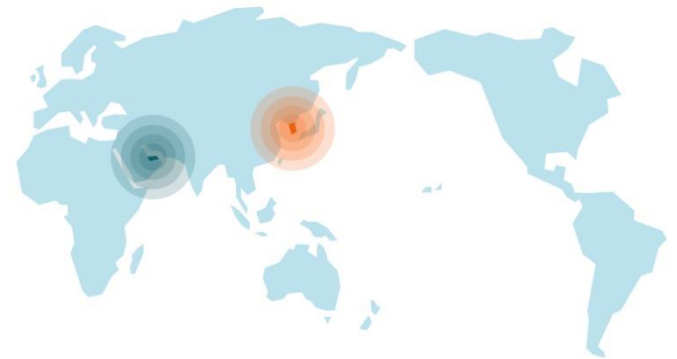
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