The Evolution of Criticality Safety Regulations for the Transport of Radioactive Fissile Material in Certified Packages – 22181

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ABSTRACT

This paper[a] describes the evolution of regulatory controls on the transport of fissile radioactive materials that began in the middle of the last century, particularly with early efforts in the US, the UK, Canada, and France. International efforts in this respect began at the IAEA in 1957. This multi–national effort led to the IAEA issuing its first internationally recognized regulations for the *Transport Safety Regulations* in 1961, which was then identified as SS–6. Since then, the *Transport Safety Regulations* have been updated multiple times, with the latest version being issued in 2018 as IAEA Specific Safety Requirements-6 (SSR-6), *Regulations for the Safe Transport of Radioactive Material (2018 Edition)*. Supplementary guidance documents also have been issued by the IAEA over the years.

The *Transport Safety Regulations* have the objective of protecting the workers, the public and the environment by requiring, for routine, normal and accident conditions of transport: (a) containment of the radioactive contents of packages, (b) control of excessive dose rates external to packages, (c) prevention of criticality when the contents of the packages are designated as having fissile material (FM), and (d) the prevention of damage to the packages by heat. This is accomplished first by applying a graded approach and by imposing a robust set of conditions on the design, testing and operation of the packages.

As new generations enter the nuclear workforce, there is often a lack of understanding of the source and underlying logic behind the *Transport Safety Regulations*. To address this issue, Pacific Northwest National Laboratory (PNNL) initiated a knowledge management activity in 2020 to document the history and evolution of the *Transport Safety Regulations*. The knowledge management effort has two components. One component, which is discussed in this paper, covers the historical evolution of IAEA regulations related to the transport of fissile material (i.e., criticality safety) in certified transportation packages. The second component, which is discussed in a companion paper to be presented at this WM Conference, covers the evolution of the IAEA regulations related to the transport of non-fissile radioactive material in Type B and Type C certified transportation packages. Understanding the evolution of the IAEA's *Transport Safety Regulations* and their supplementary guidance documents is important

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[a] This is a technical paper that does not take into account contractual limitations or obligations under the Standard Contract for Disposal of Spent Nuclear Fuel and/or High-Level Radioactive Waste (Standard Contract) (10 CFR Part 961). For example, under the provisions of the Standard Contract, spent nuclear fuel in multi-assembly canisters is not an acceptable waste form, absent a mutually agreed to contract amendment.

To the extent discussions or recommendations in this paper conflict with the provisions of the Standard Contract, the Standard Contract governs the obligations of the parties, and this paper in no manner supersedes, overrides, or amends the Standard Contract.

This paper reflects technical work which could support future decision making by the U.S. Department of Energy (DOE or Department). No inferences should be drawn from this paper regarding future actions by DOE, which are limited both by the terms of the Standard Contract and Congressional appropriations for the Department to fulfill its obligations under the Nuclear Waste Policy Act including licensing and construction of a spent nuclear fuel repository.

because these regulations influence the development of the radioactive material transportation regulations in IAEA Member States, including in the U.S.

INTRODUCTION

This paper is a synopsis on the evolution and historical background about the development of domestic U.S. and international regulations focused on nuclear criticality safety (NCS) as applied to certified fissile material (FM) packages and their domestic and international transportation.

BACKGROUND

This paper provides a general discussion of the complexities and application of NCS for the design, certification, and transport of FM transport package including:

- Discovery of the nuclear fission process and application of NCS.
- Definition of nuclear criticality, super–criticality, sub–criticality, and nuclear criticality safety.
- Experimental and analytical processes for determining nuclear criticality and subcriticality safety for FM.
- Application of controls for the prevention of nuclear criticality.
- Application of nuclear engineering to the design and safe transport of FM.
- Development of national and international regulations to ensure safely subcritical transport of FM.

DISCOVERY OF THE NUCLEAR FISSION PROCESS

James Chadwick [1] discovered the neutron in 1932 by bombarding beryllium with alpha particles (i.e., two proton helium nucleus) ejected from Po–210 during its radioactive decay. Later in 1938 and 1939 the nuclear fission process was discovered by the experimenters Otto Hahn, Fritz Strassman, Lise Meitner, and Otto Frisch [2]. The experimenters found that if they bombarded natural uranium with neutrons having various kinetic energies, they could cause the uranium nucleus to split into two fragments having lesser atomic masses. Additionally, it was discovered that the likelihood, probability, of the reaction was dependent upon the energy of the bombarding neutron. Meitner and Frisch named the splitting process nuclear fission. The discovery led to the discovery that neutrons could induce fission with the release of two or more neutrons (e.g., approximate averages of 2.4 for U–233 and U–235 and about 2.8 for Pu–239) and a large quantity of fission product kinetic and radiation energy. It was discovered that, on average, more neutrons could be released that led to the possibility of a neutron fission chain reaction or nuclear criticality.

DEFINITION OF NUCLEAR CRITICALITY, SUPER–CRITICALITY, SUB–CRITICALITY, AND NUCLEAR CRITICALITY SAFETY

Nuclear criticality is the “critical’ state for a nuclear fission chain reaction within an assembly of fissionable material into a single item or an array of items. Fissionable material is comprised of three types of nuclides, fissile, non–fissile or fertile. They are characterized as follows.

- Fissile nuclides include U–233, U–235, Pu–239, and Pu–241. Those nuclides can maintain or support both a thermal neutron energy (i.e., $\leq \sim 0.625$ eV) nuclear fission chain reaction or high energy (i.e., $\geq \sim 100$ keV) nuclear fission chain reaction. There are other fissile nuclides but, to date, there are limited quantities and forms that do not require regulation for NCS in transport. Examples of the other fissile nuclides in relatively rare pure forms include Np–236, Pu–237, Am–242, Cm–243, Bk–247, and Cf–252. The Transport Regulations NCS requirements for the four fissile materials (e.g., U–233, U–235, Pu–239, and Pu–241) prevent the formation of configurations that could cause a nuclear criticality accident under normal and accident conditions transport. Under certain conditions of material forms and concentrations, The Transport Regulations provide relief from the fissile material NCS requirements.

- Non–Fissile includes Th–229, U–234, Np–237, Pu–238, Am–241, Cm–244, Bk–249, and Cf–250 nuclides. These nuclides can only maintain or support a nuclear fission chain reaction with high energy neutrons (i.e., ≥ ~100 keV). They are not currently identified for NCS in the Transport Regulations. As the result of continued, or future, partitioning of spent/irradiated nuclear reactor fuel, it is probable that sometime in the future this type of non–fissile fissionable material, in particular Np–237 and Am–241, will be regulated for NCS purposes.
- Fertile nuclides includes Pa–231, Th–230, Th–232, U–236, and U–238 nuclides. Those nuclides can contribute to a nuclear fission chain reaction but cannot individually support a self–sustaining nuclear fission chain reaction, and they are not currently identified for NCS control in the Transport Regulations. The Th–232, U–234, and U–238 nuclides can be transmuted within a nuclear reactor by neutron irradiation into the fissile nuclides U–233, U–235, and Pu–239.

In a fission chain reaction, a fissile nucleus absorbs a neutron and fissions spontaneously, creating two or more lighter nuclides and emitting additional neutrons. These neutrons, in turn, can be absorbed by other fissionable nuclei, releasing still more neutrons. Those high–energy fission neutrons can have many types of interactions with various non–fissionable material packaging nuclides thereby compounding the complexity of computing neutron multiplication factors, i.e., k_{eff}s, of transport systems. A critical fission chain reaction is self–sustaining when the number of neutrons released in a given time equals the number of neutrons lost by absorption or by escape from the system. It is that precise critical condition that is frequently described by a neutron multiplication factor, k_{eff}, such that

$$k_{eff} = \frac{No.\ neutrons\ born\ in\ (n+1)\ generation}{No.\ neutrons\ born\ in\ (n)\ generation} = 1. \qquad \text{(Eq. 1)}$$

Therefore, any condition that results in more neutrons born from the fission in the (n+1) generation relative to the n generation is defined as supercritical, i.e., $k_{eff} > 1$. Such a supercritical condition can produce prodigious quantities of radioactive fission products and potentially fatal radiation exposures. Alternatively, any condition that results in fewer neutrons born in the (n+1) generation relative to the n generation is defined as subcritical, i.e., $k_{eff} < 1$.

NCS is the “Protection against the consequences of a criticality accident, preferably by prevention of the accident.” [3]. NCS is specifically concerned with ensuring the safe subcriticality of FM that otherwise, without physical conditions or controls, could result in a self–sustaining nuclear fission chain reaction, criticality. The *Transport Safety Regulations* of both the IAEA in SSR–6 [4] and the NRC in 10 CFR Part 71 [5], , require the prevention of nuclear criticality accidents that could potentially impact workers, public and environment. These Transport Regulations specify controls to be exercised in the packaging and transport of U–233, U–235, Pu–239, and Pu–241 which are defined as “fissile material”.

The IAEA [4] and the NRC [5] transport regulations have always required that shipments of FM packaging designs and package contents be limited to ensure nuclear criticality safety. That is, no self–sustaining (i.e., critical) or divergent (i.e., supercritical) nuclear fission chain reaction will occur as the result of all three of the defined package test environments:

(1) Routine conditions of transport (IAEA).
(2) Normal conditions of transport (IAEA & NRC).
(3) Hypothetical accident conditions (IAEA & NRC).

To ensure safe subcriticality for all three transport conditions, it is generally accepted that the shipment of such packages must have a computed k_{eff} less than 0.95, including computed and/or experimental biases and uncertainties. That requirement could be relaxed providing there is actual experimental evidence or unusual, quality computational capability demonstrated for calculating the subcriticality of an individual package and the accumulation of packages for all three transport conditions.

Safe, subcriticality computational evaluations are dependent upon the knowledgeable application of reliably accurate fissionable, and non–fissionable material nuclide parameters (e.g., energy–dependent neutron reaction cross sections), critical and/or subcritical physical models (e.g., critical experiments relevant, or like, a subcritical determination) and accurate/precise descriptions of the package and array.

EXPERIMENTAL AND ANALYTICAL PROCESSES FOR DETERMINING NUCLEAR CRITICALITY AND SUBCRITICALITY SAFETY FOR FISSILE MATERIAL

NCS did not exist until the design and operation of the first experimental self–sustaining nuclear fission chain reaction in 1942 by Enrico Fermi and his colleagues. The experiment was called the Chicago Pile – 1 (CP–1) [6] nuclear reactor or “atomic pile”. Prior to the construction of the CP–1, it was determined by experiment with natural uranium that a neutron induced fission chain, or splitting of uranium, was possible thereby releasing large quantities of energy in the form of fission fragment kinetic energy/heat, penetrating radiation and neutrons that could continue fission chains. Fermi, and his colleagues, had determined that a divergent (potentially unsafe) or self–sustaining steady–state neutron induced nuclear fission chain reaction was possible during the assembly and operation of CP–1. Because either a steady–state or divergent nuclear fission chain reaction was determined to potentially release copious quantities of physically damaging or lethal radiation, special precautions were taken to ensure the safety of those participating in the experiment. Therein was the world’s first application of NCS during the assembly and operation of CP–1 to control the fission chain reaction. The experimenters ensured NCS by designing the CP–1 physical dimensions and controls for the CP–1 with materials (i.e., pure–graphite support structure, natural uranium metal and oxide fuel lumps/slugs, and neutron absorbing properties of cadmium and boron control elements). As the nuclear enterprise expanded through the world, NCS became integral to various nuclear energy applications including indigenous and international regulation and transportation of fissionable material that includes fissile materials having NCS concerns (i.e., U–233, U–235, Pu–239, and Pu–241).

As previously mentioned, the first experiment to establish nuclear criticality parameters was the CP–1 reactor experiment in Chicago, Illinois in 1943 [6]. Prior to the design of the CP–1 reactor experiment, uranium was only available in large quantities of natural uranium with limited isotopic proportions, i.e., 0.0053 wt. % U–234, 0.711 wt. % U–235 and 99.284 wt. % U–238. The experiment [7] was performed with purified natural uranium metal and oxide lumps, purified graphite, and neutron absorbing control elements comprised of either strips of steel–clad cadmium metal or borated steel rods. The dimensions of the CP–1 reactor core were 7.5 m x 7.5 m x 5.8 m high and was tightly surrounded by 0.3 m thick purified graphite neutron reflector. The purity of materials was required to minimize the absorption of neutrons in materials other than the uranium or the designed control elements. The leakage of neutrons from the experimental reactor was limited by the large dimensions of the core and the surrounding thick graphite neutron reflector.

Experimental results from the CP–1 reactor verified that a neutron fission chain reaction could, in fact, be designed. Previous to the CP–1 experiment it had been determined by the experimentalists, Hahn, Strassman, Meitner, and Frisch [2] that the fission process from natural uranium produced, on average, approximately 2 million electron volt (MeV) high energy, so called fast, fission neutrons (i.e., ~20,000 km/s) that were not able to permit a self–sustaining neutron chain reaction because the fission neutrons would be parasitically captured, primarily by U–238 nuclei, before the neutrons could be slowed to a much lesser energy. Low energy, so called thermal or slow, neutrons having an energy of about 0.025 eV (i.e., ~2.2 km/s) have a great probability for causing fission in the U–235 nuclei. For those reasons, Fermi and colleagues designed their heterogeneous core with lumped fuel elements to permit fast neutrons to escape the lumps of natural uranium metal and oxide, become slowed by collisions with the graphite carbon nuclei and to then scatter into nearby lumps of uranium as slow neutrons and cause further fissions.

The CP–1 experiment demonstrated that it was not possible to design smaller critical systems with natural uranium. The experiment demonstrated the need to separate U–235 from natural uranium in order to design compactly dimensioned critical systems (e.i., less than ~ 150 kg U-235 in less than ~ 0.008 m^3).

Using limited, neutron reaction measurements, verified by the 1943 CP–1 reactor experiment, and the design and operation of the Los Alamos low power (LoPo) "Water Boiler" experiment [6][8], computational efforts were undertaken by the US Manhattan Project physicists to estimate the critical parameters for a compact, relatively pure hypothetical water solutions of either U–235 or Pu–239 [9] spheres. With the theoretical predictions for U–235 and Pu–239 thermal and fast fission criticality parameters and with the "benchmark quality" CP–1 heterogeneous core and the low power "Water Boiler" homogeneous core experiments as references, work was begun in earnest to primarily develop and design a deliverable nuclear weapon as suggested by Albert Einstein [10]. Both neutron interaction nuclear data and theoretical computational methods were refined.

Following the conclusion of World War II and the beginning of the United Nations (UN) "Atoms for Peace" initiative proposed by the US President, Dwight D. Eisenhower [11], nuclear data, computational methods and critical experiment information began to be shared internationally among the UN member countries.

APPLICATION OF CONTROLS TO PREVENT NUCLEAR CRITICALITY

As previously mentioned, the control of the CP–1 experimental reactor neutron fission chain reaction was accomplished by various design and operating parameter controls. The parameter controls for NCS are, of course, established to prevent a self–sustaining or divergent neutron fission chain reaction in FM operations that would otherwise be unsafe to people, equipment, or the environment. The discipline of NCS began immediately with the design and construction of CP–1 and substantially matured as time progressed its application to packaging and transportation of FMs. The progress of NCS evolved and identified several physical parameters that were useful to ensuring that all aspects of NCS and subcriticality are addressed in the handling, processing, storing and transporting of FMs.

Nuclear criticality safety parameters have been identified historically to assist NCS engineers for the determination of fissile material system safety. The parameters include mass, absorption, geometry, interaction, concentration/density, moderation, enrichment, reflection, and volume that are frequently remembered with the acronym, MAGIC MERV. The state (i.e., k_{eff}) of sub–criticality, criticality or super–criticality for a single FM package and an array (e.g., shipment) of identical FM packages will vary depending upon the application of those parameters. Specifically MAGIC MERV is:

- Mass – The mass of FM within a package has a direct bearing on the k_{eff} of a FM package and an array of such packages. Increasing FM mass in a package generally increases the value of k_{eff} of the package. An exception to that trend includes the displacement of moderators from the payload volume of a package.
- Absorbers – Neutron absorbers (e.g., cadmium, boron, irradiated or "spent" nuclear fuel fission products) can not only parasitically absorb neutrons as blended with FM, thereby preventing them from carrying a fission chain reaction, but when placed externally to the FM,

they also can provide neutron reflection thereby returning neutrons to FM. Returned neutrons can provide support to a fission chain reaction.

- Geometry – The geometry of the FM payload, package, and assembly of packages in an array (e.g., spherical, cubical, cylindrical, planar) will affect the degree that neutrons can leak from a package or array and be lost to the package or array environment or to interact with other packages within an array, thereby either deceasing or increasing array k_{eff}.
- Interaction – The interaction of FM packages has a direct bearing on the k_{eff} of an array of such packages. Generally, an increase in the number of packages in an array will increase the k_{eff} of the array. Contrarily, if the FM packages are sufficiently sub–critical, and provide sufficient neutron isolation from other packages, an increase in the number of packages in an array will not increase an array k_{eff}.
- Concentration – The concentration or density of FM metal or compounds (e.g., kg FM/m^3) that are blended, alloyed, or dissolved within other substances (e.g., water, metal, chemical compound) can positively or negatively affect the k_{eff} of a FM package and an array of such packages. Generally, the denser the FM the greater will be the k_{eff}. This effect on k_{eff} can be counter intuitive resulting from increased or decreased neutron moderation thereby altering the neutron energy effectiveness for causing fission and neutron leakage from the FM.
- Moderation – Moderation of neutrons refers to the slowing down, or decrement of neutron kinetic energy, from its birth energy of about 2 Mev. Neutron moderation occurs by collision with light nuclides near to its proximity and occurs most rapidly when colliding with nuclides such as hydrogen, beryllium and carbon. A measure of the moderation parameter is expressed as the nuclide ratio of hydrogen to U–233, U–235, Pu–239 or Pu–241 (e.g., H/X). The effect of moderation can have multiple effects on the k_{eff} of the FM package by decreasing the concentration or density of the FM, enhancing the probability of fission by slower neutrons or enhancing the absorptions of slowed neutrons in absorbing materials.
- Enrichment – Enrichment generally refers to the fissile nuclide percentage within the chemical elements of uranium or plutonium. Typical fissile nuclide percentages for various categories of fissionable material (i.e., fissionable material includes the fissile nuclides U–233, U–235, Pu–239 and Pu–241) include:
  - Natural uranium – 0.711 wt.% U–235, 99.284 wt.% U–238, 0.0053 wt.% U–234
  - Reactor grade approximate nuclide weight percent:
    - Uranium – ≤ 5 wt.% U–235, ~94.004 wt.% U–238, ~0.006 wt.% U–234
    - Plutonium – 6 wt.% Pu–239, 20 wt.% Pu–240, 65 wt.% Pu–241, 9 wt.% Pu–242
  - Weapon grade approximate nuclide weight percent:
    - Uranium – ≥ 85 wt.% U–235, ≤ 13 wt.% U–238, ≤ 2 wt.% U–234
    - Plutonium – ≤ 95 wt.% Pu–239, ≥ 5 wt.% Pu–240

  Unlike the fissile nuclides, U–233, U–235, Pu–239 and Pu–241, the nuclides U–234, U–238, Pu–240, and Pu–242 are not fissile and, in fact, are somewhat parasitic absorbers and therefore negatively influence the k_{eff} of FM packages and arrays with increased presence.
- Reflection – Any material placed near FM can provide some degree of neutron reflection to a FM package payload or array of such packages. Water can provide a high degree of neutron reflection and is generally available throughout a transportation environment. Though some materials, such as thick regions of pure carbon graphite and beryllium, provide excellent reflector characteristics it has been internationally agreed that, for safety purposes, thick (e.g., approximately 0.2 m) full water reflection on all sides of the FM package and the array of such packages for transport provides essentially the maximum contribution to k_{eff} for packages and arrays that is to be anticipated under normal and accident conditions of transport.
- Volume – The volume available to FM within a package can understandably influence the k_{eff} of the package and an array of such packages. A smaller volume will only accommodate a smaller mass of FM and volume for moderating materials.

APPLICATION OF NCS CONTROLS FOR THE HANDLING, PROCESSING, STORING AND TRANSPORTING OF FM

NCS of FMs in processes and operating environments within the US apply two graded principles for ensuring NCS. The two principles employed by the US are specified in the ANSI/ANS-8.1-2014 consensus standard, *Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors* [3], specifically:

> "*4.1.2 Process analysis Before a new operation with fissionable material is begun, or before an existing operation is changed, it shall be determined that the entire process will be subcritical under both normal and credible abnormal conditions.*"
> "*4.2.2 Double–contingency principle Process designs should incorporate sufficient factors of safety to require at least two unlikely, independent, and concurrent changes in process conditions before a criticality accident is possible.*"

The first principle is consistent with IAEA Safety Standards, *Criticality Safety in the Handling of Fissile Material*, Specific Safety Guide No. SSG–27 [12], specifically:

> "*3.11. The safety functions needed for ensuring subcriticality should be determined and the safety measures for implementing them should be defined. The definition and substantiation of the safety functions should be based on an analysis of all initiating or aggravating events relevant to criticality safety arising from credible abnormal conditions, including human error, internal and external hazards, and loss or failure of structures, systems and components important to safety in operational states and in design basis accidents (or the equivalent).*"

The US and IAEA requirements for NCS are similar in requiring that NCS be maintained under all normal and credible abnormal conditions. Those expectations are also applied to the transport of FM but with more descriptive and required arbitrary abnormal conditions.

Application of NCS Controls for the Design of FM Packages

The IAEA and US transportation regulations have established NCS design and control criteria for FM packages and transportation to withstand specific physical insults during normal and accident conditions of transport under non-exclusive or exclusive transport. The criteria are necessarily established to be conservative to ensure safe subcriticality during either type of transport, i.e., non-exclusive or exclusive transport. The non-exclusive transport NCS design and control criteria recognizes the potential for transshipments whereby there may be intermediate storage and handoffs of FM packages by different private or commercial carriers. The exclusive transport NCS design and control criteria recognizes that the FM packages are transported under more rigorous sole use control and conditions by a single consignor of a conveyance for which all initial, intermediate, and final loading and unloading are carried out in accordance with the direction of the consignor or consignee. The US and IAEA design requirements are essentially the same for FM packages and shipments except for the limited specific allowances under "Material Excepted from Fissile Classification" (IAEA SSR–6 language, paragraph 417) [4] in the IAEA regulations and the "Exemption from classification as fissile material" (US NRC language, section 10 CFR 71.15) [5] in the NRC regulations. The US and the IAEA regulations permit NRC licensees or IAEA members, respectively, to apply for the exceptions or exemptions under the applicable regulations.

The fundamental requirements for the design and documentation of FM packages and their transport safety include testing and packaging quality assurance for FM packages. The documentation must demonstrate that the FM packages and their shipments will withstand and maintain NCS in routine, normal and accident conditions of transport tests. Those tests include:

- Free Drop.
- Crush.
- Puncture.
- Thermal.
- Immersion--fissile material.
- Immersion--all packages

Subcriticality must be evaluated and ensured for FM payloads during and/or after testing considering the following contingencies:

- Leakage of water into or out of packages.
- Loss of efficiency of built-in neutron absorbers or moderators.
- Rearrangement of the contents either within the package or as a result of loss from the package.
- Reduction of spaces within or between packages.
- Packages becoming immersed in water or buried in snow.
- Temperature changes.

Arrays of touching FM packages must be arranged into a configuration for which the maximum array k_{eff} is subcritical under the above assumed accident conditions.

NCS Control for the Transport of FM Packages

The certification of FM packages requires that a criticality safety index (CSI) be assigned to any FM package. The CSI is a number (rounded up to the next tenth) which is used to provide control over the accumulation of packages, overpacks or freight containers containing fissile material. The CSI is conditionally determined as the maximum quotient of either 50/NN or 50/ND where:

- N_N is less than or equal to one-fifth of the maximum subcritical number of undamaged packages under defined normal conditions of transport as an optimum arrangement of packages that produces the maximum neutron multiplication and
- N_D is less than or equal to one-half of the maximum subcritical number of damaged packages under defined accident conditions of transport as an optimum arrangement and interstitial hydrogenous moderation between packages for producing the maximum neutron multiplication.

The CSI value may not be less than 0.5 for an exclusive use shipment and no less than 1.0 for a non-exclusive use shipment. The value of the CSI may be zero, provided an unlimited number of undamaged or damaged packages are subcritical (i.e., N_N and N_D is effectively equal to infinity in both cases).
The aggregate CSI for a non-exclusive use shipment shall not exceed 50. The aggregate CSI for an exclusive use shipment shall not exceed 100. The value of the CSI may be zero, provided an unlimited number of packages are subcritical (i.e., N_N and N_D is effectively equal to infinity in both cases).

The CSI for an overpack, freight container, consignment or conveyance containing fissile material packages is the arithmetic sum of the criticality safety indices of all the fissile material packages contained within the overpack, freight container, consignment or conveyance.

DEVELOPMENT OF NATIONAL AND INTERNATIONAL REGULATIONS TO ENSURE SAFE SUBCRITICAL TRANSPORT OF FISSILE MATERIAL

Prior to the 1957 establishment of the International Atomic Energy Authority (IAEA) [13] and the 1961 issuance of the first IAEA *Regulations for the Safe Transport of Radioactive Materials,* Safety Series No. 6 [14], transportation safety for radioactive and fissile materials was managed by the safety controls imposed by safety authorities indigenous to United Nation member countries and agreements among members. Concerns about the transportation of radioactive materials began to be expressed as early as 1936. The need for fissile material controls were recognized following the assembly of the CP-1 reactor experiment late in 1942 and the amassing of highly enriched uranium and plutonium consistent with designs for the 1945 atomic bombs used in war.

SUMMARY AND CONCLUSIONS

This paper summarizes the authors' examination of more than seven decades of history in the development of the regulatory provisions set forth in U.S. domestic and IAEA *Transport Safety Regulations* as they relate to nuclear criticality safety in the packaging and transport of fissile radioactive materials. The paper provides a summary of historic information relating to package design, package use, and regulations as applied to certified packages relative to U.S. domestic and the IAEA *Transport Safety Regulations*.

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