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The Heritage and Usage of the Words *Fissionable* and *Fissile* in Criticality

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Norman L. Pruvost
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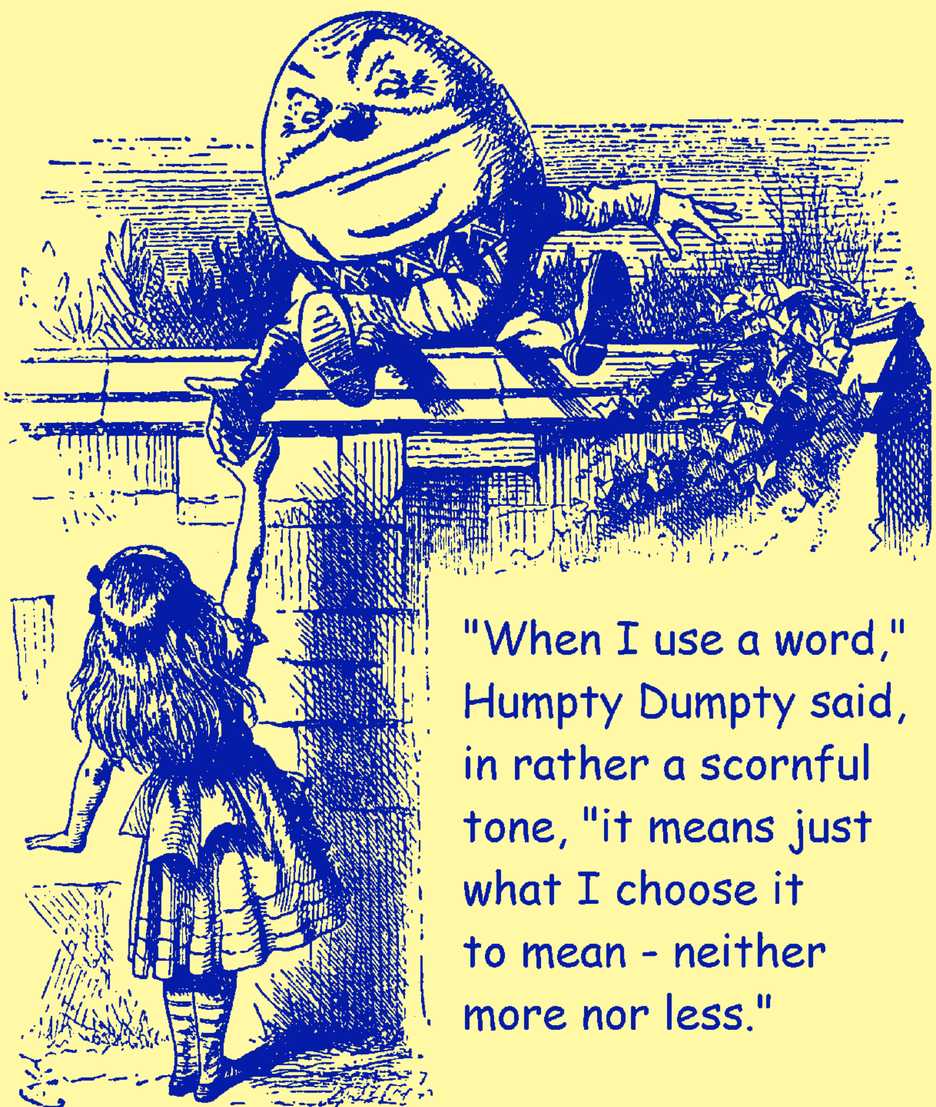

"When I use a word," Humpty Dumpty said, in rather a scornful tone, "it means just what I choose it to mean - neither more nor less."

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Preface

Proper usage of words in the criticality community is most formally defined by usage in the American National Standards. The origin of this report began in discussions among members of the working group for the revision of *American National Standard for Nuclear Criticality Control of Special Actinide Elements*, ANS 8.15. Later, Standards Subcommittee-8 chairman Thomas P. McLaughlin pointed out that other working groups might benefit from documentation of our discussions. This report captures the substance of those discussions. We hope the reader will be able to recognize our struggle to make a distinction between style and usage. We intend this report to be relevant to creators and users of standards. Our motivation for preparing this report is based on the belief that a serious waste of time and effort can result when consistent usage of *fissionable* and *fissile* is assumed.

Abstract

This report examines the origins and usage of two words - *fissionable* and *fissile* in the context of man-made nuclear criticality that was first achieved in 1942 following the discovery of the nuclear fission reaction in 1939. The fission physics primer section describes the features of the nuclear fission reaction that are of general relevance for understanding criticality. The body of the report cites specific excerpts from criticality publications to illustrate consistent and inconsistent usage. The authors annotate the excerpts in order to bring forward specific issues they judge to be relevant.

In reviewing this usage, it will become apparent to the reader that there is no clear-cut consensus on the meaning of these words and in some cases, the usage is quite disparate, even though there appears to be general agreement that *fissionable* is less restrictive than *fissile*. The purpose of this report is to provide the reader a comprehensive survey of relevant publications in order to dispel the common perception that the words are assumed to have a standard definition that is shared by everyone else.

Acknowledgments

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Name	Affiliation
Calvin M. Hopper	Chair, ANS Consensus Committee N-16 Convener, ISO TC85/SC5/WG8
Thomas P. McLaughlin	Chair, ANS Standards Subcommittee-8
Charles T. Rombough	CTR Technical Services, Inc.

Charles T. Rombough contributed the cover design, text composition, text editing, and reference checking.

Editing of this report was performed by Patricia W. Mendius. Her professional attitude, editing skills, and intellectual grasp of the issues addressed were invaluable.

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Introduction

The English language has been described as the most difficult of all languages to master. Part of the difficulty is due to numerous rules regarding pronunciation and usage and the seemingly random lack of any rules in many cases. Over time, usage of words that seem to have precise and uniformly accepted definitions will begin to change to suit the specific purposes of a people or group. These changes inevitably lead to inconsistent usage on a much larger scale.

In February of 1939, after demonstrating an experiment on the disintegration of uranium by neutrons, Otto Frisch needed a word to describe this newly discovered nuclear reaction. When he and Lise Meitner published the results of this hypothesis and experiment, a word from biology, *fission*, was borrowed to describe this new reaction.

Since that first use of the word *fission* to describe the disintegration of uranium by neutrons, numerous words have been invented to describe various aspects of the fission process to meet the needs of those involved in the field of nuclear physics. *Fissionable* and *fissile* are two such words. Both have distinct and concise meanings; however, both words have very different meanings depending on the person asked or reference consulted. It is clear that there is inconsistent usage of these two words from within the criticality community. The inconsistency penetrates into regulation, technical reference documents, facility criticality safety procedures and the American Nuclear Society standards that address nuclear criticality safety. That is, the inconsistency is pervasive in the community as a whole.

This report makes an attempt to provide a fairly comprehensive survey of definitions in relevant publications and demonstrate that, within the criticality community, these words do not have a consensual meaning.

The essence of characterizing criticality is the realization of a self-sustaining or divergent chain reaction. This chain is perceived to consist of a series of causally linked nuclear reactions that primarily, but not necessarily exclusively, involve neutrons and the fission reaction. Criticality is an observable and well defined phenomenon in the physical world. In criticality physics and in technical applications of criticality an understanding of the connection of words with the real world is essential. By real world we mean the physical world as characterized by reproducible experimental results.

The following section presents a primer on the physics of fission phenomena. We hope this primer will help the reader recognize the distinction we would like to draw between basic nuclear physics and nuclear technology. We view criticality physics and technology as properly within the nuclear technology discipline.

Fission Physics Primer

Although the word *fission* was familiar in biology, referring to the division of a cell into two daughters, it was first used in nuclear physics in 1939 to denote a totally new kind of nuclear reaction. Hahn and Strassmann[1] (1939) found that the bombardment of uranium by slow neutrons could lead to the production of barium and a lighter particle (or particles), rather than a nucleus one mass unit heavier than uranium (followed by an α and β decay chain) as expected in the (n,γ) reaction. Meitner and Frisch (1939) hypothesized that this new reaction was indeed a binary split into two nuclei about half the size of the uranium nucleus, and in their subsequent paper[2] they termed it *fission*. For the next several years this word was applied exclusively in nuclear physics to the division of a very heavy nucleus into two (still heavy) nuclei of comparable mass. This reaction was qualitatively different from all previously observed reactions, which were limited to the emission of gamma rays, neutrons, and charged light particles such as protons and alpha-particles. Principal observations connected with fission in this early period included the emission of a few neutrons on average (along with several gamma-rays), the preponderance of asymmetric division of the nucleus into its two principal products, the occurrence of spontaneous fission and the induction of fission by particles other than neutrons (gamma-rays, protons, and electrons for example). Among these, the emission of neutrons was the key to the opening of nuclear technology.

In later years with the advance of nuclear experimental techniques (in detectors, higher energy accelerators, and new kinds of accelerated projectiles such as light and heavy ions) the use of the word *fission* in nuclear physics became somewhat muddied. Developments in nuclear theory, especially the recognition of shell effects ("magic numbers") in very deformed nuclei, also played a role in extending or distorting the meaning of the word. Indeed, one pair of authors, Moretto and Wozniak[3] (1989), go so far as to call *fission* the most general of nuclear reactions. But this is a very eccentric view, managing to encompass even simple nucleon emission within the framework of fission! For a detailed discussion on modern fission theory, see *Modern Fission Theory for Criticality*, LA-14098. [4]

Apart from this, probably the most extreme use of the word is to describe the decay of ^{8}Be into two alpha-particles as *spontaneous fission*[5]. This nucleus, known in its ground state as a sharp resonance in the (α,α) scattering reaction, has a very short half-life of $\approx 10^{-16}$ s. It is a very elongated object (its first three states form a well-defined rotational band) and can be described quite accurately as two weakly bound alpha-particle-like clusters. It is thus quite different from a nucleus such as uranium, which in no way could be described as something like a coupled barium and krypton pair. The equivalent of *neutron-induced fission* in the Be case would be the ^{9}Be(n,2n) reaction. This has a threshold of about 2MeV neutron energy and involves the break-up of the residual ^{8}Be nucleus into two alpha-particles. It is an endothermic reaction and therefore not a candidate for a chain reaction.

Bombardment of ^{9}Be with neutrons can also lead to the formation of ^{6}He plus ^{4}He (threshold about 0.8MeV neutron energy). ^{6}He decays into ^{6}Li, so there is no neutron release in this reaction.

Other projectiles that can lead to forms of fission include the large range of medium to heavy ions. Various mechanisms can occur with these. One involves genuine compound nucleus formation (*fusion*) in which the identity of the projectile is lost and fission is one of the competing modes of decay. At the other extreme is *Coulomb fission*, in which there is no actual impact but the target is excited by the transient electric field of the passing projectile into a vibrational mode with enhanced likelihood of fissioning. This is akin to *photo-fission*. In yet another mechanism the projectile *grabs* part of the target nucleus without fully equilibrating its energy throughout the whole system; the apparent division into two comparable parts is known as *quasi-fission*.

The existence of the various forms of fission caused by heavy ions brings into question another word commonly used in the subject; that word is *induced*, as in *neutron-induced fission*. This usage obviously becomes somewhat absurd when extended to fission by heavy-ion bombardment through the fusion mechanism. The nucleus that is fissioning is totally different from the target nucleus. Even in its original application, *neutron-induced fission*, the fissioning nucleus (the compound nucleus) is one mass unit heavier than the target it is *inducing* to fission and can have quite different properties from the target. Only in *photo-fission* or *coulomb fission* is the fissioning nucleus unchanged in mass and charge and therefore induced to fission. We suggest therefore that this term should be avoided and the simple terms *neutron-fission*, *proton-fission*, etc. be used instead.

As far as *spontaneous fission* is concerned, a new complication in usage has arisen with the discovery of a form of radioactivity in which heavy-ions are emitted. The range of ions observed includes isotopes of carbon, neon, and magnesium. Can this be regarded as an extremely asymmetric form of fission or is it more like alpha-decay? The common factor in these reactions is that the partner in the division is the double-shell nucleus ^{208}Pb or a nucleus close to it. This would seem to make the decay more akin to that of ^{8}Be in which a cluster model is the appropriate theoretical description. It is probably best to avoid including such decays within the terminology of *fission*; we should refer to them as *heavy-ion radioactivity*. This still leaves the question of how to divide the classification between extremely asymmetric fission and *partition*. This must be largely a matter of judgment. Our feeling would be that if the yield for the mass division is still clearly on the wing of a continuous and monotonically decreasing statistical distribution, then it should be included within the classification of fission.

Another term that arises in the study of the fission mechanism is *cold fission*. This is used for the case in which the fission fragments formed just after scission have no excitation energy or excess deformation energy that can be converted to excitation energy. All the available energy in the original compound nucleus is converted into kinetic energy of the fragments. Cold fission events are genuine fission but they form only a small fraction of the total fission yield.

Strong theoretical arguments have been made to limit the definition of *fission*. The key recognition that was made in interpreting the original observations on slow neutron bombardment of uranium was that division into two smaller nuclei would be a highly exothermic reaction, even without the extra excitation energy brought in by the neutron. The near-stability of uranium against spontaneous fission would be due to the resistance of the *surface-tension* to the disruptive Coulomb forces, a resistance that would be overcome by sufficient elongation of the nucleus; thus, a potential energy barrier would exist, high enough to give a large spontaneous fission half-life but comparable with the binding energy brought into the compound nucleus by a neutron. The liquid drop theory of fission was developed from these ideas (Bohr and Wheeler[6], 1939). From this theory, barrier heights could be estimated and the nature of mass division could be studied. Businaro and Gallone[7] (1955) found that for nuclei like uranium, the potential energy valleys for the observed asymmetric division were apparently formed well beyond the deformation of the fission barrier. For nuclei with much lower charge-to-mass ratio, the elongation at the barrier is much larger and is closer to the onset of the asymmetric potential energy valleys. At a critical value of Z^2/A the asymmetric valleys open at the barrier deformation. Nuclei near silver ($Z \approx 47$, $A \approx 110$) appear to be close to this critical value. Nix[8] (1972) considers that nuclei with lower values of Z^2/A will partition in a highly asymmetric way that can no longer be considered as true fission, and he postulates this "Businaro-Gallone" critical point as a lower limit to the mass and charge range of nuclei decaying by fission.

For these much lighter nuclei the fission barrier is calculated to be about 55 MeV. With such a high barrier, spontaneous fission will have an extremely long half-life that is not measurable, and fission cross-sections will be negligible in the face of competing reactions, no matter how large the projectile energy. Below mass number ≈100, fission ceases to be an exothermic reaction, iron ($A \approx 56$) being the most stable nucleus.

We cannot leave this section on usage in the basic nuclear physics of fission without considering another word, *fissility*, apparently similar to *fissile*, which we shall consider below. *Fissility* has a very precise definition stemming from the liquid drop theory, but its usage seems to have crept in at a fairly advanced stage into the development of fission theory. The fissility parameter x is the ratio of Z^2/A of the nucleus to the value $(Z^2/A)_{\text{limiting}}$ that a spherical liquid drop would require to be just unstable to fission. The lower the value of x, the more elongated the nucleus must be at the barrier, and the higher the barrier will be. *Fissility* is only very loosely related to the definition of *fissile*. The original term for the parameter x was *fissionability parameter* (Bohr and Wheeler[6], 1939). Today, Z^2/A is only a required parameter for the theorists in making sophisticated calculations of nuclear energies as a function of deformation, but it is no longer available as a single measure for getting quantitative or semi-quantitative estimates of fission properties. [4]

When we turn to the role of fission in technology, we find that we need not be constrained by the terminology used in basic nuclear physics. In nuclear technology, the only reactions that are of interest to be considered *fission* are the highly exothermic ones in which neutrons are emitted as a secondary product. They also have to be the *neutron-fission* reactions because neutrons are the only secondary products that are capable of sustaining a fission chain reaction. The only other products that are emitted copiously are gamma rays, and these are of too low energy to have a significant photo-fission cross-section. The two most important words that must be defined clearly are *fissionable* and *fissile*. Neither is widely used, except in very loose ways, in basic nuclear physics.

A Survey of Publications

In this section, we will review the historical usage of the words *fissionable* and *fissile* and some words related to fission. We make no claim that the survey provided is exhaustive. The excerpts presented below contain the words *fissionable* and *fissile* as used by various authors and reference documents. Some excerpts contain the word *fission* and words related to *fission*, specifically*, fissions*, *fissioning*, and *fissioned* as inflected forms of *fission* as a verb. In addition, some excerpts contain the words *fission* and *fissionability.* We have also elected to include excerpts that contain words invented by some authors who have suggested their use. We are referring specifically to the words *cosmium* (excerpt 6), *fisside* (excerpt 17), *fissility* (excerpt 23), *non-fissile* (excerpt 28), *fissible* (excerpt 31), and *fissium* (excerpts 32 and 39). *Cosmium* seems to be an archaic word from early nuclear fission theory. *Fisside* does not seem to be widely used. *Fissility* has an etymology that predates the heritage period (see paragraph below) but once again appears to be a word relevant to nuclear fission theory but not criticality safety. *Non-fissile* occurs in the ANS-8.15 standard[9], *Fissible* was introduced by Kelly and Clayton[10] but without going through the standards consensus process. *Fissium*, in so far as we can determine, has never been used in the U.S. criticality safety community. In all cases, the excerpts should contain sufficient text to provide context. We hope that we have selected a large enough context to accurately reflect the intentions of the author. Comparison of these excerpts illustrates the potential for consistent and inconsistent usage. The source materials have been limited to U.S., U.K., and ISO references. The authors are accountable for the selection of excerpts; they are not accountable for the content of the excerpts.

The Heritage Period is defined to be the time interval from February 11, 1939 (the first appearance of the word *fission* in the nuclear scientific literature) to January 19, 1975 (the termination of the Atomic Energy Commission). This period coincides closely with the duration of the Manhattan Engineering District followed by the Atomic Energy Commission. More importantly, the Heritage period includes six of the seven criticality accidents in nuclear processing facilities in the United States. The performance of the majority of the criticality experiments defining the physical basis of criticality safety occurred during this time frame as well as the development of national standards to embody technical and administrative good practice for criticality safety. These three elements (accident experience, experimental data, and the American Nuclear Society's consensus standards) remain the foundation of technical criticality safety to the present time. *Heritage* is defined by *The American Heritage Dictionary of the English Language*[11] (2000, pg. 821) as "…(2) Something other than property passed down from preceding generations; legacy; tradition." It is this meaning of the word *heritage* that we intend for this report.

Similarly, *usage* is defined in the same reference (pg. 1894) as "…(3) The way in which words or phrases are actually used, spoken, or written in a speech community." It is this meaning of the word *usage* that we intend for this report.

Editor's note: *The American Heritage Dictionary of the English Language* is the dictionary recommended to Los Alamos National Laboratory by IM-1, the Laboratory's Writing and Editing Group.

The American Heritage Dictionary[11] defines criticality from a physics standpoint as "The point at which a nuclear reaction is self-sustaining." For usage as intended in this report, the definition provided in the 1976 and 1986 editions of the American Nuclear Society Glossary of Terms in Nuclear Science and Technology[12,13] (and shown below) is the genesis for what we believe is an appropriate definition.

> criticality: The condition of being *critical*.
>
> critical: Fulfilling the condition that a medium is capable of sustaining a *nuclear chain reaction* has an effective multiplication factor equal to unity. (A *nuclear reactor* is critical when the rate of neutron production, excluding neutron sources whose strengths are not a function of fission rate, is equal to the rate of neutron loss.)

The definition of criticality provided in Reference 11 is in the form of an abstract noun. Usage of the word criticality within this report remains as an abstract noun but with a modification to denote that criticality is a composite community, including regulators, experimentalists, practitioners, and others, concerned with the physical phenomena of criticality.

To distinguish the excerpts that follow, they are indented and appear in a larger size as illustrated below. Also, the entire excerpt is enclosed in quotation marks. An excerpt may include multiple blocks of text that are sequential but may or may not be disjointed.

This is regular text.

> " This is excerpt text. "

When a reference is cited in an excerpt, the reference number is replaced by a non-numeric symbol (e.g. *, †). This is done to avoid confusion with references cited within this report.

Pre-Heritage Period
(Before February 11, 1939)

The three definitions below are taken from *The Oxford English Dictionary, Second Edition, Volume V*,[14] prepared by J. A. Simpson and E.S.C. Weiner, Clarendon Press-Oxford, 1989, pg. 970. They are included here to illustrate that the words *fission*, *fissile*, and *fissility* were in use in the English language prior to the Heritage period.

> " **fission…** sb.[ad. L. *fission-em,* n. of action f. *findere* to split] **1.** The action of splitting or dividing into pieces. **1865** *Pop. Sc. Rev.* Jan. 177 Fission or the separation of cuttings is used to perpetuate the same variety. 2. *spec.* in *Biol.* The division of a cell or organism into new cells or organisms, as a mode of reproduction. **1841-71** T. R. JONES *Anim. Kingd.* 49 In some elongated species the fission is effected in a longitudinal direction. **1846** Patterson *Zool.* 38 A Medusa may actually be generated .. by fertile ova, by germination, and by spontaneous fission. *transf.* **1883** ABBOTT *Alphabet*, Vau had the singular fate of generating four other letters by a sort of spontaneous fission. "

> " **fissile…**, a. Also 7 fissel, 8 fissil. [ad. L. *fissil-is*, f. *findere* to cleave: see - ILE. Cf. Fr. *fissile*.] **1**. Capable of being divided or split; cleavable; inclined or tending to split. **1661** LOVELL *Hist. Anim. & Min.* Introd., Some are Fissil, as the spectacle stone; others not, as mettals. **1756** C. LUCAS *Ess. Waters* II. 128 It springs slowly through a soft fissil rock. **1830** LYELL *Princ. Geol.* (1875) II. III. xlviii. 572 Layers of drift peat, sand or *fissile* clay. **1857** H. MILLER *Test. Rocks* xi. 427 They communicate often a *fissile* character to the stone in which they occur. **1887** BOWEN *Virg. AEneid* VI. 180 Ash-hewn timbers and *fissile* oaks with the wedges are rent. "

> “ **fissility**…,[f. FISSILE + -ITY.] The quality of being *fissile* or cleavable. **1670-81** In BLOUNT *Glossogr.* **1689** G. HARVEY *Curing Dis. by Expect.* xxii. 178 The knowledge of ..the fissility of a stone. **1837** J. MACCULLOCH *Attributes God* III. xlv. 202 Had the fissility of slate not been known it would scarcely have been credited. **1882** GEIKIE *Text-bk. Geol.* II.II. para. 6. 121 This superinduced fissility or *cleavage* has resulted from an internal rearrangement of the particles. ”

A discussion between Otto Frisch and an American biologist, William A. Arnold in January of 1939 regarding an experiment that demonstrated a newly discovered nuclear process where uranium is shown to disintegrate into nuclei with an atomic number of about 40-50 was recalled later by Arnold [15]. This discussion provides insight into the first use of the word “fission” in a published scientific journal.

> **“**Later that day Frisch looked me up and said, ‘[Y]ou work in a microbiology lab. What do you call the process in which one bacterium divides into two?’ And I answered, ‘binary fission.’ He wanted to know if you could call it ‘fission’ alone, and I said you could.**”**

Heritage Period

(February 11, 1939 through January 19, 1975)

1. 1939:

Letter to the Editor, Lise Meitner and O. R. Frisch, *Nature*, Vol. 143, p. 239 (Feb. 11, 1939).

> " Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction
>
> It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of c. 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.
>
> By bombarding thorium with neutrons, activities are obtained which have been ascribed to radium and actinium isotopes.* Some of these periods are approximately equal to periods of barium and lanthanum isotopes† resulting from the bombardment of uranium We should therefore like to suggest that these periods are due to a 'fission' of thorium which is like that of uranium and results partly in the same products.
>
> * See Meitner, L., Strassmann, F., and Hahn, O., *Z. Phys.*, **109**, 538 (1938).
> † Hahn, O., and Strassmann, F., *Naturwiss.*, **27**, 11 (1939). "

Authors' Note: As the pioneering paper on the physical interpretation of the startling new radiochemical results of Hahn and Strassmann, its definition of *fission* takes precedence over all subsequent uses of the word.

2. 1939:

Letter to the Editor, Lise Meitner and O. R. Frisch, *Nature*, Vol. 143, p. 471 (March 8, 1939).

" Products of the Fission of the Uranium Nucleus

O. Hahn and F. Strassmann* have discovered a new type of nuclear reaction, the splitting into two smaller nuclei of the nuclei of uranium and thorium under neutron bombardment. Thus they demonstrated the production of nuclei of barium, lanthanum, strontium, yttrium, and, more recently, of xenon and cesium.

... After about two hours, however, the evaporated sample was found to decay considerably more slowly than the precipitate, presumably on account of the more long-lived fission products found by Hahn and Strassmann.*

From these results, it can be concluded that the 'transuranium' nuclei originate by fission of the uranium nucleus. Mere capture of a neutron would give so little kinetic energy to the nucleus that only a vanishing fraction of these nuclei could reach the water surface. So it appears that the 'transuranium' periods, too, will have to be ascribed to elements considerably lighter than uranium.

* Hahn, O., and Strassmann, F., *Naturwiss.*, **27**, 11, 89, and 163 (1939). "

Authors' Note: In a letter to the editor of Nature, Meitner and Frisch refer to a paper by Hahn and Strassmann published January 6, 1939. Less than one month following publication of their first letter, Meitner and Frisch again use the word *fission*, as introduced by them in their previous letter to Nature (see excerpt 1), to describe the disintegration of uranium by neutron bombardment. It should be noted that the Hahn and Strassmann paper did not assert that their experimental results confirmed the discovery of a new nuclear reaction.

3. 1939:

"The Mechanism of Nuclear Fission," Niels Bohr and John Archibald Wheeler, *Physical Review*, Vol. 56, p. 426, September 1, 1939.

" The new type of nuclear reaction thus discovered was given the name "fission" by Meitner and Frisch,* who on the basis of the liquid drop model of nuclei emphasized the analogy of the process concerned with the division of a fluid sphere into two smaller droplets as the result of a deformation caused by an external disturbance.

Examination of the coefficients of α_2^2 in the above expression for the distortion energy, namely,

$$4\pi r_o^2 O A^{2/3}(2/5)\{1-(Z^2/A)[e^2/10(4\pi/3)r_o^3 O]\} \qquad (10)$$

makes it clear that with increasing value of the ratio Z^2/A we come finally to a limiting value

$$(Z^2/A)_{\text{limiting}} = 10(4\pi/3)r_o^3 O/e^2 \qquad (11)$$

beyond which the nucleus is no longer stable with respect to deformations of the simplest type.

* L. Meitner and O.R. Frisch, *Nature*, **143**, 239 (1939). "

Authors' Note: The above reference is reproduced in part in excerpt 1. The expression for $(Z^2/A)_{\text{limiting}}$ is original and appears again in excerpt 6. This expression is also referred to in the Fission Physics Primer of this report.

4. 1945:

Atomic Energy for Military Purposes, Henry DeWolf Smyth, p. 24. (originally published in 1945 by the United States Government, now issued by Stanford University Press, Stanford, California).

> " 1.53. On January 16, 1939, Niels Bohr of Copenhagen, Denmark, arrived in this country to spend several months in Princeton, N. J., and was particularly anxious to discuss some abstract problems with Einstein. (Four years later Bohr was to escape from Nazi-occupied Denmark in a small boat.) Just before Bohr left Denmark two of his colleagues, O. R. Frisch and L. Meitner (both refugees from Germany), had told him their guess that the absorption of a neutron by a uranium nucleus sometimes caused that nucleus to split into approximately equal parts with the release of enormous quantities of energy, a process that soon began to be called nuclear "fission." The occasion for this hypothesis was the important discovery of O. Hahn and F. Strassmann in Germany (published in *Naturwissenschaften* in early January 1939) which proved that an isotope of barium was produced by neutron bombardment of uranium. "

Authors' Note: This excerpt is included as an example of the early heritage period acceptance of the word fission as a proper name for the nuclear reaction described in excerpt 1. This is the official report issued by the U.S. Government on the development of the atomic bomb.

5. 1952:

The Elements of Nuclear Reactor Theory, Samuel Glasstone and Milton C. Edlund, D. Van Nostrand Company, Inc., Princeton, New Jersey, November 1952, p. 62.

" CHARACTERISTICS OF THE FISSION REACTION

Introduction

> 4.1. Although many nuclear reactions were known prior to 1939, they were all of the type in which a relatively light particle or a gamma-ray photon was expelled, so that the atomic and mass numbers of the product nucleus were not very different from those of the target. In that year, however, there was discovered the process of fission, mentioned in § 2.22 and § 3.35, whereby a uranium nucleus, after capture of a neutron, splits into two parts which differ considerably from the target element. "

Authors' Note: The fission process, as defined in this excerpt, is introduced in a descriptive fashion. The textbook further describes fission by "thermal" and "fast" neutrons without any technical differentiation or utilization of the words *fissionable* or *fissile*.

6. 1953:

"Nuclear Constitution and the Interpretation of Fission Phenomena," David Lawrence Hill and John Archibald Wheeler, *The Physical Review*, **89**, 5 (March 1, 1953) pp. 1113, 1120, 1139, 1140, and 1143.

> “ pg. 1113: Here the “fissionability parameter” x is defined as in Fig. 2 to be 1/2 the ratio of Coulomb energy to surface energy of the spherical nucleus,
>
> $$x = \frac{1}{2}\frac{E_c}{E_s} = \frac{1}{2}\frac{\frac{3}{5}(e^2/r_o)}{4\pi r_o^2 O}\frac{Z^2}{A} = (Z^2/A)/(Z^2/A)_{\text{limiting}}$$ ”

Authors’ Note: Figure 2 cited above and reproduced below provides a plot showing the critical form of unstable equilibrium. The purpose of the excerpt from pg. 1113 is to point out that the parameter x is labeled as *fissionability parameter*. The word $(Z^2/A)_{\text{limiting}}$, shown below Figure 2, is defined in excerpt 3.

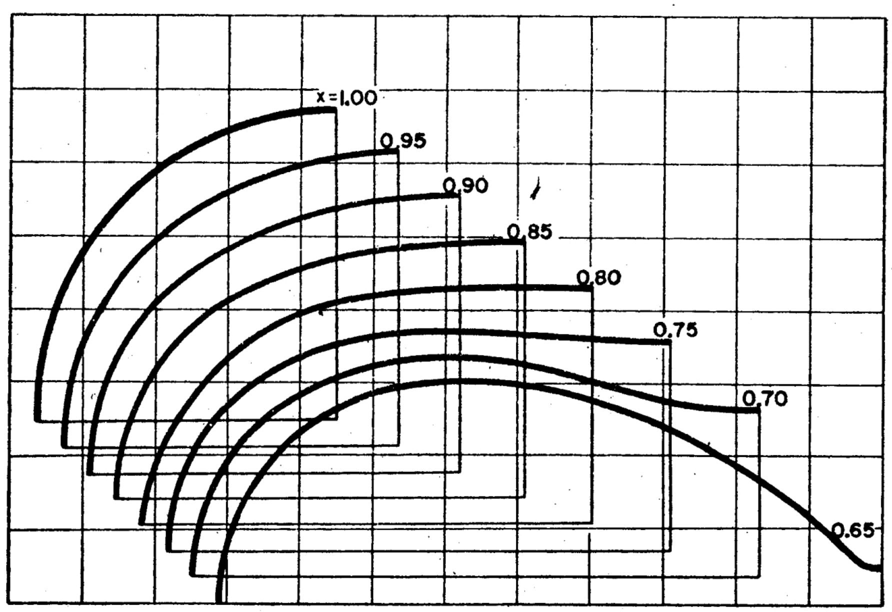


FIG. 2. Critical form of unstable equilibrium.

This critical form depends, in the approximation of the simplest liquid drop model, only upon the ratio of the square of the charge number to the first power of the mass number; or more conveniently, upon the dimensionless parameter:

$$x = \frac{(\text{charge})^2}{10 \times \text{volume} \times \text{surface tension}} = \frac{Z^2e^2}{10A(4\pi/3)r_0^3 O} = \frac{(Z^2/A)}{(Z^2/A)_{\text{limiting}}},$$

“ pg. 1120: For an imaginary nucleus, “cosmium,” sufficiently far beyond the known limits of stability, x will be 1, and the nucleus will already be unstable against fission in its spherical form.

pg. 1140: The linear relation shown holds not only for the labeled nuclei but also for the nucleus cosmium (Figs. 2, 51) for which $(Z^2/A) \approx 47$ and which undergoes spontaneous fission in a time of the order of the period of the lowest order vibration for such a nuclide as U^{238} (Fig. 1). ”

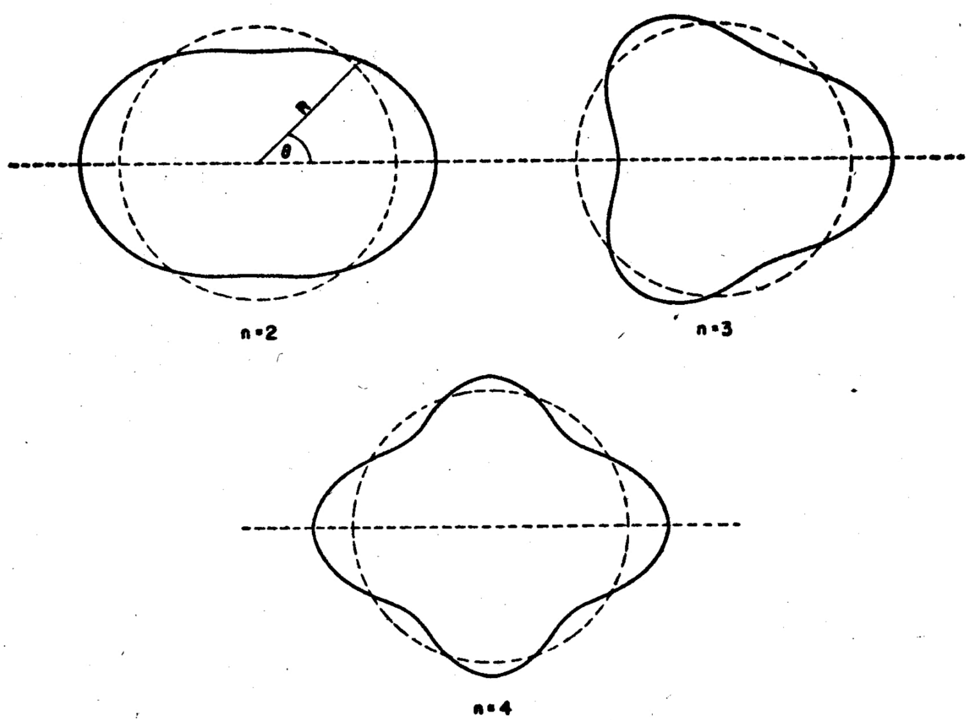


FIG. 1. Independent modes of small oscillation of a liquid droplet.

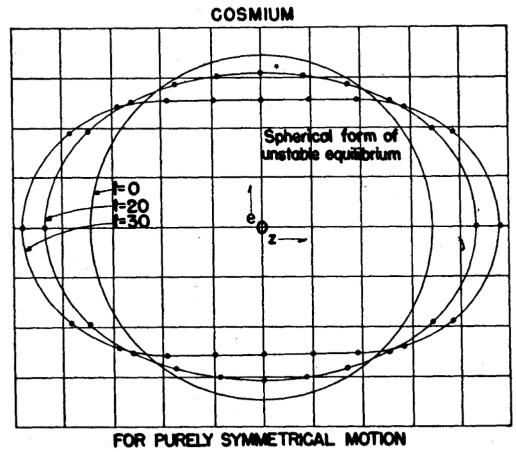
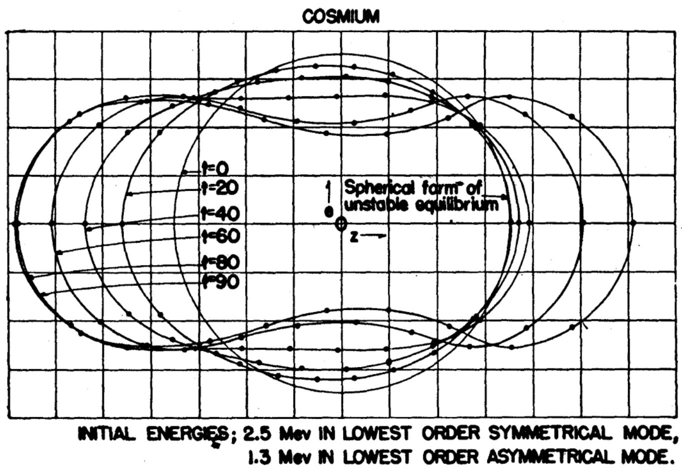
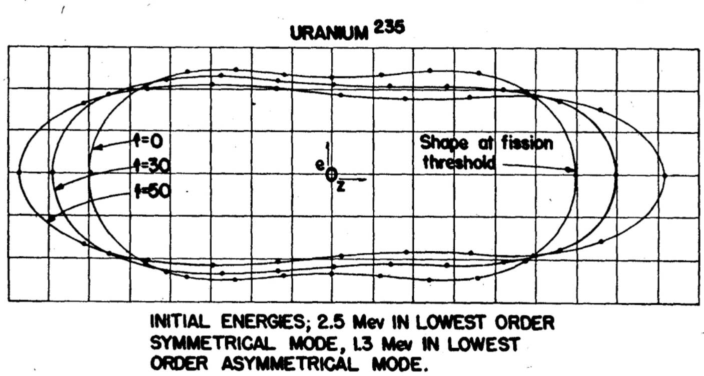


FIG. 51(a)



(b)



(c)

FIG. 51. Results of dynamical analysis of nuclear fission carried out [D. L. Hill, Phys. Rev. **78**, 330 (1950); **79**, 197 (1950); Ph.D. dissertation, Princeton University, Princeton, New Jersey (unpublished)] on the basis of simple liquid drop model.

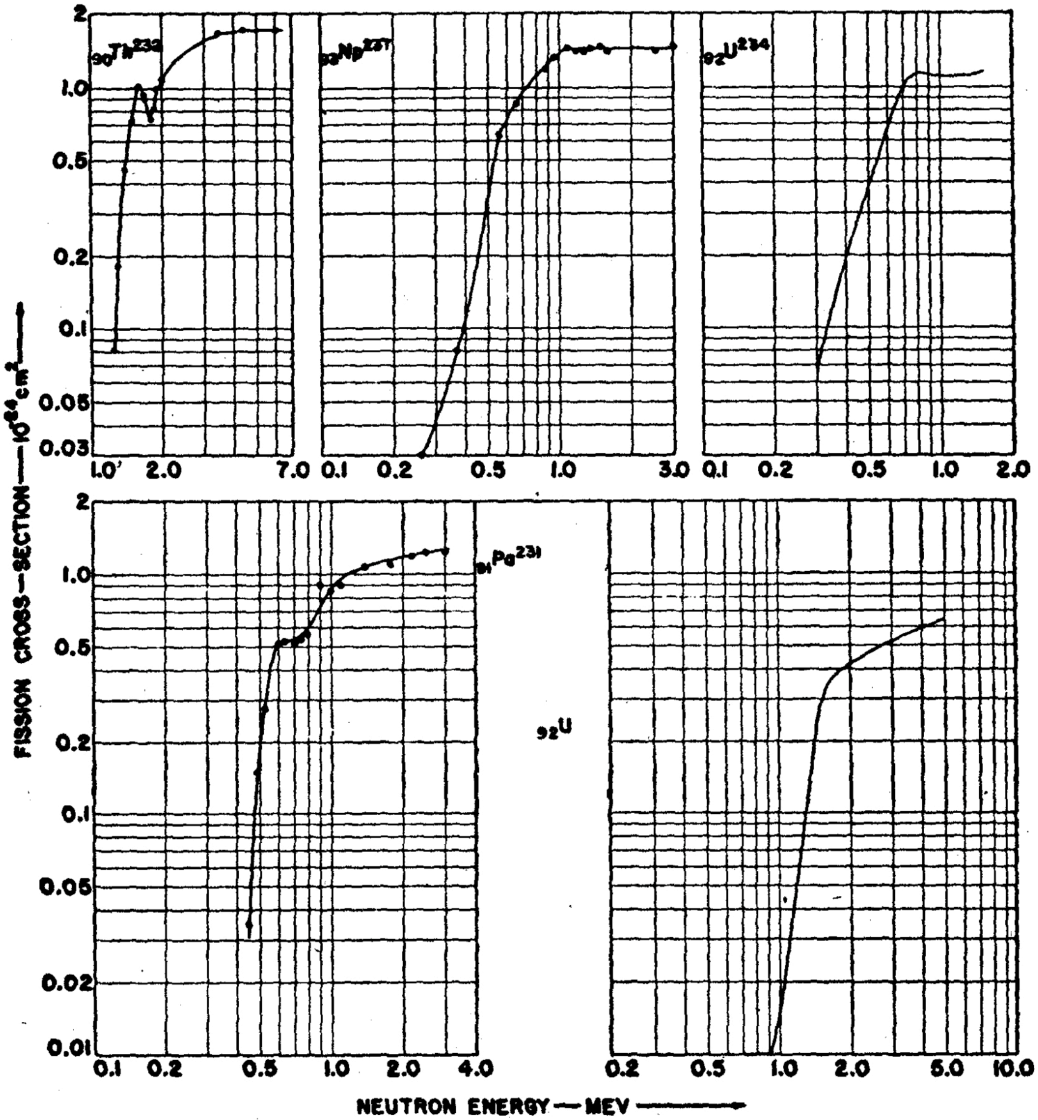


Fig. 43. Neutron fission cross section as a function of neutron energy for five fissile elements. All data are taken from the compilation of reference 29.

Authors' Note: Reference 29 from above is U.S. Atomic Energy Commission Unclassified Document AECU-2040, 1952 (unpublished). The figure above has been included as the earliest use of the word fissile in the heritage period that we have located. The five nuclides presented in the figure above are not considered to be fissile by current accepted usage.

7. 1954:

Title 42 United States Code Section 2014. Definitions (The Atomic Energy Act of 1954, as amended).

> " (c) The term "atomic energy" means all forms of energy released in the course of nuclear fission or nuclear transformation.
>
> (aa) The term "special nuclear material" means (1) plutonium, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the Commission, pursuant to the provisions of section 2071 of this title, determines to be special nuclear material, but does not include source material; or (2) any material artificially enriched by any of the foregoing, but does not include source material. "

Authors' Note: Definitions of *fission*, or of any words related to fission, are not given. However, note that the word *fission* appears in (c) above.

8. 1955:

"Nuclear Properties of the Very Heavy Elements," J. O. Newton, *Progress in Nuclear Physics*, Vol. 4, Pergammon Press, 1955, pp. 269.

> " Absorption of a thermal neutron will produce a compound nucleus having an excitation equal to the neutron binding energy. If the neutron binding energy is greater than the fission threshold energy the fission cross section may be large, otherwise it will be very small. Since the binding energy of the odd neutron is greater in an even-even nucleus than in an odd nucleus, odd target nuclei are more likely to be thermally fissile than even-even target nuclei. For a nucleus which is not thermally fissile we might expect the excitation function for fission to show a sharp rise in the neighbourhood of threshold and then remain fairly constant. This is found in general to be so. "

Authors' Note: This excerpt is included to illustrate the use of *thermally fissile*. We see in this excerpt the use of the word *fissile*. In connection with the adverb *thermally* the usage implies a large fission cross-section for thermal neutrons. This sense predominates in subsequent authors' usage of *fissile*. The word *fission threshold energy* that is used in this article is misleading. For heavy nuclei fission is an exothermic reaction, even spontaneous fission from the unexcited ground state being energetically possible, so there is no threshold in the proper sense of the word. What occurs is a barrier effect; when the excitation energy of the fissioning nucleus is equal to or greater than the fission barrier energy, the probability of fission is enhanced. As the excitation energy decreases below the barrier, the probability of fission decreases in an approximately exponential manner, due to quantal tunnelling, rather than dropping abruptly to zero.

9. 1956:

"Nuclear Safety Guide," LA-2063, A. D. Callihan, W. J. Ozeroff, H. C. Paxton, and C. L. Schuske, September 1956.

Authors' Note: The word *fissionable* is not defined in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document has a Bibliography with forty-two citations. When a word occurs in the Bibliography or the Table of Contents, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, or footnotes in the body of the document. The word fissile does not appear in the document.

Not included in the word count is use of the words "fissioning material" which occurs once and "spontaneous fission" which occurs once.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissionable material (s)	20
fissionable isotope (s)	5
fissionable system (s)	3
fissionable metal	2
fissionable atoms	1
fissionable element	1
fissionable nuclei	1
fissionable metal systems	1
fissionable solutions	1

10. 1957:

"Nuclear Safety Guide," TID-7016, A. D. Callihan, W. J. Ozeroff, H. C. Paxton, and C. L. Schuske, 1957.

Authors' Note: The word *fissionable* is not defined in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document cites thirty references plus a "selected reading list." When a word occurs in the reference list, the titles of the "selected reading list," or the Table of Contents it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, or footnotes in the body of the document. The word fissile does not appear in the document.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissionable material (s)	21
fissionable isotope (s)	5
fissionable system (s)	2
fissionable atoms	2
fissionable metal	1
fissionable metal systems	1
fissionable element	1
fissionable nuclei	1
fissionable solutions	1

11. 1958:

"Considerations on the Probability of Nuclear Fission," Robert Vandenbosch and Glenn T. Seaborg, The Physical Review, Vol. 110, No. 2, p. 507, April 15, 1958.

" I. Introduction

In their original considerations of the fission process employing the liquid-drop model, Bohr and Wheeler [*] showed the potential importance of a fissionability parameter Z^2/A which represents the ratio of the nuclear Coulomb repulsive energy to the stabilizing nuclear surface energy. This parameter has been used to designate the relative tendency of different heavy nuclei to undergo thermal-neutron-induced fission.[†,**]

[*] N. Bohr and J. A. Wheeler, Phys. Rev. **56**, 426 (1939).
[†] J. R. Huizenga and R. B. Duffield, Phys. Rev. **88**, 959 (1952).
[**] G. T. Seaborg, Phys. Rev. **88**, 1429 (1952). "

Authors' Note: Here, the fissionability parameter is referred to as Z^2/A without any reference to the denominator, $(Z^2/A)_{\text{limiting}}$ as shown in excerpts 3 and 6.

12. 1958:

The Physical Theory of Neutron Chain Reactors, Alvin Weinberg & Eugene P. Wigner, The University of Chicago Press, 1958, pp. 106-107.

> " Any nucleus may undergo fission if it is in a sufficiently highly excited state.
>
> The excitation energy can be imparted to a nucleus by subjecting it to γ-radiation or by bombarding it with high-energy particles. In the latter case the high-energy particle may lose some of its energy by inelastic collision, which then appears as excitation energy of the target nucleus. The most important way, however, to form a nucleus in an excited state (which then may undergo fission) is to form a compound state between two colliding nuclei which is, as was elaborated above, always in a rather highly excited state. Usually, one of the two colliding particles is a neutron.
>
> As was mentioned before, neutron-induced fission is of greater practical importance than photofission. The threshold for the n-fission reaction is less than the γ-fission threshold of the compound nucleus by the binding energy of the neutron to the target nucleus. As a result, some of the *n*-fission thresholds are "negative"; that is, fission can be induced by thermal neutrons. Nuclei for which this is the case are called "fissionable." "

Authors' Note: Given the stature of Weinberg and Wigner and the vintage of their textbook, the text "any nucleus may undergo fission if it is in a sufficiently highly excited state" appears to be surprisingly superficial. As we explained in the Fission Physics Primer, nuclides below the Businaro-Gallone point (in practice, the stable nuclides below about mass 110) split, according to the liquid drop model, in a highly asymmetric way that may defy the original definition of fission. In any case, the splitting of nuclides below about mass 100 is an endothermic reaction, which is useless, even in principle, for the purposes of a chain reaction. For all nuclides lighter than about thorium the neutron fission cross-section is so small (the lightest with a measured fission cross-section appears to be bismuth, for which the cross-section is 1μb at 23 MeV) that they are useless, in practice, for a chain reaction. We prefer to view Weinberg and Wigner's remark as in the nature of literary license, akin to the views of some of the later more extreme nuclear theorists.

13. 1958:

The Transuranium Elements, Glenn T. Seaborg, Addison-Wesley Publishing Co., Inc., 1958, p. 238.

> " For the nucleus (Z,A) to be fissionable (that is, be such that fission is able to compete very favorably with other processes of de-excitation) with thermal neutrons, Bohr and Wheeler point out that the binding energy of a neutron to nucleus (Z,A) must exceed the critical deformation energy of the nucleus (Z,A + 1). "

Authors' Note: In this excerpt the word *fissionable* is used in the most conservative way, far more restrictive than in many later definitions. In fact it is used in the sense that many later authors restrict to *fissile*.

14. 1961:

"Nuclear Safety Guide, Rev. 1", TID-7016, Subcommittee 8 of the American Standards Association Sectional Committee N6 and Project 8 of the American Nuclear Society Standards Committee, Goodyear Atomic Corporation, 1961.

Authors' Note: The words *fissionable*, and *fissile* are not defined in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document cites 47 references plus a "selected reading list." When a word occurs in the reference list, the titles of the "selected reading list," or the Table of Contents, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, and footnotes in the body of the document. This is the first appearance of the word fissile in the Nuclear Safety Guide series.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissionable material (s)	34
fissionable isotope (s)	15
fissionable atom (s)	3
fissionable metal	3
fissionable nuclei	1
fissionable mass	1
fissionable units	1
fissionable solutions	1
fissile material	1

15. 1961:

"Chapter IX, Criticality," C. M. Nicholls, E. R. Woodcock and A. H. Gillieson, *Chemical Processing of Reactor Fuels*, Academic Press Inc., New York, 1961, pp. 353 and 364.

> " In the case of certain isotopes, of which the naturally occurring uranium-235, and the artificially produced uranium-233 and plutonium-239 are of major importance, the compound nucleus initially formed breaks up immediately into two nuclei of nearly equal mass, together with an average of two to three neutrons, and some gamma rays. This type of nuclear breakdown is called *fission*, and the isotopes which can undergo such breakdown are known as *fissile* isotopes. Material containing these isotopes is referred to as *fissile material*.
>
> 5. The Fissile Chain Reaction
>
> In the fission reaction, the most important factor is that for every neutron causing fission, at least one fission neutron is produced. The actual numbers depend on the fissile materials involved and on the energy of the initiating neutrons, but, as shown in Table III, for thermal neutrons the average number varies between 2.5 and 3. Since, of the neutrons produced, a high proportion are potentially capable of causing fission in another fissile nucleus, once initiated there is the possibility that the fission reaction will be maintained without further external influence, i.e., that a *self-sustaining fissile chain reaction* will take place. "

Authors' Note: In this use of the word *fissile*, it is implicit that fission is caused by thermal neutrons, i.e., neutrons in thermal equilibrium with a solid or liquid moderator.

16. 1961:

Blizard, E. P., Editorial, Nuclear Science and Engineering, Vol. 9, 1961, pg. i.

“

“Fissionable” and “Fissile”

It is seldom that we can increase both the power of our language and the concordance of tongue of the world's two largest English-speaking groups. Yet such a possibility is offered us in a suggestion from a subcommittee on nomenclature of the International Standards Organization.* They propose that the words *fissionable* and *fissile*, which have heretofore had common meanings, be differentiated so that the latter refers to a special case of the first, hoping thereby to permit an economy of words with increased clarity of meaning. New definitions are proposed as follows.

Fissionable: the property of a heavy nucleus such that it can be broken into two nearly equal fragments. Thus U^{238} is said to be fissionable by neutrons of energy greater than 1 Mev or by photons of energy greater than 5.31 Mev.

Fissile: the property of a heavy nucleus such that the binding energy of an additional neutron is sufficient to raise the resultant nucleus above the fission threshold. [Disregarding rare cases such as Pu^{240} in which measurable fissioning occurs below the fission threshold by the tunnel effect, this definition can be paraphrased to mean fissionable by neutrons of essentially zero kinetic energy. Thus in common usage U^{233}, U^{235}, and Pu^{239} will be called fissile because they are fissionable by room temperature thermal neutrons.]

It is our suggestion that this distinction of meaning and sharpening of our vocabulary be adopted by the American Nuclear Society and by the contributors to its journal. The transition need not be abrupt nor taken for granted. Adoption of the new meanings will be indicated where it occurs until it becomes common usage.

Everitt Blizard

* Technical Committee 85 Subcommittee 1 on Symbols, Units, and Nomenclature in Nuclear Energy, from their May 1960 meeting in Geneva. ”

Authors’ Note: Although the above editorial is a brave attempt to bring order to an unruly subject, the definition of the two words *fissionable* and *fissile*, it flounders on the former. As we discussed in the Fission Physics Primer, it is expected that all heavy nuclides above about mass 110 can undergo a fission reaction in principle. Yet we would hesitate to call ^{209}Bi, for example, a fissionable nuclide, even though it has a fission cross-section of over 1 μb at neutron energies greater than 23 MeV. It also introduces the spurious concept of threshold. In the example of ^{238}U being fissionable by neutrons of energy greater than 1 MeV, it should be noted that at this energy the fission cross-section is about 15 mb. At 0.9 MeV it is still 10 mb, and there is a measurable fission cross-section down to energies as low as 720eV. The photon energy of 5.31 MeV quoted is even more startlingly precise. We believe that this energy is based on a measurement of photo-fission made with a mono-energetic gamma-ray source. This is a spot measurement; such sources are limited in number and their energies are quite widely separated. A measurement of the fission probability of ^{238}U as a function of excitation energy using the ^{236}U(t,pf) reaction (bombardment of ^{236}U with a triton, which deposits 2 neutrons and some energy in the nucleus, thus releasing the proton, followed by the fission of the compound ^{238}U nucleus) shows measurable fission probability down to about 4.8 MeV or lower.

17. 1964:

Report of the SPERT I Destructive Test Program on an Aluminum, Plate-Type, Water-Moderated Reactor," R. W. Miller, Alain Sola (Euratom), and R. K. McCardell, IDO-16883, AEC Research and Development Report, Reactor Technology, TID-4500 (30th Ed.), Issued: June 1964, pg. ii, Abstract and pg. iv.

> " Abstract: …These pressures in combination with widespread melting were responsible for completely destroying the core, dispersing melted fuel, damaging other reactor hardware, and causing the release of about 0.7 percent of the fisside content of the core to the atmosphere.
>
> pg. iv: Contamination of the facility and fisside release to the atmosphere was generally very slight since the fisside content of the core was small. Water was removed from the vessel for criticality control shortly after the test, and, even with this reduction in shielding protection, personnel were able to enter the area for observation of the reactor about four hours after the test.
>
> pg. iv: It is estimated from radiological measurements taken in the area around the reactor building during the test that less than 0.7 percent of the fisside content of the core was released to the atmosphere. Radioiodines were not detected, but less than 0.01 percent of the iodines are calculated to have been released to the atmosphere. "

Authors' Note: This seems to be the first use of the word *fisside*. It is not certain if it is a contraction of *fissile nuclide, fissionable nuclide* or *fission product nuclide*.

18. 1964:

"Critical Dimensions of Systems Containing U^{235}, Pu^{239}, and U^{233}," H. C. Paxton, J. T. Thomas, Dixon Callihan, and E. B. Johnson, Los Alamos Scientific Laboratory and Oak Ridge National Laboratory, Report TID-7028, June 1964.

Authors' Note: No definition of *fissile* is given in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document contains a Table of Contents and one hundred and thirty References. When a word occurs in the Table of Contents or References it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, or footnotes in the body of the document. The word fissionable does not appear in the document.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissile material (s)	7
fissile solution	3
fissile element	1
fissile isotope	1
fissile metal	1
fissile mixture	1
fissile sphere	1
fissile units	1

19. 1965:

Physics of Nuclear Kinetics, G. Robert Keepin, Addison-Wesley Publishing Company, Inc., 1965, Footnote on p. 3.

> " *Regarding the use of "fissile" and "fissionable," we shall adopt the convention recommended by the American Nuclear Society.† Thus, "fissile" will herein refer to those heavy nuclides which can be fissioned by thermal neutrons (notably U^{235}, Pu^{239}, and U^{233}), while "fissionable" refers generally to all heavy nuclides which can be fissioned by whatever means.
>
> † E.P. Blizard, editorial in *Nucl. Sci. and Eng,* **9,** No. 3, p. i (1961). "

Authors' Note: The Blizard editorial is reproduced in part as excerpt 16 above. Again the word *fissionable* is used in a way that is too general to be of any practical use. But the definition of *fissile* is also somewhat qualitative. Here is a list of some fission cross-sections for thermal neutrons. First the three mentioned in the excerpt: ^{235}U, 583 b, ^{239}Pu, 748 b, ^{233}U, 529 b. Others are, in increasing Z and A number, ^{223}Ra. 0.7 b; ^{227}Th, 202 b, ^{228}Th, < 0.3 b, ^{229}Th, 31 b, ^{233}Th, 15 b; ^{230}Pa, 1500 b, ^{231}Pa, 201 b, ^{232}Pa, 700 b; ^{231}U, 400 b, ^{232}U, 75 b, ^{237}U, 2 b, ^{236}Np, 2500 b, ^{238}Np, 2090 b; ^{236}Pu, 165 b, ^{237}Pu, 2455 b, ^{238}Pu, 18 b, ^{240}Pu, 0.06 b, ^{241}Pu, 1011 b, ^{242}Pu, < 0.2 b, ^{243}Pu, 196 b; , ^{241}Am, 3.2 b, ^{242m}Am, 6950 b, ^{242g}Am, 2100 b, ^{243}Am, 0.2 b; etc. Where do we draw the line between *fissile* and *non-fissile*?

20. 1966:

"Criticality Control in Operations with Fissile Material," H. C. Paxton, LA-3366, January 15, 1966, p. 7.

" Preface

> This account is intended to promote a broadened base for nuclear safety and to help make available a feel for criticality control to anyone who works with fissile material.*
>
> *For our purpose, "fissile" materials are the usual reactor fuels, U^{235}, Pu^{239}, and U^{233}. The term "fissionable" refers to a broader class that includes, as well as these common fuels, other isotopes that can fission, e.g., U^{238}, Pu^{240}, and Th^{232}. "

Authors' Note: In this document the use of the word *fissile* appears to be too restrictive. On the other hand two of the nuclides that are included as examples of *fissionable* would not be able to sustain a chain reaction with unmoderated neutrons. Again we come up against the question of where we draw the line in describing a nuclide as *fissionable*. The fast neutron cross-sections ("plateau" values for first-chance fission) of ^{238}U, ^{231}Pa, ^{232}Th, ^{227}Ac and ^{226}Ra are respectively 0.5 b, 1 b, 0.15 b, 0.04 b and 0.003 b.

21. 1968:

Criticality Handbook, Volume 1, R. D. Carter, G. R. Kiel, K. Ridgway, ARH-600, June 30, 1968, p. I.C.-2.

> " Fissile materials are those nuclides capable of sustaining a nuclear chain reaction. Known fissile nuclides are: ^{233}U, ^{235}U, ^{237}Np, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{241}Am, ^{242}Am, ^{243}Am, ^{244}Cm, ^{247}Cm, ^{244}Cf, and ^{251}Cf. "

Authors' Note: ^{238}Pu is classified as *non-fissile* in ANSI/ANS-8.15-1981, American National Standard for Nuclear Criticality Control of Special Actinide Elements, Table 1 entitled "Subcritical Mass Limits for Non-Fissile Actinide Nuclides." The word *fissile* is employed in a much more general sense than in much of the earlier usage. In this example the degree of moderation of the neutrons is immaterial for the definition.

22. 1971:

The Illustrated Nuclear Encyclopedia, edited by Erik Bergaust, G. P. Putnam's Sons, New York, 1971, pp. 42-43.

> " *Fissionable Material* – Any material fissionable by slow neutrons. The three basic ones are uranium-235, plutonium-239, and uranium-233.
>
> *Fissile Material* – While sometimes used as a synonym for fissionable material, this term has also acquired a more restricted meaning, namely, any material fissionable by neutrons of all energies, from thermal (slow) to fast; for example, uranium-235 and plutonium-239. *See* Fissionable Material.
>
> *Fission* – The splitting of a heavy nucleus into two approximately equal parts (which are nuclei of lighter elements), accompanied by the release of a relatively large amount of energy and generally one or more neutrons. Fission can occur spontaneously but usually is caused by nuclear absorption of gamma rays, neutrons, or other particles. "

Authors' Note: In this excerpt it is hard to see any distinction between *fissile material* and *fissionable material*, except for some hypothetical nuclide with a high thermal neutron fission cross-section and a very low fast neutron fission cross-section.

23. 1972:

"Theory of Nuclear Fission and Superheavy Nuclei," James Rayford Nix, LA-DC-72-769, August 15, 1972, pp.10 and 11.

" The two shape-dependent terms in the liquid-drop model are the Coulomb energy, which tends to pull the nucleus apart, and the surface energy, which tends to hold it together. The relevant parameter for specifying the static properties of an idealized nucleus is the ratio of these two energies evaluated for a spherical shape. This ratio, when modified by a factor of 2 for convenience, is called the fissility parameter x,

$$x \equiv \frac{E_c^{(0)}}{2E_s^{(0)}} .$$

The larger the value of x, the more easily the system fissions. When $x \geq 1$ an idealized nucleus is unstable with respect to fission, whereas for $x < 1$ it has a finite barrier against fission.

The Coulomb energy of a spherical nucleus is proportional to the charge squared and inversely proportional to the nuclear radius, or, said differently, is proportional to Z^2 divided by $A^{\frac{1}{3}}$,

$$E_c^{(0)} = a_c Z^2 / A^{\frac{1}{3}} .$$

The surface energy of a spherical nucleus is proportional to the surface area, or $A^{\frac{2}{3}}$, but in addition contains a surface-asymmetry term that causes the surface energy to decrease with increasing neutron excess,

$$E_s^{(0)} = a_s A^{\frac{2}{3}} \left[1 - \kappa \left(\frac{N - Z}{A} \right)^2 \right] .$$

Inserting these two expressions into the above definition leads to the result that x is proportional to Z^2/A, but it also contains a term that causes x to increase with increasing neutron excess,

"

$$x = \frac{Z^2/A}{\left(\frac{2a_s}{a_c}\right)\left[1-\kappa\left(\frac{N-Z}{A}\right)^2\right]}.$$

Authors' Note: A precise definition is given here for the *fissility parameter*. This is in fact very similar to the definition of *fissionability parameter* defined by Hill and Wheeler (see excerpt 6), but is extended to include additional physical properties that the nuclear liquid drop may possess. The difference here is in the denominator where $(Z^2/A)_{\text{limiting}}$ (see excerpt 3) has been replaced with a new expression.

Post-Heritage Period
(January 20, 1975 to Present)

24. 1976:

Glossary of Terms in Nuclear Science and Technology, prepared by ANS-9, The American Nuclear Society Standards Subcommittee on Nuclear Terminology and Units, Harry Alter, Chairman, 1976 (Revision of N1.1-1967), pg. 41, 42, and 64.

> " **fissionable**.
> (1) Of a *nuclide*: capable of undergoing *fission* by any process.
>
> (2) Of a material: containing one or more fissionable nuclides.
>
> **fissile**. Of a *nuclide*, capable of undergoing *fission* by interactions with *slow neutrons*.
>
> **fission**, thermal. *Fission* caused by *thermal neutrons*.
>
> **fissium**. (1) *Fissile* material artificially mixed with *fission product* elements to simulate the material resulting from *fission*. The composition of the mixture will depend upon the material and conditions of irradiation to be simulated. (2) An equilibrium mixture of fission products in *nuclear fuel* that has undergone successive cycles of irradiation and *pyrometallurgical processing*.
>
> **neutrons, slow**. Neutrons of kinetic energy less than some specified value. This value may vary over a wide range and depends on the application, such as reactor physics, shielding, or dosimetry. In reactor physics the value is frequently chosen to be 1 eV; in dosimetry the *effective cadmium cutoff* is used. (See also *neutrons*, *fast* and *neutrons*, *intermediate*.
>
> **neutrons, thermal**. Neutrons in thermal equilibrium with the medium in which they exist. "

Authors' Note: The glossary does not clarify whether or not thermal neutrons are included as a component of slow neutrons. Also, fission by slow neutrons is recognized as *fissile*. Fission, thermal is defined but there is no analogous entry for fission, slow.

25. 1977:

The Effects of Nuclear Weapons, compiled and edited by Samuel Glasstone and Phillip J. Dolan, United States Department of Defense and the Energy Research and Development Administration, 1977, page 633.

> " Fission: The process whereby the nucleus of a particular heavy element splits into (generally) two nuclei of lighter elements, with the release of substantial amounts of energy. The most important *fissionable materials* are uranuim-235 and plutonium-239; fission is caused by the absorption of neutrons. "

Authors' Note: Although the above excerpt would appear to aspire to the level of a technical definition of the fission reaction, it remains descriptive twenty-five years after the definition provided in excerpt 5 by the same author.

26. 1978:

"Nuclear Safety Guide, Rev. 2," TID-7016 Revision 2, NUREG/CR-0095, ORNL/NUREG/CSD-6, J. T. Thomas, Ed. Prepared for the U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research Under Interagency Agreement DOE 40-550-75, NRC FIN No. B0163-6, Union Carbide Corporation, Nuclear Division, June 1978.

Authors' Note: The words *fissionable* and *fissile* are not defined in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document has a Table of Contents, List of Figures, List of Tables, and References. When a word occurs in the Table of Contents, List of Figures, List of Tables, or References, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, or footnotes in the body of the document.

By comparison with excerpts 9 and 10, the first two versions of the Nuclear Safety Guide in September of 1956 and 1957, respectively, the word fissile was not used. Revision 1 of the Nuclear Safety Guide, excerpt 14, has one occurrence of the word fissile. In Revision 2 of the Nuclear Safety Guide we see a definite shift in usage from fissionable to fissile.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissionable material (s)	16
fissionable isotope (s)	5
fissionable atoms	1
fissile material (s)	84
fissile nuclide (s)	7
fissile isotope (s)	6
fissile metal (s)	6
fissile solution	2
fissile system	2
fissile units	2
fissile content	1
fissile limits	1

27. 1979:

PNL-SA-4868 Rev. 5, "Anomalies of Nuclear Criticality," E. D. Clayton, Pacific Northwest Laboratory, June 1979, page 88.

> " Nuclides such as $^{231}_{91}Pa$, $^{237}_{93}Np$, $^{238}_{94}Pu$, $^{240}_{94}Pu$, $^{241}_{95}Am$, $^{244}_{96}Cm$, and $^{252}_{98}Cf$ contain even numbers of neutrons and all are fissionable, though not fissile. Fissionable nuclei are considered those for which a chain reaction can be set up, with the majority of fissions caused by high energy neutrons. Fissile nuclei are those for which it is possible to set up a chain reaction in which the majority of fissions are caused by thermal or slow neutrons. It follows that the known nuclei which are fissile are fissionable, but not the converse. "

Authors' Note: It seems to us that the definitions of *fissionable* and *fissile* given here are very reasonable ones. However, it is **not** an incontrovertible rule that target nuclides containing an even number of neutrons are not fissile.

28. 1979:

"Subcritical Limits for Special Fissile Actinides," H. K. Clark, Savannah River Laboratory, December, 1979, *Nuclear Technology* **48**, page 164.

> **“** The definition of fissile nuclide is being altered here from the Standard definition given in the American National Standard *Glossary of Terms in Nuclear Science and Technology* ANS-9/ANSI N1.1-1976 to denote those nuclides having an odd number of neutrons in the nucleus. Despite some special cases mentioned below, this definition appears to be more useful and is unequivocal. The Standard definition is a nuclide “capable of undergoing fission by interaction with slow neutrons.” According to either definition ^{233}U, ^{235}U, ^{239}Pu, and ^{241}Pu are fissile and ^{238}U is not. However, according to the Standard definition, ^{234}U, ^{237}Np, ^{238}Pu, ^{240}Pu, ^{241}Am, ^{244}Cm, and ^{246}Cm are fissile because they have thermal fission cross sections, although in some cases very small; according to the altered definition, they are non-fissile. For these nuclides, the relative thermal capture and fission cross sections are such that the nuclides cannot be made critical in moderated systems, which suggests that the definitions may be made to coincide by extending the Standard definition to include those nuclides capable of being made critical with slow neutrons. Such is not always the case: ^{232}U and ^{236}Pu, which have an even number of neutrons and approximately equal thermal capture and fission cross sections, can perhaps be made critical with slow neutrons, but ^{237}U, which has an odd number, has a very small thermal fission cross section and cannot be made critical. **”**

Authors’ Note: ANS-9/ANSI N1.1-1976 defines a fissile nuclide as a nuclide “...capable of undergoing *fission* by interaction with *slow* neutrons.” See excerpt 24. However, the explicitly stated definition (of having an odd number of neutrons in the nucleus) is unsound (as the writer goes on to show by a specific example - ^{237}U with a thermal fission cross-section of 2 b and a capture cross-section of 443 b!).

29. 1981:

ANSI/ANS-8.15-1981, American National Standard for Nuclear Criticality Control of Special Actinide Elements. (Reaffirmed September 12, 1995.) American Nuclear Society.

" 3.2 Glossary of Terms

fissile nuclide.[†] A nuclide capable of undergoing fission by interaction with slow neutrons provided the effective thermal neutron production cross section, $\overline{\nu\sigma_f}$, exceeds the effective thermal neutron absorption cross section, $\overline{\sigma_a}$.[*]

[†] American National Standard Glossary of Terms in Nuclear Science and Technology, N1.1-1976 (ANS-9). American Nuclear Society, La Grange Park, Ill.

[*] Most actinide nuclides containing an even number of neutrons are non-fissile, but there may be exceptions, such as ^{232}U and ^{236}Pu, which have even numbers of neutrons and approximately equal thermal capture and fission cross sections, which perhaps can be made critical with slow neutrons. Conversely, whereas most nuclides with an odd number of neutrons are fissile, ^{237}U, which is an odd-N nuclide with a very small thermal fission cross section, cannot be made critical with thermal neutrons. "

Authors' Note: In the Glossary, the definition of the term *fissile nuclide* seems to us to be admirably precise, and grasps the spirit of what many earlier writers were groping towards. With this definition we can answer the question in our note to excerpt 19 - which nuclides are fissile and which are not? It turns out that in the list given, most of the nuclides with fission cross-sections of several hundred barns or greater are fissile under this definition; their capture cross-sections, when known, are smaller than their fission cross-sections. ^{236}Pu (σ_f = 165 b, σ_γ = 31 b) is fissile and ^{238}Pu (σ_f = 17 b, σ_γ = 552 b) is not. ^{232}U (σ_f = 77 b, σ_γ = 75 b) is probably marginally fissile while ^{237}U (σ_f = 2 b, σ_γ = 443 b) is certainly not (this is a neat reversal of the oft-cited rule that nuclides with an odd number of neutrons are fissile while those with even neutron number are not). Another interesting pair comprises ^{229}Th (σ_f = 31 b, σ_γ = 61 b) and ^{233}Th (σ_f = 15 b, σ_γ = 1500 b). Neither is fissile (another breakage of the even neutron rule), but while they have rather similar fission cross-sections, their large difference in capture cross-section implies that while the former is marginally non-fissile, the latter is far from being fissile. The above definition infers, but does not explicitly address, the question of whether a system composed exclusively of the nuclide or a system composed of a mixture of the nuclide and other materials in an infinite medium is capable of achieving criticality. The words "effective" and "thermal" in the definition of a fissile nuclide are not defined. Also, the definition does not clarify the distinction between slow neutrons and thermal neutrons.

The words *fissionable*, *fissile* and *non-fissile* are not defined in the above Standard. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The Standard cites four references. When a word occurs in the reference title, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, and footnotes in the body of the Standard.

WORD	**NUMBER OF TIMES WORD IS USED IN THE DOCUMENT**
fissionable materials	2
fissionable units	2
fissile nuclide (s)	10
non-fissile nuclides	4
non-fissile isotope (s)	2
fissile isotopes	1
non-fissile Actinide nuclides	1
fissile Actinide nuclides	1

30. 1984:

McGraw-Hill Dictionary of Scientific and Technical Terms, Third Edition, Sybil P. Parker, Editor in Chief, McGraw-Hill Book Company, 1984, p. 612.

> " **fissionable** [NUCLEO] **1.** A property of material whose nuclei are capable of undergoing fission. Also known as fissile. **2.** A material capable of fission.
>
> **fissile** [GEOL] Capable of being split along the line of the grain or cleavage plane. [NUCLEO] *See* fissionable.
>
> **fission** [BIOL] A method of asexual reproduction among bacteria, algae, and protozoans by which the organism splits into two or more parts, each part becoming a complete organism. [NUC PHYS] The division of an atomic nucleus into parts of comparable mass; usually restricted to heavier nuclei such as isotopes of uranium, plutonium, and thorium. Also known as atomic fission; nuclear fission. "

Authors' Note: The definition of *fissile* is clearly limited to mineralogy, ignoring completely its usage in nuclear science. The dictionary then merges, for nuclear science, the definitions of fissile and fissionability, thus obliterating some two decades of progress towards a useful distinction.

31. 1985:

Letter to the Editor, R. E. Kelley and E. D. Clayton, Nuclear Science and Engineering, Volume 91, Number 4, December 1985, page 481.

> " The term "fissionable" is sometimes used to refer to nuclides in a general sense, although some of them can support a self-sustaining chain reaction and some cannot, which leads to confusion.
>
> **fissile nuclide:** A *nuclide* capable of undergoing *fission* by interaction with *slow neutrons*, provided the effective neutron production cross section, $\overline{\nu\sigma_f}$, exceeds the effective absorption cross section, $\overline{\sigma_a}$.
>
> *Proposed New Definition*:
>
> **fissible nuclide:** A nuclide that cannot support a slow-neutron chain reaction but is only capable of a fast-neutron chain reaction, provided that the effective fast-neutron production cross section, $\overline{\nu\sigma_f}$, exceeds the "effective" fast-neutron removal cross section. "

Authors' Note: This letter reiterates the sound quantitative definition of *fissile* introduced in excerpt 29. It is a pity that the authors did not proceed to give an equally quantitative definition to *fissionable*, relating it to criticality in a spectrum of unmoderated or poorly moderated fission neutrons. Instead, they attach such a definition to a new word *fissible*, which does not seem to have become popularly accepted.

32. 1986:

Glossary of Terms in Nuclear Science and Technology, prepared by ANS-9, The American Nuclear Society Standards Subcommittee on Nuclear Terminology and Units, Harry Alter, Chairman, 1986, pp. 50-51.

> " **fissionable:** (a) Of a *nuclide*, capable of undergoing *fission* by any process; (b) of a material, containing one or more fissionable nuclides.
>
> **fissile nuclide:** A *nuclide* capable of undergoing *fission* by interaction with *slow neutrons*, provided the effective neutron production cross section, $\overline{\nu\sigma_f}$, exceeds the effective absorption cross section, $\overline{\sigma_a}$.
>
> **fission, nuclear:** The division of a heavy nucleus into two (or, rarely, more) parts with masses of equal order of magnitude, usually accompanied by the emission of neutrons, *gamma radiation*, and, rarely, small charged nuclear fragments.
>
> **fissium:**
>
> (a) *Fissile* material artificially mixed with *fission product* elements to simulate the material resulting from *fission*. The composition of the mixture will depend on the material and conditions of irradiation to be simulated.
>
> (b) An equilibrium mixture of fission products in *nuclear fuel* that has undergone successive cycles of irradiation and *pyrometallurgical processing*. "

Authors' Note: Note that the definition of *fissile* has changed from the 1976 edition of the glossary, excerpt 24. This document, published in 1986 by the American Nuclear Society, never achieved the official status of a standard. However, the document was prepared under the same rules for a consensus standard and therefore represents a consensus perspective. The American Nuclear Society Standards Subcommittee has again lent its authority to the precise definition introduced in excerpt 29. But again the word *fissionable* is defined in a far too general way to be useful.

33. 1987:

"Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U, 1986 Revision," H. C. Paxton and N. L. Pruvost, LA-10860-MS, July 1987.

Authors' Note: The words *fission* and *fissile* are not defined in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document has a Table of Contents and one hundred ninety-five references. When a word occurs in the Table of Contents or the References, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, or footnotes in the body of the document.

WORD	**NUMBER OF TIMES WORD IS USED IN THE DOCUMENT**
fissionable material (s)	4
fissile material (s)	9
fissile isotope	1
fissile metal	1
fissile mixture	1
fissile sphere	1
fissile units	1

34. 1989:

"Fission Throughout The Periodic Table," L. G. Moretto and G. J. Wozniak, **50 Years With Nuclear Fission**, **April 25-28, 1989**, edited by James W. Behrens and Allan D. Carlson, ANS/NIST Topical Meeting on Fifty Years with Nuclear Fission (1989: Washington D.C. and Gaithersburg, Md.), published by the American Nuclear Society, pp. 481-482.

> " The answer to the simple question, "What is fission?" is not unique but depends upon the space and time cross section of the scientists to whom the question is addressed.
>
> Even among "experts," fission is typically associated with heavy elements. If its presence is acknowledged, as far down as the Lead region and even lower, its existence becomes progressively more evanescent as one moves farther down the periodic table and its cross section becomes lost in the abyss of nanobarns. Most emphatically, fission is believed to be a unique kind of compound nucleus reaction when compared with the more commonplace decays, like those involving the emission of protons, alphas and other "particles."
>
> In this way we have reached a very remarkable conclusion. Fission, rather than being a peculiar process relegated to the upper reaches of the periodic table and to a remote area of nuclear physics cultivated by oddball scientists, surprisingly turns out to be <u>the</u> most general, all-pervasive reaction in compound-nucleus physics. "

Authors' Note: This excerpt is from a theoretical physics paper that takes an extreme view of the generality of the fission process. It also reveals that inconsistent usage may also occur at the basic nuclear physics level. A second example of inconsistent usage at this level can be found in the first entry of Table 1, Reference 5 and is described in the Fission Physics Primer of this report.

35. 1989:

LA-11627-MS, "Glossary of Nuclear Criticality Terms," Hugh C. Paxton, October 1989, page 5.

> " **fissionable nucleus:** A nucleus capable of fission by neutrons of some energy. Fissionable nuclei include ^{238}U, ^{240}Pu, and others with neutron-energy fission thresholds, in addition to those that are fissile. See *fissile nucleus*.
>
> **fissile nucleus:** A nucleus capable of fission by thermal neutrons, provided the effective neutron production cross section, $\overline{\nu\sigma_f}$, exceeds the effective absorption cross section, $\overline{\sigma_a}$. The common fissile nuclei are ^{235}U, ^{239}Pu, and ^{233}U.* **See** *absorption*, *neutron*; *fission*, *nuclear*.
>
> * *Glossary of Terms in Nuclear Science and Technology,* 1986, revision, prepared by ANS-9, the American Nuclear Society Standards Subcommittee on Nuclear Terminology and Units, Harry Alter, chairman, American Nuclear Society Publication, La Grange Park, IL. "

Authors' Note: The above Glossary of Terms is reproduced in part in excerpt 32 above. The precise definition of *fissile* introduced in the Glossary of the ANS Standard is adopted in this document. But the spurious concept of threshold instead of the barrier tunnelling effect is used to separate the concept of *fissionable* from *fissile.*

36. 1994:

Understanding Radioactive Waste, Fourth Edition, Raymond L. Murray, Battelle Press, 1994, pp. 35 and 179.

> " page 35: The terms "fissionable" and "fissile" are often used to describe types of nuclei. All nuclei can be made to undergo fission if the bombarding neutron has high enough energy. In other words, all nuclei are fissionable, but only a few, the fissile isotopes, can be fissioned with slow (thermal) neutrons. These are uranium-235, uranium-233, plutonium-239, and plutonium-241.
>
> page 179, GLOSSARY: **Fission** – splitting of nuclei by neutrons. "

Authors' Note: In this excerpt *fissionable* is again used in too general a sense to be useful (or even accurate), while the nuclides stated to be *fissile* are too limited in number.

37. 1995:

Order DOE O 420.1, U.S. Department of Energy, Subject: Facility Safety, Approved: 10-13-95. Section 4.3, Nuclear Criticality Safety, pp. 9-10.

“ **4.3.3 Specific Requirements.**

a. Contractor Criticality Safety Programs (CCSPs) shall apply to operations involving fissionable materials that pose a criticality accident hazard. Fissionable nuclides of concern to this section are listed in Table 4.3-1. The assignment of nuclides to the three columns in Table 4.3-1 is based on typical conditions. DOE Elements shall ensure that each contractor organization shall determine which column is appropriate to the fissionable nuclides existing in its inventory, whether listed in this table or not expressly included. Specific technical information concerning differences in behavior of these nuclides relevant to their differing abilities to support a self-sustaining nuclear chain reaction may be found in ANSI/ANS-8.1-1983, R88 and ANSI/ANS-8.15-1981, R87.

Table 4.3-1. Fissionable Nuclides of Criticality Concern

Nuclide	Nuclide	Nuclide
92U233*	93Np237	91Pa231**
92U235*	94Pu238	92U232**
94Pu239*	94Pu240	92U234**
	94Pu241	96Cm246**
	94Pu242	98Cf250**
	95Am241	98Cf252**
	95Am242m	99Es254**
	95Am243	
	96Cm243	
	96Cm244	
	96Cm245	
	96Cm247	
	98Cf249	
	98Cf251	

* existing in quantities and forms that lead to the major focus of nuclear criticality safety

** existing in isolated quantities less than potential minimum critical mass (per ANSI/ANS-8.15-1981, R87, "Nuclear Criticality Control of Special Actinide Elements") ”

Authors' Note: In this report we find an implicit definition in the use of *fissionable*, namely, nuclides that can support criticality. In this sense it includes the nuclides that are generally regarded as *fissile*.

38. 1996:

"Nuclear Criticality Safety Guide", Norman L. Pruvost and Hugh C. Paxton, Editors, LA-12808, September 1996.

Authors' Note: The words *fissionable* and *fissile* are not defined in this technical reference document. However, in order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The document has a Table of Contents, List of Figures, List of Tables, and one hundred and fifty references. When a word occurs in the Table of Contents, List of Figures, List of Tables, or References, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text, tables, figures, or footnotes in the body of the document.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissionable material	9
fissionable objects	2
fissile material	66
fissile density	12
fissile nuclide (s)	12
fissile unit (s)	9
fissile solution (s)	6
fissile metal	5
fissile system (s)	3
fissile species	2
fissile atomic ratio	1
fissile atomic species	1
fissile-bearing components	1
fissile-bearing region	1
fissile cores	1
fissile oxides	1
fissile solute	1

39. 1997:

International Standard, ISO 921:1997(E/F/R), Second edition, 1997-02-01, "Nuclear energy - Vocabulary," pg. 95, 96, 98, and 162.

" **483 fissionable** <nuclide>
capable of undergoing **fission** by any process

484 fissionable <material>
containing one or more **fissionable** (483) **nuclides**

467 fissile <nuclide>
capable of undergoing **fission** by interaction with **slow neutrons**

NOTE - The exact classification may be found in regulatory documents.

468 fissile <material>
containing one or more **fissile nuclides**

470 fissile material
material containing one or more **fissile** (or rarely, **fissionable**, for example, ^{238}Pu) **nuclides**, and capable of being made **critical** under appropriate conditions

471 fissile nuclide
nuclide capable of undergoing **fission** by interaction with **slow neutrons**

NOTE - This term does not apply to nuclides whose slow neutron fission **cross-section** is negligibly small, for example ^{238}U.

485 fissium
artificial mixture of the natural elements represented among the **fission products** to simulate the chemical composition of the material resulting from **fission**

NOTE - The composition of the mixture will depend on the irradiated material and the conditions of irradiation to be simulated.

486 fissium
fission product component in the mixture of **nuclear fuel** and fission products reached after repeated passage of the fuel through a specified fuel cycle involving pyrometallurgical processing

823 nuclear fission
fission
division of a heavy **nucleus** into two (or, rarely, more) parts with masses of equal order of magnitude, usually accompanied by the emission of **neutrons**, **gamma-radiation**, and, rarely, small charged nuclear fragments ”

Authors' Note: This relatively recent document (1997) has slipped back to very imprecise definitions of both *fissionable* and *fissile*.

40. 1998:

ANSI/ANS-8.1-1998, American National Standard for Nuclear Criticality Safety in Operations with Fissionable Materials Outside Reactors, American Nuclear Society.

" **3. Definitions**

3.1 Limitations. The definitions given below are of a restricted nature for the purposes of this standard. Other specialized terms are defined in *Glossary of Terms in Nuclear Science and Technology*.*

* *Glossary of Terms in Nuclear Science and Technology*. "

Authors' Note: The reference above is reproduced in part as excerpt 32. In order for the reader to gain an impression of what words are used and with what frequency they are used, the table below is provided. The standard cites nine references. When a word occurs in the reference title, it is not included in the count. That is, the count is intended to reflect the frequency of the word as it occurs in the text and footnotes in the body of the standard.

WORD	NUMBER OF TIMES WORD IS USED IN THE DOCUMENT
fissionable material (s)	9
fissionable isotopes	1
fissionable units	1
fissile nuclide (s)	10
fissile concentration	1
fissile material	1
fissile solute	1

41. 2000:

The American Heritage Dictionary of the English Language: Fourth Edition, 2000, pg. 665.

“ **fissionable**

ADJECTIVE: Capable of undergoing fission: "*fissionable nuclear material*."

OTHER FORMS: **fissionability** - NOUN

fissile

ADJECTIVE: **1.** Possible to split. **2.** *Physics* Fissionable, especially by neutrons of all energies. **3**. *Geology* Easily split along close parallel planes.

OTHER FORMS: **fissility** - NOUN

fission

NOUN: **1.**The act or process of splitting into parts. **2.** A nuclear reaction in which an atomic nucleus, especially a heavy nucleus such as an isotope of uranium, splits into fragments, usually two fragments of comparable mass, releasing from 100 million to several hundred million electron volts of energy. **3.** *Biology* An asexual reproductive process in which a unicellular organism divides into two or more independently maturing daughter cells.

VERB: Inflected forms; **-sioned, -sion·ing, -sions**

TRANSITIVE VERB: To cause (an atom) to undergo fission.

INTRANSITIVE VERB: To undergo fission. ”

Authors' Note: Assuming that there is general agreement that grammar follows usage, we note that the editors of the dictionary do not hesitate to provide grammar implying that they are aware of usage in the fields of physics, geology, and biology. The usage panel of this edition of the American Heritage Dictionary included Freeman J. Dyson, writer and Professor of Physics, Institute for Advanced Study, Princeton, NJ. Despite the presence of such knowledgeable and distinguished individuals on the usage panel, the definitions of fissionable and fissile are again merged as in excerpts 22 and 30. Excerpts 22, 30, and 43 illustrate that reiteration of dictionary definitions is not sufficient to establish proper usage. Proper usage should be established from within the profession. In this case, the standards, not dictionaries or regulatory documents, should serve as the appropriate reference for proper usage.

42. 2004:

Code of Federal Regulations, Energy, 10, Part 830, Revised as of January 1, 2004, 10CFR830 (1-1-2000 Edition), p. 519. Published by the U.S. Government Printing Office. This excerpt was obtained on September 13, 2004 from U.S. Government online Code of Federal Regulations.

> " **Department of Energy**
> **§830.3 Definitions**
>
> *Fissionable materials* means a nuclide capable of sustaining a neutron-induced chain reaction (e.g., uranium-233, uranium-235, plutonium-238, plutonium-239, plutonium-241, neptunium-237, americium-241, and curium-244). "

Authors' Note: This document uses a precise definition of *fissionable*. Note that it encompasses the *fissile* nuclides.

43. 2004:

Code of Federal Regulations, Energy, Title 10, Volume 2, Part 71, Revised as of January 1, 2004, 10CFR71 (1-1-2004 Edition), "Part 71 - Packaging and Transportation of Radioactive Material," p. 281. Published by the U.S. Government Printing Office. This excerpt was obtained on September 13, 2004 from the U.S Government online Code of Federal regulations.

> " **Nuclear Regulatory Commission**
> **§71.4 (Definitions)**
>
> *Fissile material* means plutonium-238, plutonium-239, plutonium-241, uranium-233, uranium-235, or any combination of these radionuclides. Unirradiated natural uranium and depleted uranium, and natural uranium or depleted uranium that has been irradiated in thermal reactors only are not included in this definition. Certain exclusions from fissile material controls are provided in §71.53. "

Authors' Note: ^{238}Pu is listed as *non-fissile* in ANSI/ANS-8.15-1981, American National Standard for Nuclear Criticality Control of Special Actinide Elements, Table 1 titled "Subcritical Mass Limits for Non-Fissile Actinide Nuclides." See excerpt 29 above. ^{238}Pu is also listed as *not fissile* in PNL-SA-4868, Rev. 5, "Anomalies of Nuclear Criticality" E. D. Clayton, Pacific Northwest Laboratory, June 1979, page 88. See excerpt 27 above. In fact, the thermal neutron capture cross-section (540 b) is so much higher than the fission cross-section (18 b) that it is certainly not fissile under the definition in the glossary of ANSI/ANS-8.15-1981 (excerpt 29). Apart from this, the definition of *fissile material* given in this excerpt is excessively limited, there being several other nuclides known to be fissile or possibly fissile under the 1981 definition. It would appear that, in this case, any technically based justification for defining Pu^{238} as fissile has been abandoned in favor of a definition designed to meet administrative, regulatory-based needs. We have not located any NRC technical document that clarifies the basis for labeling Pu^{238} as fissile. It should be noted that anticipated changes to 10CFR71 will remove Pu^{238} from the category of fissile isotopes.

Conclusions

The heritage of the words *fission* and *fissile* predate the beginning of the Heritage period, as pointed out in the section titled "Pre-Heritage Period". The word *fissionable* presumably also predates the Heritage Period where it would have been utilized in a context other than nuclear fission. Our interest, however, is heritage and usage in the Heritage and Post-Heritage Periods and in the context of nuclear fission as a physical phenomenon resulting in criticality. We recognize that criticality is properly considered as a subject within nuclear technology even though the understanding of criticality rests on basic nuclear physics concepts.

We think that usage of the words *fissionable* and *fissile* is not consistent within the criticality community either within or between the Heritage and post-Heritage periods. We have pointed out specific aspects of inconsistency in the form of Authors' Notes attached to the excerpts. There is no compelling reason to expect consistent usage because, during the Heritage period, individual sites had distinctively different missions and technologies. The lack of consistent usage is not an inherent weakness of the English language. The introduction of more words will not result in systematic usage or clarity of thought.

Physics structure is the proper basis for developing an appropriate language structure. At present, language structures are created and utilized to mistakenly arrive at physics structures. The physics and terminology of the fission reaction do not directly suggest a clear basis for proper usage of the words *fissionable* and *fissile* in criticality. Even if a fresh start with definition of proper usage were to occur, this would not imply that a classification structure for criticality exists amongst the Actinide nuclides capable of criticality. No such classification structure should be attempted until much more reliable and detailed knowledge is in place.

Consistent usage of the word fissile appears to be well established for the nuclides U^{233}, U^{235}, and Pu^{239} and that is towards the definition given in the Glossary of ANSI/ANS-8.15-1981 (excerpt 29). Unfortunately, *fissionable* is still very much a Humpty Dumpty word.

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3. "Fission Throughout The Periodic Table," L. G. Moretto and G. J. Wozniak, **50 Years With Nuclear Fission**, **April 25-28, 1989**, edited by James W. Behrens and Allan D. Carlson.
4. J. Eric Lynn, *Modern Fission Theory for Criticality*, LA-14098, February, 2004.
5. Dorin N. Poenaru and Marin S. Ivascu, editors, Particle Emission from Nuclei, Volume III, CRC Press, 1989, Page 4, Table 1.
6. "The Mechanism of Nuclear Fission," Niels Bohr and John Archibald Wheeler, *Physical Review*, Vol. 56, p. 426, September 1, 1939.
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