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CRITICALITY SAFETY BASIS FOR THE IAEA TRANSPORT REGULATIONS

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ABSTRACT

After PATRAM 2010, the IAEA initiated an ambitious effort to compile a technical basis document (TecBasDoc) covering the 2012 Edition of the Regulations for the Safe Transport of Radioactive Material (SSR-6). Radioactivity (including spontaneous fission) and criticality are the two identified hazards during transport that SSR-6 apply to. The objective of SSR-6 is nuclear criticality safety and radiation protection together. The scope of SSR-6 is movement of radioactive material, including fissile material, on various modes of transport (land, water, air), between nuclear sites. The radioactive material fits as a dangerous goods material (Class 7) into the international modal transport regulations.

Criticality safety is protection against harmful consequences of an energy release from a criticality accident, preferably by prevention of the accident. This paper focuses on criticality safety while another paper focuses on radiation protection. A third paper on the TecBasDoc effort covers package testing, which is important for demonstration of compliance both of radiation protection and of criticality safety.

The criticality safety provisions (requirements, options and specifications) of SSR-6 are add-ons to the radiation protection provisions. Practical concerns and safety concerns need to be covered in a transparent way (clear line between requirement at one end and objective and scope at the other end). The IAEA approach has basically worked well for more than 50 years. Experience and change industry needs have led to improvements (e.g. abandonment of the common Transport Index). The combination of criticality safety and radiation protection may still not be transparent to developers and users of SSR-6, e.g. radiation protection programme, excepted package, LSA-I, confinement system, and radioactive material.

The IAEA TecBasDoc effort has led to a compilation of many documents, most in an electronic format, to support conclusions on the basis for the current SSR-6. Previous provisions and some discussions on proposals are justified since they provide essential information and support preparation of future proposals. The paper presents criticality safety in chapter 11 of the TechBasDoc. It will reference another, thicker document that contains more details, discussions and quotes from original papers. Chapter 11 is intended to cover all aspects of criticality safety in transport. The subchapter headings are reflected in the chapters of this paper. They are introduction, objective, scope, safety culture, definitions, general requirements, performance standards, demonstration of compliance, authorization and approval, pre-shipment controls (including UN number assignment), transport including transit storage and references. Each paragraph in SSR-6 will be referred to at least once in chapter 11 of the TecBasDoc.

A lot more can be achieved. SSR-6 developers and users of can contribute to the quality of the TecBasDoc by providing additional information or by asking relevant questions, indicating missing information.

INTRODUCTION

The IAEA effort to create a technical basis document (TecBasDoc) essentially started in 2010 (in Paris), the week after PATRAM 2010. The project is described in a separate PATRAM 2013 paper [1]. The need for such a document has often been obvious during transport-related criticality safety design, evaluation, review and discussions as well as during review and revision of the IAEA Transport Regulations. The TecBasDoc covers the 2012 Edition of the Regulations (SSR-6) [2].

The effort to find informative documentation has included extensive and successful searches on the internet, in various archives and even in a museum. The IAEA archives produced a large number of old documents and correspondence. The substantial Modification 1 of the 1964 Edition of the Regulations was formally released by IAEA to be effective on 1st May 1966 [3]. It was found, without any reference, in the Swedish National Archives together with reports from the first two IAEA panels that met in 1959 to prepare the Transport Regulations. The documents are classified but have been made available to IAEA. Essential documents from the early development have also been found in the UK National Archives.

This paper will focus on (nuclear) criticality safety (in older documents sometimes referred to as nuclear safety), leaving radiation protection to the more general paper [1]. It turns out that there are probably not many paragraphs in SSR-6 without any criticality safety implication. Many paragraphs are written with radiation protection in mind but they can be modified or even interpreted to apply to criticality safety. The major reason for some incomplete texts is that the criticality safety provisions were added to existing radiation protection provisions (some always apply). This is a reasonable procedure since the vast majority of shipments of radioactive materials does not justify criticality safety control.

The separation of criticality safety and radiation protection can be seen as a fundamental technical basis for the Regulations. The hazard sources are fundamentally different. The traditional approach is also to separate the two disciplines from each other. This has been obvious in the IAEA history of development of the Transport Regulations. Even the initiation was split into two panels. One panel on small radioactive sources and another on large radioactive sources and criticality. The criticality safety specialists in that second panel were few and worked separately from others. This separation has continued and remains in practice today (informally). Other procedures have been attempted at some meetings but have not worked out well. The majority of people working with development and use of SSR-6 are neither radiation protection nor criticality safety specialists. The TecBasDoc is essential to support their work.

The structure of this paper follows the proposed criticality safety chapter 11 of the TecBasDoc. That chapter is intended to be a complete reference for criticality safety in transport. This means that some text in SSR-6 will be referred to both in criticality safety and in radiation protection TecBasDoc information. The structure is: Introduction (1), objective (2). scope (3), safety culture (4), definitions (5), general requirements (6), performance standards (7), demonstration of compliance (8), authorization and approval (9), pre-shipment (10), transport including transit storage (11) and finally references (12). Each paragraph in SSR-6 will be referred to at least once in chapter 11 of the TecBasDoc.

The paper highlights selected issues that have caused difficulties or that are special for other reasons. When paragraph numbers are presented, they refer to the 2012 edition of SSR-6.

OBJECTIVE

There are two hazard sources that require regulation: radioactive decay and energy release from a potential nuclear criticality. The title of the IAEA Safety Glossary [4] demonstrates the distinction: “Terminology Used in Nuclear Safety and Radiation Protection”. The objective of SSR-6 is to protect people and the environment from radioactive decay and from a criticality accident, preferably by prevention of the accident [5], without causing unacceptable side-effects (other hazards, perturbations of society, etc.).

A criticality accident results in an energy release, of which radiation is only a small fraction. This has been observed in such accidents but is better known from intentional applications such as nuclear weapons and nuclear fission reactors. Radiation protection may include the radiation consequences of a criticality accident and some of the emergency preparedness (and response if the accident did happen in transport) but this is not sufficient. Criticality safety accounts for nuclear safety in transport, including all potential consequences of an unintentional energy release from criticality and how to stop it.

A report on criticality accidents [6] includes at least one case (C-8), sometimes referred to as the SL-1 accident, with lethal consequences, due to kinetic movement of equipment and not to radiation. A quote by Fairbairn [7] reveals that the total energy release from criticality may have been an even larger concern when the Regulations were first introduced: “Because of emotive reaction to the “Atomic Bomb", considerable difficulty was experienced in the early 1960s in persuading transport organizations, e.g. RID, to adopt the prescriptions recommended for the Safe transport of fissile materials.”

Paragraph 104 of SSR-6 presents methods “how to” meet the objective. The radioactive decay hazard is accounted for by containment, protection from external radiation and protection from heat generated by radioactive decay. The criticality hazard is accounted for by prevention of the accident. It is essential that the objective of SSR-6 is evident to all people developing and applying SSR-6.

SCOPE

The scope is what SSR-6 applies to, what it regulates and what it intends to assure radiation protection and criticality safety for. The scope of SSR-6 does not include actions that are explicitly covered by the scope of other regulations. When there is doubt about whether an action is covered by more than one set of regulations, or none at all, the situation must be clarified.

The text in paragraph 106 appears to confuse the scope of SSR-6 with actions that are required to comply with SSR-6. Measurements of irradiated nuclear fuel are required by SSR-6 but such actions are not covered by its scope. Design, fabrication, repair and maintenance of packagings may even involve radioactive material but such activities are not within the scope of SSR-6 (except for minor modifications that are covered by normal conditions of transport or in approval certificates). SSR-6 may even contain requirements that are useful for safe operation at a nuclear site or during emergency response, without including such operations in the scope.

From the history of the IAEA Transport Regulations it is clear that the scope of SSR-6 includes type of dangerous goods (radioactive material, including fissile material) in an essentially complete package, modes of transport (land, water, air) and a clear distinction of what transport refers to (movement of radioactive material between nuclear sites, not within such sites).

SAFETY CULTURE OF IAEA

Introduction to safety culture as interpreted here

Safety culture is a very popular concept today. It is interpreted simply as “the way things are actually done here”, which agrees with the more formal definition in the Glossary [4]. The management organization involved is IAEA and the conclusions are based on the development and application of the Transport Regulations since 1959. Even though the term “safety culture” has not been used often during the history of the Transport Regulations, topics such as common sense, transport environment information, lessons-learnt, science, engineering, human factor consideration, philosophy, principles, standards, flexibility, transparency, clarity, simplicity, consistency, completeness, literal and subjective interpretations of requirements, etc. may be covered. The procedures for initiating, developing and maintaining the Transport Regulations belong to the safety culture category. The way problems and differences of opinion have been and are handled is an essential safety culture feature.

History of the IAEA Transport Regulations

Criticality safety was accounted for already from the beginning of the IAEA development of the Transport Regulations. Transport of nuclear fuel was the topic of a triggering proposal that became by IAEA accepted in 1958 [8]. The following quotes from published documents [9, 10] from 1962-1963 are supported by official IAEA documents [8, 11]:

Quote 1 [9]: “6. On 31st March, 1959, the United Nations Committee of Experts, …, recommended … that the I.A.E.A. be entrusted with the drafting of recommendations on the transport of radioactive substances, within the general principles of the Committee of Experts on the Transport of Dangerous Goods … This was endorsed on 17th July, 1959, by a Resolution of the Economic and Social Council of the United Nations.

7. This marks the date of the raising of the official United Nations umbrella under which I.A.E.A. activities in this field could be conducted, but the origin of the IAEA work came some months earlier. It was in the last quarter of 1958 that the Swedish Governor to the Agency proposed that a Working Party should be appointed to produce an IAEA manual on the transport of radioactive materials”.

Quote 2 [10]: “In 1959, a Swedish proposal was made that the I.A.E.A. should take the initiative to pull together the existing regulations, to distil the best from them and to produce a model set of regulations. … These two panels working diligently and quickly, produced two sets of regulations, one for the ores and isotopes and one for the fissile and larger materials. These were then welded together into the regulations which were published in 1961.”

The publication of SSR-6 in 2012 was preceded by at least ten meetings of criticality safety specialists in a few years. The result is improved provisions for shipping fissile material without being labelled as fissile in some cases and without requiring competent authority design approval in other cases. The improvement is more consistent safety, while the options have been expanded to solve some of the needs of the industry.

Nuclear criticality safety as a professional discipline

Nuclear criticality safety means [5] "Protection against the consequences of a criticality accident, preferably by prevention of the accident." Protection is the objective (what to achieve) while prevention is a method (how to meet the objective). Even though radiation has been the most harmful consequence of criticality accidents in the past, the much larger kinetic energy may be lethal [7] and cause other harm.

When the first edition of the Regulations was prepared, the prevention strategy was even stronger than today since the potential configurations and accident conditions (including criticality accidents with fast energy spectra and positive reactivity feedbacks) were not as easy to predict.

Later reviews and revisions of the Regulations demonstrate that criticality has not been ruled out as a potential consequence of a credible accident scenario. During the years preceding the 1985 edition of the Regulations, immersion below 15 metres of water and severe crush forces were considered for the performance standards. It was decided that containment of radioactivity in some cases justified consideration of such environmental influences while criticality safety did not. The 1996 edition of the Regulations added consideration of crush forces for criticality safety, partly to account for "moderate" air accident crush forces. The criticality safety of severe air accidents was accounted for in the 1996 edition only for individual packages without external moderation sources (rain, etc.).

The basis for these conclusions is that criticality is not allowed but efforts to prevent criticality at all costs would lead to unacceptable side-effects. Making packages even more robust, to survive deep sea immersion or high-speed air accidents without any significant criticality potential, would probably be more hazardous than the criticality consequences. The standards definition [5] of criticality safety as protection from the consequences, preferably by prevention, of the accident, is applied in the Regulations.

Structure of SSR-6

The detailed structure of the Regulations was modified about five years ago to simplify harmonization with international modal transport regulations. This process should continue. Other changes should be considered for clarity.

Section III should compile the general requirements further, including the nuclear safety aspects (energy release, not only in the form of radiation). Section V should refer to Section III to account for problems (including the human factor influence) that might not have been accounted for by complying with the performance standards.

Section IV is now headed "Classification and limits". It appears as if the limits are really definitions and are even used to define radioactive material in Section II and the scope of the Regulations. The pre-defined limits could be moved to Section II, in direct association with paragraph 236. Requirements to establish values that are not included in SSR-6 appear to be appropriate in Section VI (materials).

Pre-shipment requirements and actual transport requirements should be separated into two Sections. The pre-shipment requirements in Section V could be moved to Section IV. Section V could then be cleaned to only contain transport and transit storage requirements, while referring to other Sections as appropriate.

“What to do” versus “how to do it”, requirements versus guidelines and performance standards

The ambition for regulations (and for many standards) is that they should provide “what to do” requirements and not “how to do it” guidelines. This should not be confused with the need for regulations and standards to provide “how to do it” requirements (not guidelines). The “what to do” requirements should be equivalent to the overall objective and scope. The “how to do it” requirements should be transparent in the sense that the relationship with the overall objective and scope is clear. Various sets of “how to do it” requirements in SSR-6 are referred to here as performance standards.

Knowledge base

This topic covers all kinds of information, including nuclear data, methods to simulate neutron transport, critical experiments, critical excursion measurements, criticality accident experience, the transport environment, lessons-learnt from transport experience and from application of the Regulations, etc.

The TecBasDoc effort is an IAEA contribution to support the knowledge base. PATRAM and other conferences, as well as journals and other publications, provide means for sharing scientific knowledge but also for presenting more subjective views. IAEA is now collecting the most essential references in an electronic database to be made available to developers and users of the Regulations.

Establishment of confidence, stability, flexibility and common sense

Only experience can be used to determine if the goals of achieving confidence, stability, flexibility and common sense have been reached, so far. There have been very few serious transport accidents or near accidents involving serious harm from radioactivity. There have been no transport accidents leading to criticality. This demonstrate that the performance standards and the general requirements appear to work safely (but not necessarily efficiently).

The stability of the Regulations is often referred to as a reason for rejecting suggestions for improvement, even for direct correction of errors. That may sometimes be assigned to lack of information such as the TecBasDoc. Stability is something to strive for (unless it is stable chaos). Flexibility is also something to strive for but care is needed in complicated issues related to criticality safety. Temporary needs may encourage hasty solutions that have been rejected previously, for good reasons. Special arrangement provides flexibility but appears to be difficult to establish as a perfectly safe option. Common sense is always strived for, but it requires correct information and understanding to be relied upon.

The human factor – Positive and negative contributions

Influence by the human factor can never be completely accounted for by performance standards. It is essential to recognize that the human factor can also be a positive safety influence. Situations that appear not to be quite right by somebody, maybe without clear evidence of problems, sometimes turn out to involve real hazards. A recognized basis for the Regulations is that the performance standards do not necessarily account for all credible accident scenarios. The CSI method is known not to be validated and to have theoretical weaknesses. The competent authorities are expected to identify any realistic criticality hazard due to mixing of non-identical packages in the same configuration. This additional control is a recognized basis for acceptance of the CSI method.

The ALARA principle

The As-Low-As-Reasonably-Achievable (ALARA) principle is recognized in paragraph 301. Even though it is expressed in radiation protection terms, it is consistent with the criticality safety objective of protection against the consequences of a criticality accident, preferably by prevention of the accident.

Transparency, clarity, consistency

The objective and scope of SSR-6 should always be transparent when various requirements are prepared and interpreted. This may justify some cross-referencing, and even duplication, of requirements in SSR-6 to avoid missing an essential requirement. Some requirements should not be interpreted literally and this needs to be made clear. Some examples follow:

- The requirement for an infinite number of packages to be subcritical. Accounting for gravity would make that requirement complicated.
- The requirement for optimum moderation of fissile material. If not the moderating material is already present in the package, the requirement is intended to account for only ordinary water from the environment, not any other moderating material.
- The requirement for a 30 minute fire is intended to verify the predicted consequences from no fire at all up to the maximum length and temperature of the fire. The assumptions used in the criticality safety assessment shall account for the test results but shall not be dictated by them.

The lack of transparency in the definition of LSA-I, excepted package and radiation protection programme (and previously the containment system) have caused problems. It will probably continue to do so until the definitions are made clearer about the connections to criticality safety.

Responsibility

Responsibility for safety needs to be clearly assigned. The current paragraph 106 may be a source for confusion about the essential scope of SSR-6. There are examples from national regulations (e.g. Code of Federal Regulations, CFR, in the USA) where clarifications have been needed to specify what code shall be applied when multiple, conflicting codes otherwise would apply simultaneously. Delegation and acceptance of responsibility must be assured for all operations. Overlaps and gaps in requirements and regulations are significant sources of accidents and poor emergency response.

Graded approaches

The radioactive material, for criticality safety the fissile material, should be the first grade in retaining safety. When possible, the materials can be processed into forms that are simple to keep subcritical or to retain containment for. Radioactive sources may simply be allowed to decay to reduce their hazards. The packaging and the fitting of the packaging to the intended radioactive contents is the next grade. The third and final grade is the administrative controls required during transport to preserve safety. In criticality safety this is often a method that is given low priority since it is sensitive to human factor mistakes. It is interesting to note that the subcriticality of fissile-exceptions in the past has relied purely on the administrative accumulation control of fissile material, even when such a control has not been required.

Handling differences of opinion

The development of the Regulations has seen many controversial issues. For those of us who work or have worked with criticality safety, it is obvious that the source of many heated discussions and other communication problem has been the lack of transparent and correct information.

The most serious misunderstanding may be the handling of the 15 g fissile-exception option, initiated by the Woodcock & Paxton paper published in 1961 [12]. To the surprise of involved specialists, the first edition of the Regulations voided some of the essential conditions for the fissile-exception to be safe.

Formal and registered IAEA correspondence [13], during 1962 and 1963 between member states and IAEA, reveals that there were high barriers between criticality safety specialists and administrators responsible for drafting and publishing the Regulations. Similar barriers have been noticed later and can be seen even today. Without directly revealing the persons involved, the following quote is telling:

“A word about criticality specialists… Frankly, and I would emphasise that this is information for you on a personal basis, it would be extremely embarrassing for /the ABC organization/ to be asked to provide either Mr X or Mr Y for part of the March meeting. I remain firmly of the view that the Panel would be confused rather than helped by such explanation as a criticality specialist might provide.”

It appears as if the confusion had already set in and has continued ever since. There were other letters criticizing Mr X. Today, Mr X appears to have been right on spot with his criticized recommendations.

Consideration of interaction with other activities and hazards

IAEA has accounted for other concerns than radioactivity and criticality in relation to transport. This has been achieved both in the Regulations and in other documents, such as guides, and by conducting meetings. Potential problem areas but also potential benefits of coordination have been discussed. Examples of other considerations include influence of the radioactive material on other transported goods (e.g. photographic film), security, non-proliferation, third-part liability, preservation of the environment and information to the public.

DEFINITIONS

There are currently 49 separate definition paragraphs in SSR-6, with some containing several items. Definitions are needed to make SSR-6 clear and correct. Some of the definitions are not as clear as they could easily be. Often this is the case when a radiation protection term is applied to criticality safety as well. Specific comments have been made below for some selected definitions.

Containment system and confinement system

Before the confinement system was introduced in 1996, the containment system had a function that the confinement system was supposed to clarify. The containment system was required to be subcritical when flooded internally with water (unless there were multiple water barriers) and reflected by water. Some competent authorities found this awkward to specify.

The containment system shall consist of packaging components (paragraph 213). The containment function for radiation protection may be performed by the fuel rod cladding, a component of the contents. There would be then be no packaging components required. For the same package design, criticality safety may require a "strongback"; a structure to separate fuel assemblies and containing neutron absorber materials. If the whole strongback could be moved as one unit during loading and unloading of the contents, as well as under emergency conditions, it made sense to require the water-reflected, water-flooded strongback containing fuel assemblies to be subcritical.

The definition in paragraph 209 of the confinement system fails to catch the original intentions. They appear to have been lost, except in one country: the USA. The confinement system was not implemented there for national transport. It was considered to be redundant and the term was used for other purposes.

There is no technical basis for the current definition and the application in a few requirements is not implemented consistently neither with original intentions nor with the definition. This has been recognized at recent IAEA meetings.

Fissile material and radioactive material

SSR-6 has the objective to cover two very different hazards, radioactivity and nuclear criticality, based on what at first may appear to be only the radioactivity of the material. Radioactivity exists in all materials so the exemption values for a radioactive material may be set to account for the criticality hazard.

^{235}U is the only nuclide that could potentially result in a lower activity exception level for criticality safety than for radiation protection. In the past, the exemption value for ^{235}U may have approached what could perhaps have been a potential criticality hazard, accounting for the human factor, sampling errors, etc. In practice it is still unlikely to find uranium consisting of pure ^{235}U in transport. A small fraction of ^{234}U, historically expected to increase due to the enrichment process, dominates the radioactivity of uranium.

The criticality safety basis for the radioactivity exemption values for all nuclides appears to be acceptable.

LSA-I material, excepted package, radiation protection programme (RPP)

"LSA material" in paragraph 226 and "excepted package" in paragraph 230 are defined without any reference to or indication of criticality safety. LSA is related to the radiation hazard from a body intake of radioactive material. This is not typical for a criticality accident. The excepted package is defined as "package type", with the message that criticality safety is handled as an additional requirement.

Section IV prevents LSA-I material from being assigned as FISSILE. There is an additional criticality safety property of LSA-I material, not indicated by the definition. This applies also to excepted package that may be classified for any fissile material in Section IV but has no UN number for it. Section V prohibits an excepted package from carrying fissile material assigned as FISSILE. The RPP in paragraph 576 allows replacement of CSI control with some other accumulation control for criticality safety. There are also other applications where criticality safety needs to be covered in the RPP.

The dual purposes (radiation protection and criticality safety) of LSA-I material and excepted package have caused significant problems during the revision of the Regulations. The RPP needs to be clarified. The basis for these concepts should be better documented and their purposes reflected in their definitions.

GENERAL REQUIREMENTS

Section III of SSR-6 is headed “General provisions” but that text is not complete, in particular when criticality safety needs to be accounted for. Criticality safety is more than protection against radioactivity and even more than protection against radiation from criticality. Protection from the energy release associated with a criticality accident is required. It would be easy to expand from radiation protection to include nuclear safety in the text of Section III.

Paragraph 673(a) is essentially a general requirement but it is burdened with the “how to” requirement to prevent criticality in accident conditions of transport. Prevention is a method and not an absolute objective. This means that credible accident conditions for containment of radioactive material have to be assumed not credible accident conditions for subcriticality. This complies with the established criticality safety definition of protecting against the consequences of an energy release from a criticality accident, preferably by prevention of the accident. It requires flexibility in the view of accident conditions.

If the expected criticality consequences are very low, at least compared with other hazards, a credible criticality potential may be sufficiently acceptable not to require compliance with the typical criticality safety performance standards. Examples are immersion below 15 metres of water as well as severe aircraft accidents and crush forces (before 1996). Paragraph 673(a) still applies and may be interpreted such that criticality shall be prevented primarily by preventing severe airplane crashes and deep sea immersion of packages rather than trying to design the packages to be subcritical when such accidents occur.

PERFORMANCE STANDARDS

Performance standards in SSR-6 provide a basis for “how to comply” with the general “what to achieve” requirements. The performance standards for designs are found in Section VI, those for pre-shipment controls in Sections IV, parts of Section V and in Section VIII while those for the transport and transit storage operations are found in other parts of Section V. Demonstration of compliance with the performance standards, mainly for Section VI, is found in Section VII, see next chapter.

Compliance with performance standards is required but not necessarily sufficient for safe transport. The general requirements always need to be complied with. This may be particularly evident in criticality safety where one of the reasons for requiring multilateral approval is a need for each competent authority to consider “the full picture” on its territory.

Package design for fissile material

A package design is a combination of a fissile material design (including other components of the contents) and a packaging design. In a case where the packaging design is not accounted for, the fissile material design remains. There are package designs and material designs that require multilateral approval and others that are already authorized by specifications in SSR-6.

The basis for relying on designs is that demonstration of compliance and, when relevant, obtaining competent authority approval for each package to be transported in each environment is rarely a reasonable solution. The resulting cost of performance standards is sometimes an excessive conservatism, where the actual package configuration and transport environment cannot come anywhere near the accident conditions of transport.

Demonstration package designs for fissile material

Figure 1 represents an actual package design for fissile material from more than 50 years ago [14]. It was used (at the Hanford and Savannah River nuclear sites) for plutonium transport. It is shown here to demonstrate the technical basis for some performance standards in SSR-6.

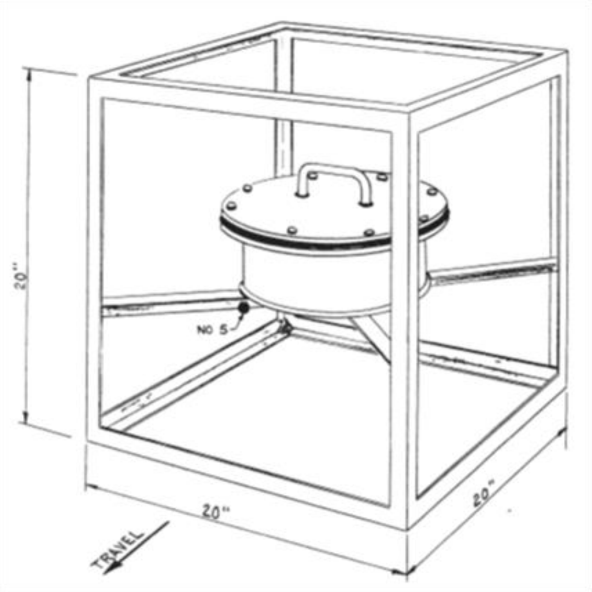

Figure 1. Birdcage plutonium package [4]

A birdcage type of design was seen as a typical US alternative 50 years ago. The typical UK alternative was based on prevention of strong neutron interaction between packages. Examples were included in early editions of the Regulations and typically included wood and cadmium.

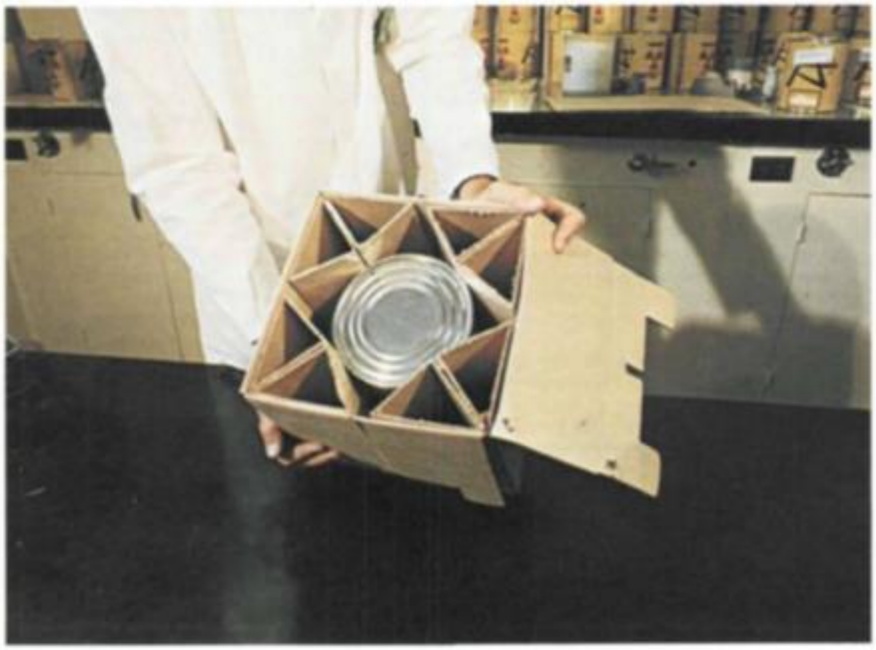

Figure 2. Type A package, including spacing (IAEA Bulletin Vol. 21, No. 6) [15]

Figure 2 shows a Type A package [15] that may demonstrate typical features of many fissile-excepted packages in the past. The inner container here could perhaps be a Type A package on its own and could have been constructed from polyethylene. The outer, cardboard packaging could perhaps be an Industrial Package Type I (Type IP-I) on its own. This package type could contain fissile-excepted materials of the "15 g fissile" type before the 2012 SSR-6 edition. It was not the package type envisioned when the Woodcock & Paxton paper [12] was published and first applied.

Uncertainties, irradiated nuclear fuel properties, dimensions and environmental temperature

Uncertainties in properties of the package contents require accounting for by paragraph 677. The location limits its application to package design. Such a requirement makes more sense in Section IV, together with UN number assignment and pre-shipment controls.

Irradiated nuclear fuel properties may be accounted for either by a peak reactivity method (maximum k_{eff} during credible irradiation) or by a burnup credit method. A general requirement for measurements to verify the actual burnup of the irradiated fuel was introduced in 1996, after significant discussion. It is not generally applied to burnup credit in transport. A requirement to verify the properties applies to all contents, not only irradiated fuel, and is a pre-shipment control. When justified, specific measurement requirements can be specified in competent authority approval certificates.

A 10 cm minimum external dimension of a package is required for radiation protection (prevent the package from being lost, surface to put labels on, etc.) but it is used directly to control subcriticality. This is a reason why paragraph 634 (radiation protection) applies to routine conditions while the criticality safety paragraph 678(a) applies to normal conditions as well. The origin of the 10 cm criticality safety requirement may be associated with the Woodcock & Paxton paper [12] used as a basis for the first edition of the Transport Regulations. The 10 cm minimum dimension assures some spacing and thus neutron leakage (good for criticality safety) from a finite array of packages.

Figure 1 indicates the influence of spacing for criticality safety. The "bird" appears to have about 10 cm minimum dimensions. Paragraph 678(b) requires that a package shall not allow the entry of 10 cm cube under normal conditions. The basis is that a small package shall not enter the envelope of another larger package. Figure 1 appears to contradict this requirement and would probably not be designed that way today. However, it is possible to accept larger than 10 cm openings if the spacing is not accounted for. The spacing structure in Figure 1 can then be accounted for in the tests to reduce damage to the bird but not in the calculation models of arrays of packages.

Until 1996, the Regulations were not quite clear on the environmental temperature range under which subcriticality shall be demonstrated. The range was specified for radiation protection purposes (Type B(U) package) but not for criticality safety.

Neutron moderation from sources external to the package

The basis for accounting for neutron moderation from sources external to the package includes other materials than water. Moderation from vehicle fuel materials was considered during the first development of the Regulations. Moderation from external materials such as graphite, heavy water, beryllium and polyethylene have also been discussed. The conclusions have been to limit the performance standards to pure, normal water. If a consignment is prepared or carried out under circumstances that make more exotic external source moderation credible, the general requirement in paragraph 673(a) applies.

Neutron reflection from sources external to the package

Neutron reflection from the surroundings (including other transported goods) of an individual package or an array of packages needs to be accounted for. Concrete and other materials have been known to be potentially better reflectors than ordinary water since the first development of the Regulations. Full water reflection (20 cm or more) was selected as the only source for the performance standards since it is present in many environments and can closely surround a package or an array of packages, something that does not apply to other credible reflectors. If a consignment is prepared or carried out under circumstances that make more exotic reflection conditions credible, the general requirement in paragraph 673(a) applies.

Subcriticality of an individual package

The requirements for an individual package are more severe than for each package in an array. The basis is that in a large number of packages one or a few may be "outliers", meaning that they are outside the specifications. The human factor is a significant source of such outliers. It has been considered too conservative to assume that all packages in an array are outliers.

Water leaking into or out of available spaces of an individual package in normal and accident conditions, even if tests show that this will not happen, accounts for the human factor. SSR-6 provides an option, applying multiple water barriers, not to consider moderation from the outside but it is not an easy option.

Neutron reflection of an individual package has become a problem, in particular since 1996 when the confinement system was introduced. The primary requirement is for subcriticality of the reflected package. As can be seen from Figure 1, flooding of the package causes better reflection than just reflection around its envelope. Flooding of the package in Figure 1 is essentially the same as flooding (drowning?) the "bird". This is required for accident conditions. Another term for the bird was usually the containment system (or vessel). The containment system was required to be subcritical when reflected by water. The packaging may contain a better reflector than water (e.g. lead or steel) and this is directly accounted for.

Earlier the Regulations required a specified maximum critical mass fraction, in the same shape as the containment system. The required degree of subcriticality is not specified in SSR-6.

There is a special advantage of requiring subcriticality for the containment system, including the fissile material. When such a unit can be, or even normally is, handled separately from other packaging components, the information can easily and reliably be applied to loading and unloading of the containment system with fissile material from the package, as well as to emergency response.

The containment system was not always easy to adapt to subcriticality requirements. The confinement system was intended to solve such concerns in 1996. It has not worked. The problems with the confinement system and the reflection requirements for an individual package justify revision of SSR-6.

Subcriticality of arrays of packages

The basis for having requirements both for normal and accident conditions is that the overall probability distribution of criticality occurrence should be balanced. The normal condition package array is larger than the accident condition array (5N compared with 2N). Other parameters are more extreme for accident condition arrays (accident condition packages, water moderation between packages). To achieve further balance, different neutron multiplication factor limits may be applied.

The factor 5N is not a normal condition of transport and neither is the array being close-packed and water-reflected. It accounts for extreme influences of the human factor. “Normal conditions” in paragraph 684 refer to the package and not to the array condition. That is not the case in paragraph 673(a).

Recent research into the early development (in particular the years 1959-1964) of the Regulations clarifies some of the complicated work and heated debates that occurred at that time. The factor 5N was originally applied to accident condition packages. Paragraph 15.2.2 of the 1961 edition required for Fissile Class II:

“In this class the number of packages which are allowed to be shipped together is so limited that a critical assembly would not be formed in any credible circumstances even if five times the allowable number were to collect together.”

This explains why 250 packages were included in the Woodcock & Paxton paper [12] for the fissile-exception cases. They were considered to be 5N accident condition packages (the maximum number of any packages with radioactive material per conveyance was assumed to be 50). The packagings were assumed to be Type B, preserving their dimensions and retaining their contents under accident conditions. Requirements for Fissile Class II packages in Annex II of the 1961 edition of the Regulations were based on the same 5N calculation model even though N varied.

The criticality safety specialists at the time had a long-term, balanced view for criticality safety in the Regulations. Other interests and views corrupted their plans (see text under safety culture above) and the result was a significant inconsistency in the generous requirements for fissile-exceptions. The assumed Type B packagings became IP-1 packages that were not even required to retain their contents under normal conditions of transport. Spacing arrangements and containment systems of steel that were relied on to survive accident conditions became polyethylene bottles with spacing arrangements of cardboard (compare Figure 2) that may not even survive the normal condition tests. Assumed limits of 50 packages per conveyance became a single overpack with no CSI value or FISSILE label. Such an overpack allowed more fissile nuclides per volume unit than a package based on an approved package design. The fissile material in the overpack could have optimum moderation under routine conditions.

Compliance with the performance standards is required but the general requirement of paragraph 673(a) is also required. Paragraphs 684 and 685 require 5N and 2N packages respectively to be subcritical but they are not requirements intended to be taken literally. They are intended to cover neutron interaction between packages, not actual stacking of packages (gravity). If e.g. the actual normal transport involves stacking of packages more than five levels high, paragraph 673(a) may require the configuration of more than five levels high to be subcritical also when accounting for gravity. If stacking of accident condition packages would be likely, paragraph 673(a) may require consideration of that as well.

Paragraph 685(c) was proposed by the author and accepted to be included in the 1996 edition of the Regulations. Similar proposals had been made earlier and temporarily accepted and then rejected. The reason is that it is an explanatory text of existing requirements, not a new requirement. An array of fissile material units that have escaped their packagings is still an array of packages (the fissile material is the main component of a package). To keep SSR-6 clean, the author proposes removal of paragraph 685(c). There is no technical basis for it as a separate requirement.

The CSI as a method for controlling subcriticality

The index method (CSI in SSR-6) applied for controlling subcriticality of arrays of units with fissile material has not been validated. Its range of applicability has never been properly evaluated by criticality safety specialists involved in the development of the Regulations. This has been clearly stated by several people at different times. The first editions of the Regulation contained a general requirement to account for "inter-mingling" of different types of packages. Some understanding of the potential problem was there from the beginning. The inter-mingling requirement was removed without any technical basis. The only suggested solution was to rely on multilateral approval to recognize any potential safety problem. The industry has not provided any alternatives.

The lack of validation of the CSI method is important to establish since people are known to have applied it to storage of fissile material at nuclear sites. The method may be significantly less safe at such sites if there are no packagings or equivalent neutron absorbing materials separating the fissile materials in different locations.

Fissile material designs intended for special purposes

Paragraph 606, new in SSR-6, allows a fissile material to be designed for special purposes. At this time those purposes are limited to a fissile material design that is essentially inherently subcritical. It requires multilateral approval and can be applied in paragraph 417(f) to avoid assignment as FISSILE. The principle of such materials had already been applied in paragraphs 417(a) and (b). The intended basis for this option is not quite clear, it seems to vary depending on who is asked. The actual implementation in SSR-6 indicates that it provides possibilities somewhere between a package design and special arrangement. The performance standards are weaker than for package designs. The competent authority is thus provided more flexibility.

Package designs included in SSR-6

There are a number of package designs in SSR-6 for which no further authorization by competent authorities are required for criticality safety purposes. The general criticality safety requirements, as well as the performance standards, are complied with for all these designs. The concept of an effectively infinite accumulation is essential. This means that the accumulation was not considered credible when the provision was introduced in the Regulations and that no need for revision has been considered justified.

- A basis for exempting material that is not defined as radioactive material in paragraph 236 is that such material cannot produce a criticality accident neither packaged nor unpackaged;
- Packaged radioactive materials are exempted as fissile materials in paragraph 222 if the packages contain less than 0.25 g of defined fissile nuclides, not including fissile nuclides in natural and depleted uranium that is either unirradiated or irradiated in a thermal neutron spectrum. The design relies on the assumption that the number of accumulated packages is limited to a few thousand, making the configuration effectively infinite while being subcritical under credible conditions;
- Packaged fissile materials with properties that make them essentially inherently subcritical under any conditions of transport (however, pre-shipment conditions need to be controlled). This includes designs specified in paragraphs 417(a) and (b).
- Packages with very small quantities of defined fissile nuclides per package (3.5 g ^{235}U for low-enriched uranium, 2.0 g fissile nuclides in other uranium or plutonium) and small quantities of fissile nuclides per consignment (45 g and 15 g respectively). These designs in paragraphs 417(c)

and (d) rely on the assumption that even an effectively infinite accumulation of consignments of such packages under credible conditions is not sufficient for criticality;

- Less than 45 g of defined fissile nuclides, unpackaged or packaged, in a consignment under exclusive use. Again, even an effectively infinite number of such consignments is considered subcritical under credible conditions. This option in paragraph 417(e) is the only option for shipping unpackaged fissile materials.
- The package designs specified in paragraphs 674 and 675 are essentially equivalent to package designs approved in multilateral approval certificates. A difference, besides the authorization method, is that the specific packaging identification is not specified. Demonstration of compliance of a few package properties (dimensions and containment under normal conditions) need to be made without competent authority approval.

Besides the assumptions on very low credibility for exceeding the design-basis accumulations, the human factor has been considered when specifying individual package limits.

Fissile-exception designs now removed or significantly revised

The TecBasDoc should contain information on previous provisions that have been removed and also about proposals that are still open for discussion or have been rejected. A purpose is to learn in general from the discussions and in particular to make the information available to people contemplating similar proposals.

The “15 g fissile exception” provision, introduced with the first edition of the Regulations and essentially still present, has undergone significant changes since it was first suggested in 1960. Paragraph 674(c) in SSR-6 is now closer to the original intent by Woodcock & Paxton than ever before. It was not intended to provide a lower criticality risk, even though it has been perceived that way. The SSR-6 implementation makes it clear that the exception is from competent authority approval, not from lower criticality safety control requirements. In fact, subcriticality relies almost entirely on administrative controls.

Drafts from 1962 and 1963 of the proposed 1964 edition of the Regulations reduced the fissile-excepted quantity from 16 g ^{235}U to 3 g of ^{235}U. This is confirmed both by IAEA documents and by publications, e.g. [16]. There are now many documents in the TecBasDoc collection that discuss the surprising lack of accumulation control of this past fissile-exception. It has been controversial since the beginning.

There are other fissile-exceptions that have been removed due to the lack of accumulation control, lack of consideration of compression (e.g. 5 g of fissile nuclides per 10 litres) and chemical concentration (diluted fissile nuclides). A major reason has often been the potential lack of safety in accident conditions, accounting for the human factor as well.

DEMONSTRATION OF COMPLIANCE WITH PERFORMANCE STANDARDS

Paragraphs 701 and 716 of SSR-6 essentially require that subcriticality shall be demonstrated. It is possible to use real transport packages with intended fissile material contents to demonstrate subcriticality under normal and accident conditions. Measurements of the critical mass (approach to critical) has been done to support the safety report for the package design S/23/B(M)F [17] used for transport of irradiated MTR fuel elements from Sweden to the USA during many years. A fraction of 80 % of the about 2850 g ^{235}U estimated critical mass was used to account also for burnup credit [17]. A single package with fresh water-flooded fuel would have become supercritical (3000 g ^{235}U).

Evaluation of critical experiments, with similar materials and configurations as in the normal and accident conditions of transport for a particular package design, can also be seen as some demonstration of compliance.

Fortunately, today the availability of sophisticated computers, software and data allow very accurate simulation of the neutron transport equation. Some of the engineering input data needs to be verified against the Section VII tests required by the performance standards in Section VI.

The normal and accident conditions of the performance standards for an individual package are to some extent specified in subparagraphs 684(b) and 685(b) for arrays. The paragraph numbers in Section VII may be the same for an individual package and for an array of packages, but the actual tests and resulting conditions of the individual package and of a package in an array may be very different. The application of the same paragraphs for radiation protection (Type A and Type B(U) packages) may also show significantly different results.

Section VI determines what tests are required to support the demonstration of compliance for different scenarios and both Sections VI and VII determine in what order sequential tests shall be carried out.

Tests to demonstrate normal conditions of transport

The paragraphs 719-724 contain tests that are used to verify some of the performance standards assessment for normal condition packages required in paragraphs 682(b) and 684(b). These tests are covered in another PATRAM paper [18]. The TecBasDoc should contain the basis why these tests are used to demonstrate criticality safety compliance for normal conditions of transport.

Tests to demonstrate accident conditions of transport

The paragraphs 727-737 contain tests that are used to verify some of the performance standards assessment for accident condition packages required in paragraphs 682(c), 683 and 685(b). These tests are covered in another PATRAM paper [18]. The TecBasDoc should contain the basis why these tests are used to demonstrate criticality safety compliance for accident conditions of transport.

AUTHORIZATION AND APPROVAL

Transport is authorized either directly by the Regulations or with additional support from a competent authority approval certificate. Section VIII contains requirements and specifications for when and how such approvals are obtained and what they shall contain.

Exemptions from approval requirements

The following optional paragraphs cover package designs for fissile material that are authorized by SSR-6 and do not require additional competent authority approval of their criticality safety design:

- Packaged fissile materials that are exempted in packages specified in paragraph 222;
- Packaged fissile material according to paragraphs 417(a)-417(f) (to apply paragraph 417(f) an applicable fissile material design must be multilaterally approved according to paragraph 806 previously) and that comply with the consignment conditions of paragraph 570;
- Unpackaged fissile material according to paragraphs 417(e) and 570;
- General package designs (unspecified packagings) according to paragraphs 674 and 675.

Competent Authority approval requirements

Multilateral approval is required for fissile material designs in paragraphs 806 and for package designs with fissile material in paragraphs 814-816. Special arrangements may require criticality safety approval. Shipment approval may be required when the total CSI exceeds 50 and exclusive use is applied. Transitional arrangement may also require approval. The Radiation Protection Programme may require criticality safety approval, e.g. for a special use vessel if the accumulation control based on CSI is not applied as specified in SSR-6. The definition of confinement system specifies that the competent authority shall agree to it (now redundant since the competent authority certificate shall contain this information).

PRE-SHIPMENT REQUIREMENTS

Selection of package design, consignment configuration and transport means are options that the consignor must decide on quite early. Pre-shipment requirements specified in Section IV (UN number assignment) and parts of Section V can be considered as performance standards for pre-shipment. General requirements as found in Section III and in paragraph 673(a) also apply.

Assignment of packaged fissile material as FISSILE

Paragraph 417 requires all packaged fissile material to be assigned a UN number as FISSILE, except for some options that are provided in the subparagraphs 417(a)-(f). Packages for which paragraphs 674 and 675 are applied require the same FISSILE assignment as packages for which competent approval certificates are applied. The FISSILE assignment is used to support administrative controls for criticality safety during normal transport as well as to support emergency preparedness.

Exceptions from requirement of assignment as FISSILE

Subparagraphs 417(a)-(f), together with paragraph 570, specify the conditions for a package in a specific consignment may be excepted from FISSILE assignment. The basis for the exception is that, assuming that the fissile material properties and quantities are adequately determined, no subcriticality control is needed and that emergency preparedness related to criticality safety is not needed.

Additional pre-shipment controls

Section V contains many additional pre-shipment requirements. The FISSILE labels and CSI values are essential for criticality safety. Compliance needs to be maintained and sometimes verified during transport. Pre-shipment controls may fit better in Section IV, together with the UN number assignments.

TRANSPORT AND TRANSIT STORAGE

This is the activity that the objective and scope of SSR-6 apply to. The previous activities may be required and often must be confirmed during transport and transit storage. Sometimes there are changes of the consignment during transport or transit storage. Paragraph 105 assures that criticality safety is obtained by compliance with SSR-6. Paragraph 307 requires the competent authorities to assure compliance with SSR-6. The general requirements, e.g. in Section III and in paragraph 673(a), need to be complied with during transport and transit storage.

Most of Section V can be seen as performance standards for transport and transit storage. Section V should focus on the actual transport requirements, moving the pre-shipment requirements to Section IV. Section V could then refer to maintenance and verification of pre-shipment controls, as appropriate. The consignments may change during transport, e.g. resulting in new total CSI values.

SUMMARY AND RECOMMENDATIONS

The TecBasDoc effort has resulted in an extensive set of references that can be used to reasonably objectively document the criticality safety basis for SSR-6. The early documentation from IAEA panels and correspondence with member states have turned out to be surprisingly applicable today. An essential information source has been the IAEA archives in Vienna. Unfortunately, the archives are not complete since the correspondence files usually include only letters but rarely attachments.

The 1959 panel meeting reports, as well as the 1966 formal Modification 1 to the 1964 edition of the Regulations were found only in the Swedish National Archives but were classified, causing significant complications. The UK National Archives have preserved many documents of value and some have been copied. A missing report from 1962 was found in the British Post Museum. The European Commission in Brussels submitted missing IAEA documents to the IAEA archives (translated into French).

IAEA documents from the last 40 years appear to have been preserved and found even though all are not available electronically.

The recommendation is to support the IAEA TecBasDoc effort to compile essential documentation and making it available in an electronic format. Still missing references have been identified during the TecBasDoc project. They include some of the IAEA panel reports and associated supportive UK reports. The UK National Archives are almost certain to have more of value. Archives in the USA and France may have preserved some of the documents and correspondence from that time. Participants in panels of the early period or their organizations, including the international modal transport organizations (e.g. RID and IATA), may also have preserved missing documents.

The TecBasDoc is proposed to have a single but complete chapter 11 on criticality safety in transport. This means that all aspects related to criticality safety should be covered since the other chapters focus on radiation protection. Duplication of information can be avoided by references to other chapters. Specialists on criticality safety in transport are recommended to contribute by checking, condensing and completing chapter 11. Differences of opinion may be best to document, rather than expressing majority conclusions.

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