Threat Analysis for the Transport of Radioactive Material

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The Swedish Nuclear Power Inspectorate (SKI) is responsible for the supervision of the transport of nuclear material and nuclear waste, and also authorization for the transport of nuclear material. SKI is also responsible for preparedness planning as concerns antagonistic threats to these transports. It is therefore important for SKI to have a comprehensive picture of potential threats, of weak points along the chains of transport, and of different measures that can be taken in order to prevent or mitigate antagonistic actions.

In 2004, SKI commissioned a pilot-study to investigate the conditions for a revised set of regulations regarding physical protection for the transport of radioactive material. The pilot-study was to develop a model by which a comprehensive threat analysis could be carried out. For this purpose, a working group was formed, representing a wide range of competencies, including staff from the Nuclear Power Inspectorate, the Swedish Maritime Administration, the National Criminal Investigation Board and the Swedish Defence Research Agency. The group met in a series of structured workshops employing the non-quantified modelling method *morphological analysis*. The workshops were facilitated by the author.

Method

A threat analysis concerning the physical protection of transports involving radioactive material (nuclear fuel, nuclear waste and other radioactive substances) is a complex area of study involving a number of disparate, non-quantifiable factors. These factors involve, for instance, technical, organisational, political, ethical and national security issues, and must be approached on the basis of expert judgements and evaluations. For this reason, FOI was commissioned by SKI to employ computer-aided *morphological analysis*, which is a flexible, non-quantified modelling method developed at FOI during the 1990s. Morphological analysis is especially useful for the initial structuring of very complex socio-technical issues when there is limited time and resources.

General morphological analysis (GMA) was developed by Fritz Zwicky - the Swiss-born astrophysicist and aerospace scientist based at the California Institute of Technology (CalTech) - as a method for structuring and investigating the total set of relationships contained in multi-dimensional, non-quantifiable, problem complexes (Zwicky 1966, 1969).

Zwicky applied this method to such diverse fields as the classification of astrophysical objects, the development of jet and rocket propulsion systems, and the legal aspects of space travel and colonization. He founded the Society for Morphological Research and advanced the "morphological approach" for some 40 years, between the early 1930's until his death in 1974.

More recently, morphological analysis has been applied by a number of researchers in the USA and Europe in the fields of policy analysis and futures studies (Rhyne 1995, Coyle 1996, Ritchey 1997-2006). In 1995, advanced computer support for GMA was developed at the Swedish Defence Research Agency (Ritchey, 2003). This has made it possible to create non-quantified inference models, which significantly extends MA's functionality and areas of application. Since then, some 80 projects have been carried out using computer aided morphological analysis, for structuring complex policy and planning issues, developing scenario and strategy laboratories, and analyzing organizational and stakeholder structures.

GMA goes through a number of iterative steps or phases which represent cycles of analysis and synthesis – the basic method for developing (scientific) models (Ritchey, 1991). The analysis phase begins by identifying and defining the most important dimensions of the problem complex to be investigated. Each of these dimensions is then given a range of relevant values or conditions. Together, these make up the variables or parameters of the problem to be structured. A morphological field is constructed by setting the parameters against each other, in parallel columns, representing an n-dimensional configuration space (See Figure 1, below). A particular constructed "field configuration" (morphotype) is designated by selecting a single value from each of the variables. This marks out a particular state or (formal) "solution" within the problem complex.

Ideally, one would examine all of the configurations in the field, in order to establish which of them are possible, viable, practical, interesting, etc., and which are not. In doing so, we mark out in the field a relevant "solution space". The solution space of a Zwickian morphological field consists of the subset of configurations, which satisfy some criteria – one of which is *internal consistency*. However, a typical morphological field of 6-10 variables can contain between 50,000 and 5,000,000 formal configurations, far too many to inspect by hand. Thus, the next step in the analysis-synthesis process is to examine the internal relationships between the field parameters and *reduce* the field by identifying, and weeding out, all mutually contradictory conditions.

This is achieved by a process of *cross-consistency assessment* (CCA). All of the parameter values in the morphological field are compared with one another, pair-wise, in the manner of a cross-impact matrix (Figure 2). As each pair of conditions is examined, a judgment is made as to whether – or to what extent – the pair can coexist, i.e. represent a consistent relationship. Note that there is no reference here to direction or causality, but only to mutual consistency. Using this technique, a typical morphological field can be reduced by up to 90 or even 99%, depending on the problem structure.

There are two principal types of inconsistencies involved here: purely logical contradictions (i.e. those based on the nature of the concepts involved); and empirical constraints (i.e. relationships judged be highly improbable or implausible on empirical grounds). Normative constraints can also be applied, although these must be used with great care, and clearly designated as such.

Who ?	Objective	Do what ?	Where ?	Type of radioactive material
Individual	Revenge	Stop the transport	Sea	Plutonium
Small group (<8), no insider	Influence opinion	Steal the transport as a whole	Road	Uranium, fissile and irradiated
Small group (<8), with insider	Economic profit	Steal the cargo	By air	Uranium, fissile, not irradiated
Large group (>8), no insider	Political press	Demolish/burn	Railway	Waste with fissile material
Large group (>8), with insider	Extortion			Waste without fissile material
	Create confusion			Raw material/ semi-produce

Figure 1: Example of a threat model with one" threat profile" highlighted.

		Who ?					Objective						Do what ?				Where			
		Individual	Small group (<8), no insider	Small group (<8), with insider	Large group (>8), no insider	Large group (>8), with insider	Revenge	Influence opinion	Economic profit	Political press	Extortion	Create confusion	Stop the transport	Steal the transport as a whole	Steal the cargo	Demolish/burn	Sea	Road	By air	Railway
Objective	Revenge																			
	Influence opinion																			
	Economic profit																			
	Political press																			
	Extortion																			
	Create confusion																			
Do what ?	Stop the transport																			
	Steal the transport as a whole																			
	Steal the cargo																			
	Demolish/burn																			
Where	Sea																			
	Road																			
	By air																			
	Railway																			
Type of radioactive material	Plutonium																			
	Uranium, fissionable and irradiated																			
	Uranium, fissionable, not irradiated																			
	Waste with fissionable material																			
	Waste without fissionable material																			
	Raw material/ semi-produce																			

Figure 2. Cross-consistency matrix for the threat model (Figure 1).

When the solution (or outcome) space is synthesized, the resultant morphological field becomes an inference model, in which any parameter (or multiple parameters) can be selected as "input", and any others as "output". Thus, with computer support, the field can be turned into a laboratory with which one can designate initial conditions and examine alternative solutions.

The morphological approach has several advantages over less structured approaches. Zwicky called MA “totality research” which, in an “unbiased way attempts to derive all the solutions of any given problem”. It may help us to discover new relationships or configurations, which may not be so evident, or which we might have overlooked by other – less structured – methods. Importantly, it encourages the identification and investigation of boundary conditions, i.e. the limits and extremes of different contexts and factors.

The method also has definite advantages for scientific communication and – notably – for group work. As a process, the method demands that parameters, conditions and the issues underlying these be clearly defined. Poorly defined concepts become immediately (and embarrassingly) evident when they are cross-referenced and assessed for internal consistency.

Threat analysis for nuclear transports

The *focus question* developed by the subject specialist group was the following:

“What are the most important factors involving the transport of nuclear material and nuclear waste , as concerns conditions and regulations for protective measures, and how do these factors relate to each other?”

We began by developing a number of provisional morphological fields in order to get a common perspective on the problem area. (Please note: the fields and models presented in this paper do not represent the full scope of the models developed for the Swedish Nuclear Power Inspectorate. The parameters have been altered in order protect sensitive information.) The first four fields developed concerned:

- General threat situations (figure 1, above)
- Transport situations
- Actor scenarios
- Strategic measures

These fields were then condensed into a single 8-dimensional model which integrated *what can happen* with *suitable preventive measures* (Figure 3). Had we been carrying out a full, comprehensive threat analysis, instead of a “proof-of-principle” pilot study, we would have concentrated in developing this model. However, with the limited time available, we applied the following arguments, in order to reduce the size and complexity of the model.

- The *aim* or *purpose* of a particular antagonistic action against a nuclear transport is certainly of interest for the purpose of intelligence gathering, but is not of great importance for the present study. At this point, we are primarily interested in *what* possible antagonistic actions can be carried out against a transport, not why they are carried out.

- Likewise, a detailed description of the actors involved is not required for this preliminary study.
- Eventually, it will be important to designate high risk vs. low risk transports, depending on the nature of the materials being transported and how they are transported. However, in the present study, this need not be an important parameter. We wish to investigate the protection of transports of radioactive materials *in general*, irrespective of how dangerous the material is considered to be. Which types of transports are to be considered "high risk", and therefore warrant "maximum protection", is a later policy issue.
- We found that the "information parameters" ("Information about the transport" and "Who gets information") had little influence on the other parameters. We also found that there is a major conundrum concerning such information, and decided to leave this factor to a later – dedicated – investigation.

Thus, the most important contexts for the present study – given limited time and resources – were the following:

1. Where is the material in the transport chain?
2. What actions can be "perpetrated" against the transport at each step in a transport chain?
3. What different measures can be applied in order to protect and/or mitigate the transport against such actions, at each transport step?

Transport situation	Where is the cargo in the transport chain ?	Actor/threat	Does what ?	Information about the transport	Who gets information	Physical protection/ technical measures	Administrative routines and measures
Import of UF_6	Onboard Swedish merchant vessel (open water)	Terrorist group	Destroy	Info on physical protection	Sender	Heavily armed escort	Limit the quantity of cargo
Spent fuel to storage	Onboard Swedish INF vessel (open water)	Organised crime	Highjack the whole transport	Advanced transport notification	Receiver	Lightly armed escort	Limit the number of people involved
Transit EU-to-EU country	Merchant vessel on way in or out of Swedish port	Organised nuclear power protesters	Steal the whole transport (when unattended)	Info on transport authorization	Carrier	Unarmed escort	Upgrade route planning
Import of fresh MOX	INF vessel on way in or out of Swedish port	General environmental activists	Rob the cargo	Dangerous goods documentation	Forwarding (shipping) agent	Hardened/attack protected vehicle	Upgrade personnel monitors
Fresh nuclear fuel to NPP	Loading/Unloading in port (not specially protected areas)	Lone "revenger"	Steal the cargo (when unattended)	Commercial information	Local authorities	Hardened/ protected container	Increased measures for secrecy
Swedish vessel outside of Sweden	Loading/Unloading in port (in specially protected areas)		Stop/hinder the transport	Goods and vehicle labelling	Regional authorities	Basic-level protection	Transponder
Nuclear waste for treatment	Temporary storage in port area			No information	Nuclear Power Inspectorate		Basic level routines
MTR fuel	Road transport				Radiation Protection Agency		
	Rail transport				Police		
	Planned stop during road transport				Customs		
	Unplanned stop during road transport				Foreign authorities		
	Arrival to/ departure from nuclear facility						

Figure 3. Eight-dimensional integrated model (slightly altered from original).

The prototype "proof-of-principle" model

The prototype model consists of four parameters, as shown in Figure 4. These were subjected to a cross-consistency assessment (CCA), where the following *assessment keys* were applied:

"— " = This pair of conditions can co-exist, i.e. the is no contradiction.

"X" = This pair of conditions cannot co-exist, i.e. they are contradictory (for instance, the measure "Seal off the geographical area" is not consistent with the transport instance of "Aboard a Swedish merchant vessel (open water)".

"K" = This pair of conditions can co-exist, but is either highly improbable or, for other reasons, uninteresting for the study.

Transport step: where is the cargo in the transport chain?	What is the transport subjected to ?	Level of physical protection/technical measures	Administrative routines and measures
Onboard Swedish merchant vessel (open water)	Destroy	Police guard/escort	Increased secrecy
Onboard Swedish INF vessel (open water)	Highjack the entire transport (when attended)	Unarmed escort	Up-graded trustworthiness checks on personnel
Merchant vessel on way in or out of Swedish port	Steal the entire transport (when unattended)	Continual surveillance of vehicle and cargo	Up-graded admittance controls
INF vessel on way in or out of Swedish port	Rob the cargo (when attended)	Seal off geographical area	Limit the number of people involved
Loading/unloading in port (not in special protected areas)	Steal the cargo (when unattended)	Rapid police mobilisation	Protected parking areas
Loading/unloading in port (in special protected areas)	Stop/hinder the transport	Hardened/attack protected vehicle	Up-graded delivery supervision
Temporary storage in port area		Hardened/ protected containers	Present SKI levels
Road transport		Present SKI levels	
Rail transport			
Planned stop during road transport			
Unplanned stop during road transport			
Arrival to/ departure from nuclear facility			

Figure 4: Prototype model for proof-of-principle (altered slightly from the original).

When the morphological field is compiled into an inference model, all configurations which contain internal contradictions (one or more "X"s) are deleted from the solution space. Configurations containing one or more "K"s are left in the solution space, but but can be toggled on and off.

The model can be examined in the following way:

1. Select a "Transport step": for example, left-click on "*Planned stop during road transport*" (Figure 5)

2. Under parameter "What is the transport subjected to?" are those *general actions* which the working group judged to be the most likely or credible for the selected transport step.

3. Select one of these actions, e.g. "Demolish/burn" (Figure 6)

4. The measures which are judged to be most relevant for the selected transport step and selected actions are shown in the blue cells on the right.

Transport step: where is the cargo in the transport chain?	What is the transport subjected to ?	Level of physical protection/technical measures	Administrative routines and measures
Onboard Swedish merchant vessel (open water)	Destroy	Police guard/escort	Increased secrecy
Onboard Swedish INF vessel (open water)	Highjack the entire transport (when attended)	Unarmed escort	Up-graded trustworthiness checks on personnel
Merchant vessel on way in or out of Swedish port	Steal the entire transport (when unattended)	Continual surveillance of vehicle and cargo	Up-graded admittance controls
INF vessel on way in or out of Swedish port	Rob the cargo (when attended)	Seal off geographical area	Limit the number of people involved
Loading/unloading in port (not in special protected areas)	Steal the cargo (when unattended)	Rapid police mobilisation	Protected parking areas
Loading/unloading in port (in special protected areas)	Stop/hinder the transport	Hardened/attack protected vehicle	Up-graded delivery supervision
Temporary storage in port area		Hardened/ protected containers	Present SKI levels
Road transport		Present SKI levels	
Rail transport			
Planned stop during road transport			
Unplanned stop during road transport			
Arrival to/ departure from nuclear facility			

Figure 5.

Transport step: where is the cargo in the transport chain?	What is the transport subjected to ?	Level of physical protection/technical measures	Administrative routines and measures
Onboard Swedish merchant vessel (open water)	Destroy	Police guard/escort	Increased secrecy
Onboard Swedish INF vessel (open water)	Highjack the entire transport (when attended)	Unarmed escort	Up-graded trustworthiness checks on personnel
Merchant vessel on way in or out of Swedish port	Steal the entire transport (when unattended)	Continual surveillance of vehicle and cargo	Up-graded admittance controls
INF vessel on way in or out of Swedish port	Rob the cargo (when attended)	Seal off geographical area	Limit the number of people involved
Loading/unloading in port (not in special protected areas)	Steal the cargo (when unattended)	Rapid police mobilisation	Protected parking areas
Loading/unloading in port (in special protected areas)	Stop/hinder the transport	Hardened/attack protected vehicle	Up-graded delivery supervision
Temporary storage in port area		Hardened/ protected containers	Present SKI levels
Road transport		Present SKI levels	
Rail transport			
Planned stop during road transport			
Unplanned stop during road transport			
Arrival to/ departure from nuclear facility			

Figure 6.

Any parameter in a morphological model can be employed as the primary *driver*. One can thus start by selecting "Level of physical protection/technical measures" in order to see which transport steps and actions are most relevant (Figure 7).

Transport step: where is the cargo in the transport chain?	What is the transport subjected to ?	Level of physical protection/technical measures	Administrative routines and measures
Onboard Swedish merchant vessel (open water)	Destroy	Police guard/escort	Increased secrecy
Onboard Swedish INF vessel (open water)	Highjack the entire transport (when attended)	Unarmed escort	Up-graded trustworthiness checks on personnel
Merchant vessel on way in or out of Swedish port	Steal the entire transport (when unattended)	Continual surveillance of vehicle and cargo	Up-graded admittance controls
INF vessel on way in or out of Swedish port	Rob the cargo (when attended)	Seal off geographical area	Limit the number of people involved
Loading/unloading in port (not in special protected areas)	Steal the cargo (when unattended)	Rapid police mobilisation	Protected parking areas
Loading/unloading in port (in special protected areas)	Stop/hinder the transport	Hardened/attack protected vehicle	Up-graded delivery supervision
Temporary storage in port area		Hardened/ protected containers	Present SKI levels
Road transport		Present SKI levels	
Rail transport			
Planned stop during road transport			
Unplanned stop during road transport			
Arrival to/ departure from nuclear facility			

Figure 7.

Conclusions

Morphological analysis is based on the fundamental scientific method of alternating between analysis and synthesis. For this reason, it can be trusted as a useful, conceptual modeling method for investigating problem complexes, which cannot be treated by formal mathematical methods, causal modeling and simulation. We have found the method highly useful for the present study, which has allowed for a number of specific conclusions.

There are a number of possible, new and up-graded measures that can be taken in order to increase the safety and security of nuclear transports. It is especially interesting to attempt to identify those measures which would give the broadest effect for a given cost. By "broad effect" we mean that the measure should be efficacious for as many of the transport steps and actions as possible.

The morphological model revealed that the following three measures in the category *Level of physical protection/technical measures,* gave the broadest effect for conditions in Sweden:

1. Police guard/escort
2. Unarmed escort
3. Continual surveillance of vehicle and cargo

Both of the *escort measures* stand out as interesting alternatives, since there are some positive side effects associated with them. An escort could provide additional functions and thereby lead to safer, more secure transports. The escort could include a specialist in, for example, the nuclear material being transported and in radiation detection. This would be of benefit even in the case of a road or loading accident. Also, a standardised and institutionalised form of escort (whether armed or not) should lead to better routines for co-operation with police and rescue services, as well as better trained personnel.

As concerns the *Administrative routines*, the measures which provided the broadest effects were:

1. Increased secrecy
2. Up-graded security checks on personnel
3. Up-graded administrative controls

Another central aspect of the threat analysis – which was discussed during the working sessions but not included in the prototype model – was the potential ”dangerousness” of different transported nuclear substances. This concerns both the radiological consequences of an emission, and the potential consequences of the proliferation of nuclear material to other countries and actors. However, which types of transports are to be considered *high risk*, and therefore warrant special measures, is a policy issue which lies outside the scope of the present pilot study.

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